New Wavelength-tuning Method in Optical Ring Resonators with Liquid Crystal Cladding: exploiting the Longitudinal E-field.

Wout De Cort[1,2], Jeroen Beeckman[1], Richard James[3], F. Anibal Fernandez[3], Roel Baets[2] and Kristiaan Neyts[1]

[1] Liquid Crystals and Photonics group, Department of Electronics and Information Systems, Ghent University 41, Sint-Pietersnieuwstraat, Gent 9000, Belgium

[2] Photonics Research Group, Department of Information Technology, Ghent University 41, Sint-Pietersnieuwstraat, Gent 9000, Belgium

[3] Department of Electronics and Electrical Engineering, University College London, Torrington Place, London, WC1E 7JE, UK

ABSTRACT

We demonstrate tuning of the resonance wavelength of silicon-on-insulator optical ring resonators. The devices are clad with a layer of nematic liquid crystal. The electrooptic effect of the anisotropic liquid crystal allows us to change the effective index of the TE waveguide mode with an externally applied voltage. The electric field will reorient the liquid crystal director which alters the refractive index of the cladding layer. The evanescent tails of the waveguide mode feel this change. The change in effective index has a direct effect on the resonance wavelength. In our setup, the director tilts from an orientation parallel to the waveguides to an orientation perpendicular to the substrate. This way, it is the longitudinal component of the electric field of the light that experiences the largest change in refractive index. Starting from this principle, we show experimental tuning of the resonance wavelength over 0.6nm towards shorter wavelengths. Theoretical considerations and simulations with a finite element modesolver capable of handling full anisotropy confirm the experimental results and provide insights in the tuning mechanism.

Keywords: silicon-on-insulator, liquid crystal, ring resonator, anisotropy, wavelength tuning

1. INTRODUCTION

Optical networks require components to filter out specific wavelengths from a broad spectrum. Ring resonators are excellent components for this task as they show resonance for certain wavelengths. For this reason they are already being used as basic elements in (de-)multiplexers. In reconfigurable networks the filtering of wavelengths needs to be adjustable and the ring resonators need to be tunable. This tuning can be realized in a number of ways: temperature, carrier injection or with appropriate cladding layers as we will show in this article.

Liquid Crystals XIII, edited by Iam Choon Khoo, Proc. of SPIE Vol. 7414
74140D · © 2009 SPIE · CCC code: 0277-786X/09/$18 · doi: 10.1117/12.825669

Silicon-on-insulator (SOI) is now widely recognized as the major material system for the fabrication of photonic components. There are three major reasons for the success of the SOI material system for photonics. First of all, it is transparent around 1550 nm, which is the main wavelength band used in telecommunication. A second reason is that it has a very high refractive index contrast. It consists of a Si substrate, covered with an insulating layer of SiO_2 (n = 1.47). On top of the SiO_2 there is a thin layer of crystalline Si (n = 3.45) in which the photonic structures are defined. This high index contrast allows the design of very small components as the light is strongly confined to the Si core waveguide. The third reason is that the processing of these photonic structures in SOI can be done with the techniques and equipment used in CMOS technology. This allows mass production and renders the individual components very cheap compared to those made in other materials[1]. Si, however, also has some major drawbacks. It is nearly impossible to efficiently generate light in Si due to its indirect bandgap. Therefore the photonic components in Si are limited to passive functionality. Influencing the refractive index through carrier injection is also not very efficient in Si. It is clear that for several functions Si alone will not do the job and inventive solutions are needed. When it comes to light generation, we have seen extensive research towards integration of III-V semiconductor materials on Si[2,3]. Concerning wavelength tuning in Si components, scientists have proposed thermal tuning[4] next to carrier injection. Another method to achieve this tuning is to apply a cladding layer of which the refractive index can easily be changed. Liquid crystal (LC) is an interesting option. It is an anisotropic material of which the orientation of the rod-like molecules can be changed with an externally applied electric field. The light of the mode travelling in the waveguide below the LC feels the change in refractive index in the cladding. This change can be big, a Δn of 0.2 is common in nematic LCs, and will affect the effective index of the mode. The effect will be bigger with weaker confinement as a larger part of the light will then be in the cladding. Photonic components with a liquid crystal cladding have been demonstrated before[5,6,7]. The mechanism behind the tuning, however, has not yet been fully clarified and there is potential for improvement with regard to the tuning range. With this work we hope to shed more light on this interesting material combination.

