

# **Multicore Fiber Cavity Arrays for future Applications in Optomechanical Metamaterials**

Florian Matthias Giefer

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I hereby declare that the work presented here was formulated by myself and that no sources or tools other than those cited were used.

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1. Supervisor: Prof. Dr. Sebastian Hofferberth
2. Supervisor: Prof. Dr. Martin Weitz



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# Contents

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|          |                                                                                      |           |
|----------|--------------------------------------------------------------------------------------|-----------|
| <b>1</b> | <b>Introduction</b>                                                                  | <b>1</b>  |
| <b>2</b> | <b>Motivation and Foundations</b>                                                    | <b>3</b>  |
| 2.1      | Introduction to Fabry-Perot Cavities . . . . .                                       | 3         |
| 2.2      | Fiber Fabry Perot Cavities . . . . .                                                 | 8         |
| 2.3      | Cavity Optomechanics . . . . .                                                       | 9         |
| 2.3.1    | Optomechanical Spring Effect . . . . .                                               | 11        |
| 2.4      | Laterally coupled multi membrane systems . . . . .                                   | 11        |
| 2.5      | Desired Geometry . . . . .                                                           | 13        |
| 2.5.1    | Achieving simultaneous resonance in the multicore fiber cavity array . . . . .       | 15        |
| <b>3</b> | <b>Multicore Fiber Interface</b>                                                     | <b>17</b> |
| 3.1      | Fiber Cavity Manufacturing . . . . .                                                 | 17        |
| 3.1.1    | CO <sub>2</sub> Laser Ablation Tests . . . . .                                       | 18        |
| 3.1.2    | Alternative methods: Backside wet Etching . . . . .                                  | 20        |
| 3.1.3    | FIB-Machining of Multicore Fiber Surfaces . . . . .                                  | 21        |
| 3.1.4    | Surface Characterization and CO <sub>2</sub> Laser Smoothing of FIB-Fibers . . . . . | 36        |
| 3.2      | Mechanical Stability of the Fiber . . . . .                                          | 40        |
| 3.3      | Fiber Mirror Coating . . . . .                                                       | 41        |
| 3.4      | Splicing Multicore Fibers . . . . .                                                  | 42        |
| 3.5      | Fiber Cavity Array Demonstration . . . . .                                           | 44        |
| 3.5.1    | Transmission, Reflection and Quantification of Channel Crosstalk . . . . .           | 45        |
| 3.5.2    | Cavity Array and Finesse Measurement . . . . .                                       | 48        |
| 3.5.3    | Cavity Detuning and Changes Through Tilt Introduction . . . . .                      | 50        |
| <b>4</b> | <b>Mechanical Resonator Dimer Tests</b>                                              | <b>51</b> |
| 4.1      | Measurement Setup . . . . .                                                          | 51        |
| 4.2      | Structure Iterations and Measurements . . . . .                                      | 53        |
| <b>5</b> | <b>Conclusion</b>                                                                    | <b>59</b> |
| <b>A</b> | <b>Appendix</b>                                                                      | <b>61</b> |
| A.1      | Fiber Mirror Manufacturing Images . . . . .                                          | 61        |
| A.1.1    | Additional SEM and ion images . . . . .                                              | 61        |
| A.1.2    | Interferometer Images of CO <sub>2</sub> Laser Smoothing . . . . .                   | 67        |

|                        |                                                        |           |
|------------------------|--------------------------------------------------------|-----------|
| A.1.3                  | Multicore Fiber Inventory . . . . .                    | 73        |
| A.2                    | Fiber Cavity Array Measurement Additions . . . . .     | 74        |
| A.3                    | Mechanical Membrane Spectra . . . . .                  | 80        |
| A.4                    | Statement on Digital Tools and AI Assistance . . . . . | 82        |
| <b>Bibliography</b>    |                                                        | <b>83</b> |
| <b>List of Figures</b> |                                                        | <b>92</b> |
| <b>List of Tables</b>  |                                                        | <b>95</b> |

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## Introduction

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The foundation for the field of optomechanics was the discovery that light carries momentum. This was already hinted at through the observation that tails of comets systematically point away from the sun. Even though there is historical evidence suggesting that this fact was already known before, Johannes Kepler was one of the first to explain it by a repulsive force emanating from the sun, what we would call radiation pressure nowadays [1, 2].

The field of cavity optomechanics explores systems where a mechanically compliant element interacts with the light in an optical resonator through radiation pressure. The consequences of such interaction were first analyzed in the context of interferometer-based gravitational wave detectors, where the shot noise of photons and the corresponding radiation pressure limit the measurement precision by shifting interferometer mirrors and thus altering the interferometer arm length [3]. Most modern detectors, such as LIGO, employ Fabry-Perot cavities before the interferometer arms (power recycling mirrors) and in the interferometer arms to increase the effective path length [4]. Thus a lot of effort was and is invested to understand and manage optomechanical effects [5–13]. This is especially necessary because optomechanical phenomena play a bigger role in cavity based systems, as the cavity enables repeated interaction between light and mechanics, boosting the effective coupling strength. The technological utilization of cavity optomechanics proved to be immensely useful beyond gravitational wave research [14], e.g. in high precision sensing technology [15–20] and for the implementation of quantum networks by enabling coherent conversion between the microwave and the optical regime [21–27].

A flexible, miniaturized optical Fabry-Perot cavity platform that allows the integration of microscopic mechanical resonators with direct fiber-coupled in- and output are so-called fiber Fabry-Perot cavities (FFPCs). These fiber cavities are optical resonators constructed from one (with mirror substrate) or two mirror-coated fiber end facets. Initial devices with low finesse emerged for filtering applications in optical communications [28]. Higher Finesse variants came up significantly later and were initially created with mirror transfer techniques to the fiber end facets [29]. Soon the community mostly converged on CO<sub>2</sub> laser surface ablations and subsequent Bragg reflector coating, as demonstrated by Hunger et al. in 2010 [30]. The resulting fiber cavities feature strong miniaturization and inherent fiber coupling. Because of this and their positioning flexibility plus small mode volume, they are ideal for rapid prototyping of optomechanical structures on the tens of micrometer size scale, while also offering many important applications for cavity enhanced sensing or cavity QED [28].

Recent advances have sparked interest in opto-acoustic circuit and metamaterial structures [31–42], as platforms for controlled multi-mode light-mechanics interactions, and stimulate increasing ambitions

for the creation of optomechanical logical circuits with rising complexity [43–45]. An optomechanical metastructure with multiple optomechanical coupling sites would require a reliable local optical interface to each individual site, while ideally keeping the advantages of fiber cavities that make them so useful for individual resonator optomechanics. This would require integrating many fiber cavities in a tight space. A similar challenge has also been faced within optical telecommunications applications, where rising bandwidth demands led to the introduction of space division multiplexing. To be able to transmit multiple optical modes in one fiber, while keeping many of the advantages of (single strain) single mode fibers, so called multicore fibers, were introduced. Multiple cores are encased in a single cladding, engineered for low crosstalk [46, 47]. This thesis aims to combine fiber-optic cavities with this multi-core technology and realize optical cavity arrays on the end facets of telecom multicore fibers at 1550 nm to establish them as a possible interface to optomechanical metamaterials.

In this thesis a fiber with 7 cores will be used to achieve an array of seven cavities with a single fiber. If a sufficient manufacturing precision is achieved and combined with a core specific length tuning capability (a possible approach is outlined in Sec. 2.5.1) a simultaneous resonance of the array could become possible. Then these multicore fiber based cavity arrays could also have important applications in atomic physics like cavity QED experiments on coupled atomic ensembles or as localized interface for optical lattices and tweezer arrays, for example experiments like [48]. An alternative approach was recently demonstrated by Shaw et al. who advanced the applications of cavity arrays for atomic physics experiments significantly through the introduction of their “cavity-array microscope” for the interface of multiple single atoms. They also demonstrated an array of up to 500 low finesse cavities (without atoms) [49]. The Finesse is limited through the high number of optical surfaces needed in the cavity volume to form the array, as this setup uses macroscopic mirrors with a micro lens array. This problem would be mitigated by the multicore fiber approach demonstrated here, while e.g. through introduction of a fiber array (with techniques as in [50]), a potentially similar scaling of the cavity number could be achieved.

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## Motivation and Foundations

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As already explained in the introduction, the scaling of optomechanical devices to full metamaterials is currently an active area of research and these kind of devices would strongly benefit from a localized control over individual resonator sites. A possible approach to achieve that control is the interface of the material with an array of optical micro cavities. This thesis aims to be a first step in the investigation whether fiber-based micro cavity arrays are a viable route to achieve this desired control of optomechanical metamaterials. Other cavity array platforms like the one by Shaw et al. can only achieve limited finesse through the high number of optical surfaces [49] and approaches like the one by Ding et al., where the high quality mirror is applied to an ultra clean silicon wafer and where the mirror geometry is created by selective etching of the silicon [51], can reach very high finesse but still can not reach the same small mode volumes as fiber cavities, which would be useful as e.g. the optomechanical coupling strength (Eq. 2.14) scales beneficially with smaller mode volume. In the following sections some key concepts on fiber cavities and optomechanical devices will be introduced and with this knowledge a concept how localized control over optical metamaterials can be achieved is presented. In the chapters after that the progress to realization of this platform during this master thesis is demonstrated.

### 2.1 Introduction to Fabry-Perot Cavities

Fabry-Perot cavities are a standard tool in optics, the basic idea of a Fabry-Perot cavity is to trap light by reflecting it back and fourth between two mirrors, which enables very high light intensities and repeated opportunities for light matter interaction. The first concepts will be introduced along the lines of [52]. We will investigate an idealized system of two plano-parallel mirror surfaces and light propagating towards the first mirror with a normal incident angle, for simplicity the finite penetration depth of the reflected light into the mirror is ignored here. Upon reaching the first mirror there is a non vanishing component of the incoming light that will be transmitted. Let the second mirror be placed behind the first mirror after a distance of  $L$ , a part of the light that was transmitted through the first mirror will be reflected from the second one (another part is transmitted) and upon hitting the first mirror there will again be a reflected and transmitted part and so on. Depending on the length  $L$  there will be configurations in which the light constructively interferes, this happens if the acquired path difference after one round trip is a whole number multiple (here  $m$ ) of the wavelength (at  $m + \frac{1}{2}$  we would get destructive interference). At the same time we know that the light had to traverse a distance of  $2L$  for the roundtrip, so we know

that on resonance we have

$$2L = m \cdot \lambda_{\text{med}}.$$

Here  $\lambda_{\text{med}}$  is the wavelength of the light in the cavity medium. The wavelength in a medium can be calculated as  $\lambda_{\text{med}} = \frac{c}{\nu \cdot n}$ , where  $c$  is the vacuum speed of light,  $n$  the refractive index and  $\nu$  the light frequency. If we plug this in and solve for  $\nu$  we get

$$\nu_m = m \cdot \frac{c}{2nL}. \quad (2.1)$$

We can then find for neighboring resonances that they will be spectrally spaced by

$$\Delta\nu_{\text{FSR}} = \nu_{m+1} - \nu_m = \frac{c}{2nL}.$$

$\Delta\nu_{\text{FSR}}$ , is called free spectral range. It should be noted that  $\Delta\nu_{\text{FSR}}$  is also the inverse of the time light needs to complete a full round trip, named  $\tau_{\text{RT}}$ , in the cavity (as can be seen from the condition that a distance of  $2L$  has to be traversed by light traveling at speed  $\frac{c}{n}$ , so one gets  $\frac{c}{n} \cdot \tau_{\text{RT}} = 2L$ ).

$$\Delta\nu_{\text{FSR}} = \frac{c}{2nL} = \frac{1}{\tau_{\text{RT}}} \quad (2.2)$$

If one sketches the circulating and reflection power spectrum of the cavity one would get a behavior as visible in Fig. 2.1 (a) and (b), with characteristic (approximately) lorentzian shaped extrema upon resonant light frequency at a given length (or on resonant length for constant light frequency). The width of the resonances at constant FSR is determined by the losses of the resonator, in the ideal case just mirror transmission, but one can keep it more general by introducing an intensity attenuation factor  $r^2$  that characterizes the losses on each round trip, governed by the mirror transmission, scattering and absorption. The following explanation is based upon [53].

$$r^2 = R_1 R_2 \exp(-2\alpha_s L) \quad (2.3)$$

Here  $\alpha_s$  is the absorption coefficient of the medium and  $R_1$  and  $R_2$  the respective mirror power reflectivities. We can define the finesse as:

$$\mathcal{F} := \frac{\pi r^{1/2}}{1 - r} \quad (2.4)$$

If one plugs Eq. 2.3 into Eq. 2.4 we can get:

$$\mathcal{F} = \frac{\pi (R_1 R_2 \exp(-2\alpha_s L))^{1/4}}{1 - \sqrt{R_1 R_2 \exp(-2\alpha_s L)}}$$

If we assume absorption to be negligible we can recover a Formula for the finesse that is ideal to get a first idea of the optimal finesse experimentally achievable by two mirrors of given reflectivity.

$$\mathcal{F} = \frac{\pi (R_1 R_2)^{1/4}}{1 - \sqrt{R_1 R_2}} \quad (2.5)$$

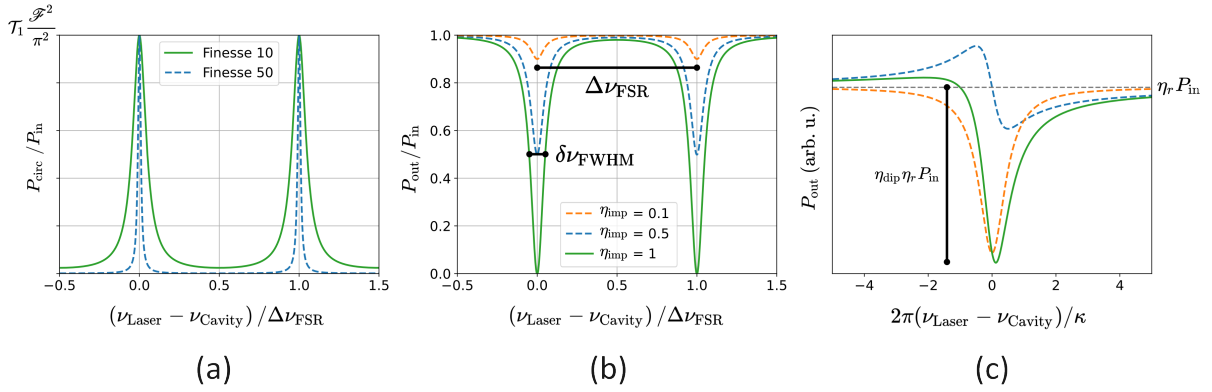


Figure 2.1: Plots to visualize cavity resonance line shape. **(a):** Relative circulating Power in an idealized Free Space Fabry Perot cavity against Frequency. Two different finesse situations are plotted (green and blue lines). **(b):** Idealized free-space cavity reflection Line shape with three different impedance-matching situations. **(c):** Reflection Lineshape of a Fiber Fabry Perot cavity (green line) against normalized detuning, the mode filtering effect of the fiber leads to a distortion of the lorentzian dip (orange dotted line) which can be characterized by an additional dispersive component (blue dotted line). These plots were inspired by [54].

On the other hand it is also possible to absorb the mirror reflectivities into the absorption coefficient and define a new loss quantifier  $\alpha_r = \alpha_s + \frac{1}{2L} \ln \frac{1}{R_1 R_2}$ .

$$\begin{aligned} \mathcal{F} &= \frac{\pi (R_1 R_2 \exp(-2\alpha_s L))^{\frac{1}{4}}}{1 - \sqrt{R_1 R_2 \exp(-2\alpha_s L)}} \\ &= \frac{\pi \exp(-\alpha_r L/2)}{1 - \exp(-\alpha_r L)} \end{aligned}$$

If we then assume the losses to be small ( $\alpha_r L \ll 1$ ) we can get an approximation formula that relates the finesse to the losses per roundtrip by expanding the exponential up to first order.

$$\mathcal{F} \approx \frac{\pi}{\alpha_r L} - 1/2 \quad (2.6)$$

We can then neglect the  $-1/2$  and bring  $\alpha_r$  into a more familiar form by separating the logarithm and then using the approximation  $\ln(1-x) \approx -x$  thus we can get

$$\alpha_r \approx \alpha_s + \frac{1-R_1}{2L} + \frac{1-R_2}{2L}.$$

If we plug this into Eq. 2.6 we get

$$\mathcal{F} \approx \frac{2\pi}{(1-R_1) + (1-R_2) + 2\alpha_s L}$$

We can now introduce the Power Transmission and Loss factor at the mirrors  $\mathcal{T}$  and  $\mathcal{L}$ . Furthermore it is noteworthy that other external loss sources similar to  $\alpha_s$  can also be considered [55], we can thus



formulate the slightly more general approximation of the finesse

$$\mathcal{F} \approx \frac{2\pi}{\mathcal{T}_1 + \mathcal{L}_1 + \mathcal{T}_2 + \mathcal{L}_2 + \sum \mathcal{L}_{\text{ext}}}, \quad (2.7)$$

where  $\sum \mathcal{L}_{\text{ext}}$  is the sum over all external losses.

Experimentally the relation

$$\mathcal{F} \approx \frac{\Delta\nu_{\text{FSR}}}{\delta\nu_{\text{FWHM}}}, \quad (2.8)$$

which is fulfilled for  $\mathcal{F} \gg 1$ , is also of utmost importance, as free spectral range and width of the resonance are experientially well accessible.

Furthermore the finesse is related to the mean number of round trips through the cavity (this explanation is now additionally to [53] based on [55]). We can understand this in more detail by substituting Eq. 2.2 and Eq. 2.6 into Eq. 2.8, through which we can define a characteristic power decay time  $\tau_{\text{decay}}$  based on the fact that  $c\alpha_r$  is the loss per unit time.

$$\delta\nu_{\text{FWHM}} \approx \frac{c\alpha_r}{2\pi} = \frac{1}{2\pi\tau_{\text{decay}}}$$

Please note that we can write at the same time:

$$\delta\nu_{\text{FWHM}} \approx \frac{\Delta\nu_{\text{FSR}}}{\mathcal{F}} = \frac{1}{\mathcal{F}\tau_{\text{RT}}}$$

From this we can extract the mean number of round trips, given by the quotient of decay and round trip time

$$n_{\text{RT}} \approx \frac{\tau_{\text{decay}}}{\tau_{\text{RT}}} = \frac{\mathcal{F}}{2\pi}$$

We can now take a closer look on the resonance line shape with an explanation following [54], please also look there for a derivation of the following concepts. If we again consider the mirrors to be fully characterized by their power Reflectivity, Transmission and Losses and ignore other loss channels we can find for the circulating power in the resonator

$$P_{\text{circ}} = P_{\text{in}} \mathcal{T}_1 \frac{\mathcal{F}^2}{\pi^2} \frac{1}{1 + 4 \frac{\mathcal{F}^2}{\pi^2} \sin^2 \left( 2\pi \frac{\nu}{2\Delta\nu_{\text{FSR}}} \right)},$$

if we assume  $\mathcal{T}, \mathcal{L} \ll 1$  and  $\mathcal{L}_1 = \mathcal{L}_2$ . At higher finesse the individual peaks of this spectrum can be approximated by Lorentzian line shapes. We can now introduce the so called impedance-matching factor

$$\eta_{\text{imp}} = \left( 1 - \left( \frac{\mathcal{T}_1 - (\mathcal{T}_2 + 2\mathcal{L})}{\mathcal{T}_1 + \mathcal{T}_2 + 2\mathcal{L}} \right)^2 \right),$$

this factor is characterizing how similar the transmission through the first mirror is to the losses, if we have  $\mathcal{T}_1 = \mathcal{T}_2 + 2\mathcal{L}$  the factor becomes one and we say that we are critically coupled. We can now also check how the reflected power behaves and will find that it has the same spectral behavior as the

intracavity Power but will feature a minimal Power on resonance given by

$$P_r = (1 - \eta_{\text{imp}}) P_{\text{in}}.$$

This basically means: If we are ideally impedance-matched the reflection will drop to zero upon resonance and all the light will be transmitted into the resonator. The effect of impedance-matching on the resonance shape is indicated in Fig. 2.1(b). The depth of the resonance will simply be  $P_{r_{\text{depth}}} = \eta_{\text{imp}} P_{\text{in}}$ .

So far we treated optical cavities that consist of two planar mirrors, as one can imagine: It is basically impossible to make them exactly parallel, meaning in reality light can escape from the resonator already after a few cycles, which limits the achievable finesse. We can add a confining potential for the light by changing our mirror geometries to concave spherical surfaces. A ray transfer matrix calculation can show us a condition for the stability of optical cavities, the following explanation is again based on [53], where also the calculation can be found. We say that a optical resonator is stable if the condition

$$0 \leq G_1 G_2 \leq 1 \quad (2.9)$$

holds, where  $G_i = 1 - L/\mathcal{R}_i$  and  $\mathcal{R}_1, \mathcal{R}_2$  are the radii of curvature of the two cavity mirrors, because in an idealized picture the distance of a light ray from the optical axis will not grow indefinitely with an increasing number of round trips. If the inequality becomes an equality one calls the cavity conditionally stable, in this regime small alignment errors will make the cavity unstable. If the inequality is not fulfilled we call the resonator unstable. Notably the misalignment sensitivity in the stability region is not constant, this is relevant for Sec. 2.5 and is explained in [56]. Finally it is worth to take a quick look at the size of the cavity mode at the waist and at the Mirror (explanation again based on [54]). We can find for the cavity mode waist size that

$$w_0^2 = \frac{L\lambda}{\pi} \sqrt{\frac{G_1 G_2 (1 - G_1 G_2)}{(G_1 + G_2 - 2G_1 G_2)^2}},$$

and for the size at mirror one

$$w_{M_1}^2 = \frac{L\lambda}{\pi} \sqrt{\frac{G_2}{G_1 (1 - G_1 G_2)}}. \quad (2.10)$$

As we can see the mode size at the mirror is length and mirror shape dependent, this means in general there will be a mode mismatch between the incoming laser and the cavity mode. We can characterize this by introducing a mode matching efficiency factor  $\epsilon$  [54, 57] and define an in coupling efficiency  $\eta_{\text{dip}}$  as

$$\eta_{\text{dip}} = \epsilon \cdot \eta_{\text{imp}}. \quad (2.11)$$

This effect is of course especially relevant for fiber cavities where the incoming laser mode is of a constant size determined by the fiber core. These problems limit the coupling efficiency for fiber cavities, attempts at improving this were made, e.g. by Saravanan through addition of a Graded index fiber pice [58], but central limitations are the length accuracy of the fiber pieces, the cleaves and the splicing (because it destroys the fiber structure at the interface).

## 2.2 Fiber Fabry Perot Cavities

Most conventional Fabry-Perot cavities use macroscopic mirrors with sizes bigger than the millimeter regime, but it is possible to achieve substantial advantages for some applications by using Fiber Fabry-Perot cavities (FFPCs), these are just cavities formed from so called Fiber Mirrors, where an optical fiber end facet is machined to have a spherical ablation (for mode confinement) and is then coated with a Distributed Bragg reflector (DBR). Fiber cavities can be beneficial to use because of the easy optical access from the side, their small form factor, their trivial optical access to the cavity mode via the fiber and their small mode volume, as a lot of measurement quantities scale beneficially with that (e.g. Eq. 2.14). As the goal of this thesis is to manufacture an array of cavities with an optical multi core fiber it is important to understand some particularities of fiber cavities. First, because of the small fiber size (125  $\mu\text{m}$ ) and the finite size in which the ablation on the mirror surface approximates a sphere sufficiently, clipping losses can not be ignored for longer cavities and lead to a length dependent finesse. We can formulate an approximation of these clipping losses as [30]

$$\mathcal{L}_{\text{cl}} = \exp\left(-2 \frac{(D/2)^2}{w_{M_i}^2}\right)$$

for one reflection, where  $D$  is the diameter of the effective mirror area and  $w_{M_i}$  the beam radius at this mirror (as from Eq. 2.10), we can consider it as an additional loss in Eq. 2.7 and see directly that it will reduce the maximally reachable finesse. Another important concept for fiber cavities is the spatial mode filtering effect of the fiber core on the returning light. Part of the light from the cavity (strength dependent on mode size and offset between cavity axis and core) enters the fiber cladding instead of the fiber core and is largely lost on the way to the detector. This leads to a reduction in the reflection baseline by a factor  $\eta_r$ , but this also complicates the interference between the directly reflected light from the first mirror and the cavity leakage field, a calculation done by J. Gallego in [54] (on which the following explanation is based) shows that this actually leads to a deformation of the cavity reflection lineshape (while the intra cavity shape and transmission are unaffected). This deformation of the reflection is given by an additional dispersive component to the otherwise lorentzian lineshape. To now understand the reflection signal a bit better we can use our knowledge that  $\eta_r$  reduces the reflection baseline to  $\eta_r \cdot P_{\text{in}}$  and deduce a formula for the depth of the resonance

$$P_{\text{r}_{\text{depth}}} = \eta_r \eta_{\text{dip}} P_{\text{in}}.$$

Please note that the factor  $\eta_{\text{dip}}$  has now a significantly more complicated form than Eq. 2.11, because the additional dispersive component actually also slightly changes the resonance dip depth and frequency of the minimum as visible in Fig. 2.1(c). Experimentally we call the depth of the resonance in percent (relative to the reflection baseline) the coupling depth ( $CD = P_{\text{r}_{\text{depth}}} / P_{\text{in}}$ ), in fiber cavities this is an easy to use quantifier to get a qualitative understanding of how well the cavity is impedance and mode matched.

To understand  $\eta_{\text{dip}}$  in this situation in more detail we can look at the approximate formula for the detected power in reflection  $P_{\text{out}}$  in dependence of the normalized detuning  $\delta = 2\pi\Delta/\kappa = 2\pi(\nu_{\text{Laser}} - \nu_{\text{Cavity}})/\kappa$

(where  $\kappa = 2\pi \cdot \delta\nu_{\text{FWHM}}$  is the cavity decay rate) found by Gallego [54]

$$\frac{P_{\text{out}}(v)}{P_{\text{in}}} = \eta_r - \eta_{\mathcal{L}} \left( \frac{1}{1 + \delta^2} - \mathcal{A} \frac{v}{1 + \delta^2} \right),$$

here  $\eta_{\mathcal{L}}$  characterizes the amplitude of the lorentzian component and  $\mathcal{A}$  the amplitude of the dispersive part, both also carry a dependence on the mode matching efficiency  $\epsilon$ . One can find the minimum of this function at

$$v_{\text{min}} = \frac{1}{\mathcal{A}} \left( 1 - \sqrt{1 + \mathcal{A}^2} \right).$$

If we plug this back in we find for the minimal reflected power:

$$\frac{P_{\text{out, min}}}{P_{\text{in}}} = \eta_r - \frac{1}{2} \eta_{\mathcal{L}} \left( \sqrt{\mathcal{A}^2 + 1} + 1 \right)$$

## 2.3 Cavity Optomechanics

As already explained in Sec. 1 the field of cavity optomechanics basically originated from the effort to control the noise in interferometer-based gravitational wave detectors. We now want to understand the mechanism behind the optomechanical interaction in more detail, the following explanations largely follow those in [14]. We can start out by trying to understand the Hamiltonian of a basic optomechanical System with a coupled radiation and mechanical vibration mode. The individual uncoupled Hamiltonians can be formulated as harmonic oscillators.

$$\hat{H}_{\text{opt}} = \hbar\omega_{\text{opt}}\hat{a}^\dagger\hat{a},$$

here  $\omega_{\text{opt}}$  is the frequency of the light mode and  $\hat{a}^\dagger\hat{a}$  the the number of photons circulating in the optical mode of the cavity ( $\hat{a}^\dagger$  and  $\hat{a}$  individually are the harmonic oscillator ladder operators).

$$\hat{H}_{\text{mech}} = \hbar\Omega_{\text{mech}}\hat{b}^\dagger\hat{b}, \quad (2.12)$$

while here  $\Omega_{\text{mech}}$  is the mechanical frequency and  $\hat{b}^\dagger\hat{b}$  is the number of phonons in the mechanical mode. The introduction of the optomechanical interaction now means that the frequency of the light field depends on the mechanical displacement of the mechanical oscillator. We can taylor expand this dependency to:

$$\omega_{\text{opt}}(x) = \omega_{\text{opt}} + x \frac{\partial\omega_{\text{opt}}}{\partial x} + \dots$$

We now discard all orders higher than one and introduce the so called frequency pull  $G = -\frac{\partial\omega_{\text{opt}}}{\partial x}$ , which is just a measure of how much the optical frequency shifts depending on mechanical displacement. This allows us to approximate the coupled Hamiltonian as:

$$\hat{H}_0 = \hbar \left( \omega_{\text{opt}} - G\hat{x} \right) \hat{a}^\dagger\hat{a} + \hbar\Omega_{\text{mech}}\hat{b}^\dagger\hat{b} + \dots$$

If we from now on assume the system to be a Fabry-Perot cavity with a movable end mirror following the harmonic oscillator potential (as characterized by Eq. 2.12) we know already from the context of Eq.

2.1 that the light frequency is a whole number multiple  $m$  of the FSR

$$\nu_{\text{opt}} = m \frac{c}{2L}.$$

Or as angular frequency

$$\omega_{\text{opt}} = m \frac{\pi c}{L}.$$

If we now look at the derivative of that we see that

$$G = -\frac{\partial \omega_{\text{opt}}}{\partial x} = \frac{\omega_{\text{opt}}}{L},$$

which already indicates the anti-proportional behavior between coupling and cavity length that is also present in Eq. 2.14. This behavior explains why it is beneficial for optomechanical applications to use short cavities. From the Hamiltonian we can further find through a spatial derivative that the radiation pressure force is

$$\hat{F}_{\text{rad}} = \hbar G \hat{a}^\dagger \hat{a}, \quad (2.13)$$

and depends on the number of photons  $\hat{a}^\dagger \hat{a}$ , which will be relevant for understanding how the optical field can modify the frequency of the mechanical oscillation, as explained in Sec. 2.3.1. The quantum harmonic oscillator position operator is defined as

$$\hat{x} = \sqrt{\frac{\hbar}{2m_{\text{eff}}\Omega_{\text{mech}}}} (\hat{b} + \hat{b}^\dagger).$$

Where  $x_{\text{zpf}} = \sqrt{\frac{\hbar}{2m_{\text{eff}}\Omega_{\text{mech}}}}$  is the so called Zero point fluctuation and  $m_{\text{eff}}$  the effective mass of the vibrating object, which is just the mass participating in the vibration (regions that move stronger contribute more to  $m_{\text{eff}}$  than regions that move less). Now we can reformulate the Hamiltonian to

$$\hat{H}_0 = \hbar \omega_{\text{opt}} \hat{a}^\dagger \hat{a} - \hbar g_0 \hat{a}^\dagger \hat{a} (\hat{b} + \hat{b}^\dagger) + \hbar \Omega_{\text{mech}} \hat{b}^\dagger \hat{b},$$

as the position operator is given by  $\hat{x} = x_{\text{zpf}} (\hat{b} + \hat{b}^\dagger)$ , and we define here a single photon coupling strength as

$$g_0 = G \cdot x_{\text{zpf}} = \frac{\omega_{\text{opt}}}{L} \sqrt{\frac{\hbar}{2m_{\text{eff}}\Omega_{\text{mech}}}}. \quad (2.14)$$

At the same time the total strength of the optomechanical coupling will of course depend on the number of photons in the cavity, we can find after a somewhat lengthy calculation (please see [14] for details) that the total coupling strength is given by

$$g = g_0 \sqrt{\bar{n}_{\text{cav}}},$$

where  $\bar{n}_{\text{cav}}$  is the Photon number circulating inside the cavity with  $\bar{n}_{\text{cav}} = \langle \hat{a}^\dagger \hat{a} \rangle$ . This has the experimentally useful implication that we can always increase the optomechanical coupling strength by increasing the finesse of our cavity or the power of our input laser (up to the point where thermal effects have to be considered).

### 2.3.1 Optomechanical Spring Effect

With the optomechanical spring effect it is possible to optically tune the resonance frequencies of mechanical resonators in a cavity, we want to use this technique for steering vibrations through chains of coupled mechanical devices, which is motivated in the following Section 2.4. As one can see in Eq. 2.13, the radiation pressure force depends on the number of photons in the cavity, but the number of photons depends on the detuning of the cavity and a change in the position of the mechanical resonator in the cavity (for example a movable mirror or membrane on the mirror) can slightly shift the resonance condition of the cavity and thus alter the number of photons. This means (for a sufficiently high slope of the resonance), if our laser is slightly detuned to the cavity the movement of the mechanical resonator will lead to either significantly more or less photons in the cavity. In other words, the radiation pressure force depends on the position of the mechanical oscillator, and for small displacements we can approximate this relation as linear, meaning the membrane will not only feel the mechanical but also an additional “optical spring” [59]. With another lengthy calculation (full derivation again in [14]) one can find for the frequency shift through the spring effect in the limit of large cavity decay that

$$\delta\Omega_{\text{mech}}(\Delta)\big|_{\kappa \gg \Omega_{\text{mech}}} = g^2 \frac{2\Delta}{\kappa^2/4 + \Delta^2},$$

where  $\kappa$  is the cavity decay rate and  $\Delta = (\nu_{\text{Laser}} - \nu_{\text{Cavity}})$  is the detuning of the laser to the cavity, this is a valid approximation in our case as  $\kappa = 2\pi \frac{c}{2nL \cdot \mathcal{F}}$  will be on the order of 10 GHz for our system ( $L \sim 50 \mu\text{m}$  and  $\mathcal{F} \sim 1000$ ), while the membranes we aim to manufacture operate in the single digit MHz regime. We can then see that the mechanical frequency will decrease for a red-detuned laser ( $\Delta < 0$ ) and increase for a blue-detuned laser ( $\Delta > 0$ ).

## 2.4 Laterally coupled multi membrane systems

We start out with a simple toy model to understand the basic behavior of coupled mechanical membranes with an overlapping membrane skin. The model will treat the membrane skins as two vertically movable point masses with mass  $m$  and assume them to be transversally coupled with a spring of spring constant  $k_t$ , we assume furthermore a restoring force of the membranes to the equilibrium position governed by the spring constant  $k_m$  (See Fi. 2.2(a)). We assume that the transversal spring changes length upon movement of the membrane skins by  $\Delta l$ , given by the Pythagorean theorem. We can write the Lagrangian

$$\begin{aligned} \mathcal{L} &= \frac{1}{2}m(\dot{z}_1^2 + \dot{z}_2^2) - \frac{1}{2}k_t \cdot (\Delta l)^2 - \frac{1}{2}k_m \cdot (z_1^2 + z_2^2) \\ &= \frac{1}{2}m(\dot{z}_1^2 + \dot{z}_2^2) - \frac{1}{2}k_t \cdot \left( \sqrt{l_0^2 + (z_1 - z_2)^2} - l_0 \right)^2 - \frac{1}{2}k_m \cdot (z_1^2 + z_2^2) \\ &\approx \frac{1}{2}m(\dot{z}_1^2 + \dot{z}_2^2) - \frac{1}{2}k_t \cdot \frac{(z_1 - z_2)^2}{2l_0^2} - \frac{1}{2}k_m \cdot (z_1^2 + z_2^2). \end{aligned}$$

Where the approximation  $\sqrt{1+x^2} \approx 1+x^2/2$  was used, with this the problem gets essentially equivalent to a coupled pendulum and we can follow a standard theoretical mechanics textbook like [60] for the

solution. We can now simplify the Lagrangian with a coordinate substitution

$$z_1 = \theta_1 + \frac{\theta_2}{2},$$

$$z_2 = \theta_1 - \frac{\theta_2}{2}.$$

And get the new Lagrangian

$$\mathcal{L} = \frac{m}{2} \left( 2\dot{\theta}_1^2 + \frac{\dot{\theta}_2^2}{2} \right) - \frac{1}{4l_0^2} k_t \cdot \theta_2^2 - k_m \cdot (\theta_1^2 + \theta_2^2/4).$$

Now we find the equations of motion via the Euler Lagrange equations.

For  $\theta_1$  we thus get:

$$2m\ddot{\theta}_1 + 2k_m\theta_1 = 0$$

And for  $\theta_2$ :

$$\frac{m}{2}\ddot{\theta}_2 + \left( \frac{k_t}{2l_0^2} + \frac{k_m}{2} \right) \theta_2 = 0$$

We can then extract the oscillation frequencies

$$\omega_1 = \sqrt{\frac{k_m}{m}}, \quad \omega_2 = \sqrt{\frac{k_m + k_t/l_0^2}{m}}.$$

We can see that there is an in phase mode in which the coupling spring is not stretched and does thus not change the frequency ( $\omega_1$  is the same as in the uncoupled case) and there is now a second out of phase mode in which the spring is stretched and the coupling changes the frequency. As this model is too simplistic to predict the frequencies of actually physical coupled membranes we use finite element analysis via *Comsol Multiphysics* for that.

