Design of a Multiple-reference Time-domain Optical Coherence Tomography System

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Optical coherence tomography (OCT) is a non-invasive, three-dimensional imaging technique that offers close-to-histology-level image quality [1]. In conventional time-domain (TD)-OCT systems depth scanning is achieved by modifying the relative optical path length difference of the reference and the sample arms in a sequential way using mechanical scanners. Due to the moving reference mirror TD-OCT systems require an inherently long acquisition time. To overcome this problem non-moving part solutions have been proposed such however, each solution has its own drawbacks [2-4].

Integrated optics offers unique solutions for OCT systems. Miniaturized OCT systems have recently garnered attention for their high potential in overcoming the size and cost issue of the bulky OCT systems. One major advantage of integrated optics is that the operation of the existing optical components can be reconfigured by controlling the material properties using temperature, voltage, or pressure. Despite this unique feature, OCT based on integrated optical components has as yet not utilized it properly.

In this work, by exploiting the unique features of integrated optics, the design of a novel high-speed TD-OCT system based on a non-moving scanning approach is presented. Figure 1 is the schematic of the integrated-optics-based multiple-reference TD-OCT system in which the micro-chip is outlined by the red dashed-rectangle. For ease of understanding the first two levels of the light tapping mechanism are demonstrated. Here, a central wavelength of 800 nm, an axial resolution of 20 µm, and a depth range of 1 mm are aimed at. Light coming from a broadband light source will be divided into two arms with a 3-dB coupler; half towards the sample, half towards the reference arm. There will be several electro-optically-controlled directional couplers placed on both sample and reference arms at certain distances. Imaging of different depths will be controlled by the additional length increment between consecutive reference beams (i.e. a in Fig. 1). According to the Nyquist sampling theorem the step size of the beam scanning should not be more than half of the axial resolution, i.e. 10 µm, which defines the length difference between consecutive reference points as a = 14 µm for this design.

The material system is 250 nm thick ion-sliced lithium niobate film on oxidized silicon wafer. The oxide thickness is 3 µm. The refractive index of the LN is 2.25 at 800 nm, and its electro-optic (EO) coefficient is (r_{33} ~ 30 pm/V) [5]. Single mode rib waveguides with 0.23 µm of slab height and 1 µm of waveguide width were designed. For defining the waveguides ion-implantation-assisted wet etching is a promising technique as it provides lower propagation losses compared to other methods.

Directional couplers used in this system were designed to act as voltage-controlled electro-optic switches with nanosecond switch time. A metallic electrode was placed on one of the straight waveguides of the coupler [Fig. 2(a)]. With applied voltage, the effective refractive index of the straight waveguide section is locally increased due to electro-optic effect which induces a phase difference between coupler arms. When there is no voltage on the electrodes, the lights on both arms will be in phase and the incoming light will be cross-coupled to the other coupler arm. The tapped lights from both sample and reference arms interfere at the beam combiner and directed to an on-chip photodetector. At a certain voltage value (i.e. V = 15 Volts for this design, Fig. 2 (b)), a π phase difference is generated between coupler arms which avoids cross-coupling of the light and forwards it to the next stage where the next depth point will be imaged. This operation will be performed in a sequential order by switching the directional couplers on and off until all depth points are scanned (i.e. *N* in Fig. 1).

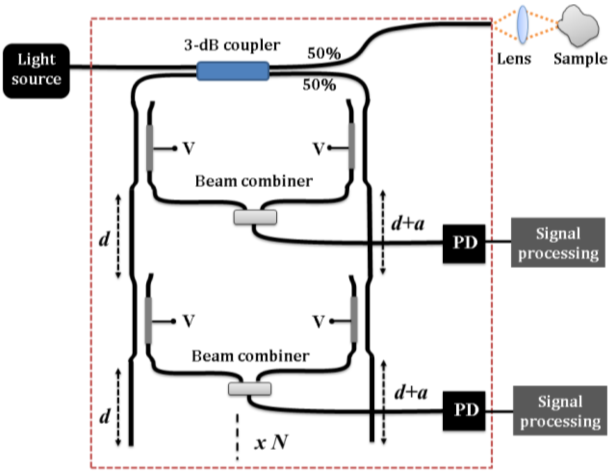

Fig. 1. Schematic of the proposed multiple-reference arm TD-OCT system based on integrated optics. The micro-chip is outlined by the red dashed-rectangle.

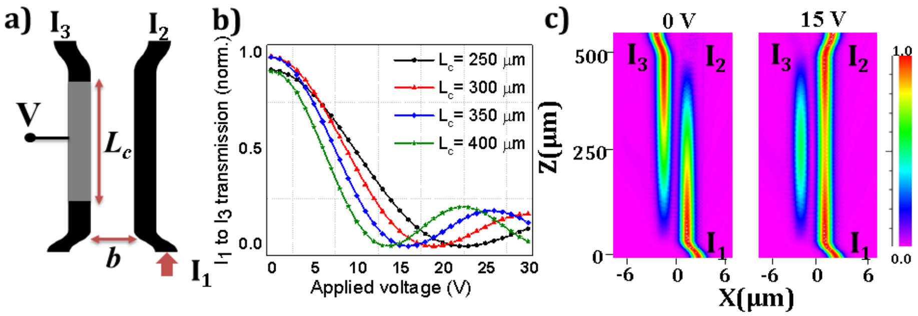

Fig. 2. (a) The schematic of the electro-optically-controlled directional coupler. (b) The amount of cross-coupling of input light at different voltage values for different electrode lengths. (c, right) Voltage is OFF, the light will be cross-coupled to the other channel, (c, left) For V = 15 Volts, the input light will stay in the same arm.

In summary, the concept and design of an integrated-optics-based multiple-reference TD-OCT system in LN-on-silicon platform were introduced. The proposed design will not only solve the speed limitation of the TD-OCT systems but also make it a widely accessible cheap and rugged point-of-care system.

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