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Electrotunable in-plane one-dimensional photonic structure based on silicon and liquid crystal

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The model of the electro-optical effect, due to the reorientation of liquid crystal molecules from a pseudoisotropic to a homeotropic state, in a composite photonic structure with a liquid crystal filler, is elaborated. A composite (110) grooved silicon photonic structure for the middle infrared range was designed and fabricated on a silicon-on-insulator platform. Polarized reflection spectra, demonstrating the electro-optical effect, have been obtained by means of Fourier transform infrared microscopy. The relative shift of the band edge at half intensity in the region of 10 μm was found experimentally to be 1.6% compared to 2.2% as predicted by theory. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2430626]

For the last decade photonic crystals (PCs) have attracted a great deal of attention from the research community due to their ability to control the propagation of light in solid materials.[1–3] Silicon is the most attractive of the variety of different suitable materials due to the well developed fabrication technology and possible application of microstructured silicon elements for all silicon based photonics.[4] For many possible applications (such as tunable filters, optical switches, and waveguides) the tuning of PC properties during operation is extremely important. As photonic crystals consist of at least two alternating layers (components), tuning can be performed by changing the refractive index (n) of one of the components, which, in turn, will affect the position of the photonic band gap (PBG) or so-called stop band in the registered spectral range. The suggested recently approach[5] to use a combination of PCs with liquid crystals was the most prospective one for fabrication of tunable photonic devices. Since liquid crystals possess a quite significant birefringence in the infrared (IR) range (up to $\Delta n=0.2$), variation of the low refractive index has a much greater impact on the PBG shift than high refractive index variation $\Delta n=0.01$ (Ref. 6) depending on temperature.

Thermal or electric external forces are normally used for liquid crystal (LC) reorientation in photonic composite structures. However, the number of publications devoted to experimental investigations of the electrotuning effect is significantly less than the number of those devoted to the thermotuning effect and mainly deal with PC-LC composite structures such as LC-opal composite structures,[7–9] microporous Si-LC structures,[10,11] and multilayered one-dimensional (1D) PC with liquid crystal cavity.[12] This is, in particular, due to the difficulties with electric field application to the matrices based on electroconductive materials.

This letter is devoted to the design and fabrication of 1D PC-LC composite structures based on microstructured grooved Si for the molding of in-plane light propagation with a demonstration of the electrotuning effect.

To demonstrate this effect, we have chosen a periodic structure with a minimal number of periods $m=2$ (Fig. 1). As will be shown below, this number of periods is enough to reveal the electro-optical effect on the shift of the stop bands. For experimental convenience we have performed calculations of the reflection spectra, R, for structures with a lattice period $A=D_{\mathrm{Si}}+D_{\mathrm{LC}}=6$ μm (at $D_{\mathrm{Si}}=2.4$ μm and $D_{\mathrm{LC}}=3.6$). Spectra R were calculated using the transfer matrix method[13] (TMM) at normal incidence of light for the model shown in Fig. 1(a) at $n_{\mathrm{Si}}=3.42$, $n_{\mathrm{LC}}=1.56$, $m=20$ [Fig. 2(a), dotted line], and $m=2$ [Fig. 2(a), solid line] in order to demonstrate the difference in the reflection spectra of a two-period structure compared to a multiperiod 1D PC. In both cases the first stop band (or PBG) is located outside of the working region of our mercury cadmium telluride detector, which has a range of 1.5–15 μm, while the secondary PBGs are within this range and also have $R\approx 1$ due to the high optical contrast, $n_{\mathrm{Si}}/n_{\mathrm{LC}}=3.42/1.56$.[14,15] As can be seen from Fig. 2(a) the secondary high reflection bands correspond to the position of PBGs for the multiperiod 1D PC, but show slightly smaller values of R maximum (0.92–0.99) and less sharp edges.

Let us now model the variation of n_{LC} in the grooves from the pseudoisotropic ($n=\sqrt{(2n_o^2+n_e^2)/3}=1.56$) (Refs. 15 and 16) to the homeotropic ($n=1.49$) LC state and calculate the IR reflection spectra for the structure considered above, i.e., with $f=0.4$ and $m=2$. The calculated spectra R are shown in Fig. 2(b) in the wavelength range of 4–16 μm. The presence of only one interference peak between the regions of high reflection at 9.5 and 13 μm enables us to see the shift of the edges of these bands more clearly than for the structure with 20 periods shown in Fig. 2(a). The interesting fact is that the shift of both the edges for each of these stop bands has been revealed. In order to understand this phenomenon we plotted PBG maps.[3,17] These gap maps are based on the calculation of the reflection spectra for all possible f values (from 0.01 to 0.99) followed by the selection of regions, λ, with R values satisfying the condition $R>z$, where

