Optical filters fabricated in hybrimer media with soft lithography

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Fabrication and characterization of guided-mode resonance filters made by soft lithography are presented. As these resonant elements are highly sensitive to parametric variations, it is important to develop methods for their reliable fabrication. Thus, we provide a fabrication process that is consistent and simple, employing an elastomeric mold and a UV-curable organic–inorganic hybrid material. Measured spectra show ~81% reflectance and ~8% transmittance at a resonance wavelength of 1538 nm. The filter's linewidth is ~4.5 nm, and the sideband reflectance is ~5%. Experimental and theoretical results are in good agreement.

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Methods of microscale and nanoscale patterning can be applied to fabricate a variety of optical devices. Periodic layered structures are found in integrated optics, communication systems, spectroscopy, lasers, and in many other important optical systems. Diffractive optical elements and photonic crystals consist of fine periodic patterns affecting the spectrum, polarization, phase, and amplitude of light. Often, holographic interferometry, or direct electron-beam patterning, is used to define the periodic structure. As an alternative method, soft lithography has been shown to be effective for fabricating and transferring periodic patterns and structures as reported in recent papers [1–8]. Accordingly, in this Letter, we present resonant narrowband optical filters fabricated by soft lithography in hybrimer compounds.

We employ a new material system for fabricating the optical filters. As reported previously, a hybrimer is a typical organic–inorganic hybrid material fabricated using a solgel process [9,10]. Details of the process can be found in [11]. Hybrimers have several advantageous properties, including high modulus, low surface tension, low shrinkage, and high etching resistance. In particular, they have been reported to have excellent optical properties including high transparency (>90% in the visible region), controllable refractive indices, low optical loss (<0.2 dB/cm), low birefringence ($\sim 10^{-4}$), and low viscosity compared to common UV-curable polymers [11,12]. Also, these materials possess thermal stability beyond 300 °C. The versatile properties of hybrimers offer new options for practical applications related to micro-optical devices. In the case of the fluorinated hybrimer used in this paper, an organoalkoxysilane precursor functionalized with a perfluoroalkyl chain is used in the solgel reaction to lower surface tension of the final compound. Hybrimers qualify both as molds and as resists in nanoimprint lithography [10]. Significantly, there is no additional chemical treatment needed to release the mold because of the presence of fluorine molecules in the hybrimer compound.

Thus, under study are guided-mode resonance filters fabricated by soft lithography with these hybrimer materials. The term guided-mode resonance (GMR) refers to a rapid variation in the intensities of the electromagnetic fields in a periodic waveguide, or photonic crystal slab, as the wavelength or the angle of incidence of the excitation light is varied around their resonance values. A resonance occurs when incident light is phase matched to a leaky guided mode allowed by the waveguide–grating structure [13]. Devices based on resonant waveguide modes have been theoretically predicted and experimentally verified [13–20]. However, these verified devices were made with conventional materials and processes.

Figure 1 shows a schematic procedure for fabrication of a GMR device using the micro-molding-in-

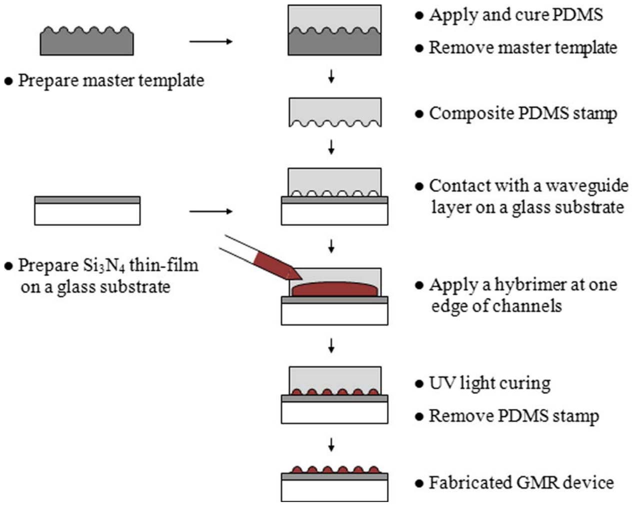

Fig. 1. (Color online) Schematic fabrication process yielding a GMR filter by MIMIC [1].

capillaries (MIMIC) method. MIMIC is one of several soft lithography methods proposed by Whitesides and co-workers, and it is simple to apply [1,2]. The first step in the fabrication is preparing a master template, which has the grating structure on a surface of a silicon wafer or a glass substrate. For the results reported here, we use a commercial holographic grating (Newport Co., 900 grooves/mm) as a master template. This grating has 1111 nm grating period and ~340 nm grating depth. The grating has a sinusoidal profile.

