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Novel polymer-based resonant grating-waveguide structures

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Abstract

New configurations for polymer-based multilayered grating-waveguide structures whereby the waveguide layer is spun-coated over a Si substrate and the grating layer is obtained by holographic recording, are presented. Such structures are demonstrated in a hybrid semiconductor–organic material configuration. Experimental results reveal a spectral bandwidths down to 1 nm at FWHM with an incident intensity reflectivity reaching 72%. Narrow bandwidth, high reflectivity along with considerably simpler fabrication entailing the possibility of cost reduction as compared to costs compared to currently used pure semiconductor technologies, make these original grating-waveguide structures relevant candidates towards WDM optical communication networks. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Optical communication; WDM; Polymer waveguide; Optical switches; Optical filters

1. Motivation

Pressing demands for inexpensive yet reliable and efficient components have lead many researchers to consider polymers. Such materials become increasingly attractive to the formation of different optical structures, potentially enabling the replacement of traditionally used inorganic materials such as $LiNbO_3$ or semiconductors for WDM applications. Lately, novel polymers have been introduced that could be of use in ultra-fast optical components [1]. Diffraction anomalies from gratings have been originally observed by Wood [2], followed by many theoretical investigations by number of researchers [3–7]. These investigations have been expanded to resonance anomalies in grating-waveguide structures (GWS), and included new theoretical and experimental developments [8–11]. The basic configuration of a GWS shown in Fig. 1 is composed of a thin dielectric or semiconductor waveguide layer, and an additional transparent layer in which a grating is formed. When such a GWS is illuminated with an incident light beam, most of the beam is directly transmitted, while the rest is trapped by diffraction in the waveguide layer while being also partially re-diffracted out of the waveguide. At a specific resonant wavelength and angular orientation of the incident beam the re-diffracted beam interferes destructively with the transmitted beam, so that the incident beam is then completely reflected from the GWS. For complete theoretical considerations, see [12]. Extremely narrow resonance bandwidths of about 0.1 nm were reported and a modulation rate of 10 MHz were demonstrated with active GWS [13–16], suggesting that they could be very attractive in optical communication systems as spectral filters and switches. So far, GWS have been mainly based on semiconductor materials that are both rather difficult to fabricate and costly, therefore requiring to consider other technologies so as to improve both performance and industries prospects.

Investigations involving the formation of gratings in polymeric materials have been actively pursued throughout the past two decades [17–21]. Such attempts concentrated on the illumination of a grating pattern onto a polymer film eventually leading to the formation of photo-induced relief grating in it. Following this work the resonant grating structures based on such induced gratings in azo-aromatic polymer films were demonstrated [22,23].

We report in the following sections on a novel GWS configuration, where the structure is composed of a hybrid polymer–semiconductor configuration. The advanced polymer materials used for the fabrication of the waveguide layer [24–27] are expected to lead to GWS that can be readily fabricated at a low cost, making them attractive as photonic devices for DWDM optical communication systems. First, we present the theoretical considerations involved in designing such structures as well as outline the simplified fabrication procedure require for this new design. Next, we report on some experimental results of such polymer-based GWS. We will also point to future possible applications as well as further research directions.

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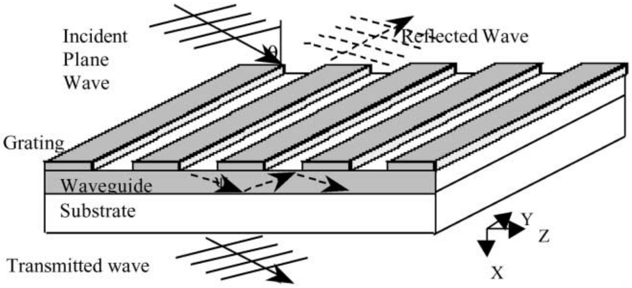

Fig. 1. Basic configuration of a GWS.

2. Fabrication procedure

The fabrication steps of the GWS are based on a multilayer deposition process on top of a Si-wafer spun-coated by a bottom buffer layer of spin on glass (SOG, sol–gel silica). Following each layer spin-coating step, the wafer is baked in the oven. The waveguide layer is made of a 30% molar ratio disperse-red-one chromophore side chain polymethyl methacrylate (DR1–MMA, $n = 1.6$ at $\lambda = 1.55\ \mu m$). Finally, a Shipley S1805 photoresist layer is spun-coated under laminar-flow conditions. Exposure of the grating is done within 48 h, with an argon laser at 363.8 nm and a grating period of about 1000 l/mm. Development times range between 10 and 30 s in a 1:1 developer:water solution. For our experiment, the buffer layer thickness was 1.7 μm, the waveguide thickness was 0.9 μm, the grating period was about 1 μm and the thickness of the grating layer ranged from 0.4 to 0.9 μm for the different samples (see Fig. 2a). In order to verify the shape and thickness of the grating layer we analyzed the various samples using an AFM setup. An example of one such recorded grating is presented in Fig. 2b. It is seen in this figure that the grating depth is 0.85 μm, the grating period is 0.96 μm and that the shape is indeed periodic.