Coupled mechanical oscillators that are slightly more complicated than this toy problem have versatile applications in the context of optomechanics, one interesting being sensors. As a simple model again: Imagine a chain of identical coupled mechanical membranes and a vibration traveling through the chain, if we neglect internal material losses the vibration can travel unimpeded. If we now change the structure of one of the membranes for example by adding mass or altering its particular spring constant, a comparison with the equation above makes it clear that this will in general change the frequencies of the membrane. One could imagine this mass difference originating from some sort of analyte, for example the surface of a particular membrane could be functionalized with a protein binding to some molecule that we want to detect. If we now actuate a membrane in the chain (e.g. possible through pulsed irradiation with laser light) on one side of the binding position and read out the vibrations on the other side (e.g. with a Setup as described in Sec. 4.1) we can detect the presence of the analyte because it will impede the vibration spread through the chain, as the mismatch in frequencies leads to partial reflection of the incoming pulse (example setup sketch in Fig. 2.2(b)). Some sensor platforms that share characteristics with what was described above can be found in [61–65]. Another important realization is that this eigenfrequency shift of one membrane in the chain does not have to arise through a change of mass or composition of the membrane, via the optomechanical Spring effect, as described in Sec. 2.3.1

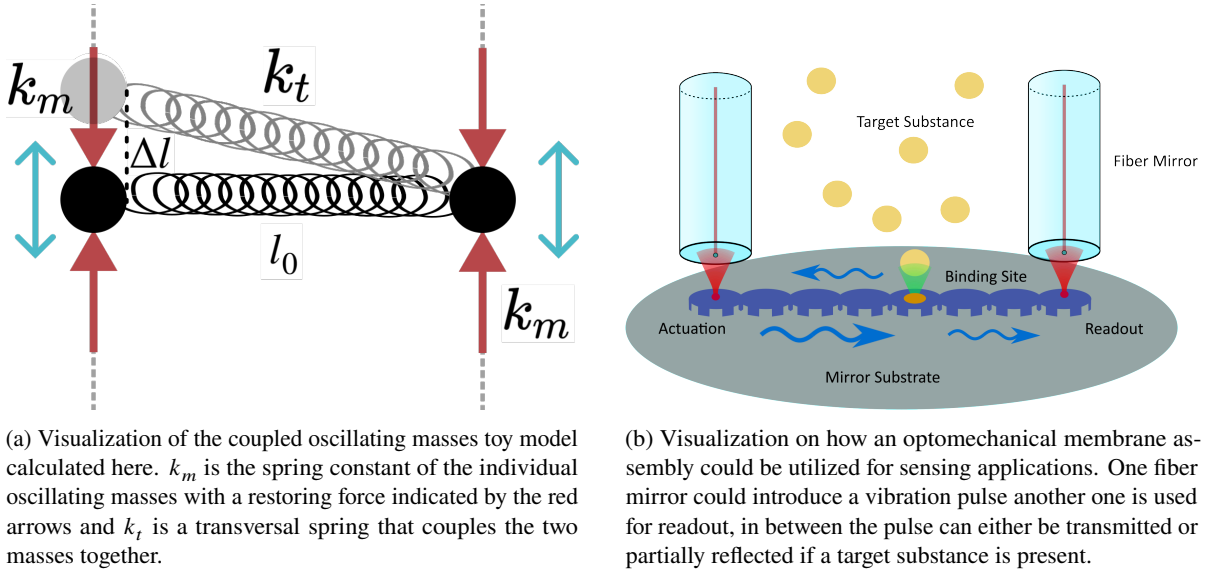


Figure 2.2

it is also possible to achieve a frequency change, meaning the movement of vibrations through a complex mechanical membrane system could for example be steered with a cavity interface. Such a system could e.g. find application for a metamaterial driven approach to mechanical computing [66].

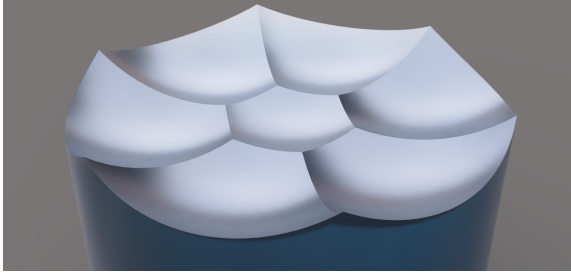
## 2.5 Desired Geometry

As already explained in Chapter 1, lateral arrays of optical cavities, especially in the simultaneous resonance case, could be very interesting for achieving localized control over vibrations in optomechanical multi resonator structures or also as interfaces for arrays of trapped atoms. As already mentioned in the introductory text to this Chapter 2 short cavity lengths are often desirable for optomechanics. Closely packed optical micro cavities have already been achieved on fused-silica substrates e.g. by Dolan et al. [67], where they achieved a finesse of around 460. We hope to improve on this in the future by the additional smoothing technique pioneered by Patrick Maier [68] that are explained in Detail in Chapter 3, through choosing a different platform for the cavity array to achieve easy individual optical access to the cavities (explained in the following) and through the incorporation of a tuning layer under the mirror as explained in Sec. 2.5.1.

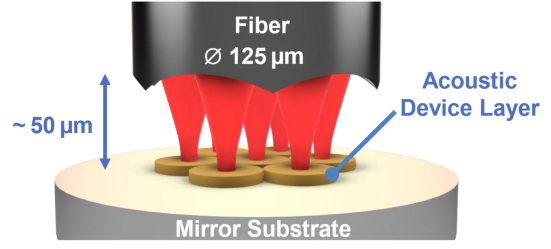
Inspired by moves of the telecommunication industry to develop multicore fibers as a means to increase data throughput, one could think about combining these with an ablation array on the end facet of the fiber to generate an optical cavity array with easy individual optical access to each cavity. These multicore fibers (MCFs), similar to normal fibers, consist of a cladding, but feature multiple cores. This enables simultaneous transmission of multiple laser beams through one fiber. A variety of commercial products are on the market, we chose a seven core design with one central and 6 outside cores arranged in a hexagonal shape<sup>1</sup>, this design was chosen as it promises a nice balance between possible usable mirror surface and cavity packing density (note that because of the core arrangement

<sup>1</sup> Fibercore, Laser Components: <https://www.lasercomponents.com/en/product/standard-multicore-fibers/>





(a) 3D render of the ideal fiber surface geometry.



(b) 3D render of interface to acoustic device layer.

Figure 2.3: 3D renders of ideal fiber surface geometry and a multicore fiber interfacing an acoustic device layer, made with Autodesk Fusion.

there is over proportionally more available mirror surface for the cores on the 7 core fiber than for the 12 core fiber from the same supplier), more details about the manufacturing process can be found in Chapter 3. One problem with this product was the acrylate coating on the fiber, this is explained in more detail in Sec. 3.2. Some experiments have already established array interfaces to multiple coupling sites from bundles of closely packed and uncoated optical fibers, e.g. [69] for individual atom interfaces or efforts by the company Illumina [70, 71] who used a fused optical fiber bundle with very dense core packing for biological applications, but the fiber bundles in their system require short fiber length and are less optimized for low crosstalk compared to multicore fibers. Multicore fibers on the other hand have to adhere to telecommunication standards, and often feature additional layers around the cores to limit crosstalk [46] (so called trench assisted multicore fibers), potentially allowing that multiple atomic or mechanic coupling sites could be interfaced with just one fiber while keeping largely independent cavities.

As already mentioned, short cavity lengths are beneficial for our optomechanical application, but this has to be balanced with the space needed for our optical device layer. We estimate that the mechanical devices in question will restrict our cavity length to not be smaller than  $20\text{ }\mu\text{m}$ , but it is good to have some buffer because there is the danger of crashing the fiber mirror into the acoustic layer if they are too close. To achieve higher finesse at longer cavity lengths it is important to reduce clipping losses as much as possible (see also Sec. 2.2). That means that the mirror ablations of the cavity array should be as big as possible, ideally touching each other with no wasted space in between, and should approximate a sphere very well around the whole ablation area. If one imagines placing 7 spheres, their centers aligned to the cores, hovering over the end facet of a fiber and cutting away the intersection, one would get a geometry as shown in Fig. 2.3(a) (provided one cuts deep enough to machine the whole surface). This would be the ideal geometry that allows for the lowest clipping losses, but to make manufacturing more effective and to have the same geometry on each core we decided later to manufacture the outer six ablations also as hexagons, similar to the center (see Sec. 3.1.3). An image how the cavity system could look like when interfacing an acoustic device layer is visible in Fig. 2.3(b).

From the stability condition for optical resonators (Eq. 2.9) we get the fundamental restriction that for our cavity

$$L \leq \mathcal{R}_1 \quad (2.15)$$

has to hold, because we want to construct a cavity with one concave and one flat mirror ( $\mathcal{R}_2 = \infty$  so  $G_2 = 1$ ), as this allows the use of a macroscopic mirror substrate for the second cavity mirror that can

e.g. easily hold an acoustic device layer. Furthermore we can check Eq. 2.10 and insert a case  $L < \mathcal{R}$  as well as  $G_2 = 1$  and will find a scaling of the mode size on the curved mirror as  $\sim \sqrt{\mathcal{R} \cdot L}$ , this means our mode size grows with higher  $\mathcal{R}$ , meaning that we should not use too large  $\mathcal{R}$  as to avoid clipping losses, but at the same time the radius of curvature has to be large enough to support the cavity length in accordance with Eq. 2.15. Additionally, there are regions of different misalignment sensitivities of the cavity for different combinations of  $G_1$  and  $G_2$  [56], as  $G_1 = 1 - L/\mathcal{R}_1 = 1$ , we ideally use a  $G_2$  around 0.1 – 0.4. It also has to be considered that small ROCs are more difficult to manufacture, and the then needed closer proximity to the second mirror can also reduce the optical access from the sides. In addition, cavities that are too long or have too big ROCs are not ideal because this, as already explained, leads to clipping losses if the mirror size is not sufficient (here we have to note that the maximal possible ablation diameter will be around 35  $\mu\text{m}$  as this is limited by the core spacing of the multicore fiber), but other effects are also relevant:

- The larger the mode in the cavity becomes the bigger is the mode mismatch between cavity and fiber mode, leading to a reduced coupling depth. But the coupling depth is an important parameter for optomechanical measurement sensitivity, as it sets the slope of the lock and by that the signal transduction (see chapter 4 for more details).
- A big mode leads to a wider spatial average over the surface of an acoustic device in the cavity during measurement, this could distort our measurement results as the outside parts of an e.g. circular membrane will have smaller deflection from their resting position during oscillation compared to the inside parts. Also the membrane has to be bigger at some point to avoid clipping of the mode with the membrane edge, which complicates manufacturing.

From this one can conclude that a cavity length of around 50  $\mu\text{m}$  and an ROC of about 150  $\mu\text{m}$  make a good compromise between the mentioned effects. The maximum structure depth is a direct consequence of the ROC and the given core spacing. As the area should be used as efficiently as possible, the form of the central mirror will be a hexagon. The cores of the used multicore fiber are spaced by 35  $\mu\text{m}$ , meaning that the most distant point of the central mirror will be  $\frac{35}{\sqrt{3}}$   $\mu\text{m}$  away. Using the Pythagorean theorem one can get this formula (see also Fig. 2.4(a)) for the relation between radius  $r$ , Chord length  $l$  and distance of the Chord center to the surface  $h$  of a sphere:

$$\left(\frac{l}{2}\right)^2 + (r - h)^2 = r^2$$

This means, if we want to optimize milling efficiency (process outlined in Sec. 3.1.3) by choosing the minimal necessary milling depth to achieve full structuring of the mirror, we can just plug  $r = 150$   $\mu\text{m}$  and  $l = 2 \cdot \frac{35}{\sqrt{3}}$   $\mu\text{m}$  into this formula and solve it for  $h$ . This results in:

$$h = r - \frac{1}{2}\sqrt{l^2 + 4 \cdot r^2} = 1.367 \mu\text{m}$$

### 2.5.1 Achieving simultaneous resonance in the multicore fiber cavity array

To have a cavity array that can reliably interface a number of different coupling sites it would be beneficial to achieve a simultaneous resonance between all the cavities in the array, i.e. all of the cavities should

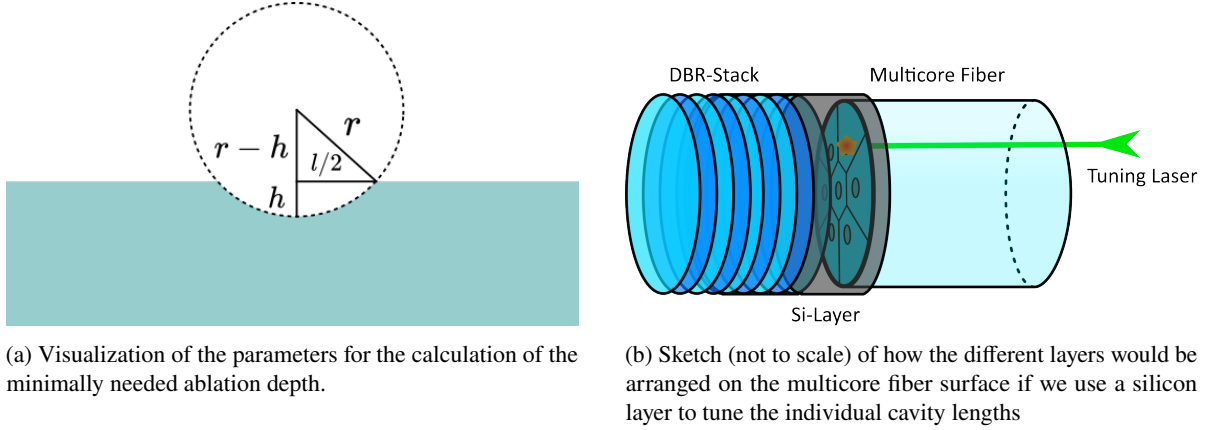


Figure 2.4

have exactly the same length. How exactly the lengths have to match can be easily found by a simple calculation. If we go for a target finesse of around 1000 we know from Eq. 2.8 that the spectral width of the resonances is

$$\delta\nu_{\text{FWHM}} = \frac{\Delta\nu_{\text{FSR}}}{\mathcal{F}}.$$

We know further that a spectral spacing of the resonances of one FSR will occur if the cavity length is changed by  $\lambda/2$ . This means we can calculate the maximally allowed length deviation  $\Delta L_{\text{max}}$  of the individual channels of our cavity array at our operation wavelength of 1550 nm as

$$\Delta L_{\text{max}} = \frac{\lambda/2}{\mathcal{F}} = 0.775 \text{ nm},$$

provided we assume the cavities of the array to be in simultaneous resonance if the spectral deviation is less than one FWHM of the resonance. This means taking great care during the manufacturing process is very important but this can not yield the needed precision alone, if we check out the results from Sec. 3.1.4, we see that we will have to compensate for length differences in the cavities of a few dozen nanometers. We were inspired to a possible solution for that by a paper by Kurtscheid et al. [72]. They used a silicon expansion layer under the DBR of a cavity mirror in combination with a laser that is absorbed by the silicon layer to locally reshape the mirror geometry and managed to get a controlled height change on the order of up to 50 nm. This process has a reversible thermal expansion component and a permanent component that probably originates from crack formation and partial delamination in the tantalum pentoxide layer of the DBR, this was e.g. investigated in more detail by Vretenar et al. [73]. We want to employ a similar technique for our multicore fiber mirrors, the idea would be to also apply a silicon layer to the fiber surfaces before the DBR coating and then fine tune the length of the cavities with a second laser that is absorbed by this silicon layer (Fig. 2.4(b)).

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## Multicore Fiber Interface

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In this chapter the manufacturing process that we developed for the creation of fiber cavity arrays with a geometry as explained in Sec. 2.5 is laid out and their implementation into a simple characterization experiment is demonstrated. In the first sections three different approaches for the creation of the necessary spherical ablations on the fiber ends are investigated. The most effective approach shows to be Focused Ion Beam milling (FIB milling) with subsequent CO<sub>2</sub> laser smoothing. The manufacturing of the fiber samples with focused ion beam milling is described and afterwards it is shown how a gold mirror coating can be applied to them. They can then be connected to a so called multicore fanout that enables individual optical access to each of the cores. With the help of this device the fiber mirror is then used to construct a fiber cavity array.

### 3.1 Fiber Cavity Manufacturing

Central for the use of a fiber in an FFPC is the (ideally) spherical ablation on the fiber surface, these holes can be achieved by a number of different methods, by far the most common one, as explained in Chapter 1 is based on CO<sub>2</sub> laser ablation. For this process (and also the other ones presented later) the fibers have to be prepared with a clean and flat end facet. We use a procedure called *cleaving* for that, the fiber is put under tension and a blade produces an initial crack that propagates through the whole fiber cross section. The Bonn Fiber Lab has multiple different commercial devices for this task, but the author mostly used the Fujikura CT-101<sup>1</sup>. In an application like fiber cavities a goal for this process is to achieve a very smooth surface and a low cleave angle. Surface irregularities lead to scattering and thus losses in the cavity. The cleave angle negatively affects the mode matching, which is intuitive, as the fiber axis and cavity axis will be slightly tilted with respect to each other if a subtractive manufacturing method for the ablation is used. To second order it can also affect the losses in the cavity if the ablation geometry itself gets distorted. The author characterized the cleave quality for the fibers in this thesis by inserting the fibers into a splicer (a device further explained in Sec. 3.4), the splicer has a feature to detect the cleave angle in order to decide whether a splice can be performed, for most tasks in this thesis (especially for fiber mirror production) the author only used fibers with a cleave angle below 1°.

In the Bonn Fiber shooting setup (the following explanation is based on [74]) a 17 W CO<sub>2</sub> laser at 9.3 μm is pulsed via an Acousto Optic Modulator (the RF amplitude applied to the AOM also selects

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<sup>1</sup> <https://www.fusionsplicer.fujikura.com/de/products/fortgeschrittenes-glasfasertrenngerat-ct-101-102/>

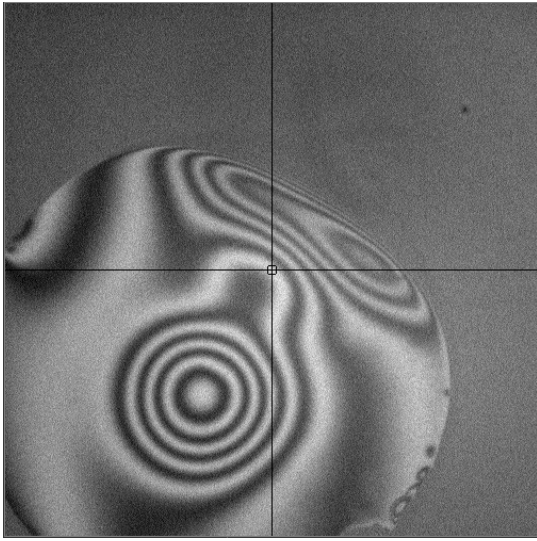
the pulse power) and then focused on a fiber end facet. The fiber can be moved between the shooting position in front of a ZnSe-Lens, and a surface analyzing interferometer with a precise digitally controlled translation stage. The Interferometer consists of a Mirau objective, a camera and a light source that is coupled to the optical axis between camera and Mirau objective via a beam splitter plate. This setup allows application of CO<sub>2</sub> laser pulses to a fiber surface and subsequent inspection of the result with the interferometer. Usually, the Bonn shooting setup is used for experiments that need to create ablations on fiber surfaces for fiber cavity production. After the ablation procedure the fibers can be coated with a mirror, most often a DBR and used in single or double sided fiber cavities.

### 3.1.1 CO<sub>2</sub> Laser Ablation Tests

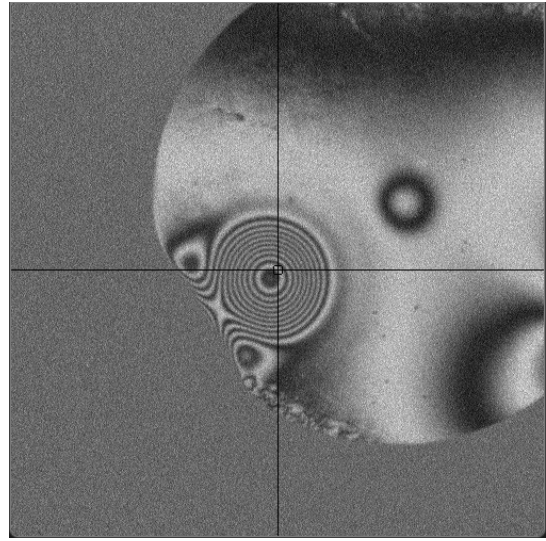
In the first weeks of this thesis the author investigated if the capabilities of the Bonn fiber shooting setup are sufficient for the creation of an approximation of the desired ablation geometry explained in Sec. 2.5. The main problem that was identified is the somewhat obvious fact that a laser pulse that is applied to the center of a fiber and to the edge (where the six outside cores in the 7 core fiber geometry sit) melts the fiber surface differently. A comparison of two shots with the same power, once applied to an outside core and once to an inside core is visible in Fig. 3.1(a), the shot parameters were optimized for the central core. These shots used 4 pulses with a length of 11 ms and one second delay between the pulses at around 1 W laser power with a distance to the beam focus of around 0.542 mm (the position of the fiber behind the lens is given by a setting called *ydiff* that characterizes the distance the fiber moves forward upon transfer from the interferometer to the shooting position, the *ydiff* value for the focus was measured to be about 5.158 mm and for the ablation presented here it was chosen as 5.7 mm). Known shot parameters for single core fibers were only of limited usefulness for finding these parameters on multicore fibers as they seem to thermally react differently, likely because of different material composition, e.g. from the possible isolation layers between the cores that are discussed in Sec. 3.1.3. As one can see in the image the shot that was applied to the outside core of the fiber melted the fiber in this region uncontrollably while the same shot in the center produced a good circular ablation form. The author wants to propose the explanation that the heat can escape from the shot region in the center much easier as there is a symmetric amount of material around it, while the shots on the side have the heat escaping much slower to the edge of the fiber than to the center, leading to a stronger and more asymmetric melting.

Of course the effect of stronger melting can be somewhat compensated by reducing the power that is applied to the outside core compared to the central one. So instead of producing a good ablation shape on the inside core, the author tried to optimize the process for an outside core instead (*ydiff* of 4.98 mm, 10 pulses, duration 6.7 ms,  $P = 0.55$  W, delay 100 ms). The best structure that was achieved is visible in Fig. 3.1(b), the ablation center looks much better, but the asymmetry of the ablation remains, limiting the potentially useful mirror area significantly. Again a shot with the same parameters was applied to the center of the fiber, as one can easily see that ablation is small and shallow compared to the outside one, from this we can conclude that even if one accepts the asymmetry of the ablation on the outside core the central core would require totally different parameters. In this context it is important to note that in regards of ablation size, depth and RoC the shooting parameters are strongly coupled with each other (e.g. laserpower, distance from focus, pulse number and duration each can influence all these aspects of the result). Especially if one also considers that ablations of sufficient size for the low clipping losses that we desire (as outlined in Sec. 2.5) will also influence neighboring ablations through their presence, e.g. by changing the heat flow pattern on the surface, it becomes clear that a CO<sub>2</sub> laser approach for the manufacturing of the ablations will be highly complicated and restrictive.





(a) A multicore fiber with a CO<sub>2</sub> laser shot applied to the center and one of the outside cores. The shooting parameters were optimized for the central core.



(b) A multicore fiber with a CO<sub>2</sub> laser shot applied to the center and one of the outside cores. The shooting parameters were optimized for the outside core.

Figure 3.1: CO<sub>2</sub> laser Ablation Shooting Results

Furthermore, because a simultaneous resonance of the individual cavities is desired which requires high deviations between the ablations to be as small as possible, but certainly smaller than the maximal tuning capability of the desired silicon layer below the mirror as explained in Sec. 2.5.1, we concluded that it makes sense to use a different, more controllable approach. So as CO<sub>2</sub> laser ablations on fibers have limitations that even in the ideal case would restrict us to smaller usable mirror surfaces, and reduce our control of RoC and structure depth significantly, other possible techniques for surface machining of a fiber were investigated. A technique for precise removal of material with only limited heat introduction to the fiber is needed. Focused Ion Beam milling, as explained in Sec. 3.1.3, is such a technique. Ions (most often Gallium) are accelerated, formed to a beam and then focused on the sample region. At currents in the nA regime these ions can ablate many cubic microns per hour from a surface. Commercial machines are available to produce such a beam, steer it and shoot it onto a sample, often combined with an integrated electron microscope for imaging. Because these machines enable almost arbitrary ablation geometries, maximizing the mirror area becomes very easy, also one can avoid the imperfect sphere approximation at the edge of a CO<sub>2</sub> laser shot (because of the gaussian profile of the laser). These devices were already used for highly reproducible single ablations on fiber surfaces by Maier et al. [68]. The author of the cited paper helped us with transferring the techniques to multicore fibers. One problem is that the surface quality of FIB milled fibers is worse than the quality of CO<sub>2</sub> laser treated fibers, but Maier et al. showed that this can be mitigated by applying a defocused CO<sub>2</sub> laser shot to the surface of FIB produced fibers. The resulting surfaces are similarly smooth to normal CO<sub>2</sub> laser formed ablations while the underlying FIB milled shape (that can be made more complex than ever possible with CO<sub>2</sub> laser ablations) is not significantly affected.

### 3.1.2 Alternative methods: Backside wet Etching

Another manufacturing approach that we initially considered is laser induced backside wet etching. This machining method is often used to micro machine glass substrates. The key idea is that the substrate is partially submerged in a solution with a strong absorber and a laser is fired through the substrate, if the intensity in the beam is high enough the absorber can become very hot directly at the interface of glass and absorber solution. This hot absorber can then remove material from the substrate surface. A paper in which it was managed to reduce crack formation for this method by addition of phosphoric acid to a copper sulfate absorber solution [75] made us think this could potentially also work to machine the end facets of optical fibers. The author later found out a related process using a 532 nm laser and a different absorber without the crack suppressing phosphoric acid additive was already conducted on optical fibers by Vass et al., but this led to a highly porous and uneven fiber surface [76].

A very promising factor for the application of backside wet etching in optical fiber surface machining is that the laser light can just be applied into the back end of the fiber while the front is submerged in the absorber solution. Because the light is guided within the fiber core this method should feature an intrinsic core centering of the ablations. Laser induced backside wet etching was developed as a manufacturing technique in the 1990s by Wang et. al [77], now LIBWE setups often employ lasers in the near infrared region in combination with a copper sulfate solution, this was largely pioneered by Huang et al. [78]. Nowadays the largely accepted mechanism is that the copper sulfate undergoes rapid heating during irradiation, leading to the formation of a bubble that is hot enough to melt the glass surface and simultaneously carries away material from the surface through thermal expansion. Simultaneously the hot environment leads to the decomposition of copper sulfate to copper oxide that absorbs even more light [75]. Kwon et al. discovered that addition of phosphoric acid to the absorber solution can inhibit crack formation by high temperature conversion of ortho phosphoric acid to para phosphoric acid which can react with the glass to form a protective silicon phosphate layer [75]. They used peak pulse intensities of  $\sim 8 \text{ kW/cm}^2$ . Because of the small core diameter ( $\approx 5 \mu\text{m}$ ) of the fiber these kinds of intensities can be reached relatively easily with just a few mW of power.

As a first test we wanted to check if we can see some ablation effect at all, Kwon and Huang both used a laser at 1064 nm [75, 78], we only had a 780 nm laser at hand, but as the absorption of copper sulfate is also strong at 780 nm [79], this was not deemed a problem for a first test. So a single mode fiber was cleaved, submerged into an solution of 1.6 g copper and 4 mL phosphoric acid in 16 mL water (loosely following parameters similar to Kwon et al.), the basic experimental setup can be seen in Fig. 3.2(a). Then approximately 6 mW of cw power were introduced to the fiber for about a minute leading to a clearly visible ablation shown in Fig. 3.2(a). The resulting surface quality is bad and the ablation shape very irregular, but this is not surprising, Kwon et al. have used pulsing of the laser in the kilo hertz regime with pulse lengths on the order of 100 ns, it is thus expected that the heating is much less localized in the situation presented here, potentially leading to higher thermal deformations in the bulk of the material and subsequent cracks, while the long heating time of a single bubble probably also leads to deformations. Afterwards the author also incorporated pulsing of the laser with an AOM for a more controllable ablation process, but a full search for optimal parameters never materialized as it became clear that a FIB is the most promising approach. Still the initial test demonstrates that ablations on fiber end facets can be done by backside wet etching in copper sulfate solutions, while the etching is induced from a laser guided in the fiber. Even though this approach was ultimately not used for the work in this thesis it remains of interest for fiber machining, as potentially it might allow for very deep ablations with high aspect ratio (similar to the microchannels fabricated in [75]) that at the same time feature

intrinsic core centering. As a next step the effects of pulsing frequency and pulse length on the ablation process have to be investigated and a comparison if 780 nm light works similarly well to 1064 nm has to be conducted.

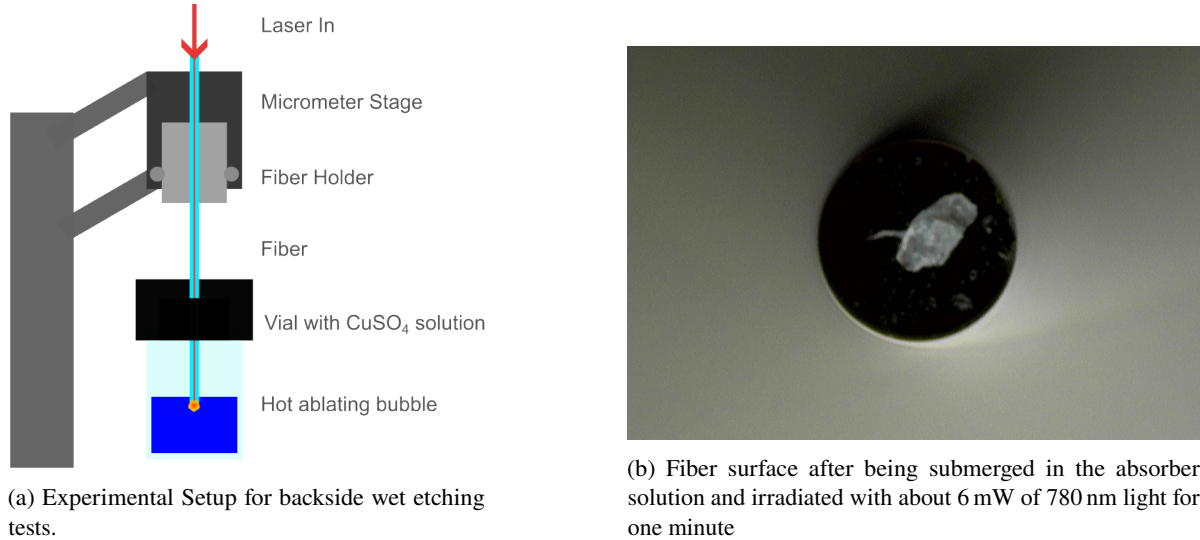


Figure 3.2: Setup and result of the backside wet etching test.

### 3.1.3 FIB-Machining of Multicore Fiber Surfaces

The FIB tests done for this thesis were conducted together by the author and JinHee Bae (Fz Jülich, PGI-9), who also taught the author to use the device and helped this thesis immensely with her knowledge about FIB machining, on an FEI Helios Nano Lab 600i at the *Forschungszentrum Jülich*. The following explanations are largely based on practical experience and the FIB user manuals for the Machines in Jülich and Ulm [80, 81] (a shortened version can be accessed online [82]), more in depth information can be found in a textbook on FIB machining like the one from Orloff et al. [83]. An image of the interior of the device is visible in Fig. 3.3(a). On top the electron column for the integrated Scanning electron microscope capabilities of the FIB is visible, on the left is the ion column, in which Gallium ions are accelerated and can then be impacted on a sample to create the milling effect. Please note that the ion column and the electron column stand at a  $52^\circ$  angle relative to each other. It is possible to image the sample with both the electron and the ion source (even though the ion image is always of significantly worse quality), but because of the tilt angle there is a perspective shift between the two. For ion patterning the sample has to be tilted to the ion column, then the structure file that will be patterned can be placed in the FIB control software over the ion image to select the location of the structure. The Fiber holder is visible in Fig. 3.3(b), with a design kindly provided by Patrick Maier, University of Ulm, who used it for his work on a FEI Helios Nano Lab 600 [68], and supported the work in this thesis with his knowledge about the FIB machining of fibers. The holder is screwed into the electrical 5 axis stage of the device.

Before sample introduction, the whole holder, including the fibers, was already coated with a conductive material to prevent charging. It was decided to sputter around 15 nm of gold for the coating, as any rests of it can easily be removed by a mixture of nitric and hydrochloric acid (which is much more difficult

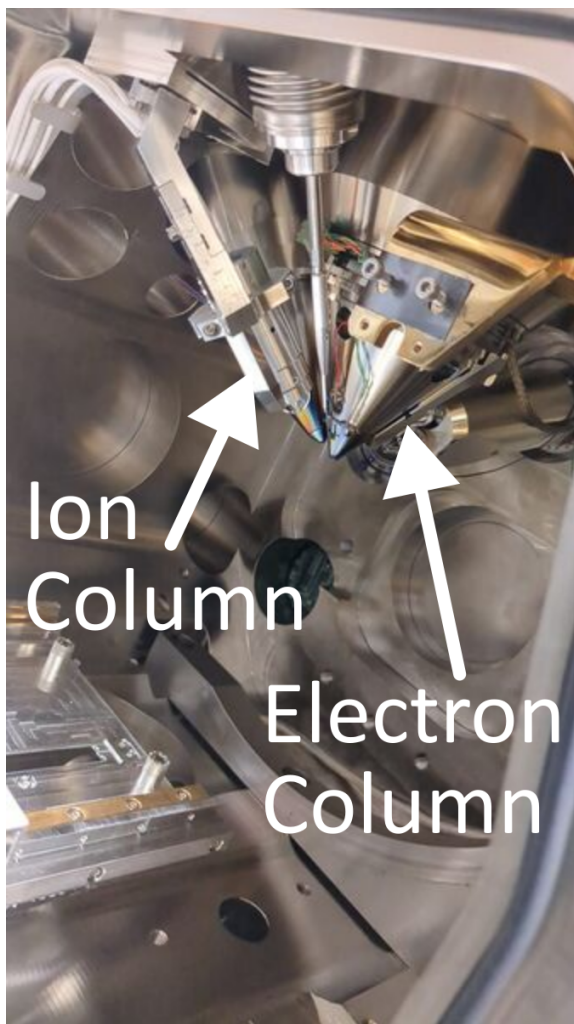


with platinum for example), the rationale was that this could be useful later when a mirror coating will be applied to the fibers, as any kind of leftover coating could reduce the adhesion of the mirror (as explained in Sec. 3.4 the splices of the fibers suffered significant more from this in the end). Then the chamber is closed and a vacuum is pumped. Starting at a pressure around  $10^{-5}$  mbar the Scanning Electron Microscope (SEM) can be used to find the holder and then the individual fibers. After the fiber surface was centered in the SEM image the beam is focused and corrected for astigmatism by changing the current through the stigmator coils, which in contrast to simple focusing is a two dimensional optimization problem. These optimizations are essential for a good image quality. A helpful strategy is to go to the edge of the fiber or some dust particle because these complex, visually easy to distinguish, structures make the optimization much easier, it is also important to understand that this is a coupled optimization process, changing the stigmator settings also often makes change of the focus necessary [84].

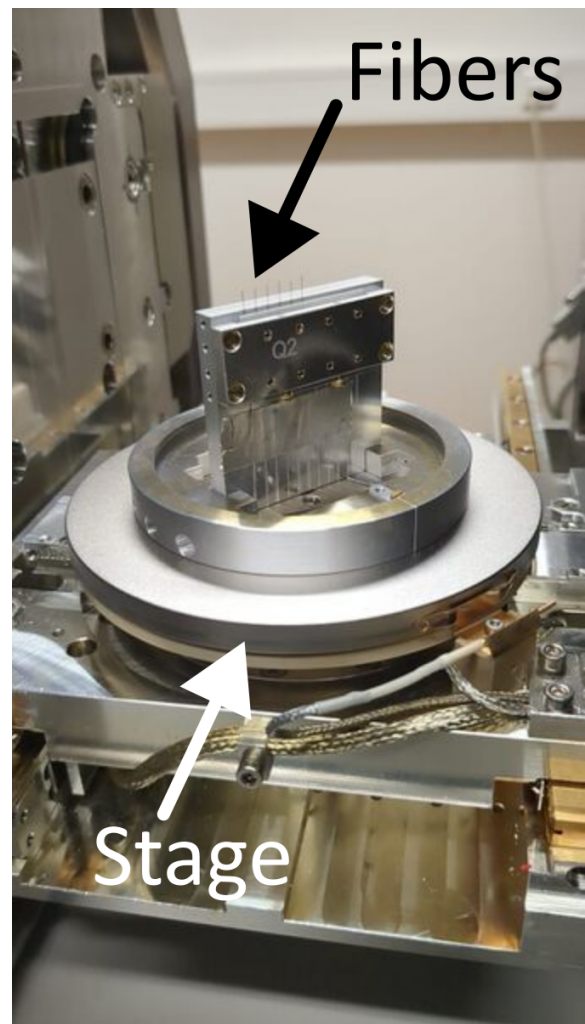
As soon as a good quality image is achieved, the fiber end facet has to be tilted towards the ion column for the milling process and the eucentric position has to be set by raising/lowering the sample. With this procedure we achieve that the point where the axis of the electron beam, the axis of the ion beam and the stage rotation axis intersect is close to the sample surface, by this we ensure that there is minimal de-focusing and movement of the image when the stage is rotated (please note that this explanation is simplified, in reality the beam coincidence point is slightly shifted from the eucentric point [80], but this can be neglected in our case). Practically our procedure was that we moved the fiber edge to the center of the electron image, repeated this after tilting and plugged the corresponding height difference, as recorded from the stage, into the eucentric height setting in the control software. After that, milling can start, but in order to achieve higher control about the process a focusing of the ion beam can also be conducted, even though the ion beam will usually not be strongly enough de-focused to negatively affect patterning a well focused ion beam can still be of interest, because it can ideally lead to the situation that the cores of the fibers become visible in the ion beam image, making the centering of the ablations much more precise. But even if perfectly focused, the quality of the ion beam image is just generally always significantly worse than the electron image.

Another problem is that focusing of the Ion beam is always very destructive, especially at the high currents present here. The focusing has to be done at the current that shall be used for the milling process, as different current settings lead to slightly different foci and field of views because this setting is made by placing physical apertures in the beam [82]. During the focusing there is constant ablation of material, an electron image of the damage done by focusing the Ion beam can for example be seen on the right of the fiber in Fig. 3.14(b). Hence a precise focusing of the Ion beam was not always possible to achieve, and also the visibility of the cores varied widely with position in the image, probably because of a combination of variations in the beam aberrations depending on position, local charging and detection non-uniformities, both detector intrinsic and because of different relative orientation of sample and detector [85]. Furthermore after the gold layer got removed, the accumulative charging made the image quality worse over time, meaning most ablations had to be centered to the cores purely by the information visible on the electron beam plus the known nominal core spacing of 35  $\mu\text{m}$ ) and fiber diameter of 125  $\mu\text{m}$ .

