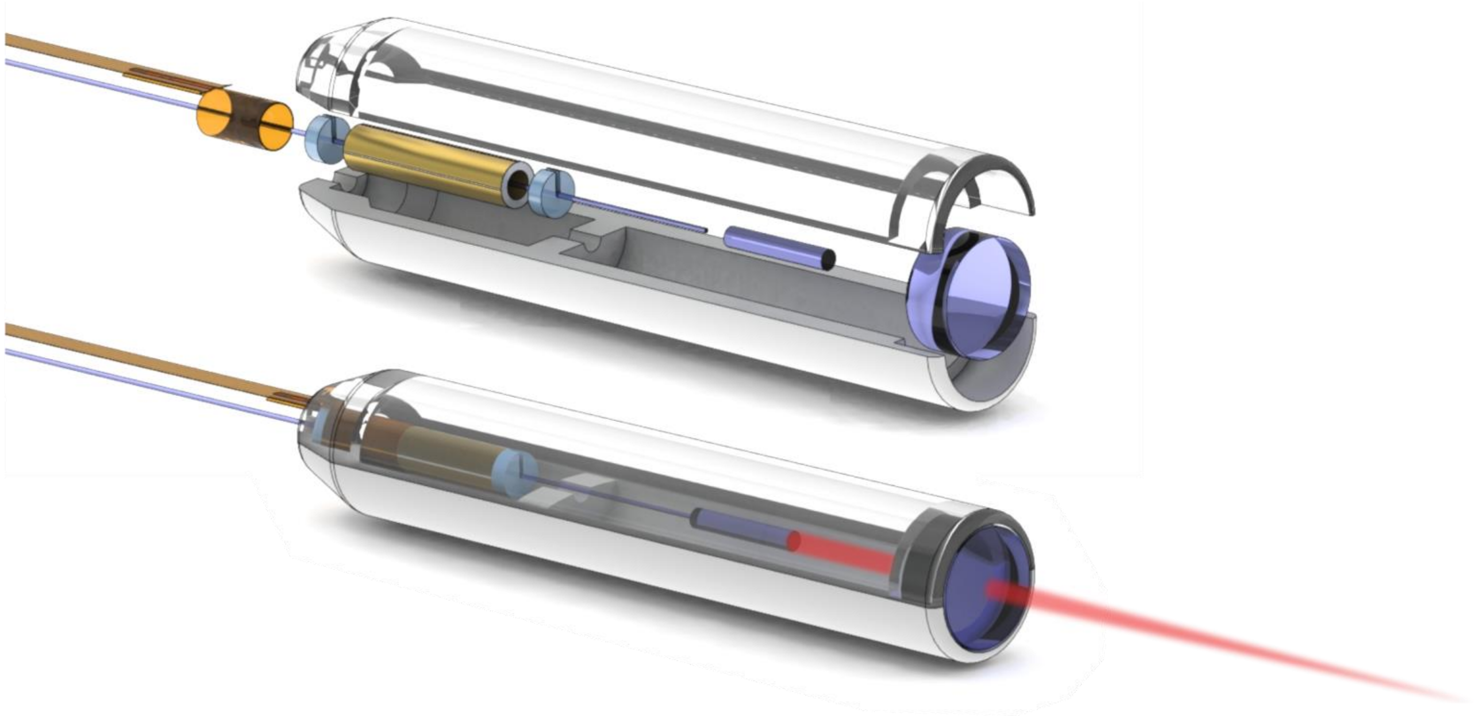
Compact OCT scanner for a bimodal endoscopic probe

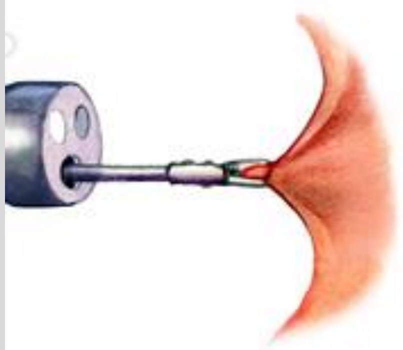


Sergio Vilches

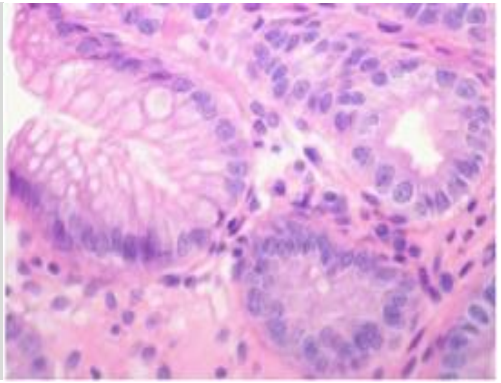
Motivation
Optical biopsy

Conventional endoscopic biopsy (*ex situ, ex vivo*)

Biopsy



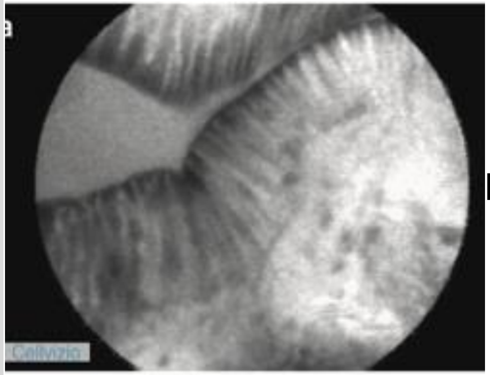
Histology



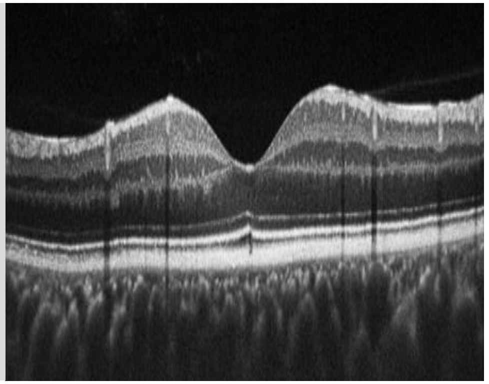
Diagnostic

Optical biopsy (*in situ, in vivo*)

Microscopy



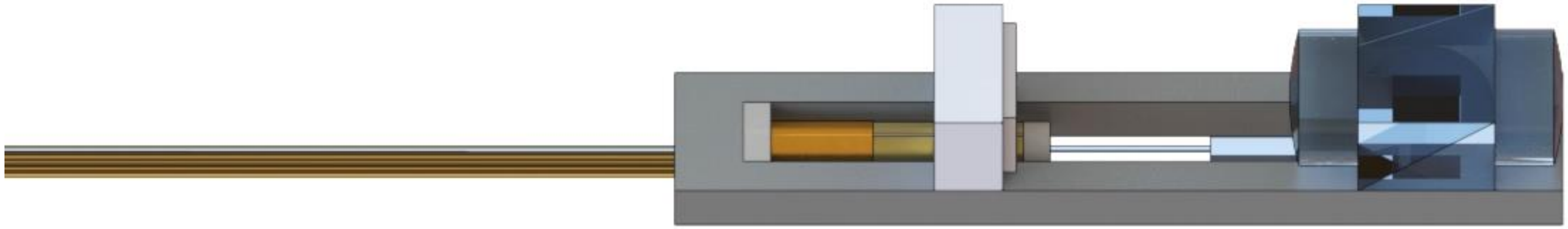
OCT



Diagnostic

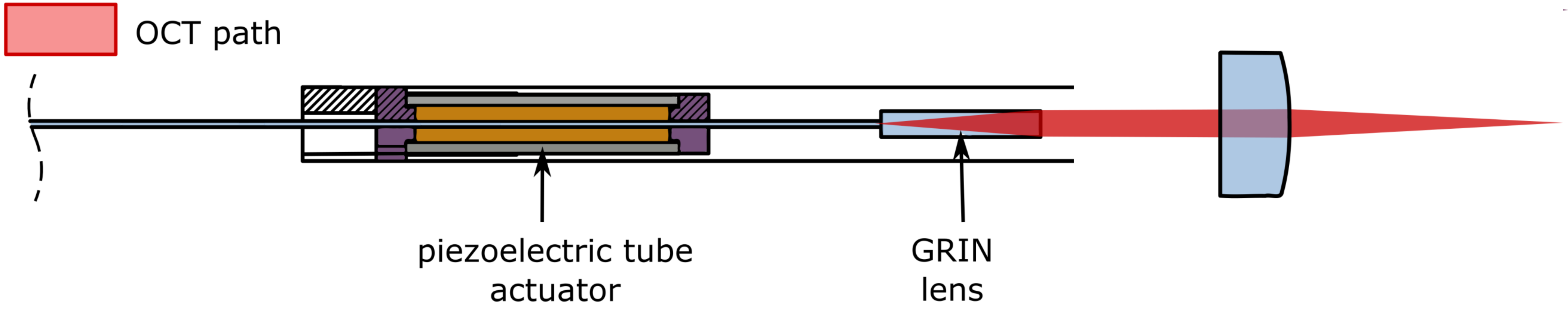
- Arteriovenous Malformation Fujii T. Kuwano H.
- Transversal OCT image of the macula J. A. Flatter and J. Carroll,
- http://colorectalsurgeonssydney.com.au/?page_id=425
- joimax GmbH

Fiber scanner
Bimodal implementation: Size



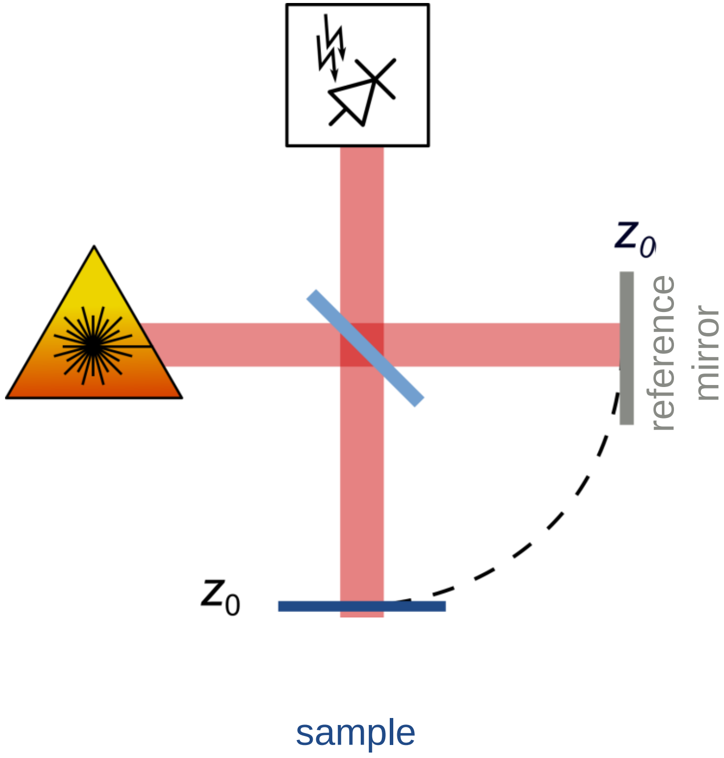
$13 \times 2 \times 3\ \mathrm{mm}^3$

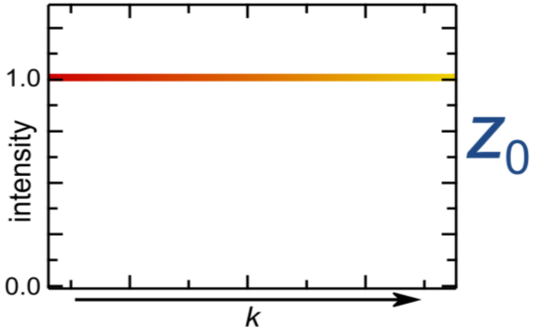
Fiber scanner
Bimodal implementation



Swept-Source Optical Coherence Tomography SS-OCT
Theory

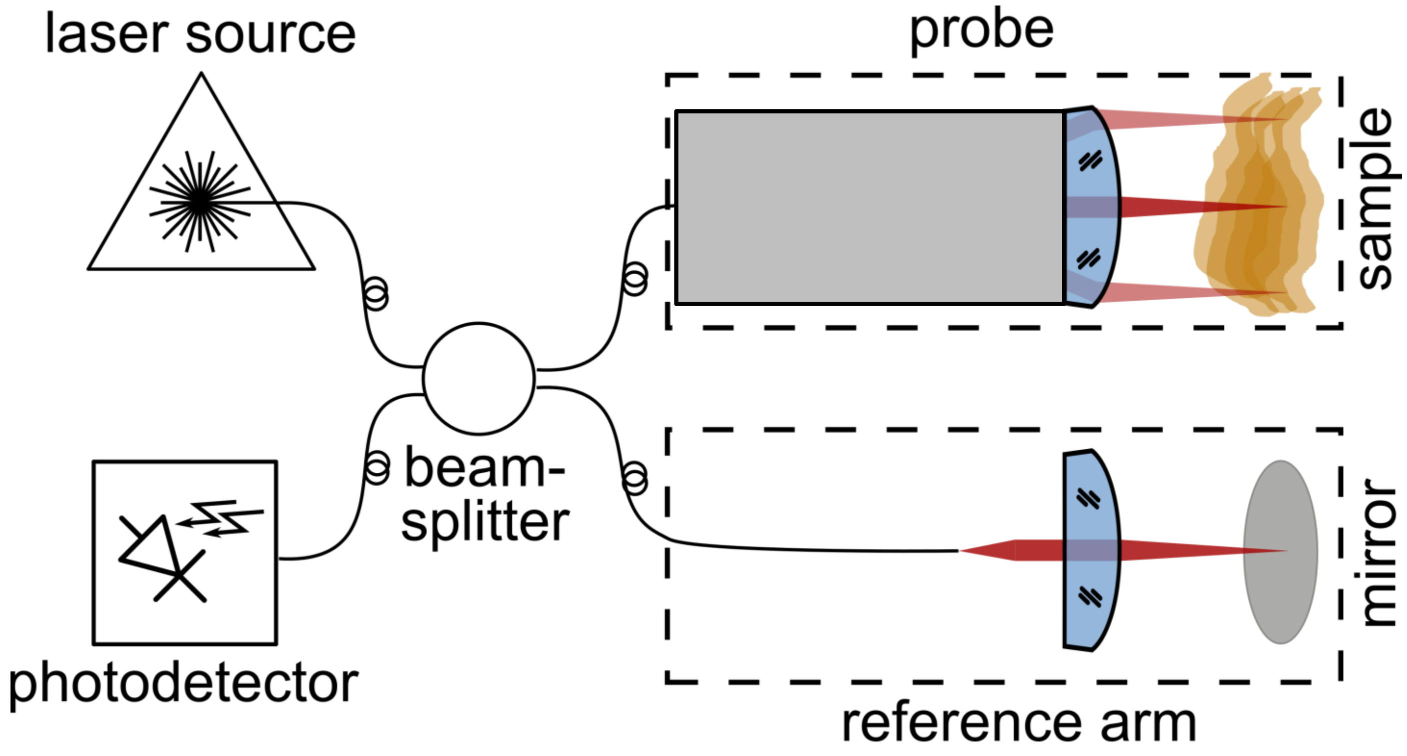
Single sample reflector | **Multiple reflectors**





$$I_D(k) = I_{M1} + I_R + 2\sqrt{I_{M1}\, I_R}\, cos\,(2\,k\,\,(z_{M1} - z_R))$$

Swept-Source OCT:
Fiber scanner requirements



Optical requirements:

