ELSEVIER

Optical Materials 17 (2001) 149–154

OPTICAL Materials

www.elsevier.nl/locate/optmat

Hybrid semiconductor polymer resonant grating waveguide structures

G. Levy-Yurista [a,*], A.A. Friesem [a], E. Pawlowski [b], L. Kuller [b], R. Ludwig [b], H.G. Weber [b], A. Donval [c], E. Toussaere [c], J. Zyss [c]

[a] Department of Physics of Complex Systems, Weizmann Institute of Science, Rehovot 76100, Israel

[b] Heinrich-Hertz-Institut für Nachrichtentechnik Berlin GmbH, Einsteinufer 37, Berlin D-10587, Germany

[c] Laboratoire de Photonique Quantique et Moleculaire, (UMR CNRS #8537), Ecole Normale Superieure de Cachan, 61 av. du president Wilson, 94235 Cachan, France

Abstract

When illuminated with an incident beam of light, grating waveguide structures (GWS), of specific geometrical and optical parameters, have a resonant behavior. Under such behavior, an incident beam, which is normally completely transmitted, is wholly reflected at a certain wavelength, with a very narrow resonance spectral bandwidth. Thus, such structures can serve as very narrow spectral filters for a variety of applications. After reviewing the basic principles, we present polymer-based grating waveguide structures which were fabricated using spin-coating techniques and holographic recording of gratings. Experimental results yielded narrow bandwidth optical filtering, with 55% reflection efficiencies and 1 nm bandwidth at FWHM. Also, we present our latest theoretical and experimental developments of semiconductor and polymer-based grating waveguide structures. The results reveal that for semiconductor-based grating waveguide structures the resonance spectral bandwidth can be as low as 0.1 nm, and the contrast ratio as high as 1000, with finesses greater than 10 000. Such structures were placed inside a laser cavity and served as a back mirror to determine lasing wavelength. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Resonant gratings; Optical filters; Polymer elements; Hybrid structures

1. Introduction

Diffraction anomalies from gratings have been originally observed by Wood [1], followed by many theoretical investigations by a number of researchers [2–6]. These investigations have been expanded to resonance anomalies in grating waveguide structures (GWS), and included new theoretical and experimental developments [7–12]. 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 diffracted, trapped in the waveguide layer, and subsequently, partially rediffracted outwards. At a specific resonant wavelength and angular orientation of the incident beam the rediffracted beam interferes with the transmitted beam, so that the incident beam is completely reflected from the

* Corresponding author. Tel.: +972-8-9342051; fax: +972-8-9344109.

E-mail address: feguy@wisemail.weizmann.ac.il (G. Levy-Yurista).

PII: S0925-3467(01)00039-8

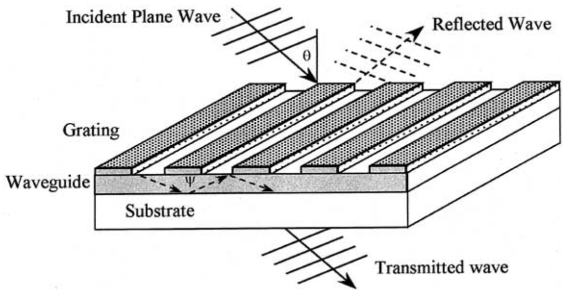

Fig. 1. Basic configuration of a grating waveguide structure (GWS).

GWS. Extremely narrow resonance bandwidths of about 0.1 nm were reported and a modulation rate of 10 MHz was 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.

Preliminary work involving the formation of simple gratings in polymeric materials was done in the past [17–20]. This work concentrated on recording the interference pattern onto a polymer film so as to form a relief grating in it. Subsequent work involved resonant grating structures in these polymers [21,22].

Here we present how new polymer materials can be exploited for forming advanced grating waveguide structures. The polymer materials are used to form the waveguide layer [23,24] leading to GWS that can be readily fabricated at a low cost. As such they would be attractive as photonic devices for the DWDM optical communication systems [25–27]. The high demands in integrated optics for inexpensive yet reliable and efficient components have driven many researchers to look into polymers. Lately, novel polymers have been introduced that could serve in ultra fast optical components [25]. In the following sections we describe the novel GWS configuration, where the structure is composed of a hybrid polymer-semiconductor configuration. This novel design leads to a significant reduction of time-consuming procedures as well as fabrication costs. We also present experimental results showing spectral bandwidths as low as 0.1 nm with contrast ratios greater than 1000. Finally we describe how a GWS can be incorporated inside a semiconductor laser cavity.

