Tunable Liquid Crystal-Resonant Grating Filter Fabricated by Nanoimprint Lithography

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***Abstract*—We demonstrate a tunable filter consisting of a subwavelength resonant grating filter cladded by a liquid crystal cell. The resonant wavelength of the grating filter is tuned by electrically varying the refractive index of the liquid crystal. A tuning range of around 20 nm has been achieved.**

***Index Terms*—Gratings, liquid crystal devices, resonant waveguide grating filter, tunable filter.**

I. Introduction

Subwavelength resonant grating (SRG) filter [1]–[4] is a reflective narrowband optical filter using a layer of gratings with the feature size smaller than the wavelength of light so that there is no diffraction loss [5]. For a SRG filter with fixed geometry, refractive indices and incident angle, its resonant wavelength is fixed. Yet, there is a great need to make a SRG filter tunable, as such filters are attractive to many applications from optical modulators [6] to tunable lasers [7] because of its inherently simple and compact structure, and narrow and sharp reflection peak. A simple way to tune SRG resonant wavelength is to change the incident angle [8], but the reflection angle will change accordingly as well, making signal collection complicated; it is also undesirable when a normal reflection is needed (e.g., feedback for lasers [7]). Tunable resonant gratings based on microelectromechanical systems are recently proposed and investigated numerically [9]. An alternative is to have an SRG that can be electro-optically tuned through a voltage bias.

It is known that the resonant wavelength of a SRG is sensitive to the refractive indices of the grating, as well as its adjacent cladding layer [10]. Therefore, a change in index of the cladding layer can change the resonant wavelength. This can be exploited to implement a tunable SRG filter if an active layer with a tunable index is incorporated into the grating structure. It was previously demonstrated that electrical current through a semiconductor SRG can be used to tune its resonant wavelength [11] and a tuning range of 0.8 nm is achieved. A similar tuning range has been demonstrated using thermally tuned SRG [12]. By incorporating the electro-optic polymer DR1 into a resonant grating structure, an optical modulator was demonstrated [13]. To dramatically increase the tuning range, the use of liquid crystal is attractive as it has, with proper anchoring, some of the largest known electro-optic coefficients. If nematic liquid crystal is used as the grating cladding layer, the resonant wavelength of the filter can be tuned electrically since an applied electric field changes the extraordinary index of the liquid crystal seen by the incident light [14], [15].

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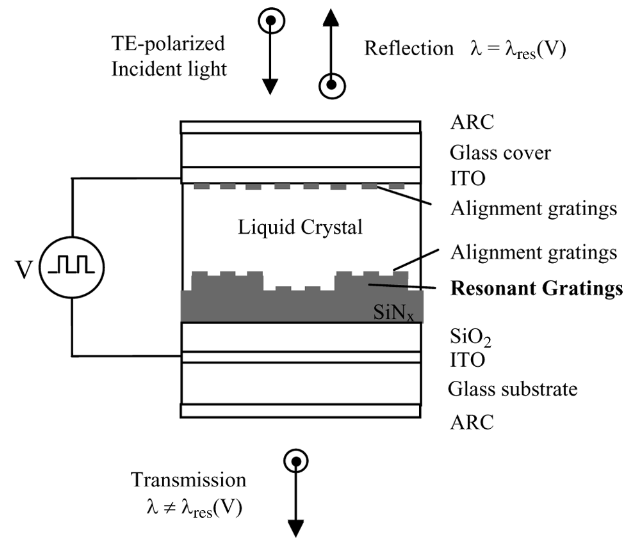

Fig. 1. Schematic of a tunable LC-SRG filter incorporating a SIGs structure.

Here, we present a tunable SRG implemented by superimposing a short-pitch gratings for aligning liquid crystal molecules onto a larger-pitch SRG. This device is tuned directly by voltage, has no moving part, is very compact and compatible with standard high-throughput silicon processing and, in particular, nanoimprint lithography, therefore, it is potentially low cost and can be integrated with other components. A tuning range of 20 nm has been achieved.

II. Experiments

The schematic of the tunable liquid crystal-subwavelength resonant grating (LC-SRG) structure is shown in Fig. 1. It consists of two gratings: a shallow, short-pitch grating for liquid crystal alignment superimposed onto a deeper, larger-pitch resonant grating, both are patterned onto a silicon nitride (SiN_x) thin-film layer. The two gratings are parallel. Nematic liquid crystal is introduced on top of the superimposed gratings (SIGs). The two indium tin oxide (ITO) layers serve as the low optical loss electrodes to apply an electric field across the liquid crystal cell. The purpose of the silicon dioxide (SiO_2) layer is to isolate the resonant grating from the ITO on the substrate. The thickness of the liquid crystal cell is controlled by spacers (not shown in Fig. 1) between the resonant gratings and the glass cover, and the glass cover also has a layer of SiN_x gratings patterned on the liquid crystal side to align the liquid crystal molecules. The bottom of the substrate and the top of the cover are both coated with commercial anti-reflection coatings (ARC).