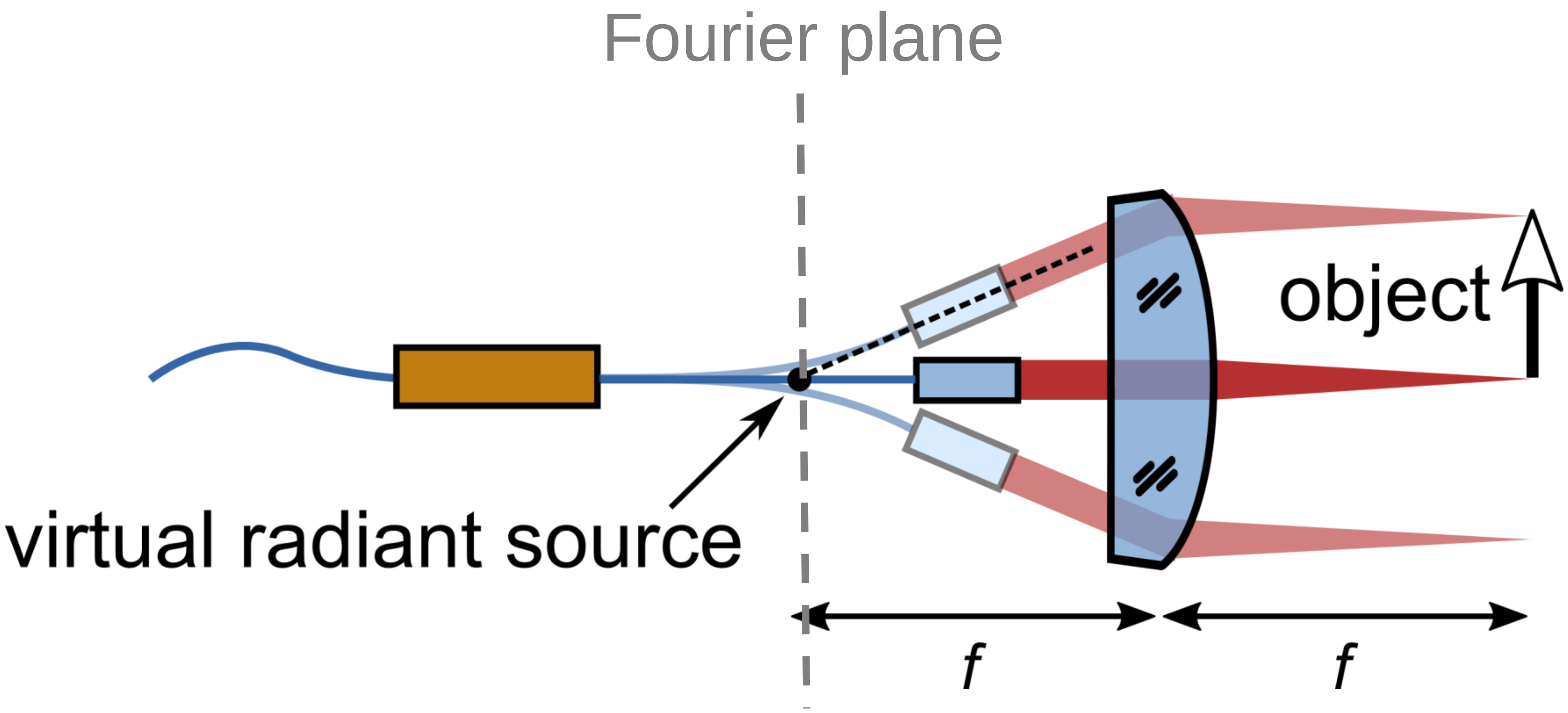
- Long depth of field: > 2 mm
- Scanning mechanism
- High field of view for 2 mm lens
- Telecentric

Mechanical requirements:

- Diameter < 3.3 mm
- Scanning mechanism adequate for OCT sampling rate (100 kHz)

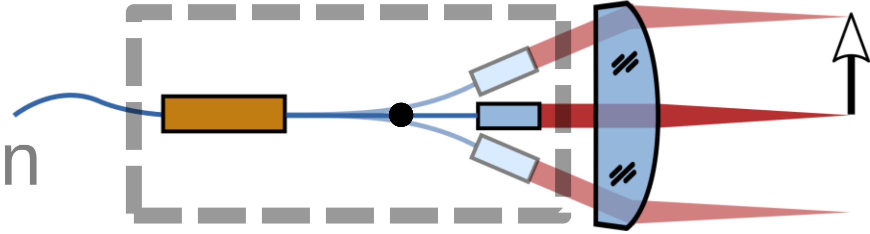
Fiber scanner

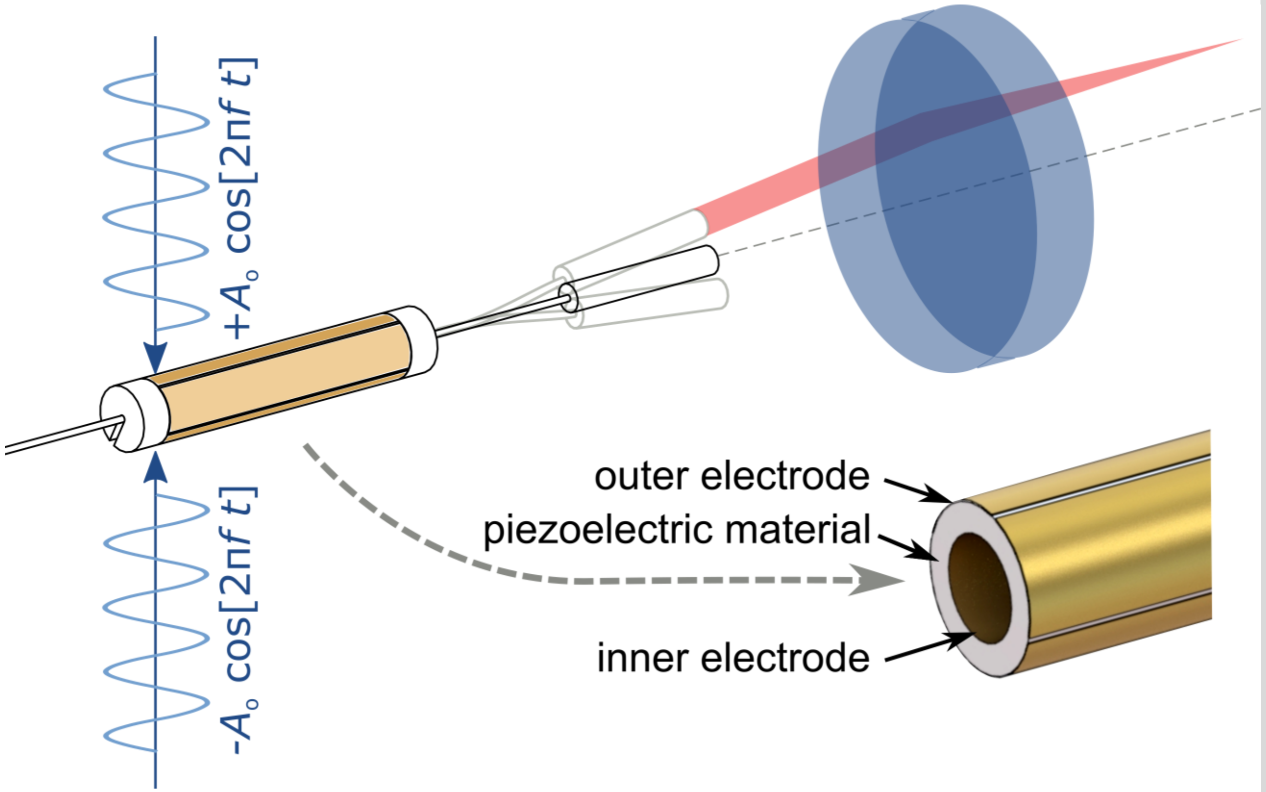
Fourier plane scanner

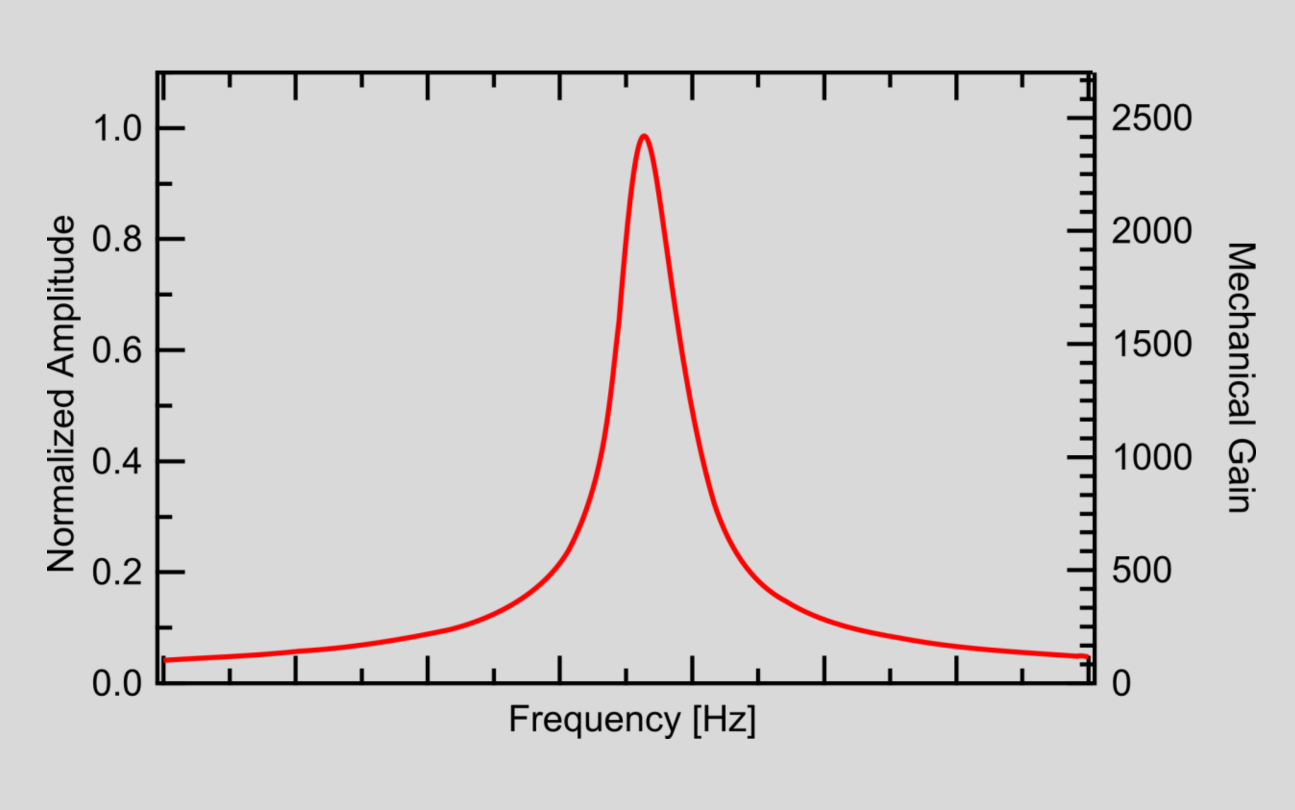


Fiber scanner

Piezoelectric actuation + Mechanical amplification

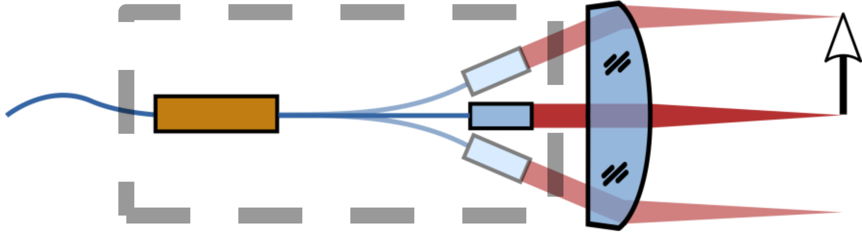


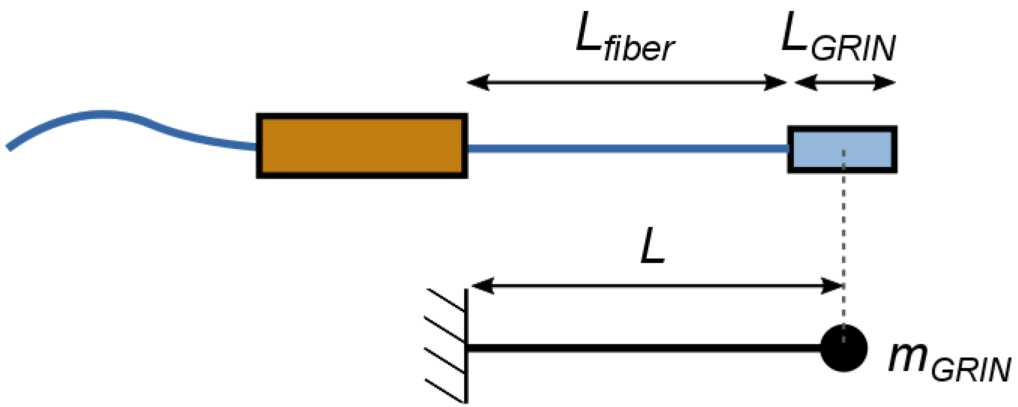




Fiber scanner

Resonance frequency estimation



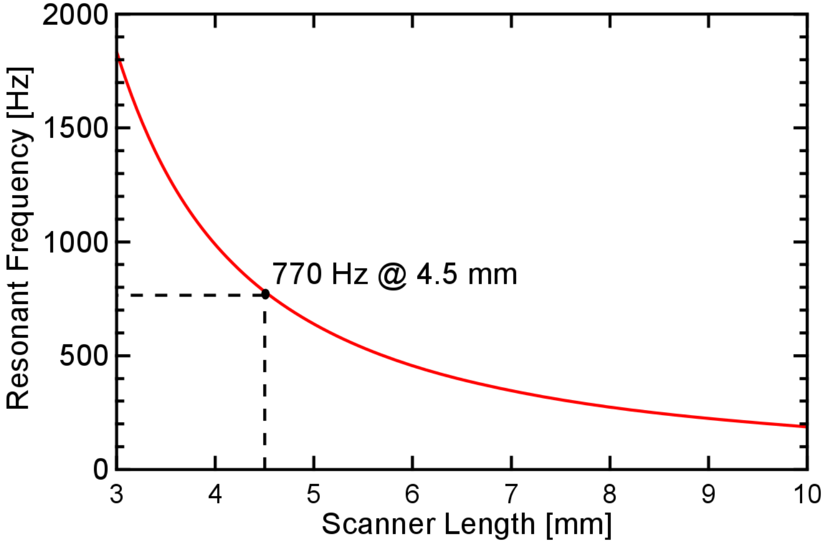


$$f_{\mathrm{res}} = \frac{1}{2\pi}\sqrt{\frac{K_{\mathrm{cantilever}}}{m_{\mathrm{GRIN}}}}$$