In this paper we will discuss SOI ring resonators designed for TE polarized light clad with nematic LC. In the next section we will explain the fabrication of the cells. The third section will show the experimental results. In the last section we will discuss the theory and simulations carried out to clarify the tuning mechanism.

2. CELL STRUCTURE

2.1. Assembly

We start from an SOI chip which consists of a Si substrate, a 2μm thick insulating layer of SiO_2, and a 220nm layer of crystalline Si in which the photonic structures are defined. Using UV-curable glue mixed with spacers (1.6μm diameter) we attach a glass plate on top of the chip. This glass plate is covered with Indium Tin Oxide (ITO), a transparent and conducting material. We also spin an alignment layer on the glass. This layer, when it is rubbed, gives the director of the LC a preferential orientation parallel to the rubbing direction. There are several materials available which align the director in a planar fashion. We use nylon-6 in the fabrication of our cells. It is spincoated on the glass, baked and finally rubbed. When the glass is attached to the chip it is placed on a hotplate together with the LC. We use 5CB, 4'-n-pentyl-4- cyanobiphenyl, a commercially available nematic LC, in our experiments. The LC is heated to its isotropic state and deposited on the glass plate. Cappilary forces draw the LC into the cell. To avoid defects and the forming of domains in the LC, we cool the cell down gradually. The contacts necessary to apply the electric field are formed by the ITO and the Si substrate. A schematic view of the structure can be seen in Fig. 1.

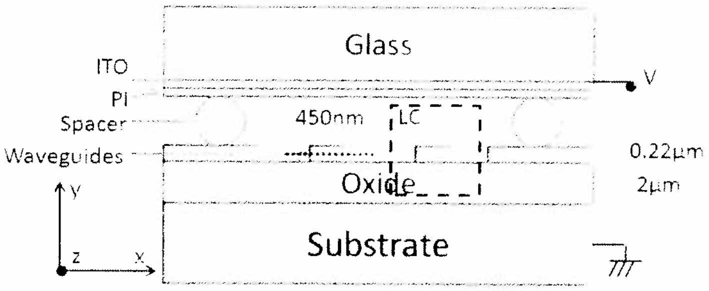

Fig 1. Schematic view of the SOI structure with liquid crystal cladding.

2.2. Alignment

The alignment of the director at the glass plate is well defined thanks to the alignment layer. On the surface of the SOI chip, however, it is not desirable to have an additional alignment layer as the effect of the LC on the effective index will then decrease dramatically or even disappear completely. To achieve maximal tuning a very weak alignment on the Si substrate is necessary. Even when no alignment layer is present on a surface, the LC still feels a certain anchoring and in practice, weak alignment is difficult to achieve[8]. Therefore it is essential to know how the LC behaves on a structured surface like an SOI chip. We designed a test structure in SOI consisting of a waveguide flanked by Si rectangles forming two gratings to investigate the behaviour of the LC. We cover the entire structure with 5CB and seal it of with a glass plate. The glass plate is covered with an alignment layer which forces the director on the glass surface parallel to the waveguide. The cell is placed under a polarization microscope with crossed polarizers for observation. We align the polarizer parallel to the rubbing direction and the analyzer perpendicular to it. The image obtained can be seen in Fig. 2.

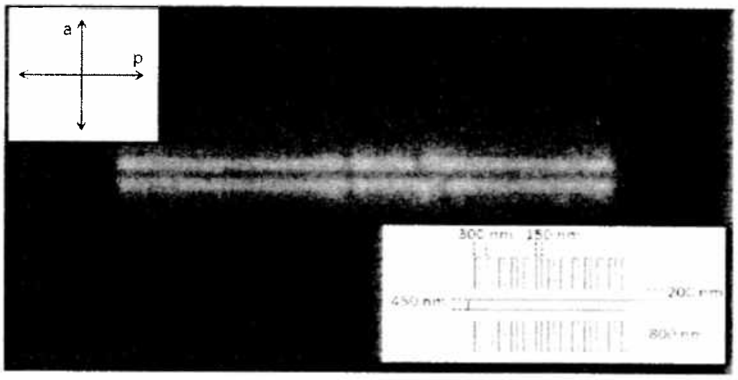

Fig. 2. Waveguide and grating covered with 5CB observed through a polarisation microscope. Polarizer is parallel to the waveguide and the analyzer is perpendicular to it. In the inset, a schematic top view of the structure can be seen.