Assume that TE-polarized (electric field parallel to grating) light is normally incident upon the structure and that the orientation of the director of the nematic liquid crystal is initially planar-anchored along the grating lines. When the external applied field is off, the incident light sees the refractive index of the long axis of the liquid crystal molecule, and the resonant grating filter will have a corresponding resonant wavelength. When the applied field is turned on to above the Frederiks transition threshold, the director reorients at an angle according to the amplitude of the applied field, and the incident light will see a new index of the liquid crystal. The resonant wavelength of the filter will, thus, be blue-shifted as the effective index of the cladding decreases.

The period of the resonant grating is determined by the desired operating wavelength range which should be around 1 μm for operation around 1500–1600 nm. However, the strength of liquid crystal anchoring is known to increase with shorter anchoring grating period [16]. Thus, a smaller period (200 nm) grating of shallow depth (20–40 nm) is superimposed onto the larger period resonant grating to improve anchoring. A deep submicron-pitch alignment grating is very effective in achieving anchoring [17], and the order parameter attained by using deep submicron pitch gratings can be substantially larger than that obtained by a 1-μm pitch grating [18]. As the shorter period is deeply subwavelength compared with the incident light, it has little effect on the resonance of the larger period grating.

In the fabrication of the SIG used in LC-SRG, an ARC-coated quartz substrate with a thickness of 0.5 mm is coated (on the other side) commercially with an ITO layer with a measured resistivity of 110 Ω per square. Then, 500 nm of SiO_2 is deposited on the ITO by plasma-enhanced chemical vapor deposition (PECVD), followed by PECVD of 450 nm of SiN_x. The 200-nm pitch gratings is imprinted into spun-on resists by thermal nanoimprint lithography, using a mold prefabricated by interference lithography. A thin residual resist layer is removed by O_2 reactive ion etching (RIE). Electron-beam evaporation of 5 nm of Cr is then carried out, followed by liftoff of unwanted resist lines by immersing the sample in warm acetone. The gratings are then transferred into the underlying SiN_x layer by fluoride-based RIE process and followed by the strip-off of Cr using Cr-7.

To obtain the final SIG structure, nanoimprint resist is then directly spun on the sample, and 1-μm pitch gratings is imprinted by thermal nanoimprint lithography. The alignment of orientation of the second-level mold relative to the 200-nm gratings is done by visually aligning the wafer flats to within 0.5°. In this approach, only the orientations of the two sets of gratings need to be aligned, and they are aligned parallel to each other. Our LC-SRG filter does not require the relative positional alignment between the first and second levels. Again, a thin residual resist layer is removed by O_2 RIE.

The 1-μm gratings is transferred into the silicon nitride (with the 200-nm gratings already prefabricated in it as described above) by fluorine-based RIE using the imprinted polymer grating lines as etching mask. During the anisotropic RIE, the 200-nm gratings is preserved. Finally, the remaining polymer resist is washed away by solvents. The tilt-angle scanning electron microscope (SEM) image of a SIG is shown in Fig. 2. The image shows that the depth of the 200-nm period gratings is about 30 nm, while the 1-μm gratings are etched 100 nm.

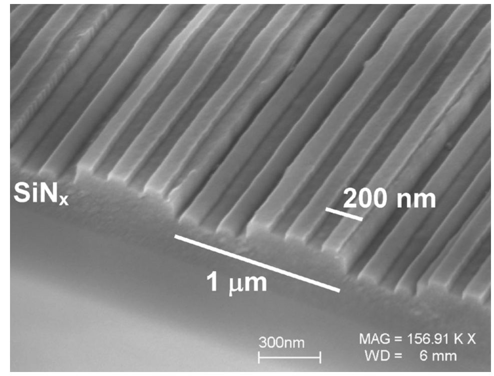

Fig. 2. Tilt-angle SEM image of SIG structure fabricated by a double nanoimprint lithography process. The longer gratings has 1-μm period and 100-nm depth. The shorter gratings has 200-nm period and 30-nm depth.

After the fabrication of SIG, a liquid crystal cell is assembled on top using commercially available Mylar polyester film (DuPont) of 2.5 μm in thickness and an ITO-coated glass cover to confine the liquid crystal on top of the SIG. On the ITO-coated glass cover, a 200-nm pitch anchoring grating in PECVD SiN_x is fabricated by nanoimprint. The commercially available liquid crystal E7 (Merck) is sucked into the cell through capillary force while the entire cell is maintained at a temperature of 80 °C, which is above the nematic-isotropic transition temperature of E7. The liquid crystal E7 has $n_{||} = 1.75$ and $n_{\perp} = 1.52$, giving a maximum Δn of 0.23. After the liquid crystal is filled, its temperature is slowly ramped down to room temperature at rate of -5 °C/hr.

