Towards ultranarrow bandwidth polymer-based resonant grating waveguide structures

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The needed parameters and configurations that would lead to the achievement of ultranarrow spectral bandwidths in polymer-based resonant grating waveguide structures are presented. These include the addition of an upper polymeric layer to the basic configuration and increasing the waveguide thickness. The results reveal that spectral bandwidths as narrow as 0.15 nm at 1.5 μm can be achieved. © *2004 American Institute of Physics.* [DOI: 10.1063/1.1644330]

Polymer-based devices for optical communication and integrated optics are becoming increasingly important in recent years due to their ease of fabrication and pronounced electro-optical properties which, in some cases, are superior to those of inorganic or semiconductor based devices. They have been incorporated into a wide range of applications, including low voltage high speed electro-optic modulators,[1] switching,[2,3] passive filters,[4] and grating couplers.[5–7] In this letter we report on a polymer-based resonant grating waveguide structure (GWS) that can serve as an ultranarrow spectral bandwidth filter for dense wavelength division multiplexing applications. Specifically, we established the criteria for designing and fabricating such GWS.

Grating waveguide structures are planar multilayer structures. In their most basic configuration they are comprised of a surface relief grating, a waveguide layer and a substrate. The basic configuration is depicted in Fig. 1. When such GWS are illuminated with an incident light beam, most of the light is directly transmitted through. The remaining light is diffracted by the grating into the waveguide layer, and as it propagates it is partially diffracted outwards both in the transmission and reflection direction. At a specific wavelength and angular orientation of the incident beam, a "resonance" condition occurs, where the outward diffracted beam, in the transmission direction, destructively interferes with the transmitted beam, so that the incident light beam is completely reflected. Such diffraction anomalies were originally investigated mainly with gratings, and subsequently expanded to include a combination of gratings and waveguides.[8–13]

In order to estimate the influence of different relevant parameters on the resonance spectral bandwidth, we begin with the results of the coupled wave analysis which was applied to resonant GWS.[14] This analysis was an adaptation of the coupled wave analysis for distributed feedback lasers.[15] Accordingly, the normalized reflection intensity near resonance R, at normal or near normal incidence illumination, is given by

$$R = \frac{4h_1^2(\Delta k h_3 - h_2)^2}{[(\Delta k h_3 - h_2)(\Delta k h_3 + h_2) - \Delta k_z^2]^2 + 4h_1^2(\Delta k h_3 - h_2)^2},$$

(1)

where Δk_z is the angular wave vector deviation from resonance and Δk is the wave vector deviation. The constant h_1 represents the coupling between the radiation field and the modes in the waveguide, written as

$$h_1 = \frac{j\Delta\varepsilon^2 k^4}{2\beta} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} G(x,x')\xi_{-1}(x')\xi_1(x')$$
$$\times \phi(x')\phi^*(x)dx'dx,$$

(2)

where k is the incident wave vector, β is the propagation constant of the mode in the waveguide, $\phi(x)$ the mode envelope, $G(x,x')$ is the Green's function solution of the three layer structure and ξ_{-1} originates from the Fourier series expansion of the dielectric constant ε in the grating region;

$$\varepsilon(x,z) = \varepsilon_0(x) + \Delta\varepsilon \sum_{m\neq 0} \xi_m(x)e^{-jmKz},$$

(3)

with K the grating wave vector and $\Delta\varepsilon$ the dielectric modulation of the grating.

The constant h_2 represents the coupling constant for Bragg reflection between the counterpropagating modes of the waveguide, written as

$$h_2 = -\frac{1}{2\beta} \int_{-\infty}^{+\infty} \Delta\varepsilon k^2 \xi_2(x')\phi(x')\phi^*(x')dx'.$$
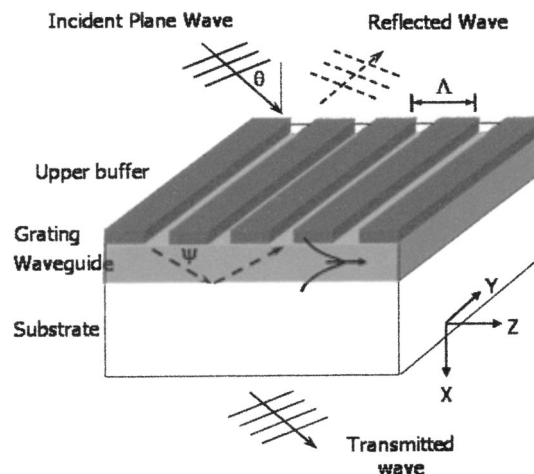
(4)

FIG. 1. Basic configuration of a resonant grating waveguide structure. It is formed as a multilayer stack consisting of a substrate, waveguide, grating, and upper polymeric layers.