We see that the largest part of the image remains black. This means that there is no retardation present in most of the cell. The linearly polarized light coming from the polarizer only sees the long axis of the molecule and experiences no birefringence. It reflects from the surface of the chip and is blocked at the analyzer. The two bright lines seen in the figure represent the gratings. The lines are bright because there is a twist in the director orientation from top to bottom. The molecules at the SOI surface rotate to align along the ribs of the grating[9]. This causes the incoming light to experience birefringence. Its polarization state changes and after reflection it partly passes the analyzer resulting in the two bright lines in the image. The dark interruptions on the bright lines are formed by disclinations. These are separation lines between a region of clockwise twist and counterclockwise twist. The two situations are energetically equivalent. The conlusion of these observations is that the top alignment layer forces the director in a certain orientation, parallel to the rubbing. On the surface of the chip, however, the director follows the ribs of the intersecting surfaces.

We also study the SOI rings with LC cladding under the polarization microscope. The polarizer and analyzer are perpendicular to each other and at an angle of 45 degrees with the rubbing direction. With no voltage applied we get a pink colour. The spectrum of the transmitted light allows us to estimate the thickness of the cell at 5μm. When we apply a voltage between the ITO and the Si substrate the cell turns dark. Here we note that the cell never becomes fully dark even with maximal applied voltage. This is most likely because on the glass and on the SOI surface, the molecules are anchored and are not able to tilt completely to a vertical position. This will cause some retardation in the cell and consequently some light will be transmitted.

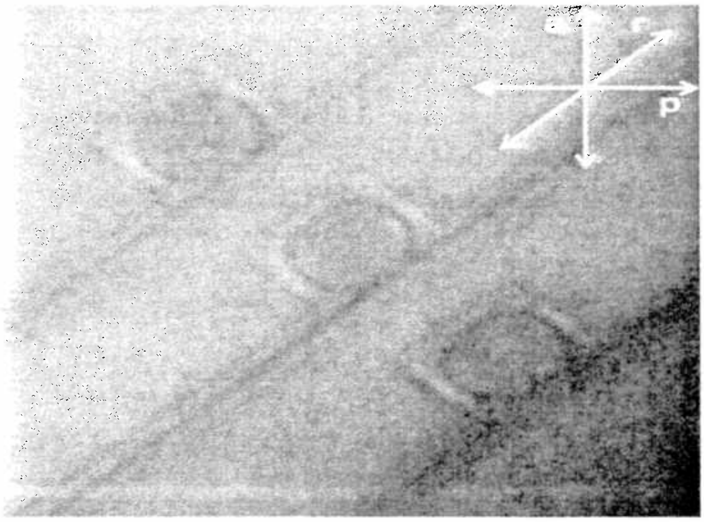

Fig. 3. The SOI rings can be clearly seen under a polarization microscope. The direction of the polarizer (P), analyzer (A) and rubbing (R) are indicated by the arrows on the right.

3. OPTICAL CHARACTERISATION

3.1. Setup

The photonic chips we use are equipped with grating couplers. These are periodic structures designed to couple light from an optical fiber to the nanophotonic waveguides and vice versa[10]. Light is coupled in and out vertically with an efficiency of 30%. This method makes the alignment of optical fibers with the photonic structures easy. The light source sends light through the optical fiber. With polarization controllers, we can make sure that TE light is coupled into the waveguides. The second grating coupler couples light again to an optical fiber. We can use a tunable laser and power meter as source and detector or we can deploy a superluminescent LED and spectrum analyzer. A signal generator is used to apply an electric field between the SOI chip and the ITO on the glass cover. We use a square wave with 1kHz frequency. This AC signal is necessary to avoid charge buildup problems in the cell. For different values of the voltage we measure the output of the ring resonators.

