Light modulation with electro-optic polymer-based resonant grating waveguide structures

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Abstract: A novel modulator design incorporating an E-O polymer into a resonant grating waveguide structure is presented. Using purely polymeric material we developed a resonant grating waveguide structure having low loss and high finesse, with approximately 2nm spectral line width at 1.55μm. An externally applied voltage modulates the refractive index of the E-O waveguide, thereby shifting the resonance wavelength and modulating the incident light at MHz rates. Such modulator operates in free space and does not involve waveguide patterning nor the need for facet conditioning and coupling common to operation in the Mach-Zehnder type configuration.

OCIS codes: (050.1970) Diffractive optics; (060.4080) Modulation; (230.2090) Electro-optical devices; (230.5750) Resonators.

References and links

1. M. Lee, "Dielectric constant and loss tangent in $LiNbO_3$ crystals from 90 to 147GHz," Appl. Phys. Lett. **79,** 1342–1344 (2001).
2. Y. Shi, C. Zhang, H. Zhang, J. H. Bechtel, L. R. Dalton, B. H. Robinson and W. H. Streir, "Low (sub-1-volt) halfwave voltage polymeric electro-optic modulators achieved by controlling chromophore shape," Science **288,** 199–122 (2000).
3. M. Lee, H. E. Katz, C. Erben, D. M. Gill, P. Gopalan, J. D. Heber and D. J. McGee, "Broadband modulation of light by using an electro-optic polymer," Science **298,** 1401–1403 (2002).
4. R. W. Wood, "On a remarkable case of uneven distribution of light in a diffraction grating spectrum," Philos. Mag. **4,** 396–402 (1902).
5. R. Petit, *Electromagnetic Theory of Gratings* (Springer-Verlag, Berlin, 1980).
6. T. Tamir and S. Zhang, "Resonant scattering by multilayered dielectric gratings," J. Opt. Soc. Am. A **14,** 1607–1616 (1997).
7. I. A. Avrutskii, G. A. Golubenko, V. A. Sychugov and A. V. Tischenko, "Light reflection from the surface of a corrugated waveguide," Sov. Tech. Phys. Lett. **11,** 401-402 (1985).
8. S. S. Wang, R. Magnusson, J. S. Bagby and M. G. Moharam, "Guided-mode resonances in planar dielectric-layer diffraction gratings," J. Opt. Soc. Am. A **7,** 1470–1474 (1990).
9. S. Peng and G. M. Morris, "Experimental demonstration of resonant anomalies in diffraction from two-dimensional gratings," Opt. Lett. **21,** 549-551 (1996).
10. A. Sharon, S. Glasberg, D. Rosenblatt, and A. A. Friesem, "Metal-based resonant grating waveguide structures," J. Opt. Soc. Am. A **14,** 588–595 (1997).
11. P. Rochon, A. Natansohn, C. L. Callender, and L. Robitaille, "Guided mode resonance filters using polymer films," Appl. Phys. Lett. **71,** 1008–1010 (1997).

#7581 - $15.00 USD Received 25 May 2005; revised 2 June 2005; accepted 3 June 2005

12. R. J. Stockermans and P.L. Rochon, "Narrow-band resonant grating waveguide filters constructed with azobenzene polymers," Appl. Opt. **38,** 3714–3719 (1999).
13. A. Donval, E. Toussaere, J. Zyss, G. Levy-Yurista, E. Jonsson, A. A. Friesem, "Novel polymer-based resonant grating waveguide structures," IEEE J. Quantum Electron. **37,** 1030–1039 (2001).
14. A. Sharon, D. Rosenblatt, A. A. Friesem, H. G. Weber, H. Engel, and R. Steingueber, "Light modulation with resonant grating waveguide structures," Opt. Lett. **21,** 1564–1566 (1996).
15. N. Dudovich, G. Levy-Yurista, A. Sharon, A. A. Friesem, and H. G. Weber, "Active semiconductor-based grating waveguide structures," IEEE J. Quantum Electron. **37,** 1030–1039 (2001).
16. A. Donval, E. Toussaere, R. Hierle, J. Zyss, "Polarization insensitive electro-optic polymer modulator," Appl. Phys. **87,** 3258–3262 (2000).
17. D. Rosenblatt, A. Sharon and A. A. Friesem, "Resonant grating waveguide structures," IEEE J. Quantum Electron. **33,** 2038–2059 (1997).
18. P. Sheng , R. S. Stepleman ans P. N. Sanda, "Exact eigenfunctions for square-wave gratings: Application to diffraction and surface-plasmon calculations," Phys. Rev. B **26,** 2907–2917 (1982).