A total of 23 fibers was produced with the FIB over the course of eight sessions. In the following paragraphs there will be a chronological summary about the lessens learned during each of them and a list of all fibers can be found in Tab. A.1.



(a) Image of the FIB interior, the electron column is visible in the middle, the ion column can be seen on the left.

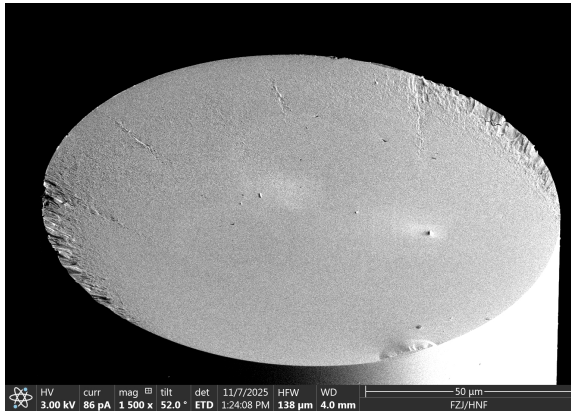


(b) Image of the sample holder, carrying six fibers, attached to the FIB stage system.

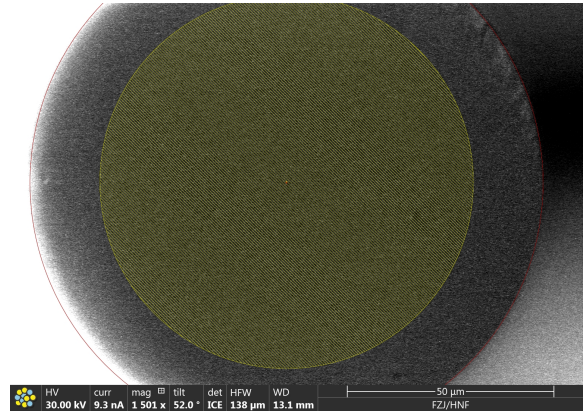
Figure 3.3: Images of the FIB interior

### Session 1 - Initial tests

The author and JinHee Bae tried to understand the behavior of the sample in the device, a main goal for this first manufacturing session was to locate the fiber cores in the SEM image. We started with settings for the ion beam recommended by Patrick Maier (9.3 nA ion current and 30 kV acceleration voltage). After the first fiber was located with the SEM (Fig. 3.4(a)) it was found out that observation of the cores can be achieved by milling a circular pattern on the fiber surface until the gold layer is removed over the cores (Fig. 3.4(b)) and optimizing the contrast setting of the image afterwards. The rationale was not removing all the gold to limit charging effects. During the first session we did not take a good image of these circular mills, but a similar image is visible in Fig. 3.14(b).



(a) SEM image of a cleaved fiber surface.



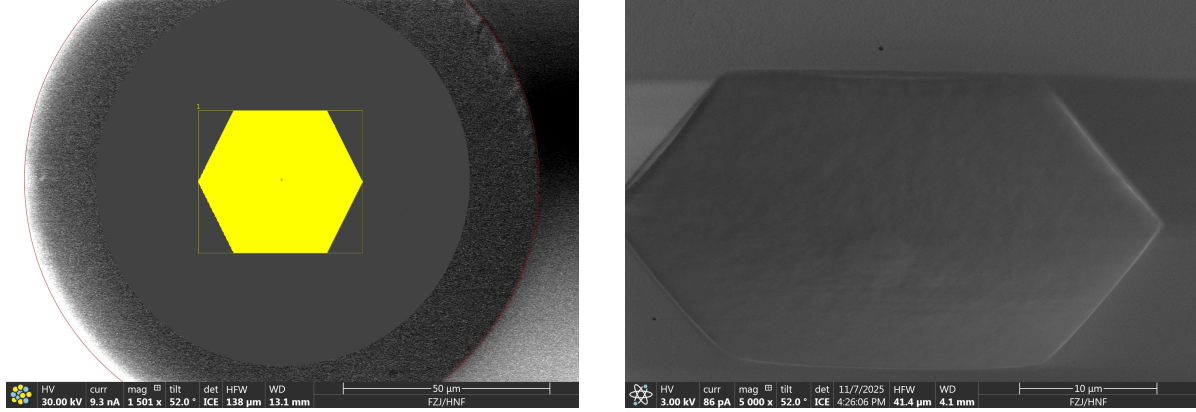
(b) Ion Beam image of the fiber surface with circular milling pattern to remove the gold layer over the cores

Figure 3.4: FIB Session 1, bare fiber surface in SEM and ion beam image

To simplify the ideal design explained in Sec. 2.5 for efficient production, it was decided to use a hexagon shape for each of the cores (instead of just the central one), this leads only to a comparatively small loss of mirror surface (which is also quite far away from the optical axis), while making manufacturing significantly easier, as only one milling pattern has to be used for each fiber, and correct rotation of the individual structures becomes easy. To achieve patterning of the sample with a user defined shape the FIB control software expects import of so called stream files. These files essentially only contain a short header specifying the file type ("s" for steam file), the total number of points to mill and a number that allows the user to command the FIB to loop over the file multiple times. After the header just a long list of mill times with corresponding coordinates follow. The coordinates basically are commands to the Digital Analog converter of the FIB to deflect the beam to a certain region of the sample and can basically be thought of specifying the pixel in the ion beam image where the beam should hit.

Patrick Maier kindly provided us with his script for the creation of stream files, but he only used fully spherical ablations (so with a circular form on the end facet of the fiber) on his samples, so for the creation of hexagons the author of this thesis wrote an accompanying python script to take spherical stream files and cut out regular hexagons. After the import of the stream file the FIB control software displays the structures specified by the file as yellow patterns, they can freely be placed on the ion beam image to create an ablation there. This can be seen in Fig. 3.5(a), please note that we did not figure out how to correctly focus the ion beam for the sample yet, this is why the ion beam images look very fuzzy, an optimally focused ion beam image can be seen in Fig. 3.16(b), but this is not really a problem for the

ablation process, as the beam size is still very much smaller than the pattern. Interestingly the cores seemed to show significantly more clearly after an ablation patterning was started, as there seems to be a slightly differential milling rate on core and cladding (Fig. 3.5(b)), which is not unexpected, in general milling rates of a FIB can vary significantly depending on the material [80].



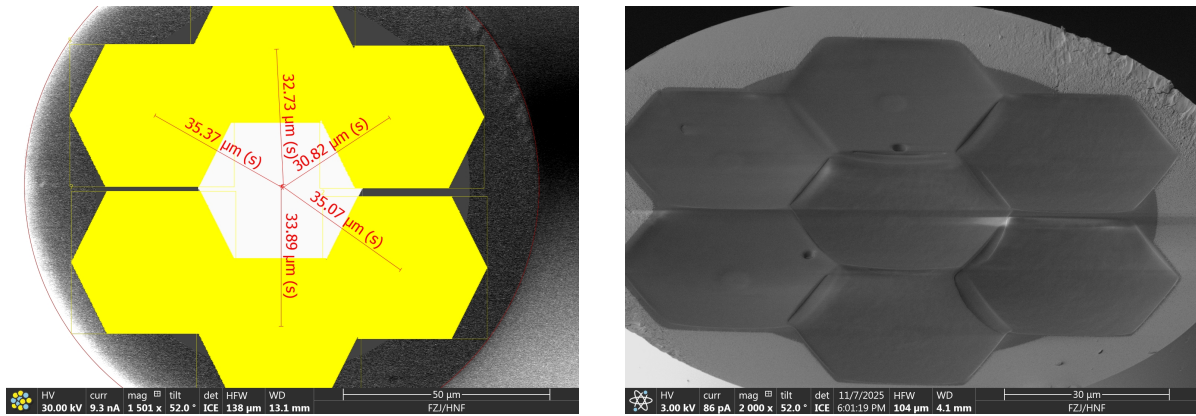
(a) Ion beam image of the fiber, the yellow structure is the imported stream file and can be placed freely on the fiber surface.

(b) SEM image after the patterning of the imported structure was concluded. The ablation shows the fiber core in the center relatively clearly.

Figure 3.5: FIB Session 1

It was also discovered that the sizes of the ablations were slightly bigger than expected with the used stream file. Patrick Maier already warned us that something like this could happen, as the FIB he used (Helios Nano Lab 600) and the one at Forschungszentrum Jülich HNF (Helios Nano Lab 600i) are slightly different models with potentially a different physical size on the sample corresponding to a detector pixel. We were able to compensate this easily afterwards by changing a scaling factor in the script that we determined with a few calibration mills. But because we already started with milling a fiber we decided to continue and not care about the slight overlap of the ablations for the first fiber (Fig. 3.6(a)), the resulting surface shape of the fiber is visible in Fig. 3.6(b). Please note the additional surface defects like the one to the left or right above the central ablation, we ended up seeing this kind of structure more often (e.g. also visible in Fig. 3.13(b) with a zoom in in 3.14(a)), we came up with the hypothesis that these are bubbles formed by gas enclosures into the glass of the fiber during manufacturing. We will use a numbering convention to identify the fibers throughout this thesis. This first Fiber is called Fiber 1 from now on and the following fibers are numbered in chronological order of manufacturing, please see Tab. A.1 for a full list of all manufactured fibers. Two more test fibers were manufactured during this first session for ablation size calibration.





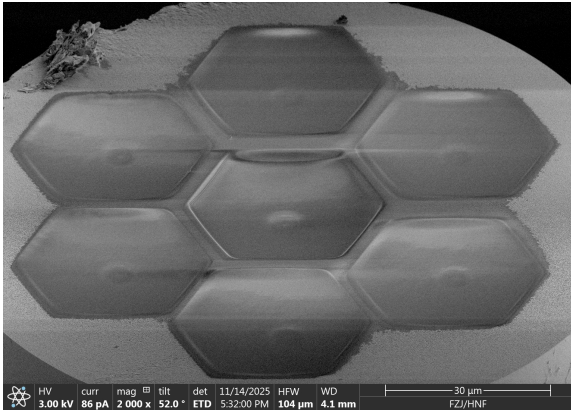
(a) Ion beam image after the central ablation was made with 6 more stream files placed on the other cores. The FIB software offers tools for distance and angle measurements.

(b) Resulting fiber surface after the stream files in (a) were executed. This is the first manufactured Fiber and we will call it Fiber 1

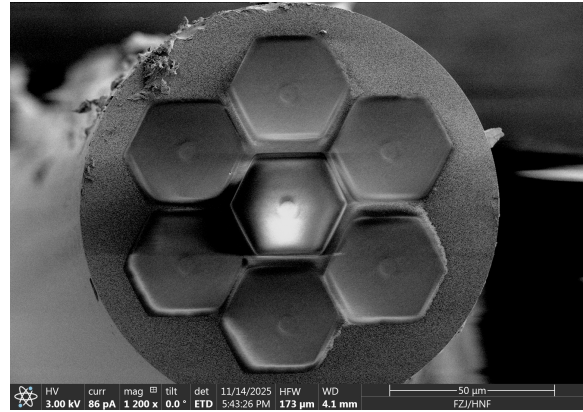
Figure 3.6: FIB Session 1 (Fiber name: 1 in Tab. A.1)

## Session 2 - Start of Production

During the second FIB session we started by scaling the stream file appropriately. The idea was to leave a little gap between all the ablations, so that a CO<sub>2</sub> laser pulse, as used for smoothing in Sec. 3.1.4, will not melt them into each other. The resulting fiber can be seen in Fig. 3.7. Afterwards the author wanted to optimize the milling time of the file, but made a mistake during import, leading to very shallow ablations as visible in Fig. 3.8, the fiber was later discarded. We also started to make electron beam images of the fiber after the FIB process was done and the fiber was tilted back to the electron column. This allows a first qualitative understanding of how well the ablations are centered to the cores, as can be seen in Fig. 3.7(b) and Fig. 3.8(b) (please note that we only did this consistently for every fiber from session 4 onwards). In the current configuration this core centering is not really optimal, as already mentioned in the introductory text to this section Sec. 3.1.3, the core position is relatively difficult to find in the ion image. Later we developed a strategy to exploit the slightly differential milling of the cores compared to the cladding for better visibility in the ion image, as explained in the part on Session 7 of Sec. 3.1.3.

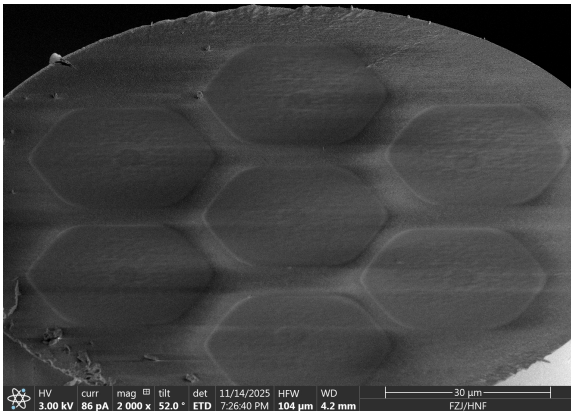


(a) SEM side view of the fiber after the patterning process.

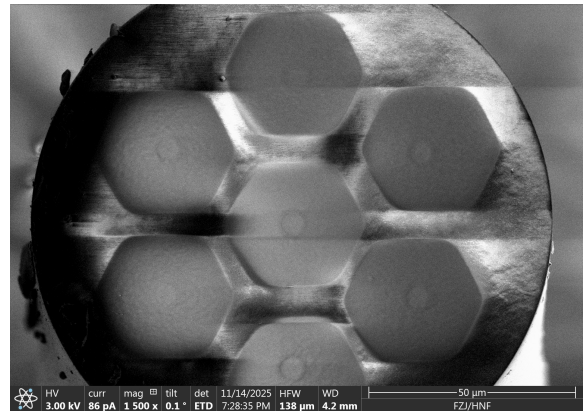


(b) SEM head on view of the fiber after the patterning process.

Figure 3.7: FIB Session 2 (Fiber name: 4 in Tab. A.1), the ablations were made smaller to leave a few microns space between each ablation in order to prevent the CO<sub>2</sub> Laser in the smoothing step to melt them into each other.



(a) SEM side view of fiber 5, patterned with wrongly prepared stream file.



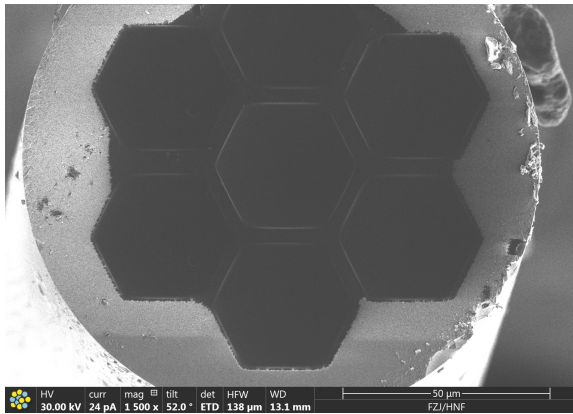
(b) Head on SEM image of fiber 5, patterned with wrongly prepared stream file.

Figure 3.8: FIB Session 2 (Fiber name: 5 in Tab. A.1), the streamfile encoding the pattern had wrong depth data and the ablations were too flat. The fiber was later discarded.

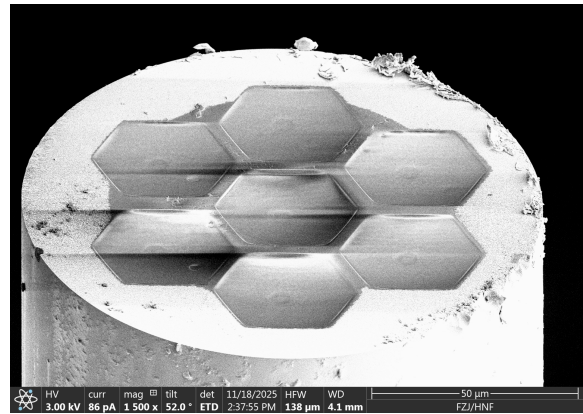
### Session 3 - Improved Ion Imaging

We continued producing more fibers with similar parameters to before. The results are visible in Fig. 3.9 and 3.10. In Fig. 3.10(b) one can nicely see the strategy we came up with to optimize core centering. We started out by finding the cores of the fiber in the SEM image which was relatively easy to do most of the time, then we conducted distance and angle measurements of the cores relative to each other and to well visible features on the fiber surface and after that transferred these measurements to the ion beam image. Based on this information the initial ablation position was selected. As already mentioned, the core visibility becomes much better after material was removed by the FIB, likely because of differential milling rates between core and cladding, this is also consistent with the analysis done in Sec. 3.1.4. It is

furthermore possible to do SEM images during the patterning process. So we started the patterning where we expected the core to be, based on the distance measurements, did an SEM image, stopped the patterning, corrected the position and started the patterning again, this is also what happened with the central core in Fig. 3.10. The change is so strongly visible because here, in addition to a position correction, there was also a rotation correction done. But as one can imagine, the drawback to this approach is that the depths of the ablations becomes less reproducible, as not every core gets the same ion dose anymore, this was also analyzed in Sec. 3.1.4 and to have a good comparison the fibers of session 8 (Sec. 3.1.3) were produced without this correction step and a worse core centering was accepted. Furthermore we discovered that we can identify the cores in the ion beam image much better at lower ion beam currents as visible in Fig. 3.11(a), where 24 pA were used. As explained in the introductory text to this section (Sec. 3.1.3), the image shifts upon current change and the focus point is different for different currents (Fig. 3.11(b)), meaning this discovery was only of limited usefulness. The ablations have to be done at higher currents to have a reasonable milling time. The 9.3 nA of ion current used so far for the ablation need a patterning time of about 10 minutes per core.

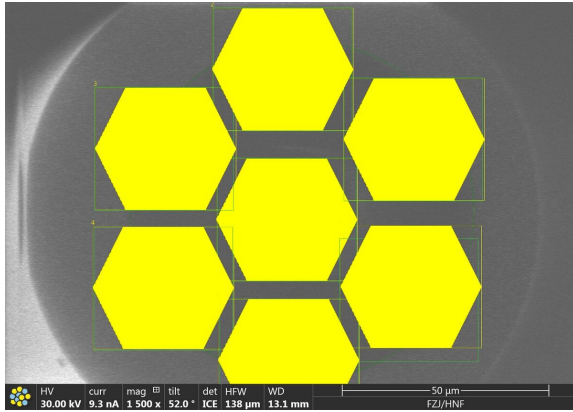


(a) Head on Ion Beam Image of fiber 6 after patterning.

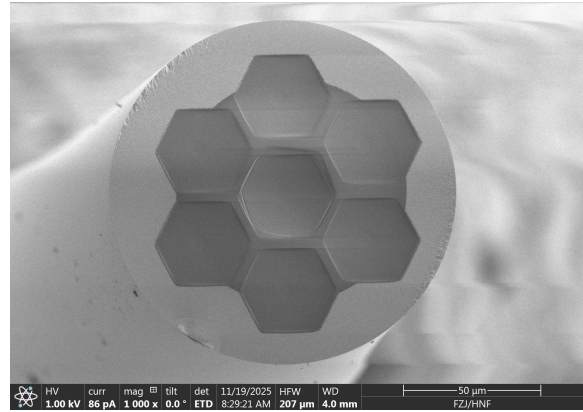


(b) SEM side view image of fiber 6 after patterning.

Figure 3.9: FIB Session 3 (Fiber name: 6 in Tab. A.1)

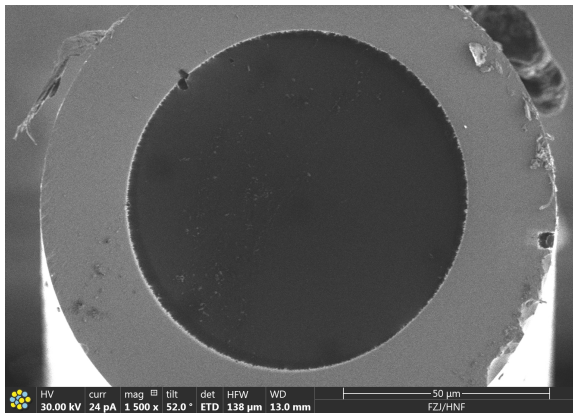


(a) Ion beam image of Fiber 7 during the alignment of the ablation geometries (yellow hexagons).

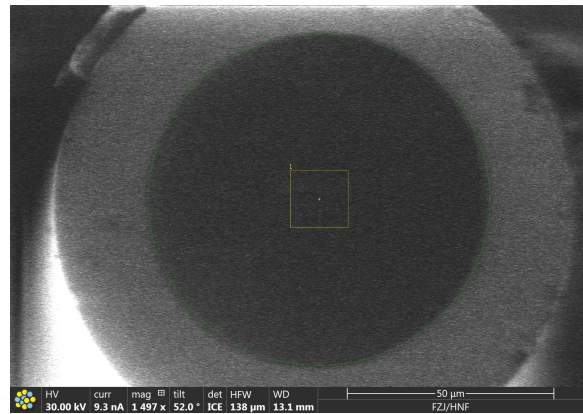


(b) Head on SEM image of Fiber 7, the effect of the net dose increase by our core alignment correction procedure can be strongly seen on the central core.

Figure 3.10: FIB Session 3 (Fiber name: 7 in Tab. A.1)



(a) 24 pA ion beam image of Fiber 6 before patterning, the cores are visible as dark spots.



(b) 9.3 nA ion beam image of Fiber 6 before patterning.

Figure 3.11: FIB Session 3, Comparison of a 24 pA ion beam image and a 9.3 nA ion beam image.

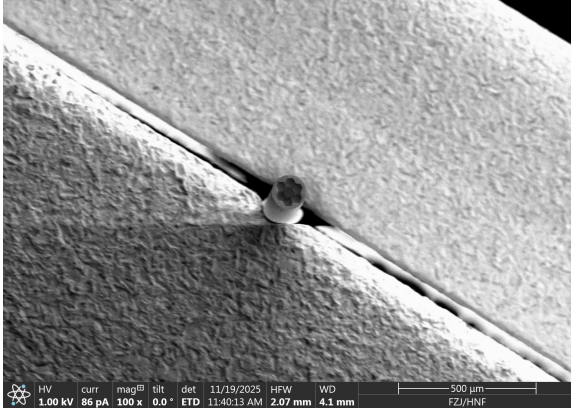
#### Session 4 - More efficient production

Because we started to understand the process better we were able to produce 4 more fibers, the resulting surfaces are visible in Fig. A.1, A.2, A.3 and A.4. We also took an image of how the fibers are clamped in the holder (Fig. 3.12(a)).

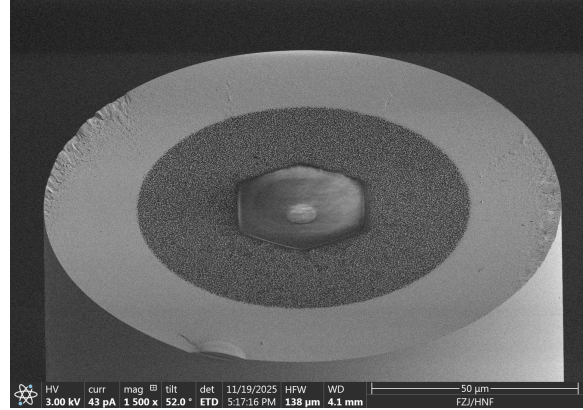
While creating the circular mill for better core visibility, we found an interesting regime where the gold layer is almost removed but thin remaining gold specks still limit the charging as can be seen in Fig. 3.12(b). The structure visible in the milled circle are likely also indicative on the level of surface roughness that has to be expected to be present inside of the ablation crater (if we assume the gold is not sintering to itself here as in Session 7 Sec. 3.1.3), usually this roughness in the ablation is not really visible with the SEM because of charging effects that smear out the image, this is why the crater in the



center of the image looks smoother. There is no gold left there so charges accumulate, leading to the features being just not resolvable.



(a) Zoomed out SEM view of fiber 8 in the holder

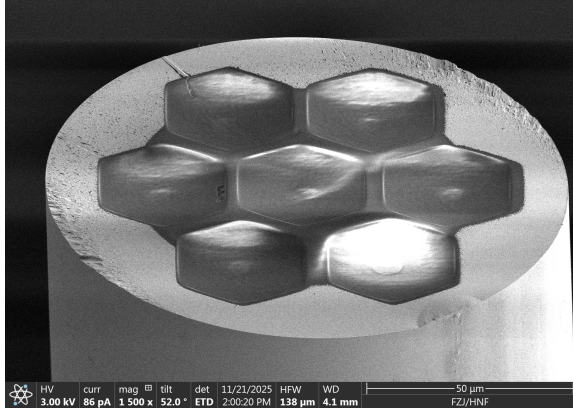


(b) SEM view of fiber 11 during production, the circular mill had the ideal dose to just partially remove the gold layer, making the surface structure visible.

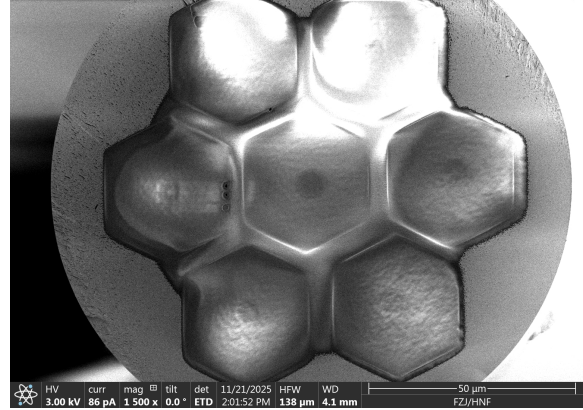
Figure 3.12: FIB Session 4

### Session 5 - Higher Ion Current

Production continued and we made four more fibers, the resulting surfaces are visible in Fig. 3.13, A.5, A.6, and A.7. Fig. 3.14(a) is a zoomed in SEM image of the bubble structures visible in Fig. 3.13, similar bubbles were already seen on previous fibers (like the one from session one). During this FIB session 5 we also took an image (Fig. 3.14(b)) that shows a clear circular structure around each of the cores of the multicore fiber, something like this is expected to exist as most multicore fibers use additional isolation layers (also called trenches, that isolate the cores from each other by providing an additional low refractive index region) around the cores to limit crosstalk [46]. To increase manufacturing speed we decided to switch the ion current from 9.3 nA to 21 nA, now the milling time reduces from about 10 min to around 4 min per core.

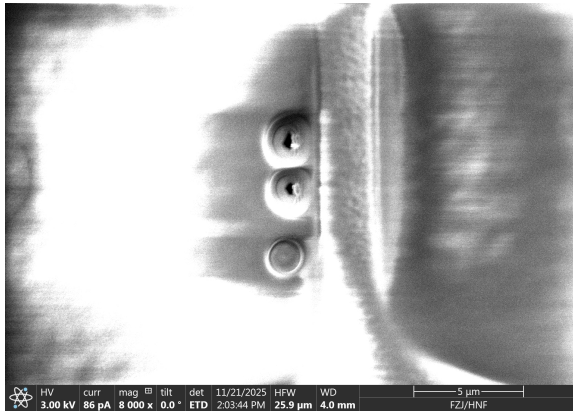


(a) SEM side view for fiber 12

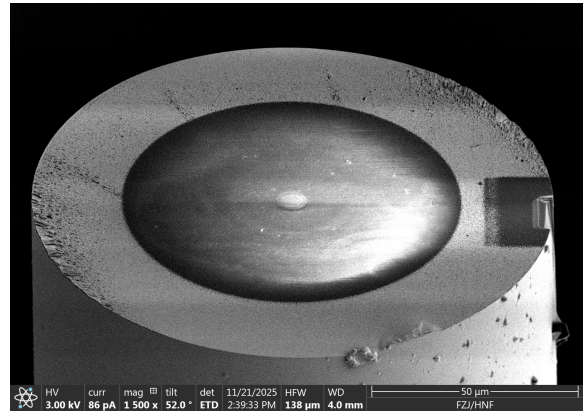


(b) SEM head on view for fiber 12

Figure 3.13: FIB Session 5 (Fiber name: 12 in Tab. A.1), there is a bubble structure visible on the ablation on the left.



(a) Zoom in on the bubble structures present on fiber 12, we hypothesize these get created through gas enclosure while the fiber is drawn.



(b) Sometimes Rings show around the fiber cores, we assume them to be so called trenches for crosstalk limitation.

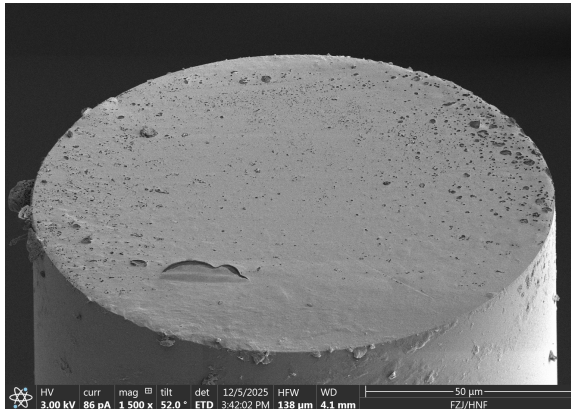
Figure 3.14: FIB Session 5, SEM image of bubbles in the fiber surface and of possible crosstalk limitation trenches.

### Session 6 - Continued Production at higher Current

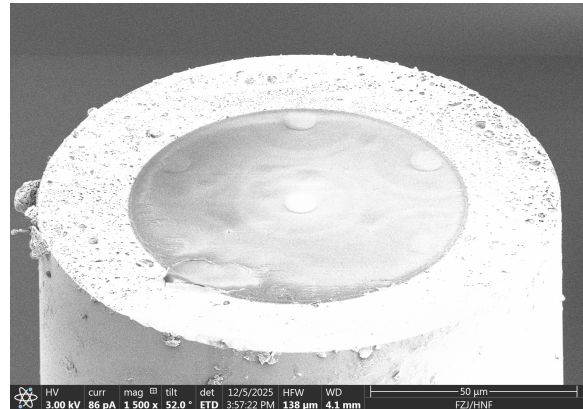
Three more fibers were produced with the higher current setting of 21 nA, the results are visible in Fig. A.8, Fig. A.9 and Fig. A.10.

### Session 7 - Gold delamination and ion imaging

When we observed the first fiber of the day in the SEM we noticed delamination of the gold, as visible in Fig. 3.15. During this session we reused remaining unmilled fibers from the last session, we have done this before without any problems, but outside temperatures were relatively low after the last session and the author carried the fibers back to Bonn, so probably the strong thermal cycle led to a loss of adhesion of the gold layer to the fiber. We decided that for future FIB sessions the fiber surfaces should always be freshly gold sputtered on site. Apart from that the manufacturing went well, but because the clumps of gold likely also made the surface quality of the ablations much worse (as the FIB can not compensate for already present surface irregularities) we decided it would be worth to sacrifice a fiber for some tests on how to improve core visibility in the ion image. The solution is relatively simple: We discovered that we can mill a circular pattern with a depth of a few hundred nanometers and keep observing the fiber surface in the ion beam image, at some point, likely again because of the differential milling rates between core and cladding the cores start showing (Fig. 3.16). The downside is that this strategy increases the milling time per fiber significantly as a large amount of material has to be removed across the whole fiber. It is also important to mill over the whole area that later on will be covered by ablations, because otherwise one will get steep drop offs in the height in some areas within the ablation, which is to be avoided for a smooth mirror geometry. This approach could be an interesting strategy to keep good core centering while also implementing the measures from FIB Session 8 (Sec. 3.1.3) for better ablation depth matching. During this session two more regular fibers were produced, their surfaces are visible in Fig. A.11 and Fig. A.12.

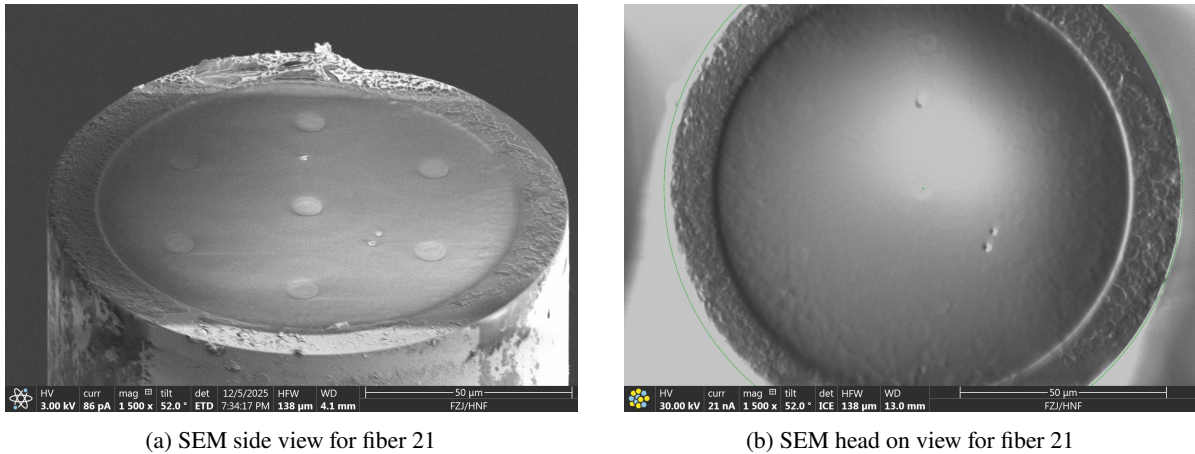


(a) SEM image before the circular mill.



(b) SEM image after the circular mill, one can see strong irregularities through the gold sticking to itself.

Figure 3.15: A fiber surface before milling during FIB session 7, we think thermal stress led to delamination of the gold layer.



(a) SEM side view for fiber 21

(b) SEM head on view for fiber 21

Figure 3.16: FIB Session 7 (Fiber name: 21 in Tab. A.1), this was a testfiber to see how long we have to mill until we can see the fiber cores in the ion beam image consistently. After a few hundred nanometers of milling almost on the entire fiber surface the cores became visible.

### Session 8 - RoC optimization and depth matching

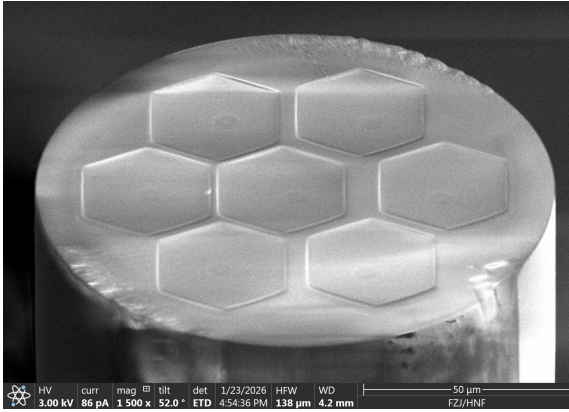
Session 8 was conducted with multiple weeks time delay to session 7, which allowed the author to conduct most of the surface analysis from Sec. 3.1.4. This interferometric surface analysis for the previous fibers, showed that the ablations so far come out with significantly smaller RoC than expected. Patrick Maier already told us that the nominal RoC of the stream files given through his script is not perfectly exact. In our case this situation gets worsened. There are three known effects that will contribute to this:

- The milling rate is in general strongly material dependent [80], it is possible, and to some extent expected that the milling rates on the multi core fibers differ from the ones on single core fibers (for which the script was calibrated), this seems even more likely if we consider the possibility of the presence of some isolation layer (also called trench) in between the cores, as potentially identified in Session 5 (Sec. 3.1.3)
- The currents that can be used in the Ulm FIB are in general similar to the ones in Jülich [80, 81], but there is a catch: The ion current is regulated by placing apertures in the ion beam path, these apertures can show aging effects [86]. Patrick Maier tried characterizing and compensating this for their system, but of course this can be very different for the FIB in Jülich. This means it is expected that the currents compared between the machines in Ulm and Jülich are not exactly the same, even for the same current setting.
- Probably the main reason (identified by JinHee Bae) is that the FIB in Jülich did not have a premade so called "application file" for silicon dioxide, which would contain a sputter yield correction for the given material, while Patrick Maier had one on their device, meaning the received doses are expected to be different.

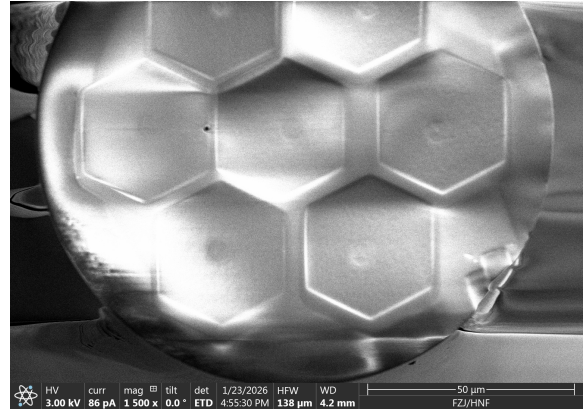
But this should essentially just be a rescaling problem, to show that we can also create ablations with an RoC closer to the optimum stated in Sec. 2.5 two more fibers were milled with a nominal RoC (as set by the script from Patrick Maier) of 250 µm and 300 µm respectively. The resulting SEM images can be



seen in Fig. 3.17 and Fig. 3.19 their surfaces are analyzed in Sec. 3.1.4. Additionally we were able to get good visibility ion beam images of the ablations, as shown in Fig. 3.18. Furthermore, we stopped the praxis, used for all previous fibers, to correct core alignment problems after the patterning has started, as this will allow us to get a best case height deviation measurement between the cores. This will be critical to have, as it allows us to estimate how much additional height tuning has to be done to get all cavities to a simultaneous resonance (with the strategies explained in Sec. 2.5.1). The height deviations are also analyzed in Sec. 3.1.4. After the two fibers were manufactured, a fiber (fiber 6), which was broken anyways after gold mirror coating (Sec. 3.3), was cut with the ion beam to take a look at the crossections of the ablations. We initially thought that we would be able to get a better understanding of depth and especially gold layer thickness this way, but because this cutting procedure requires strong use of the ion beam almost all conductive material on the fiber surface was removed in this region, leading to strong charging effects, which limited the usefulness of the images we took more than we expected. Nevertheless an SEM image of the fiber (with the mill region marked in yellow) and a zoomed in image on the cross section of two of the ablations on this fiber can be seen in Fig. A.13, the cores show nicely (as vertical columns on the left and right) and one can get a rough ablation depth estimation.

