# Wide tuning of silicon-on-insulator ring resonators with a liquid crystal cladding

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

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

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

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

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

Received July 13, 2011; revised September 1, 2011; accepted September 3, 2011; posted September 7, 2011 (Doc. ID 150988); published September 27, 2011

Wide electrical tuning of silicon-on-insulator ring resonators is demonstrated using a top cladding layer of nematic liquid crystals. A tuning range of 31 nm is demonstrated for ring resonators guiding the TM mode, covering nearly the entire C-band of optical communications. Ring resonators guiding the TE mode can be tuned over 4.5 nm. The combination of a liquid crystal director calculation and a fully anisotropic mode solver confirms the interpretation of these experimental results. The realization of broad and low-power tuning in silicon-on-insulator opens up new opportunities in the field of tunable lasers, filters, and detectors. © 2011 Optical Society of America

*OCIS codes:* 130.7408, 160.3710.

Wide tuning of integrated optical components is desirable for applications ranging from reconfigurable telecom networks to spectroscopy. Silicon photonics is one of the important platforms for photonic integration [1]. Silicon-on-insulator (SOI) is an excellent material system for passive waveguiding, fast modulation and detection, [2] but lacks the capabilities for broad low-power tuning (among others). Therefore, efficient SOI filters that can be widely tuned at low power have not yet been demonstrated. Ring resonators are sophisticated resonant structures often used in larger telecommunication components such as (de-)multiplexers. They are able to filter narrow wavelength bands from a broad spectrum. In SOI they can be very small, with a large $Q$-factor and low losses. Tuning SOI ring resonators is often done thermally [3] or by carrier injection/depletion (mostly used for fast modulation [4]). These methods require constant power supply and the tuning range is limited. For example, thermal tuning of ring resonators over 30 nm requires a temperature difference of the order of 300 deg. The work we present here allows wide tuning with virtually no power. A layer of nematic liquid crystals (NLC) is used as a cladding on SOI ring resonators. By applying an electric field across this layer we tune the resonance of the ring resonators. This technique was demonstrated before but with only limited results (1 nm tuning range) [5–7]. In our work, ring resonators for TM-polarized (transverse magnetic field) light as well as for TE-polarized (transverse electric field) light are used.

A layer of E7, a commercially available NLC is drawn between the SOI chip and a glass plate, which is attached to the chip using UV-curable glue mixed with spacers (see Fig. 1). The chip consists of a Si substrate, an insulating oxide layer, and a 220 nm thick Si layer in which the waveguides and resonators (Fig. 2) are defined. Silica spacers of 6 $\mu$m diameter control the distance between the chip and the glass. On the glass plate there are two additional layers. The first is a homogeneous transparent indium tin oxide (ITO) layer for contacting. The second is a spin-coated nylon-6 layer. When rubbed, this layer provides an initial director orientation for the NLC. Metallic wires are soldered to the ITO and the silicon substrate for contacting. When a voltage is applied, the electric field lines will be perpendicular to the substrate and the ITO layer. From our experience we know that E7 aligns in a planar fashion on an Si or $SiO_2$ substrate [6]. The director is capable of aligning to local structures (such as waveguides) down to nanometer scale. It is fair to assume that the director is everywhere parallel to the waveguides and in the plane of the substrate. In the presence of an electric field the director reorients itself vertically along the field lines (Fig. 3). Because of the small dimensions of the waveguides, there are no pure TM and TE modes and electric field components exist along all three major axes. The normal ($Y$) component of the (quasi-) TM mode extends far into the cladding. This is beneficial for interaction of the light with the NLC. When there is no electric field present, the director is oriented parallel to the waveguide. The $Y$ component "feels" a low value of the dielectric constant (the ordinary dielectric constant of the LC) in the cladding and the mode has a low effective refractive index ($n_{\mathrm{eff}}$). When the external field reorients the director, the $Y$ component feels an increasing dielectric constant. A fully vertical director results in the "high" extraordinary dielectric constant seen by the $Y$ component. This gives rise to a high $n_{\mathrm{eff}}$ of the TM mode. The case for the more confined (quasi-) TE mode is different. The LC interacts mainly with the $Z$ component at the sidewalls of the waveguide and the transversal $X$ component. The tuning principle used causes a decreasing value of the dielectric constant along the $Z$ axis but leaves it unchanged along the $X$ axis.

