Optically tuned resonant optical reflectance filter

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We describe the design, fabrication, and characterization of a narrow band tunable guided mode resonance (GMR) reflectance filter that is actuated by optically induced trans-cis isomerization of an azobenzene liquid crystal. Constructing a plastic replica-molded containment cell with a rubbed polyimide film to initially direct the liquid crystal molecular orientation parallel to the grating lines of the GMR filter, isomerization caused by exposure to a \( \lambda = 532 \) nm laser results in a \(-25\) nm shift of the resonant reflected wavelength. © 2008 American Institute of Physics. [DOI: 10.1063/1.2890713]

Guided mode resonant (GMR) filters represent a novel and a unique class of reflectance filters that are capable of reflecting a narrow resonant band of wavelengths with nearly 100% efficiency for wavelengths spanning from UV to IR.2−7 GMR filters can exhibit the same bandwidth and reflection efficiency as multilayer Bragg filters, but can be fabricated using a one-dimensional (1D) or two-dimensional periodic grating structure combined with a single high refractive index thin film deposition using either lithography8,9 or plastic-based replica molding10,11 to form the required subwavelength grating structure. Since the demonstration of the first static GMR filters,12,13 efforts have been made to incorporate materials with variable refractive index that can be controlled either optically14 or electrically15−19 that can result in a filter with properties that are tunable. Applications for tunable filters include laser eye protection, optical limiting for sensor protection,20 optical switching, video display, and optical memory, where selective opening or closing of an optical passband can be utilized. Suitability of tunable GMRs for these applications will be determined by the extent of wavelength tuning, tuning speed, and the cost of efficiently fabricating GMRs over large surface areas.

In this work, we describe the design, fabrication, and characterization of a tunable GMR in the visible wavelength range that is fabricated with a plastic-based nanoreplica molding process on flexible substrates that incorporates an azobenzene liquid crystal (azo-LC) as a variable refractive index material that is actuated by exposure to a pump laser beam. A \(-25\) nm resonant wavelength shift is obtained that maintains its state after the pump laser is turned off.

Azobenzene liquid crystals are a unique class of material that incorporate novel features from both liquid crystals and azobenzene molecules.21 They have the long range ordering of liquid crystals, such as the nematic mesophase, while simultaneously exhibiting photo isomerization between trans- and cis-configurations typical of azobenzene molecules. Absorption of electromagnetic radiation at the correct wavelength range enables photo isomerization which changes the refractive index properties of the bulk material.

The device cross section schematic is shown in Fig. 1. A 1D periodic grating is produced using UV-cured polymer (UVCP) material on a polyethylene terephthalate (PET) substrate. A thin film layer of titanium dioxide (TiO2) is deposited over the UVCP grating. Facing the grating structure from above is an upper PET substrate containing a replicated spacer that sets the gap distance between the grating structure and the upper substrate, and polyimide (PI) film for liquid crystal alignment. The two PET substrates are hermetically sealed creating an empty cavity into which azo-LC material is subsequently injected. In this letter, the \( z \) direction is vertical to the device substrate, the \( x \) direction refers to the direction perpendicular to the grating lines, and the \( y \) direction is parallel to the grating lines as shown. Light is incident upon the structure from the bottom, propagating in the +\( z \) direction with its electric field parallel to the grating lines (TE mode). At the resonant wavelength for TE illumination, an optical standing wave develops with its electric field oriented in the \( y \) direction. The wavelength of resonant reflection is referred to as the peak wavelength value (PWV). The rubbed PI film homogeneously aligns the azo-LC parallel to the grating lines. Exposing the azo-LC to 532 nm illumina-

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FIG. 1. (a) A cross section schematic view of the device is shown. The grating period is \( \Lambda = 370 \) nm with a height of \( d = 55 \) nm. The TiO2 thickness is \( t = 90 \) nm and the LC cell is \( L = 5 \) \( \mu \)m thick. (b) The experimental pump probe diagram is illustrated. Incident light (broadband or HeNe laser) travels through a polarizer and illuminates the device. The transmitted light is coupled to a spectrometer or photodiode. A cw Nd:YVO4 pump laser is used.
ation will induce photoisomerization from *trans* to *cis*. This change causes a decrease in the refractive index of the azo-LC layer along the *y* direction. As a result, the TE PWV will shift to shorter wavelength values.