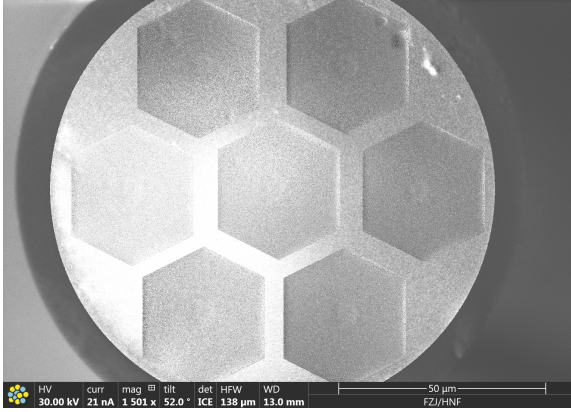


(a) SEM side view for fiber 22

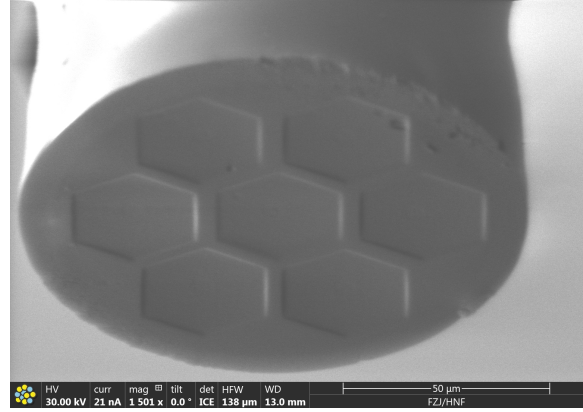


(b) SEM head on view for fiber 22

Figure 3.17: FIB Session 8 (Fiber name: 22 in Tab. A.1), this fiber was manufactured with a higher nominal RoC of 250 μm and without core alignment correction to improve the depth matching of the ablations.

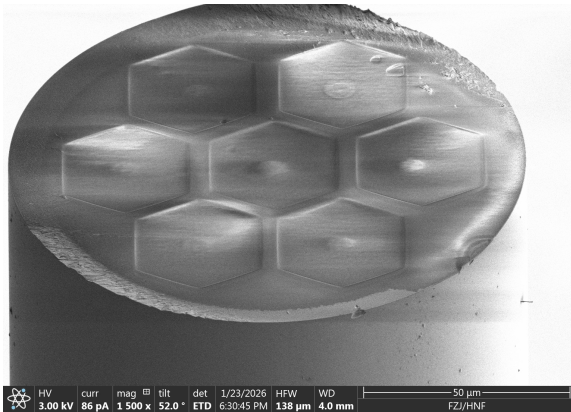


(a) Head on Ion beam image of fiber 23

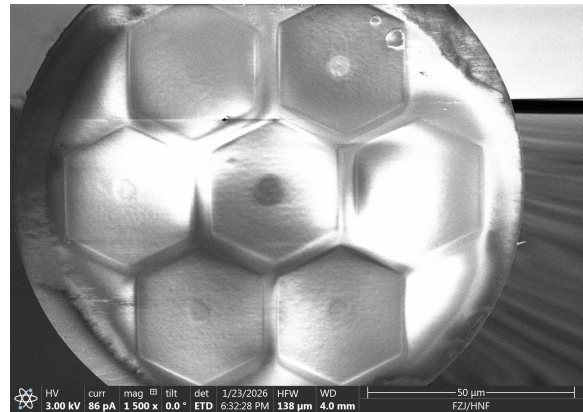


(b) Side view Ion beam image of fiber 23

Figure 3.18: FIB Session 8: Well focused ion beam images of fiber 23



(a) SEM side view for fiber 23



(b) SEM head on view for fiber 23

Figure 3.19: FIB Session 8 (Fiber name: 23 in Tab. A.1), this fiber was manufactured with a higher nominal RoC of 300 µm and without core alignment correction to improve the depth matching of the ablations.



### 3.1.4 Surface Characterization and CO<sub>2</sub> Laser Smoothing of FIB-Fibers

To characterize the Fiber surfaces, the green light interferometer, integrated in the Bonn CO<sub>2</sub> shooting setup, was used. Interferometer images of the Fibers directly after the FIB milling are visible in Fig. A.14(a)-A.24(a) on the left. As can be seen from the images, the surface quality of the fibers after the FIB procedure is poor, this is visible for example in the roughness of the interference fringes in the ablations. This roughness is especially high because of the high currents (9.3 – 21 nA) and acceleration voltages (30 kV) needed to remove the material sufficiently fast. That would strongly limit the maximal finesse we could achieve with these fibers, now we want to employ the same smoothing technique for FIB milled fiber surfaces as developed by Patrick Maier et al. [68], namely the application of a defocused CO<sub>2</sub> laser shot to the fiber surface. The melting of the surface ensures that surface tension pulls high frequency irregularities away, promising excellent surface quality similar to other CO<sub>2</sub> laser ablation methods, while essentially preserving the overall shape given by the FIB, which allows much more complex geometries and a shape that even for larger distances to the optical axis remains a good approximation to a sphere (contrary to the gaussian profile from directly CO<sub>2</sub> laser ablated fibers).

The fibers were smoothed with 2 times 10 pulses with 6.7 ms length each and power of 3.3 W, the power is chosen to barely melt the surface, leading to a smoothing effect without the destruction of the FIB milled features. The before mentioned parameters were selected by shooting at multiple testfibers. First the focus point was searched and centered to the fiber, afterwards the fiber was moved away from the focus, the power was increased and because stage and beam axis were not perfectly aligned some regular position correction of the fiber was necessary. As soon as a position where the whole fiber melts evenly was found, the dose was reduced until only slight melting on the surface occurred, the *ydiff* value (compare with Sec. 3.1.1) was selected as 6.9 mm, which means we operate at a distance from the focus of around 1.742 mm. Interferometer images of the fiber surfaces after the smoothing are visible in Fig. A.14(b)-A.24(b) (please note that only the surfaces of fibers from sessions 2 to 5 were analyzed like this and smoothed because of operational restrictions of the shooting setup).

The control software of the surface profiling interferometer of the CO<sub>2</sub> laser setup has an algorithm to extract the surface geometry from a sequence of multiple Interferometer images. The resulting surface geometries were plotted, two example images, one before and one after the smoothing, are visible in Fig. 3.20. The author wrote a python script to average the height values of the pixels around the ablation and, by detecting the minimum, the ablation depth can be calculated (Fig. 3.23(d)). Afterwards a sphere is fitted to each of the individual ablations (images of a cross section with the fit are visible in Fig. 3.22(a) before the smoothing and in Fig. 3.22(b) after the smoothing) and the radius of curvature is extracted. Depths and RoCs are visualized in histograms in Fig. 3.23(a) and 3.23(b). The fact that the difference to the spherical fit in Fig. 3.22(a) shows a very visible bump on the fiber core supports the hypothesis stated in Sec. 3.1.3 that there are slightly different milling rates on core and cladding, but in comparison with Fig. 3.22(b) one can nicely see how the feature was smoothed out through the CO<sub>2</sub> laser pulse.

The most demanding use cases for a cavity array are the ones in which a simultaneous resonance of the individual cavities is needed, as this requires precisely similar cavity lengths, even already at comparatively low finesse (as explained in Sec. 2.5.1). As tip and tilt deliver enough degrees of freedom to get at least three cavities to the same length, the mainly interesting quantities are the distances of the ablation minima to a plane of constant distance to the other cavity mirror. The position of this plane can be changed by alignment, so to characterize how well the cavities can perform in the ideal case the ablation minima positions were extracted and a plane was fitted to them, a histogram of the average distances of the ablations to the plane per fiber is visible in Fig. 3.23(c). In the ideal case we get a

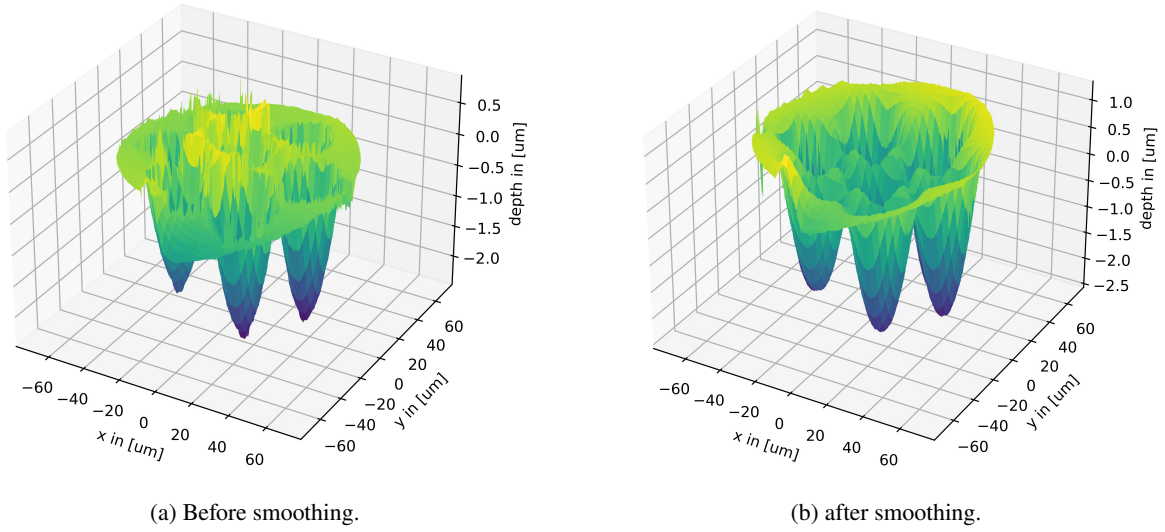
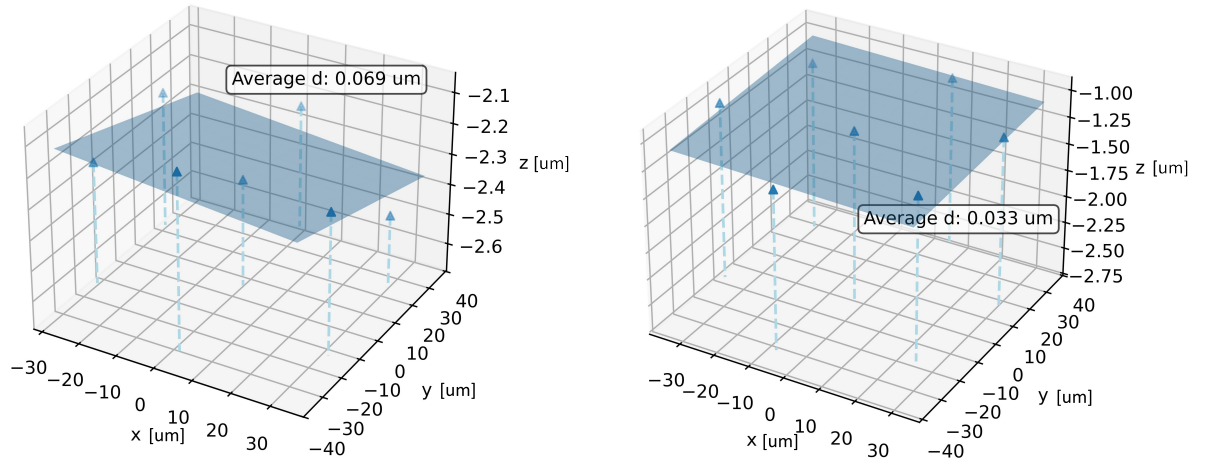


Figure 3.20: 3D surface reconstruction of Fiber 13 before and after smoothing

deviation of around 69 nm (Figure 3.21(a)).

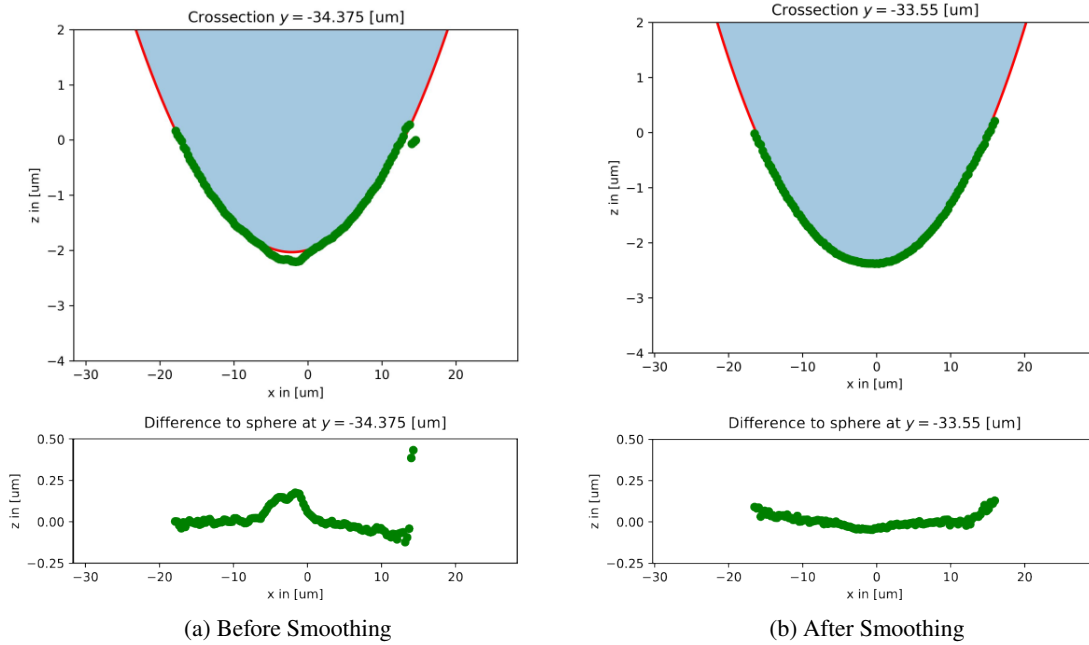
The current geometry is mainly limited through cleave shape and FIB workflow, as it is very difficult to image the fiber cores with the ion beam and as there is also a significant tolerance in the core position originating from the manufacturing process. So a high risk for slight errors in the ablation positioning arises, which would lead to a cavity axis that is shifted relative to the cores, negatively affecting mode matching. The FIB is continuously imaging the fiber while the ion beam is running, interestingly the cores start to show significantly clearer a few seconds after the patterning has started, probably because of slightly differential milling rates between the cores and the cladding (as explained in Sec. 3.1.3), often revealing the pattern to be off center. In the first batch of Fibers this was corrected by aborting the patterning, realigning the structure and starting the process again. This fixes the problem of being slightly off axis quite well but of course makes the depths of the ablations less reproducible, as some ablations with initially bad alignment will have received multiple seconds more ion beam irradiation. Starting from FIB session 8, it was decided to accept a possible mismatch of the optical axes and the cores in favor of a more reproducible depth. At the same time we wanted to optimize the radius of curvature, because as one can see in Fig. 3.23(a) we got an average RoC in the 60 to 70  $\mu\text{m}$  range in the previous FIB sessions, this is significantly less than the 150  $\mu\text{m}$  that we aimed for, but this is just a calibration problem (as explained in the text to Session 8 in Sec. 3.1.3). So we milled two fibers without optimizing the core alignment, interferometer images of the resulting surface geometries can be seen in Fig. A.25. One of the fibers was milled with a nominal RoC of 250  $\mu\text{m}$  and one with 300  $\mu\text{m}$ , this resulted in measured RoCs of 110.57  $\mu\text{m}$  and 135.76  $\mu\text{m}$ , meaning a nominal value of around 350  $\mu\text{m}$  would probably be ideal, this should quickly be verified with another test mill in the future. We now get an ideal case deviation of the ablation minima from the fitted plane of around 33 nm (Fig. 3.21(b)), meaning that we start entering a regime where usage of the silicon layer, as explained in Sec. 2.5.1, could allow us to achieve the simultaneous resonance case. We hope that we can improve the core centering in the future and keep the depth matching by implementing the measures we tried during session 7 (Sec. 3.1.3), so by milling so much material away across the whole fiber that the cores get visible at some point because of the differential milling rate between core and cladding and then create our ablations after that.



(a) Plot of the ablation minima for fiber 8 with a plane fitted to them.

(b) Plot of the ablation minima for the newly manufactured fiber with a nominal RoC of 300 μm and without core centering correction.

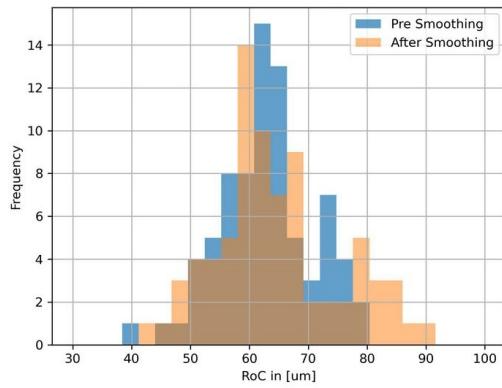
Figure 3.21: Average deviation of the ablation minima from a plane fit, this is an important quantifier for the performance of our array for an application where simultaneous resonance is required, as a plane can be compensated via an alignment change.



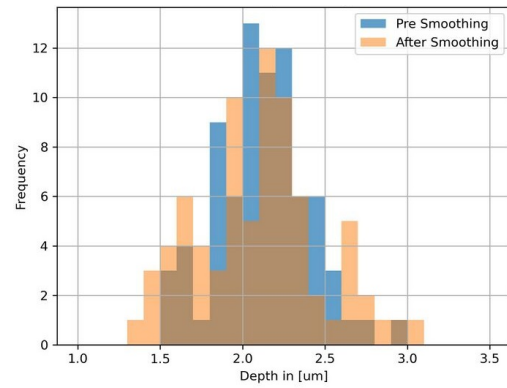
(a) Before Smoothing

(b) After Smoothing

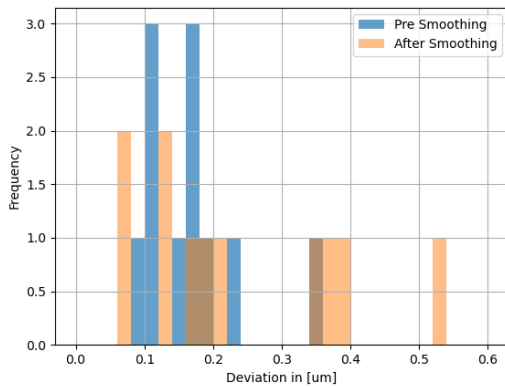
Figure 3.22: Cross section of an ablation on Fiber 13 (green data points) with a spherical fit (red line) and below the difference between fit and data. Once plotted before the smoothing and once after.



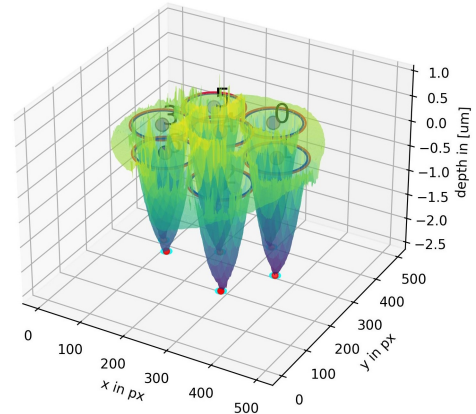
(a) Histogram of Ablation RoCs, before Session 8 (Sec. 3.1.3).



(b) Histogram of Ablation Depths, before Session 8 (Sec. 3.1.3).



(c) Histogram of average deviation of Ablation minima from fitted Plane, before Session 8 (Sec. 3.1.3).



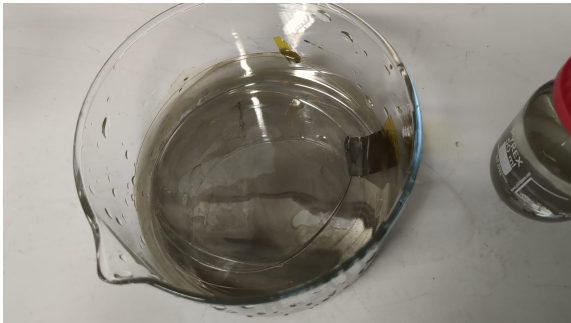
(d) Plot of the Fiber Surface Geometry of fiber 13 (before Smoothing) during the processing to extract structure depth, the red dots show the detected minima point and the purple one the base height. The circles show the regions that were averaged to calculate these.

Figure 3.23: Fiber Surface Analysis Histograms and Surface Plot.

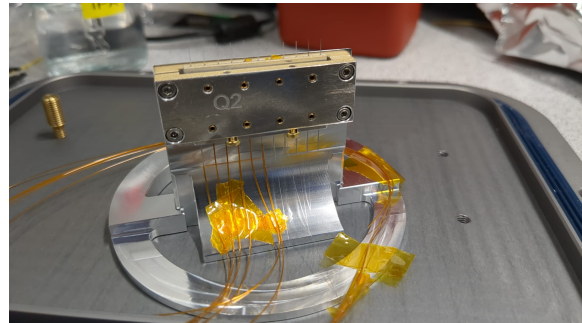
### 3.2 Mechanical Stability of the Fiber

As bare optical fibers are inherently fragile they are almost always handled with some kind of protective coating, most of the time made of metal or plastic. A metal coating has the advantage that it is stable at higher temperatures and is inherently better vacuum compatible than most plastics. As a DBR mirror coating procedure can heat the fibers to several hundred degrees Celsius while requiring good vacuum, a protective coating that can withstand these conditions with only low outgassing is required for most potential use cases involving high reflectivity mirrors. At the time we were unable to find a supplier offering multicore fibers with such a coating for a reasonable price. The supplier we decided to use was *fibercore* via the distributor *Lasercomponents*<sup>2</sup>, they offered also compatible multicore fanouts and the seven core layout promised efficient use of the available end facet area (as explained in Sec. 2.5). These fibers came with an Acrylate coating, which is not very thermally stable [87], thus we had to replace it to get fibers that could withstand a mirror coating procedure. Companies like IVG fiber<sup>3</sup> sell metal coated optical fibers for purposes like these, but until late 2025 their standard portfolio did not include multicore fibers<sup>4</sup>. This is why the author tried to find a self made vacuum compatible and temperature stable solution.

The approach was to try to cover the fiber in silver with the help of a silver nitrate based solution. To achieve this the Acrylate coating was stripped from the fiber mechanically, and the surface was wiped clean with isopropyl alcohol, then the fiber was introduced to the silvering solution, the author followed a recipe for chemistry classes<sup>5</sup>. This had partial success some regions of the fiber featured a thick silver layer and were noticeably more stable, but other regions were not covered at all. Upon close inspection this can be seen in Fig. 3.24(a), one can notice that the fiber below the tape piece on the right is slightly thicker.



(a) The first tests with the silver coating solution were conducted in a crystallizing dish, one can see the partial silver layer on the fiber.



(b) Redesigned FIB fiber holder, six of the fibers are mechanically protected through a Kapton tube.

Figure 3.24: Efforts to improve the mechanical stability of the fibers.

<sup>2</sup> <https://www.lasercomponents.com/en/product/standard-multicore-fibers/>

<sup>3</sup> <https://www.ivgfiber.com/>

<sup>4</sup> <https://web.archive.org/web/20251119102842/https://www.ivgfiber.com/>

<sup>5</sup> <https://www.fachreferent-chemie.de/versilbern-von-glasflaschen/>

Some tests were conducted with different amounts of stirring or shaking during the reaction, but a homogeneous coating was not achieved. This problem became obsolete when the author discovered that the company allectra sold small Kapton tubes<sup>6</sup>, these were ideal to insert the fibers into during manufacturing for added stability and became our preferred choice for this task. A FIB holder in which the fibers were protected via these Kapton tubes can be seen in Fig. 3.24(b). This FIB holder was slightly changed compared to the original design by Patrick Maier (which is visible in Fig. 3.3(b)), to allow use of significantly longer fibers. Because of the mechanical limitations that arise when handling bare optical fibers without any protective coating the first fibers that were produced by the FIB were only a few centimeters in length (to avoid breakage).

### 3.3 Fiber Mirror Coating

To form cavity mirrors the manufactured Fibers need a reflective coating, ideally a high reflectivity DBR, as this would enable higher finesse, but this requires long lead time, as we are dependent on a commercial company for this. Lower quality DBRs and metal coatings can be done in house much easier. We aim for a 40 nm target thickness gold coating with a 3 nm chromium adhesion Layer. The gold and chromium were thermally evaporated onto the fiber surfaces, the author wants to thank Paul Steinmann for showing him how to operate the machine and helping to understand which gold thickness will be optimal by sharing his code. The evaporation machine is visible in Fig 3.25(a), the fibers were mounted at the top after the second shutter, the machine uses two small wolfram boats to hold both the gold and Chromium metal pieces. After the metal pieces and fibers are introduced the machine is closed and a vacuum is pumped. The boats are electrically heated until the containing metal starts evaporating, a piezoelectric crystal (top left) can monitor the evaporation rate (after opening of the first shutter), when the correct rate is reached the second shutter opens and the fiber surface is coated. A Transfer-matrix calculation done with the python tmm package<sup>7</sup> shows that for a 40 nm gold layer on top of a 3 nm chromium layer on a fiber we expect a reflectivity of about 97 % and transmittance of about 0.6 %. From this we can calculate the theoretically achievable maximum finesse against a high reflectivity substrate ( $R_2 \sim 99.999\%$ ) via Eq. 2.5 as

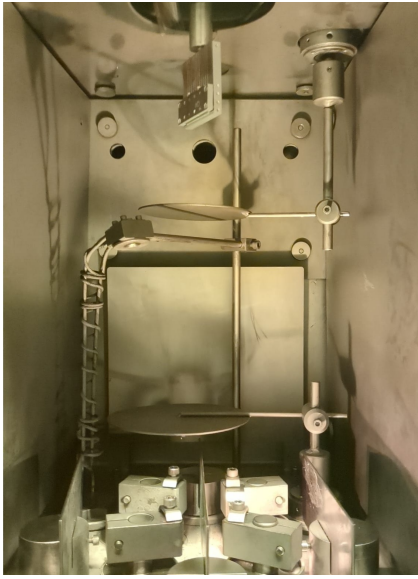
$$\mathcal{F} = \frac{\pi(R_1 \cdot R_2)^{1/4}}{1 - \sqrt{R_1 \cdot R_2}} \approx 206.21, \quad (3.1)$$

To understand the quality of the surface after evaporation a fiber (fiber 15) from the holder was introduced back into the interferometer setup, an interference image is visible in Fig. 3.25(b). As there were no surface defects visible (compare also with Fig. A.16(b)) the author moved on in trying to practically demonstrate the cavity array, next the fiber has to be connected to the multicore fanout.

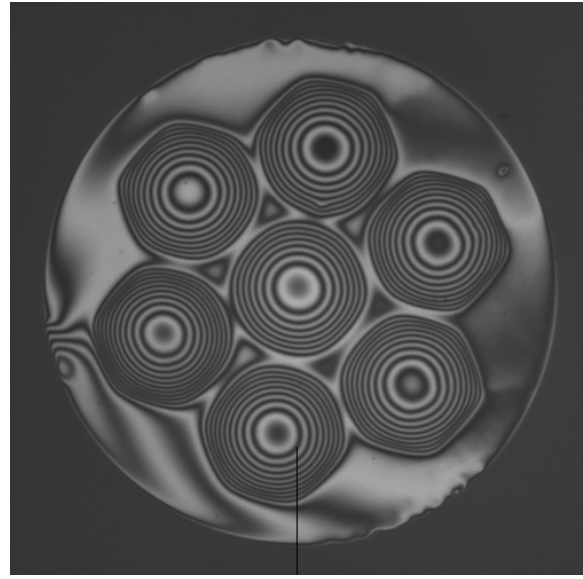
<sup>6</sup> <https://www.allectra.com/de/products/312-kap-tube-02-300-2/>

<sup>7</sup> <https://pypi.org/project/tmm/>





(a) The coating machine interior, on the bottom side of the image the connectors for the two evaporation boats can be seen, on the top the sample is mounted. In between the sample and the evaporation boat are the two shutters and on the top left the piezo to measure the evaporation rate is visible.



(b) Interferometer Image of the surface of fiber 15 after gold coating, please also compare to Fig. A.16(b).

Figure 3.25: Gold coating procedure

### 3.4 Splicing Multicore Fibers

The cores of the mirror coated fiber have to be individually addressable, to achieve that the fiber was connected to a multicore fiber fanout which features a bare multicore fiber on one side and seven single core fibers with FC/APC connectors on the other side<sup>8</sup>. This device is visible in Fig. 3.26(a). The laser input can just be connected to one of the single core fibers and will be transmitted to the corresponding core of the multicore fiber.

We want to use Fusion Splicing to connect the fiber mirror to the fanout, for this a device called Splicer, precisely positions the fibers in front of each other and aligns them with the help of cameras, then an electrical arc melts them together. We used the Fujikura ARCMaster FSM100P+<sup>9</sup> as it offers the possibility to rotate the fibers and a feature to view the fiber end facets, as one can imagine this is essential for the splicing of multi core fibers, as the cores have to be rotated onto each other. Furthermore the splicer enables the user to design custom splice programs. The device is visible in Fig. 3.26(b).

Before the fiber can be spliced the end facet has to be cleaved, as explained in the beginning of Sec. 3.1. The author used pre-programmed parameters for polarization maintaining fibers as a starting point for the splicing and iterated on those for the multicore fibers (as there was no pre-made program for multicore fibers). For longer test fibers good results were easy to achieve, but because the first fibers we

<sup>8</sup> Fibercore, Laser Components: <https://www.lasercomponents.com/en/product/standard-multicore-fibers/>

<sup>9</sup> <https://www.europe.fujikura.com/markets/industrial/specialty-splicers-and-accessories/fsm-100p-2/>

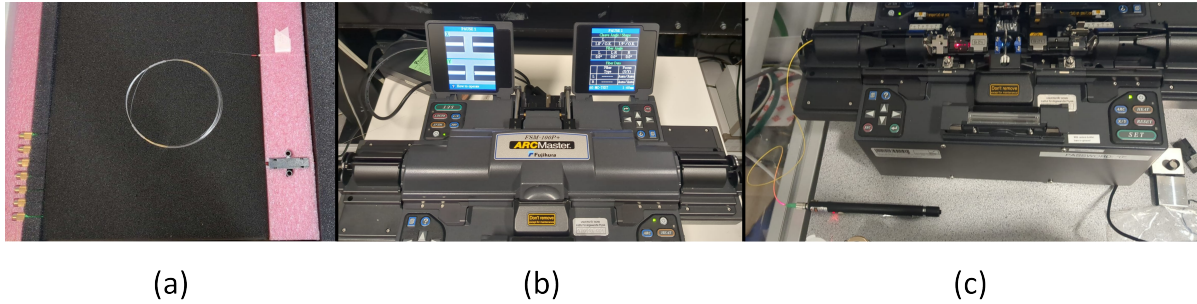
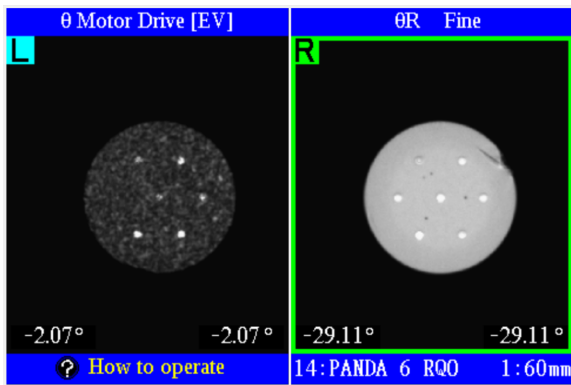


Figure 3.26: (a) Image of the multicore fiber fanout, the 7 FC/APC connectors can be seen on the left, in the middle is the output a 5 m multicore fiber piece. (b) The Splicer Fujikura FSM100P+ features cameras for viewing the end facets of the fibers and has a rotational degree of freedom, which is essential to splice multicore fibers. (c) A red laser pointer connected to an optical patch cable is used to illuminate a short fiber mirror piece that is not long enough to reach the illumination LED.

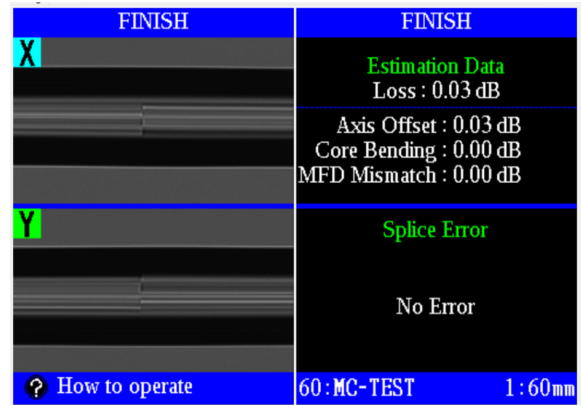
milled with the FIB were limited to only a few centimeters in length (for the mechanical stability reasons explained in Sec. 3.2 and because of restrictions imposed by the first fiber holder) they were not long enough to reach the LED that is needed for illumination in the end facet view mode, but observing the end facets is essential for aligning the cores onto each other. As a workaround the author instead added a singlemode fiber with a red laser pointer attached to it. The end facet of this fiber was placed in front of the fiber mirror. This construction is visible in Fig. 3.26(c), the transmission turned out to be high enough to view the fiber surface with the integrated end facet viewer as can be seen in Fig. 3.27(a).

As soon as the end facet is visible the cores can be manually rotated on top of each other and after that the splicer can fuse them together. The first attempt in doing that with a fiber mirror yielded quite bad results though, the splice showed a bubble and had intolerable high channel crosstalk. To improve on that the author did multiple arc calibrations (an automated calibration program in which the melting pattern of the fibers is analyzed), a parameter sweep of the arc current and repositioned the electrodes. After that bare multicore fibers could be spliced with low loss (Fig. 3.27(b)) consistently.

The next fiber mirror suffered from problems again, as there seemed to be contamination from the mirror coating process at the end facet (Fig. 3.28(a)). Usually this amount of dirt on the outside of the fiber is no problem, but in this case it turned out to be conductive (so likely gold from the mirror coating process), this led to a visible shift of the arc to the left during splicing, the result of the splice clearly showed this uneven melting in the fiber thickness. As the amount of fibers that are possible to use was quite limited and each of the short fibers has only enough length for one to two cleaves the author tried to save the fiber. For that a 1550 nm laser was attached to the fanout and the reflection measured, after applying two additional arcs to the splice point a clear and relatively stable reflection signal was observed for each of the cores, the resulting splice geometry is visible in Fig. 3.28(b). This allowed the author to proceed to the demonstration of the cavity array.

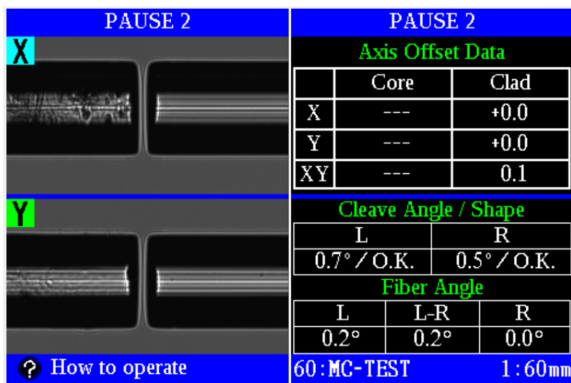


(a) End facet of the fiber imaged by the end facet viewing system of the Fujikura FSM100P+. The left fiber is the fiber mirror and is illuminated via a red laser pointer.

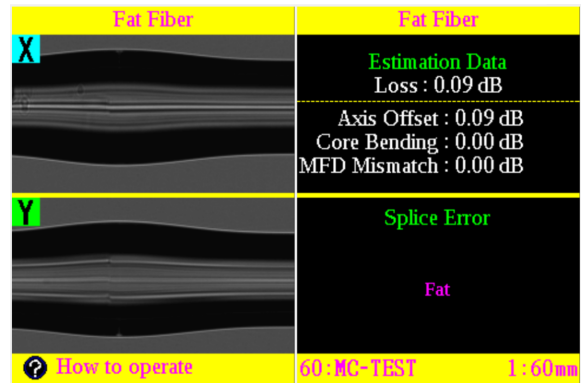


(b) Splice result of two bare multicore fibers after multiple arc calibrations, electrode realigning and optimization of the arc power.

Figure 3.27



(a) Multicore fiber mirror (left) and fanout (right) before splicing. The fiber mirror side seems to have some contamination with conductive particles.



(b) Fiber mirror and fanout after the splice, the arc shift towards the more conductive side lead to uneven melting, but with two rears it was possible to get visible reflection signals on each of the multicore fiber channels.

Figure 3.28

### 3.5 Fiber Cavity Array Demonstration

In this section the multicore fiber mirror will be used in combination with a mirror substrate to create a cavity array. In the first section some preliminary characterization of the coating, like mirror transmission and reflection, is done and the crosstalk between the individual channels is analyzed, afterwards the cavity array is constructed and the finesse is estimated. Then it is demonstrated how two cavities can be tuned into simultaneous resonance via an alignment change.

### 3.5.1 Transmission, Reflection and Quantification of Channel Crosstalk

Before building a cavity array from the fiber mirror that was spliced to the fanout, the transmission, reflection and channel crosstalk were measured. For the transmission measurement a photodiode was placed behind the mirror coated side of the fiber, a laser power of  $14.12 \text{ mW} \pm 0.02 \text{ mW}$  was coupled to a core via the fanout and the alignment between fiber and detector chip was optimized until the photodiode voltage became maximal. Then an oscilloscope trace of the photo diode voltage was taken, this procedure was repeated for each of the 7 cores. The results are shown in Fig. 3.31(a), the raw data can be found in Fig. A.26(b). Contrary to the expected transmission values from transfer matrix calculations (Sec. 3.3) these transmission values substantially exceed the expected 0.6%. Initially the reason was suspected to be some mistake during the measurement (like too much background light), but as a later repetition of the measurement yielded similar results another hypothesis seems much more likely: The used measurement process for the transmission can not distinguish if light is guided in the core of the fiber or the cladding. Because of the splice problems explained in the previous section we expect a non negligible amount of scattering to occur into the cladding.