1. Introduction

Transferring information at high bit rates involves encoding electronic data signals into a lightwave carrier by modulating the light in phase or amplitude. This is usually done with an electooptic (E-O) modulator, where the signal voltage changes the refractive index of an E-O dielectric optical waveguide, modulating the phase of the guided lighwave. In present technology, lithium niobate is the E-O material most widely used in high-speed optical modulators. However due to certain loss mechanism there is serious doubt whether it will be useful for bandwidths larger than $100GHz$ [1]. Recently, polymeric electro-optic materials have attracted much interest as such candidate material. Polymeric E-O materials owe their non-linear (NL) properties to highly NL dyes imbedded in a polymer matrix. By carefully controlling the structure of the dye molecule is was possible to obtain record high E-O coefficient $r_{33} \sim 60pm/V$, resulting in a $sub-1V$ halfwave voltage, E-O modulator [2]. It was also demonstrated that by characterizing and selecting appropriate combinations of material, the favorable properties of polymers, such as low index mismatch between microwave and optical waves, can be exploited to essentially eliminate all dielectric factors degrading high frequency response. In such a manner modulation rates of up to $1.6THz$ were demonstrated [3].

Resonant grating waveguide structures (GWS) are planar multilayer structures. In their most basic configuration they are comprised of a surface relief grating, a waveguide layer and a substrate. When such GWS are illuminated with an incident light beam, most of the light is directly transmitted while the rest is diffracted, trapped in the waveguide layer, and subsequently, partially rediffracted outwards. At a specific wavelength and angular orientation of the incident beam, a "resonance" condition occurs, where the rediffracted beam 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 [4]-[10].

Most experimental investigations demonstrated the resonance behavior in passive GWS, which were fabricated with semiconductor material, dielectric materials and only recently with polymeric materials [11]-[13]. Even active GWS, whose resonance wavelength can be dynamically varied, were investigated. Specifically, a shift of the resonance wavelength is achieved by changing the refractive index in the waveguide or in adjacent layers of the GWS. Light modulation has been demonstrated with semiconductor-based active GWS [14, 15]. These GWS were fabricated from InP/InGaAsP material and involved the application of an external electric field in a forward voltage or reverse voltage configuration. Light modulation with frequencies as high as 5MHz were achieved.

In this letter we present, for the first time to our knowledge, experimental results showing light modulation in active polymer based resonant GWS. The active part of the GWS is com-

#7581 - $15.00 USD Received 25 May 2005; revised 2 June 2005; accepted 3 June 2005

prised of an electro-optic polymer, forming the waveguide layer. An externally applied field modulates the refractive index of the waveguide layer, shifting the resonance wavelength and resulting in modulation of the reflected intensity, when the structure is illuminated with an incident beam of a fixed wavelength of $1.55\mu m$. Such GWS can be fabricated with relatively simple spin coating technology, yielding a very cost effective light modulator. Similar electro-optic polymers have been successfully exploited in integrated optics channel waveguides for modulation or switching applications typically in a Mach-Zehnder type configuration [16]. Typically, these integrated configurations require complicated pigtailing and butt-end coupling to minimize losses, which are circumvented in our configuration.