2. Theoretical considerations

In general, the resonance wavelength λ_0 of a GWS is related to the grating period Λ in accordance to

$$n_{cl} k \sin\theta + mK = n_{wg} k \cos\psi, \tag{1}$$

where n_{cl} is the refractive index of the cladding layer above the structure, n_{wg} is the refractive index of the waveguide layer, θ is the angle of the incident light and ψ the angle of the diffracted light as shown in Fig. 1, $k = 2\pi/\lambda_0$ is the light wave-vector at resonance, $K = 2\pi/\Lambda$ is the grating wave-vector, and m is an integer ($m = 1$ for the simplest case of a single mode waveguide).

We have also developed a coupled wave model using Green's function formalism, which is particularly useful for analyzing the resonance behavior of a GWS [15]. This coupled wave model is an adaptation of a model used for analyzing DFB lasers that was developed by Kazarinov and Henry [28], and provides details on both the spectral bandwidth as well as the angular beamwidth.

3. Hybrid semiconductor polymer-based GWS

3.1. General considerations

A schematic polymer-based GWS configuration is shown in Fig. 2. The structure is designed such that the buffer layer is located in-between the polymer-based GWS and the Si substrate. For light to be confined to the guided modes it is required that the cladding and substrate layers have a lower refractive indices than that of the waveguide. However, since the Si wafer has a higher refractive index than the polymer waveguide we need to add a buffer layer between them. Such interaction is a cause of guided modes energy leakage resulting in a degradation of the resonance characteristics.

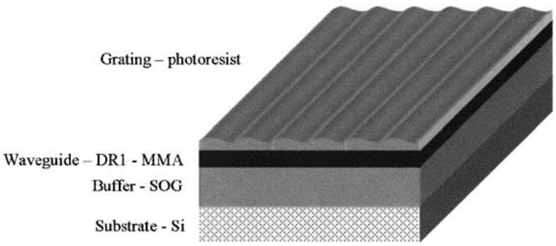

Fig. 2. Representative polymer-based GWS configuration. SOG buffer layer thickness is 1.7 μm, DR1–MMA waveguide layer thickness is 0.9 μm, grating period is about 0.96 μm and layer thickness is measured to be 0.4–0.8 μm for the different samples.

3.2. Fabrication procedure

For the fabrication of the GWS we used a substrate of Si-wafer on which a bottom buffer layer of SOG is deposited by spin-coating technology. The waveguide is formed with a 30% molar ratio disperse-red-one chromophore side chain polymethyl methacrylate (DR1-MMA, $n = 1.6$ at $\lambda = 1.55$ μm). The photoresist layer is spin-coated under laminar-flow conditions with Shipley 1805 photoresist. Exposure of the grating is done with an argon laser at 363.8 nm and a grating period of about 1000 l/mm. 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. In order to verify the shape and thickness of the grating layer we analyzed the various samples using an AFM technique.

3.3. Experimental procedure and results

The experimental set-up for testing the polymer-based GWS includes a tunable external cavity diode laser operating at wavelengths around 1.55 μm. The beam from the laser illuminates only a small part of the sample area according to its diameter (about 4 mm^2). The spectral resolution of the laser system is 0.003 nm. Part of the laser beam was normally incident, through a beamsplitter, onto the sample, which was placed on a translating and rotating stage (sub-micron and sub-arcsecond resolutions, respectively). For normalization, part of the incident plane wave that was reflected from the beamsplitter was monitored by an additional detector. The light reflected from the sample was collected onto one detector. A computer was used for controlling the wavelength of the tunable laser and the position and angle of the sample carrying