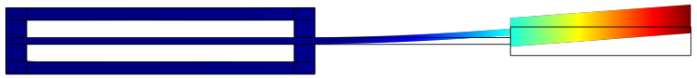
$$K_{\mathrm{cantilever}} = \frac{3EI}{L^3} = \frac{3\pi}{4}\frac{E_{\mathrm{fiber}} r_{\mathrm{fiber}}^4}{L^3}$$

$$f_{res} \propto \sqrt{\frac{d_{fiber}^4}{L_{fiber}^3 m_{GRIN}}}$$

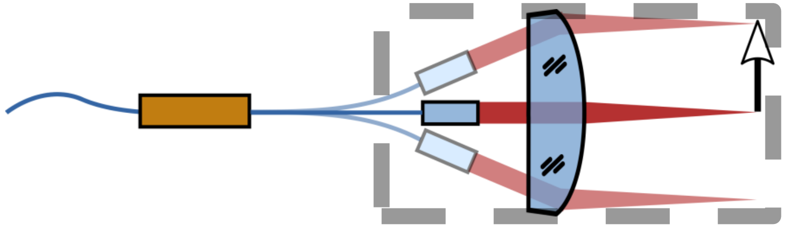
Analytical Calculation
770 Hz

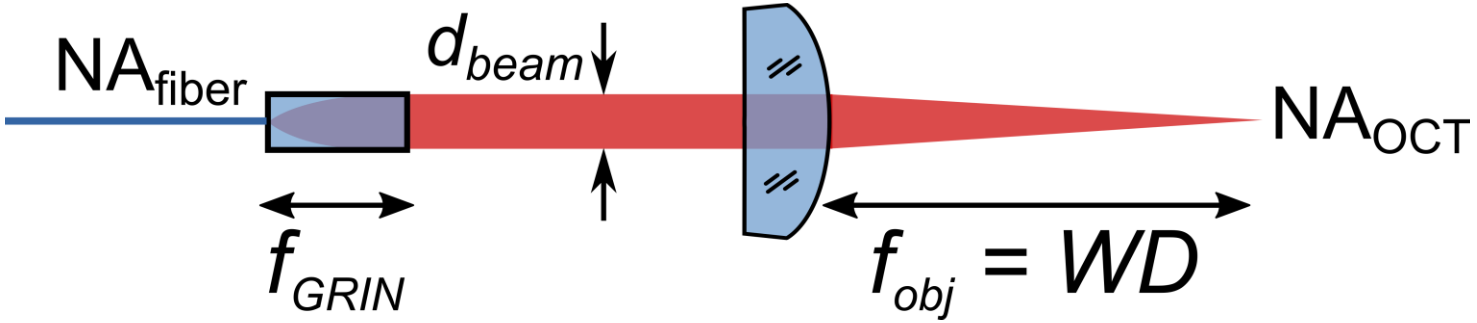


COMSOL Simulation:
762 Hz



Optical performance
Geometrical optics





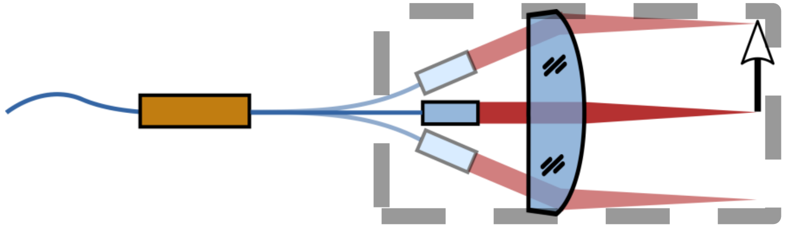
$$d_{\text{beam}} \simeq 2 \cdot f_{\text{GRIN}} \cdot \text{NA}_{\text{fiber}} \simeq 2 \cdot f_{\text{obj}} \cdot \text{NA}_{\text{OCT}}$$

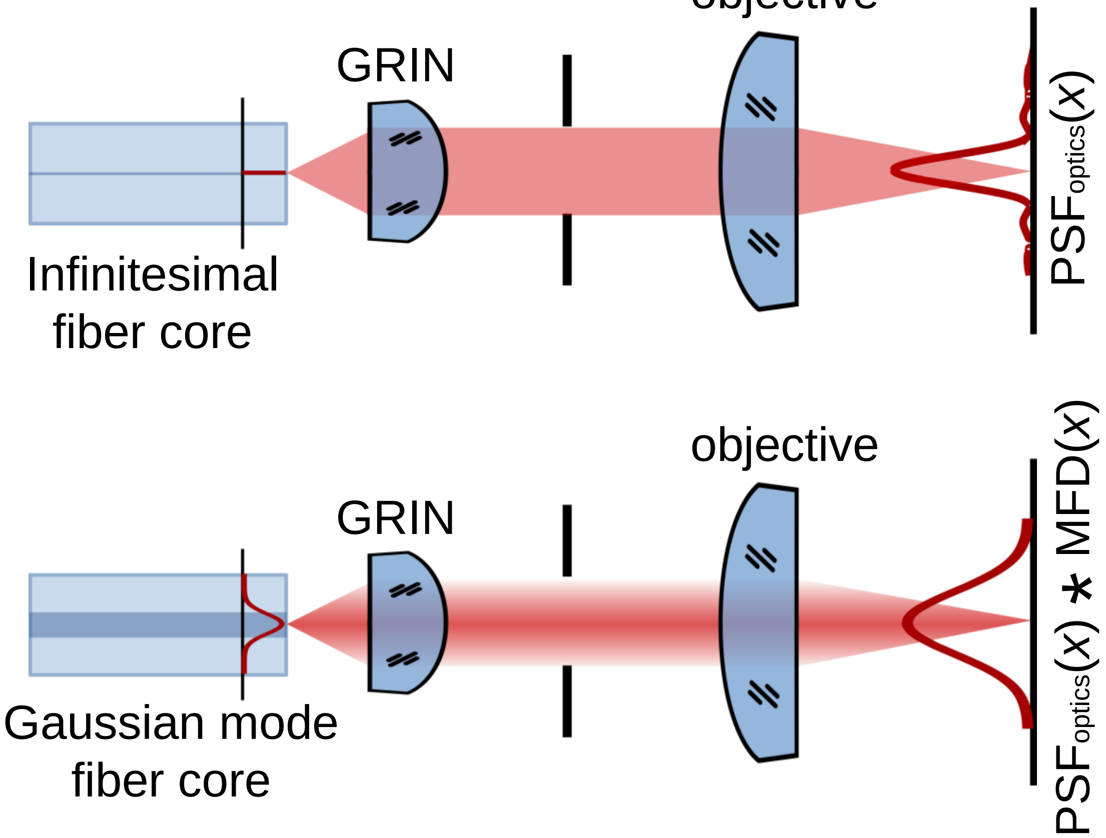
$$f_{\text{GRIN}} \cdot \text{NA}_{\text{fiber}} = f_{\text{obj}} \cdot \text{NA}_{\text{OCT}}$$

Parameter	Value
NA_{fiber}	0.18
NA_{GRIN}	0.2
f_{GRIN}	0.91 mm
d_{beam}	0.3 mm
f_{obj}	7.5 mm
NA_{OCT}	0.022

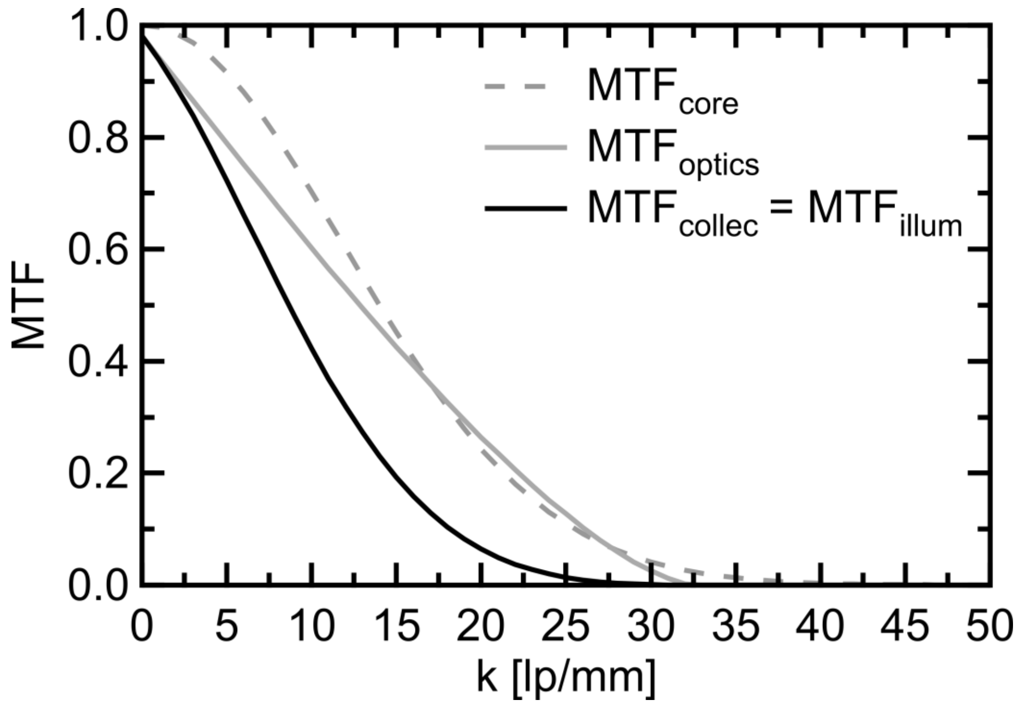
Optical performance

Fourier optics: illumination PSF





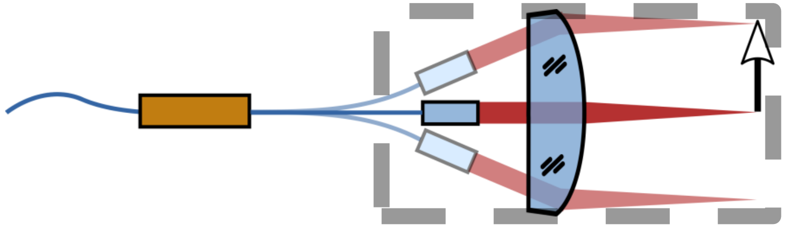
$$\mathrm{MTF}_{\mathrm{ill}}(\mathbf{k}) = \mathrm{MTF}_{\mathrm{core}}(\boldsymbol{k}) \cdot \mathrm{MTF}_{\mathrm{optics}}(\boldsymbol{k})$$

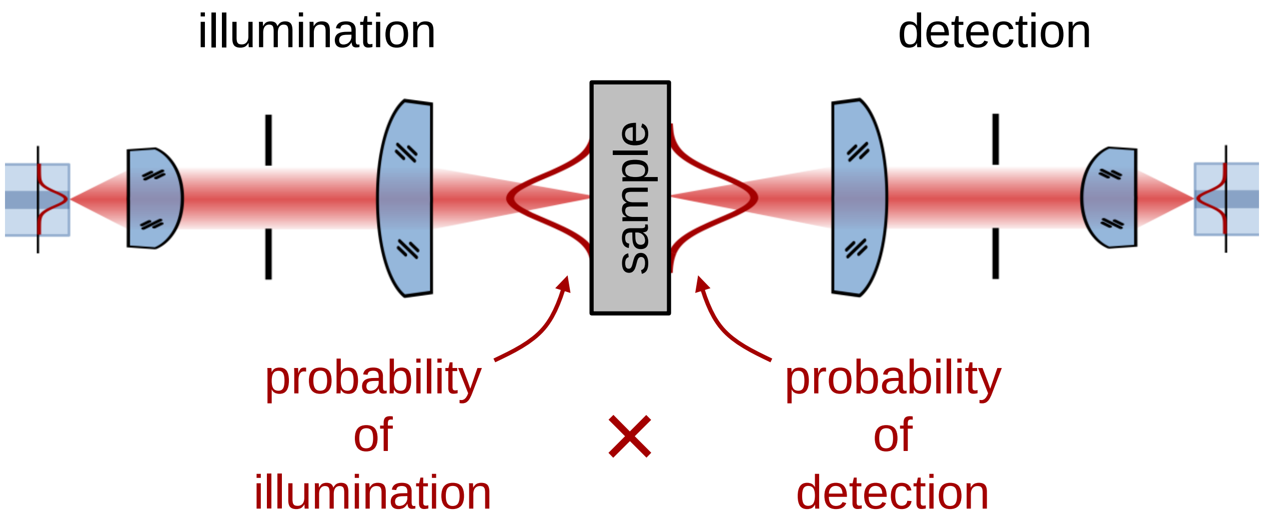


UNI FREIBURG

Optical performance

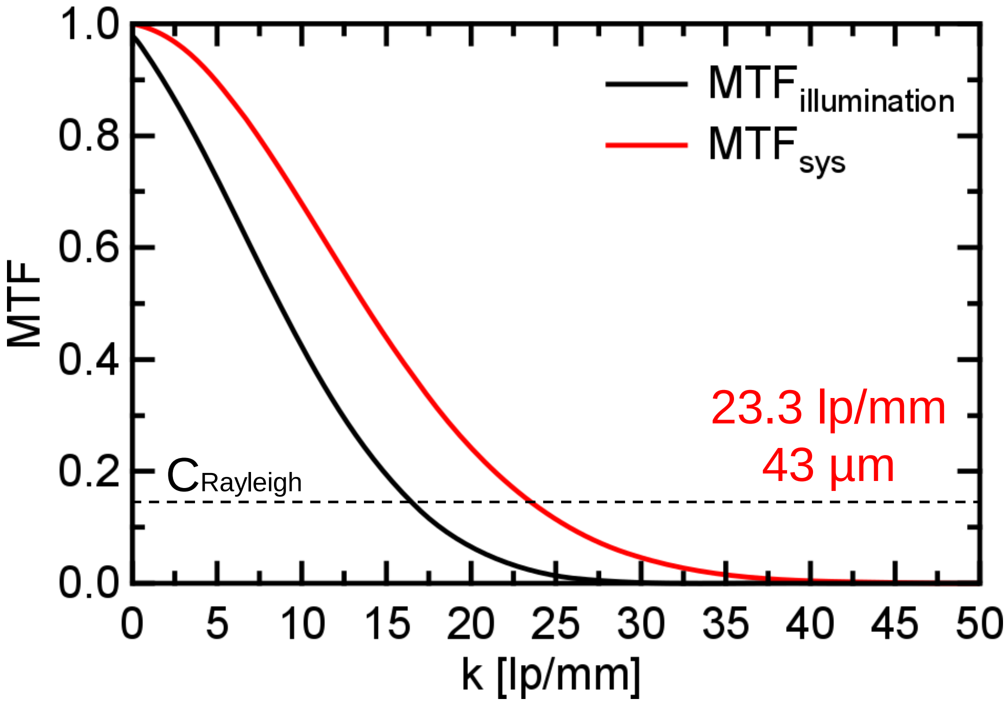
Fourier optics: illumination + collection





