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Improvements in Optical Fiber Based Distance Sensor Fabrication for Ophthalmic Micro-Surgery Integration

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Abstract: When microsurgery tools are employed in invasive intraocular procedures, the confined space inside the eye represents a patient safety challenge. We propose an integrated fiber sensor, which measures micrometer resolution spacing between tool and tissue.

1. Introduction

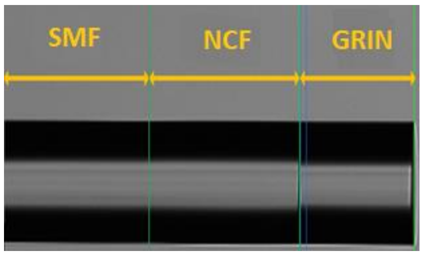
Vitreoretinal surgery is a challenging endeavor, requiring skilled and highly trained surgeons to deal with the constraints imposed by the geometry of the human eye, as well as the physiologic tremor and lack of positional stability [1]. In recent years, several robotic systems have been proposed to enhance vitreoretinal surgery [2]. The safety and functionality of these robotic systems could potentially be enhanced by integrating a thin fiber-optic distance sensor into the robotic tool. This would relay its position relative to delicate tissue such as the retina, in real time and with an accuracy on the order of micrometers.

Early distance-sensor probes based on low-coherence interferometry (the principle underpinning optical coherence tomography) were fabricated using bare single-mode fiber (SMF), however the absence of focusing optics results in a maximum working distance of only a few hundred micrometers [2]. If small lengths of non-core fiber (NCF) and gradient index (GRIN) fiber are fused to the tip of SMF probe, the working distance can be improved. Interferometry also requires a reference optical signal, which can be obtained by a reflection from the end of the fiber (known as a common path interferometer, CPI). However the magnitude of the reflection depends on the physical properties of the medium the probe is placed into [3]. The aim of this study was to explore optimized probe structures, by fusing GRIN and NCF fiber to the SMF (Fig. 1 left) to control the output beam parameters, as well as applying a thin Au (gold) coating to control the reflectivity of the fiber tip to optimize the interference signal.

2. Methods

The distance sensor fiber probes were fabricated using a Vytran GPX-300 glass processing system, and comprise Hi1060 SMF, NCF (Thorlabs, FG125LA) and multimode GRIN fiber (Thorlabs, GIF-650), as represented in Fig. 1 (left). The NCF section acts as a beam expander, while the GRIN fiber length focuses the diverging beam to a point at some fixed working distance. The sub-millimeter lengths of NCF and GRIN fiber determine the optical beam waist and the working distance of the sensor. Since the power reflectivity estimated by the Fresnel equation for a fiber probe immersed in water is about 0.36%, the amount of returned power forming the reference signal for the common-path low coherence interferometer is too small for efficient operation, resulting in a weak signal compared with the same probe operating in air (where the reflectivity is 4%). A thin Au coating applied through sputtering on the tip of the probe increases the reflectivity of the fiber end, and hence the reference power level, and makes this independent of the refractive index of the medium that the probe is placed into. The Au layer must be kept sufficiently thin to maintain acceptable optical power transmission to the sample. The Au coating was found to exhibit good adherence to glass in fluid environments, and is removed only if significant mechanical pressure is applied.

The distance sensor was integrated into a low-coherence common-path interferometer (CPI). The light source is an Axsun swept source centered at 1060 nm with coherence-limited axial resolution of 8 μm in air. Due to its fast sweep rate (100 kHz), it is tolerant to interference pattern wash-out due to motion. Light is sent to and from the probe using a fiber coupler, with returning light directed to a balanced photodetector. Balanced detection is also employed in order to reduce noise, and it is achieved via a small amount of power diverted from the source using a second fiber coupler, controlled using a variable optical attenuator. The spectral interference patterns formed from the interference between the light scattered from an object, such as the retina, with the reference reflection will exhibit modulations at different frequencies. These correspond to layers of different reflectivity, located at different depths in the sample. The amplitude of the modulation is proportional to $\sqrt{R}$, where R is the reflectivity of the sample, which allows the spectra to be transformed, via a Fast Fourier Transform (FFT), into an A-scan (reflectivity with depth profile) [4], in which individual layers of the object can be seen. Acquisition software was developed in LabVIEW to determine the distance to the top layer of the object and display this to the user in real time. The distance measured to the closest layer is displayed through a visual bar and also via a numerical value, to a precision of 10 µm. Sonification of the distance was used to aid the user in manipulating the sensing tool without the need to look at the display at the same time, potentially providing an additional safety feature.



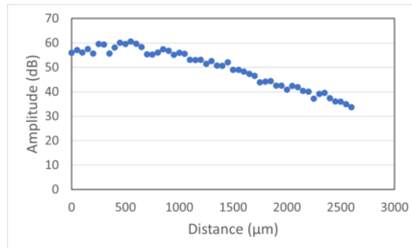


Fig. 1.Distance sensor probe, showing the three sections of fiber after fusing (left); A-scan amplitude values measured at every 50 µm depth steps, in a water medium (right)

3. Results and Discussion

Following a series of trial fabrications, a probe was developed which generated a spot size of 42.9 µm at a working distance of 630 µm. The Au gold coating thickness was controlled by sputtering for different periods of time. If all of the light reflected from the fiber tip was coupled back into the fiber, then the maximum interference amplitude for a 100% reflective sample would require a reflectivity of 33%. In practice, a much lower reflectivity is required, both to optimize signal to noise ratio (SNR) for realistic samples and to ensure sufficient light reaches the sample, given that only a small fraction of the light attenuated by the gold coating is actually collected by the fiber. Following a series of reflectivity and power transmission measurements of identical probes sputtered with a series of various Au thicknesses, the best practical results in terms of SNR were achieved from a probe sputtered for 5 s, giving a reflectivity of 19.4%, while maintaining a power of 0.25 mW to the sample. The amplitude values measured for A-scans recorded at various distances from a mirror, in a water medium, are displayed in Fig. 1 (right).

The 5s sputtered probe was also compared directly with the un-sputtered version. SNR measurements of the signal from a multilayered target (infrared viewing card) demonstrated that the sputtered probe is effective in both air and water; while the two probes function similarly in air, the un-sputtered probe exhibits a significant drop in performance in water (SNR dropping from 40.8 dB in air to 22.2 dB in water), whilst the sputtered probe does not. The sensor probes were effective so far in distance measurements performed on non-organic multi layered samples, at a maximum range of 2 mm.

In conclusion, the distance sensor probe demonstrated good performance in water and hence suitability to ultimately be integrated into a robotic surgical tool. In future work, its potential to enhance control and improve feedback to the surgeon when performing ophthalmic surgery will be explored.

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