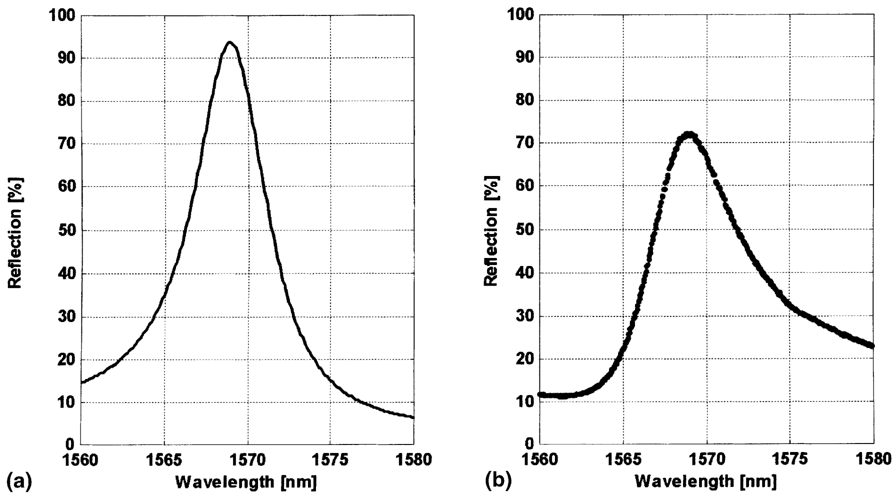

Fig. 3. (a) Calculated normalized reflected intensity as a function of wavelength, for a polymer-based GWS having the following parameters: SOG buffer layer thickness is 1.7 μm, DR1–MMA waveguide thickness is 0.9 μm, photo-resist grating thickness is 0.82 μm and it's period is 1.027 μm; (b) Experimental normalized reflected intensity as a function of wavelength, for the polymer-based GWS of the same parameters. It is seen that there is a very good agreement between theoretical calculations and experimental measurements.

stage, as well as for monitoring all measurements from the various detectors. In order to set the polarization of the incident light we used a polarizer and a $\lambda/2$ plate. We measured and evaluated the resonance behavior of the different GWSs.

We simulated the resonance spectral behavior of the several polymer-based GWS using the eigenfunction algorithm [29] and the GSOLVER software [30]. We then measured their characteristics. Fig. 3(a) shows the calculated results for a polymer-based GWS sample with a structure similar to that of Fig. 2 with a grating layer thickness of about 0.82 μm. Fig. 3(b) shows the corresponding experimental results for the same sample. As evident, calculated and experimental results are in good agreement. These results depend mainly on design parameters and can be controlled to very high accuracy. For example, decreasing grating thickness will result in narrowing 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 at resonance for a GWS with no losses at all. The discrepancy between the measured and predicted results is attributed to undesirable loss mechanisms. We expect that reduction of these undesirable losses will lead to increased finesse and improvement of the intensity contrast ratio, especially of the reflected intensities.

4. Semiconductor GWS inside a laser cavity

4.1. Free space characterization

We performed some preliminary experiments to determine whether a GWS can serve as a back-mirror of a semiconductor laser. For these experiments, we designed and fabricated several passive GWS of a structure similar to that depicted in Fig. 1. We measured the spectral resonance behavior of these GWSs. The results are presented in Fig. 4. They show the normalized reflected intensity as a

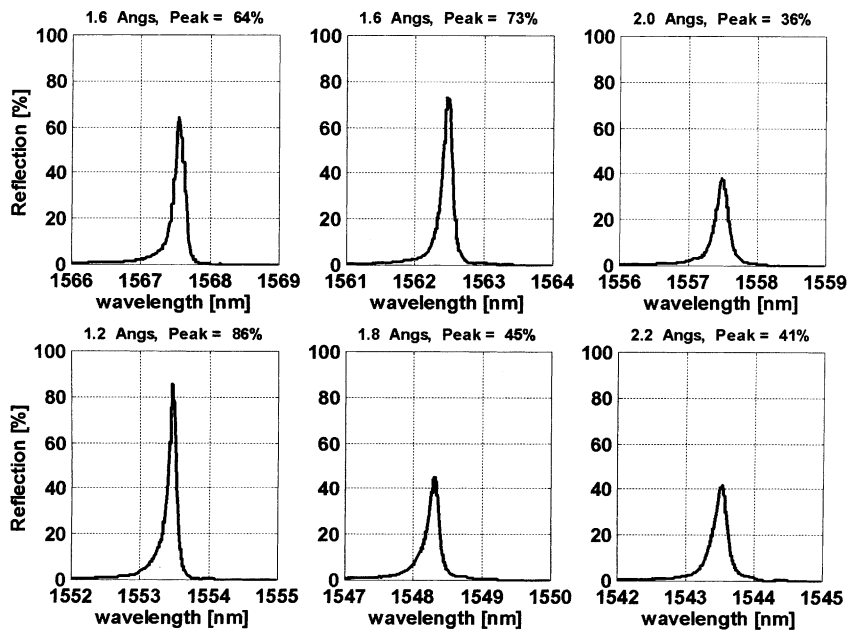

Fig. 4. Resonance behavior of several passive GWS. The best result is in the lower left corner demonstrating bandwidth of 0.12 nm and a reflection peak of 86%.

