MOEMS optical delay line for optical coherence tomography

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Abstract. Micro-Opto-Electro-Mechanical optical coherence tomography, a lab-on-chip for biomedical applications is designed, studied, fabricated and characterized. To fabricate the device standard PolyMUMPS processes is adopted. We report the utilization of electro-optic modulator for a fast scanning optical delay line for time domain optical coherence tomography. Design optimization are performed using Tanner EDA while simulations are performed using COMSOL. The paper summarizes various results and fabrication methodology adopted. The success of the device promises a future hand-held or endoscopic optical coherence tomography for biomedical applications.

1. Introduction

Electro-optic (EO) materials are shown to exhibit their potential as optical waveguide for precise and continuous laser beam guiding, manipulation, signal processing and controlled light guiding capabilities [1, 2, 3]. Optical modulation is performed using bulk photo-refractive materials and also by adopting electro-optic, magneto-optic, thermo-optic effects or combination of these effects. However, the electro-optic effect is preferred over other optical effects due to its simplicity, linearity, easy availability of large number of material as well as due the size factor. Also, the fast response time of less than few picoseconds and an ultra-wide wavelength bandwidth of over several hundred nanometres make this more attractive [1]. The EO modulators are being used in variety of applications including wave guiding, frequency manipulation, intensity or amplitude modulation, phase generation, polarization splitting, electro-optic switches, filters and other optoelectronic modulation device.

Optical coherence tomography (OCT) is an emerging imaging technique that examines, non-destructively internal structure of the biological tissues. It is based on hetero-dyne mixing of near-infrared light back-scattered from the sample under study, which could carry information. OCT relies on the principle of coherence gating, using the limited coherence length of a broadband source, whose bandwidth basically determines the achievable resolution. As the low coherence light back reflects from sample layers and the reference light, they are recombined and get interference at the detector. The larger band width leads to better transverse resolution and high resolution along image depth [2]. Most of fiber based or free space OCT used mechanically scanned optical component to delay the reference signal over a few millimetres [3, 4]. Except time-domain OCT (TD-OCT), most of the OCT technique does not require optical time delay. To realize a TD-OCT system on chip, we will have to...
always consider for optical delay generation. However, it is desirable to scan the reference path with no moving part. Various researchers have performed optical delay generation by mean of various techniques [5, 6] and also proposed complete integrated TD-OCT on a chip as glucose monitoring device [7].

The possibility to modify the refractive index of a material with an applied electric field allow in the optical light modulation for various applications. Lithium Niobate guided wave optical modulator are widely used for long-haul communication systems and optical signal processing systems. Silicon [8] and EO polymer [9], [10] is also a useful candidate for such applications. Currently it appears that significant challenges remain for EO polymer material to be commercial used in long-haul optical communication. The linear EO phenomena, is capability of an anisotropic material, without an inversion symmetry, to linearly change the refractive index with an applied electric field. An applied electric field, parallel to the optical axis of an electro-optic material structure or poled electro-optic doped polymer chromospheres changes its index by a quantity of \( \Delta n = -\frac{1}{2}n_0 r_{33} E \). Where \( n_0 \) is the refractive index of electro optic responded material without applied electric field (E), \( r_{33} \) is an element of the linear electro-optic tensor or electro-optic coefficient. An example of various electro-optic materials such as LiNbO3, Doped Polysilicon and DR1 (Dye) doped SU-8 polymer with their refractive index \( n_0 \) 3.2, 1.57, 1.45 and electro-optic coefficient of 30.8×10\(^{-12}\)m/V, 25.0×10\(^{-12}\)m/V and 30.8×10\(^{-12}\)m/V, respectively. It is to be noted that the magnitude of EO coefficient of these materials are very small, however, the beam can be sufficiently modulated with controlled voltage in order to realize light beam modulation. The design and development process is approached systematically using fourfold method viz., (i) To optimize the losses in the waveguides such that wave propagates through the waveguide and reflect back to the detector port (ii) To generate optical delay in the waveguide such that the expected Doppler shift occurs in the medium (iii) finding and designing suitable ports for launching light into the device and extract it to detector and (iv) fabricating the device with optimized values.