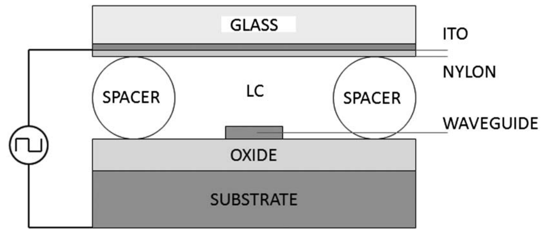


Fig. 1. Schematic cross section of a device consisting of an SOI substrate with LC cladding, sealed off by a glass plate with a transparent ITO electrode and nylon alignment layer.

 © 2011 Optical Society of America

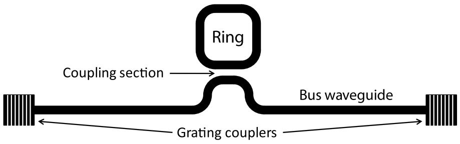


Fig. 2. Schematic top view of a ring resonator.

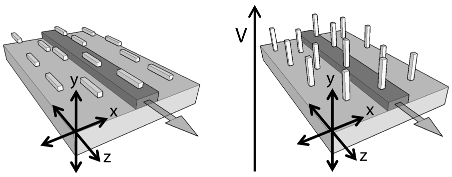


Fig. 3. Reorientation of the LC director.

This results in a decreasing $n_{\mathrm{eff}}$ for the TE mode. The TM ring resonators under study have a bend radius of 20 $\mu$m and four straight sections of 10 $\mu$m each. The waveguides measure 220 nm high by 450 nm wide. The coupling section is 4 $\mu$m long and the gap between the bus waveguide and the resonator is 550 nm wide. The TE resonators have a 15 $\mu$m bend radius, 12 $\mu$m straight sections, and a 2 $\mu$m long coupling section that is 250 nm wide. The bus waveguide is equipped with grating couplers. These couple light from an optical fiber to the waveguide and back. The polarization of the light is controlled by polarization wheels. A tunable laser is used as a light source and the output is measured with a power meter. A square wave of 10 kHz is applied to the electrodes with a voltage source. The AC voltage prevents ion drift in the NLC, which can cause shielding of the electrodes. The output is measured for different voltage levels. For 100 V, a tuning range of 31 nm toward longer wavelengths is achieved for TM-polarized light (Figs. 4 and 5). We can measure only wavelengths within the spectral window of the grating couplers. Therefore, we start tracking an equivalent resonance mode located three free spectral ranges toward shorter wavelengths when the boundaries of the spectral window are approached. Around the steepest part of the curve (Fig. 5) a tuning of around 1 nm/V is observed. For TE-polarized light, a tuning range of 4.5 nm toward shorter wavelengths is observed (Figs. 6 and 7). The overlaps of the TE and TM mode with the LC cladding are typically 10% and 30%, respectively. Moreover, as the TE mode is strong near the sidewalls where the director is anchored by both the $SiO_2$ and the sidewalls, the difference in tuning range is intuitively understood. The $Q$-factor of the TM ring drops from 11,500 to 4000 and rises back to 10,000 at high voltages. For the TE ring the $Q$-factor drops from 38,000 to 8500 and increases again to 17,000. This effect is probably due to the formation of LC domains, which increase the optical losses due to scattering. As the chip surface is not treated, there can be local differences in tilting (e.g., the rodlike molecule can start tilting from either end) causing formation of domains. A surface treatment giving some pretilt to the molecules will be needed to overcome this problem. A threshold voltage of 5 V is needed to compensate for the elastic forces holding the NLC director in place. At higher voltages a saturation effect is seen. The resonance does not shift much further for increasing voltages. This means that the director is fully reoriented