If the transmittance on the cladding is slightly higher than on the cores this could explain the mismatch. On first sight it is not immediately clear how that can happen, but one has to keep in mind that during splicing the fiber tip was mechanically heavily stressed, as (because of the short length) clamping had to occur close to the mirror and the fiber had to be placed right behind the illumination fiber in the V-groove of the fiber holder in the splicer. It can not be excluded that this led to some mechanical damage to the mirror coating. Nevertheless the coating on the fiber cores themselves is somewhat protected through the rest of the fiber, as the gold coating on the cores sits around a micron deep in the ablations (compare with Sec. 2.5), potentially explaining why the demonstration in Sec. 3.5.2 still worked. Furthermore, because of the hexagonal ablation projection (in 2D) and spherical geometry (in 3D), there are multiple sections at the edge of each ablation where the surface drops off almost vertically, this region is hard to coat with a similar thickness to the rest of the fiber. And indeed if one images the fiber again in the surface profiling interferometer, but keeps the light source off (so basically just a camera) and instead illuminates a channel with a laser pointer via the fanout one can clearly see light emerging from the cladding, especially at the edges of the ablations, where the gold coating is likely thinner (Fig. 3.29).

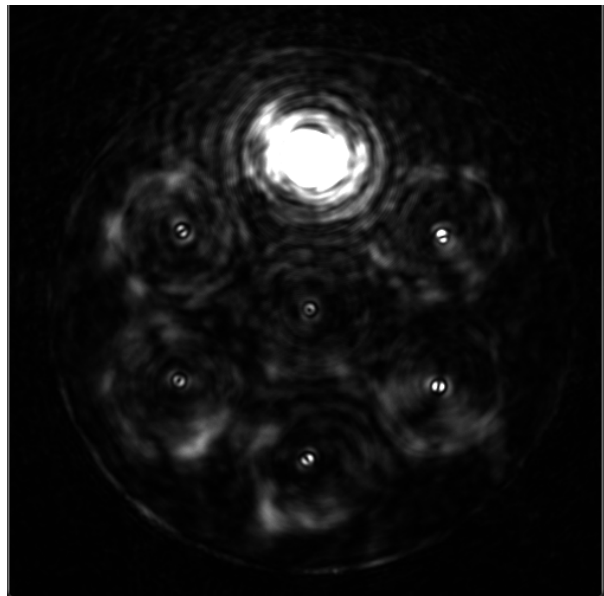


Figure 3.29: A laser pointer is used to illuminate a channel of the multicore fiber via the fanout, it is clearly visible that light also emerges from other cores and the cladding, especially around the ablation edges.

After the transmission measurement the reflection and channel crosstalk were evaluated. The reflection

was measured by introducing the laser to a fiber circulator<sup>10</sup>, the second channel of the circulator was connected to one of the seven cores of the multi core fiber via the fanout and the photodiode to the third port (see Fig. 3.30(a)). Please note that the circulator still had a non negligible amount of loss from port two to port three, this loss was measured to be a factor of  $0.772 \pm 0.002$ . The power was unchanged compared to the previous measurement. The results of the reflection measurement are visible on the diagonal of Fig. 3.31(b), the raw data can be found in Fig. A.26(a).

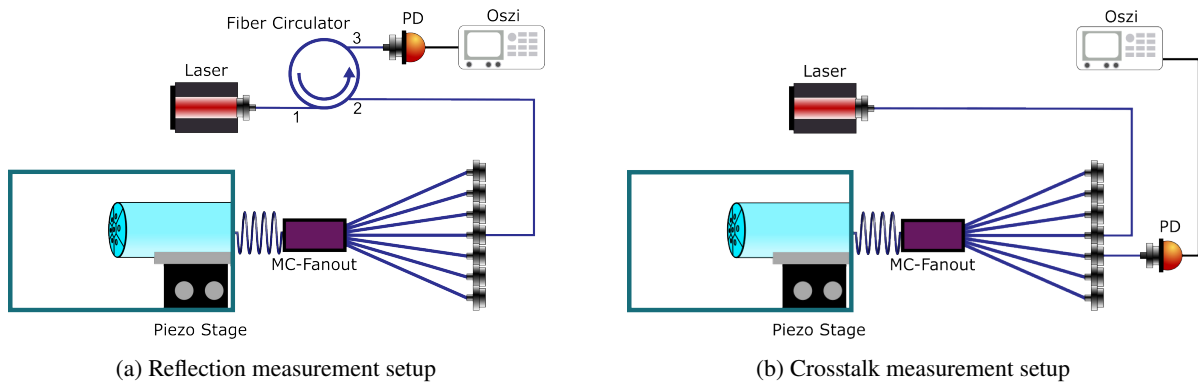


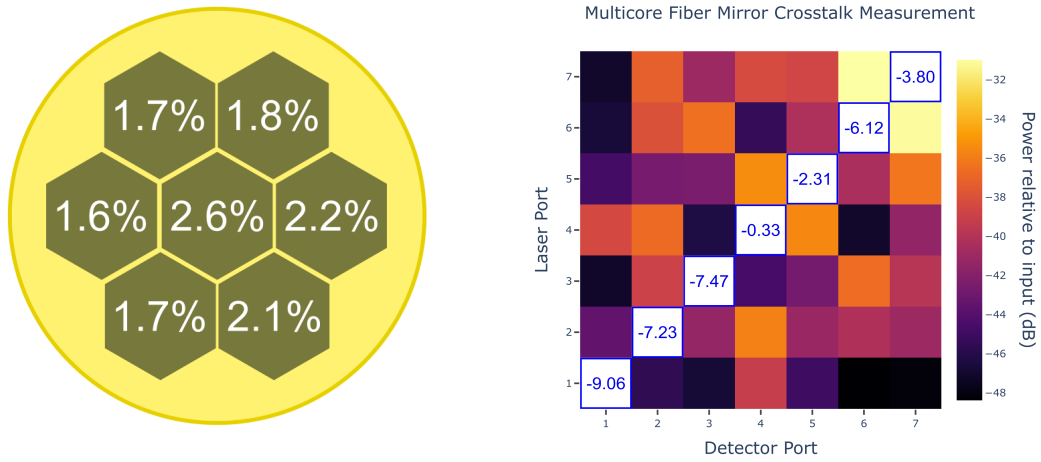
Figure 3.30: Setup sketches for the crosstalk and reflection measurements of the multicore fiber mirror.

The crosstalk between the individual cores was measured by coupling the laser to one of the cores at a time and measuring the power that leaves the fanout through one of the other ports (see Fig. 3.30(b)). These measurements were conducted with an input laser power of about 14 mW (small input power drifts were regularly checked after every seven measurements and compensated in the calculation, this was necessary because the measurement took multiple hours). The rawdata can be found in Tab. A.2 and the results are visualized in the off diagonal elements of the colormap Fig. 3.31(b). The direct reflections (measured with the circulator setup) of course show a much higher returned power, this is why they are not visualized by color to avoid loosing detail for the other cores. As expected there is a mirror symmetry along the diagonal visible, which makes intuitive sense, it should not matter for the scattering from one core to the other if we send the laser into the first one and measure at the second one or vice versa. The fact that the symmetry is not perfect is probably because of drifts in the fiber shape over time. The author tried his best to fixate the fiber firmly, but already before the measurement it was clear that there is a non negligible amount of change in the reflection if the fiber is slightly bend which can be a typical sign of a low quality splice. As visible both in Fig. 3.31(a) and Fig. 3.31(b) the center core (which is port four on the fanout) has the lowest loss in reflection and also features the highest transmission. This indicates that it has the best splice quality, which is expected as the center core does not need an optimized rotation of the two fibers during splicing to achieve low losses.

In Comparison with the fanout data sheet it becomes clear that the fanout itself contributes significantly less to the total crosstalk than the sum of splice and mirror coating, the crosstalk data measured by the manufacturer is shown in Tab. 3.1, please note that this data was measured by fibercore by splicing the multicore fiber fanout to a second calibrated fanout and checking the power on the other cores (those without laser input) in transmission. Such a measurement scheme is of course not possible here because of the fiber mirror, but the main difference is just that the light measured in reflection will have traversed the same fanout and splice twice in our case and just once in their case, meaning it is a reasonable

<sup>10</sup> ThorLabs 6015-3-APC <https://www.thorlabs.com/item/6015-3-APC>

approximation to just infer a factor of 2 (3 dB) for a fair comparison. Because of the problems explained in Sec. 3.4 it seems likely that the splice is the main limiting factor for the crosstalk. This is a reassuring conclusion for possible future applications of multicore fiber mirrors, as high quality splices of multicore fibers are industrially (because of the high demand for the telecommunication industry) well developed, just our fiber preparation process, the used splice parameters and our available tools are not ideal yet, the largest gain can probably be achieved by either protecting the fiber splice ends during mirror coating mechanically or cleaning the fiber end chemically before the splice to avoid the problems shown in Sec. 3.4. Another possibility could be the incorporation of a 3D printed microphotonic element to circumvent the splice all together, as recently demonstrated by Li et al. [88].



(a) Sketch to visualize the measured transmission through the fanout, splice and coating for every core.

(b) Heatmap visualizing reflected Power and Power scattered to other cores for each fanout port. A fiber mirror was spliced to the multicore side of the fanout.

Figure 3.31: Measurement results of coating transmission and channel crosstalk

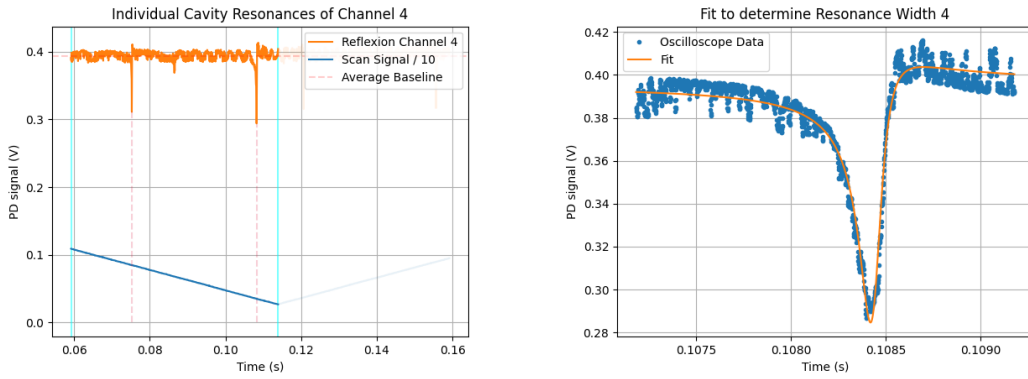
Table 3.1: Transmission matrix as stated by the fanout manufacturer fibercore (C-band average, dB)

| Ref. device<br>(output) | ch. no. |       |       |       |       |       |       |
|-------------------------|---------|-------|-------|-------|-------|-------|-------|
|                         | 1       | 2     | 3     | 4     | 5     | 6     | 7     |
| 1                       | –       | -71.2 | -70.3 | -73.8 | -75.3 | -75.7 | -69.4 |
| 2                       | -71.3   | –     | -76.0 | -72.1 | -71.4 | -75.4 | -71.7 |
| 3                       | -69.7   | -75.0 | –     | -72.1 | -69.2 | -71.5 | -68.1 |
| 4                       | -72.2   | -71.1 | -70.5 | –     | -71.8 | -72.6 | -69.8 |
| 5                       | -73.1   | -74.2 | -79.2 | -73.7 | –     | -73.3 | -66.5 |
| 6                       | -73.3   | -71.5 | -72.1 | -73.4 | -70.8 | –     | -64.9 |
| 7                       | -76.4   | -78.0 | -77.5 | -72.2 | -70.0 | -72.7 | –     |



### 3.5.2 Cavity Array and Finesse Measurement

To now realize the cavity array and measure the finesse of the individual cavities, the multicore fiber mirror was placed on a piezo stage (ThorLabs MAX312D/M<sup>11</sup>) facing a DBR mirror substrate. A triangular voltage ( $\sim 1 \text{ V}_{\text{pp}}$ , 20 Hz) was applied to the piezo amplifier<sup>12</sup> (with a gain of  $\sim 7.5 \frac{\text{V}}{\text{V}}$ ) which was then connected to the piezo stage to scan the cavity length and a laser was sent through one of the cores via the fanout. The Cavity reflection signal was measured via a circulator and photodiode, placed before the fanout. Cavity resonances showed when the stage was used to position the fiber surface in close proximity to the substrate. The alignment was optimized for each of the cores and the Cavity Spectra visible in Fig. 3.32 and Fig. A.27 to Fig. A.32 were measured. The experimental setup is visible in Fig. 3.33(a). The piezo scan input voltage was chosen at around  $1 \text{ V}_{\text{pp}}$ , because it allows to cover a full Free Spectral Range of the cavity. From measuring the time delay between the two resonances we can calibrate the time axis of the oscilloscope via the theoretically expected Free Spectral Range, but this calibration factor will be present both for  $\Delta\nu_{\text{FSR}}$  and  $\delta\nu_{\text{FWHM}}$ . As the finesse can be determined via Eq. 2.8 as the quotient of the two this calibration factor will cancel (if we assume the scale to be linear) and it is therefore legitimate to determine the finesse via the Quotient of the FSR and resonance FWHM in the time domain directly.



(a) Cavity scan over a Free Spectral Range on the cavity at fanout Channel 4. The resonance position and the average reflection power baseline are indicated.

(b) Zoom in on one of the cavity resonances. The resonance is fitted with a fano lineshape and the width extracted for finesse determination.

Figure 3.32: FSR scan and resonance shape data of channel 4.

For some of the cores the reflection baseline in the oscilloscope trace was quite unstable, probably because of power fluctuations caused by the unstable splice, which also affected the Quality of the fits for the resonances, nevertheless the extracted values can be used to get a first approximation of the finesse that is achievable in practice with a gold coating. Care was taken to apply an appropriate offset voltage to position the cavity resonances in the linear part of the triangular scan, for that the points where the piezo changes directions should be avoided. In table Tab. 3.2 the FSR and FWHM (extracted from the fits) in the time domain as well as the calculated finesse can be seen for all 7 cavities of the array.

The FSR is extracted directly from the minima in the oscilloscope trace, this is possible because the width of the resonance and the oscilloscope time resolution are small compared to an FSR. The

<sup>11</sup> [https://www.thorlabs.com/item/MAX312D\\_M](https://www.thorlabs.com/item/MAX312D_M)

<sup>12</sup> <https://www.thorlabs.com/item/MDT693B>

| Channel | FSR (s) | FWHM (s)                           | Finesse         |
|---------|---------|------------------------------------|-----------------|
| 1       | 0.0349  | $(1.04 \pm 0.07) \cdot 10^{-04}$   | $335 \pm 24$    |
| 2       | 0.0355  | $(9.04 \pm 0.30) \cdot 10^{-05}$   | $392 \pm 13$    |
| 3       | 0.0324  | $(9.00 \pm 0.23) \cdot 10^{-05}$   | $361 \pm 9$     |
| 4       | 0.0329  | $(1.401 \pm 0.014) \cdot 10^{-04}$ | $235.2 \pm 2.4$ |
| 5       | 0.0332  | $(1.51 \pm 0.06) \cdot 10^{-04}$   | $220 \pm 9$     |
| 6       | 0.0340  | $(1.81 \pm 0.07) \cdot 10^{-04}$   | $187 \pm 7$     |
| 7       | 0.0330  | $(1.575 \pm 0.024) \cdot 10^{-04}$ | $209.6 \pm 3.2$ |

Table 3.2: Free spectral range, resonance width and finesse of the seven cavities measured.

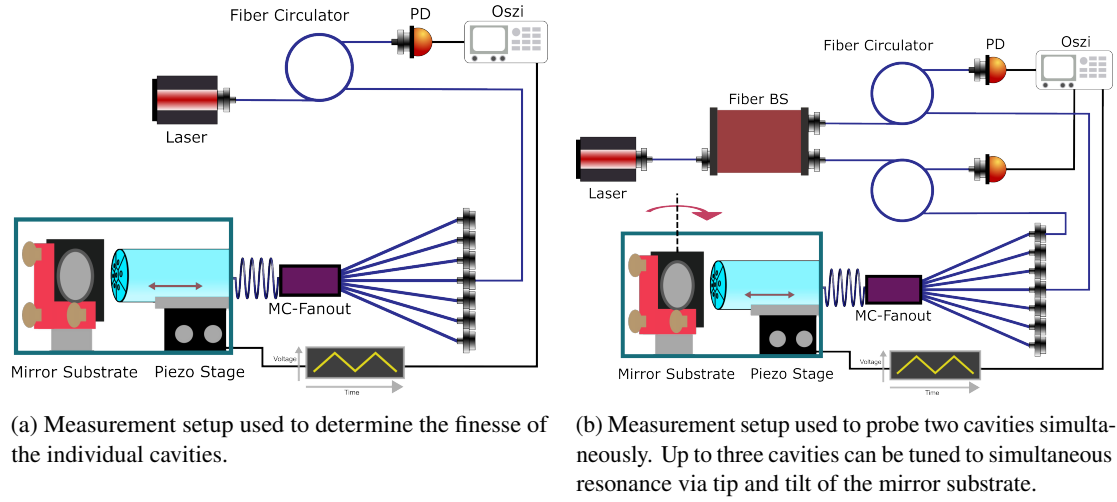


Figure 3.33: Cavity array measurement setups.

oscilloscope is assumed error free, as the splice induced power fluctuations dominate (they can be seen as high frequency wiggles in Fig. 3.32(b) for example), these power fluctuations have a strong effect on the fit uncertainties. The numerical error written here on the finesse is fully given by these uncertainties of the fit of the resonance, but this of course does not account for all relevant sources of error, immensely important is also the mechanical stability of the setup and possible nonlinearities in the piezo scan, this is hard to quantify for an individual measurement series though. To get a better idea how the mechanical stability affects the system many measurements of the same cavity would be required, the scattering of the resulting finesse values would be a good quantifier for that.

Mechanical instability can both increase and decrease the measured finesse, as a vibration moving the fiber against the scan direction can expand the apparent width of the resonance (the fiber stays longer at the resonance position then expected) and a vibration moving in the same direction can compress it. Potential scan nonlinearities, especially strong around the points where the piezo changes direction, could be investigated by tracking the apparent size of a fixed frequency interval, e.g. given by a cavity FSR or electro optical modulator sidebands (for a higher finesse cavity) when the piezo offset voltage is changed. Nevertheless, this measurement already gives us a rough estimate of the achieved finesse, the fact that some finesse values are higher then the theoretical expectation of around 200 (Eq. 3.1) is not very surprising given the power fluctuations and potential insufficient mechanical stability. A

better splice and a firm mechanical connection between the piezo stage and the substrate holder could improve these shortcomings. Still we also have to consider the possibility that the gold layer is slightly thicker than the 40 nm we aimed for, which would also increase the maximal possible finesse, this is well possible, as there was no dedicated calibration of the evaporated layer thickness done.

### 3.5.3 Cavity Detuning and Changes Through Tilt Introduction

As already explained in Sec. 3.1.4, depth variations in the ablations are currently preventing the whole cavity array from reaching simultaneous resonance. To characterize the detuning of the individual cavities to each other one of the channels, channel 4 (the one in the middle of the fiber), was selected as a reference because it was the least noisy and had a high reflection signal. All of the other 6 cavities were measured once simultaneously to channel 4 without changing the alignment in between measurements. For this measurement the laser was send through a 50:50 fiber beam splitter and the two outputs were attached to a fiber circulator each. The second port of each circulator was attached to individual ports of the multicore fanout and on the third circulator port was a photodiode. The measurement setup is sketched in Fig. 3.33(b) and the results are visible in Fig. 3.34, A.33 and A.34. Please note that the photodiode voltage of channel 4 was divided by five for better visibility.

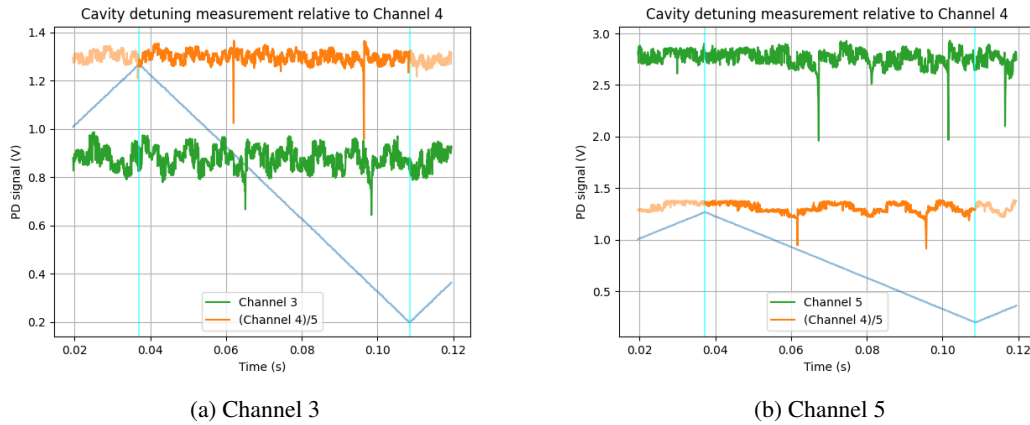


Figure 3.34: Oscilloscope traces showing the time (and correspondingly spatial position) offset between resonance on channel 4 and 3 (a) and 4 and 5 (b). The triangular piezo scan signal is visible in the background.

In principle one has enough degrees of freedom via the tip and tilt of the fiber relative to the mirror substrate (as explained in Sec. 3.1.4) to achieve simultaneous resonance for three cavities, as we only had two 1550 nm photo diodes at hand, a demonstration of how two resonances can be shifted on top of each other via mirror tilting was done. Recombining multiple beams on a single photodiode is not recommendable for this measurement, as one effectively builds a Michelson interferometer, which makes the measurement very sensitive to length fluctuations. The measurement was conducted by continuously scanning the length of the cavity with the piezo while changing the tilt angle of the substrate relative to the fiber, oscilloscope traces were taken at regular intervals to verify the progress. The results are shown in Fig. A.35, it is visible that it was possible to make the resonances overlap with a deviation of less than  $\delta\nu_{FWHM}$ , a more stable system and a more precise angle control would probably enable even better results.

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## Mechanical Resonator Dimer Tests

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To investigate how an acoustic layer like the one described in Sec. 2.4 can be constructed, the author conducted initial tests with membrane dimers. These consist of two adjacent membranes with overlapping drum skin parts, which is the simplest possible structure of laterally coupled membranes. A long term goal of the research presented here is the realization of localized optical control over the flow of vibrations in multi resonator structures. A central idea is to use the optomechanical spring effect as explained in Sec. 2.3.1 to tune the resonance frequency of individual membranes in the material, which in consequence allows one to introduce (partially) reflective elements in the membrane structure on command, as explained in Sec. 2.4. If each membrane shall be interfaced with one channel of the multicore fiber cavity array developed in Chapter 3, then the membrane spacing is governed by the core spacing of the multicore fiber used, which in our case was 35  $\mu\text{m}$ . For the manufacturing of the membranes a commercial micro 3D printing system (Nanoscribe PPGT+<sup>1</sup>) was utilized. This system uses two-photon-absorption from an IR laser in an UV curing photoresist to print sub-micrometer scale voxels (as the intensity for this 2 photon process is only high enough right at the focus of the beam). With this strategy it is very easy to manufacture objects on the micrometer scale. The beam is controlled with an AOM and moved through the sample with two so-called Galvo mirrors or the sample is moved relative to the beam with a piezo. For more details on this process [89] can be consulted, further information on experimental details of the membrane project in our experiment can be found in the theses by Daniel Stachanow [90] and Lukas Tenbrake [91]. Please note that everything presented in the following happened before the multicore fiber platform was operational, so throughout the measurements in this chapter a single core fiber mirror was used to interface one of the two drums of the dimer. In the following section the measurement setup used to investigate the mechanical resonance frequencies of the membrane dimers is introduced and afterwards the results and the implications of these for the membrane geometry choice and printing process are discussed.

### 4.1 Measurement Setup

To interface an optomechanical coupling site that was manufactured on a mirror substrate with an optical cavity, a device to precisely position a fiber mirror over the structure is needed. Inspired by Mader et al. [92] who used such a setup as a microscope, these devices will be called fiber microscopes here. The fco

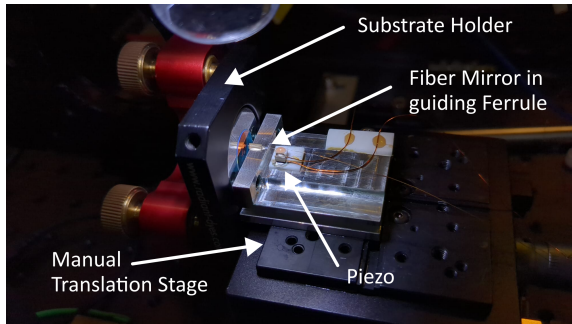
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<sup>1</sup> <https://www.nanoscribe.com/en/>

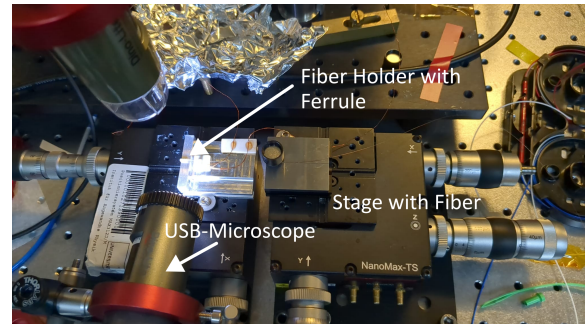
experiment in Bonn maintains two fiber microscopes for the purpose of optically interfacing mechanical structures, one that enables vacuum measurements (to avoid air dampening), and one for measurements under ambient conditions. The former named *Vacuum Fiber Microscope* was built by the author in his Bachelor thesis [93] and the author helped to maintain and upgrade it over time. Due to limited availability of measurement time on the *Vacuum Fiber Microscope*, the author reinstated the previously damaged *Ambient Fiber Microscope* (as air dampening is not a limiting factor for the tests presented here). The basic operational principle between the *Ambient Fiber Microscope* and the *Vacuum Fiber Microscope* is quite similar. In the ambient fiber microscope (as shown in Fig. 4.1(a)) an electrically controlled stage system is used to place a membrane that was printed on a mirror substrate in front of the fiber mirror. The cavity length is controlled with a manual translation stage and a screw is used to stabilize the cavity length against vibrations by pushing against the substrate holder from the fiber holder. The cavity length can be scanned with a piezo crystal that is attached to the fiber holder on one and the fiber on the other side.

The main steps required to make the ambient fiber microscope operational again were the reglueing of the piezo visible in the center of Fig. 4.2(a) and the search in our stock for a high quality fiber mirror to use. The fiber mirror should feature a high coupling depth (ideally 90 – 100%) when testing against a bare mirror substrate and a finesse of around a thousand, as our signal transduction in the later measurements will scale with that (see below). After a fitting fiber was found, it was threaded through a glass ferrule positioned at the tip of the fiber holder (meant for suppressing transversal vibrations of the fiber) and then glued to the piezo. This process can be seen in Fig. 4.1(b), where two USB microscopes and two translation stages were used to correctly position the fiber. The holder can then be placed on the manual stage and positioned in front of the mirror substrate holder (Fig. 4.1(a)).

After positioning the fiber over a membrane and selecting the desired cavity length, one can start the measurement process of the mechanical resonances. For that a setup as seen in Fig. 4.3 is used. The 780 nm laser is introduced to the fiber cavity and the back reflection is sent onto a photodiode via a beam splitter. If one scans the cavity length via the piezo crystal, cavity resonances will show. The thermal motion of the membrane will wiggle these resonances back and forth, because they effectively modulate the optical length of the cavity. If one stabilizes the cavity length, e.g. with a side of fringe lock via a PID



(a) Picture of the Ambient Fiber Microscope cavity region, the mirror substrate is mounted in a holder on the left, which is attached to an electrical stage system to move it transversally to the cavity axis, on the right is the fiber holder, which is mounted to a manual stage to control the cavity length.



(b) Image of the fiber being threaded through the ferrule of the fiber holder. The stage on the right is used to precisely move the fiber into position and two USB microscopes image the ferrule entrance, afterwards the fiber is glued to the piezo visible in the middle of the fiber holder on the left.

Figure 4.1: Images of the *Ambient Fiber Microscope*

circuit giving a correction signal to the piezo, this wiggling of the resonance will translate to a change of the received power on the photodiode. If we analyze this with an electrical spectrum analyzer (ESA) we can find the mechanical resonance curve of the membrane in frequency space. The measurement sensitivity here depends on the slope of the cavity resonance, which is increased with higher finesse (thinner dips) and coupling depth (deeper dips). The author wrote a control software in python for the device that allows for repositioning of the fibers over the substrate, the taking of oscilloscope traces (Photodiode Voltage) and taking the corresponding ESA measurements. Furthermore, the software also includes a feature to conduct coupling depth surface scans over the substrate. This can be useful to find the ideal measurement position on the membrane surface, as spots with higher coupling depth will have a better signal transduction. A surface scan of one part of a double membrane is visible in Fig. 4.2(b), the high coupling depth region around the edges corresponds to the bare mirror substrate, while the 20 – 30 % region in the middle corresponds to one of the drum skins.

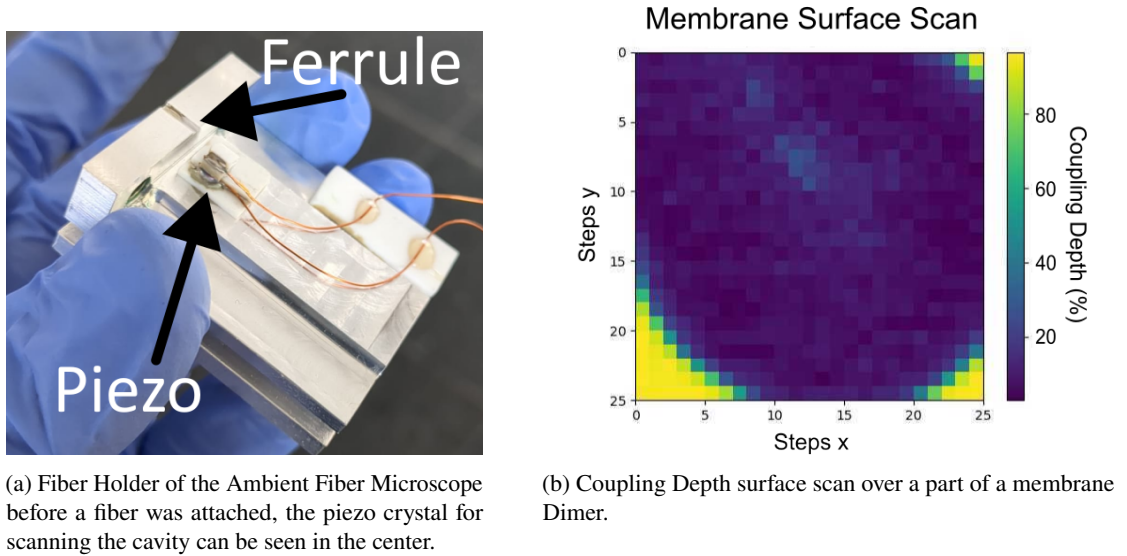


Figure 4.2: Fiber holder and membrane surface scan

## 4.2 Structure Iterations and Measurements

The spacing of the individual membranes in the dimer is given by the core spacing of the multicore fiber. We are interested in tuning the coupling between the membranes for this constant distance. The easiest way to achieve that is to change the amount of overlap of the membranes. The goal was to find an overlap that allows us to easily tune the membranes into and out of mutual resonance via the spring effect. The author started by manufacturing an array of membrane dimers where the center points of the two partners were always  $35\text{ }\mu\text{m}$  apart and the drum radius was varied between  $18\text{ }\mu\text{m}$  and  $29\text{ }\mu\text{m}$  in  $0.5\text{ }\mu\text{m}$  steps. The workflow was that the membrane geometries were first created in Comsol Multiphysics, the software has a feature that allows to partially automate the process of the geometry creation and the author wrote a script to export all membrane geometries as .stl files. After that the structures were imported into the Nanoscribe software (called *DeScribe*), correctly positioned relative to each other and the print parameters (such as hatching and slicing distance between the voxels) were set, the resulting



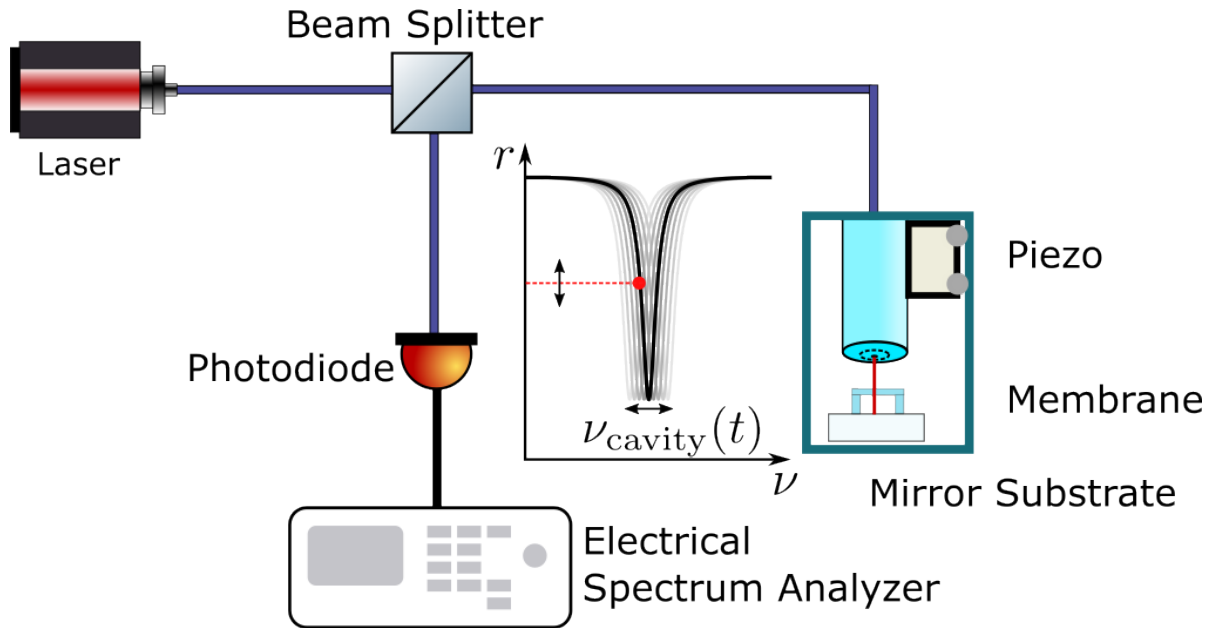


Figure 4.3: Setup used for the measurement of the mechanical Resonances of the membranes, the laser is coupled into the fiber cavity, and the reflection is observed with a photodiode. Thermal motion of the membrane creates a detectable wiggle of the photo-diode voltage in the locked state.

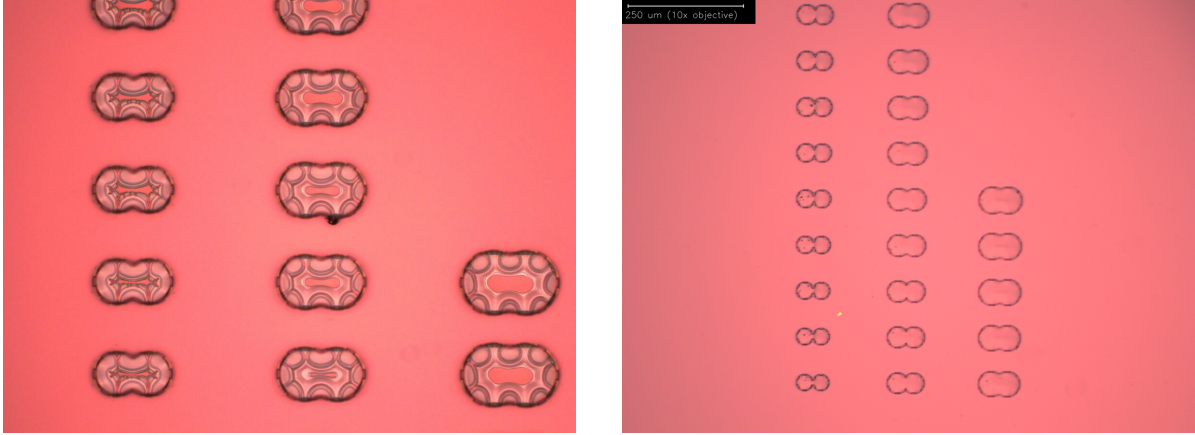
.gwl files can then be read by the printer. Usually, for single membrane structures directly printed on the substrate at these size scales, a developing time of around 20 – 40 min in the developer solvent (PGMEA) is sufficient, but for the dimers a significant amount of resist has not been flushed yet after this time (Fig. 4.4(a)). The author found that developing over night leads to much better results (Fig. 4.4(b)), the second membrane reduces access of the developer from the side and the feet in the middle trap the resist especially effective, which is probably the reason why the longer development time is necessary.

The now correctly developed sample was introduced into the ambient fiber microscope and the membranes were interfaced with the fiber mirror, which can be seen in Fig. 4.5(a), and a closer view of the cavity region from the side is visible in Fig. 4.5(b). With this first printing design the coupling depth on the membrane was limited to around thirty percent (most of the time significantly less), which made it difficult to find the mechanical resonance on the ESA. As was found out by Lukas Tenbrake from our experiment, this can be improved drastically by printing the membranes vertically instead of horizontally. We hypothesize that this makes better use of the voxel geometry of the Nanoscribe system and leads to a smoother surface finish of the membranes.

