Trimming of silicon-on-insulator ring resonators with a polymerizable liquid crystal cladding

Sofie Lambert,[1,2,3] **Wout De Cort,**[1,2,3] **Jeroen Beeckman,**[2,3] **Kristiaan Neyts,**[2,3] **and Roel Baets**[1,3]

[1]*Photonics Research Group, INTEC department, Ghent University IMEC, Sint-Pietersnieuwstraat 41, 9000 Gent, Belgium*

[2]*Liquid Crystals and Photonics Group, ELIS department, Ghent University, Sint-Pietersnieuwstraat 41, 9000 Gent, Belgium*

[3]*Center for Nano- and Biophotonics (NB-Photonics), Ghent University, 9000 Gent, Belgium*

Corresponding author: Wout.DeCort@intec.ugent.be

We demonstrate the trimming of silicon-on-insulator ring resonators with a cladding layer of polymerizable liquid crystal. An electric field is applied over the cladding layer to tune the resonance of the ring resonators, which is then fixed by UV illumination of the polymerizable liquid crystal. A range of 0.56 nm is obtained. We provide the material properties of the polymerizable liquid crystal, give a description of the tuning mechanism and present experimental results. This method opens up possibilities in the field of low-cost trimming of photonic devices. © 2012 Optical Society of America

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The strongest argument for using silicon-on-insulator (SOI) for photonics is more than likely the mass fabrication techniques available in the CMOS fabs [1]. Deep UV lithography using 248 nm or 193 nm sources has become a mature technology and can produce high volumes at relatively low cost. It has to be noted, however, that the precision requirements for CMOS are much less stringent than they are for photonics. A variation of 10% in the critical dimensions is acceptable for CMOS but dramatic for many photonic devices. Ring resonators among others are extremely vulnerable to fabrication errors. When the width of the waveguide of a ring resonator differs 1 nm from the designed value, the resonance wavelength is shifted about 1 nm [1]. As a result, the resonance of fabricated ring resonators often differs considerably from the designed value. This is of course unacceptable for many applications. To overcome the fabrication imperfections, the ring resonators have to be trimmed or tuned to the desired resonance wavelength. Active thermal tuning is an often applied technique. Metallic heaters are fabricated close to the ring resonators [2]. The heating process can become very demanding in terms of power and design effort for complicated structures with many resonators. Carrier injection or depletion [3] is a technique for tuning that requires doping of the silicon. Yet another possibility to tackle the fabrication inaccuracies, is the addition of a liquid crystal (LC) overlay on the waveguides. It has been shown that ring resonators can be electrically tuned with this extra cladding [4]. These methods offer flexibility and reversibility but require continuous supply of voltage and are therefore not very attractive for use on a large scale. Trimming techniques, on the other hand, can be used to make small nonreversible modifications to photonic ring resonators and their resonances. The use of focused ion beam etching or electron beam induced compaction as trimming methods have been demonstrated in the past [5]. In this Letter, we propose an alternative method using polymerizable liquid crystal (PLC) as an overlay. The resonance of the ring is tuned to the desired wavelength with an electric field. Then, it is fixed by polymerizing the PLC using an ultraviolet light source.

The polymerizable cladding layer is a mixture of different components. First, we use the reactive components RM23 (13%), RM82 (22%), and RM257 (53%), obtained from Merck. They are polymerizable LCs in the sense that they have a chemical structure resembling that of a regular nematic but with one or two acrylate-groups attached that allows bonding with other molecules during polymerization. Second, we add a small amount of 5CB (9%), a nonreactive nematic LC. Third, we add a photoinitiator (Irgacure 815 from Ciba—0.3%), which enables polymerization by UV illumination. Finally, we add an inhibitor (t-butylhydroquinone—2.7%) that prevents spontaneous reactions with the environment. A combination of pure LC compounds is used to increase the nematic temperature range of the mixture and to obtain a nematic phase at room temperature, which simplifies the experiments. Within that range, it behaves like a regular nonreactive LC mixture. Before polymerization, the director (i.e. the average orientation of the molecules) can be reoriented with an externally applied electric field, changing the optical properties of the material.