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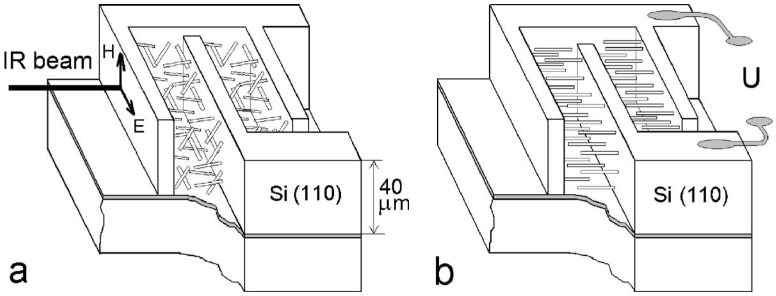

FIG. 1. Schematic of in-plane polarized FTIR reflection measurements of a composite photonic structure with two lattice periods based on a SOI platform for the electric (E) and magnetic (H) vectors of polarization. The two states of orientation of liquid crystal in the grooves are also shown: (a) pseudoisotropic and (b) homeotropic.

z is the criteria of the region selection. For the multiperiod PCs z value is very close to 1 (for example, 0.99), for structures with two periods we chose $z=0.9$ in order to clearly demonstrate the shift of the stop band due to the influence of the electric field on LC orientation. A fragment of the gap map constructed for the periodic structure with $m=2$ is presented in Fig. 2(c). As was expected, all regions of high reflection are blueshifted when the values of n_{LC} are varied from 1.56 to 1.49. By drawing lines at $f=0.4$ and $f=0.1$, which intersect a number of PBG regions, one can see three possible cases of PBG edge shift, namely (i) only the short wavelength edge is shifted, (ii) only the long wavelength edge is shifted, and (iii) both edges are shifted. Therefore, based on the gap map analysis, one can expect the appearance of different types of shifts of the reflection spectra edges. The value of $f=0.4$ was chosen to reflect the real technological conditions for the experimental verification of the electro-optical effect on one of the secondary bands of high reflection.

A silicon-on-insulator (SOI) wafer was prepared from (110)-oriented silicon (see schematic in Fig. 1). It consisted of a 40 μm thick upper n-type Si layer ($\rho=5\ \Omega$ cm), a 2 μm thick $\mathrm{SiO_2}$ insulating layer, and a 500 μm thick (110) silicon substrate. Structures with three vertical walls were etched in the top Si layer in a hot KOH solution through a surface oxide mask (see Ref. 14 for details). The LC used was the nematic liquid crystal mixture E7, based on cyano-biphenyl, manufactured by Merck with birefringence $\Delta n=0.2$ in the IR spectral range.[18] Infiltration into the grooves was performed at room temperature.

In order to apply an external voltage to the LC filler, the Si ribs were arranged in an interdigital configuration. Si electrodes were connected to the outer pads by attaching thin metal wires to the chip contact areas with a silver paste [Fig. 1(b)]. The frequency and duration of the impulse were 100 Hz and 1 ms, respectively. The reflection spectra measurements were performed using an FTS 6000 Fourier transform IR (FTIR) spectrometer in conjunction with an UMA IR microscope in the range of 1.5–15 μm (see Ref. 14 for details). The effect of LC reorientation (Fredericks transition) was originally observed by polarized optical microscopy with an initial applied electric field of 2 V and a threshold voltage at ~2–3 V. However, for FTIR measurements the applied electric field was 10 V for reliability. The response time estimated under applied square shaped ac pulses of various frequencies was found to be around 30 ms which is in agreement with the known value for nematic LC E7.[18]

Reflection spectra of the empty grooved Si matrix were measured at H- and E-polarized lights; this was followed by the fitting procedure using the TMM method. This procedure enables us to obtain more precise values of the wall and groove thicknesses. The grooved matrix was then infiltrated with LC E7 and the reflection spectra of the composite structure were measured at different polarizations and different voltages. The reflection spectra demonstrating the electro-optical effect for the investigated structure are shown in Fig.