3.2. Measurements

With the setup described above we characterize the behaviour of SOI microrings with LC cladding. The device discussed has a bend radius of 6μm. The output of the rings for 0V and 30V is shown in the inset of Fig. 4. We see that the resonance wavelength shifts towards shorter wavelengths. The magnitude of the shift is about 0.6nm which is about twice as large as previous reported shifts[5]. Compared to ring resonators with an air cladding, the dips are less deep and somewhat wider. Two main reasons can be identified. The rings were initially designed to work with an air cladding. The refractive index of the liquid crystal is obviously higher than that of air and thus coupling between the waveguide and the ring is enhanced. This renders the resonances less pronounced, the Q-factor goes down. The other reason is loss by scattering. This scattering is inevitable when working with LC.

In Fig. 4. we track the resonance wavelength as a function of the applied voltage. We see a well defined threshold voltage, which is to be expected as the voltage has to compensate for the elastic forces. In our devices this happens at 10V. The actual value of the Freedericksz transition is lower however, as we apply voltage between the ITO layer on the top glass plate and the bottom of the substrate. There will be a voltage drop over the SOI chip but it is not trivial to determine the actual magnitude of this drop. Therefore, all values of the voltage in the experiments will be an overestimation of the actual voltage over the LC. We also notice a saturation of the tuning at higher voltages. This can easily be explained when we consider that at a certain voltage the molecules near the surface will have reached their maximum tilt angle.

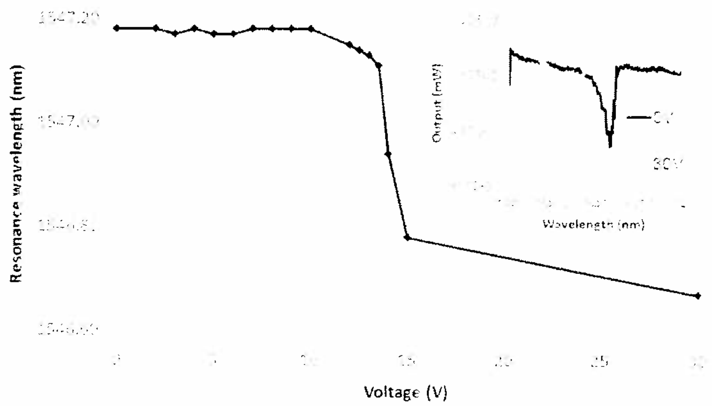

Fig. 4. Measured resonance wavelength of ring resonator as a function of applied voltage. The inset shows the output of the ring for 0V and 30V applied voltage.

4. TUNING MECHANISM

4.1. Theoretical considerations

When light travels in an anisotropic medium like LC, its refractive index $n = \sqrt{\varepsilon_r}$ is determined by the electric components of the light interacting with the relative dielectric constant of the material. The effective index of an SOI waveguide mode with LC top cladding is determined by the following equation:

$$n_{eff} = \Gamma_{Si} n_{Si} + \Gamma_{Ox} n_{Ox} + \Gamma_{LC} n_{LC} \quad (1)$$

Γ is the confinement of the light in the Si, the oxide or the LC. If we want to understand the mechanism behind the wavelength tuning in our devices, we need to take a close look at both the influence of the externally applied field on the dielectric constants and the field components of our optical modes. Our devices are designed for TE-polarized light, but the small dimensions of the waveguides do not allow a pure TE mode. Calculations show that next to the transversal E-field component (defined along the x-axis) there is also a reasonably big longitudinal component (z-axis) due to the strong confinement in the waveguide and a small normal component (y-axis). It may be clear that these components, more in particular the longitudinal component, will have an effect as well on the effective index of the mode and can not be neglected. The y-oriented component is in general very small and we will neglect its effects. All this can be seen in Fig. 5. where the electric field profiles are plotted along a horizontal cut through the waveguide (see dotted line in Fig. 1.).

