125 Micrometer Fiber Optic Sensors for Tissue Proximity Detection and B-Scan Acquisition

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Abstract: Microsurgery tools deployed in invasive procedures within confined spaces, like the intraocular region, pose patient safety challenges. We propose an integrated fiber based sensing device, with micrometer resolution proximity detection and lateral scanning imaging capabilities.

1. Introduction

Microsurgery procedures within the confined space of the vitreoretinal region of the eye requires a great deal of surgical experience in dealing with the geometrical constraints, the physiologic tremor and insufficient positional accuracy and stability [1]. Precise proximity detection of the tool tip relative to the tissue is therefore a necessity for safety and surgical guidance, which will reduce the risk of accidental damage to the tissue. Recently, systems employing robotic technologies have been proposed for vitreoretinal surgery [2], however the safety and accuracy of such systems could further benefit from the integration of an optical proximity sensor with the surgical tool employed, which is able to provide real time, micrometric resolution measurement of the distance between the tool tip and delicate tissue surfaces, like the retina. Small diameter (125 µm) fiber optics represent the most viable solution in building such sensor probes, due to their wide commercial availability and their easy integration with eye safe low coherence light sources and characterization with well-established low coherence interferometer (LCI) systems (the same technology underpinning optical coherence tomography (OCT)).

If solely a cleaved end single-mode fiber (SMF) is utilized as distance-sensor probe, the high divergence of the output beam limits the maximum working distance to just a few hundred micrometers. Therefore, in this paper, we demonstrate that if specific lengths of non-core fiber (NCF) and multimode gradient index (GRIN) fiber, respectively, are fused to the SMF, the working distance is greatly improved, as the output beam is no longer divergent. Instead, it is undergoing a two-step shaping operation: it is first expanded within the NCF and then focused by the GRIN, which acts as a lens. Part of the light reaching the tissue is backscattered, collected through the same probe, and directed to the balanced photodetector of a LCI processing.

2. Manufacturing and characterization method

The sensor probes are fabricated entirely from fiber glass, using a Vytran GPX-3400 splicer. They comprise a 2–3-meter Hi1060 SMF pigtail, while the sensing tip is 125 µm in diameter and less than 1 mm in length, comprising approximatively 350 µm NCF (Thorlabs, FG125LA), and an even smaller 70-80 µm section of GRIN fiber lens (Thorlabs, GIF-625). The optical transmission through the sensor is modelled in Zemax and the fiber section lengths are chosen towards achieving the best trade off between spot size and collection efficiency. Additionally, a very thin and mechanically resilient gold layer coating deposited through 5 seconds of sputtering on the probe tip increases the reflectivity of the distal end and makes the reflected power independent of the medium the probe is placed, as the risk of index (of refraction) matching is eliminated. A microscope image of sensor probe is depicted in Fig. 1. The sensor information is processed through an LCI system, illuminated by a broadband, 100 kHz swept 1060 nm Axsun tunable laser, synchronized with the balanced photodetector. In the LCI, there is interference arising between the photodetected light beams backscattered by the multiple layers of the tissue and the light back-reflected from the end face of the probe, thus generating a channeled spectra. Through post processing aimed at reducing non-linearities and a Fast Fourier Transform (FFT) algorithm, A-scans are obtained, with peaks corresponding to tissue layers at various depths in the sample. The higher the amplitude of the peaks in the A-scan, the higher the reflectivity of the respective layer.

Sensor measurement display software was developed in LabVIEW to quantify and illustrate visually the distance to the top layer of the object (tissue) in real time, with a precision of 10 µm. Additionally, a pitch increasing sonification function was implemented, to alert the user when they are unable to visually check the values displayed.

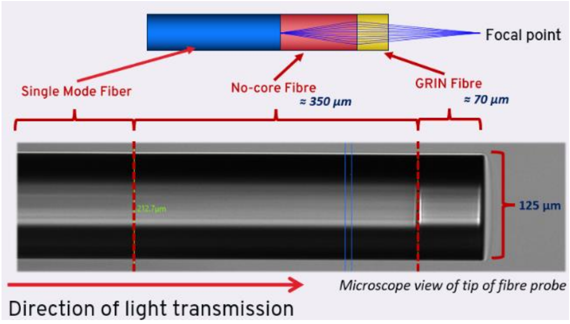

Fig. 1. Zemax modelling and microscope image of a sensor probe

3. Results and Discussion

Following manufacturing optimizations, sensor probes generated a focused spot size of approximatively 10 µm, at working distances measured in air ranging from 630 µm to 700 µm. It should be noted, however, that the effective range of the sensor is actually much higher, of more than 2 mm, as the working distance represents the distance from the detected layer at which maximum signal amplitude is recorded. A 6 dB drop in amplitude was consistently measured at a distance of approximately 1.5 mm from the sample.

For validation purposes, to demonstrate quality of the signal, the probe was manually translated perpendicular to test samples including a fluorescent test target (illustrated in Fig. 2). OCT B-scans (cross section images) were assembled from the individual axial profiles. The results demonstrate that the surface of samples such as the retina is clearly detectable. Further work requires a continuous refinement in the fiber based sensor design to increase its proximity detection range and to expand its capabilities for biomedical imaging applications within confined tissue spaces, while used in conjunction with microsurgery tools.

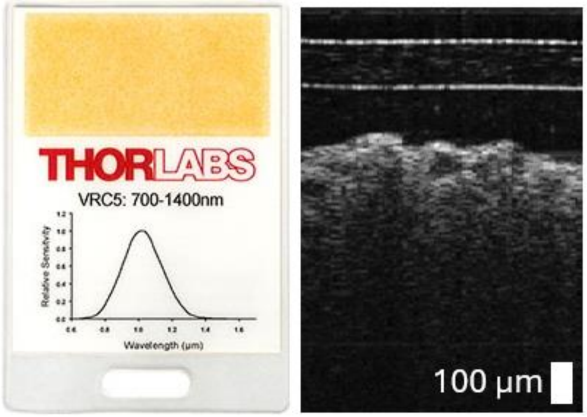

Fig. 2. (left) B-Scan of a fluorescent target (Thorlabs IR sensor card) acquired by lateral translation of a fiber sensor probe

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5. References

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