2. Design

A Schematic of fiber optics being used by us is shown in figure 1. An equivalent micro-opto-mechanical system (MOEMS) integrated circuit for TD-OCT is shown in figure 2. In the fiber optic setup the reference and sample arms compensated by either by mechanical motion of translational stages or using grating mirror combination. The same in the integrated circuit is carried out electro-optically. The EO induced change refractive index induces path deference in the reference arm, while the back scattered light from the sample arm will be obtained through a fiber optic cable.

Optical modulation is possible by externally applied DC voltage with parallel plate electrode configuration. These characteristics are very attractive in device application for optical beam manipulation in many optoelectronic systems. The designs of the waveguide with suitable electrode are discussed elsewhere [7].

**Figure 1.** Schematic of fiber-optic OCT setup with additional optical and electronic components.

**Figure 2.** The design of MOEMS_-OCT setup with all optical components integrated into a single chip.
3. Fabrication
The mask designed using the Tanner EDA L-Edit v14.1 for fabrication. The fabrication of designed chip was performed by polyMUMPs (multi user MEMS processes) technology [11]. The process steps (shown in figure 3) followed for the fabrication as:

1. The substrate is prepared with HF using standard RCA1 and RCA2 cleaning methods.
2. The MUMPs process is a three-layer poly-silicon surface micro-machining process. The process being with 100mm n-type (100) silicon wafers. Next, a 600nm low-stress LPCVD (low pressure chemical vapour deposition) silicon nitride layer is deposited on the wafers as an electrical isolation layer.
3. This is followed directly by the deposition of a 500nm LPCVD poly-silicon film Poly0 (see figure 4). Poly0 is then patterned by photo-lithography with mask Poly (see figure 4).
4. After patterning the photo-resist, the Poly0 layer is then etched in an RIE (Reactive Ion Etch) system.
5. A 2.0µm phosphosilicate glass (PSG) sacrificial layer is then deposited by LPCVD and annealed at 1050 °C for 1 in argon.
6. The wafer are then patterned with the third mask layer, ANCHOR1 and RIE. This step provides anchor hole that will be filled by the Poly1 layer.
7. After etching ANCHOR1, the first structural layer of poly-silicon (Poly1) is deposited at a thickness of 2.0µm and patterned lithographically with the Poly1 mask (see figure 4).
8. After Poly1 is etched, a second PSG layer (second oxide) is deposited and annealed.
9. The Poly1_Poly2 via provided for etch holes in the second oxide down to the Poly1 layer. This provides a mechanical and electrical connection between the Poly1 and Poly2 layers.
10. The ANCHOR2 level is provided to etch both the first and second oxide layers in one step, thereby eliminating any misalignment between separately etched holes. More importantly, the ANCHOR2 etch eliminates the need to make a cut in first oxide unrelated to anchoring a Poly1 structure, which need lesser exposes the substrate to subsequent processing that can damage either Poly0 or nitride.
11. The ANCHOR2 layer is lithographically patterned and etched by RIE in the same way as Poly1_Poly2 via.
12. The second structural layer Poly2, is then deposited (1.5µm thick) followed by the deposition of 200nm PSG.
13. Poly2 layer is lithographically patterned with the seventh mask (Poly2) and the PSG and poly-silicon layer are etched by RIE using the same processing conditions as for Poly1.
14. The final deposited layer in the MUMPs process is a 0.5µm metal layer that provides for probing, bonding and electroding.
15. The wafer is patterned lithographically with eight masks (Metal) and the metal is deposited and patterned using lift-off method.

![Fabrication Diagram](image)

**Figure 3.** Fabrication process flow followed for the fabrication of the waveguide as shown in figure 2. Details are discussed in text.
Figure 4. The fabrication method adopted is PolyMUMPs, accordingly, various masks (Poly0, Poly1, Poly2 and Metal masks) are shown in row. The final fabricated product is shown in the last figure.

4. Results and conclusions
We have presented successful fabrication of MOEMS optical coherence tomography. To the authors acknowledge, this is the first such device fabrication. The novel miniaturizations have demonstrated the realization of smaller optical coherence tomography setup. This setup could be employed for mobile and portable biomedical applications. Also, the device has the potential to use in clinical and industrial environment.

To conclude, we have designed, simulated and fabricated a MOEMS optical coherence tomography on a chip for biomedical applications. If the various characterization and packaging are successful, it would find huge amount of application in various field of Engineering, Science and Technology.

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