To print them vertically the membranes were incorporated in tower geometries. To then interface them with a fiber they have to lay flat on the mirror substrate, so after the manufacturing they were tipped over with a scalpel blade attached to a manual translation stage, which can be seen in Fig. 4.6(a). A small extra finding was that if one adds loops to the top of the membrane towers it is surprisingly easy to transfer them to another mirror substrate by threading a small (in this case 110  $\mu\text{m}$ ) wire<sup>2</sup> through them (Fig. 4.6(b)).

Upon interface of the vertically printed membranes a much better ideal coupling depth at over 90 %

<sup>2</sup> <https://www.thorlabs.com/item/WC100>



(a) Microscope image of membrane dimers with previously used development times, the resist is not fully removed from under the membrane skin yet.

(b) Microscope image of membrane dimers with extended development time. The excess resist seems to be fully removed.

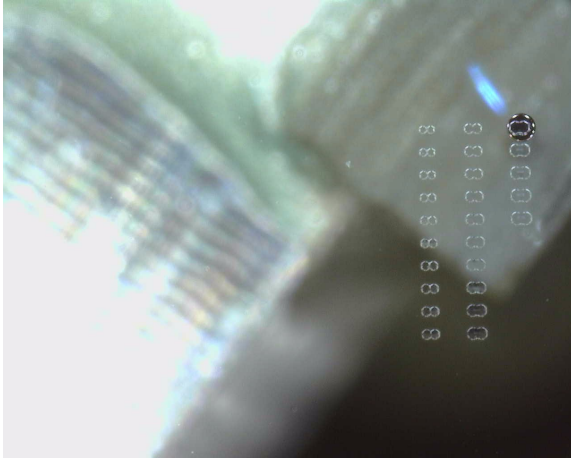
Figure 4.4: Comparison between a membrane dimer array that was in the developer solvent for  $\sim 30$  min and one that developed over night.

showed. Multiple of these membrane dimers were measured and mechanical spectra taken, one such spectrum is visible in Fig. 4.7(a). Comparison with a measurement done on the bare mirror clearly shows the effect of the membranes (Fig. A.36(a)). There are some crucial problems we face when we try to interpret those spectra, this is also why the identifications of the modes in Fig. 4.7(a) should be seen as a hypothesis and not fact.

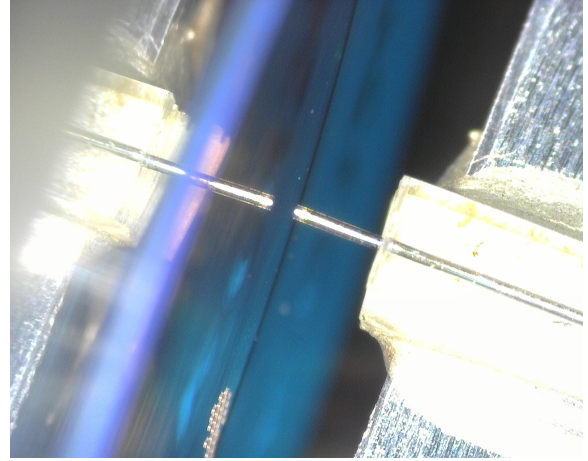
**First**, one has to understand that the height of the resonance curve for an individual mode visible in the spectrum is in general not constant between measurements and also does not have a fixed relationship with the height of other modes, even if the same membrane is measured multiple times. This is because the modes can couple differently to the optical field, as the in phase mode couples e.g. much stronger in the overlap region (as it has displacement there), but the out of phase mode does not, because the displacement there is close to zero. This means that the relative height of the peaks depends on the position of our fiber mirror over the membrane.

**Second**, the spectral position of the modes does not match our simulations, this is to some extent expected, as the actual structure geometry does not always reproduce the desired one (e.g. the membrane could be thicker/thinner because of slightly too high/low laser power during printing). For this reason the structures should be calibrated in the future, for example with the help of SEM images of the drums. This also does not have to be an effect that influences both coupled modes the same way, for example as seen in Sec. 2.4 the two modes in general do not respond the same to a change in coupling, so e.g. if there would be a slightly higher thickness of the coupling region between the two membranes (plausible because of the flushing problems during development), the measured frequencies can be significantly different to the expected ones.

**Third**, we have to consider an effect we just understood after the measurements were conducted, but which complicates everything further. We initially did not consider the substantial influence of the membrane feet on the resonance frequencies of the dimer. We chose a circular membrane geometry with feet and holes spread under the outside perimeter of the membrane skin. With increasing overlap (but apart from radius unchanged geometry) this inevitably leads to a situation where feet of one membrane



(a) An membrane dimer array with changing overlap, the picture is taken in transmission through the mirror substrate, the membrane in the top right corner of the array is currently interfaced by the fiber mirror (dark circle). For scale: The fiber diameter is  $125\ \mu\text{m}$ .

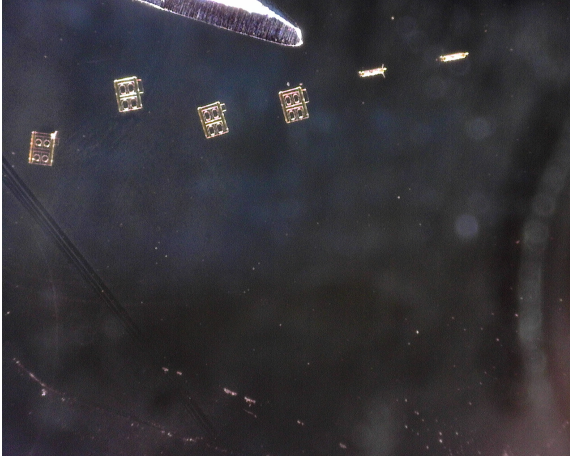


(b) USB microscope view of the cavity region in the Ambient Fiber Microscope. In the center one can see the fiber emerging and the fiber reflection in the mirror substrate. At the bottom some membranes are visible.

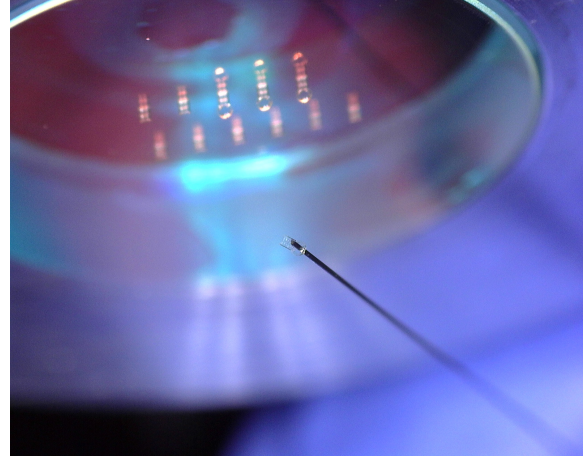
Figure 4.5: Cavity region in the Ambient Fiber Microscope

and the drum skin of the other membrane would start overlapping. Then one can choose one of two variants of how the structure should behave upon further increase of the drum radius, either the feet stay the way they are and start moving into the neighboring drum skin, or the feet get smaller. The first variant is not desirable, as this additionally anchors the drum skins at radially asymmetric positions and thus leads to a very complicated mode structure, this is the reason why we chose the second variant. However, as we later found out, the second variant is not desirable either, as the decrease of the feet size leads to a reduced confinement of especially the in phase mode of the two drum skins. This leads to an additional reduction of the in phase resonance frequency. In combination one gets a behavior (simulated) as shown in Fig. 4.8, where there is first the expected splitting of the in phase and out of phase mode, but then the feet effect that reduces the in phase mode confinement kicks in and the in phase mode is additionally reduced in frequency, leading to a crossing point. Furthermore this makes it hard to identify which of the modes in the double peak are the in phase and which are the out of phase modes, because of the crossing that occurs in the frequencies. And as the frequencies do not fit our simulations yet we do not know for sure which modes of a particular drum are splitting in which direction. For our future experiments we want a mechanical device layer with a simpler behavior. One solution could be to use a different drum geometry like a rectangular design with dedicated coupling elements between the membranes, as this should make the feet irrelevant for the coupling process.

Nevertheless, we think that we managed to record a coupled mechanical resonance, but this needs more verification. One observation that supports the hypothesis can be made if one compares Fig. 4.7(a) and Fig. 4.7(b). These are spectra taken from membranes with a radius difference of  $0.5\ \mu\text{m}$  ( $22.5\ \mu\text{m}$  and  $23\ \mu\text{m}$ ) and thus have a corresponding increase in overlap. We expect the membrane with the larger radius (Fig. 4.7(b)) to thus have a higher spectral spacing between the coupled modes (as they should sit on the right side of the crossing in Fig. 4.8). And indeed if one looks at the two peaks around  $2000\ \text{kHz}$ , one can see that the spacing increases from Fig. 4.7(a) to Fig. 4.7(b). Further spectra of membranes with



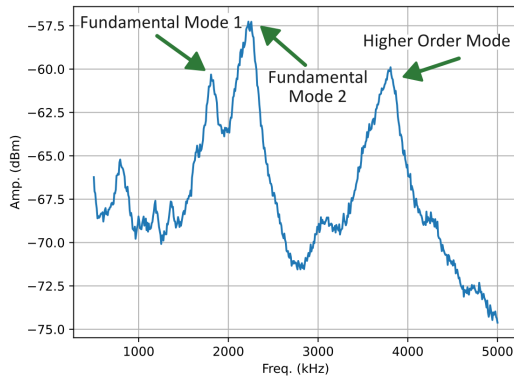
(a) A microscope image of membranes that were printed vertically in a tower geometry. The towers are pushed over with a scalpel blade visible at the top of the image.



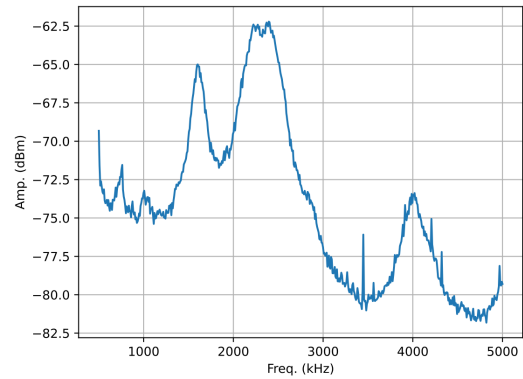
(b) Microscope Image of membranes printed in a tower geometry, some of them were fitted with a loop at the top through which a small wire can be threaded, this allows the membranes to be transferred to another mirror substrate.

Figure 4.6: Tower prints

radius  $20\text{ }\mu\text{m}$  to  $22\text{ }\mu\text{m}$  can be found in Fig. A.36, Fig. A.37 and Fig. A.38. If one looks at the splitting of the fundamental modes for these spectra one can speculate (especially because of Fig. A.38(a)) that we actually see the crossing point from our simulations (Fig. 4.8), as the splitting seems to first decrease with higher radius and then increase again. This would allow us to identify the in phase and out of phase modes in the spectra after all, but this needs to be verified with more test measurements as multiple of the spectra from Fig. A.36 to A.38 show bad visibility of the left fundamental mode, likely because of suboptimal placing of the optical interface on the membrane.



(a) Mechanical Spectrum of a membrane dimer with  $35\text{ }\mu\text{m}$  center spacing and a target radius of  $22.5\text{ }\mu\text{m}$ . The green arrow markings are a hypothesis for the mode identification, but this needs to be verified.



(b) Mechanical Spectrum of a membrane dimer with  $35\text{ }\mu\text{m}$  center spacing and a target radius of  $23\text{ }\mu\text{m}$ .

Figure 4.7

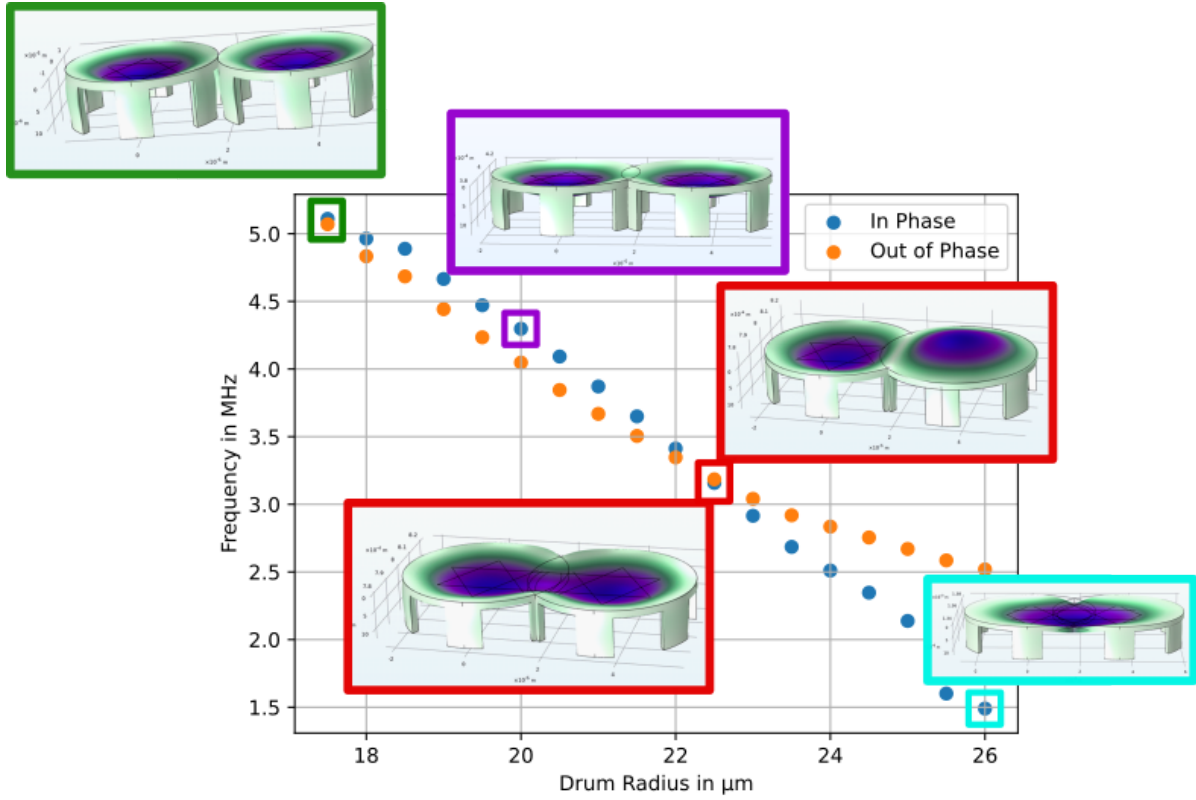


Figure 4.8: This plot shows simulation results (made with Comsol Multiphysics) of the coupled in phase and out of phase mode of the membrane dimer against increasing radius, when the feet size in the overlap region is reduced with higher radius.



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## Conclusion

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It was demonstrated how seven ablations, with high surface quality and a cavity depth accuracy down to  $\sim 30$  nm, can be manufactured on optical fiber end facets and how they can be used to create an optical cavity array. Three possible manufacturing methods were investigated, where the best approach for us showed to be focused ion beam milling (Sec. 3.1.3) with subsequent CO<sub>2</sub> laser smoothing. The manufacturing technique we employed was based on findings by Maier et al. for single core fibers [68], the approach was transferred to ablations on multicore fibers, manufactured on a different FIB device. Key steps for this were the introduction of a space efficient hexagonal ablation projection for maximization of the mirror sizes and multiple calibration mills to get the desired radius of curvature and structure size. A total of 23 fibers were manufactured with the FIB over the course of this thesis.

In Sec. 3.1.4 it was shown that the surface roughness after the high current FIB milling can be significantly reduced through the treatment of the fiber end facets with de-focused CO<sub>2</sub> laser pulses. Some of the fibers (see Tab. A.1 for details) were coated with a gold layer after the smoothing procedure to form a mirror (Sec. 3.3), then a multicore fanout was spliced to one of the fibers (Sec. 3.4). It was shown that each of the 7 cores can be addressed individually via the fanout and the transmission through the coating and the crosstalk between the channels was investigated (Sec. 3.5.1). Then the fiber was placed next to a high reflectivity substrate to form a cavity array. Cavity spectra for all seven cavities were measured and the finesse was extracted (Sec. 3.5.2), after that it was shown that two cavities (in principle also possible for three) can be tuned into simultaneous resonance via the alignment of the fiber relative to the mirror substrate (Sec. 3.5.3). The driving factor for the crosstalk was the difficult multicore splice, this could potentially be circumvented by using a fanout construction that directly attaches to the back end of the fiber mirror without requiring a splice, this could e.g. be achieved with 3D printed microphotonic structures, as demonstrated by Li et al. [88].

The multicore fiber mirrors manufactured here promise flexible creation of cavity arrays with easy optical access via a fanout device and small mode volume. For simultaneous resonance of the whole array we want to proceed with our plan to apply a silicon expansion layer below the mirror on the fiber (as explained in Sec. 2.5.1). An important step in addition to this is that we want to demonstrate the system with a high quality DBR fiber coating next to show the highest finesse we can achieve and to fully understand to what extent we are still limited by the surface quality for high finesse cavities. Optimization of the FIB and CO<sub>2</sub> laser smoothing process are promising approaches to push this limitation further, but the most effective way would be to substitute the CO<sub>2</sub> laser step for an ion beam figuring procedure. This process is used for the highest quality surface finishes in optics and in principle works similar to



FIB milling but with high spot sizes and a different ion species (e.g. Argon instead of Gallium) [94]. Some smaller optimizations can also be done by first protecting the fiber back ends before the mirror coating procedure more firmly to avoid contamination and improve the splicing results (Sec. 3.4), and second by creating one more test mill to verify our calibration of the RoC (as explained in Sec. 3.1.3 and Sec. 3.1.4). The mechanical stability of the fibers was already sufficiently improved through the measures discussed in Sec. 3.2, but in the future it might be convenient to buy a fully commercial solution.

In chapter 4, first tests of coupled mechanical membranes were conducted, the manufacturing via the Nanoscribe system and the measurement procedure via the *Ambient Fiber Microscope* were discussed. Mechanical resonances of coupled membranes were investigated, they do not fit the expectations given by finite element simulations yet, but there are some promising signs that we were able to measure a coupled mechanical resonance curve of a membrane dimer. Further tests are needed, beginning with a calibration of the structure geometry e.g. via an SEM image of the membranes. Through this we want to characterize how well the physically manufactured structures resemble the designed ones. After the structures are correctly calibrated, another measurement series with greater regards for optimal placement of the fiber over the membranes should be conducted to better understand the crossing behavior of the two fundamental modes experimentally (Sec. 4.2). Because of the complicated effect of the membrane feet on the resonance frequencies, the current circular drum geometry should be changed for a future technological application, a rectangular one with dedicated coupling structures between the membranes is probably the easiest approach.

As soon as a high reflectivity fiber cavity array with a reliable optical interface is achieved and the coupled membrane behavior is understood the two platforms should be brought together, first by a multicore interface to a membrane dimer. Then efforts should focus on scaling the system, both by increasing the cavity number (for example by utilizing a fiber with more cores or a fiber bundle similar to [69]) and by increasing the complexity of the mechanical device, with the ultimate goal of optical control over the vibrations in full mechanical metamaterials.

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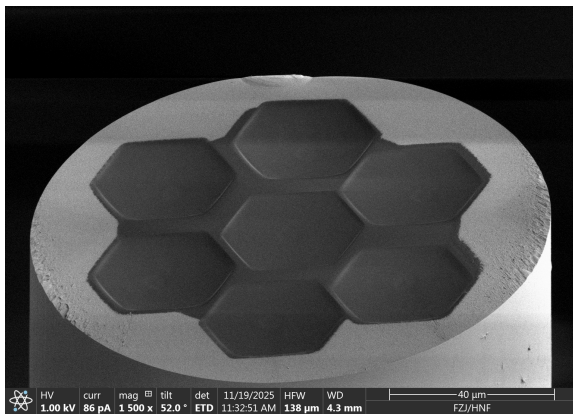
## Appendix

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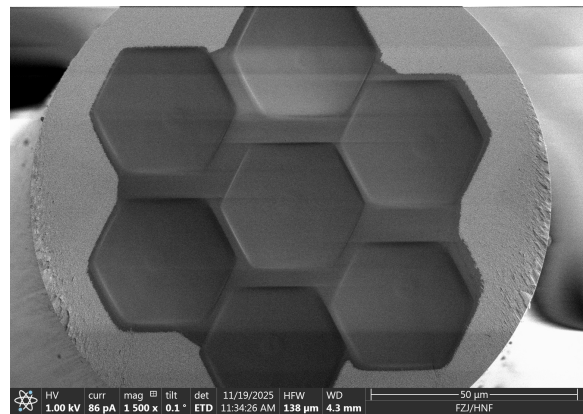
### A.1 Fiber Mirror Manufacturing Images

In Sec. A.1.1 SEM and ion beam images of fibers not explicitly discussed in Sec. 3.1.3 can be examined. In Sec. A.1.2 before and after images of the CO<sub>2</sub> Laser Smoothing process can be seen. To make tracking of individual fibers through the FIB and smoothing process easier they get a number assigned, Tab. A.1 shows an overview over all fibers. The order in which the fibers are shown in Sec. A.1.2 is the order in which their surfaces were analyzed.

#### A.1.1 Additional SEM and ion images

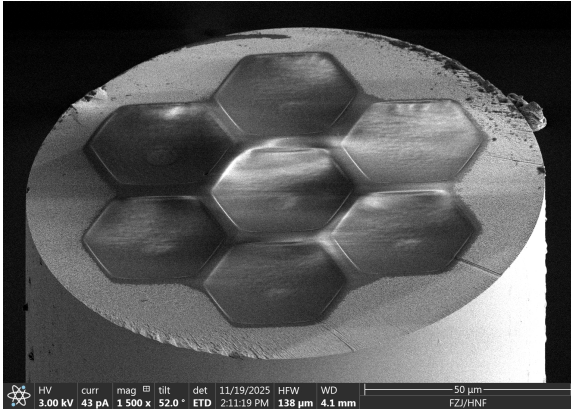


(a) SEM side view for fiber 8

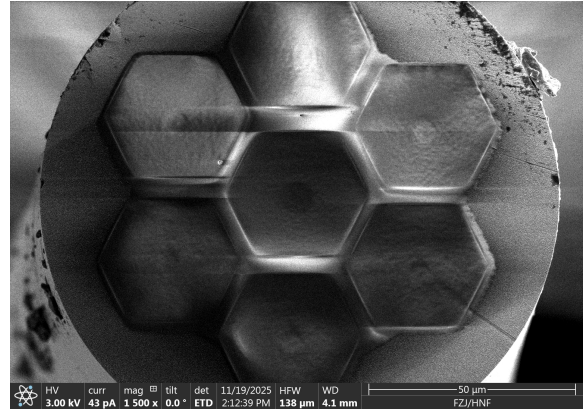


(b) SEM head on view for fiber 8

Figure A.1: FIB Session 4 (Fiber name: 8 in Tab. A.1)

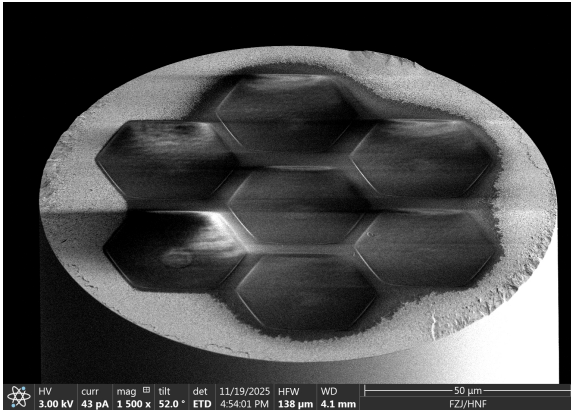


(a) SEM side view for fiber 9

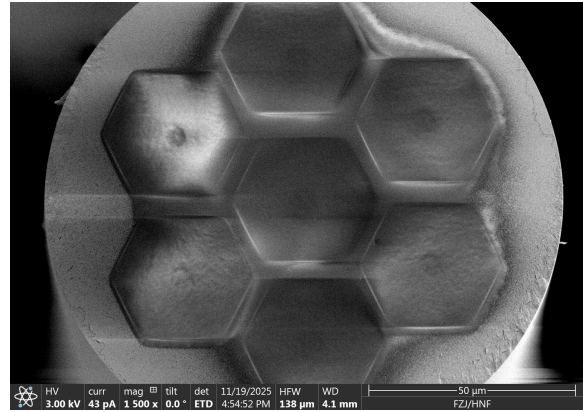


(b) SEM head on view for fiber 9

Figure A.2: FIB Session 4 (Fiber name: 9 in Tab. A.1)

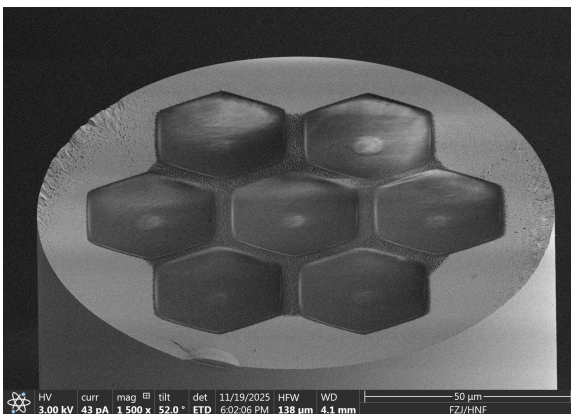


(a) SEM side view for fiber 10

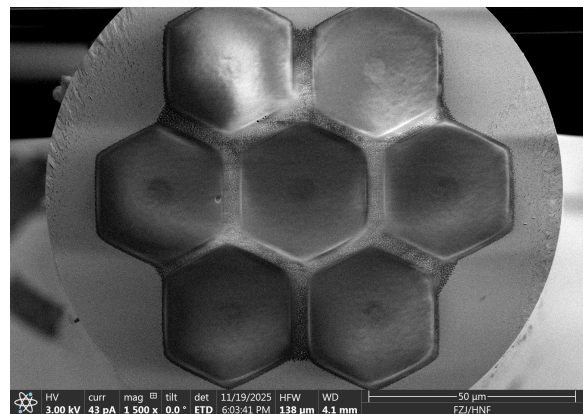


(b) SEM head on view for fiber 10

Figure A.3: FIB Session 4 (Fiber name: 10 in Tab. A.1)



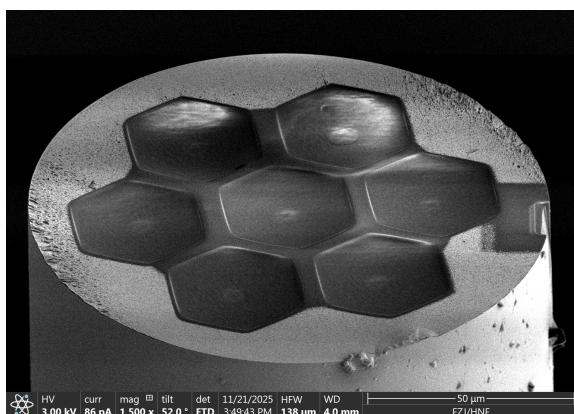
(a) SEM side view for fiber 11



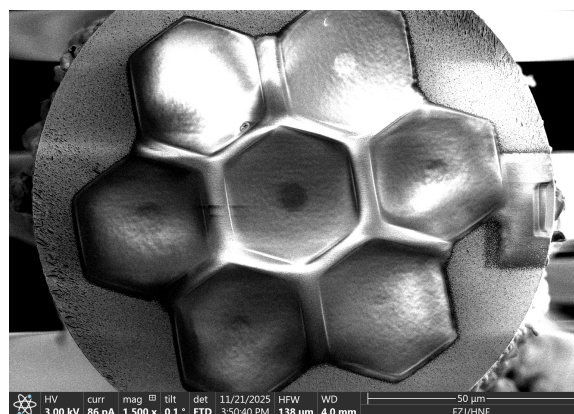
(b) SEM head on view for fiber 11

Figure A.4: FIB Session 4 (Fiber name: 11 in Tab. A.1)



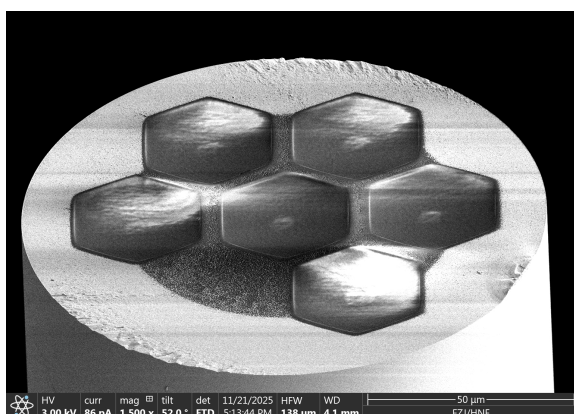


(a) SEM side view for fiber 13

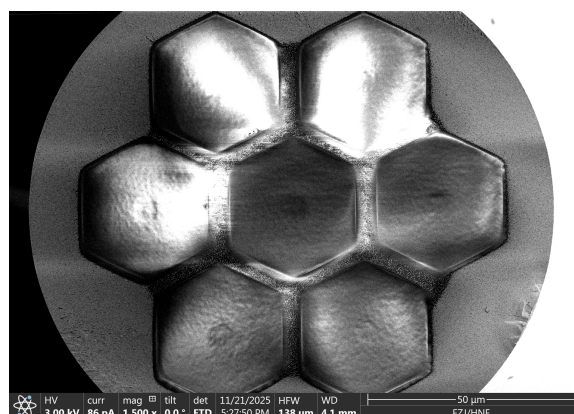


(b) SEM head on view for fiber 13

Figure A.5: FIB Session 5 (Fiber name: 13 in Tab. A.1)

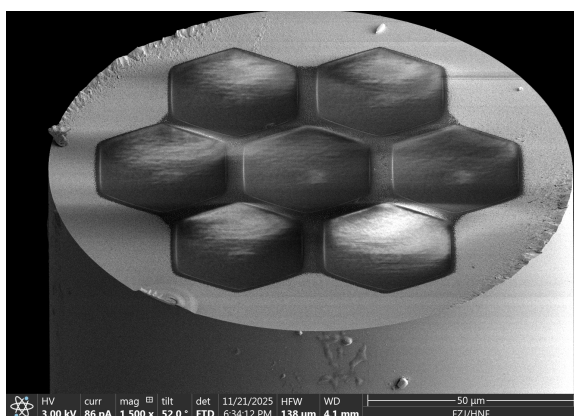


(a) SEM side view for fiber 14

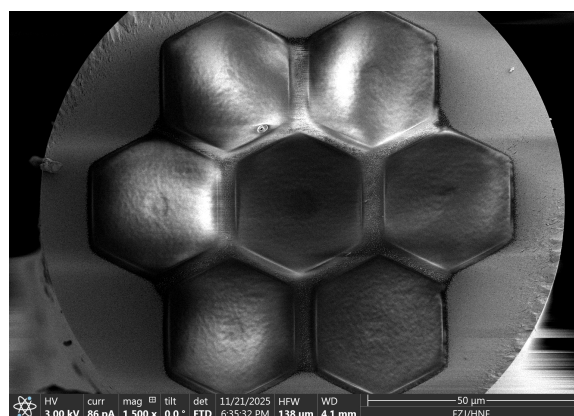


(b) SEM head on view for fiber 14

Figure A.6: FIB Session 5 (Fiber name: 14 in Tab. A.1)

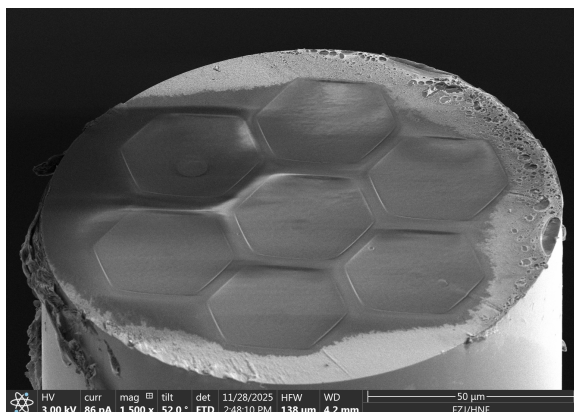


(a) SEM side view for fiber 15

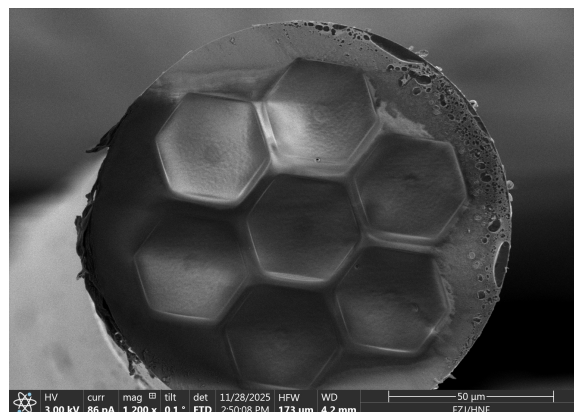


(b) SEM head on view for fiber 15

Figure A.7: FIB Session 5 (Fiber name: 15 in Tab. A.1)

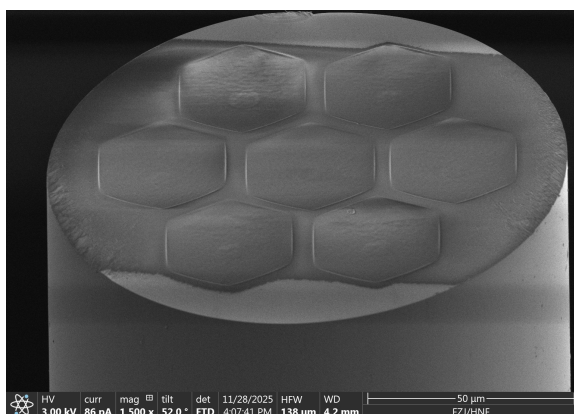


(a) SEM side view for fiber 16

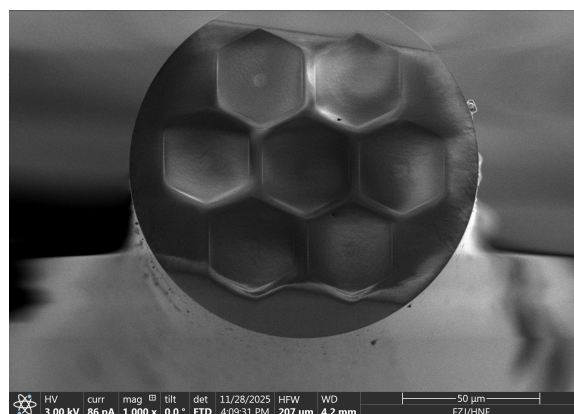


(b) SEM head on view for fiber 16

Figure A.8: FIB Session 6 (Fiber name: 16 in Tab. A.1)

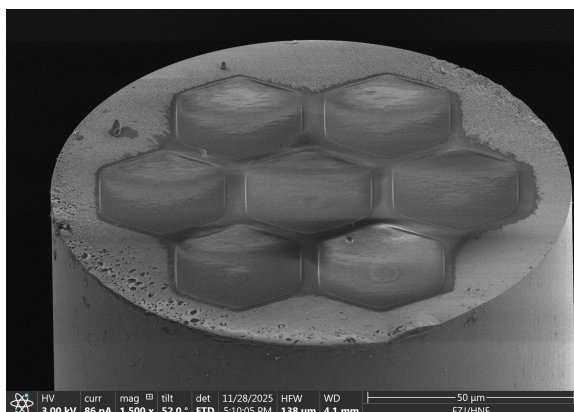


(a) SEM side view for fiber 17

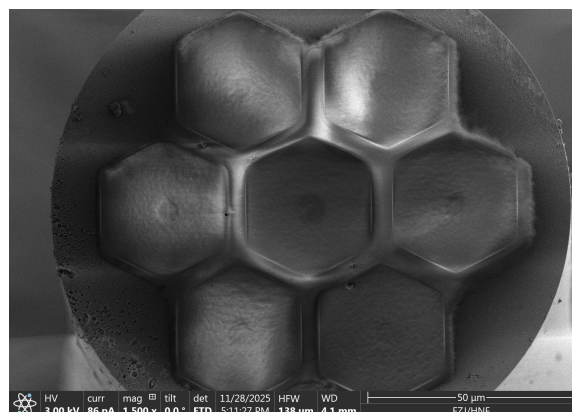


(b) SEM head on view for fiber 17

Figure A.9: FIB Session 6 (Fiber name: 17 in Tab. A.1)

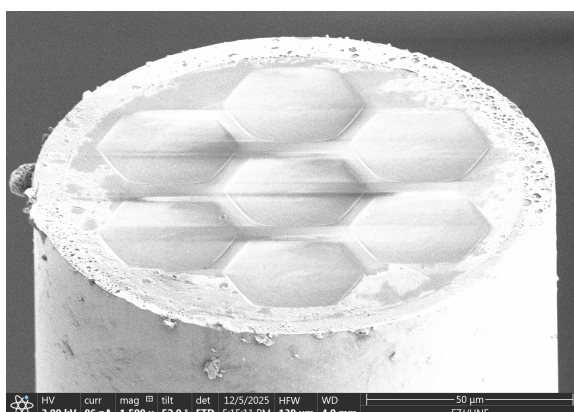


(a) SEM side view for fiber 18

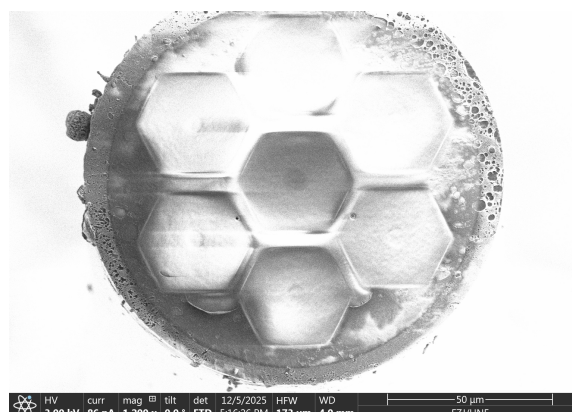


(b) SEM head on view for fiber 18

Figure A.10: FIB Session 6 (Fiber name: 18 in Tab. A.1)



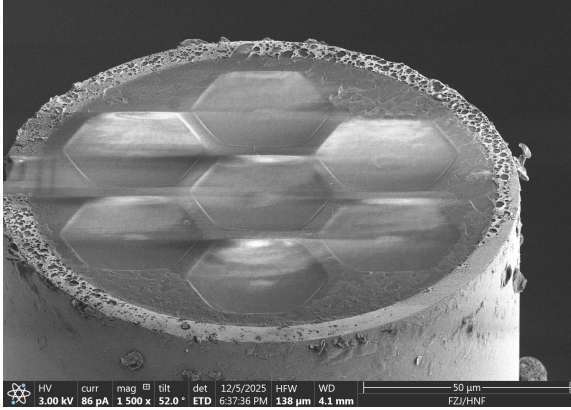
(a) SEM side view for fiber 19



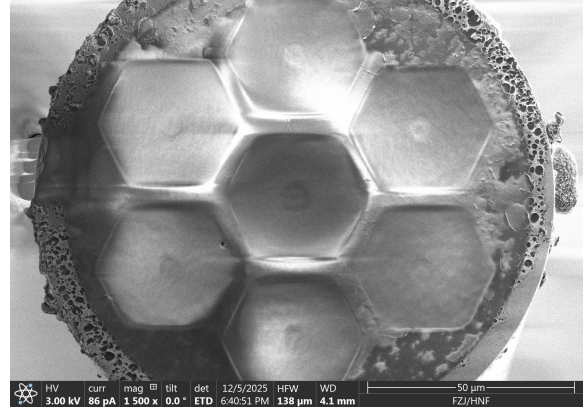
(b) SEM head on view for fiber 19

Figure A.11: FIB Session 7 (Fiber name: 19 in Tab. A.1)



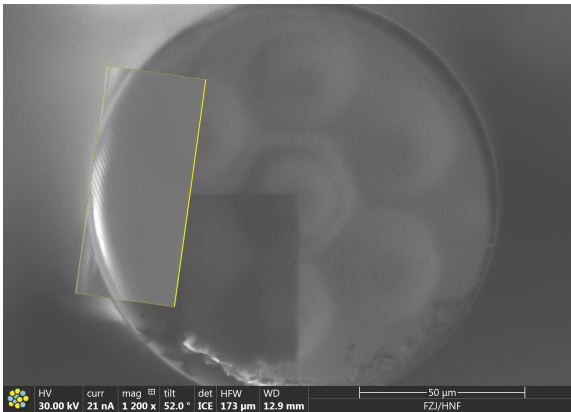


(a) SEM side view for fiber 20

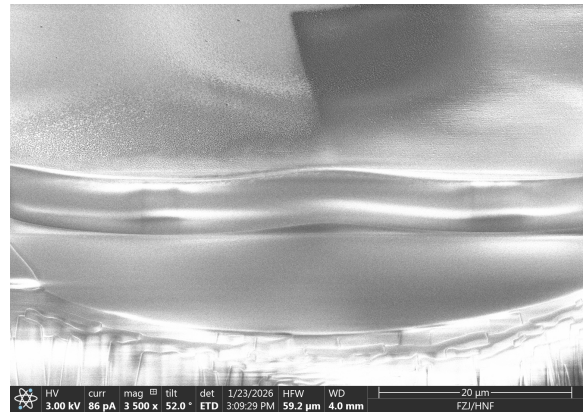


(b) SEM head on view for fiber 20

Figure A.12: FIB Session 7 (Fiber name: 20 in Tab. A.1)



(a) Head on view on the fiber where we wanted to mill the cross section, the yellow box marks the milling region.



