Superimposed grating wavelength division multiplexing in Ge-doped SiO_2/Si planar waveguides

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Abstract. An improved model of wavelength division multiplexing (WDM) by superimposed gratings in planar waveguides has been developed. Based on this theory, principal design rules of /V-channel WDM are established and a fanout capacity of 100 is estimated. Finally, four-channel WDM at 840 nm has been demonstrated on a Ge:SiO_2/SiO_2/Si planar waveguide, which was hydrogenated to enhance its photosensitivity. The superimposed gratings were written using a narrow linewidth KrF excimer laser in an interferometric setup used in inscribing fiber Bragg gratings. © 1998 *Society of Photo-Optical instrumentation Engineers.* [SO09 1-3286(98)04402-X]

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1 Introduction

In today's world, where information technology is of great importance, transmission speeds in fiber optics are an important concern. It is well known that integrated wavelength division multiplexers (WDMs) are key elements for enhancing the transmission capacity of fiber optic communication systems. In view of the requirement for WDMs, several such integrated devices have been already demonstrated, based on different concepts. The curved-diffraction-grating WDM,[1] the Mach-Zehnder WDM,[2] and the arrayed-waveguide WDM[3] are examples. Recently an alternative WDM device technology that is relatively simple, compact, potentially implementable, and integrable with other telecommunication elements has been reported in Refs. 4 to 6. In that work a theoretical investigation has been reported on wavelength division using superposition of multiple Bragg gratings on a planar waveguide (Fig. 1). In this paper we first present an improved theoretical model, and on that basis we demonstrate a four-channel WDM accomplished by superimposing four Bragg gratings on a photosensitive planar waveguide.

2 Modeling

To study the effect of coupling between the superimposed gratings and to design the WDM properly, a theoretical model was developed from the coupled mode theory.[4–6] In this model, the N gratings are designed so that each of them diffracts one particular wavelength λ_i to one particular direction θ_{Si} for a common input angle θ_R. The combined response of all the gratings to an input beam excitation at wavelength λ_R and incident angle θ_R is calculated by solving a set of N + 1 coupled-mode differential equations in the grating zone:

$$\cos\,\theta_R\,\frac{\mathrm{d}R(z)}{\mathrm{d}z}=-j\sum_{i=1}^{N}\kappa_i\exp(-j\Delta_i z)\,S_i(z),\tag{1}$$

$$\cos\,\Theta_{S_i}\,\frac{\mathrm{d}S_i(z)}{\mathrm{d}z}=-j\kappa_i\,\exp(+j\Delta_i z)\,R(z)\quad\text{for } i=1,\ldots,N,$$

where $R(z)$ is the amplitude of the input beam, $S_i(z)$ and Θ_{Si} are the amplitude and output angle of the diffracted beams, κ_i are the grating coupling coefficients as defined in Ref. 4, and Δ_i are the phase-mismatch factors. The diffraction efficiency of each grating is then calculated using

$$\eta_i(z)=\frac{\cos\,\Theta_{Si}}{\cos\,\theta_R}\,|S_i(z)|^2.\tag{2}$$

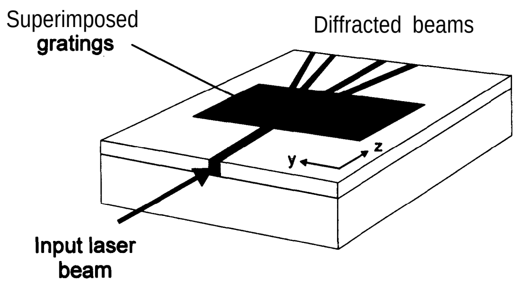


Fig. 1 A schematic diagram of a four-grating WDM on a planar waveguide.