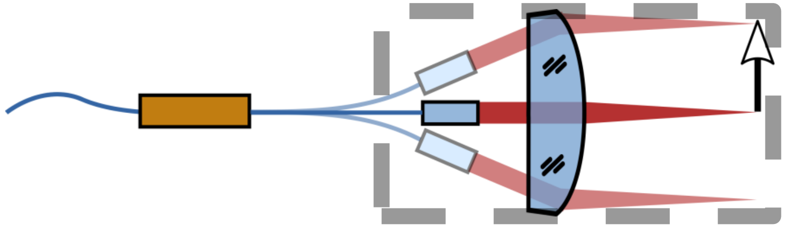
$$\mathrm{MTF_{sys}}(\mathbf{k}) = \mathrm{MTF_{ill}}(\mathbf{k}) * \mathrm{MTF_{det}}(\mathbf{k})$$

$$\mathrm{MTF_{sys}}(\mathbf{k}) \simeq \mathrm{AC}[\mathrm{MTF_{det}}(\mathbf{k})]$$

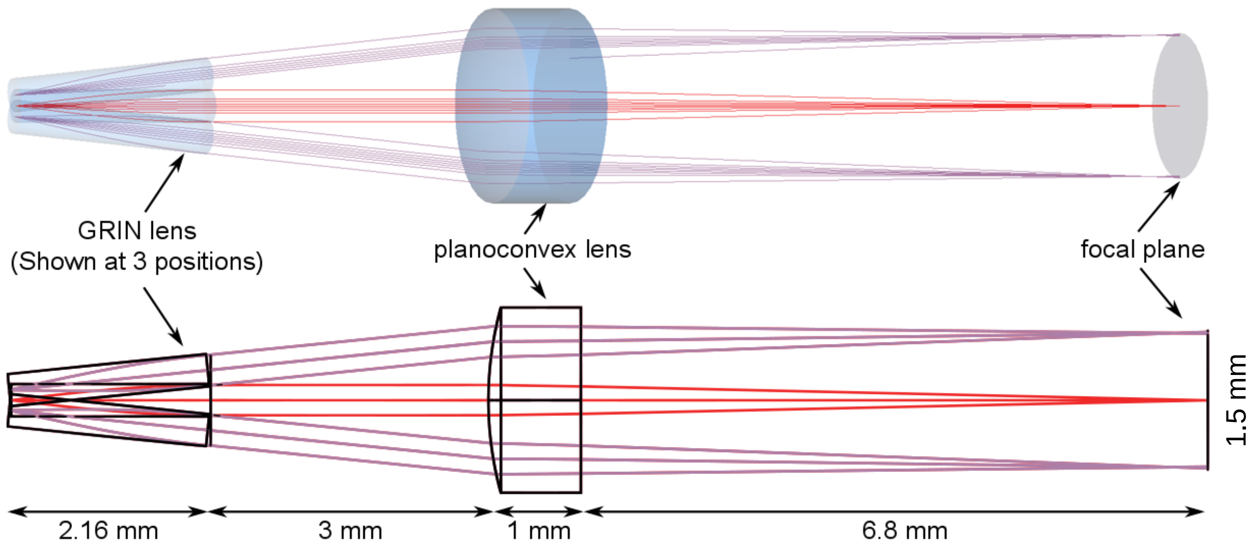


Optical performance

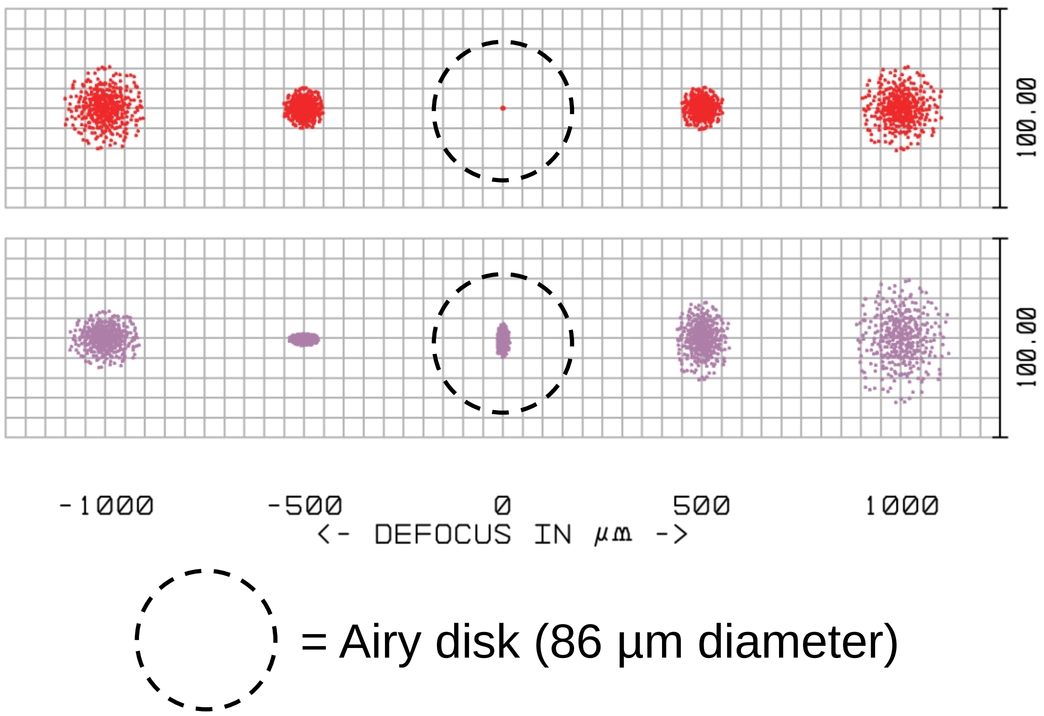
ZEMAX simulation: Geometrical raytracing



