Optically reconfigurable azobenzene polymer-based fiber Bragg filter

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Optically writable, thermally erasable surface relief gratings in thin Disperse Red 1 polymethyl methacrylate azopolymer films were used to demonstrate an arbitrarily reconfigurable fiber Bragg filter. Gratings were optically written on azopolymer-coated side-polished fiber blocks, and a write–erase–write cycle was demonstrated. Finite difference time domain simulations reveal that this optically reconfigurable device concept can be optimized in a silicon-on-insulator waveguide platform. © 2005 Optical Society of America

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Azobenzene-based polymers can act as photosensitive, nonlinear optical, or photorefractive materials and have ever increasing fields of application including programmable optical interconnects, electro-optic modulation, coherent image amplification, and holographic storage.[1] Both surface relief gratings and birefringence gratings with relatively high diffraction efficiencies have been demonstrated in azo-dye-doped polymers and their formation mechanisms, based on *cis–trans* isomerization of azobenzene, have been studied extensively.[2,3] Driving this *cis–trans* isomerization leads to the formation of surface relief gratings with almost full modulation depth.[2–4] These structures have a high index contrast yet can be erased simply by heating the polymer to above its glass transition temperature for a few minutes. The ease of formation and range of tunability of these polymer gratings make them interesting in connection with reconfigurable devices, and although birefringence gratings may be the best candidate for a real device given that read–write cycling and long-term stability are well established,[5] surface relief gratings are chosen for these first proof-of-concept experiments because of their order of magnitude larger index contrast.

Reconfigurable optical devices for telecom applications such as dispersion compensation, switching, and wavelength multiplexing are being explored in many laboratories. Bragg gratings are important elements in such systems and, therefore, reconfigurable optical Bragg grating structures with fine wavelength control and wide tunability are desirable. One approach to this problem is to incorporate a degree of tunability into existing glass-based Bragg devices through temperature tuning of the refractive index[6,7] or by piezoelectric,[8] magnetostrictive,[9] or mechanically induced strain.[10] With few exceptions,[11] these all require a continual supply of electrical power to maintain the altered wavelength and, typically, the tuning ranges are limited to a few nanometers. We demonstrate the proof of concept for an arbitrarily tunable, optically reconfigurable Bragg filter based on thin azopolymer films. We also show by means of finite difference time domain (FDTD) simulations how this approach can lead to an optimized device based on a silicon-on-insulator (SOI) planar waveguide platform.

As discussed elsewhere,[12] we optically wrote surface relief gratings in a thin film of poly(4′-[(2-(methacryloxy)ethyl)ethylamino]-4-nitroazobenzene) (pDR1M). Coupling a grating to waveguide modes can be technically realized in a number of ways. For the purposes of demonstrating the proof of concept, we chose a simple, side-polished fiber block design consisting of a single-mode fiber (Corning SMF28) glued in a V groove

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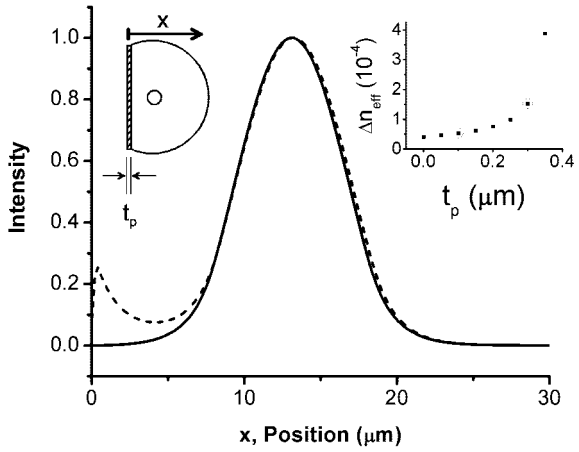

