# Fabrication of Guided-mode Resonance Devices by Soft Lithography in Hybrimers

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## ABSTRACT

Fabrication of guided-mode resonance devices made by the micro-molding-in-capillaries method is presented. The fabrication process is simple and effective, using an elastomeric mold and a UV-curable organic-inorganic hybrid material. The fabricated GMR device shows ~74% efficiency for reflectance and ~17% for transmittance at a resonance wavelength of $\lambda$ = 1550 nm. The linewidth of the device is ~5 nm and the sideband reflectance is ~4%. The fabricated device can be applied as an optical filter. A variety of resonant photonic devices can be created with this process.

***Keywords***: diffractive optical elements, guided-mode resonance, organic-inorganic materials, soft lithography.

## 1 INTRODUCTION

Diffractive optical elements and photonic crystals consist of fine spatial patterns designed to affect the spectrum, polarization, phase, and other properties of light. Periodic layered structures are widely used in integrated optics, communication systems, spectroscopy, lasers, and other important optical systems. Leaky-mode resonance effects in compact architectures enable new spectral device properties. In this paper, we present new resonant narrow-band optical filters fabricated by soft lithography in hybrimer compounds.

Devices containing thin-film diffractive optical elements can be manufactured by several common processes such as thin-film deposition, patterning, and etching. In this research, we apply nanoimprint lithography. In particular, soft lithography uses soft elastomeric materials to make patterns and structures without the use of complicated and expensive facilities. Soft lithography has been shown to be a simple and cost-effective method for fabricating and transferring patterns and structures. Therefore, the study of soft lithography has grown remarkably during the last ten years [1-7].

We present guided-mode resonance (GMR) devices fabricated by soft lithography with organic-inorganic materials. Guided-mode resonance refers to a rapid variation in the intensities of the electromagnetic fields, as the wavelength or the angle of incidence is varied around their resonance values. A resonance occurs when an externally propagating wave is phase matched to a leaky guided mode allowed by a waveguide-grating structure [8]. Devices based on resonant waveguide modes have been theoretically predicted and experimentally verified [8-16]. However, these verified devices were made by conventional photolithography processes.

Hybrimers are fluorinated organic-inorganic materials fabricated using a sol-gel process [17-19]. Hybrimers have several advantages. In particular, there is no additional chemical treatment needed to release the mold due to the presence of fluorine molecules in the hybrimer compound. Also, these materials possess thermal stability beyond 300ºC. Hybrimers have low optical loss, controllable refractive indices, and lower viscosity compared to common UV-curable polymers.

## 2 FABRICATION AND MEASUREMENT

Figure 1 shows a schematic procedure for fabrication of a GMR device using the micro-molding-in-capillaries (MIMIC) method [1]. The first step of 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 333 nm grating depth.

As an elastomeric mold, polydimethylsiloxane (PDMS) is widely used in soft lithography. We apply composite polymeric stamps as elastomeric molds for improved quality patterning [3,6]. The composite stamps consist of two parts; one part is hard-PDMS (h-PDMS), which has different mechanical properties than Sylgard 184 silicon elastomer from Dow Corning, popularly used. The other part is Sylgard 184 PDMS. H-PDMS is prepared as described in Ref. [3]. Composite prepolymer is spin-coated on a commercial holographic grating and cured in an oven. Then we pour a prepolymer of Sylgard 184 silicon elastomer on an h-PDMS layer and cure it in an oven again.

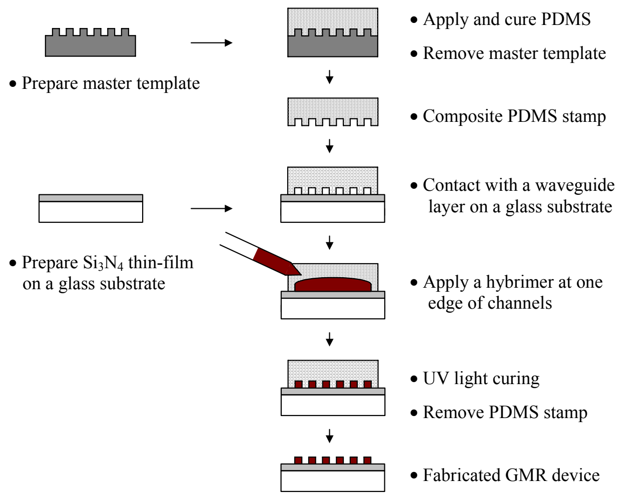



Fig. 1. Schematic fabrication process of a GMR device by MIMIC [1].

