Tunable Silicon-on-Insulator based integrated optical filters with liquid crystal cladding

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***Abstract*— We investigate the tunability of Silicon-on-Insulator (SOI) devices with liquid crystal (LC) cladding. The tuning mechanism is based on electro-optic response of the cladding to applied external electric field. The validity of this scheme is established using Mach-Zehnder interferometers (MZI). The parameters affecting the tunability of the devices are explored. Up to 20 nm shift of interference wavelength in MZI with a 150 nm thick SOI waveguide by applying 30V is demonstrated, the highest tunability range in such designs reported to date.**

***Keywords*— Tunable optical filters, Electro-optic devices**

I. INTRODUCTION

Optical tunable filters are one of the main components in optical networks. There have been several reports on miniaturized devices with the aim of achieving wide tuning range [1-3]. However, the tunability range in these proposed structures is still limited [1-3]. SOI is an attractive choice for integrated photonic circuits. Due to the high refractive index contrast, SOI allows effective miniaturization and integration of optical devices on a single chip [4]. However, the weak electro-optic effect of SOI is an obstacle in the implementation of SOI based tunable filters [5]. LCs, on the other hand, have large anisotropy that can be controlled by an applied voltage. Integration of LCs in SOI devices can therefore, be used to fabricate tunable optical devices.

In this work, we use LCs as the cladding layer of SOI based MZI. Tunability is achieved by applying a voltage, which, in turn, changes the effective index. We demonstrate up to 20nm shift in the interference wavelength in the MZI. We also observe a strong influence of the waveguide dimension on the optical properties of the devices. Using polarized microscopy, we confirm the strong influence of the SOI surface on the LC molecules at the SOI-LC interface, a defining characteristic of such small-scale hybrid devices.

II. FABRICATION OF LIQUID CRYSTAL CELLS

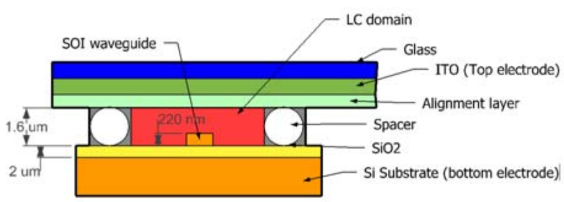

Fig. 1: Cross section diagram of LC-Cell.

The SOI-LC device is schematically shown in Fig. 1. The LC (E7 from Merck) is sandwiched between two substrates: an Indium Tin Oxide (ITO) coated glass plate and SOI substrate. The ITO on the glass plate is used as electrode layer. On top of the ITO, an alignment layer (nylon-6) for the LC is spin coated and baked. Rubbing of the alignment layer is used to align the LCs in a uniform way parallel to the Si waveguide. The Si substrate is used as the bottom electrode of the device. Glue mixed with 1.6μm glass spacers is used for attaching the SOI substrate to the top glass substrate. The spacers are used to ensure a uniform gap between the SOI substrate to the glass plate. The glue is then cured using UV light. The LC is heated up to the isotropic phase and 'injected' into the cell through capillary forces. The cell is then cooled down slowly to form a uniform alignment of the LC molecules.

III. CHARACTERIZATION PROCEDURE

The LC-SOI waveguides are characterized by measuring the transmission spectrum output from the cells. Light from a super-luminescent LED (SLED) with a wavelength range of 1.5-1.6 μm is coupled to the SOI waveguide with the help of a grating coupler and single mode fiber [6]. TE-mode propagates through the waveguide and the device. The output power is coupled out from another grating coupler at the end by using another single mode fiber. Transmission spectra are measured by a standard optical spectrum analyzer. A 1 kHz symmetric square wave signal (with equal positive and negative voltage) is used to tune the devices, thereby avoiding charge accumulation problem associated with DC voltage.

IV. MEASUREMENT RESULTS

Input light is coupled equally into both arms of MZI. The referencing arms in the MZIs used in this experiment have waveguide thickness and width of 220 nm and 450 nm whereas the testing arms use waveguides of 150 nm thickness and 400 nm width. In this way, the effect of the liquid crystal on both waveguides is different.

The output spectra of the MZI are shown in Fig. 2. The interference wavelength shifts ~20 nm with free spectral range (FSR) of 22 nm under 25 V applied voltage. To our knowledge, this is the highest tunability demonstrated in such designs to date [1-3].

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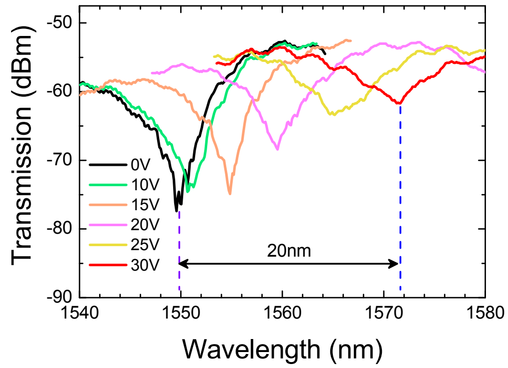

Fig. 2: Transmission spectra of MZI (400 nm width 150 nm thickness), showing a tunability of ~20 nm.