function of wavelength for six different grating periods. As shown, the resonance bandwidths at FWHM range from 0.12 to 0.26 nm. High finesses values were obtained, the best being about 13 000, for a very narrow spectral FWHM bandwidth of 0.12 nm, as shown in the lower left of Fig. 4.

4.2. Experimental procedure and results

All six GWSs were then individually incorporated into a cavity of an external cavity semiconductor laser. Here, the original rotating grating that is normally used for tuning the lasing wavelength was replaced by the passive GWSs.

With each GWS, we measured the spectral response of the laser output beam. The results are presented in Fig. 5. Each GWS results in a different wavelength, in accordance with the corresponding GWS resonance wavelength shown in Fig. 5. Side mode suppression at the different lasing lines range between 42 and 58 dB. The linewidths obtained with the GWS were comparable to those with the normally used grating. These results obviously indicate that GWS can be successfully incorporated into semiconductor lasers.

5. Conclusion

Resonant phenomena in gratings were originally studied as more of a curiousity than for practical applications. With the advent of sub-micron photolithography and planar processing technology the fabrication of such structures, where the dimensions are of the order of the wavelength of light and smaller has become feasible. Such structures of such a size scale can be used to manipulate the phase of the light, to give an interference effect with a spectral bandwidth and angular beamwidth that can be tailored for specific applications. Until recently mainly cumbersome and costly techniques such as MOCVD or MBE were used for the fabrication of such devices. We have utilized a set of analytic and numerical models for designing such structures based on novel polymeric materials that are easy to fabricate in common techniques, namely, spin-coating and holographic recording. We have presented experimental results which demonstrate that high quality polymer-based GWS can be fabricated so their performance is comparable to that predicted by theory. We believe that active polymer-based GWS will be available for demonstration in

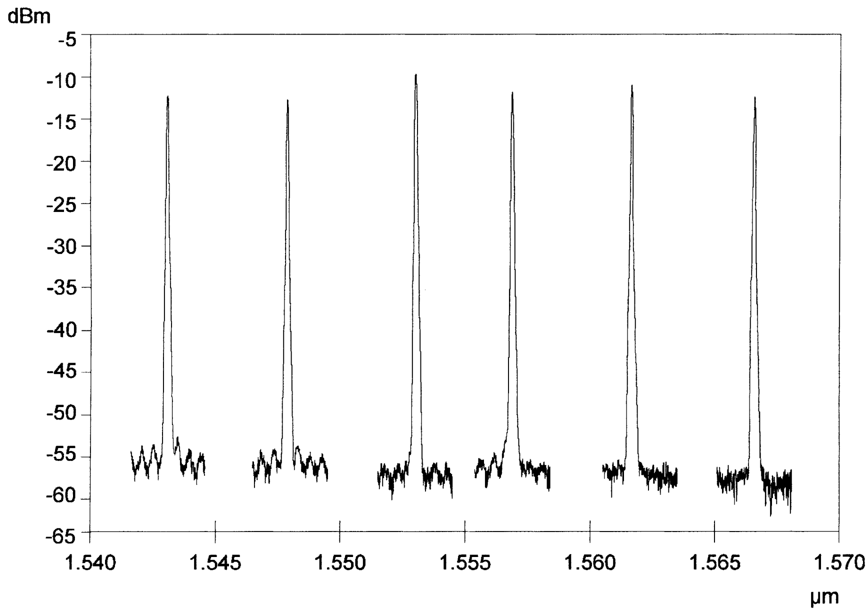

Fig. 5. Experimental measurements of lasing wavelength with six different passive GWS inside a semiconductor laser cavity.

the near future. We also presented preliminary results of the experimental set-up of a GWS as a back mirror of a laser. We first demonstrated extremely high finesse values in a free space configuration and then placed the elements successfully inside a cavity.

