Long working distance OCT-probes for robot-assisted eye surgery

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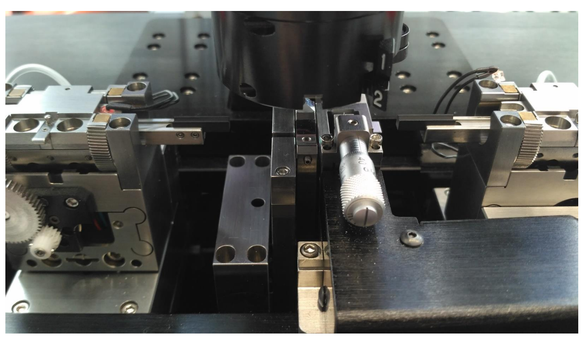
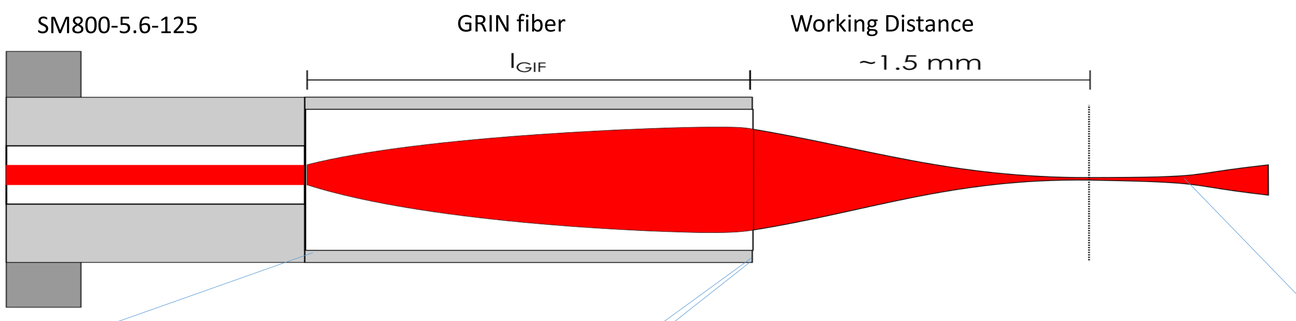
Robotic surgery has huge potential in ophthalmic surgery. Epiretinal membranes peeling may profit from robotic support. However, steering the surgical instrument without any information on the distance to the sensitive retina may be dangerous. Optical coherence tomography (OCT) can add a distance sensor to robot-assisted surgery, for improving safety and shortening surgery time. Challenges for an OCT probe are the tight space and the low signal of the thin membranes, which have to be removed.

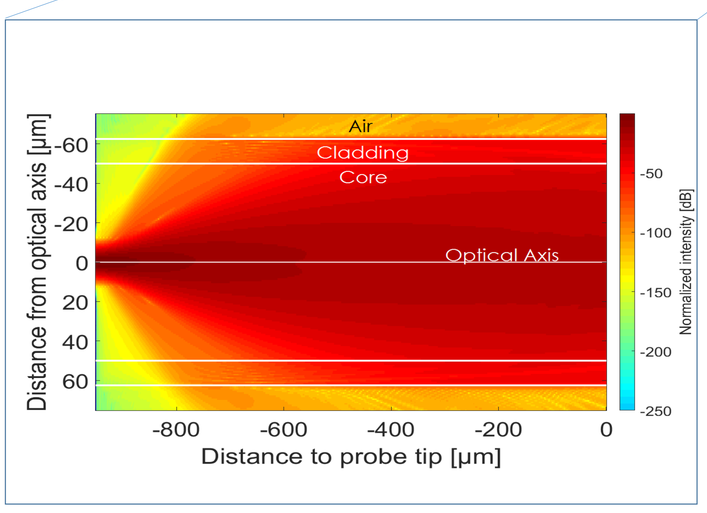
Probe design and simulation

- Fiber probe based on work of Sun et al[1].
- Optical performance was simulated with
  - Matrix formalism for Gaussian optics
  - angular spectrum based beam propagation[3]
- Fibers were built with a filament splicer with built-in cleaver (Vytran GPX-3800)
- Cleaving accuracy was 2 µm
- Working distance close to 2 mm