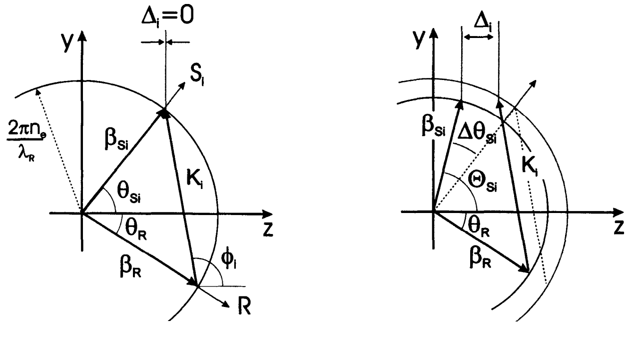
The coupling coefficient describes the strength with which a grating interacts with a guided wave. The phase-mismatch factor is a measure of the deviation from the Bragg condition and defines the maximal energy exchange between the wave R and S_i. When the Bragg condition is satisfied, $\Delta_i = 0$, and there is a maximal transfer of energy at the coupling length L_{ci} ($\eta_i = 1$ if there is only one grating). For A $_i \gg 1$ there is no transfer of energy ($\eta i \ll 1$). The phase-mismatch factor is a key parameter that determines the wavelength and angular selectivity of the gratings and thus their coupling when they are superimposed.

Following the work published in Ref. 6, an improved calculation of the phase-mismatch factor is accomplished by including the angular dispersion A θ_{Si} that results from a wavelength dispersion AX of the input beam. As shown in Fig. 2, the diffraction angle of an input wavelength $\lambda_R = \lambda_i + \Delta\lambda$ is found to be

$$\Theta_{Si} = \theta_{Si} + \Delta\theta_{Si} \approx \theta_{Si} + \frac{\sin\theta_{Si} \text{-} \sin\theta_R}{\cos\theta_{Si}} \frac{AX}{\lambda_i}, \qquad (3)$$

where the phase-mismatch factor is simply given by

$$\Delta_i = \beta_R \cos(\theta_{Si} + \Delta\theta_{Si}) - (\beta_R \cos\theta_R + K_i \cos\phi_i). \qquad (4)$$



(a) $\lambda_R=\lambda_i$ (b) $\lambda_R=\lambda_i+\Delta_i$

Fig. 2 A β diagram of the interaction of the input beam at wavelength λ_R and the grating (a) at the Bragg condition and (b) off the Bragg condition.

3 Device Design

With the improved model, it was possible to quantify different regimes of integrating couplings, which help in the design of a device. In the case of strong coupling, superimposed gratings show very large deviations from the responses expected of individual sets of gratings. In this regime it is difficult, if not impossible, to construct a conventional WDM. On the other hand, in the quasidecoupled regime, where the wavelength and angular separation are larger, the superimposed gratings give nearly independent responses and the design of an N-channel WDM is relatively straightforward.

The criterion of quasidecoupling is simply given by

$$\Delta\lambda \geq 1.5\, \Delta\lambda_{i0}, \qquad (5)$$

where AX is the wavelength separation between the adjacent channels, and $\Delta\lambda_{i0}$ is the total width at the first two zeros of the isolated grating spectrum (calculated as if the other gratings were absent). In the quasidecoupled regime, the analysis for an N-channel WDM is relatively straightforward. The expression for $\Delta\lambda_{i0}$ as a function of the key structure and operation parameter assuming a perfect collimated input beam is given by[7]

$$\Delta\lambda_{i0} = \sqrt{3}\, \frac{\lambda_i^2}{n_e L_{ci}} \frac{\cos\theta_{Si}}{1 - \cos(\theta_{Si} - \theta_R)} \qquad (6)$$

where n_e is the guided-mode effective index.

This equation shows that the grating selectivity depends on both the grating length and the diffraction angle. The longer the grating and the larger the diffraction angle, the more selective is the grating ($\Delta\lambda_{i0}$ diminishes). Therefore, the design of a WDM with evenly spaced channels with a spacing of $\Delta\lambda_{\mathrm{WDM}}$ around a central wavelength λ_c is constrained by a minimal diffraction angle under which the gratings will be strongly coupled and will give a distorted spectrum. For $\theta_R = 0$, which is the most convenient configuration, one calculates

$$\theta_{\min} = \cos^{-1}\left[\left(1 + \frac{1.5\sqrt{3}}{n_e L_{ci}} \frac{\lambda_c^2}{\Delta\lambda_{\mathrm{WDM}}}\right)^{-1}\right]. \qquad (7)$$