Therefore, a pattern with a negative replica of the master template is formed on an h-PDMS surface.

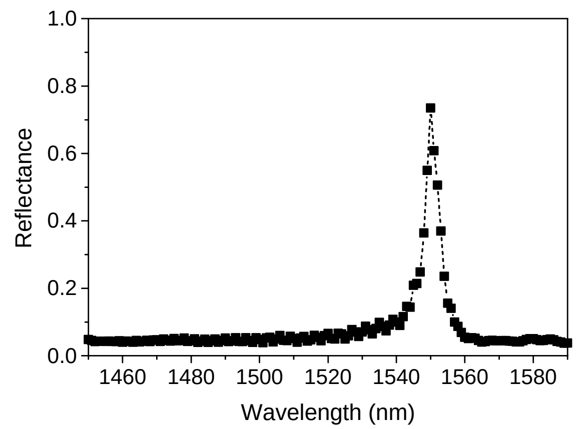
The composite mold makes contact with a silicon nitride thin film on a glass substrate. The silicone nitride film is prepared by plasma-enhanced chemical vapor deposition (PECVD) and serves as the waveguide layer of the GMR device.

A diluted hybrimer is prepared to obtain a lower viscosity prepolymer. A few drops of UV curable hybrimer are applied at one edge of the patterned surface of the composite mold. 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 hours. Finally, the channels are filled with the hybrimer prepolymer by the capillary force. After taking the composite mold set out of the chamber, the hybrimer in the h-PDMS channel is cured using a UV lamp (central wavelength $\lambda$ = 365 nm). Patterned grating structures on the silicon nitride thin film are obtained after the composite mold is peeled off.

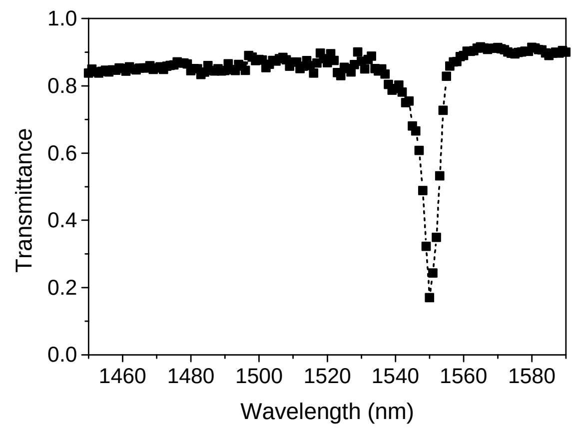
A tunable laser source is used to measure the spectral response. We set the angle of incidence ($\theta_{in}$) at 9.5º to locate the resonance wavelength of the GMR device within the operating range of the laser. Next, we measure the reflected and transmitted power for the wavelength range of 1450 nm to 1590 nm in 1 nm steps. A polarizer is used to select the laser's transverse-electric (TE) polarization.

## 3 RESULTS

Figure 2 shows the experimental spectral response of the fabricated device. The resonance wavelength (maximum point of reflectance or minimum point of transmittance) is at $\lambda$ = 1550 nm and the reflectance at




(a)



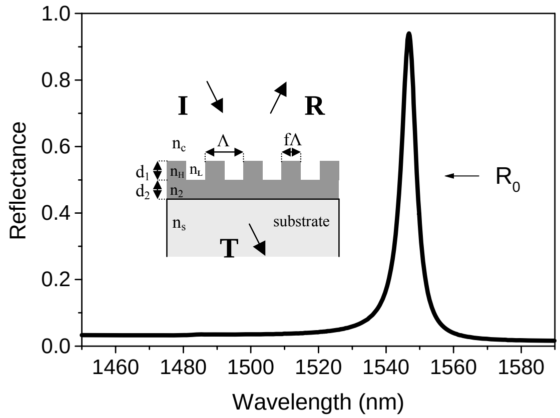

(b)

Fig. 2. Experimental spectral response of the fabricated GMR device for TE-polarization: (a) Reflectance (b) Transmittance.