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ÔFinally, h_3 is a constant related to the mode group velocity.

Using Eq. (1), it is possible to derive approximate relations for the GWS angular beamwidth $\Delta k_z^{\mathrm{FWHM}}$, and spectral bandwidth Δk^{FWHM}, as

$$\Delta k_z^{\mathrm{FWHM}} = 4\sqrt{|h_1 h_2|}, \qquad (5)$$

$$\Delta k^{\mathrm{FWHM}} = \frac{4h_1}{h_3}. \qquad (6)$$

Equation (6) indicates that the bandwidth is largely dependent on the radiation coupling term h_1. Thus, in order to control the bandwidth, we must vary the magnitude of the parameters which influence h_1. Equations (5) and (6) also indicate that the spectral bandwidth and angular beamwidth are not directly related to one another and can be independently controlled by changing the strength of the Bragg coupling h_2. For example, it is possible to obtain GWS with narrow spectral bandwidths but large angular beamwidths, which are attractive for optical applications.

Now, in accordance to Eq. (2) the main parameters that influence h_1 are the dielectric modulation $\Delta\varepsilon$ of the grating layer, the degree of overlap between the waveguide mode envelope $\phi(x)$ and the Green function $G(x,x')$ in the grating layer, and obviously the height of the grating layer. The dielectric modulation can be best controlled by depositing a polymeric layer above the grating layer, whereby the refractive index of the polymeric layer is comparable to that of the grating layer. The degree of overlap between $\phi(x)$ and $G(x,x')$ is best controlled by changing the thickness of the waveguide layer. To estimate the mode envelope dependence on the waveguide thickness, we calculated the mode extinction coefficient in a homogeneous layer above the waveguide as a function of waveguide thickness. The results indicate that the extent of the mode envelope in the layer above the waveguide is reduced as the waveguide thickness is increased. This reduction becomes very small for waveguide thicknesses larger than approximately 1.5 μm.

Using the above considerations we formed a range of polymeric resonant grating waveguide structures. We used optical quality ($\lambda/4$) glass BK7 substrates on which the wave guide and photoresist layers were spin coated. The waveguides consisted of either polyimide or DR1–PMMA polymer layers of variable thickness. The grating layer was holographically recorded in Shipley S1805 photoresist layer. The grating structure was optimized so as to minimize surface roughness, with different heat treatments, exposure, and development procedures. The waveguide layer also served as a stopping layer for the wet etching development of the grating layer and thus assisted in achieving a uniform grating. Representative SEM images of parts of the grating layer, at different magnifications are presented in Fig. 2. On top of the grating layer an upper polymeric layer of UV-curable adhesive NOA (Norland Optical Adhesives) was deposited. The refractive index of the upper polymeric layer was varied by mixing, in different ratios, NOA61, NOA65, and NOA73, so as to obtain a range of 1.506–1.540 at $\lambda = 1.5$ μm.

Some resonant grating waveguide structures had a constant thickness polyimide waveguide layer of 0.42 μm, as determined with an alpha-step instrument, a grating layer and an upper polymeric layer, whose refractive index was varied.
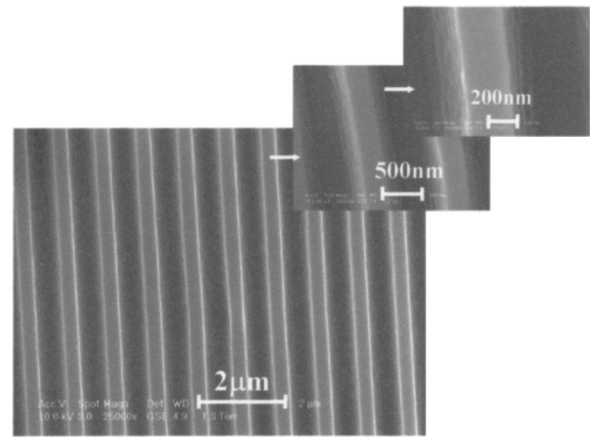

FIG. 2. SEM images of the grating layer. Insets showing enhanced images of the grating surface roughness.