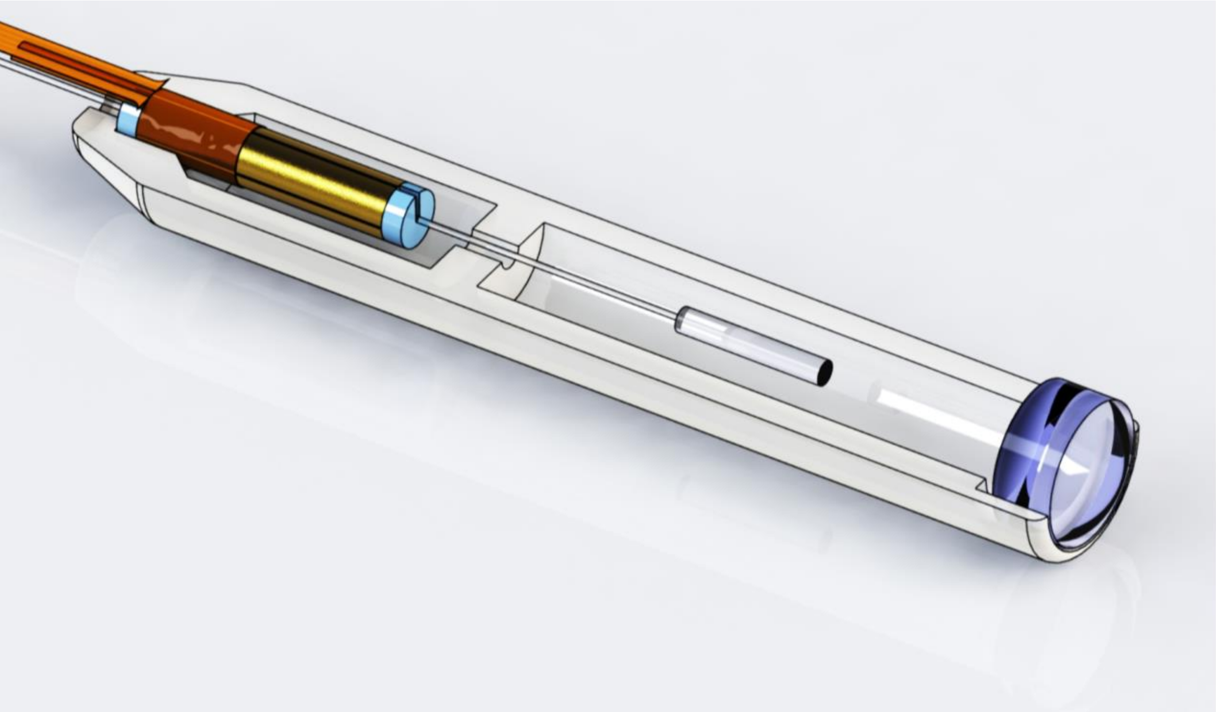
raytracing

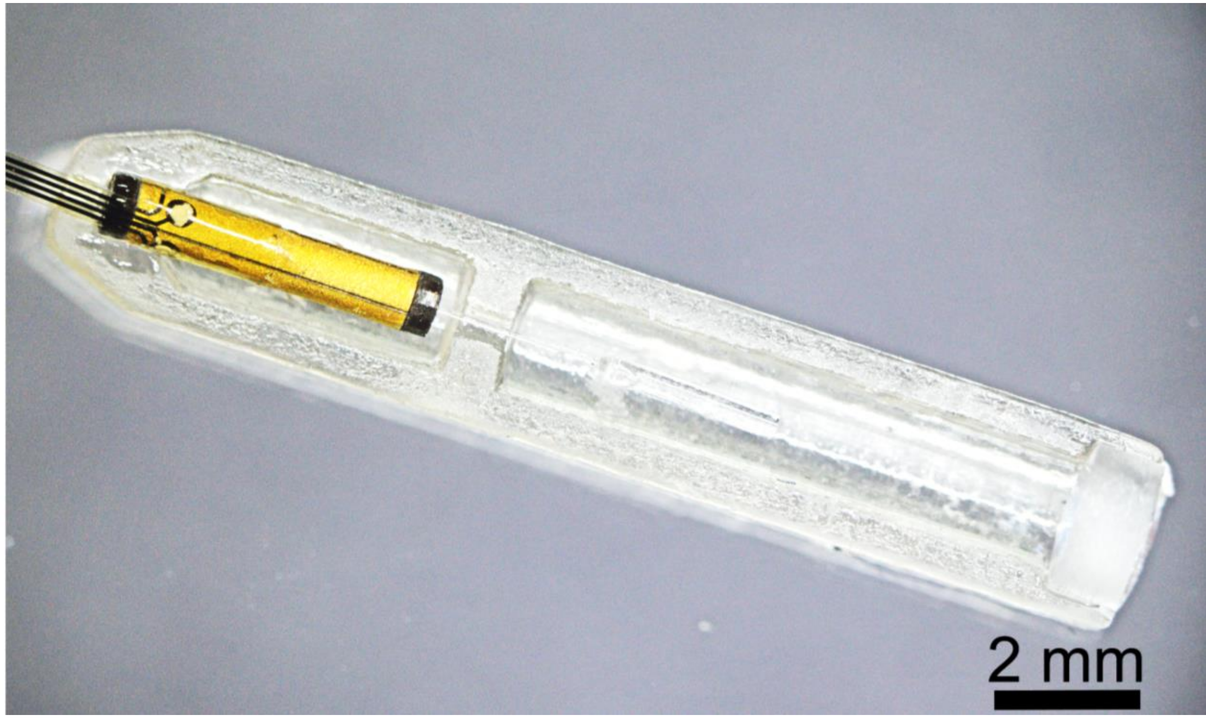


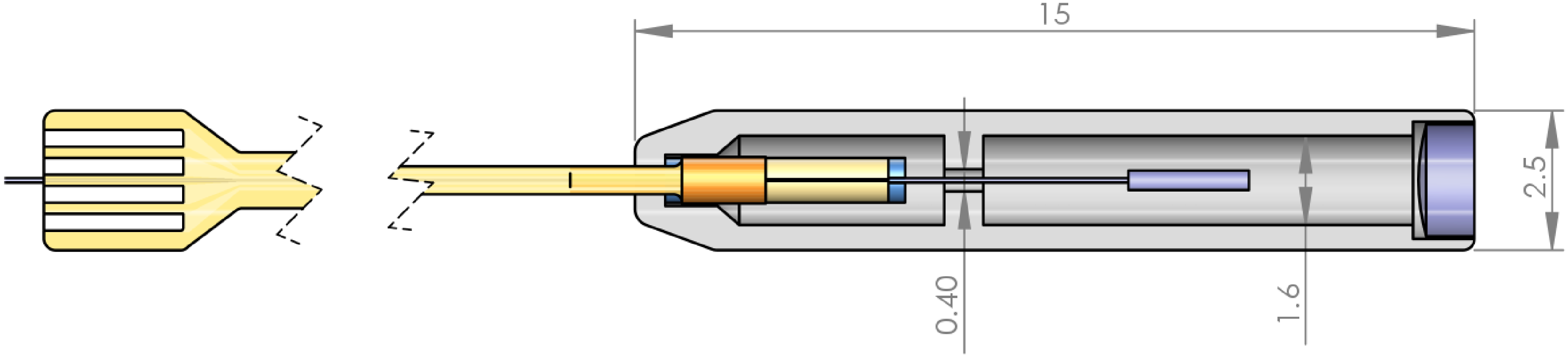
spot through focus



Implementation
Single modality probe





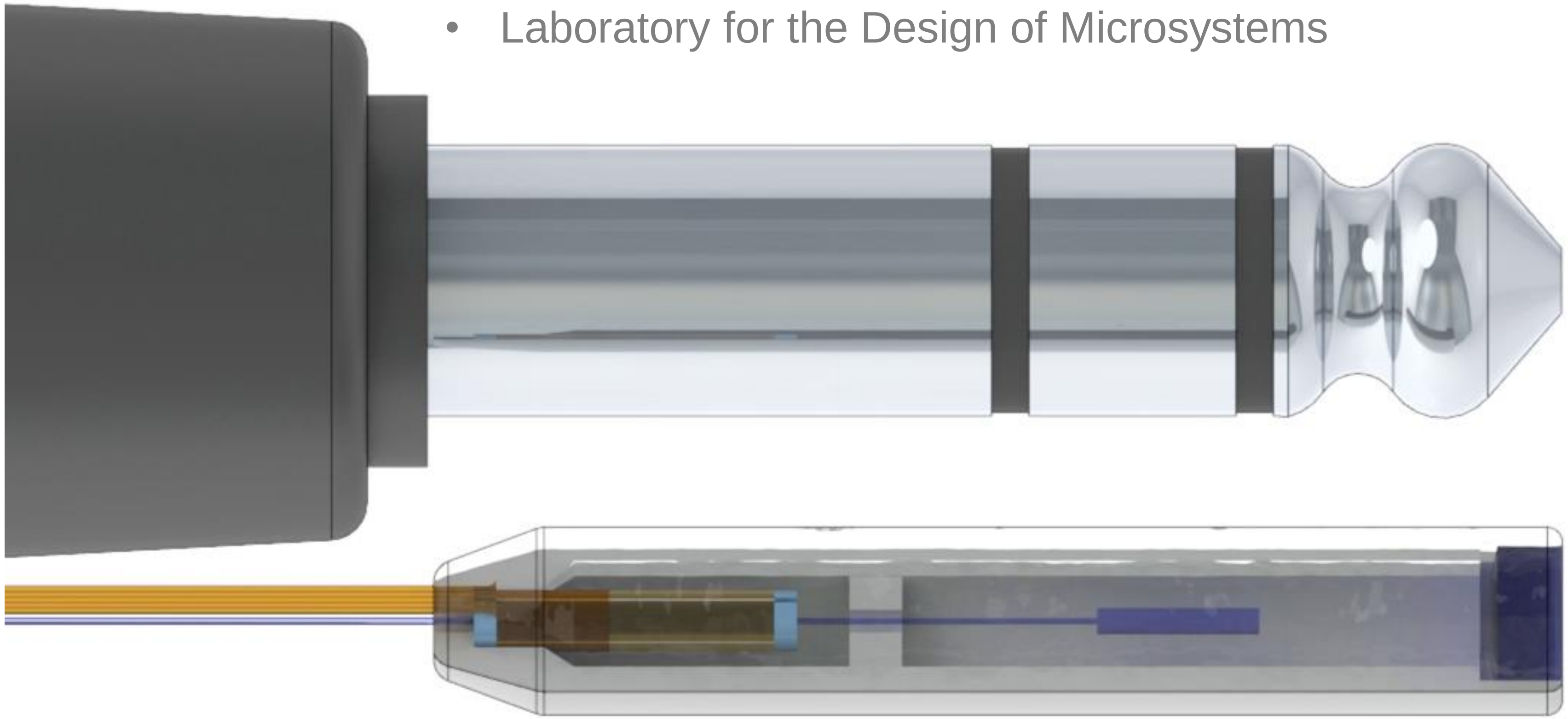


Implementation

Single modality probe: size

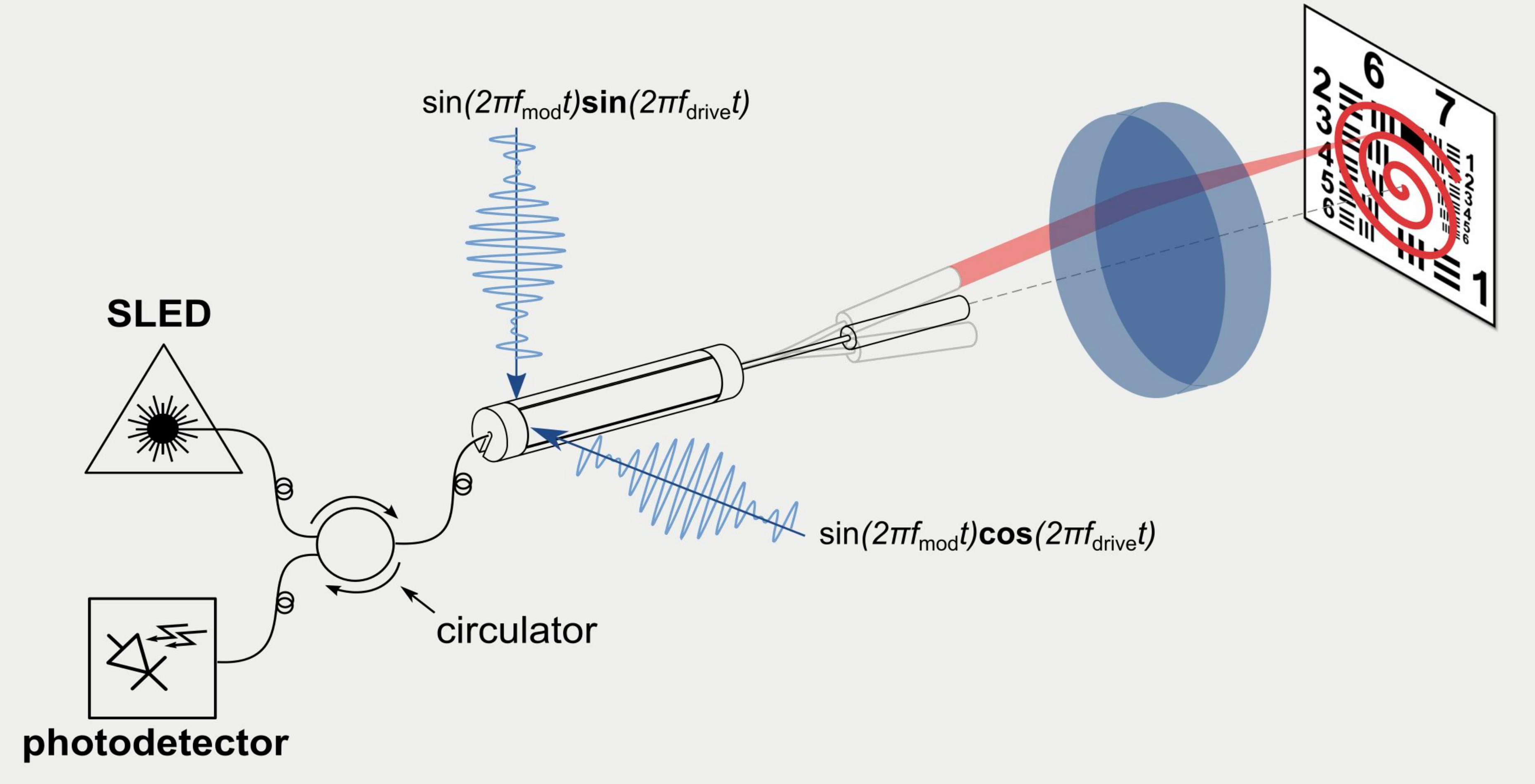
3D Printing by:

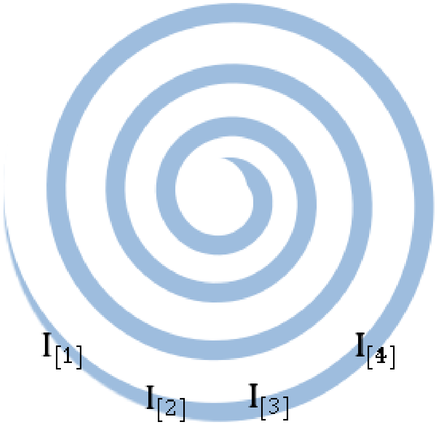
- Laboratory for Materials Processing (Bilal Khatri)
- Laboratory for the Design of Microsystems