2. Theoretical considerations

In order to estimate the expected resonance wavelength shift in the basic GWS configuration, we begin with the resonance condition relation given by [17],

$$n_c k sin\theta + mK = n_w k cos\psi, \tag{1}$$

where n_c is the refractive index of the cladding layer above the grating, n_w the refractive index of the waveguide layer, $k = 2\pi/\lambda_o$ the wave-vector at resonance with λ_o the resonance wavelength, K the grating wave-vector, whereby $K = 2\pi/\Lambda$ with Λ the grating period, m an integer for which $m = 1$ in the simple case of a single mode waveguide, θ the angle of incident light and ψ the angle of diffracted light. Using first order approximation and assuming near normal incidence angle, Eq.(1) can be solved to yield,

$$\frac{\Delta\lambda}{\lambda} \approx \frac{\Delta n}{n_w}, \tag{2}$$

where $\Delta\lambda$ is the resonance wavelength shift due to a change Δn, in the refractive index.

The refractive index change due to the application of a voltage V, across the waveguide E-O polymer is given by,

$$\Delta n = \frac{n_{w,o}^3 r_{23} \Gamma V}{2d}, \tag{3}$$

where $n_{w,o}$ is the ordinary refractive index which exists in the x,y plane, d is the distance between electrodes and r_{23} is the off-diagonal E-O coefficient. Since the excited mode we are considering is TE, i.e. the electric field is aligned parallel to the grating grooves (y direction), and the polymer was poled along the z axis as is the applied voltage, it is the off diagonal r_{23} E-O coefficient responsible for the refractive index change of interest. The confinement factor Γ is defined as the cross-sectional ratio of the mode size over the active GWS area. Substituting Eq.(3) into Eq.(2) yields the dependence of the expected resonance wavelength shift on the applied voltage for small incident angles,

$$\Delta\lambda \approx \frac{\lambda n_{w,o}^2 r_{23} \Gamma}{2d} V. \tag{4}$$

Substituting state of the art values for the E-O coefficient [2] in Eq.(4), a value of $\Delta\lambda \cong 0.1nm$ is expected ($\lambda = 1.55\mu m$, $n_{w,o} = 1.7$, $\Gamma = 0.7$, $d = 5\mu m$, $V = 10V$ and $r_{33} = 60pm/V$; r_{23} is assumed to be $\frac{1}{3}r_{33}$). In our experiments the E-O coefficient is estimated to be $r_{33} = 12pm/V$, so somewhat smaller wavelength shifts are to be expected.

3. Experimental procedure and results

The active polymer-based GWS, is schematically shown in Fig. 1. We used optical quality substrates ($\lambda/4$, $BK7$), coated with transparent ITO (Indium Tin Oxide) conducting layer, on

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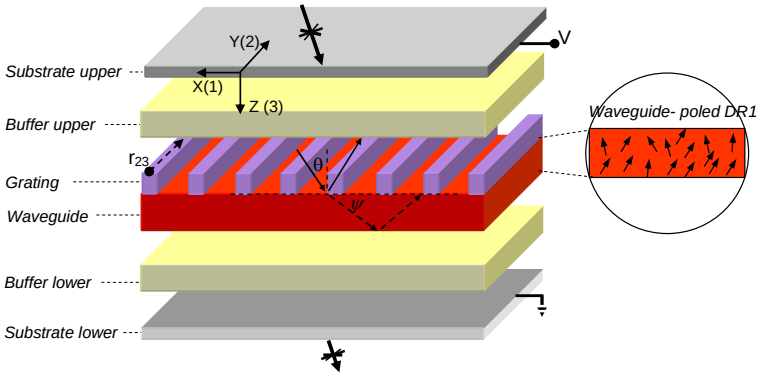

Fig. 1. Active polymer-based grating waveguide structure with an E-O polymer waveguide.