3. Experimental testing procedure and results

The experimental setup for testing the polymer-based GWS is shown in Fig. 3. It includes a tunable external cavity diode laser operating at a wavelength around 1.55 μm. The beam from the laser illuminates only a small part of the sample area depending on its diameter (about 4 mm^2). The spectral resolution of the laser system is 0.003 nm. Part of the laser beam is normally incident, through a beam-splitter, onto the sample, which is placed on a translating and rotating stage (sub-micron and sub-arcsecond resolutions, respectively). For normalization, part of the incident plane wave that is reflected from the beam-splitter is monitored by an additional detector (D1, in Fig. 3). The light reflected from the sample is collected onto another detector (D2, in Fig. 3). A computer is being used for controlling the wavelength of the tunable laser and the position and angle of the sample carrying stage, as well as for monitoring all measurements originating from the various detectors. In order to set the polarization of the incident light, we used a polarizer and a half-wavelength plate. We are, then in a position to measure and evaluate the resonance behavior of the different GWSs.

Fig. 4 shows the results for the spectral behavior of the reflected intensities for a polymer-based GWS with TE and TM polarized beams at normal incidence. The results indicate that narrow spectral bandwidths can indeed be obtained. Specifically, 45% reflection efficiencies and 1 nm bandwidth at FWHM for the TE guided mode case, and 55% reflection

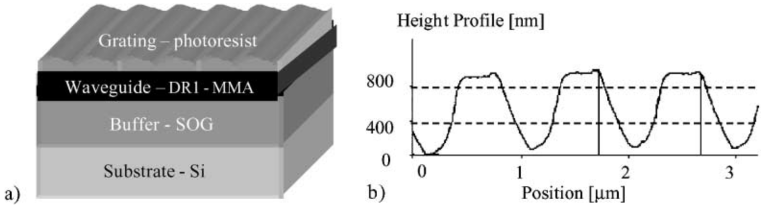

Fig. 2. (a) Representative polymer-based GWS configuration; (b) AFM measurement of a typical grating in the photoresist.

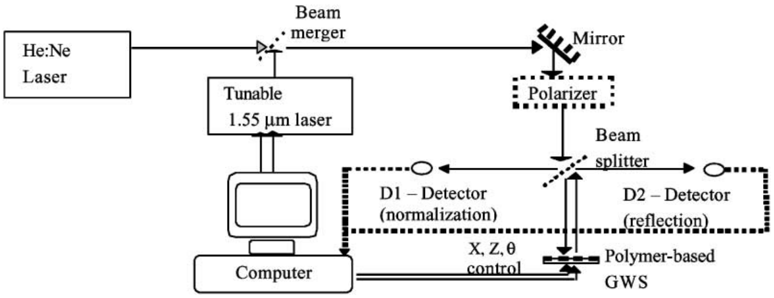

Fig. 3. Experimental arrangement for the characterization of the polymer-based GWS.

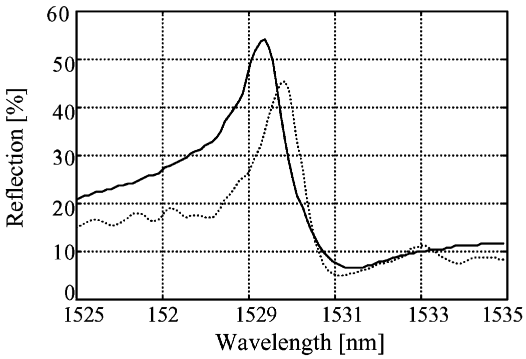

Fig. 4. Normalized experimental reflected intensities as a function of wavelength for a polymer-based GWS and TE (dashed line) or TM (solid line) modes.

efficiencies and 1.5 nm bandwidth at FWHM for the TM guided mode case could be demonstrated. The experimental results exhibit resonance peaks occurring at the vicinity of 1530 nm, thus corresponding to a finesse, i.e. $\lambda/\Delta\lambda$, for this GWS of about 1000–1500. These results depend mainly on design parameters and can be controlled to very high accuracy. For example, decreasing the grating thickness will result in narrowing of the resonance bandwidth, whereas changing the grating period will shift the resonance wavelength. It should be noted that anti-reflection coating on the substrate can eliminate almost completely off-resonance Fresnel reflections. As evident from the experimental results for the polymer-based GWS, the reflection intensities does not reach unity, as is predicted for a loss-less resonant a GWS. The discrepancy between the measured and predicted results is attributed to undesirable loss mechanisms. The losses mostly arise from: (1) waveguide thickness variations that are caused by non-uniform spin-coating of the wafer; (2) grating profile imperfections due to the etching process; (3) leakage of energy form the waveguide through the Si-wafer due to limited buffer layer width. We expect that reduction of these undesirable losses will lead to increased finesse and improvement of the intensity contrast ratio, especially for the reflected intensities.

4. Conclusion

We have utilized a set of analytic and numeric models for designing novel GWS structures based on novel polymeric materials that are easy to fabricate via easily available techniques, such as spin-coating and holographic recording. We have presented, a series of experimental results which demonstrate that high quality polymer-based GWS can be fabricated. Resonances with spectral bandwidths down to the nanometer range and significant reflected intensity variations were achieved.

We believe that active polymer-based GWS will be needed and actually available for demonstration in the near future. These can modulate laser light at extremely high rates, on the order of many GHzs by applying an external varying electric field or an optical probe. The results also suggest that applications as dynamic spectral filters, active mirrors for laser resonators, fast spatial light modulators in which many polymer-based GWS are incorporated into two-dimensional arrays may be feasible. Such structures should be useful in advanced signal processing, WDM applications and communication systems. Since the GWS are inherently planar and can be made to operate with small electro-optic effects as is currently the case with polymers, it is interesting to contemplate the further possibility of incorporating polymer-based GWS modulators directly on silicon chips for optical interconnection of processors.

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