Fabricating a Linear Variable Filter Using Nanoreplica Molding

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Abstract: We present a new technique for fabrication of a linear variable guided-mode resonance (GMR) filter based upon nanoreplica molding. The developed process utilizes a wedge-shaped elastomeric mold, which is stretched to obtain 1D gratings with a linearly graded period. A high refractive index dielectric film is deposited on the graded-period grating to serve as the waveguide layer of the GMR filter. The GMR wavelength varies in a range of 680.2–737.0 nm depending on measurement location on the filter.

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Linear variable bandpass filters with a peak transmission wavelength varying linearly in one direction and remaining uniform in the other direction are desirable for use in compact spectrum analyzers, where the filter is directly attached to a charge-coupled device (CCD) sensor, and for hyperspectral imaging as a variable filter [1]. The linear variable effect can be achieved by using a Fabry–Perot cavity with a linearly graded cavity length. Alternatively, guided-mode resonance (GMR) devices may offer a lower cost, a narrower bandwidth, and an improved wavelength range for this function [2]. Dobbs *et al.* reported a GMR-based linear variable filter that uses a grating structure in conjunction with a waveguide layer whose thickness progressively changes [3]. In this work, we present a linear variable GMR filter with a period that varies along the length of the filter. We exploit nanoreplica molding to fabricate this device whereby an elastic wedge-shaped polydimethylsiloxane (PDMS) mold is deliberately stretched to generate surface-relief gratings with a linearly graded period [4,5].

The proposed fabrication process of the linear variable GMR structures is summarized in Fig. 1(a). Initially, the PDMS mold used to fabricate the GMR device was cast from a silicon master wafer bearing a uniform one dimensional (1D) grating pattern with a period, depth, and duty cycle of 360 nm, 60 nm, and 40%, respectively. A 30-mm-thick acrylic block tilted at an angle to the top surface of the silicon master wafer was used to squeeze the uncured PDMS into a wedge shape with the tapered ends aligned parallel to the grating. Fig. 1(b) shows the cross section view of a fabricated PDMS wedge with an inclination angle, base height, rise, and length of α = 4.8°, d_1 = 4.1 mm, d_2 = 1 mm, and L = 36.7 mm, respectively. Next, a uniaxial force was applied perpendicular to the grating line to stretch the cured PDMS mold to 122.3% of its initial length. As a result, the period of the 1D grating structure increased depending on its position on the PDMS wedge. The graded grating pattern on the stretched PDMS mold was then replicated on a glass substrate using nanoreplica molding. A 160-nm-thick film of TiO_2 (refractive index = 2.1) was then deposited over the released replicated polymer grating to serve as the waveguide layer for the GMR structure.

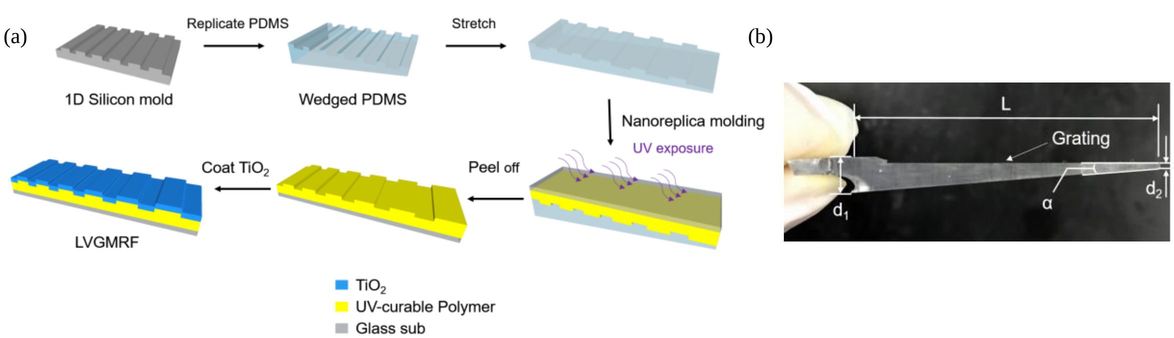

Fig. 1. (a) Schematic of the linear variable replica molding process. (b) A photo showing the cross section of the replicated wedged PDMS.

A schematic cross-sectional diagram of the linear variable GMR device is shown in Fig. 2. The Scanning Electron Microscopy (SEM) images were taken at three locations corresponding to the starting spot (x = 0 mm), the center spot (x = 10 mm), and the ending spot (x = 20 mm). To identify the optical resonances of the graded GMR filter, the periodic GMR structure was modeled using rigorous coupled wave analysis (RCWA) with the grating periods from the measurement results shown in Fig. 2(b). Fig. 3 shows the calculated transmission spectra at 11 different positions spanning a distance of 20 mm at increments of 2 mm. As noted, the wavelength of the transmission dip increases with increasing grating period. The resonance wavelength, which corresponds to the wavelength at the minimal transmittance, varies from 680.3 nm to 735.3 nm, with a uniform full-width half-maximum of approximately 7 nm.