which a number of additional layers all deposited with spin coating technology were added. First, a spin on glass (SOG) buffer layer ($n = 1.46$, $\lambda = 1.55\mu m$), was deposited on top of the glass substrate, so as to confine the guided modes in the polymer waveguide layer and prevent their leakage to the higher refractive index ITO coating. Using a numerical model based on the exact eigenmodes method [18], we calculated that a buffer layer thickness of approximately $1.8\mu m$ is sufficient to prevent mode leakage and yet not require a significant increase of the externally applied voltage. Then the waveguide and grating layers of a 30% molar ratio disperse-red-one chromophore side chain methyl methacrylate polymer (DR1-MMA $n = 1.6$, $\lambda = 1.55\mu m$) and a thin photoresist layer were deposited. The grating layer was holographically recorded in Shipley *S*1805 photoresist layer. The grating structure was optimized so as to minimize surface roughness with variable 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. The thickness of

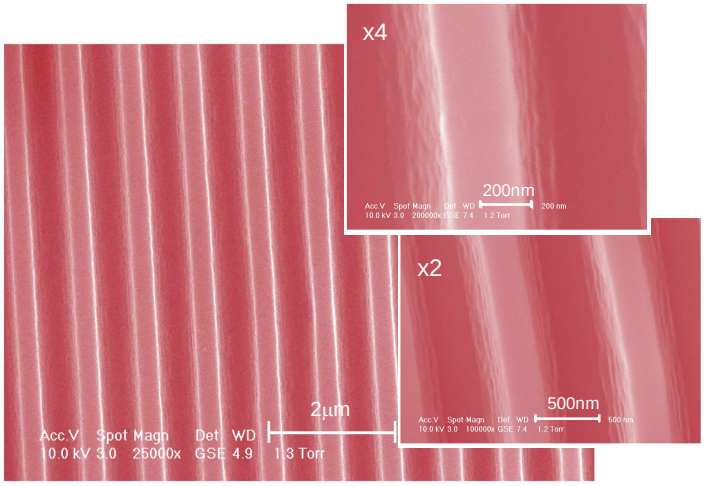

Fig. 2. *SEM* images of the grating layer. Inserts showing enhanced images of the grating surface roughness.

#7581 - $15.00 USD
Received 25 May 2005; revised 2 June 2005; accepted 3 June 2005

the waveguide layer was approximately 580*nm* and that of the grating 400*nm*. The grating period was approximately 960*nm*. The polymer waveguide layer was poled by a corona procedure rendering it E-O active. In this procedure the waveguide was heated to 120 ^oC, close to the glass transition temperature (T_g), and then a DC voltage of $5kV$ was applied for 30min. Afterwards the waveguide was cooled to room temperature while retaining the applied voltage, a step taking a few hours. On top of the grating layer an additional upper buffer layer of NOA65 optical adhesive ($n = 1.5517$, $\lambda = 1.55\mu m$), $5\mu m$ thick was deposited. Finally, an upper conducting ITO coated glass substrate was added.

The experimental setup for testing the active GWS includes a tunable external cavity diode laser operating at a wavelength near $1.55\mu m$. The light from the laser was collimated and polarized, so as to illuminate the GWS samples with a TE polarized plane wave. To obtain light modulation an external voltage derived from a special pulse-generator was applied. The pulse generator had a low duty cycle, in order to keep the power dissipation in the GWS as low as possible even at high frequencies. Square pulses with peak voltages of $40V$, rise time of 10*ns* and decay time of 60*ns* could be reached. For the light modulation experiments the incident laser light wavelength was set at the resonance wavelength, a voltage pulse across the GWS was applied using the ITO conducting layers serving as electrodes and the reflected light was detected with a fast detector. Representative experimental results for the active GWS are shown in Fig. 3 and Fig. 4. Figure 3 shows the normalized reflection intensity as a function