In the previous section we have shown that the director of the LC lies parallel to the waveguide when there is no voltage applied. This means that in this situation the x-oriented field component feels a low value of the dielectric constant as it oscillates perpendicular to the long axis of the LC molecules. The z-oriented component of the light is oriented along the director and will therefore see a high dielectric constant. These two components will mainly determine the effective index of the waveguide mode. When a static electric field is present over the LC layer, the director will turn to align itself along the fieldlines. In our devices, one electrode is formed by the substrate and the other one by the ITO on the glass plate. The

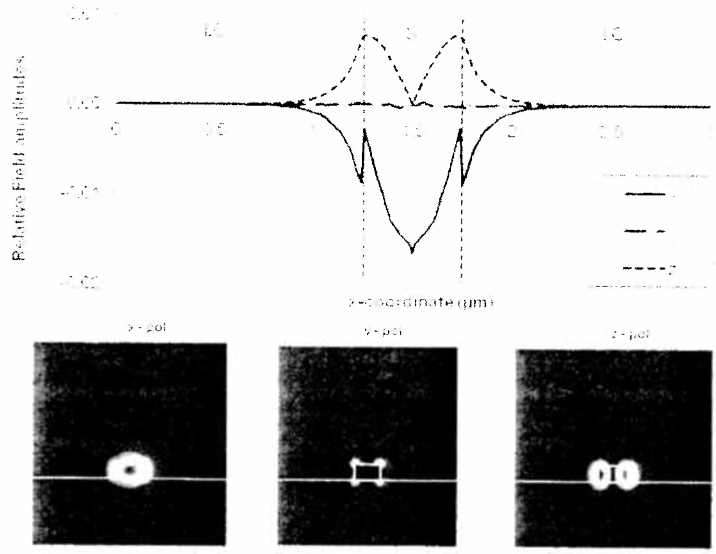

Fig. 5. (upper figure) Relative amplitude of the electric field components of the quasi TE mode in our waveguides. The field components are plotted along a horizontal cut through the waveguide. (lower figure) 2D-plots of the x-, y- and z-polarized E-fields.

fieldlines will therefore lie along the y-axis. Let's assume a situation where the field is strong enough to tilt all molecules to a vertical orientation. In this case the x-oriented field still oscillates along the short axis of the molecules and will see the same low value of the dielectric constant as before. The z-oriented component however will now no longer see the high value of the dielectric constant. As the molecules now are tilted vertically the longitudinal field will now also oscillate along their short axis. The effective index determined by these two components will now be lower than was the case without externally applied voltage.

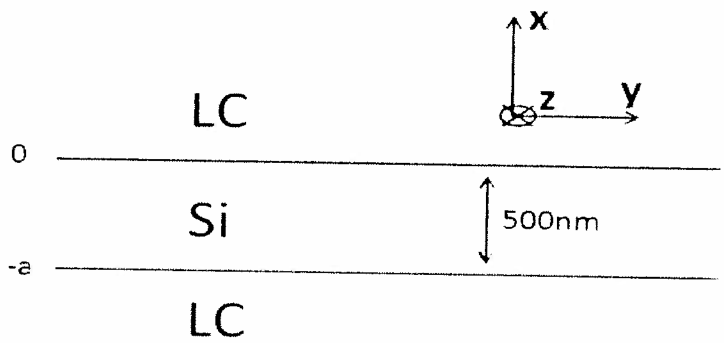

Fig. 6. Schematic view of a silicon slab waveguide flanked by LC.

To support this reasoning we calculate theoretically the effective index of the fundamental mode propagating in a 500nm wide slab waveguide flanked on both sides by LC (see Fig. 6.). We start from the Maxwell equations and use the dielectric tensor for 5CB. When the nine elements of the dielectric tensor are non zero, it is not possible to split this problem into a TE and TM part so the modes will be hybrid. We assume in our calculations that ε_{xy} and ε_{yz} are zero. This allows a separation of the problem. For the TE case, the problem is the same as in the case of an isotropic medium with refractive index determined by ε_{yy}. The TM case, which we will describe in detail, is interesting as it shows the influence of the longitudinal field component on the effective index. The longitudinal field component extends into the LC on both sides of the slab waveguide. We can write for the three regions:

$$h_{y1} = Ae^{(-\chi x)} \quad (2)$$
$$h_{y2} = B\cos(\kappa x) + C\sin(\kappa x) \quad (3)$$
$$h_{y3} = De^{(\chi(x+a))} \quad (4)$$

with

$$\kappa = \sqrt{\varepsilon_{Si}k^2 - \beta^2}, \quad (5)$$

$$\chi = \sqrt{\frac{\varepsilon_{xx}\varepsilon_{yy} - \varepsilon_{xy}^2}{\varepsilon_{xx}}}\sqrt{\beta^2 - \varepsilon_{xx}k^2} \quad (6)$$

a is the width of the waveguide, k is the wavevector and $\beta = n_{eff}k$.