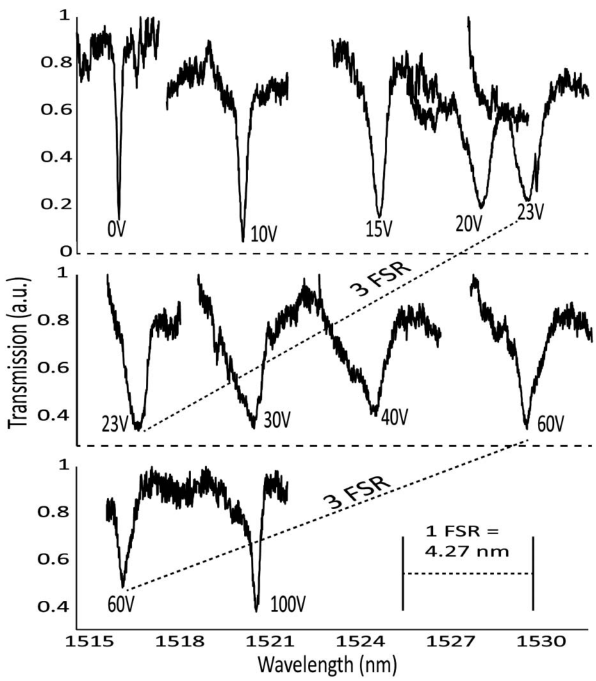


Fig. 4. TM output for increasing voltage levels.

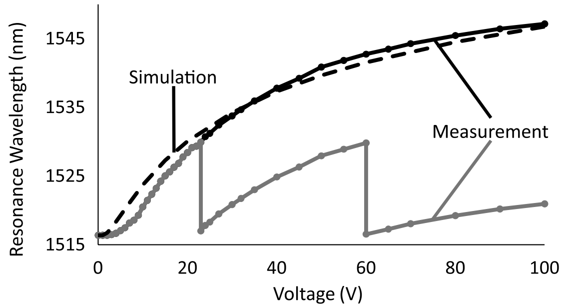


Fig. 5. Trace of the resonance wavelength of the TM mode as a function of voltage.

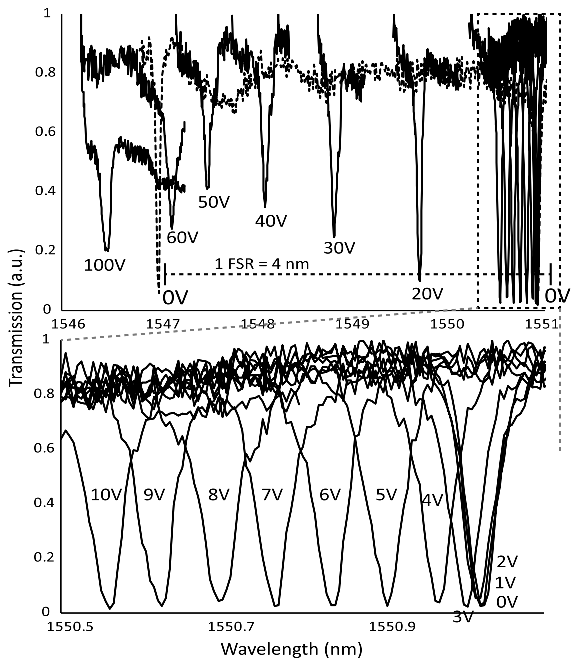


Fig. 6. TE output for increasing voltage levels.

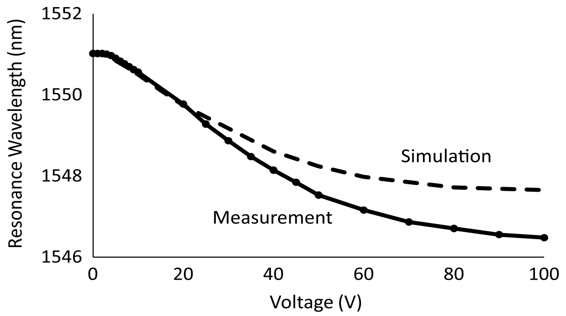


Fig. 7. Trace of the resonance wavelength of the TE mode as a function of voltage.

throughout the cell. Note that contacting the bottom Si substrate causes a considerable voltage drop across the oxide layer. The above results can in principle be achieved with much lower voltage levels provided that adequate electrodes on the chip are designed and fabricated.