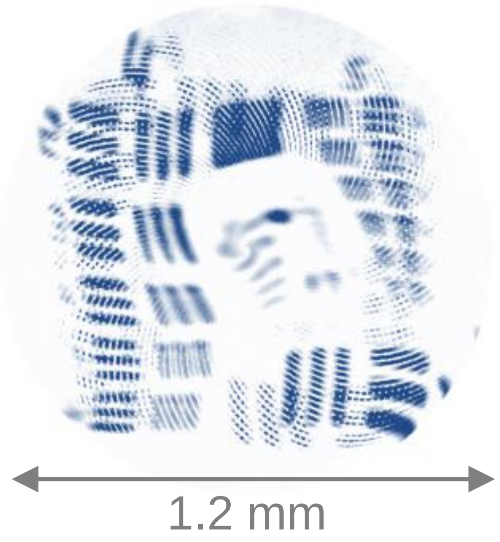


$15 \times 2.5 \times 2.5\ mm^3$

Experimental evaluation
Laser scanned imaging

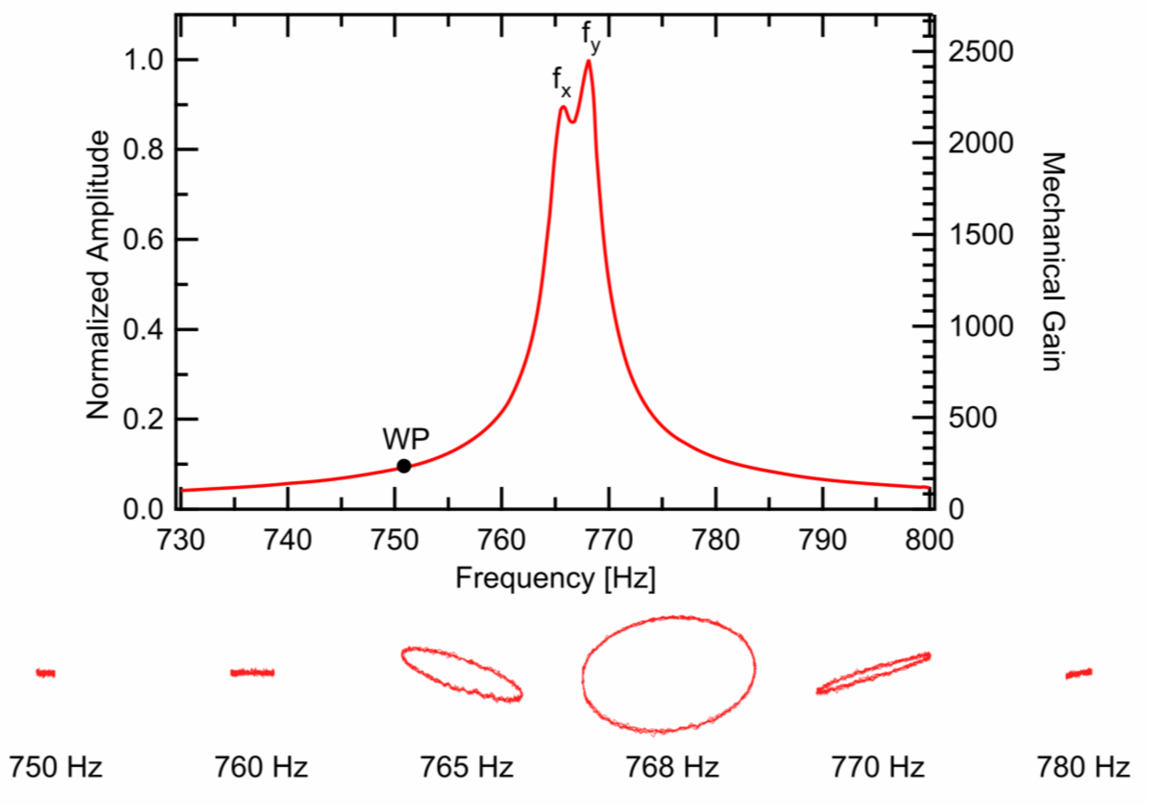




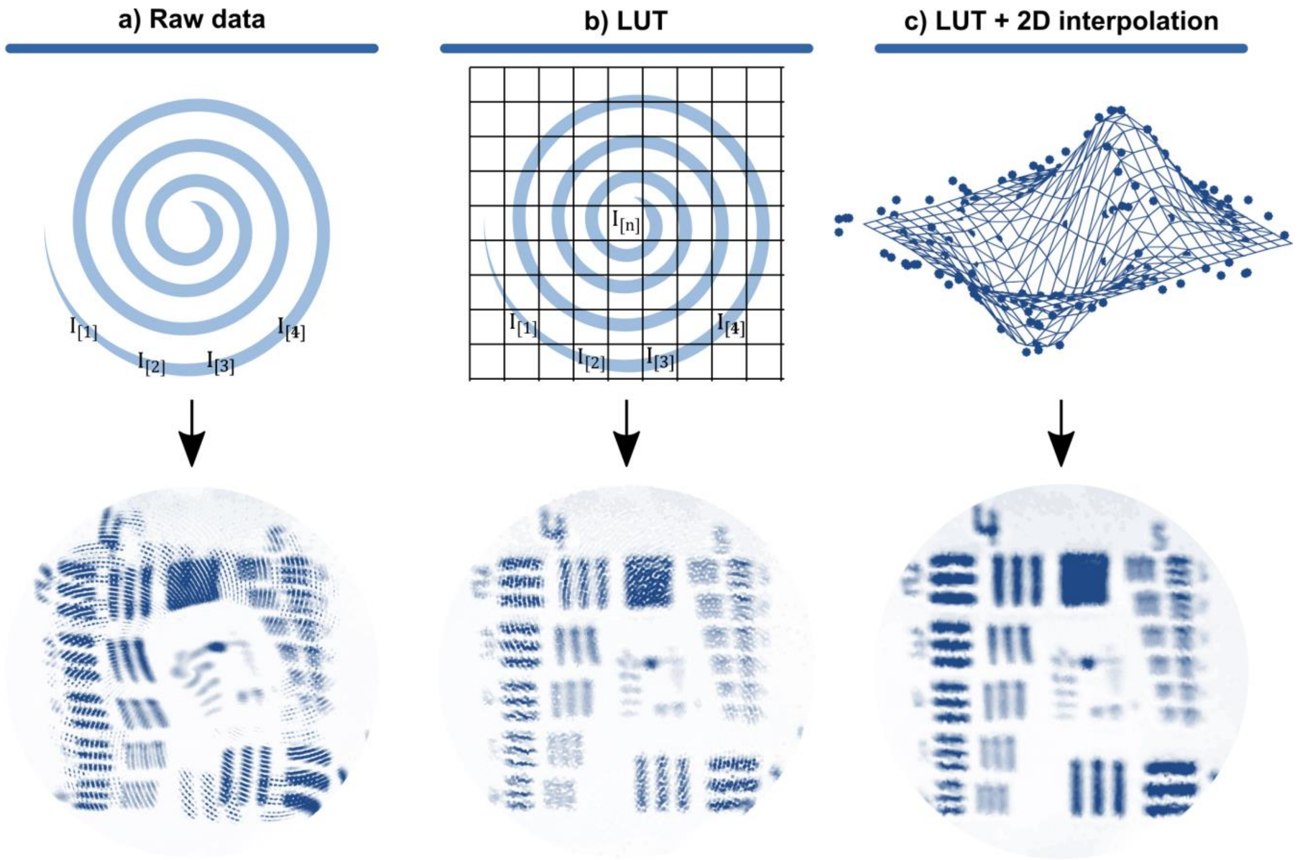


Experimental evaluation
Distortion correction

Whirl patterns



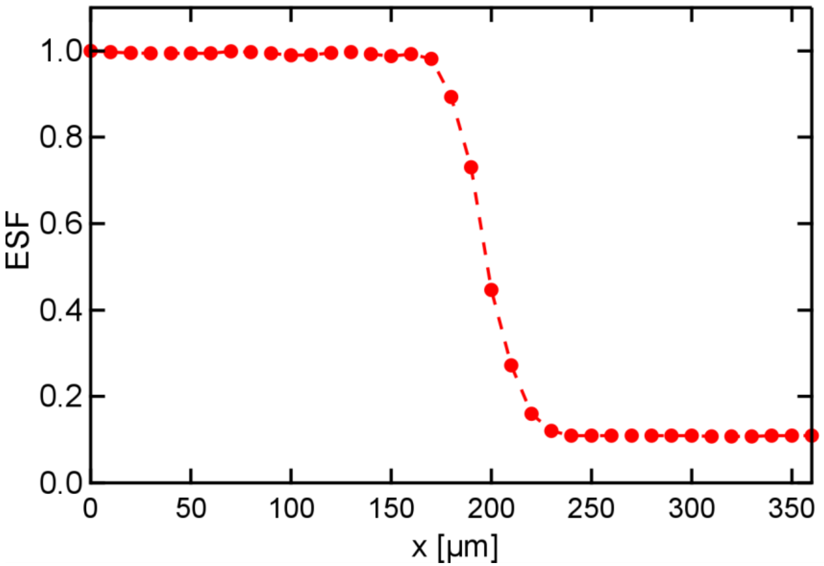
Distortion Correction



Experimental evaluation
Resolution and field of view

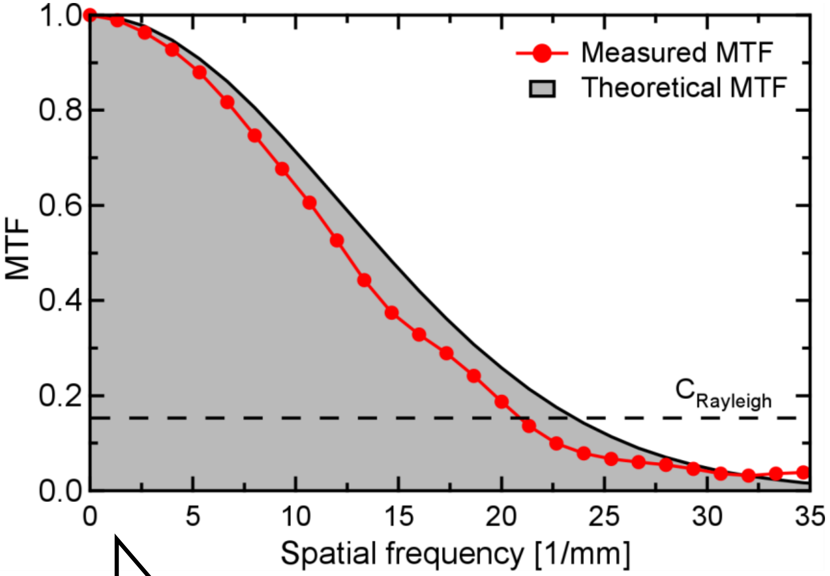
Lateral resolution: 48 µm

Depth of Field: 3.5 mm

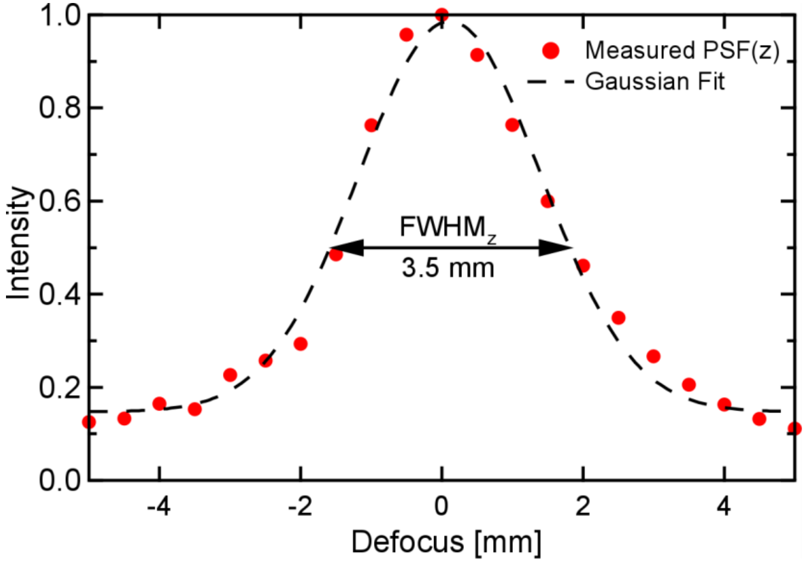


Edge Spread Function

$$\frac{d}{dx}, \mathcal{F}$$

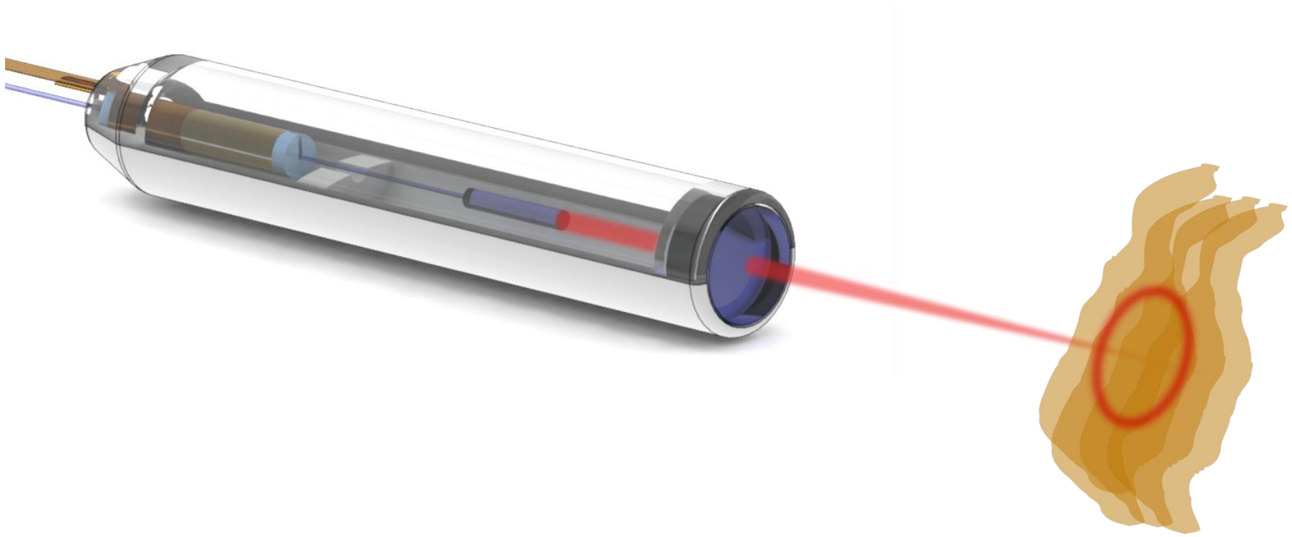


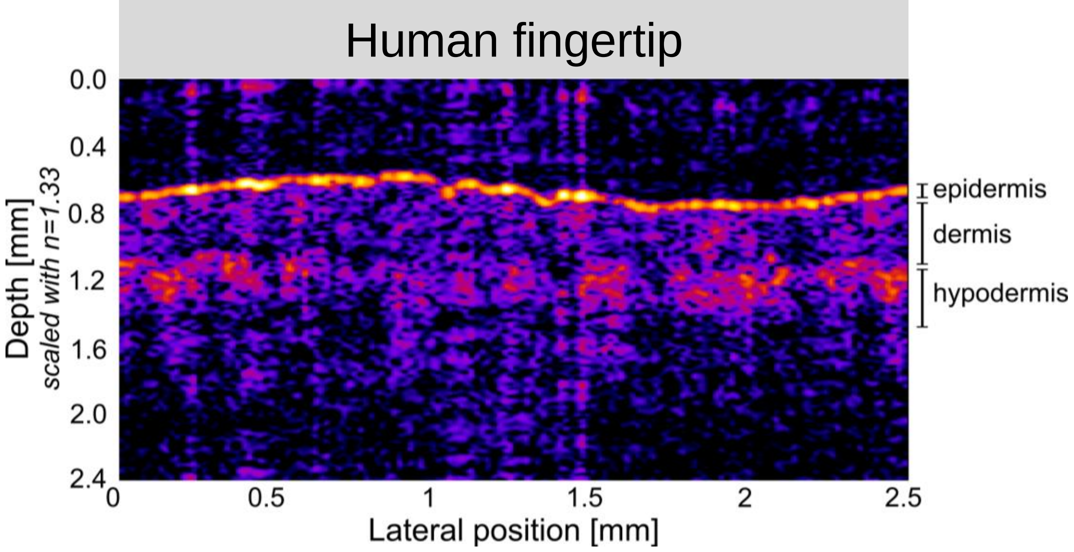
MTF

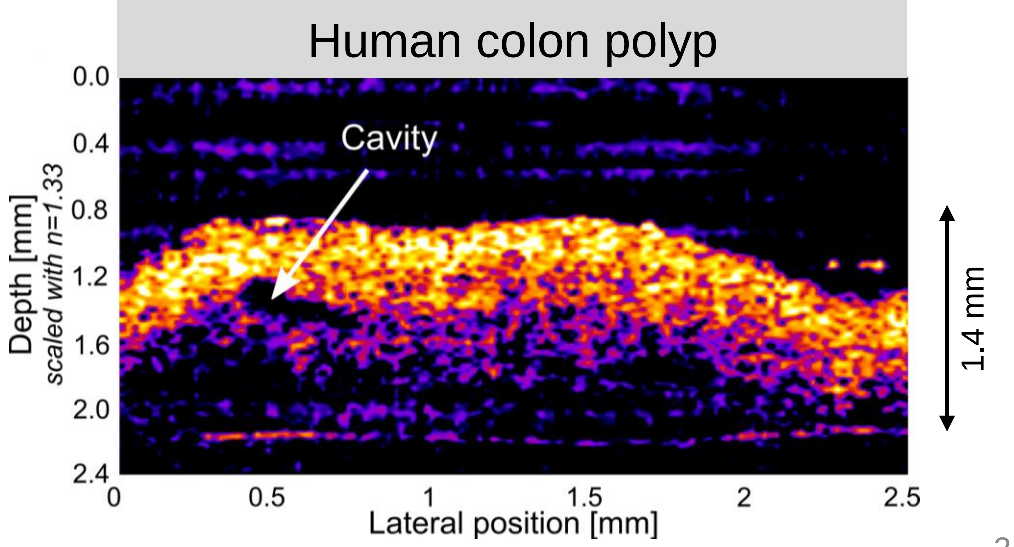


Translated mirror

Experimental evaluation
OCT cylindrical cross section imaging



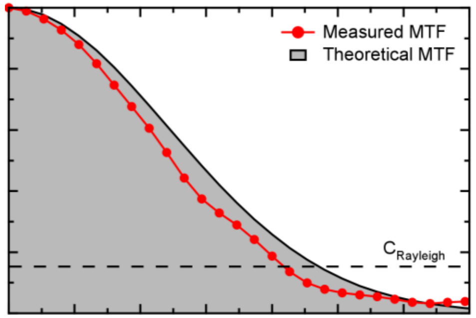


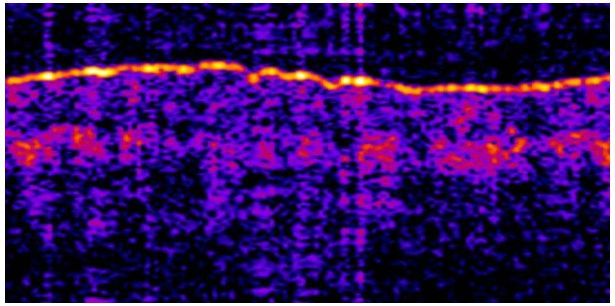


SS-OCT System from *Leitgeb Lab*

- λ_o 1340 nm
- $\Delta\lambda$ 37 nm
- Δz 27 µm

Conclusion and Outlook





OCT scanning engine

Amongst most compact in literature

Accurate optical analysis
Guideline for future fiber scanners

Reduction of imaging distortions

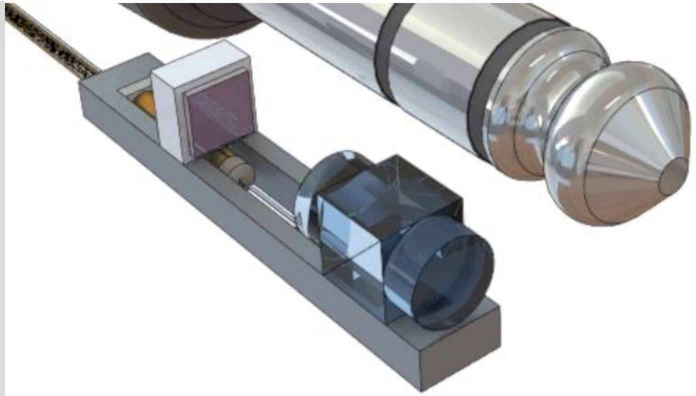
OCT imaging

Internal structures
High penetration depth

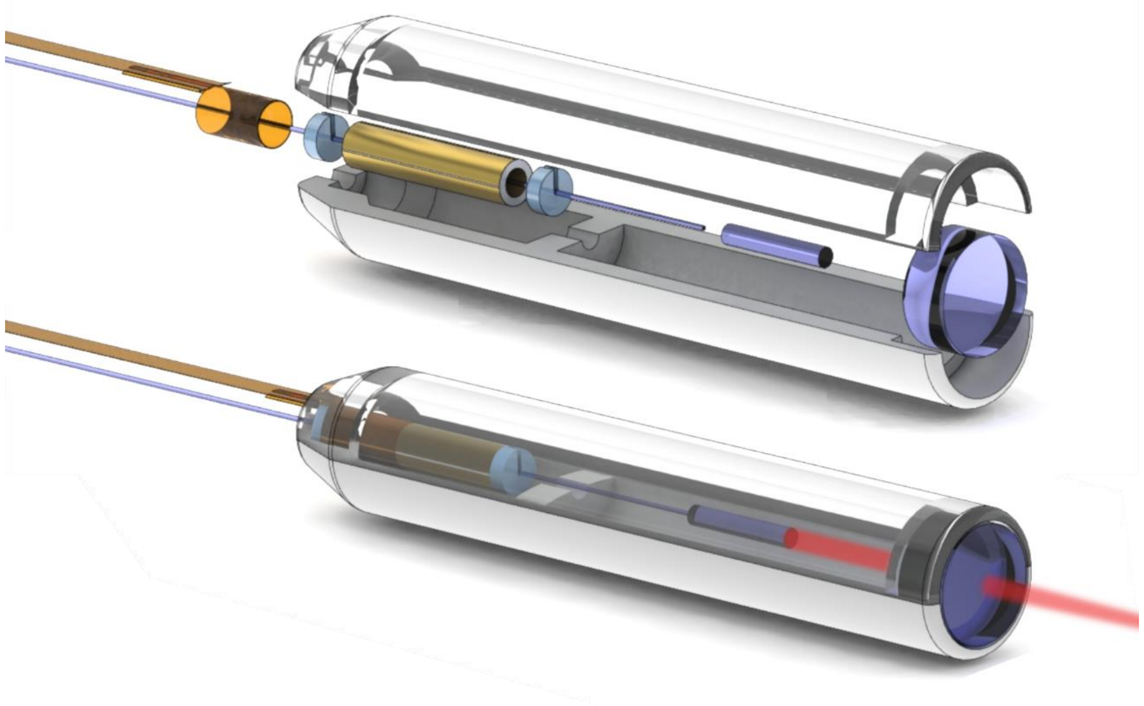
Outlook:

Integration in double modality scanner

Combination of other scanning + full-field modalities

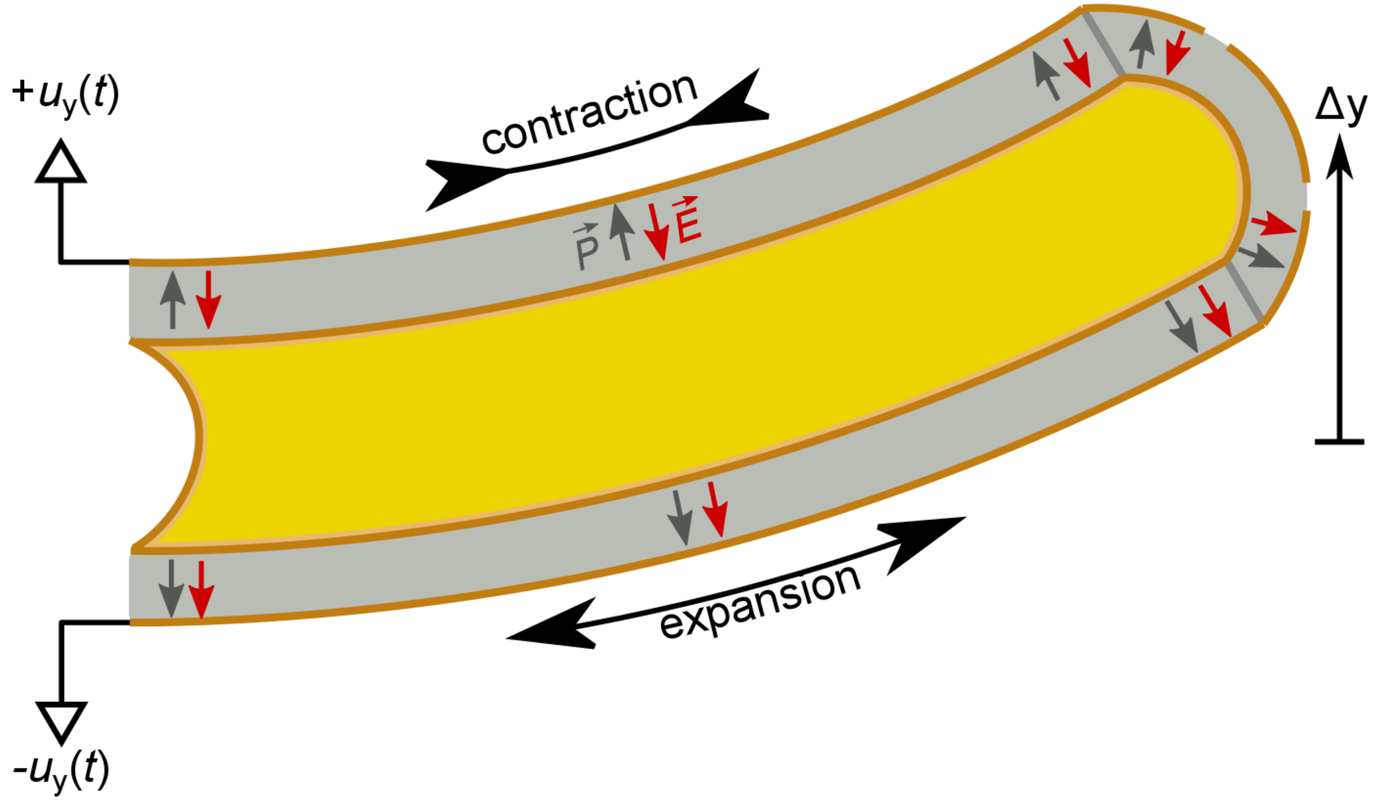


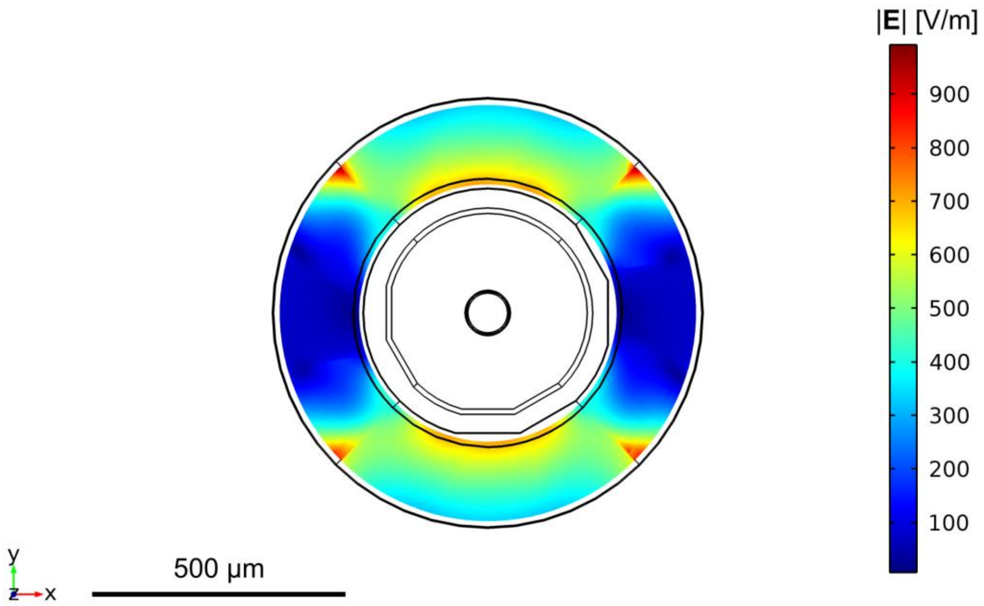
Compact OCT scanner for a bimodal endoscopic probe