As an elastomeric mold, polydimethylsiloxane (PDMS) is commonly used in soft lithography. We apply composite polymeric stamps as elastomeric molds to achieve quality patterning. Details of fabrication processes and issues, including pattern collapse and deformations, are discussed in [3–5]. The composite stamps consist of two parts; one part is hard-PDMS (h-PDMS), which has different mechanical properties than Sylgard 184 silicone elastomer from Dow Corning, popularly used. The other part is Sylgard 184 PDMS. The h-PDMS is prepared as described in [4]. This h-PDMS prepolymer is spin coated on a commercial holographic grating and cured in an oven. Then we pour a prepolymer of Sylgard 184 silicone elastomer on the h-PDMS layer and cure it in an oven again. Therefore, a pattern with a negative replica of the master template is formed on the h-PDMS surface.

The 10 mm × 10 mm composite mold is placed in contact with a silicon nitride thin film on a glass substrate. The silicon nitride film, prepared by plasma-enhanced chemical vapor deposition, serves as the waveguide layer of the GMR device. A diluted hybrimer is prepared to obtain a lower viscosity prepolymer. A few drops of the UV-curable hybrimer are applied at one edge of the patterned surface of the composite mold as indicated in Fig. 1. The applied hybrimer spreads through the channels, which are formed by contact between the patterned mold and the thin-film layer on the substrate. Then we put the composite mold set into the vacuum chamber and let it remain in low vacuum (~450 Torr) for 12 h such that the channels fill with the hybrimer prepolymer by capillary force. Subsequently, the hybrimer in the h-PDMS channel is cured using a UV lamp (central wavelength $\lambda = 365$ nm). A surface-relief-type grating structure remains on the silicon nitride film after the composite mold is peeled off.

A tunable laser is used to measure the spectral response. We set the angle of incidence (θ_{in}) at 10° to locate the resonance wavelength of the GMR device within the operating spectral range of the laser. Next, we measure the reflected and transmitted power in the wavelength range of 1450 nm to 1590 nm in 0.5 nm steps. A polarizer is used to set the polarization state.

Figure 2 shows the experimental spectral response of the fabricated device. The resonance wavelength (maximum point of reflectance or minimum point of transmittance) is $\lambda = 1538$ nm, and the reflectance at resonance is ~81%. The FWHM linewidth is ~4.5 nm, and the sideband reflectance is ~5%. The transmittance at resonance is ~8%. These results pertain to the transverse-electric (TE) polarization state of the input light.

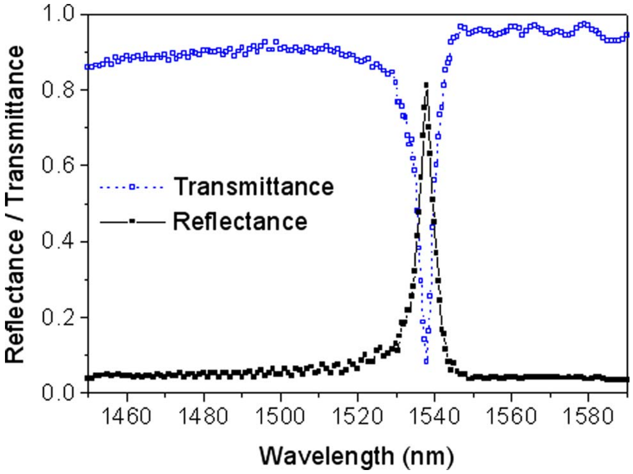

Fig. 2. (Color online) Experimental spectral response of a fabricated GMR filter for TE polarization (electric field normal to the plane of incidence). The experimental data are corrected for a 4% reflection at the backside of the substrate.