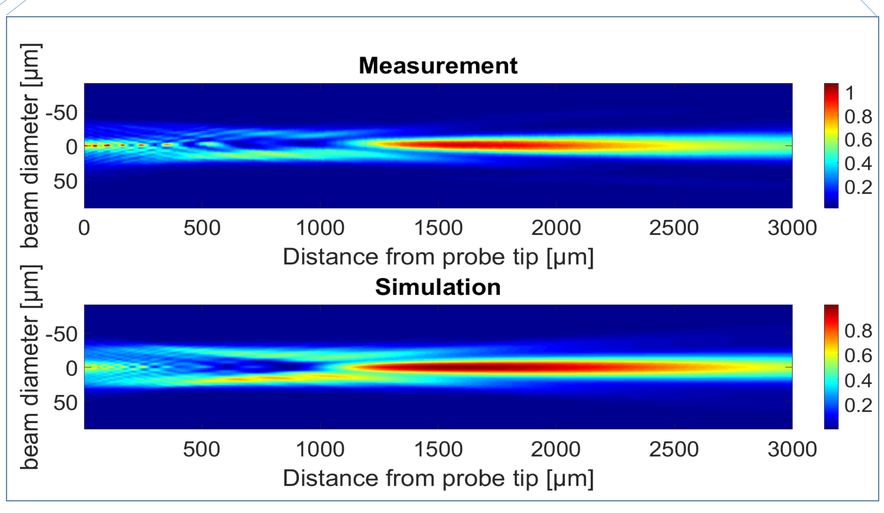


Workstation for cleaving and splicing (Vytran GPX-3800)





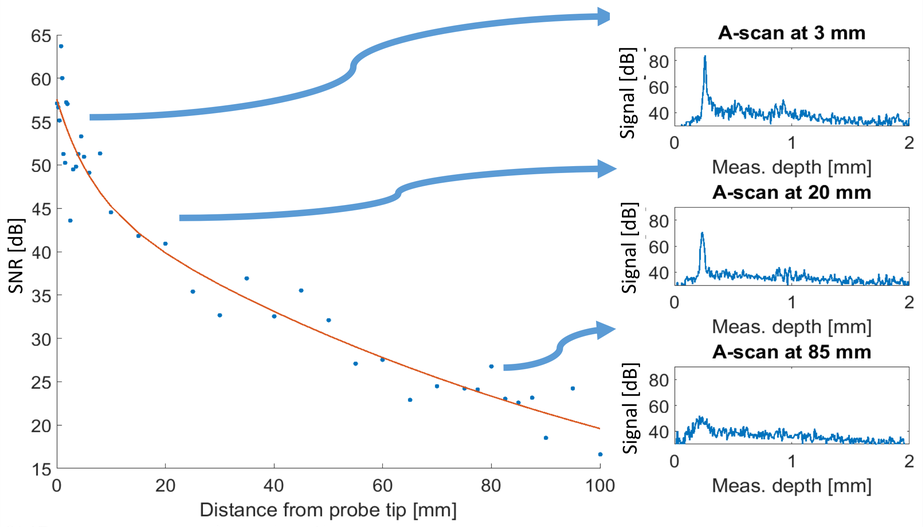
Beam path inside the GRIN fiber



Beam path in air

Measurement range

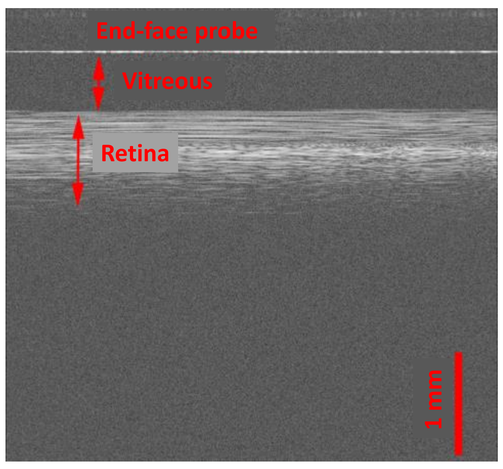
~4% Fresnel reflex still measurable in 10 cm from the probe at an SNR of 20dB



SNR over measuring depth

Ex-vivo imaging

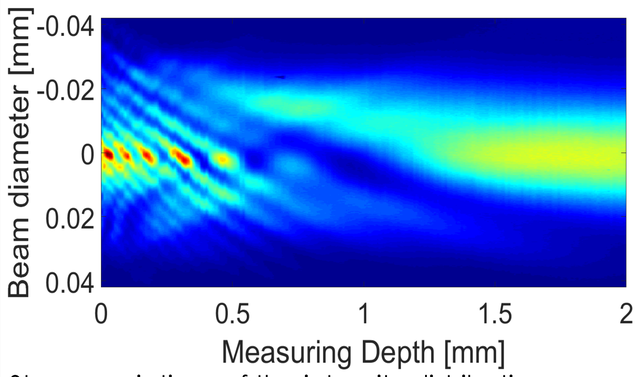
- First tests on enucleated porcine eyes
- End-face of the probe and the retina detectable