V. Parameters Affecting Tunability of The Devices

A. *Waveguide dimensions*

Our experimental observation suggests a strong correlation between the waveguide width and the change of effective indices of the devices under applied voltage. The MZIs have the same configuration as described before with either 150 nm or 220 nm thickness and varying widths of the testing arm. With known waveguide dimensions for both testing arms and referencing arms, its effective indices can be estimated. Fig. 3 illustrates the evolution of effective indices under applied voltage. The maximum change of effective index at 25 V is ~4.5×10^{-3} for the waveguide of 400 nm width and 150 nm thickness. Variation of waveguide dimensions shows that a stronger change in the effective index of the mode takes place in smaller waveguides. This is because a larger portion of the light extends into the LC cladding in smaller waveguides. Decreasing the width of the waveguides, nevertheless, introduces higher losses due to less confinement inside the core. Increase of loss is also observed under high applied voltage. This is likely due to the non-uniform reorientation of the LC molecules on the waveguide, resulting in higher scattering. This might be avoided by adding an alignment layer on the SOI substrate or designing a waveguide with flat-top planar surface such that the LC molecules can re-orient uniformly.

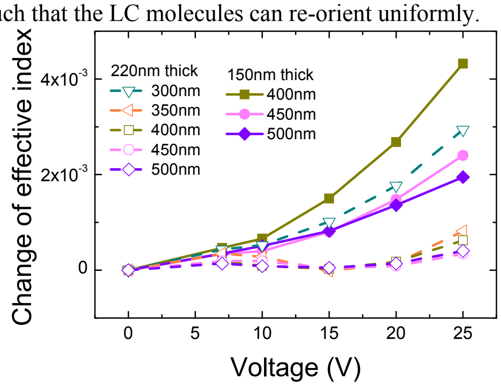

Fig. 3: The calculated change of effective index as a function of voltage depending on width of waveguide with 150 nm (open symbols, broken lines) and 220 nm (solid symbols, continuous lines) thickness. The waveguide dimensions shown here are based on coupling loss considerations.

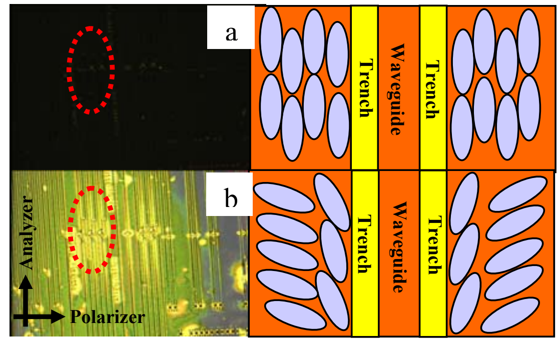

Fig. 4: Polarizing microscope image (left) with top view diagram (right) shows the director orientation on the edges of the trenches. a) at 0 V, b) at 10 V.

B. *Alignment of Liquid Crystals on a waveguide surface*

Further investigation on the tuning mechanism is carried out by cross-polarization microscope to inspect the orientation of LC molecules in the cells. In polarization microscopy, linearly polarized light passes through the sample and is reflected back to the analyzer. If the light beam experiences any birefringence, a fraction of light passes through the crossed analyzer, giving a bright image. Otherwise, a dark image appears.

MZIs are fabricated by using dark field masks which form 2µm wide trenches on both sides of the waveguide. In the initial state with the polarizer parallel to the director which defines general orientation of LC molecules, we observe a dark image (Fig. 4a). Hence, the director is uniformly aligned parallel on the SOI surface. An increase in applied voltage results in a brighter image (Fig. 4b) on the edges of the trenches but gradually becomes darker at very high voltage. This implies that under applied voltage, the director, apart from tilting due to the influence of electric field, is also twisted. Assuming a similar phenomenon on the waveguide surface, the quasi-TE mode of the waveguide should therefore, experience the ordinary refractive index of the LC (n_o=1.52) at 0V. With the increase in voltage, the LC is rotated. The mode experiences increase in refractive index toward the extra-ordinary one (n_e=1.75) resulting in an increase in effective index and red-shift of the interference wavelength.

VI. Conclusions

We have demonstrated tunability of SOI devices with LC cladding via MZI. The tuning is achieved using the electro-optic properties of E7 LC cladding. The maximum tuning range of interference wavelength in MZI achieved is ~20 nm. The study also shows that twisted LC on an SOI surface under applied voltage is responsible for this tuning. The dimension of the waveguides also affects the tunability of the devices. The structure proposed here shows great promise of realization of integrated tunable filters based on SOI and LC.

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