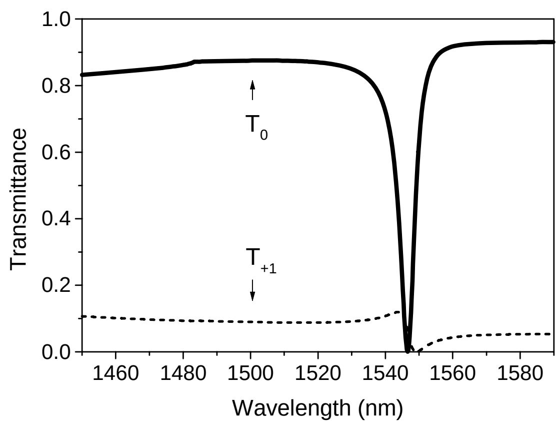
resonance is ~74%. The full-width at half-maximum (FWHM) linewidth is 5 nm and the sideband reflectance is ~4%. This sideband can be suppressed by changing the device design [15]. The transmittance at resonance is ~17%.

Figure 3 shows the calculated spectral response of the fabricated GMR device. The calculations are performed with a computer code based on rigorous coupled-wave theory [20]. The device parameters used in Fig. 3 correspond to the experimental values used in the fabrication. The calculated resonance wavelength is at $\lambda$ = 1547 nm and the FWHM linewidth is 5 nm. The measured spectral response (as shown in Fig. 2) and the calculated response (as shown in Fig. 3) show good agreement.

The calculated reflectance at resonance is ~94%. This non-100% reflection is due to the presence of the higher order transmittance at resonance as shown in Fig. 3 (b) noted as $T_{+1}$. This higher order transmittance can be eliminated and 100% reflection of the GMR device can be achieved by changing the parameters of the GMR device design.




(a)



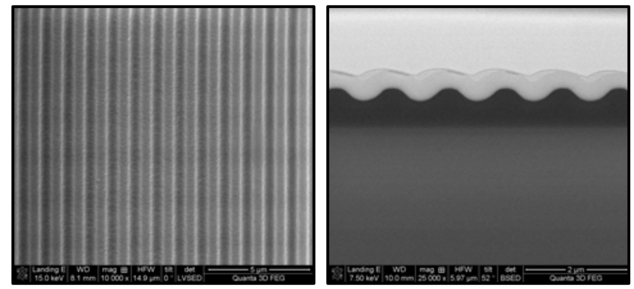

(b)

Fig. 3. Calculated spectral responses of the fabricated GMR device for TE-polarization: (a) Reflectance (b) Transmittance.
The parameters are as follows: Thicknesses, $d_1 = 256$ nm, $d_2 = 333$ nm; refractive indices $n_H = 1.51$, $n_L = 1.00$, $n_2 = 1.88$, $n_c = 1.00$, $n_s = 1.50$; grating period $\Lambda = 1111$ nm; filling factor f = 0.50; incident angle $\theta_{in} = 9.5^o$. Note that $T_o$ is the transmittance of the 0-th order and $T_{+1}$ is the transmittance of the +1-st order.

To characterize the fabricated device, we employ a scanning electron microscope (SEM). Figure 4 (a) shows a top down view of the device. The device surface looks a little rough and the roughness of the hybrimer layer causes lower efficiency than that calculated. Figure 4 (b) shows a cross-sectional view and permits comparing the parameters of the fabricated device with the original design. The parameters measured from the SEM images are very close to the parameters used in the theoretical calculations.

## 4 CONCLUSION

In conclusion, a guided-mode resonance device fabricated by the MIMIC method with a hybrimer has been presented. The fabrication process using an elastomeric composite mold is simple and effective. By using this mold,



(a) (b)

Fig. 4. SEM images of the fabricated GMR device. (a) Top down view, Magnification = 10,000. The size of the image is ~15 µm. (b) Cross-sectional view, Magnification = 25,000. Note that the white part on top is a platinum layer for protection during ion-beam sectioning and the dark part is a hybrimer grating layer and a $Si_3N_4$ waveguide layer.

the photopolymer grating structure is fabricated very easily. Moreover, a hybrimer material does not require additional chemical treatment to release a mold. Therefore, it is possible to effectively fabricate periodic photonic devices with this method and material. The fabricated GMR device shows ~74% efficiency for reflectance and ~17% for transmittance at a resonance wavelength of $\lambda = 1550$ nm and can thus be applied as an optical bandstop filter. This simple fabrication process can achieve a variety of GMR devices.

We gratefully acknowledge the NanoPort Applications Team at FEI Company for providing the results shown in Fig. 4.