The boundary conditions for the fields lead to a condition for the effective index n_{eff}.

$$-\frac{\chi}{\kappa} = \frac{-\sin(\kappa a)\kappa + \cos(\kappa a)\chi}{\cos(\kappa a)\kappa + \sin(\kappa a)\chi} \quad (7)$$

From this we can easily find the effective indices when the director is in the y- or z-direction. We find following values: $n_{eff} = 2.7552$ for a director along the propagation direction and $n_{eff} = 2.7273$ for a director along the y-axis. We see that indeed the effective index decreases when the director of the LC rotates from parallel to the propagation direction to it (y-axis).

4.2. Simulations

The calculation of the orientation of liquid crystal molecules in a random geometry and in the presence of an electric field is not an easy problem. Several equations need to be solved simultaneously. In this work we use a tool developed in collaboration between UGent and UCL. In this tool a variable order calculation[11] is used based on the minimization of the Landau-deGennes free energy functional[12]. The model is implemented in a finite-element scheme. The incorporation of the variable degree of order of the liquid crystal makes the program suited to model disclinations for which there is a rapid variation in the order parameter. Liquid crystals in combination with for example optical waveguides can be accurately modeled with this tool. Optical modeling of a waveguide surrounded by LC is also a difficult problem to tackle. The LC we use has a uniaxial anisotropy and in a general case the dielectric tensor can contain nine nonzero elements. Commercial tools exist but none of them can handle full anisotropy. The problem lies in the incorporation of longitudinal anisotropy. An asymmetry arises with respect to the propagation direction (the z direction), leading to off-axis energy transfer of the extraordinary polarization component[13,14,15]. We have developed in cooperation with UCL a mode solver that incorporates the full anisotropy of the dielectric tensor. The output of the liquid crystal calculation is used to calculate the modes. This calculation is based on the solution of the variational form of the curl-curl equation of the electric field, implemented with higher-order edge elements[16].

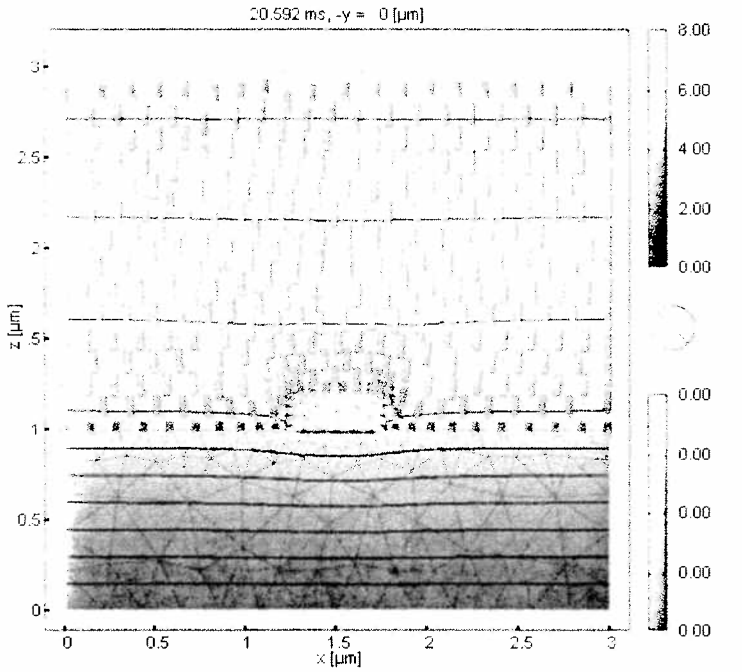

Fig. 7. Simulation of the orientation of the director. 8V is applied over the cell. The molecules can be seen to tilt upwards.