We have studied the properties of the mixture described above using a spectrometer equipped with two polarizers. The material is caught between two glass plates that are glued together using UV-curable glue mixed with spacers. On the glass plates, there is an indium tin oxide (ITO) contacting layer present as well as a polyimide alignment layer that aligns the molecules uniformly. The birefringence of the mixture was measured by examining the transmission spectrum of the cell between crossed polarizers. The cell is oriented in such a way that the rubbing direction is at an angle of 45 degrees with respect to the polarizers. Fitting the transmission spectrum with the expected theoretical transmission, calculated for example with the Jones matrix formalism [6],

$$I = M\left(\sin^2\left(\frac{\pi d \Delta n(\lambda)}{\lambda}\right)\right) + O, \qquad (1)$$

gives the wavelength dependent birefringence of the PLC. For the wavelength dependence of the mixture, we use a Cauchy expression of the form $\Delta n(\lambda) = (A + \frac{B}{\lambda^2} + \frac{C}{\lambda^4})$. The PLC has a birefringence between 0.24 and

0.28 in the wavelength range of 400 to 750 nm. When a voltage is applied over the cell, we find that the retardation Δnd decreases (see Fig. 1) due to the reorientation of the director. An AC signal is used to prevent drift of ions in the LC. Illuminating the cell with UV light, causes polymerization of the material and the retardation is measured again after polymerization. We find that polymerization results in a small drop of the retardation, but for the most part the director orientation is preserved. When the voltage is switched off, the molecules retain their frozen orientation and the birefringence remains stable. Polymerization of different cells at different voltages show similar behavior and the drop in retardation is reproducible.

We then apply this PLC mixture as a cladding layer on top of SOI ring resonators. The SOI chips consist of a Si substrate, a 2 μm thick insulating oxide layer, and a 220 nm thin Si layer in which the structures are etched. We glue a glass plate on top of this chip, using UV-curable glue mixed with spacers of 3 μm radius (see Fig. 2 and Fig. 3). The top glass plate is coated with an electrical conducting layer (ITO) and an alignment layer, respectively. The cell is filled with the PLC mixture. The alignment of the director on the rubbed surface is parallel to the input waveguides on the chip. It has been shown that on the surface of the chip, the director aligns along the waveguide structures [7]. An electric field is applied between the ITO contacting layer and the Si substrate. The director then reorients along the fieldlines with increasing voltage. The rings under study here consist of waveguides of 220 nm heigth and 500 nm width. They have a bend radius of 6 μm as shown in Fig. 3.

The TE mode in a small SOI waveguide has electric field components along all three major axes and all three contribute to the effective index. When the director is reoriented from an orientation parallel to the waveguides to an orientation perpendicular to them, it is the contribution of the z-component that will cause the largest effect. The y-component is too weak to have any influence and the x-component experiences the low dielectric constant (associated with the short axes of the molecules) during the entire process. As the z-component experiences a gradually decreasing dielectric constant (see Fig. 4), the tuning process will yield a decreasing effective index of the mode and therefore a decreasing resonance wavelength of the ring resonator.

To test this principle experimentally, we couple light from a tunable laser into the waveguides and measure
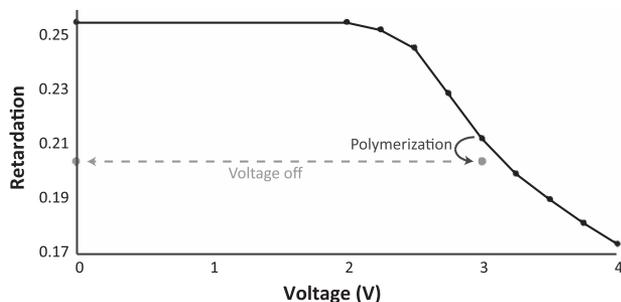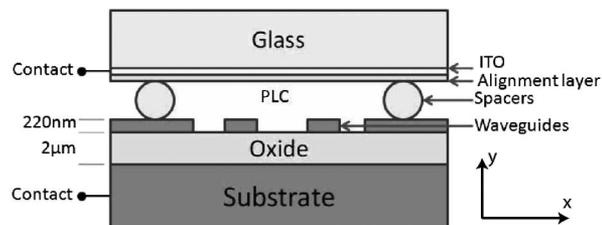
Fig. 2.   Schematic cross section of a device consisting of a SOI substrate with PLC cladding, sealed off by a glassplate with a transparent ITO electrode and polyimide alignment layer.
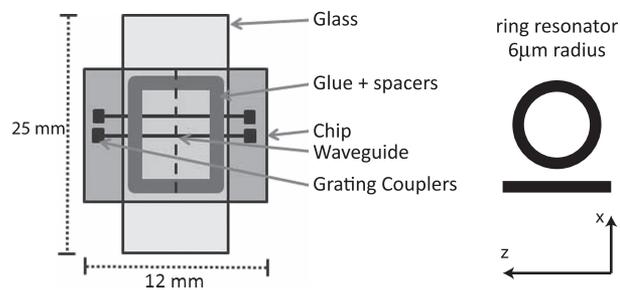
Fig. 3.   Schematic top view of a device consisting of a SOI substrate with LC cladding, sealed off by a glassplate with a transparent ITO electrode and polyimide alignment layer (left). Schematic top view of a single ring resonator with the straight waveguide below (right).
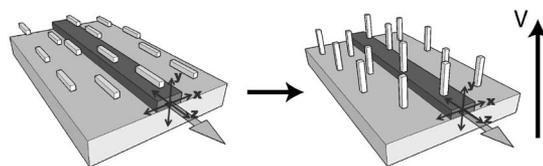
Fig. 4.   Without an electric field present, the director aligns along the waveguides. It reorients along the fieldlines whenever an electric field is applied.