To verify the interpretation of the experimental results we use two simulation tools. The first calculates the director of the NLC in a given geometry under influence of an external electric field. The variable order calculation is based on the minimization of the Landau–de Gennes free energy functional [8]. This model is implemented in a finite-element scheme. Accurate calculations of the NLC director near small structures like waveguides are possible. The results are imported into a fully anisotropic mode solver. This solver is based on the solution of the variational form of the curl-curl equations of the electric field [9]. With these tools we calculate the $n_{\mathrm{eff}}$ of the TE and TM mode in the SOI waveguide with NLC cladding. The shift in $n_{\mathrm{eff}}$ is directly related to the change in resonance wavelength: $\Delta\lambda/\lambda = \Delta n_{\mathrm{eff}}/n_g$, where $n_g$ is the group index of the mode. This allows us to calculate the resonance wavelength as a function of voltage. The anchoring strength of the surface determines whether or not the director at the surface can be reoriented easily. We distinguish between anchoring for a variation in the tilt ($a_t$, out of the plane of the surface) and for a rotational reorientation of the director in the plane ($a_p$). These parameters are not well known for materials such as Si or $SiO_2$. It is found that for $a_t = 5.10^{-4}\,\mathrm{J/m^2}$ and $a_p = 5.10^{-6}\,\mathrm{J/m^2}$, the experiments and the simulations show a good agreement (Figs. 5 and 7).

We have shown that silicon-on-insulator ring resonators can be widely tuned with a cladding layer of nematic liquid crystals. A tuning range of 31 nm is achieved for resonators guiding TM-polarized light, which is the widest yet reported. Resonators guiding TE-polarized light can be tuned over 4.5 nm. This low-power broad tuning method gives rise to a number of possibilities in the field of tunable filters, lasers, and detectors, and more generally any device requiring compact phase modulators. We have verified the result with simulations using a fully anisotropic mode solver together with a director calculation.

W. De Cort acknowledges the Institute for the Promotion of Innovation through Science and Technology in Flanders (IWT Vlaanderen). The work has been carried out in the framework of the IAP project Photonics@be of the Belgian Science Policy.

## References

1. S. Selvaraja, P. Jaenen, W. Bogaerts, D. Van Thourhout, P. Dumon, and R. Baets, J. Lightwave Technol. **27**, 4076 (2009).
2. M. Lipson, J. Lightwave Technol. **23**, 4222 (2005).
3. P. Dong, W. Qian, H. Liang, R. Shafiiha, D. Feng, G. Li, J. Cunningham, A. Krishnamoorthy, and M. Asghari, Opt. Express **18**, 20298 (2010).
4. A. Liu, L. Liao, D. Rubin, H. Nguyen, B. Ciftcioglu, Y. Chetrit, N. Izhaky, and M. Paniccia, Opt. Express **15**, 660 (2007).
5. B. Maune, R. Lawson, C. Gunn, A. Scherer, and L. Dalton, Appl. Phys. Lett. **83**, 4689 (2003).
6. W. De Cort, J. Beeckman, R. James, F. Fernandez, R. Baets, and K. Neyts, Opt. Lett. **34**, 2054 (2009).
7. W. De Cort, J. Beeckman, R. James, F. Fernandez, R. Baets, and K. Neyts, J. Opt. Soc. Am. B **28**, 79 (2011).
8. P. de Gennes and J. Prost, *The Physics of Liquid Crystals* (Oxford University, 1995).
9. J. Beeckman, R. James, F. Fernández, W. De Cort, P. Vanbrabant, and K. Neyts, J. Lightwave Technol. **27**, 3812 (2009).