(b) Zoom in to the mill region, the hexagonal ablations are visible on the top and the cores show as darker vertical columns.

Figure A.13: FIB Session 8: We tried to mill free and image a cross section of an ablation.

### A.1.2 Interferometer Images of CO<sub>2</sub> Laser Smoothing

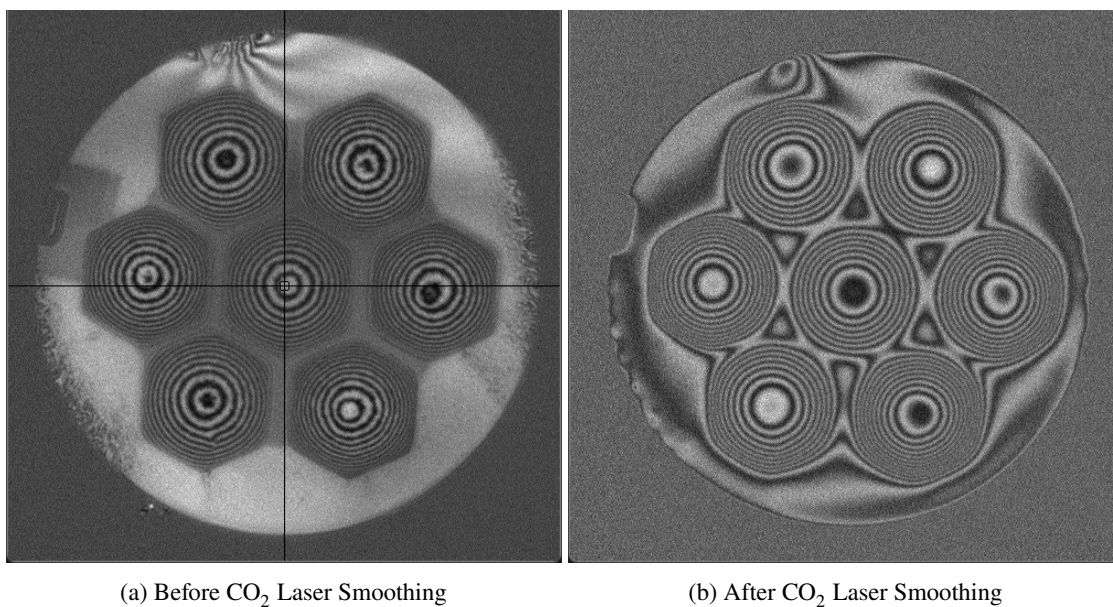


Figure A.14: Interference Microscope Images of Fiber 13

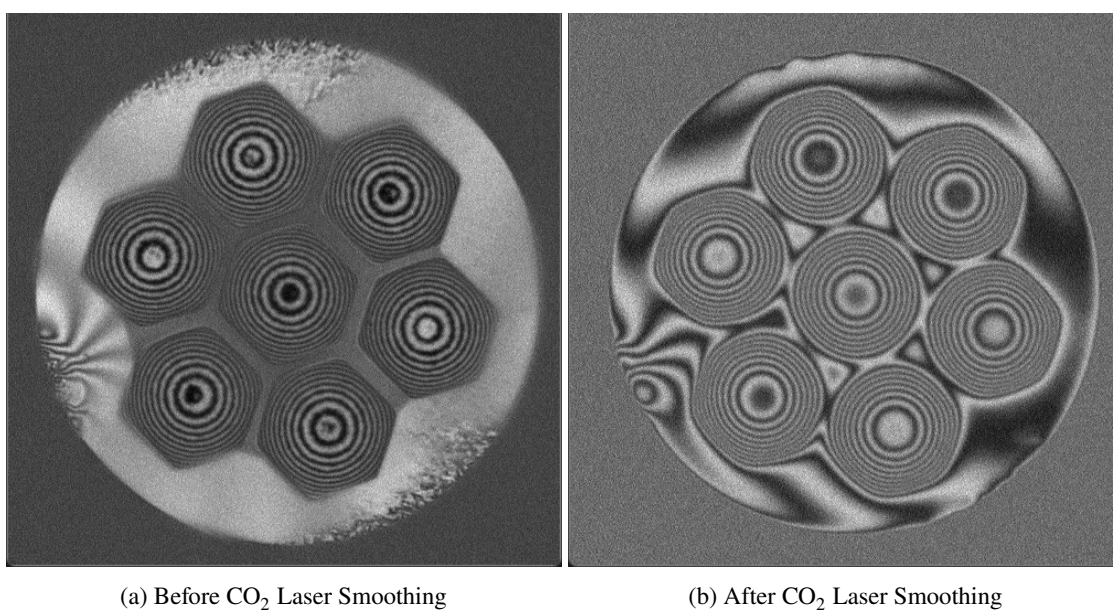
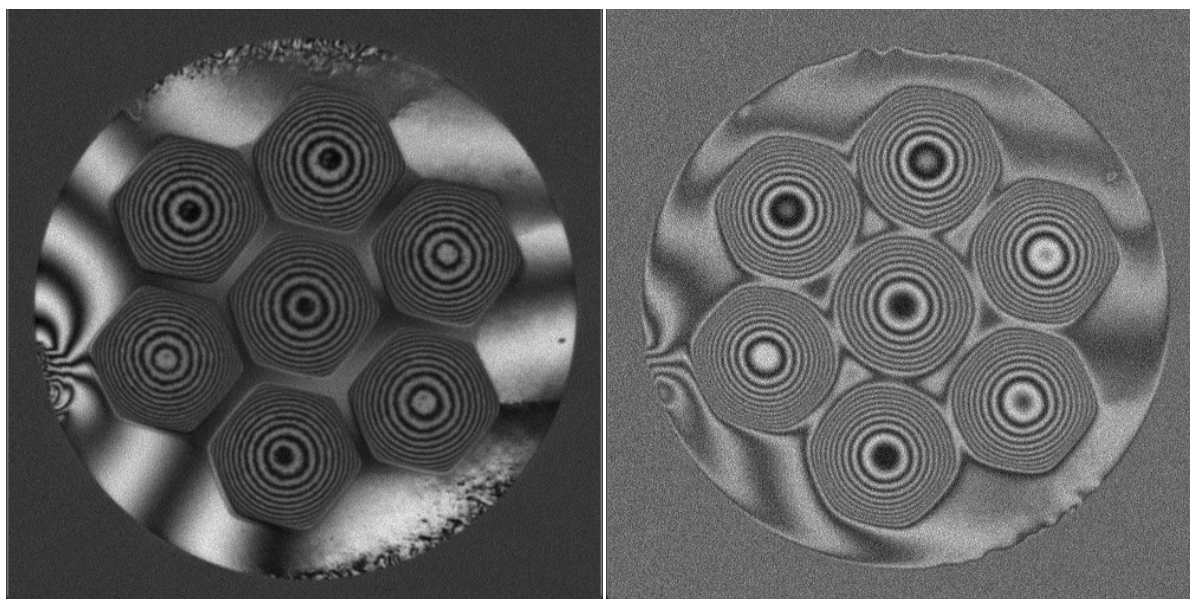


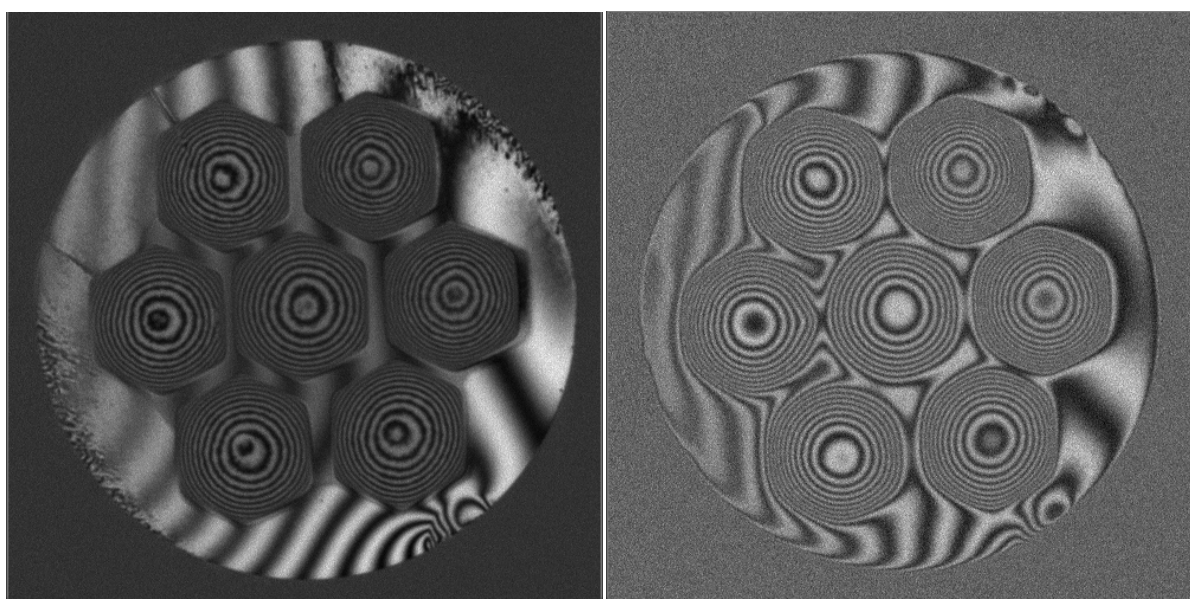
Figure A.15: Interference Microscope Images of Fiber 14



(a) Before CO<sub>2</sub> Laser Smoothing

(b) After CO<sub>2</sub> Laser Smoothing

Figure A.16: Interference Microscope Images of Fiber 15



(a) Before CO<sub>2</sub> Laser Smoothing

(b) After CO<sub>2</sub> Laser Smoothing

Figure A.17: Interference Microscope Images of Fiber 12

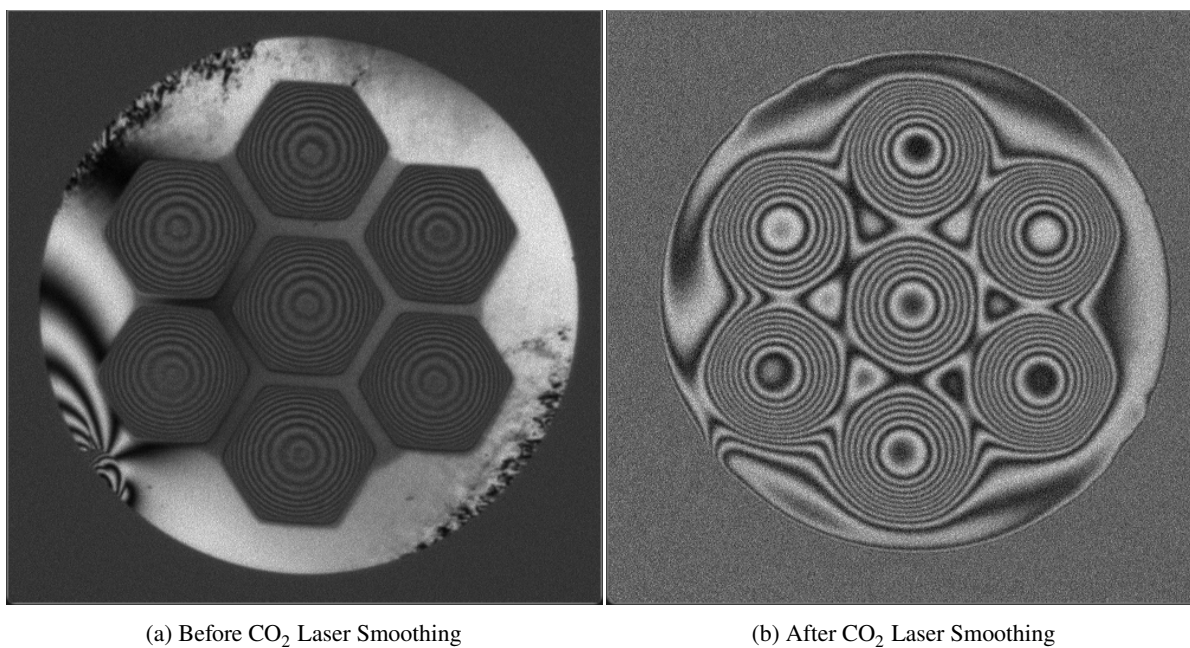


Figure A.18: Interference Microscope Images of Fiber 11

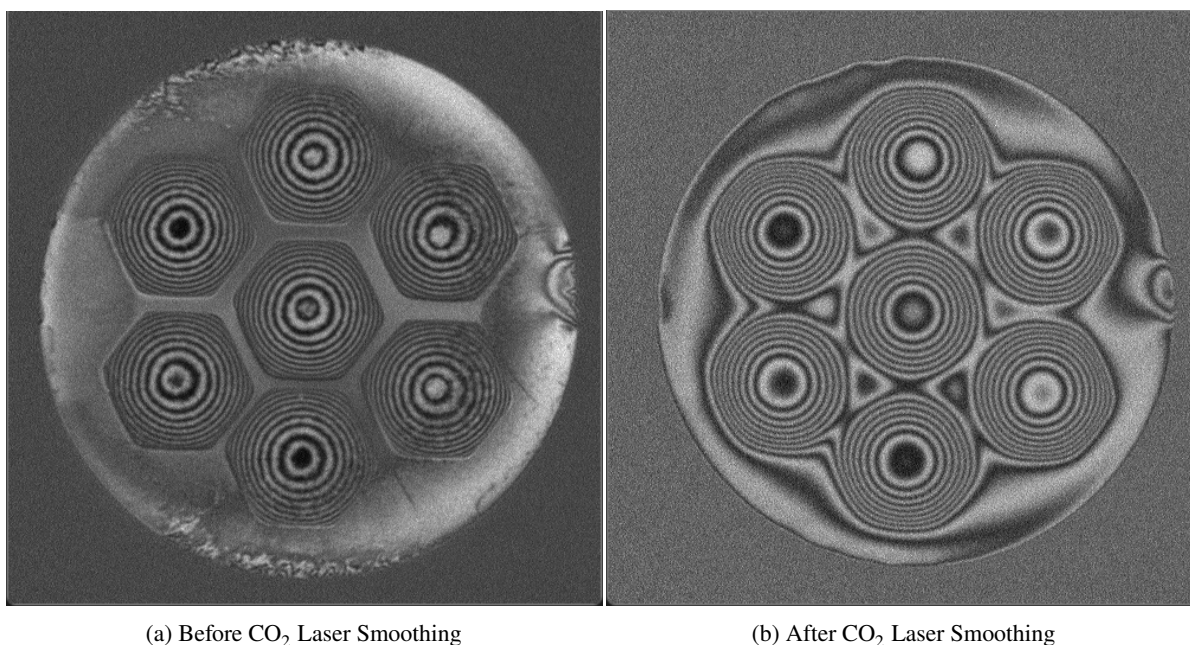


Figure A.19: Interference Microscope Images of Fiber 10



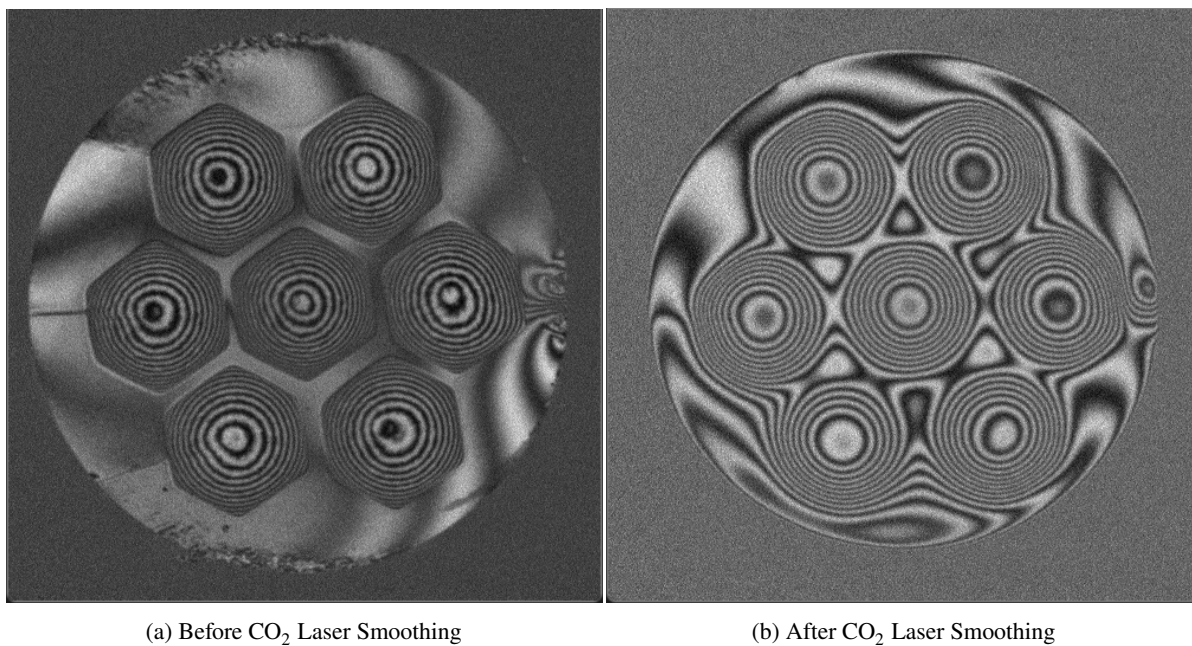


Figure A.20: Interference Microscope Images of Fiber 9

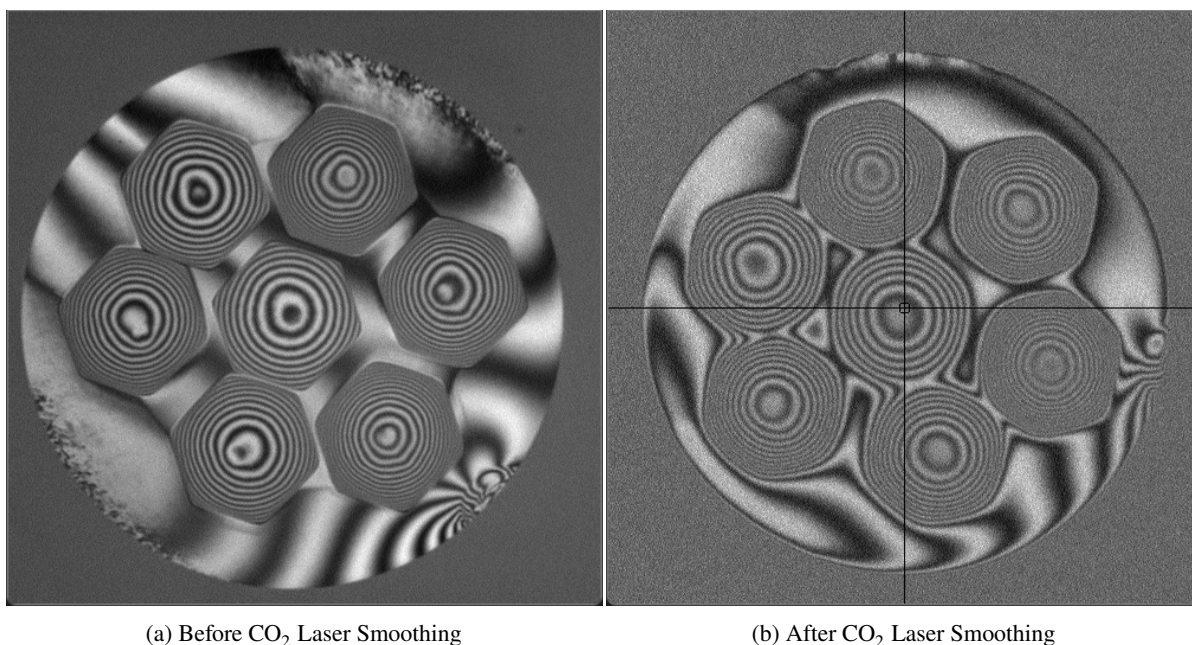


Figure A.21: Interference Microscope Images of Fiber 8



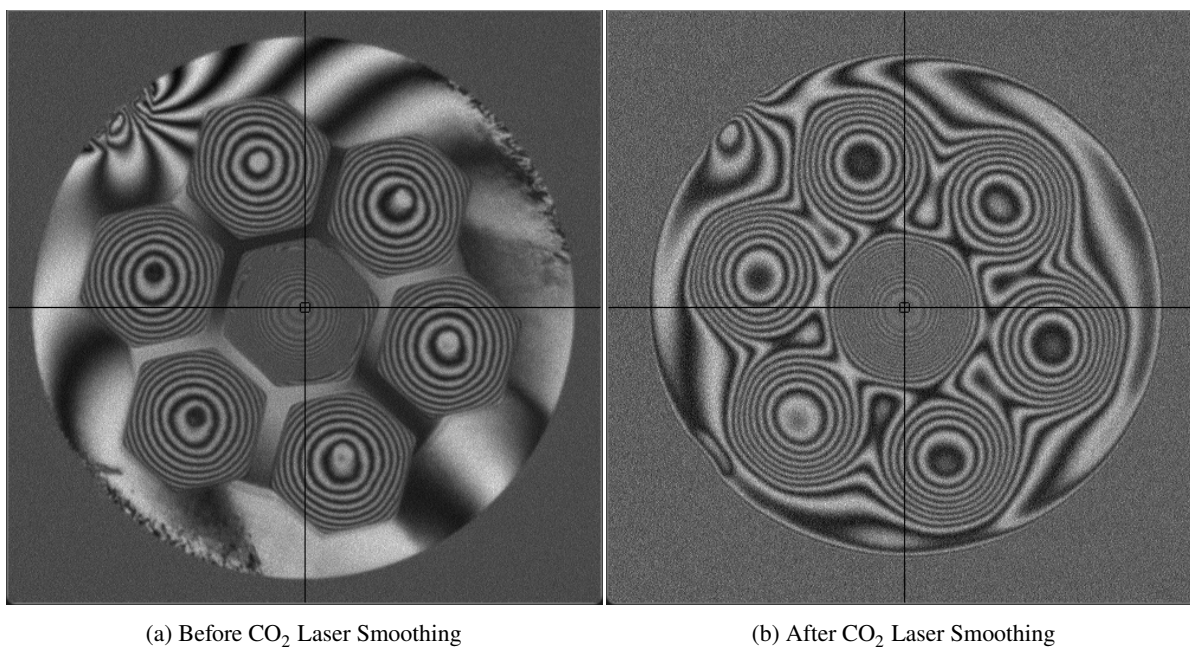


Figure A.22: Interference Microscope Images of Fiber 7

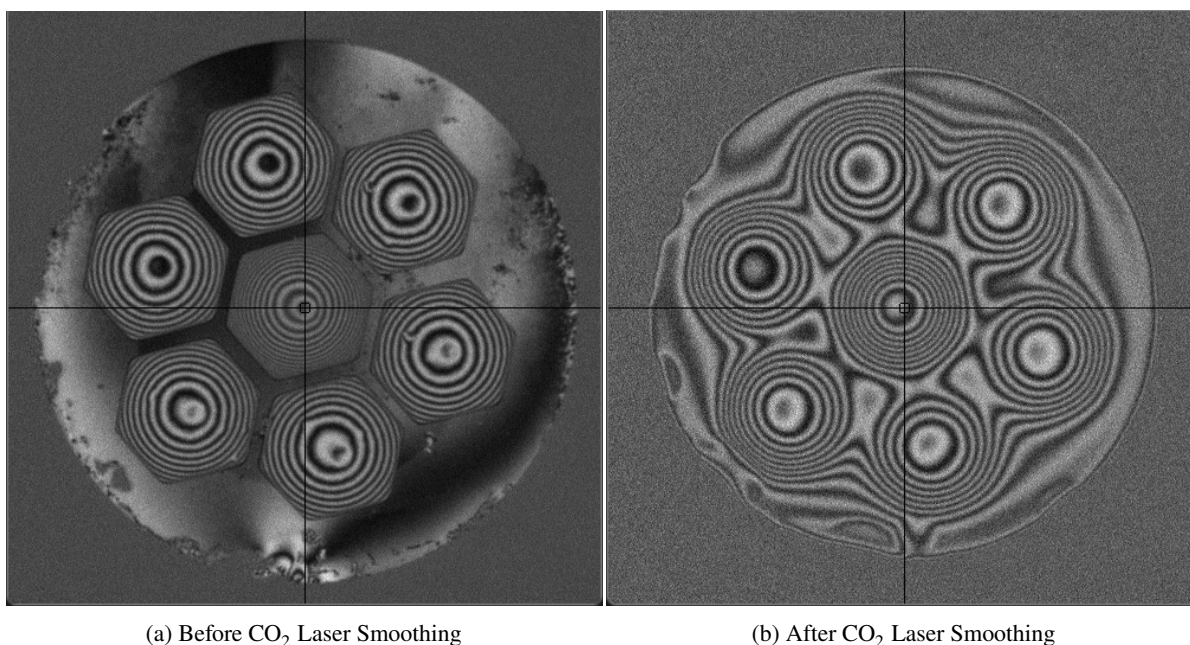


Figure A.23: Interference Microscope Images of Fiber 6

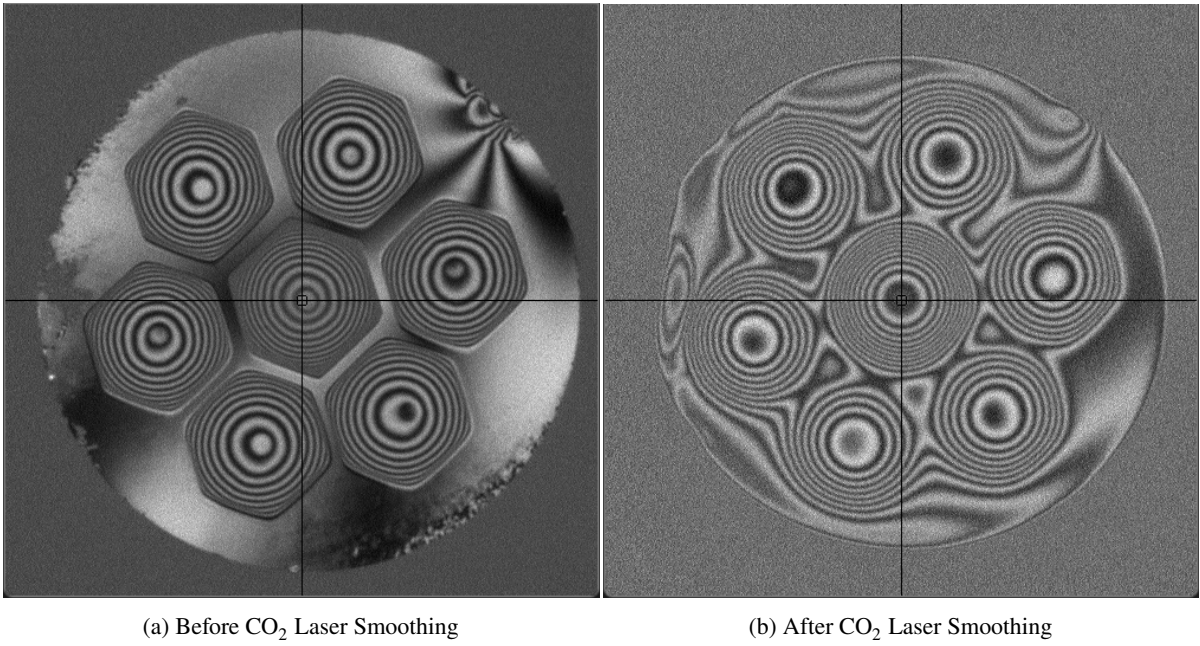


Figure A.24: Interference Microscope Images of Fiber 4

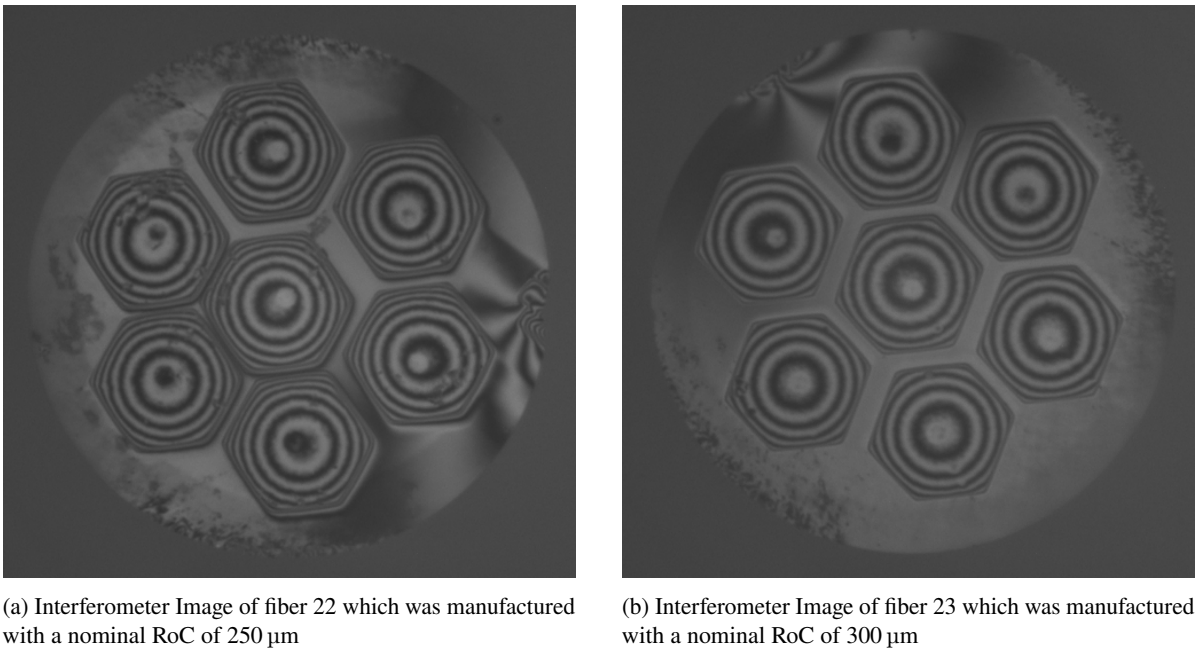


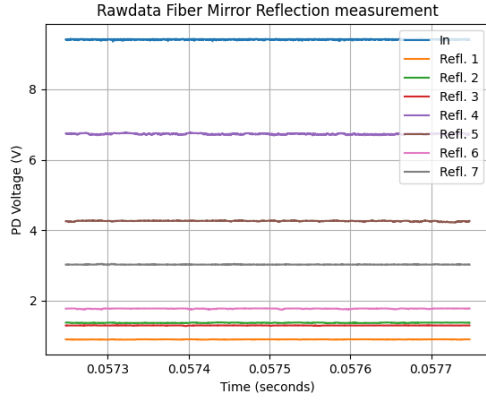
Figure A.25: Interferometer images of the fibers that were produced without core alignment correction but with optimized RoC

### A.1.3 Multicore Fiber Inventory

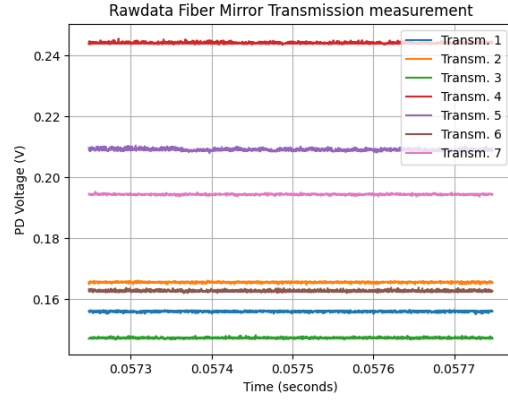
| # Fiber | FIB date   | Pos.<br>Holder | Smooth.<br>order | Pos.<br>Gold | Note                                                       |
|---------|------------|----------------|------------------|--------------|------------------------------------------------------------|
| 1       | 07.11.2025 | 1              | -                | -            | Testfiber                                                  |
| 2       | 07.11.2025 | 2              | -                | -            | Testfiber                                                  |
| 3       | 07.11.2025 | 4              | -                | -            | Testfiber                                                  |
| 4       | 14.11.2025 | 1              | 12               | -            |                                                            |
| 5       | 14.11.2025 | 4              | (11)             | (11)         | Too shallow, error while setting ablation depth, discarded |
| 6       | 18.11.2025 | 3              | 10               | 10           | Broken after Gold coating, cut in FIB                      |
| 7       | 18.11.2025 | 7              | 9                | 9            |                                                            |
| 8       | 19.11.2025 | 8              | 8                | 8            |                                                            |
| 9       | 19.11.2025 | 10             | 7                | 7            |                                                            |
| 10      | 19.11.2025 | 1              | 6                | 6            |                                                            |
| 11      | 19.11.2025 | 2              | 5                | 5            |                                                            |
| 12      | 21.11.2025 | 3              | 4                | 4            |                                                            |
| 13      | 21.11.2025 | 4              | 1                | 3            | Successful splice, used for cavity measurements            |
| 14      | 21.11.2025 | 5              | 2                | 2            | Lost during splicing attempt                               |
| 15      | 21.11.2025 | 6              | 3                | 1            | Used for first Splice Test, noisy                          |
| 16      | 28.11.2025 | 1              | -                | -            |                                                            |
| 17      | 28.11.2025 | 2              | -                | -            |                                                            |
| 18      | 28.11.2025 | 3              | -                | -            |                                                            |
| 19      | 05.12.2025 | 4              | -                | -            | Problems with conductive gold delamination                 |
| 20      | 05.12.2025 | 5              | -                | -            | Problems with conductive gold delamination                 |
| 21      | 05.12.2025 | 6              | -                | -            | Problems with conductive gold delamination                 |
| 22      | 23.01.2026 | 1              | -                | -            | Different RoC chosen (250)                                 |
| 23      | 23.01.2026 | 2              | -                | -            | Different RoC chosen (300)                                 |

Table A.1: Overview over the produced fibers, the first column shows the order in which they were produced in the FIB and the second column shows the corresponding date. Then the position they had in the FIB fiber holder is written and afterwards the order in which they were smoothed. Next there is information about their position in the holder that was used for the gold mirror coating.

## A.2 Fiber Cavity Array Measurement Additions

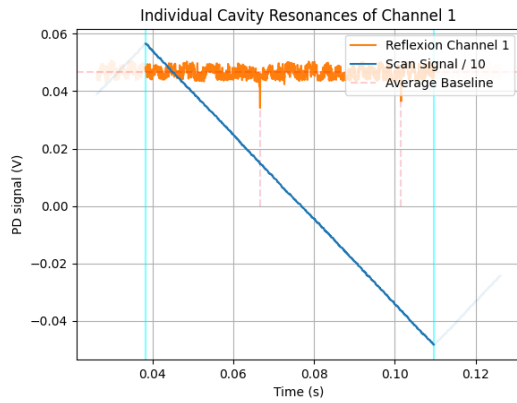


(a) Rawdata for the Reflection measurement on each channel of the multicore fiber mirror.