the output with a power detector. The in- and outcoupling is done with grating couplers that can couple light from an optical fiber into a nanophotonic waveguide. We apply a voltage to the cell with a frequency of 1 kHz and increase the amplitude in steps. For low voltage levels, we notice that the resonance wavelength remains undisturbed. We find that the threshold for tuning lies around 2.5 V. Now, the field is strong enough to start reorienting the LC molecules. Above threshold, the resonance wavelength shifts towards lower wavelengths, as predicted (see Fig. 5 and Fig. 6). The tuning range we achieve before the photopolymerization is carried out, is 0.75 nm. We polymerize the cell at 10 V, where the shift is 0.4 nm. We find that polymerizing the LC induces a small red-shift of the resonance wavelength and the resulting shift, after polymerization, is about 0.2 nm. The red-shift can be caused by different mechanisms. First, it is difficult to predict to which extent the orientation of the liquid crystal around the surfaces and edges of the SOI is preserved after photopolymerization. Second, due to the polymerization process, minor rearrangements take place inside the molecules which alter the optical anisotropy of the

Fig. 1.   Retardation of the PLC cell as a function of voltage at a wavelength of 750 nm. Upon polymerization the material is frozen.
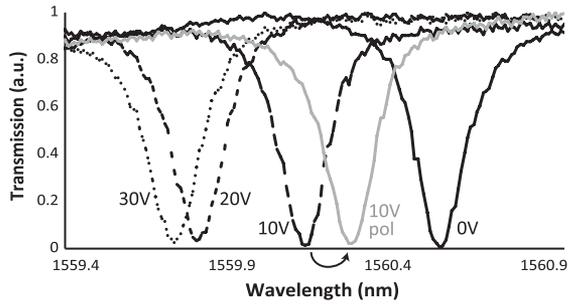
Fig. 5. Transmission of a ring resonator clad with PLC as a function of voltage. Polymerized material results in the gray curve.
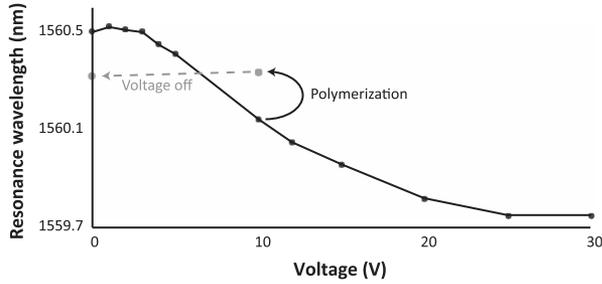
Fig. 6. Resonance wavelength as a function of voltage. The effect of polymerization is shown.

Fig. 7. Resonance shift before and after polymerization of three different cells.

liquid crystal [8]. When the voltage is disconnected, the resonance wavelength remains fixed at the trimmed wavelength. In Fig. 7, the combined measurements of three cells can be seen. One cell was polymerized at 0 V, one at 10 V (see also Fig. 5 and Fig. 6), and one at 50 V. All resonances remained stable over time after polymerization. During the polymerization, however, in all cases a red-shift occurs (see also Fig. 1). Because of the variations in the red-shift for different voltages, the overall trimming range of 0.56 nm is smaller than the tuning range before photopolymerization. More measurement points are needed to fully quantify the processes, as the magnitude of the shift remains somewhat unpredictable.

We have shown that ring resonators can be trimmed with polymerizable liquid crystals. We have studied the materials and proceeded with successfully trimming SOI ring resonators. Although careful characterization of the material is needed before this method is usable on a large scale, we believe that this can be an easy, quick, and relatively cheap method to compensate for fabrication inaccuracies.

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