The two tools described above are used to calculate the modes in SOI waveguides clad with LC. We define a simulation space of 3μm x 5μm. The Si waveguide is 450nm wide and 220nm high and rests on a 2μm thick layer of SiO_2. The cell thickness is then 3μm. The electrodes are at the bottom of the SiO_2 and at the top of the LC layer. We use the program GiD to generate a mesh we can use to calculate the LC orientation. For 0V, the molecules tilt from the pretilt angle (2°) on the top alignment layer to 0° on the chip surface. For 10V, the director reaches a maximum tilt of 90° in the middle of the cell, dropping down to 25° on the chip surface. An example of this tilting can be seen in Fig. 7. The results of these calculations can be used as input for the optical modeling. In Fig. 8. we show the evolution of the effective index of the TE mode under increasing voltages. The result is a curve that is similar to the one found in the experiments. A threshold voltage is required to overcome the elastic forces. This Freedericksz transition is indeed observed. When the voltage increases, we see clearly a saturation effect. From the simulations we find that there is a strong dependence of the shape of the curve on the anchoring strength on the surface of the SOI chip. At a certain voltage, the wavelength shift will be larger when the anchoring is weaker as the molecules on the surface are allowed to tilt more. It is far from trivial to identify the exact values for the anchoring on an SOI surface. The simulations should therefore be seen as a confirmation of the mechanism rather than an exact representation of the reality.

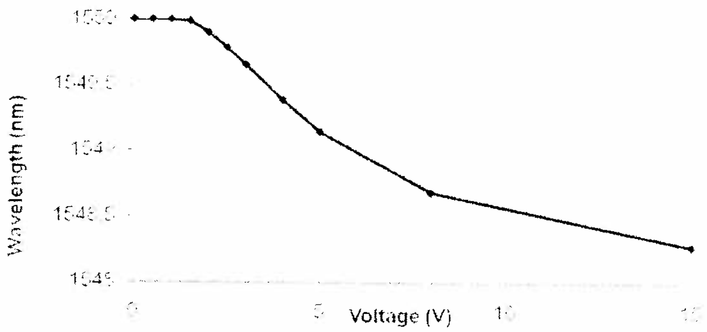

Fig. 8. Simulated shift of the resonance wavelength of the ring resonators.

4. CONCLUSION

We have shown tuning of SOI microring resonators with LC cladding. When voltage is applied the director of the LC shifts from an orientation parallel to the waveguides to an orientation perpendicular to it. This causes a blueshift in the resonance wavelength of about 0.6 nm. We explained the tuning mechanism by investigating the influence of the different field components of the mode on the effective refractive index. It appears that the longitudinal field component is the determining factor in the tuning. To our knowledge this is a new way to tune these extremely small optical structures. Simulations with a mode solver capable of handling full anisotropy back our experiments up.

References

[1] Dumon, P., Bogaerts, W., Wiaux, V., Wouters, J., Beckx, S., Van Campenhout, J., Taillaert, D., Luysaert, B., Bienstman, P., Van Thourhout, D. and Baets, R., "Low-Loss SOI Photonic Wires and Ring Resonators Fabricated With Deep UV Lithography", IEEE Photonics Technol. Lett. 16, 1328-1330 (2004)

[2] Roelkens, G., Liu, L., Van Thourhout, D., Baets, R., Nötzel, R., Raineri, F., Sagnes, I., Beaudoin, G., and Raj, R., "Light emission and enhanced nonlinearity in nanophotonic waveguide circuits by III–V/silicon-on-insulator heterogeneous integration", J. Appl. Phys. 104, 033117 (2008)

[3] Roelkens, G., Van Thourhout, D., Baets, R., Nötzel, R., and Smit, M., "Laser emission and photodetection in an InP/InGaAsP layer integrated on and coupled to a Silicon-on-Insulator waveguide circuit", Opt. Express 14, 8154-8159 (2006)

[4] Gan, F., Barwicz, T., Popovic, M. A., Dahlem, M. S., Holzwarth, C. W., Rakich, P. T., Smith, H. I., Ippen, E. P., Kartner, F. X., "Maximizing the Thermo-Optic Tuning Range of Silicon Photonic Structures", Photonics in Switching, 2007, 67-68 (2007)

[5] Maune, B., Lawson, R., Gunn, C., Scherer, A., Dalton, L., "Electrically tunable ring resonators incorporating nematic liquid crystals as cladding layers", Appl. Phys. Lett. 83, 4689-4691 (2003)