## REFERENCES

[1] Y. Xia and G. M. Whitesides, "Soft lithography," Angew. Chem. Int. Ed. 37, 550-575, 1998.
[2] Y. Xia, J. A. Rogers, K. E. Paul, and G. M. Whitesides, "Unconventional methods for fabricating and patterning nanostructures," Chem. Rev. 99, 1823-1848, 1999.
[3] T. W. Odom, J. C. Love, D. B. Wolfe, K. E. Paul, and G. W. Whitesides, "Improved pattern transfer in soft lithography using composite stamps," Langmuir, 18, 5314-5320, 2002.
[4] M. D. Tang, A. P. Golden, and J. Tien, "Molding of three-dimensional microstructures of gels," J. Am. Chem. Soc. 125, 12988-12989, 2003.
[5] J. A. Rogers and R. G. Nuzzo, "Recent progress in soft lithgraphy," Materials Today 8, 50-56, 2005.
[6] T.-W. Lee, O. Mitrofanov, and J. W. P. Hsu, "Pattern-transfer fidelity in soft lithography; the role of pattern density and aspect ratio," Adv. Funct. Mater. 15, 1683-1688, 2005.
[7] D.-H. Lee, K.-H. Park, L.-Y. Hong, and D.-P. Kim, "SiCN ceramic patterns fabricated by soft lithography techniques," Sens. Actuators A 135, 895-901, 2007.

[8] R. Magnusson and S. S. Wang, “New principle for optical filters,” Appl. Phys. Lett. 61, 1022-1024, 1992.
[9] I. A. Avrutsky and V. A. Sychugov, “Reflection of a beam of finite size from a corrugated waveguide,” J. Mod. Opt. 36, 1527-1539, 1989.
[10] S. Peng, and G. M. Morris, “Experimental demonstration of resonant anomalies in diffraction from two-dimensional gratings,” Opt. Lett. 21, 549-551, 1996.
[11] A. Sharon, D. Rosenblatt, and A. A. Friesem, “Narrow spectral bandwidths with grating waveguide structures,” Appl. Phys. Lett. 69, 4154-4156, 1996.
[12] D. L. Brundrett, T. K. Gaylord, and E. N. Glytsis, “Polarizing mirror/absorber for visible wavelengths based on a silicon subwavelength grating: design and fabrication,” Appl. Opt. 37, 2534-2541, 1998.
[13] P. S. Priambodo, T. A. Maldonado, and R. Magnusson, “Fabrication and characterization of high-quality waveguide-mode resonant optical filters,” Appl. Phys. Lett. 83, 3248-3250, 2003.
[14] Z. S. Liu, S. Tibuleac, D. Shin, P. P. Young, and R. Magnusson, “High-efficiency guided-mode resonance filter,” Opt. Lett. 23, 1556-1558, 1998.
[15] D. Shin, Z. S. Liu, and R. Magnusson, “Resonant Brewster filters with absentee layers,” Opt. Lett. 27, 1288-1290, 2002.
[16] K. J. Lee, R. LaComb, B. Britton, M. Shokooh-Saremi, H. Silva, E. Donkor, Y. Ding, and R. Magnusson, “ Silicon-layer guided-mode resonance polarizer with 40-nm bandwidth,” IEEE Photonics Tech. Lett. 20, 1857-1859, 2008.
[17] W.-S. Kim, K.-S. Kim, Y.-J. Eo, K B. Yoon, and B.-S. Bae, “Synthesis of fluorinated hybrid material for UV embossing of a large core optical waveguide structure,” J. Mater. Chem. 15, 465-469, 2005.
[18] D.-G. Choi, J.-H. Jeong, Y.-S. Sim, E.-S. Lee, W.-S. Kim, and B.-S. Bae, “Fluorinated organic-inorganic hybrid mold as a new stamp for nanoimprint and soft lithography,” Langmuir, 21, 9390-9332, 2005.
[19] W.-S. Kim, D.-G. Choi, and B.-S. Bae, “Ultraviolet-nanoimprint of 40 nm scale patterns using functionally modified fluorinated hybrid materials,” Nanotechnology 17, 3319-3324, 2006.
[20] T. K. Gaylord and M. G. Moharam, “Analysis and applications of optical diffraction by gratings,” Proc. IEEE, 894-937, 1985.



NSTI-Nanotech 2009, www.nsti.org, ISBN 978-1-4398-1782-7 Vol. 1, 2009