Others with variable waveguide thickness layer and just a grating layer. Subsequently, we added an upper polymeric layer to determine whether additional bandwidth narrowing can be obtained.

The experimental setup for evaluating the GWS included an Agilent 816 tunable laser operating at a central wavelength of 1.5 μm. The light from the laser was collimated and polarized, so as to illuminate the GWS sample with a TE polarized plane wave.

Representative experimental results are shown in Figs. 3 and 4. Figure 3(a) shows the reflection intensity fraction as a function of wavelength for a GWS with no upper polymeric layer, and Fig. 3(b) for the same GWS with an upper polymeric layer of NOA65. As evident there is a significant reduction in the spectral bandwidth, from 5.3 to 0.62 nm. The corresponding reduction in peak reflection intensity is due to the increased sensitivity to losses.[14,16] The presence of losses both reduces the peak reflection and imposes an inherit limitation on reducing spectral bandwidth. Since the inherent absorption of our polymers is very small, at the tested wavelengths, structural imperfections are the major source for loss. As seen in Fig. 2, these largely reside in the grating wall region. Figure 4 shows the normalized reflection intensity as a function of wavelength for a GWS with a DR1-PMMA polymer waveguide of thickness 1.7 μm, with an upper polymeric layer of NOA65. The measured spectral resonance
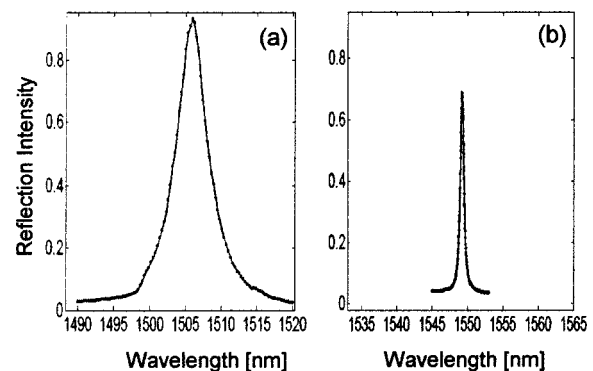

FIG. 3. Reflection intensity fraction as a function of wavelength for a GWS with and without an upper polymeric layer. (a) No buffer layer, with a bandwidth at FWHM of 5.3 nm; (b) with NOA65 upper polymeric layer, with bandwidth at FWHM of 0.62 nm. Both graphs are presented on the same scale.
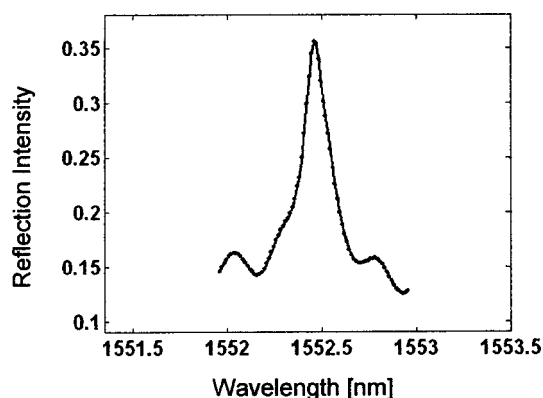
FIG. 4. Reflection intensity fraction as a function of wavelength for a narrow polymer based resonant GWS. Waveguide layer formed with DR1-PMMA polymer of thickness 1.7 μm and upper polymeric layer with NOA65 adhesive. The bandwidth at FWHM is 0.15 nm and peak reflection intensity fraction is 0.35.

bandwidth at full width half maximum was 0.15 nm. This bandwidth is the narrowest obtained with an all polymer based GWS. As a comparison, obtaining similar bandwidths with volume phase gratings will require a thickness of a few millimeters.

To conclude, polymer based GWS were fabricated and experimentally tested. The results reveal that the resonance bandwidth can be as low as 0.15 nm with peak reflection intensity fraction of 0.35. By increasing waveguide thickness and using an upper polymeric layer whose refractive index is close to that of the grating layer, it is possible to significantly reduce the spectral bandwidth. The design considerations and procedures developed here for passive GWS, could lead to the development of active GWS that include suitable electro-optic polymers.

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