Figure 3 shows the calculated spectral response of the fabricated GMR device whose model is shown as an inset. The calculations are performed with a computer code based on rigorous coupled-wave theory [21]. The device parameters used in Fig. 3 correspond to the experimental values used in the fabrication. The calculated resonance wavelength is $\lambda = 1541$ nm at $\theta_{\mathrm{in}} = 10.0°$, and the FWHM linewidth is 4.4 nm. The calculated reflectance at resonance is ~82%. This non-100% reflection is due to the presence of a higher-order transmitted wave at resonance as shown in Fig. 3 and noted as T_{+1}. As quantified in [22], small variations in the device parameters and the angle of incidence can shift the location of the

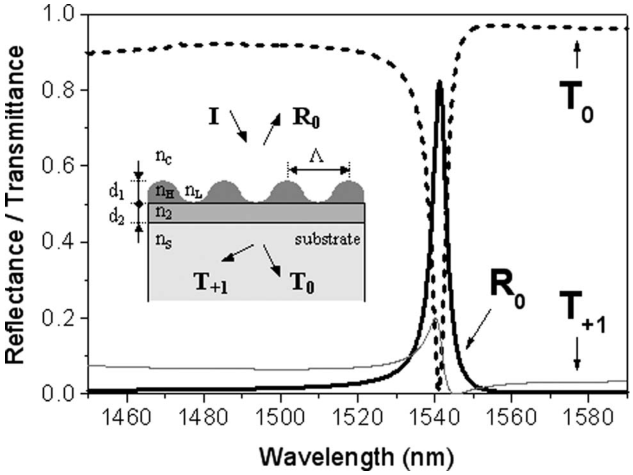

Fig. 3. Calculated spectral filter response with parameters corresponding to those of the fabricated filter for TE polarization. The parameters are as follows: thicknesses $d_1 = 333$ nm, $d_2 = 251$ nm; refractive indices $n_{\mathrm{H}} = 1.51$, $n_{\mathrm{L}} = 1.00$, $n_2 = 1.88$, $n_{\mathrm{c}} = 1.00$, $n_{\mathrm{s}} = 1.50$; grating period $\Lambda = 1111$ nm; incident angle $\theta_{\mathrm{in}} = 10.0°$.

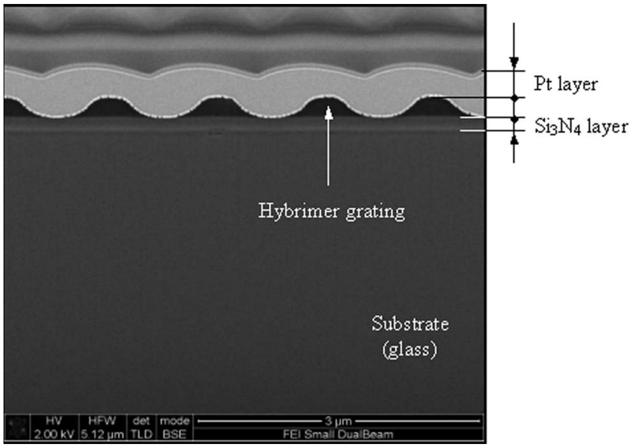

Fig. 4. Cross-sectional view of a fabricated GMR filter. The size of the image is ~5 μm $\times$5 μm. A platinum (Pt) layer was deposited for protection of the filter during ion-beam sectioning.

resonance peak significantly. For example, the calculated resonance wavelength is $\lambda = 1538$ nm, when $\theta_{\text{in}} = 10.2°$.

Figure 4 shows a cross-sectional view of the fabricated GMR filter obtained with a scanning electron microscope (SEM) indicating no apparent residual layer for the fabricated filter. Moreover, the SEM confirms the parameters used in the theoretical calculations in Fig. 3.

In conclusion, a guided-mode resonance optical filter fabricated by the MIMIC method with a hybrimer material has been presented. By combining the MIMIC, a hybrimer, and an h-PDMS mold, the photopolymer grating structure is readily fabricated without generating a residual layer. The hybrimer does not require additional chemical treatment to release the mold. The fabricated GMR optical bandstop filter shows ~81% reflectance at a resonance wavelength of 1538 nm. This method is promising for fabricating a variety of photonic devices in this class in addition to optical filters with higher efficiency than presented here.

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