Fig. 1. Calculated TE mode profiles for a fiber overcoated by uniform (no grating) polymer films of thicknesses 0.1 μm (solid curve) and 0.37 μm (dashed curve) for the parameters given in the text. The left inset shows a sketch of the geometry of the buried waveguide with the polymer film shown as the hatched area. Shown in the right inset is the change in the fiber mode index from $n_{\text{eff}} = 1.464$, calculated for a fiber cladding thickness of 2 μm and polymer overlayer thickness ranging from 0 to 0.4 μm.

having a 400 mm radius of curvature that was diamond cut into a glass substrate. The blocks were polished to a core-to-polished surface distance of 2 μm,[13] exposing the evanescent field of the fiber. Polymer films of 0.2 μm thickness were then spin coated on top of the exposed fiber cladding and 4 mm long surface relief gratings were optically written, using 5 min of 100 mW/cm^2, 488 nm argon-ion laser exposure on the section where the fiber core was closest to the surface. The spectral properties of the device were measured by coupling a TE-like mode (electric field parallel to the azopolymer film plane) into the fiber and measuring transmission while scanning the wavelength by use of a tunable laser and detector system (Agilent 8164A lightwave measurement system). The optically written gratings were thermally erased by electrically heating the glass block to a temperature of 140 °C for 2 min. This allowed for a new grating to be optically written, completely independent of any features of the original grating.

We achieved an estimate of the expected device parameters, including grating efficiency and spectral width, by calculating the modes and their effective indices with a two-dimensional mode solver.[14] The modeled structure consisted of a buried fiber with a 10 μm core width and a 1.465 core refractive index, an upper cladding thickness between 2 and 8 μm of index $n = 1.462$, and a polymer overlayer of refractive index $n = 1.63$ with variable thickness t_p. In Fig. 1 we show the TE-like fundamental mode profile of a fiber (8 μm cladding) for uniform polymer overlayers of thicknesses $t_p = 0.1$ and 0.37 μm. As intuitively expected, the mode is gradually attracted toward the high index polymer layer as the polymer thickness increases. For a polymer thickness above $t_p \sim 0.37$ μm, the portion of the fundamental mode confined in the azopolymer cladding increases at the cost of the field confined in the fiber core, resulting in substantial power leakage from the core into the polymer overcladding. This effect of coupling the fiber modes to a planar overlayer waveguide of oil, solid state,[15] or polymer[16] material has been studied previously. In the experiments reported here, the polymer layer was kept thin so as to minimize polymer guided modes. To estimate the influence of the grating on the guided light, the fiber mode effective index, for a 2 μm cladding, was calculated for a polymer thickness ranging from 0 to 0.4 μm, as shown in the right inset of Fig. 1. We consider a 2 mm long relief grating with a periodically modulated thickness ranging from $t_{p,\max} = 0.3$ μm to $t_{p,\min} = 0.1$ μm. The refractive-index difference Δn_{eff} between the effective mode indices at $t_{p,\max}$ and $t_{p,\min}$, indicated by the circles in the right inset, was then used to calculate the grating intensity reflectivity for the first-order Bragg resonance according to $r = \tanh^2(\kappa L)$, where $\kappa = \pi\Delta n_{\text{eff}}/\lambda$ is the grating coupling coefficient, L is the grating length, and λ is the vacuum wavelength.[17,18] From this we obtain $\Delta n_{\text{eff}} \sim 1.1 \times 10^{-4}$, $\kappa \sim 2.2 \times 10^{-4}$ μm^{-1} and $r \sim 18\%$. Based on a sinusoidal modulation index profile of length L, we can also obtain an estimate of the width of the resonance, from the grating bandwidth

$$\Delta\lambda = \lambda \frac{m\Delta n_{\text{eff}}}{n_{\text{eff}}} \sqrt{1 + \left(\frac{2n_{\text{eff}} d}{m\Delta n_{\text{eff}} L}\right)}, \tag{1}$$

where n_{eff} is the effective index, Δn_{eff} is the index perturbation, L is the length of the grating, and m is the modulation of the index perturbation.[18] Using the results from the two-dimensional mode solver given above, we expect the spectral width of the Bragg resonance to be $\Delta\lambda \sim 0.8$ nm. The grating reflectivity, given above, will be too low for a practical device, and, for a 13 mm long grating with reflectivity of 99%, the 0.1 nm bandwidth would be too small for many applications. Nevertheless, this simple design serves our purpose here to demonstrate the concept experimentally. As we discuss below, the grating performance can be dramatically improved by fabricating this device in a high index contrast waveguide platform such as SOI.