[6] Chigrinov, V. G., Zhou, L., Muravsky, A. A., Poon, A. W. O., "Electrically tunable microresonators using photoaligned liquid crystals", US Patent Application Publication, US 2007/0258677 A1, Nov. 8, 2007

[7] Falco, A., Assanto, G., "Tunable wavelength-selective add-drop in liquid crystals on a silicon microresonator", Opt. Commun. 279, 210-213 (2007)

[8] Desimpel, C., Beeckman, J., Neyts, K., Verstuyft, S., Van Thourhout, D., d'Havé K., and Rudquist, P. "Realization of a Four-Electrode Liquid Crystal Device With Full In-Plane Director Rotation" *IEEE Transactions on Electron Devices* 54 1295-1300 (2007)

[9] Desmet, H., Neyts, K., Baets, R., "Modeling nematic liquid crystals in the neigborhood of edges", J. Appl. Phys 98, 123517 (2005)

[10] Taillaert, D., Bienstman P., and Baets, R., "Compact efficient broadband grating coupler for silicon-on-insulator waveguides", Opt. Lett. 29, 2749-2751 (2004)

[11] James, R., Willman, E., Fernandez, F. A., and Day, S. E., "Finite-element modeling of liquid crystal hydrodynamics with a variable degree of order", IEEE T. Electron Dev. 53, 1575-1582 (2006)

[12] de Gennes, P. G., and Prost, J., [The Physics of Liquid Crystals], Oxford: Oxford University Press, 1995

[13] Gros, E. and Dupont, L., "Beam deflector using double-refraction in ferroelectric liquid crystal waveguides," Ferroelectrics 246, 219–226 (2000)

[14] Beeckman, J. , Neyts, K., Hutsebaut, X., Cambournac, C., and Haelterman, M., "Simulation of 2-d lateral light propagation in nematic-liquid-crystal cells with tilted molecules and nonlinear reorientational effect," Opt. Quant. Electron. 35, 95–106 (2005)

[15] Beeckman, J., Neyts, K., Hutsebaut, X., and Haelterman, M., "Observation of out-coupling of a nematicon," Opto-Electron. Rev. 14, no. 4, 263–267 (2006)

[16] Beeckman, J., James, R., Fernandez, F. A., De Cort, W., Vanbrabant, P. J. M., and Neyts, K., "Calculation of fully anisotropic liquid crystal waveguide modes", accepted to J. Lightwave Technol.

PROCEEDINGS OF SPIE

Liquid Crystals XIII

Iam Choon Khoo
Editor

2–5August 2009
San Diego, California, United States

Volume 7414

SPIE

Please use the following format to cite material from this book:
Author(s), "Title of Paper," in *Liquid Crystals XIII*, edited by Iam Choon Khoo, Proceedings of SPIE Vol. 7414 (SPIE, Bellingham, WA, 2009) Article CID Number.

ISSN 0277-786X
ISBN 9780819477040

Published by
SPIE
P.O. Box 10, Bellingham, Washington 98227-0010 USA
Telephone +1 360 676 3290 (Pacific Time) · Fax +1 360 647 1445
SPIE.org

Printed in the United States of America.

Publication of record for individual papers is online in the SPIE Digital Library.

SPIE Digital Library

SPIEDigitalLibrary.org

Paper Numbering: Proceedings of SPIE follow an e-First publication model, with papers published first online and then in print and on CD-ROM. Papers are published as they are submitted and meet publication criteria. A unique, consistent, permanent citation identifier (CID) number is assigned to each article at the time of the first publication. Utilization of CIDs allows articles to be fully citable as soon they are published online, and connects the same identifier to all online, print, and electronic versions of the publication. SPIE uses a six-digit CID article numbering system in which:

- The first four digits correspond to the SPIE volume number.
- The last two digits indicate publication order within the volume using a Base 36 numbering system employing both numerals and letters. These two-number sets start with 00, 01, 02, 03, 04, 05, 06, 07, 08, 09, 0A, 0B … 0Z, followed by 10-1Z, 20-2Z, etc.

The CID number appears on each page of the manuscript. The complete citation is used on the first page, and an abbreviated version on subsequent pages. Numbers in the index correspond to the last two digits of the six-digit CID number.