The results also suggest that applications as dynamic spectral filters, active mirrors for laser resonators, and 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.

Acknowledgements

This research was supported in part by the Israeli Ministry of Science.

References

[1] R.W. Wood, Philos. Mag. 4 (1902) 396.
[2] A. Hessel, A.A. Oliner, Appl. Opt. 4 (1965) 1275.
[3] M. Neviere, R. Petit (Eds.), Springer, Berlin, 1980 (Chapter 5).
[4] E. Popov, L. Mashev, D. Maystre, Optica Acta 32 (1986) 607.
[5] R. Magnusson, S.S. Wang, Appl. Phys. Lett. 61 (1992) 1022.
[6] T. Tamir, S. Zhang, J. Opt. Soc. Am. A 14 (7) (1997) 1607.
[7] G.A. Golubenko, A.S. Svakhin, V.A. Sychugov, A.V. Tischenko, Sov. J. Quant. Electron. 15 (1985) 886.
[8] I.D. Avrutskii, G.A. Golubenko, V.A. Sychugov, A.V. Tischenko, Soviet Technol. Phys. Lett. 11 (1985) 401.
[9] R. Magnusson, S.S. Wang, SPIE 2108 (1993) 380.
[10] S. Peng, G.M. Morris, Opt. Lett. 21 (1996) 548.
[11] A. Sharon, S. Glasberg, D. Rosenblatt, A.A. Friesem, J. Opt. Soc. Am. A 14 (1997) 588.
[12] S. Glasberg, A. Sharon, D. Rosenblatt, A.A. Friesem, Opt. Comm. 145 (1998) 291.
[13] A. Sharon, D. Rosenblatt, A.A. Friesem, H.G. Weber, H. Engel, R. Steingrueber, Opt. Lett. 21 (1996) 1564.
[14] A. Sharon, D. Rosenblatt, A.A. Friesem, Appl. Phys. Lett. 69 (1997) 4154.
[15] D. Rosenblatt, A. Sharon, A.A. Friesem, IEEE J. of Quant. Elect. 33 (1997) 2038.
[16] G. Levy-Yurista, A.A. Friesem, Appl. Phys. Lett. 77 (2000) 1596.
[17] X. Mai, R. Moshrefzadeh, U.J. Gibson, G.I. Stegeman, C.T. Seaton, Appl. Opt. 24 (1985) 3155.
[18] P. Rochon, E. Batalla, A. Natansohn, Appl. Phys. Lett. 66 (1995) 136.
[19] E. Toussaere, P. Labbé, Opt. Mater. 12 (1999) 357.
[20] G. Kranzelbinder, E. Toussaere, R. Mathevet, D. Josse, J. Zyss, CLEO/QELS San Francisco, 2000.
[21] P. Rochon, A. Natansohn, C.L. Callender, L. Robitaille, Appl. Phys. Lett. 71 (1997) 1008.
[22] R.J. Stockermans, P.L. Rochon, Appl. Opt. 38 (17) (1999) 3714.
[23] R. Levenson, Zyss, M. Quillec (Eds.), Chapter C-III, Kluwer Academic Publisher, Dordrecht, 1997, p. 341.
[24] R. Levenson, J. Liang. C. Rossier, R. Hierle, E. Toussaere, N. Bouadma, J. Zyss, in: G.A. Lindsay, K.D. Singer (Eds.), ACS Symposium Serie 601 (1995) 436.
[25] R. Hunsperger, Integrated Optics: Theory and Technology, fourth ed., Springer, Berlin, 1995.
[26] A. Donval, E. Toussaere, R. Hierle, J. Zyss, Appl. Phys. 87 (7) (2000) 3258.
[27] A. Donval, E. Toussaere, S. Brasselet, J. Zyss, Opt. Mater. 12 (1999) 215.
[28] R. Kazarinov, C. Henry, IEEE J. of Quant. Elect. QE-21 (1985) 151.
[29] P. Sheng, R.S. Stepleman, P.N. Sanda, Phys. Rev. B 26 (1982) 2907.
[30] GSOLVER, Grating Solver Development Company. Website at http://www.gsolver.com.