The resonance filter was fabricated by employing a nanoreplica molding process using a silicon "master" wafer as a mold template. The silicon master is an 8-in.-diameter wafer upon which a linear grating structure with a period of 370 nm and a ~50% duty cycle is patterned by deep-UV photolithography over an ~5 x 5 in.² area. The grating pattern is etched into the silicon wafer to a depth of 70 nm by reactive ion etching. A layer of liquid acrylate UVCP was drop coated on top of the silicon master. The PET substrate is then placed over the silicon master, and is then pressed over the master using a rolling cylinder. This enables the UVCP drops to form a thin continuous layer between the two surfaces and conform to the features of the master. After this has been achieved, the UVCP is cured using a UV lamp for 90 s. Next, the PET substrate is released from the master and a cured UVCP layer with a period of *λ*=370 nm and a duty cycle of ~50% is replicated on the PET substrate. Subsequently, TiO₂, serving as the high index layer, was deposited in Fig. 2, for a difference of 091115-2 Yang et al.

incident. Since the PWV is sensitive to the angle of incidence of incoming light, it is possible to shift the PWV so that it spectrally overlaps with the 632 nm emission line of the HeNe laser. A Si photodiode is placed at output end of the device to collect the transmitted 632 nm light. The photodiode is connected to an oscilloscope and the data are recorded using a custom LABVIEW program. Initially, most of the 632 nm light is transmitted by the device and a maximum signal is observed from the photodiode. When the pump laser is turned on, the PWV shifts and spectrally overlaps with the 632 nm light. Thus, the light from the HeNe is blocked by the device, and the photodiode signal decreases and stabilizes at ~0 V, as shown in Fig. 3. From the data, the response time of the device is 80 ms and the contrast ratio between on and off values is 100:1. The contrast ratio corresponds to a reflection efficiency of at least 99% for the reflectance filter. In addition, the time dependence of the PWV shift on the pump laser power was investigated. A continuously variable neutral density filter was placed in front of the pump laser, and a Si power meter was used to measure the amount of pump power incident on the device. Figure 3 (inset) illustrates that the time it takes for the PWV to shift decreases nonlinearly with increasing pump power. The spectral change of the HeNe laser transmission was also observed by replacing the photodiode with a spectrometer as previously described. Figure 4 shows the initial spectrum of the laser with a reduced transmitted intensity at 632 nm due to the PWV. Notice that the HeNe laser also has an emission line at 612 nm. This emission wavelength is initially allowed to pass. After the filter is pumped with the 532 nm laser, the PWV shifts to 612 nm and blocks that wavelength while allowing the 632 nm light to transmit.

![FIG. 2. Transmission spectrum illustrating TE PWV shift. The initial (solid) and final (dotted) spectra indicate a shift of ~25.39 nm due to trans-cis photoisomerization of azo-LC. The transmission efficiency is below 10%.](http://apl.aip.org/apl/copyright.jsp)
The time response is determined by the mechanism by which the azo-LC undergoes photoisomerization upon exposure to 532 nm radiation. Absorption of the pump laser light by the azo-LC molecules changes their phase from nematic (trans) to isotropic (cis). Thus, the refractive index of the azo-LC layer changes which shifts the PWV. The azo-LC director is initially along the grating lines due to the rubbed PI film. Thus, the refractive index is $n_{\text{cis}} = 1.57$. After photoisomerization, the refractive index is $n_{\text{trans}} = 1.726$. After photoillumination of 532 nm radiation, absorption of the pump laser light on flexible substrates using nanoreplica molding. The reflected wavelength was optically tuned over 25 nm using a 532 nm cw laser. Tuning was achieved by incorporating a layer of azo-LC which changed its refractive index upon illumination of 532 nm radiation.

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