Sergio Vilches

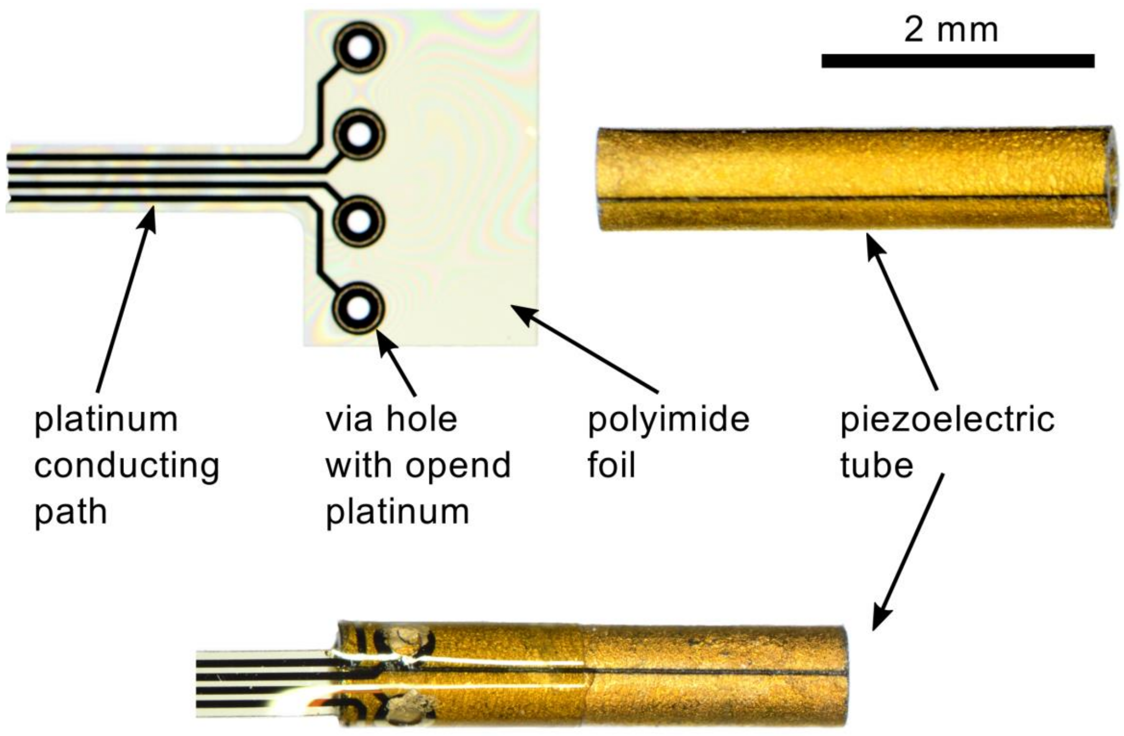
Piezoelectric tube actuator

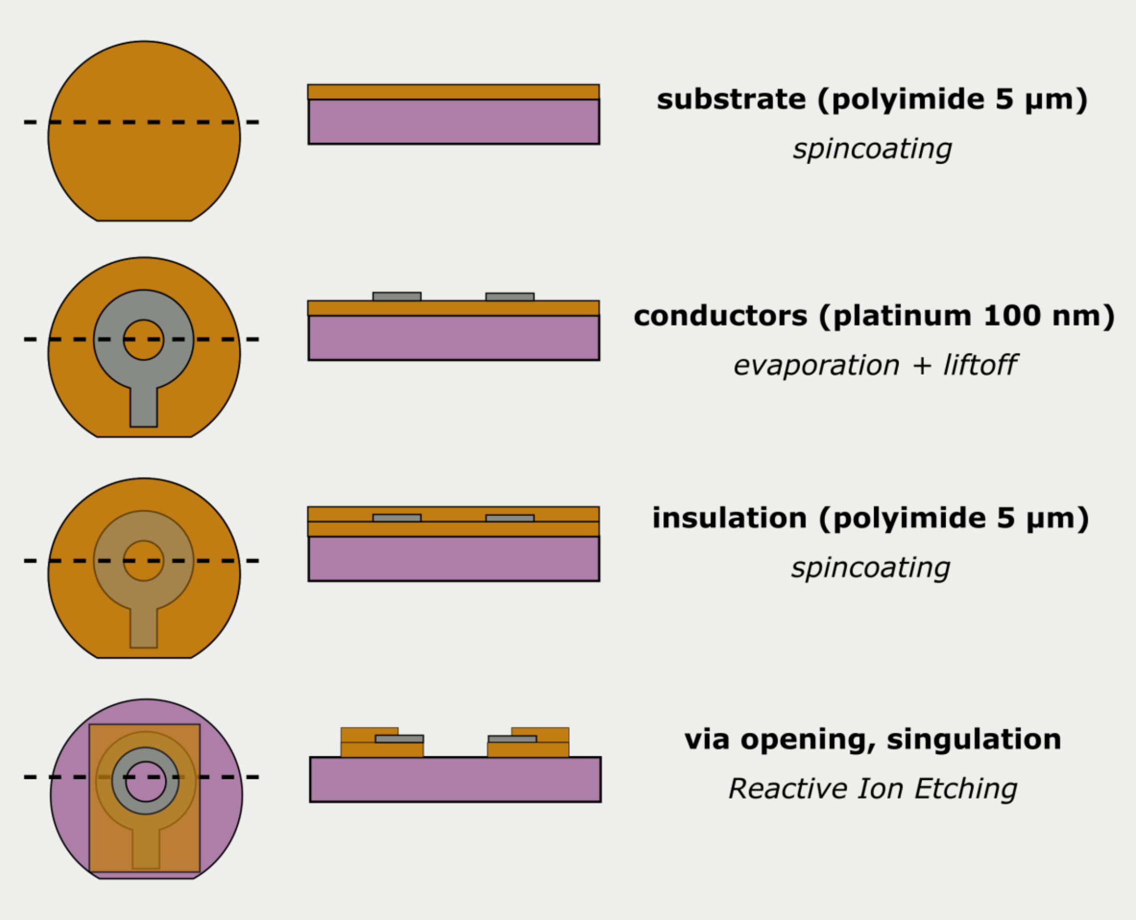




$$\Delta y = V\frac{2\sqrt{2}d_{31}L^2}{\pi D h}$$

Implementation
Electrical contacts





Confocal resolution

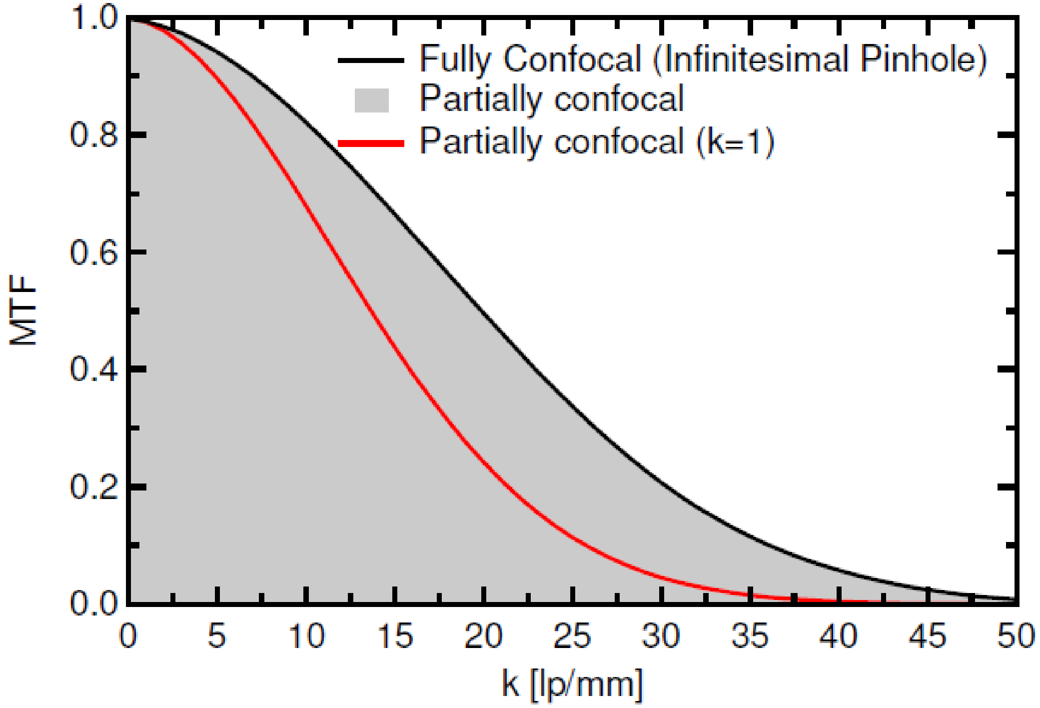
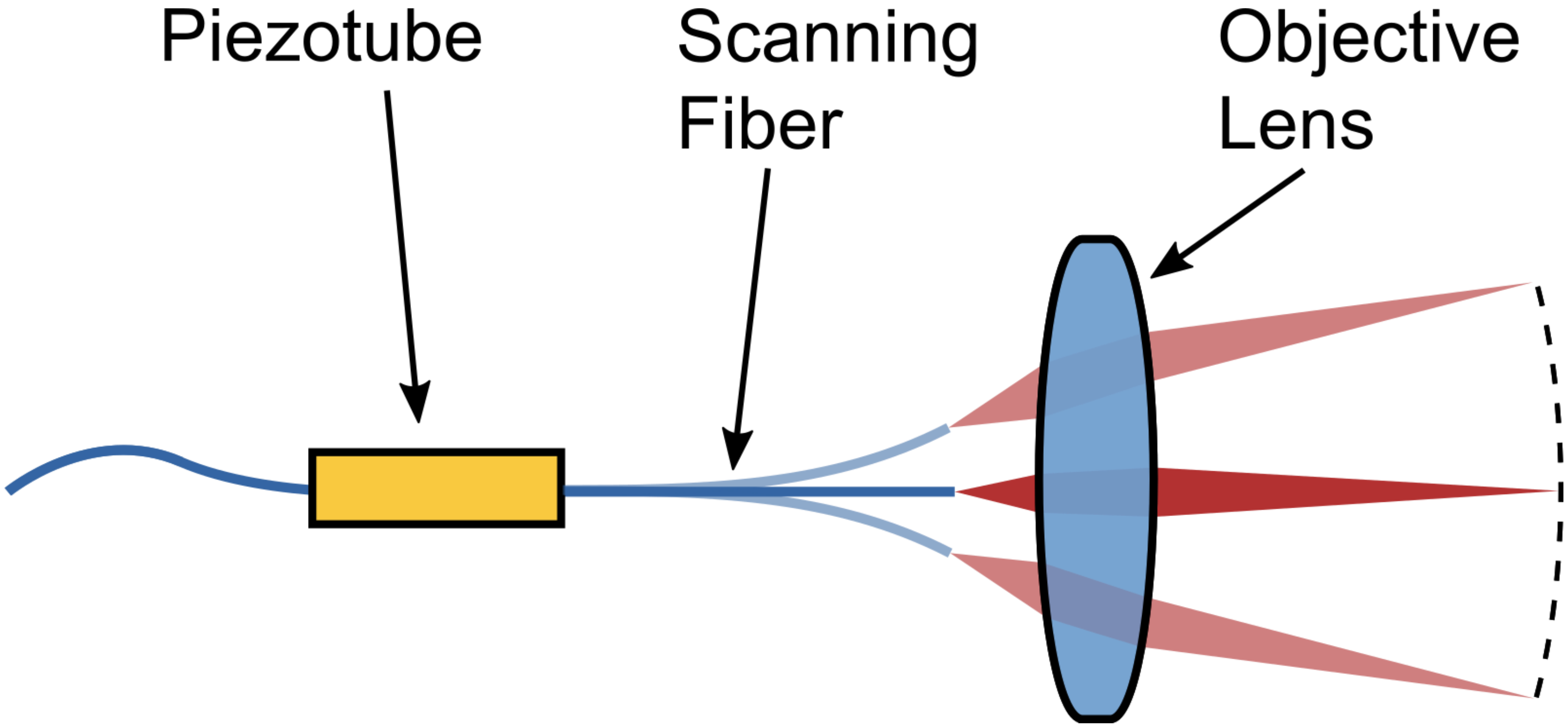
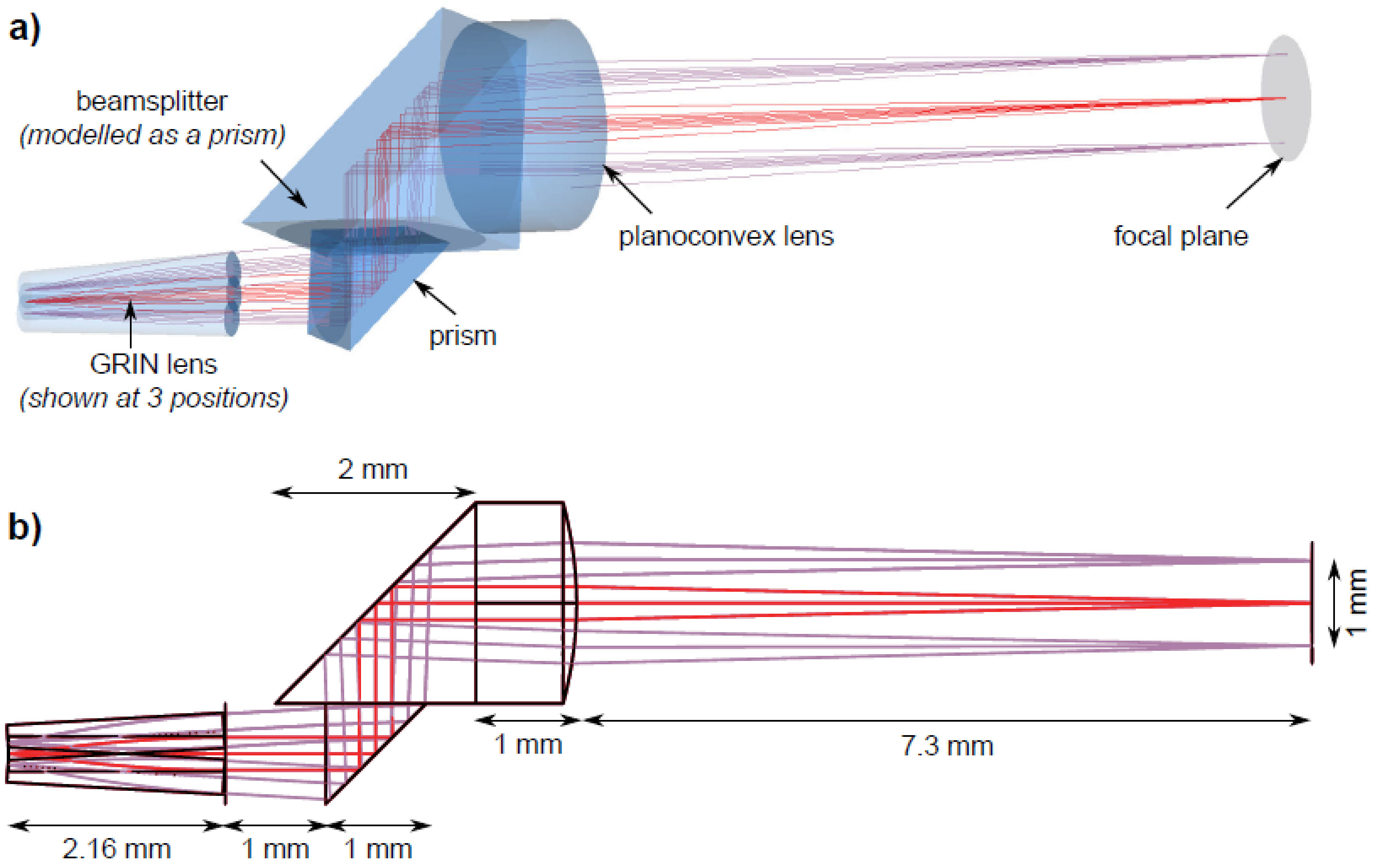


Figure 2.6: Comparison of the simulated MTF of a confocal system with infinitesimally small pinhole (black) and with a pinhole with a truncation factor $K = 1$ (red), as used in this work. The shaded area represents the possible MTFs locus for any truncation factor.

Non-telecentric scanning



ZEMAX raytracing of bimodal probe



Sources of optical backreflections inside the probe

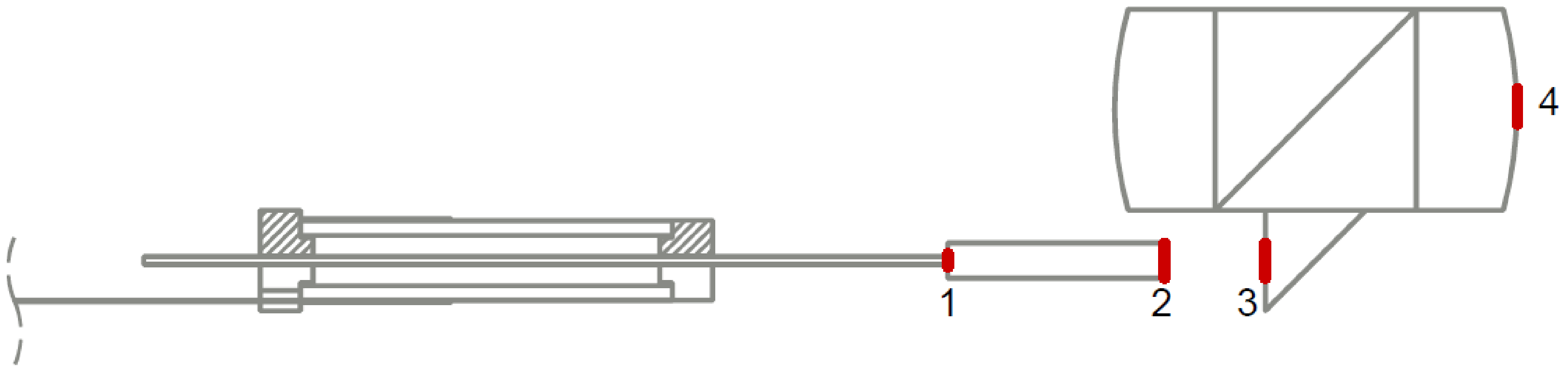
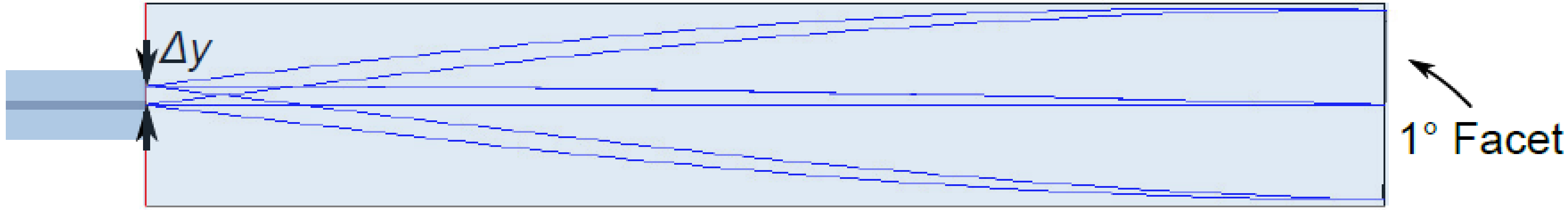


Figure 3.6: Schematic of the multimodal probe showing the main interfaces where backreflections can originate (red). 1) Fiber - GRIN. 2) GRIN - air gap. 3) Air gap - prism. 4) Objective - air.



Fiber-GRIN Bonding

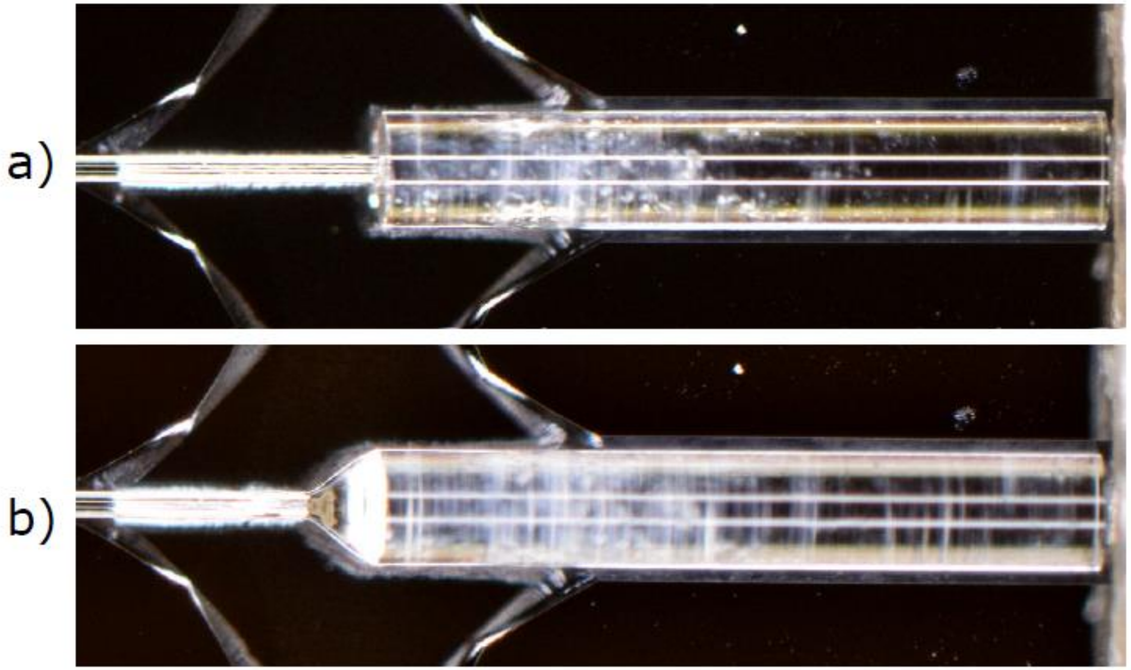
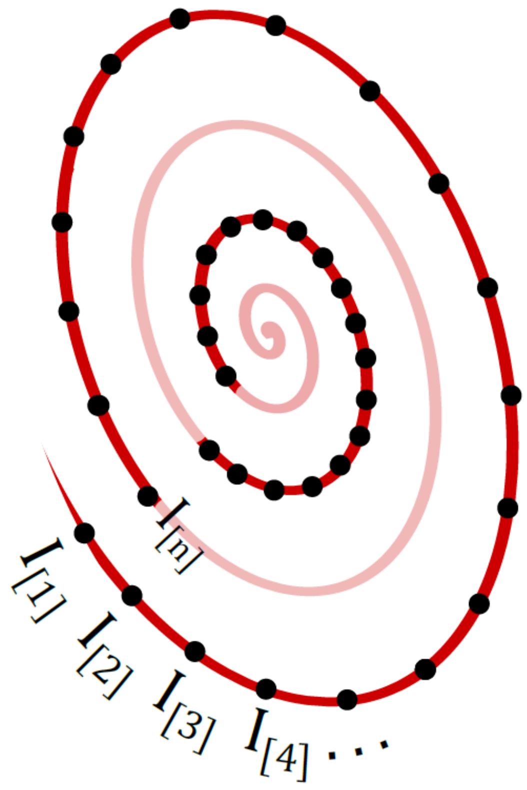


Figure 4.6: **a)** Photography of the tip of the fiber (left) and GRIN lens (right) seating in the alignment tool. **b)** Bonding with UV-curable adhesive.

Spiral scanning
Sampling

$$N_{\mathrm{rings}} = f_{\mathrm{drive}} / f_{\mathrm{mod}}$$

$$n = \frac{f_{\mathrm{s}}}{f_{\mathrm{drive}}}$$



Implementation
Performance

	Design Value	Probe 1	Probe 2	Probe 3
Cantilever Length [mm]	4.5	4.45	4.44	4.10
Field of View [mm]	1.3	1.1	1.2	1.2
Resonant Frequency [Hz]	762	744	765	842
Coupling Efficiency	-	0.53	0.61	0.58
Backreflectivity [%]	-	0.011	0.004	0.018

Effect of cantilever length in GRIN angle