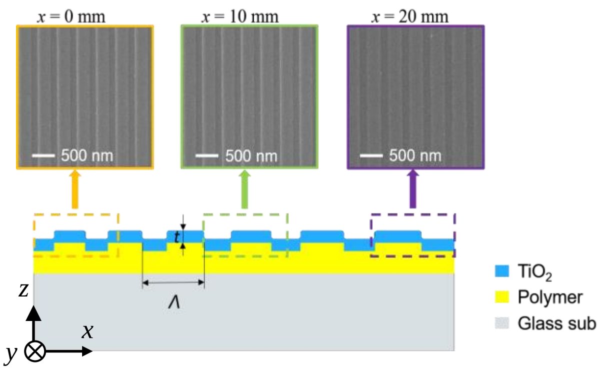

Fig. 2. Schematic cross section of the GMR filter structure (not to scale) and the SEM images of the replicated grating at three different positions on the sample. The labeled *x* values represent the locations of the measurements along the gradient direction of the GMRF sample. The grating periods of the left panel, center panel, and right panels are Λ = 421.8 nm, Λ = 438.7 nm, and Λ = 463.3 nm,

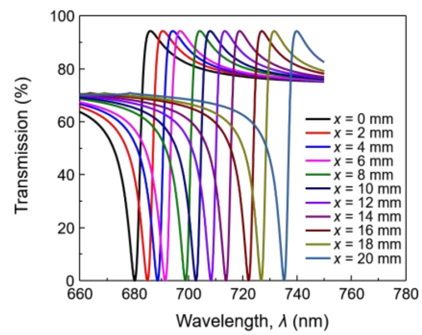

Fig. 3. Calculated transmission spectra obtained by the RCWA simulation for the graded GMR filter at 11 locations spanning 20 mm at increments of 2 mm.

Fig. 4(a) shows the measured transmission spectra at 11 locations corresponding to the above numerical study. At *x* = 0 mm, the resonance wavelength is 680 nm, and the resonance gradually shifts to 737 nm at *x* = 20 mm, which clearly demonstrates that the spectral position of the optical resonance is directly related to the location of measurement for the GMR device. The total shift of the resonance wavelength is 57 nm over a distance of 20 mm, resulting in a gradient of 2.85 nm/mm. Fig. 4(b) shows the dependence of resonance wavelength on the lateral position along the gradient direction of the grating period. For comparison, the result of the numerical simulation is plotted in red. Fig. 3 and Fig. 4 show good agreement between the simulation and experimental results.

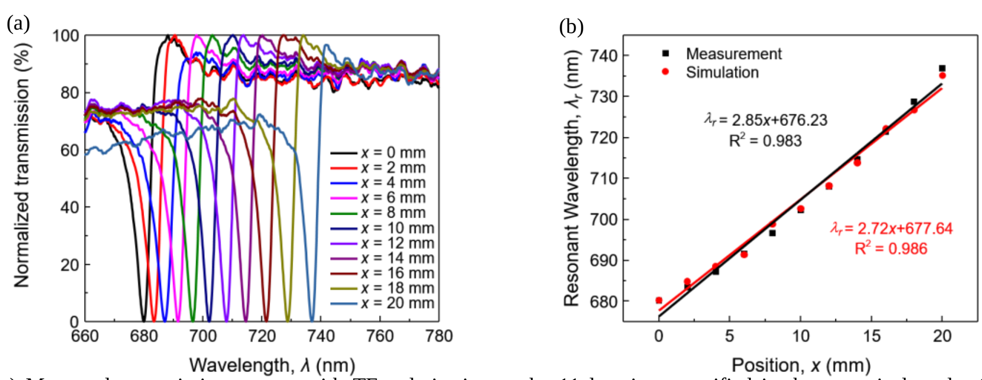

Fig. 4. (a) Measured transmission spectra with TE polarization at the 11 locations specified in the numerical study. (b) Dependence of measured and calculated resonant wavelengths on the lateral position. The resonant wavelength values are fitted by the solid lines.

The spectral bandwidth is another performance metrics of linear variable filters. We measured transmission spectra with incident beam sizes of 1 mm, 2 mm, 3 mm, and 4 mm. When the beam spot size decreases from 4 mm to 2 mm, the bandwidth reduces from 10.4 nm to 7.8 nm. With a beam spot size of 1 mm, the measured bandwidth of 6.5 nm is close to that of the RCWA simulation, which ignores the gradient of the grating period. Therefore, when the beam size is as small as 1 mm, the bandwidth is limited by the resonance linewidth, rather than the non-uniformity of the grating pattern.

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