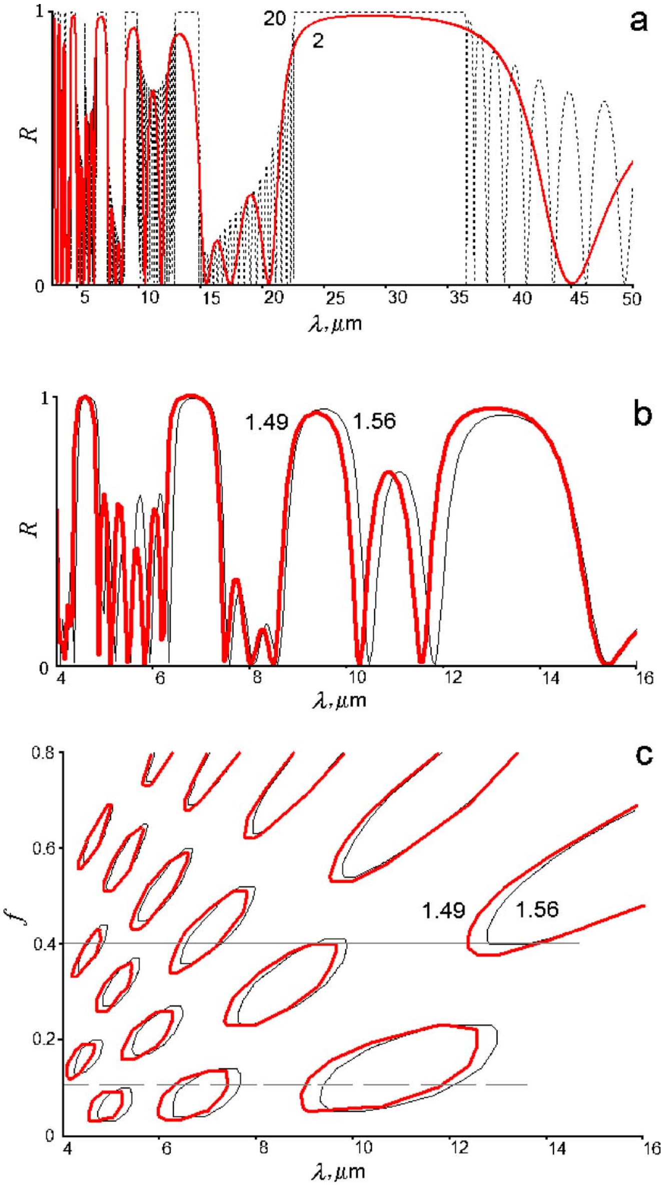

FIG. 2. (a) Calculated reflection spectra of 1D PCs based on grooved silicon with $f=0.4$ and number of periods $m=2$ (solid line) and $m=20$ (dotted line) filled with liquid crystal ($n_{\mathrm{LC}}=1.56$). (b) The calculated reflection spectra for a composite photonic structure with $m=2$ with refractive index values $n_{\mathrm{LC}}=1.56$ (thin line) and $n_{\mathrm{LC}}=1.49$ (thick line). (c) The gap map fragments of PBGs with high reflection regions ($R>0.90$) calculated for a photonic Si–LC structure with $m=2$, $A=6\ \mu$m, $n_{\mathrm{LC}}=1.49$, and 1.56 at normal incidence of light.

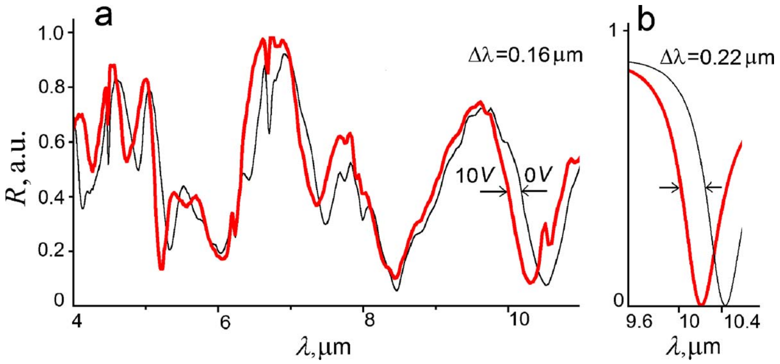

FIG. 3. (a) Experimental and (b) calculated (part of the secondary stop band) the *E*-polarized reflection spectra in *E* polarization, without (0 V, thin line) and with (10 V, thick line) an applied electric field for composite photonic structure based on grooved Si filled with LC E7 with two lattice periods.

3 (for simplicity only the *E*-polarization is shown). However, exactly the same effect has been observed for *H*-polarized spectra.

The comparison of the experimental [Fig. 3(a)] and calculated [Fig. 2(b)] spectra demonstrates a good agreement between the positions of the main reflection bands. It is important to note that the shift of the experimental reflection bands at 0 and 10 V was observed in the whole spectral range for practically all bands of high reflection as was predicted from the calculated spectra shown in Fig. 2(b). The electro-optical effect was estimated for the long wavelength edge of the calculated [shown in detail on Fig. 3(b)] and experimental [Fig. 3(a)] secondary stop band in the region of $\sim 10\ \mu$m. The calculated shifts are $0.22\ \mu$m and $\Delta\lambda/\lambda = 0.22/10.15 = 2.2\%$ in relative shift units. The experimental electro-optical shifts estimated in the same way are $0.16\ \mu$m and 1.6%, respectively.

Thus, in this letter we have shown that for grooved Si-LC 1D composite photonic structures the shift of the stop-band edge under an applied electric field is quite large even for a transition of the LC from pseudoisotropic to homeotropic alignment. The relative shift of the band edge at half intensity in the region of $10\ \mu$m was estimated as being 2.2% theoretically and 1.6% experimentally.

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