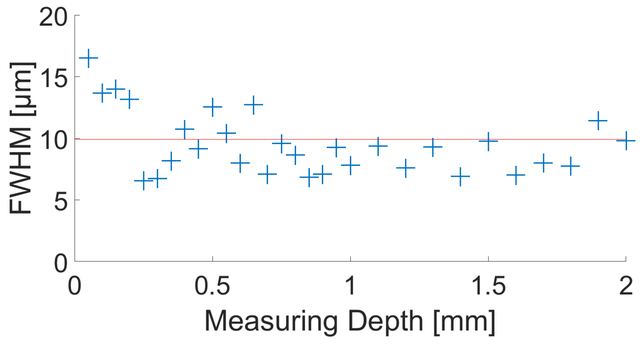
Interference pattern

Reflections at the jacket of GRIN lens create strong interferences between GRIN lens and focus. This has influence on

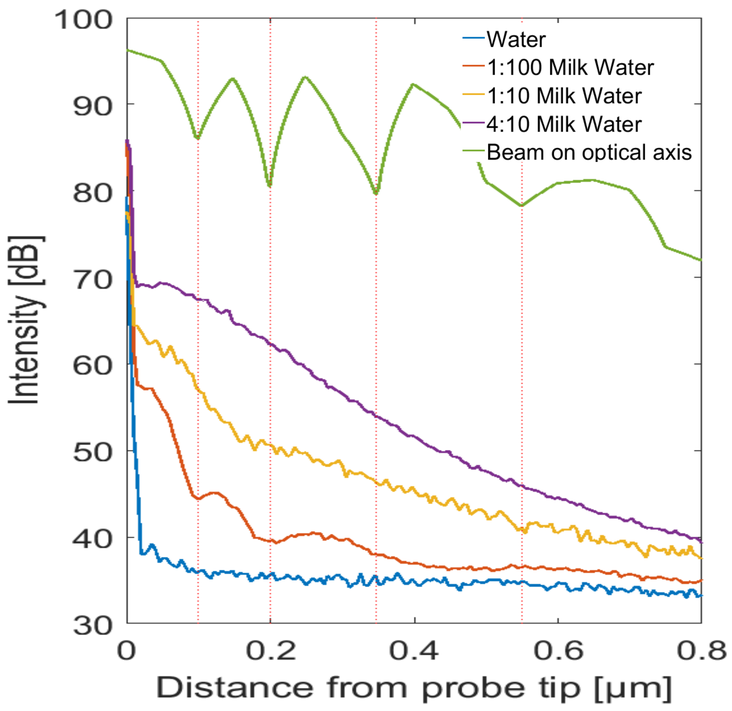
- Axial resolution: Rays with differing optical path lengths meet in one point of the focus and broaden the axial point spread function (PSF)
- Signal intensity: Intensity in the focus varies to interference; this effect is only visible at low scattering



Strong variations of the intensity distribution between GRIN lens and focus



Axial resolution at different distances from probe tip



Beam intensity on optical axis and OCT signal strength in differently scattering milk-water mixtures

Summary

We have developed and built an optical fiber probe with an outer diameter of 125 mm, which can be used as a distance sensor in ophthalmic instruments. Working distances up to 2.25 mm with spot sizes around 100 µm for standard SMF diameter probes were achieved. Reflecting surfaces were detected in more than 100 mm distance. The apparent interference pattern had only slight effects on resolution and signal, when analyzing biological samples. Other probe designs with smaller spot sizes and longer working distances are possible using multimode fibers and larger diameter GRIN lenses.

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References:
[1] Sun, X. et al. "Design of a long working distance graded index fiber lens with a low NA for fiber-optic probe in OCT application". In: Proceedings of SPIE 8938 (2014), pp. 1–7.
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[3] Lorenser, D. et al. "Accurate modeling and design of graded-index fiber probes for optical coherence tomography using the beam propagation method". In: IEEE Photonics Journal 5.2 (2013), pp. 3900015–3900015.