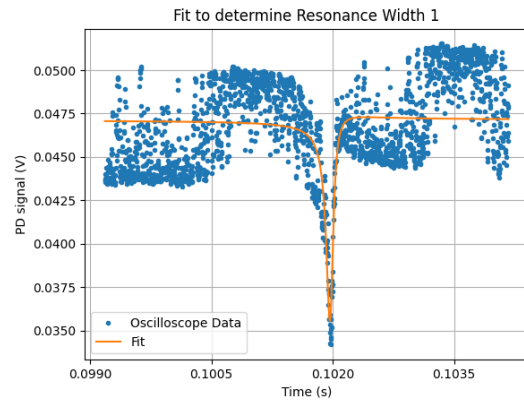


(b) Rawdata for the transmission through each channel of the fiber mirror (with the same input as for the reflection measurement in a).

Figure A.26: Rawdata for Transmission and Reflection Measurement



(a) Cavity scan over a Free Spectral Range on the cavity at fanout Channel 1. The resonance position and the average reflection power baseline are indicated.



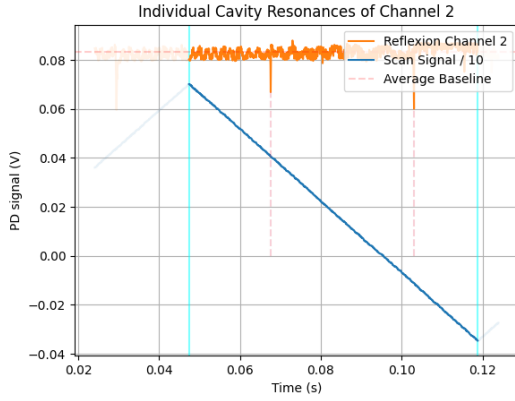
(b) Zoom in on the resonance shape for Channel 1.

Figure A.27: FSR scan and resonance shape data of Channel 1

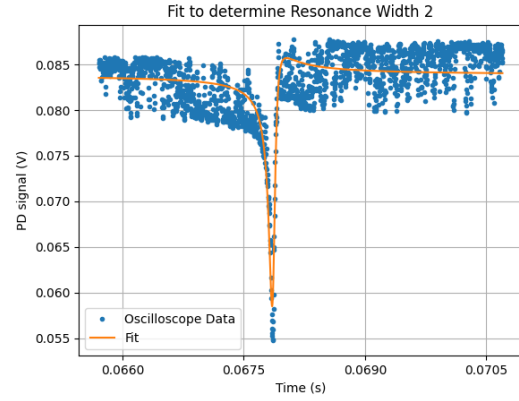
| Laser Port                         | PD Port | Refl. Power    |                   | Laser Port                         | PD Port | Refl. Power    |                   |
|------------------------------------|---------|----------------|-------------------|------------------------------------|---------|----------------|-------------------|
|                                    |         | abs. (nW)      | rel. (dB)         |                                    |         | abs. (nW)      | rel. (dB)         |
| Input Power 14.00 mW $\pm$ 0.02 mW |         |                |                   | Input Power 14.01 mW $\pm$ 0.02 mW |         |                |                   |
| 1                                  | 2       | 385.3 $\pm$ 10 | -45.60 $\pm$ 0.11 | 5                                  | 1       | 472 $\pm$ 20   | -44.72 $\pm$ 0.18 |
| 1                                  | 3       | 293.1 $\pm$ 10 | -46.79 $\pm$ 0.15 | 5                                  | 2       | 755 $\pm$ 20   | -42.68 $\pm$ 0.12 |
| 1                                  | 4       | 1690 $\pm$ 30  | -39.18 $\pm$ 0.08 | 5                                  | 3       | 792 $\pm$ 10   | -42.48 $\pm$ 0.06 |
| 1                                  | 5       | 442.8 $\pm$ 5  | -45.00 $\pm$ 0.05 | 5                                  | 4       | 4037 $\pm$ 50  | -35.40 $\pm$ 0.05 |
| 1                                  | 6       | 203.0 $\pm$ 5  | -48.39 $\pm$ 0.11 | 5                                  | 6       | 1269 $\pm$ 10  | -40.43 $\pm$ 0.04 |
| 1                                  | 7       | 212.0 $\pm$ 10 | -48.20 $\pm$ 0.20 | 5                                  | 7       | 3310 $\pm$ 30  | -36.27 $\pm$ 0.04 |
| Input Power 14.12 mW $\pm$ 0.02 mW |         |                |                   | Input Power 14.04 mW $\pm$ 0.02 mW |         |                |                   |
| 2                                  | 1       | 632 $\pm$ 10   | -43.49 $\pm$ 0.07 | 6                                  | 1       | 303 $\pm$ 10   | -46.66 $\pm$ 0.14 |
| 2                                  | 3       | 1033 $\pm$ 10  | -41.36 $\pm$ 0.04 | 6                                  | 2       | 2216 $\pm$ 40  | -38.02 $\pm$ 0.08 |
| 2                                  | 4       | 3680 $\pm$ 30  | -35.84 $\pm$ 0.04 | 6                                  | 3       | 3140 $\pm$ 50  | -36.50 $\pm$ 0.07 |
| 2                                  | 5       | 1070 $\pm$ 20  | -41.20 $\pm$ 0.08 | 6                                  | 4       | 404 $\pm$ 10   | -45.41 $\pm$ 0.11 |
| 2                                  | 6       | 1346 $\pm$ 20  | -40.21 $\pm$ 0.06 | 6                                  | 5       | 1322 $\pm$ 20  | -40.26 $\pm$ 0.07 |
| 2                                  | 7       | 1125 $\pm$ 10  | -40.99 $\pm$ 0.04 | 6                                  | 7       | 10940 $\pm$ 50 | -31.08 $\pm$ 0.02 |
| Input Power 14.15 mW $\pm$ 0.02 mW |         |                |                   | Input Power 14.07 mW $\pm$ 0.02 mW |         |                |                   |
| 3                                  | 1       | 270.2 $\pm$ 10 | -47.19 $\pm$ 0.16 | 7                                  | 1       | 272 $\pm$ 20   | -47.14 $\pm$ 0.32 |
| 3                                  | 2       | 1830 $\pm$ 20  | -38.88 $\pm$ 0.05 | 7                                  | 2       | 2647 $\pm$ 20  | -37.26 $\pm$ 0.03 |
| 3                                  | 4       | 484 $\pm$ 10   | -44.66 $\pm$ 0.09 | 7                                  | 3       | 1124 $\pm$ 50  | -40.98 $\pm$ 0.19 |
| 3                                  | 5       | 753 $\pm$ 5    | -42.74 $\pm$ 0.03 | 7                                  | 4       | 2068 $\pm$ 10  | -38.33 $\pm$ 0.02 |
| 3                                  | 6       | 3052 $\pm$ 20  | -36.66 $\pm$ 0.03 | 7                                  | 5       | 1924 $\pm$ 40  | -38.64 $\pm$ 0.09 |
| 3                                  | 7       | 1480 $\pm$ 30  | -39.80 $\pm$ 0.09 | 7                                  | 6       | 11240 $\pm$ 50 | -30.98 $\pm$ 0.02 |
| Input Power 14.06 mW $\pm$ 0.02 mW |         |                |                   |                                    |         |                |                   |
| 4                                  | 1       | 2001 $\pm$ 20  | -38.47 $\pm$ 0.04 |                                    |         |                |                   |
| 4                                  | 2       | 2972 $\pm$ 30  | -36.75 $\pm$ 0.04 |                                    |         |                |                   |
| 4                                  | 3       | 329 $\pm$ 10   | -46.31 $\pm$ 0.13 |                                    |         |                |                   |
| 4                                  | 5       | 3907 $\pm$ 40  | -35.56 $\pm$ 0.04 |                                    |         |                |                   |
| 4                                  | 6       | 272 $\pm$ 10   | -47.13 $\pm$ 0.16 |                                    |         |                |                   |
| 4                                  | 7       | 995 $\pm$ 10   | -41.50 $\pm$ 0.04 |                                    |         |                |                   |

Table A.2: Raw data for the fiber mirror crosstalk measurement, the Input Laser power was regularly checked to limit errors originating from potential power drifts.



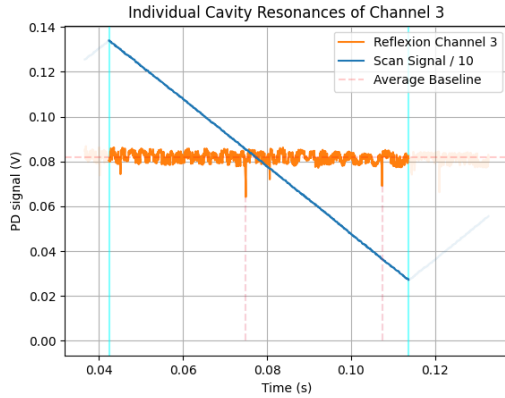


(a) Cavity scan over a Free Spectral Range on the cavity at fanout Channel 2. The resonance position and the average reflection power baseline are indicated.

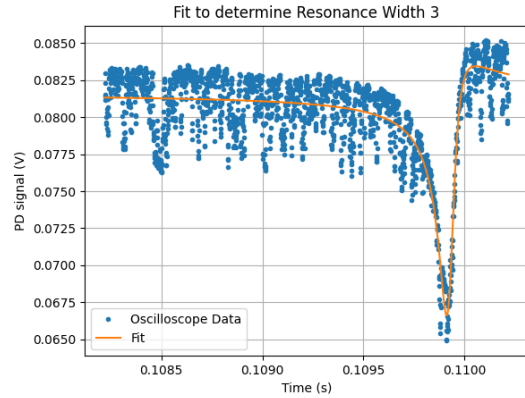


(b) Zoom in on the resonance shape for Channel 2.

Figure A.28: FSR scan and resonance shape data of Channel 2

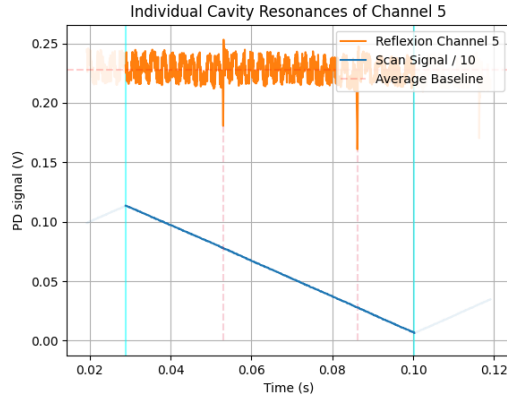


(a) Cavity scan over a Free Spectral Range on the cavity at fanout Channel 3. The resonance position and the average reflection power baseline are indicated.

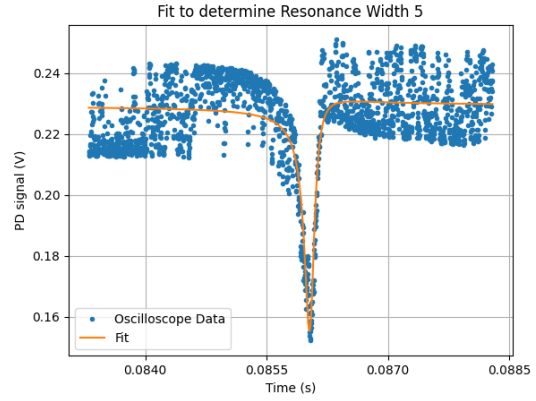


(b) Zoom in on the resonance shape for Channel 3.

Figure A.29: FSR scan and resonance shape data of Channel 3

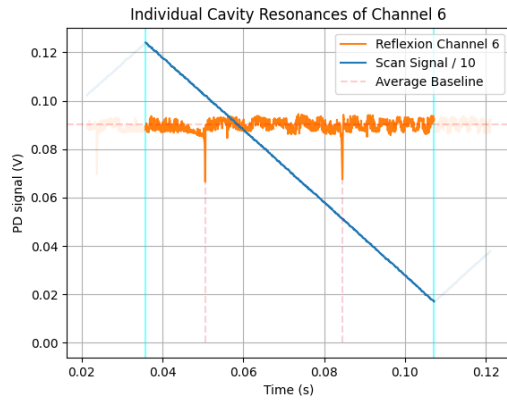


(a) Cavity scan over a Free Spectral Range on the cavity at fanout Channel 5. The resonance position and the average reflection power baseline are indicated.

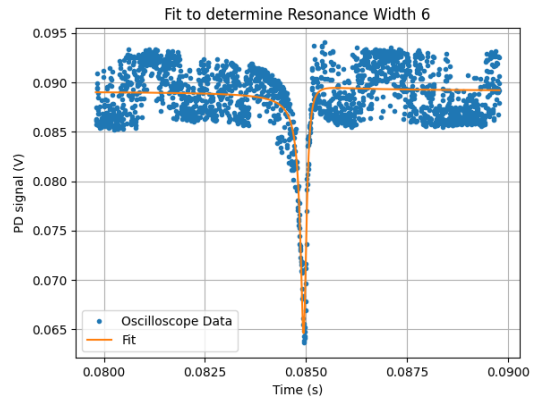


(b) Zoom in on the resonance shape for Channel 5.

Figure A.30: FSR scan and resonance shape data of Channel 5

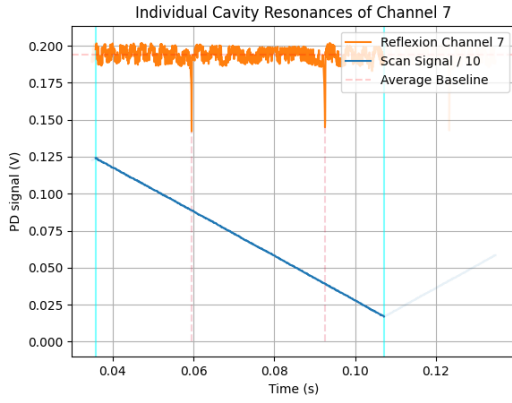


(a) Cavity scan over a Free Spectral Range on the cavity at fanout Channel 6. The resonance position and the average reflection power baseline are indicated.

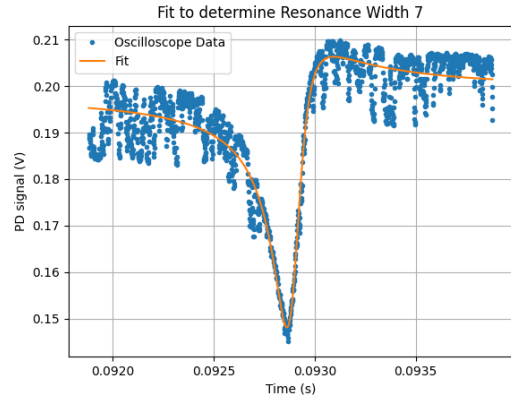


(b) Zoom in on the resonance shape for Channel 6.

Figure A.31: FSR scan and resonance shape data of Channel 6

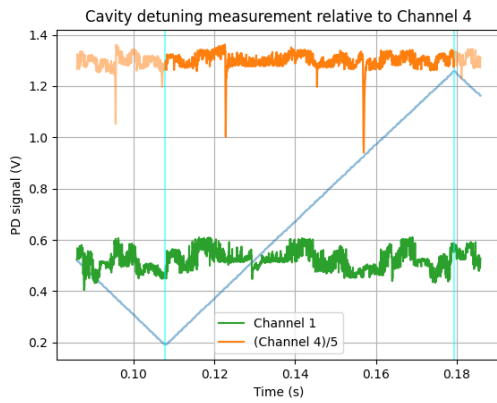


(a) Cavity scan over a Free Spectral Range on the cavity at fanout Channel 7. The resonance position and the average reflection power baseline are indicated.

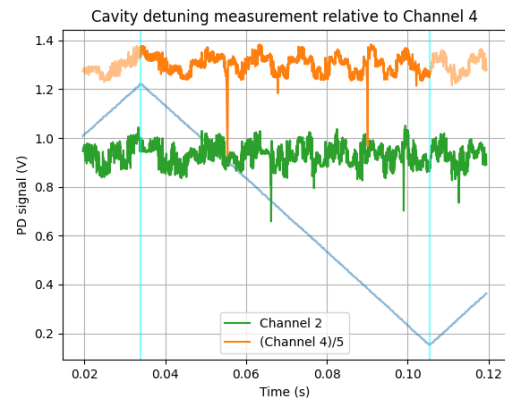


(b) Zoom in on the resonance shape for Channel 7.

Figure A.32: FSR scan and resonance shape data of Channel 7

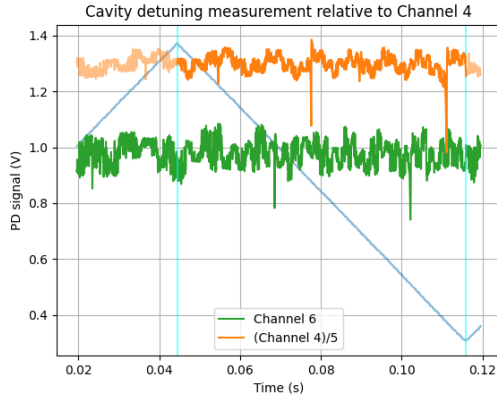


(a) Cavity Resonances of channel 1 and 4.

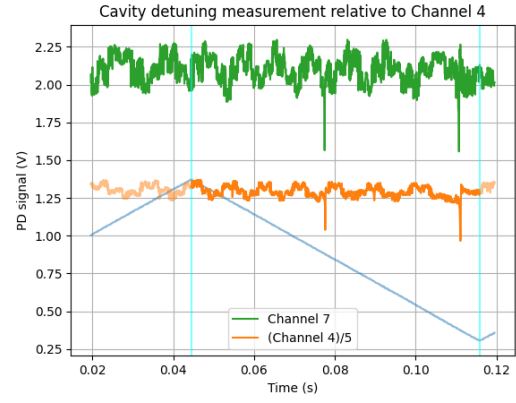


(b) Cavity Resonances of channel 2 and 4.

Figure A.33

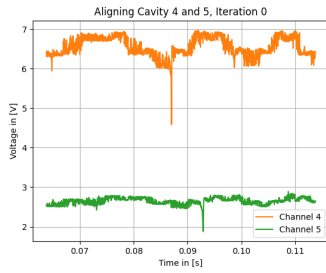


(a) Cavity Resonances of channel 6 and 4.

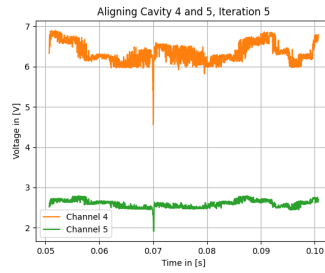


(b) Cavity Resonances of channel 7 and 4.

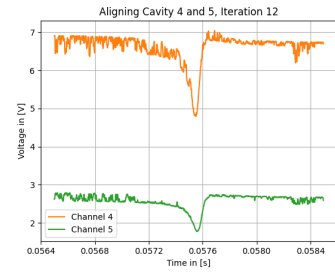
Figure A.34



(a)



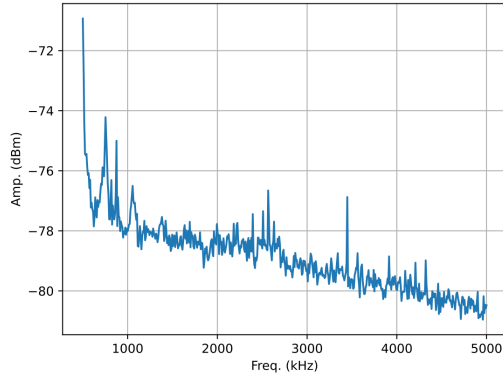
(b)



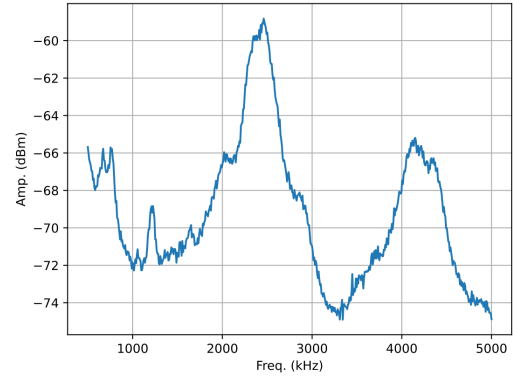
(c)

Figure A.35: Demonstration of tuning two cavities to simultaneous resonance via tilt adjustments of the mirror substrate relative to the fiber. (a) shows the initial situation, the tilt was adjusted and the resonance position checked in each iteration. After 12 iterations the cavity resonances overlap well relative to their width, visible in (c).

### A.3 Mechanical Membrane Spectra

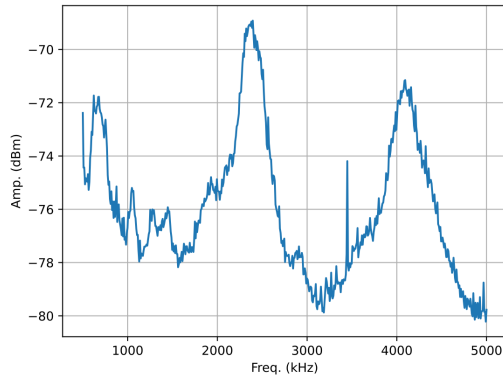


(a) Spectrum with a locked cavity but without membrane.

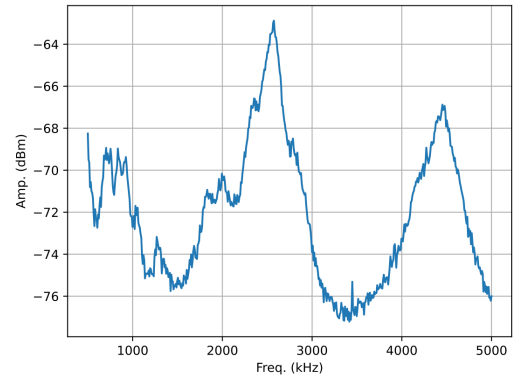


(b) Mechanical Spectrum of a membrane dimer with 35  $\mu\text{m}$  center spacing and a target radius of 20  $\mu\text{m}$ .

Figure A.36



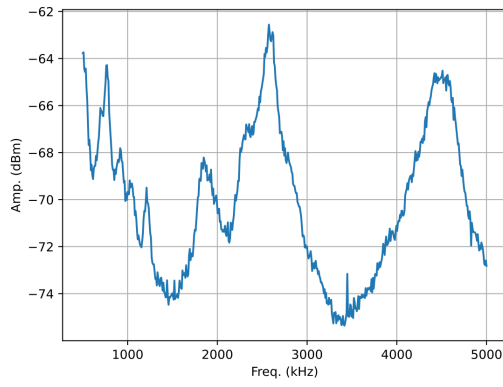
(a) Mechanical Spectrum of a membrane dimer with 35  $\mu\text{m}$  center spacing and a target radius of 20.5  $\mu\text{m}$ .



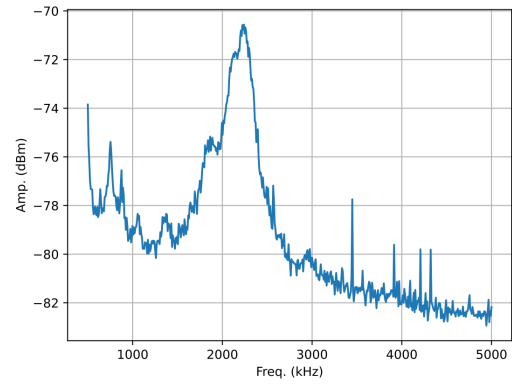
(b) Mechanical Spectrum of a membrane dimer with 35  $\mu\text{m}$  center spacing and a target radius of 21  $\mu\text{m}$ .

Figure A.37





(a) Mechanical Spectrum of a membrane dimer with 35  $\mu\text{m}$  center spacing and a target radius of 21.5  $\mu\text{m}$ .



(b) Mechanical Spectrum of a membrane dimer with 35  $\mu\text{m}$  center spacing and a target radius of 22  $\mu\text{m}$ .

Figure A.38

| Application                                 | Used Tools                                                                                            |
|---------------------------------------------|-------------------------------------------------------------------------------------------------------|
| Programming Language                        | Python                                                                                                |
| Programming help and Debugging              | ChatGPT                                                                                               |
| Literature Search                           | Google (Scholar), ChatGPT, Recommendations from Colleagues                                            |
| Data Analysis and Visualization             | Pandas (Python), Matplotlib (Python), Plotly (Python), Scipy (Python), uncertainties-package (Python) |
| Transfermatrix calculations for gold mirror | tmm-package (Python), Code from Paul Steinmann for cross-checking                                     |
| Mechanical Simulations                      | Comsol Multiphysics                                                                                   |
| 3D renders and CAD design                   | Autodesk Fusion, Autodesk Inventor                                                                    |
| 2D graphics design                          | Microsoft PowerPoint, Inkscape                                                                        |
| Typesetting                                 | L <sup>A</sup> T <sub>E</sub> X in Overleaf with Uni Bonn physics thesis template <sup>1</sup>        |

Table A.3: List of digital tools used for this thesis.

## A.4 Statement on Digital Tools and AI Assistance

During the making of this thesis multiple digital tools were used. This includes assistance of AI tools for programming tasks and literature search, the correctness of answers given by AI was independently verified by the author. An overview over the used digital tools can be found in table Tab. A.3. The text of this thesis was fully written by the author and for polishing only spellchecking and human proofreaders were consulted.

<sup>1</sup> <https://www.pi.uni-bonn.de/brock/en/thesis-guide>

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## List of Figures

---

|      |                                                                                                                                                                                                                                                                                      |    |
|------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----|
| 2.1  | Plots to visualize cavity resonance line shape . . . . .                                                                                                                                                                                                                             | 5  |
| 2.2  | Visualizations for a two membrane toy model and how a membrane chain could be used for sensing . . . . .                                                                                                                                                                             | 13 |
| 2.3  | 3D renders of ideal fiber surface geometry and a multicore fiber interfacing an acoustic device layer, made with Autodesk Fusion. . . . .                                                                                                                                            | 14 |
| 2.4  | Visualization for the ablation depth calculation and of the fiber structure with an added silicon layer . . . . .                                                                                                                                                                    | 16 |
| 3.1  | CO <sub>2</sub> laser Ablation Shooting Results . . . . .                                                                                                                                                                                                                            | 19 |
| 3.2  | Setup and result of the backside wet etching test. . . . .                                                                                                                                                                                                                           | 21 |
| 3.3  | Images of the FIB interior . . . . .                                                                                                                                                                                                                                                 | 23 |
| 3.4  | FIB Session 1, bare fiber surface in SEM and ion beam image . . . . .                                                                                                                                                                                                                | 24 |
| 3.5  | FIB Session 1 . . . . .                                                                                                                                                                                                                                                              | 25 |
| 3.6  | FIB Session 1 (Fiber name: 1 in Tab. A.1) . . . . .                                                                                                                                                                                                                                  | 26 |
| 3.7  | FIB Session 2 (Fiber name: 4 in Tab. A.1), the ablations were made smaller to leave a few microns space between each ablation in order to prevent the CO <sub>2</sub> Laser in the smoothing step to melt them into each other. . . . .                                              | 27 |
| 3.8  | FIB Session 2 (Fiber name: 5 in Tab. A.1), the streamfile encoding the pattern had wrong depth data and the ablations were too flat. The fiber was later discarded. . . . .                                                                                                          | 27 |
| 3.9  | FIB Session 3 (Fiber name: 6 in Tab. A.1) . . . . .                                                                                                                                                                                                                                  | 28 |
| 3.10 | FIB Session 3 (Fiber name: 7 in Tab. A.1) . . . . .                                                                                                                                                                                                                                  | 29 |
| 3.11 | FIB Session 3, Comparison of a 24 pA ion beam image and a 9.3 nA ion beam image. . . . .                                                                                                                                                                                             | 29 |
| 3.12 | FIB Session 4 . . . . .                                                                                                                                                                                                                                                              | 30 |
| 3.13 | FIB Session 5 (Fiber name: 12 in Tab. A.1), there is a bubble structure visible on the ablation on the left. . . . .                                                                                                                                                                 | 31 |
| 3.14 | FIB Session 5, SEM image of bubbles in the fiber surface and of possible crosstalk limitation trenches. . . . .                                                                                                                                                                      | 31 |
| 3.15 | A fiber surface before milling during FIB session 7, we think thermal stress led to delamination of the gold layer. . . . .                                                                                                                                                          | 32 |
| 3.16 | FIB Session 7 (Fiber name: 21 in Tab. A.1), this was a testfiber to see how long we have to mill until we can see the fiber cores in the ion beam image consistently. After a few hundred nanometers of milling almost on the entire fiber surface the cores became visible. . . . . | 33 |



## List of Figures

---

|      |                                                                                                                                                                                                                                                                                                |    |
|------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----|
| 3.17 | FIB Session 8 (Fiber name: 22 in Tab. A.1), this fiber was manufactured with a higher nominal RoC of 250 $\mu\text{m}$ and without core alignment correction to improve the depth matching of the ablations. . . . .                                                                           | 34 |
| 3.18 | FIB Session 8: Well focused ion beam images of fiber 23 . . . . .                                                                                                                                                                                                                              | 35 |
| 3.19 | FIB Session 8 (Fiber name: 23 in Tab. A.1), this fiber was manufactured with a higher nominal RoC of 300 $\mu\text{m}$ and without core alignment correction to improve the depth matching of the ablations. . . . .                                                                           | 35 |
| 3.20 | 3D surface reconstruction of Fiber 13 before and after smoothing . . . . .                                                                                                                                                                                                                     | 37 |
| 3.21 | Average deviation of the ablation minima from a plane fit, this is an important quantifier for the performance of our array for an application where simultaneous resonance is required, as a plane can be compensated via an alignment change. . . . .                                        | 38 |
| 3.22 | Cross section of an ablation on Fiber 13 (green data points) with a spherical fit (red line) and below the difference between fit and data. Once plotted before the smoothing and once after. . . . .                                                                                          | 38 |
| 3.23 | Fiber Surface Analysis Histograms and Surface Plot. . . . .                                                                                                                                                                                                                                    | 39 |
| 3.24 | Efforts to improve the mechanical stability of the fibers. . . . .                                                                                                                                                                                                                             | 40 |
| 3.25 | Gold coating procedure . . . . .                                                                                                                                                                                                                                                               | 42 |
| 3.26 | Connection of the Multicore Fanout . . . . .                                                                                                                                                                                                                                                   | 43 |
| 3.27 | Connection of the Multicore Fanout Part 2 . . . . .                                                                                                                                                                                                                                            | 44 |
| 3.28 | Connection of the Multicore Fanout Part 3 . . . . .                                                                                                                                                                                                                                            | 44 |
| 3.29 | A laser pointer is used to illuminate a channel of the multicore fiber via the fanout, it is clearly visible that light also emerges from other cores and the cladding, especially around the ablation edges. . . . .                                                                          | 45 |
| 3.30 | Setup sketches for the crosstalk and reflection measurements of the multicore fiber mirror. . . . .                                                                                                                                                                                            | 46 |
| 3.31 | Measurement results of coating transmission and channel crosstalk . . . . .                                                                                                                                                                                                                    | 47 |
| 3.32 | FSR scan and resonance shape data of channel 4. . . . .                                                                                                                                                                                                                                        | 48 |
| 3.33 | Cavity array measurement setups. . . . .                                                                                                                                                                                                                                                       | 49 |
| 3.34 | Oscilloscope traces showing the time (and correspondingly spatial position) offset between resonance on channel 4 and 3 (a) and 4 and 5 (b). The triangular piezo scan signal is visible in the background. . . . .                                                                            | 50 |
| 4.1  | Images of the <i>Ambient Fiber Microscope</i> . . . . .                                                                                                                                                                                                                                        | 52 |
| 4.2  | Fiber holder and membrane surface scan . . . . .                                                                                                                                                                                                                                               | 53 |
| 4.3  | Setup used for the measurement of the mechanical Resonances of the membranes, the laser is coupled into the fiber cavity, and the reflection is observed with a photodiode. Thermal motion of the membrane creates a detectable wiggle of the photo-diode voltage in the locked state. . . . . | 54 |
| 4.4  | Comparison between a membrane dimer array that was in the developer solvent for $\sim 30$ min and one that developed over night. . . . .                                                                                                                                                       | 55 |
| 4.5  | Cavity region in the Ambient Fiber Microscope . . . . .                                                                                                                                                                                                                                        | 56 |
| 4.6  | Tower prints . . . . .                                                                                                                                                                                                                                                                         | 57 |
| 4.7  | Mechanical resonances of two membranes with 0.5 $\mu\text{m}$ radius difference . . . . .                                                                                                                                                                                                      | 57 |
| 4.8  | This plot shows simulation results (made with Comsol Multiphysics) of the coupled in phase and out of phase mode of the membrane dimer against increasing radius, when the feet size in the overlap region is reduced with higher radius. . . . .                                              | 58 |

## List of Figures

---

|                                                                                                                                   |    |
|-----------------------------------------------------------------------------------------------------------------------------------|----|
| A.1 FIB Session 4 (Fiber name: 8 in Tab. A.1) . . . . .                                                                           | 61 |
| A.2 FIB Session 4 (Fiber name: 9 in Tab. A.1) . . . . .                                                                           | 62 |
| A.3 FIB Session 4 (Fiber name: 10 in Tab. A.1) . . . . .                                                                          | 62 |
| A.4 FIB Session 4 (Fiber name: 11 in Tab. A.1) . . . . .                                                                          | 62 |
| A.5 FIB Session 5 (Fiber name: 13 in Tab. A.1) . . . . .                                                                          | 63 |
| A.6 FIB Session 5 (Fiber name: 14 in Tab. A.1) . . . . .                                                                          | 63 |
| A.7 FIB Session 5 (Fiber name: 15 in Tab. A.1) . . . . .                                                                          | 63 |
| A.8 FIB Session 6 (Fiber name: 16 in Tab. A.1) . . . . .                                                                          | 64 |
| A.9 FIB Session 6 (Fiber name: 17 in Tab. A.1) . . . . .                                                                          | 64 |
| A.10 FIB Session 6 (Fiber name: 18 in Tab. A.1) . . . . .                                                                         | 65 |
| A.11 FIB Session 7 (Fiber name: 19 in Tab. A.1) . . . . .                                                                         | 65 |
| A.12 FIB Session 7 (Fiber name: 20 in Tab. A.1) . . . . .                                                                         | 66 |
| A.13 FIB Session 8: We tried to mill free and image a cross section of an ablation. . . . .                                       | 66 |
| A.14 Interference Microscope Images of Fiber 13 . . . . .                                                                         | 67 |
| A.15 Interference Microscope Images of Fiber 14 . . . . .                                                                         | 67 |
| A.16 Interference Microscope Images of Fiber 15 . . . . .                                                                         | 68 |
| A.17 Interference Microscope Images of Fiber 12 . . . . .                                                                         | 68 |
| A.18 Interference Microscope Images of Fiber 11 . . . . .                                                                         | 69 |
| A.19 Interference Microscope Images of Fiber 10 . . . . .                                                                         | 69 |
| A.20 Interference Microscope Images of Fiber 9 . . . . .                                                                          | 70 |
| A.21 Interference Microscope Images of Fiber 8 . . . . .                                                                          | 70 |
| A.22 Interference Microscope Images of Fiber 7 . . . . .                                                                          | 71 |
| A.23 Interference Microscope Images of Fiber 6 . . . . .                                                                          | 71 |
| A.24 Interference Microscope Images of Fiber 4 . . . . .                                                                          | 72 |
| A.25 Interferometer images of the fibers that were produced without core alignment correction<br>but with optimized RoC . . . . . | 72 |
| A.26 Rawdata for Transmission and Reflecion Measurement . . . . .                                                                 | 74 |
| A.27 FSR scan and resonance shape data of Channel 1 . . . . .                                                                     | 74 |
| A.28 FSR scan and resonance shape data of Channel 2 . . . . .                                                                     | 76 |
| A.29 FSR scan and resonance shape data of Channel 3 . . . . .                                                                     | 76 |
| A.30 FSR scan and resonance shape data of Channel 5 . . . . .                                                                     | 77 |
| A.31 FSR scan and resonance shape data of Channel 6 . . . . .                                                                     | 77 |
| A.32 FSR scan and resonance shape data of Channel 7 . . . . .                                                                     | 78 |
| A.33 Cavity detuning data of channel 2 and 1 relative to 4 . . . . .                                                              | 78 |
| A.34 Cavity detuning data of channel 6 and 7 relative to 4 . . . . .                                                              | 79 |
| A.35 Demonstration of cavity tuning via tilt adjustment . . . . .                                                                 | 79 |
| A.36 Spectrum without membrane and spectrum for a 20 $\mu\text{m}$ radius membrane dimer . . . . .                                | 80 |
| A.37 Spectrum for a 20.5 $\mu\text{m}$ and 21 $\mu\text{m}$ radius membrane dimer . . . . .                                       | 80 |
| A.38 Spectrum for a 21.5 $\mu\text{m}$ and 22 $\mu\text{m}$ radius membrane dimer . . . . .                                       | 81 |

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## List of Tables

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|     |                                                                                                                                                                                                                                                                                                                                                                                                    |    |
|-----|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----|
| 3.1 | Transmission matrix as stated by the fanout manufacturer fibercore (C-band average, dB)                                                                                                                                                                                                                                                                                                            | 47 |
| 3.2 | Free spectral range, resonance width and finesse of the seven cavities measured. . . . .                                                                                                                                                                                                                                                                                                           | 49 |
| A.1 | Overview over the produced fibers, the first column shows the order in which they were produced in the FIB and the second column shows the corresponding date. Then the position they had in the FIB fiber holder is written and afterwards the order in which they were smoothed. Next there is information about their position in the holder that was used for the gold mirror coating. . . . . | 73 |
| A.2 | Raw data for the fiber mirror crosstalk measurement, the Input Laser power was regularly checked to limit errors originating from potential power drifts. . . . .                                                                                                                                                                                                                                  | 75 |
| A.3 | List of digital tools used for this thesis. . . . .                                                                                                                                                                                                                                                                                                                                                | 82 |