In Fig. 2(a) we show the measured transmission spectrum of the device with a grating optically written to be resonant near 1566 nm. The grating of period $d = 536$ nm, confirmed by measuring diffraction angles with a He–Ne laser, was expected to yield a first-order Bragg reflection at $\lambda_{\text{Bragg}} = 2n_{\text{eff}} d$ near 1566 nm. In Fig. 2(b) we show the spectrum after thermal erasure of this grating by heating the block for 2 min at 140 °C, slightly above the azopolymer glass transition temperature. In Fig. 2(c) we show the subsequent optical writing of a completely new grating, resonant near 1530 nm. This write–erase–write procedure can be repeated extensively and, importantly, arbitrary changes in grating characteristics such as periodicity and chirp are possible.

We note that the insertion loss of the device in the absence of the grating is approximately 4 dB. This is attributed to light leaking from the fiber core into the

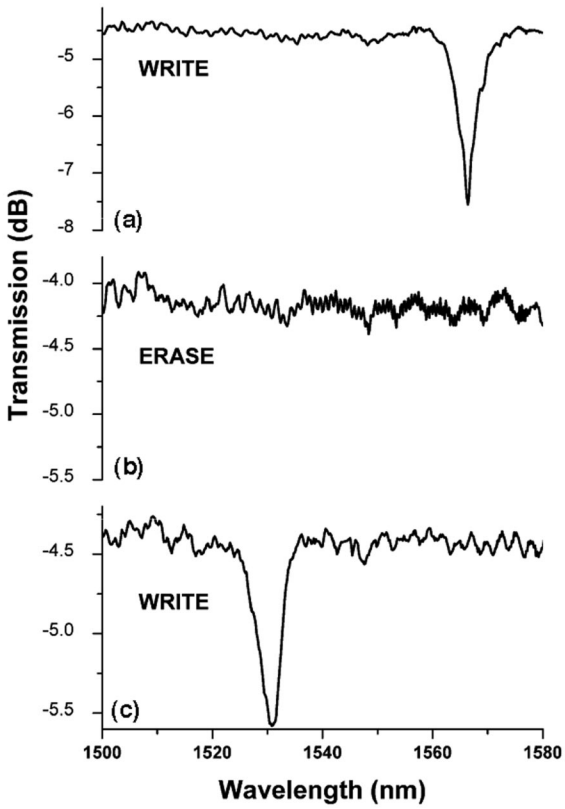

Fig. 2. Demonstration of an optically reconfigurable Bragg filter in a side-polished fiber block: (a) device transmission spectrum for an optically written grating for first-order Bragg resonance at 1566 nm; (b) device spectrum after a 2 min thermal erasure at 140 °C; (c) device spectrum for a new grating optically written for Bragg resonance at 1530 nm.