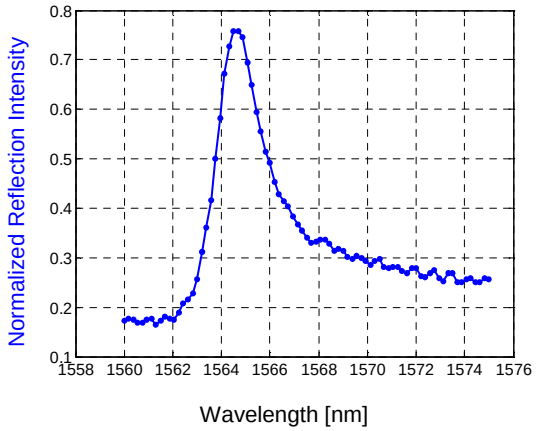

Fig. 3. Experimental normalized reflection intensity as a function of wavelength, for a polymer-based GWS.

of wavelength, where the wavelength was varied in discrete steps of 0.05*nm*. As shown, the resonance bandwidth is approximately 2*nm* and the normalized reflection intensity at resonance is approximately 80%. The relatively wide resonance bandwidth and lower than 100% reflection intensity are due to losses that result from imperfections. One such possible loss mechanism may be due to excess scattering from the rough surface of the etched grating as evident in Fig. 2. The non-zero off resonance reflection is a result of refractive index mismatch between the layers resulting in Fresnel reflections. These reflections could be significantly reduced by the addition of anti-reflection coatings. Figure 4 demonstrates light modulation with the active polymer based GWS. Figure 4(a) shows light modulation when an external voltage pulse of 0.1ms duration is applied, and Fig. 4(b) when the voltage pulse is reduced to $1\mu s$. As evident, the modulation intensity follows that of the applied voltage pulse. The modulation obtained was of approximately one percent of the incident light intensity and results shown are averaged over several driving pulse sequences. No such light modulation was detected when the incident light

#7581 - $15.00 USD Received 25 May 2005; revised 2 June 2005; accepted 3 June 2005

wavelength was shifted away from the resonance wavelength. Light modulation was performed with photodetectors in AC mode, so when the voltage pulse reaches its maximum plateau value the optical signal begins to drop. In these experiments the modulation bandwidth of 1MHz was mainly limited by the electrode configuration and driving source.

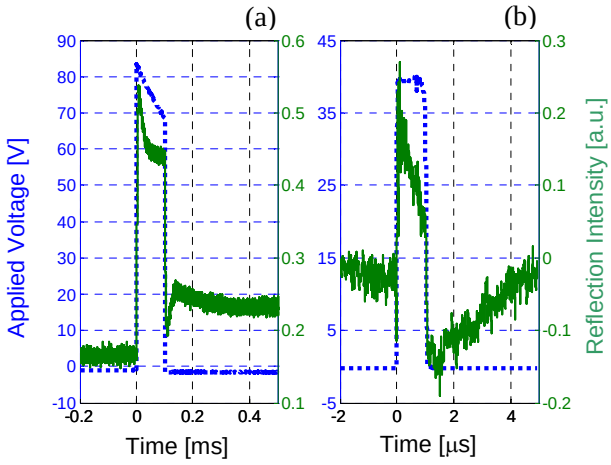

Fig. 4. Experimental normalized reflection intensity as a function of wavelength, for a polymer-based GWS. (a) Pulse duration of $0.1ms$; (b) pulse duration of $1\mu s$. Dashed curve- applied voltage; solid curve- detected reflection modulation at resonance wavelength.

4. Concluding remarks

To conclude, an active polymer based GWS was fabricated and experimentally tested. The results reveal that the resonance bandwidth can be as narrow as $2nm$, and that light modulation can be readily detected even at $1MHz$. We expect that these results can be significantly improved by reducing the needed applied voltage as well as increasing the response bandwidth, by using more advanced polymers that would have greater E-O coefficient and lower scattering losses, and by resorting to different electrode configurations for effectively applying the external voltage.

Acknowledgments

This study has been supported in part by the Israeli Ministry of Science and the German Bundesministerium for Forschung and Technologie.

#7581 - $15.00 USD
Received 25 May 2005; revised 2 June 2005; accepted 3 June 2005