III. Results and Discussion

We then measured the optical spectra of the assembled LC-SRG at different applied voltages to the liquid crystal cell using an optical spectrum analyzer at room temperature. A broadband light-emitting diode (LED) light source is used in our experiments and the resolution of the OSA is 0.06 nm. The light from the LED is polarized by a polarizer which has an extinction ratio of 30 dB. The light is incident upon the sample at normal incidence and polarized parallel to the gratings. Square wave AC voltage with a frequency of 2 kHz is used to drive the device.

Fig. 3(a) shows the measured transmittance of the LC cell at applied voltages of 0, 12.5, and 20 V. The tuning curve of the device is given in Fig. 3(b). When no voltage is applied ($V = 0$), the filter resonance occurs at a wavelength of 1596.88 nm. The full-width-half-maximum (FWHM) of the filter is around 1.5 nm at 0 V. The resonance starts to tune when the applied voltage amplitude reaches about 3 V, indicating that this is the Frederiks transition threshold for this particular liquid crystal cell. The data shows that the tuning range can reach 20 nm when a voltage of around 20 V is applied which blue-shifts the resonance to 1576.76 nm. The FWHM increases to around 1.75 nm possibly due to increased index contrast between liquid crystal

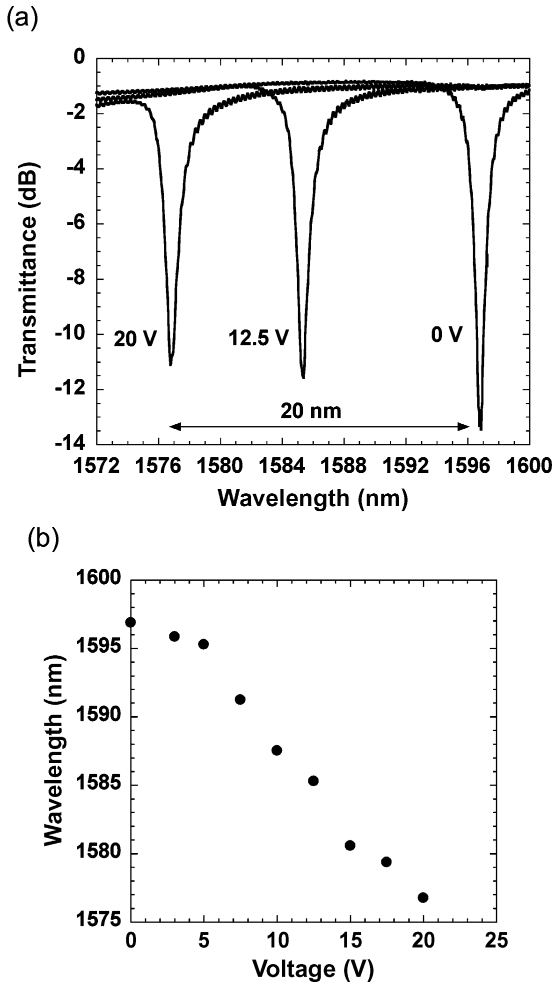

Fig. 3. (a) Measured optical transmittance of the tunable LC-SRG filter at applied voltages to liquid crystal cell of 0, 12.5, and 20 V. (b) Tuning curve of the LC-SRG filter.

and SiN_x grating. The background transmittance loss of around 1–2 dB is due to interfacial reflections, absorption loss in the ITO layer and scattering loss in the liquid crystal. The contrast of the transmittance dip is decreased from 12 dB at 0 V applied voltage to 10 dB at 20 V, possibly due to increased scattering loss in the liquid crystal.

The tuning range of this device is limited by birefringence of the liquid crystal molecule and the anchoring. The reorientation of the director of the liquid crystal under an applied electric field attains its maximum value at the middle of the cell. At the boundary, it is identically zero given ideal anchoring. However, the orientation of liquid crystal molecules closest to the resonant grating, i.e., a boundary of the cell, has the most impact on the resonance location. Thus, the actual tuning range may not attain the ideal maximum allowed by the birefringence of the liquid crystal. In addition, nonideal, finite strength anchoring may also limit the actual refractive index change when the electric field is applied.

An advantage with the SIG structure described here is that the alignment grating and the resonant grating are functionally separated and both can be designed and optimized individually for their respective purpose, making it a general and versatile approach. For example, should a larger pitch (>1 μm) resonant grating be required, the superimposed alignment grating can assure that good liquid crystal anchoring is maintained. Furthermore, the SIG approach can be adapted to other periodic structures requiring liquid crystal alignment and is not restricted to resonant gratings.

IV. Conclusion

In summary, tunable subwavelength resonant grating filter with superimposed alignment gratings on top of the resonant gratings and with liquid crystal E7 cladding as the tuning layer has been demonstrated. The filter has a 20-nm tuning range and 1.5-nm FWHM. The tuning range may be further increased through optimizing the liquid crystal anchoring mechanism and/or using liquid crystal with larger birefringence.

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