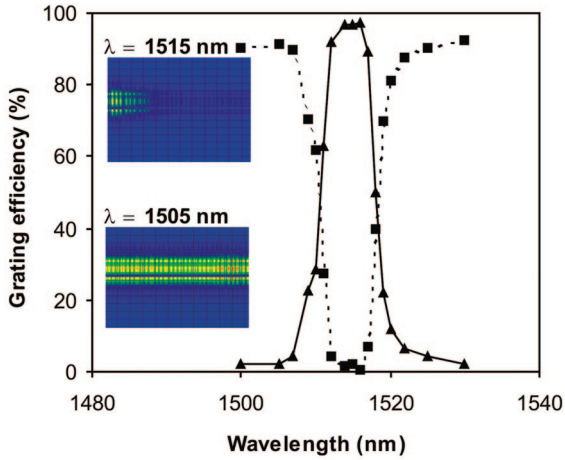

Fig. 3. High efficiency of an optically reconfigurable azopolymer cladding grating on SOI waveguide. Reflection (triangles) and transmission (squares) grating spectra were calculated with FDTD simulation (two-dimensional). A fully modulated surface grating of period 0.3 μm and length 100 μm in an azopolymer cladding layer of 0.2 μm thickness and refractive index 1.63 were assumed. A 0.3 μm Si core thickness of the SOI waveguide and a bottom oxide cladding thickness of 0.3 μm were assumed. The calculated grating is ~7 nm FWHM. The insets show TM mode evolution for wavelengths near Bragg resonance (1515 nm) and off Bragg resonance (1505 nm). The propagation length shown in the insets is 100 μm.

higher index azopolymer overcladding, as discussed above. We also observed that the measured width of the Bragg resonance in transmission (~5 nm FWHM) is substantially larger than that calculated by the coupled mode theory (~0.8 nm FWHM). This is due to the geometry of the side-polished fiber block wherein the fiber curves away from the surface of the block, which not only shortens the effective grating length, but also allows the surface grating to couple light into radiation modes for wavelengths close to the resonance. This was substantiated by measurements of the Bragg reflection into the fiber core alone, where the expected resonance width was indeed observed. Furthermore, scattered light could be directly observed at wavelengths near resonance with an IR camera, as also discussed elsewhere.[19]

The optically reconfigurable azopolymer grating concept that we have demonstrated in this simple side-polished fiber block geometry can be advantageously transferred to planar waveguide technology to make a practical reconfigurable waveguide grating filter. We suggest that it is particularly attractive to implement this concept in a SOI waveguide platform. In a SOI platform, large contrast between the refractive indices of the waveguide core (single crystal silicon, $n \sim 3.5$) and cladding (typically SiO_2, $n \sim 1.5$) results in high mode confinement in the silicon core and a strong evanescent field in the cladding in close proximity to the core. The guided mode effective index becomes increasingly sensitive to both the cladding index and the thickness when the waveguide core size is reduced to submicrometer dimensions. This effect can be exploited to make efficient, compact waveguide elements based on mode interaction with the cladding, including one with grating structures. As we show here by FDTD simulation, an azopolymer cladding grating deposited on a thin SOI waveguide can provide efficient wavelength filtering for grating lengths as short as 100 μm. The structure analyzed here is a 100 μm long first-order surface Bragg grating of period 300 nm and full depth modulation in azopolymer cladding. The polymer of 1.63 refractive index was assumed as a 0.2 μm thick layer on top of an SOI slab waveguide with a 0.3 μm Si waveguide core. The results from the FDTD simulation are presented in Fig. 3, including the reflection and transmission spectra of the device as well as the principal electric field component evolution at the first-order Bragg resonance (1515 nm) and at a detuned wavelength (1505 nm). The grating has a resonance of ~7 nm FWHM and a peak transmission of 97.5%, corresponding to a 0.11 dB loss that is mainly due to scattering losses of the grating. We believe that such compact, optically reconfigurable gratings will be relevant to various integrated optics applications including wavelength filtering and coarse wavelength division multiplexing in reconfigurable optical interconnects.

In summary, we have demonstrated an optically reconfigurable polymer Bragg grating concept. This

was based on optically writable and thermally erasable surface relief gratings in thin azopolymer films. Importantly, arbitrary changes in grating characteristics can be achieved between one write–erase cycle and the next. Our results suggest that azopolymer-based, erasable relief or birefringence gratings can be relevant to applications in next-generation reconfigurable optical waveguide devices.

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