Thus, $\theta_{\min}$ will depend on the coupling length. The longer the L_{ci}, the smaller the minimal diffraction angle. This analysis only shows the range of "good" diffraction angles, $|\theta_{Si}| \geq \theta_{\min}$, but individual adjustments of either the grating's length or its strength and good input conditions are required to ensure high diffraction efficiencies.*

In Ref. 6 the angular spacing between channels was examined by looking at the inter-grating coupling that can occur for close diffraction angles. It was found that the minimal angle spacing between channels, above which the coupling can be neglected, is of the order of a few milliradians. All considered, in the quasidecoupled regime, we find that the maximum fanout capacity of the superimposed grating WDM is of the order of 100, thus being limited only by the maximal index change inducible in the material.

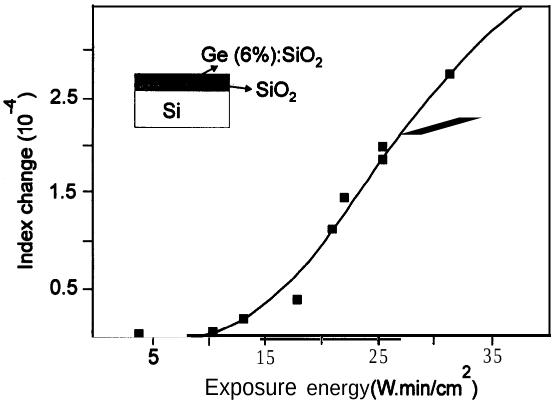


Fig. 3 Photosensitivity characterization of the Ge-doped-silica-on-silicon planar waveguide.

4 Experiments

The guiding structure of the photosensitive Ge-doped silica-on-silicon planar waveguides that was used in these experiments is shown in the inset of Fig. 3. These guides were first placed in a high-pressure hydrogen chamber that was maintained at 1500 psi at room temperature for several days, to increase their photosensitivity at the 245-nm UV band. Following the hydrogenation treatment, a two-laser beam interferometric setup was used to inscribe the gratings on the waveguides. The laser beams used in the interferometer were obtained from a narrow-linewidth KrF excimer laser.[9] Prior to writing the multiple gratings, the waveguide material was characterized in term of index change versus UV exposure in an attempt to optimize the grating diffraction efficiency. This was achieved by inscribing a simple 5-mm-long Bragg grating on identical waveguides over different exposure times. From the reflection efficiencies of the well-defined Bragg gratings inscribed on the different waveguides it was possible to estimate the index of refraction change for the different exposure times (see Fig. 3). Following this, four 5-mm-long superimposed gratings were successively exposed for 15 min with beam energy of 100 mJ/pulse at 30 Hz. They were designed to diffract at $\lambda_i = 830$, 840, 850, and 860 nm at $\theta_{Si} = +32$, -26, -30, and $+28$ deg, respectively ($\theta_R = 0$). The choice of the diffracted wavelengths is dictated by the range of tunability of the laser used for the characterization.

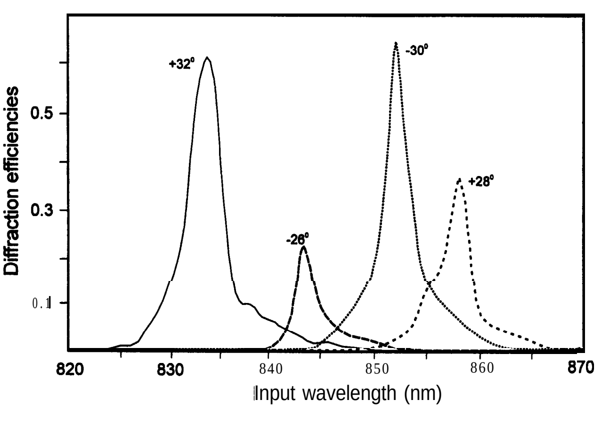
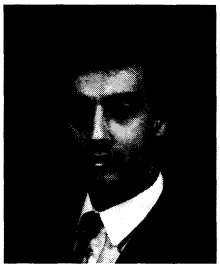


Fig. 4 Diffraction spectral response of the four-channel WDM.

To measure the diffraction efficiency versus input wavelength at each θ_{Si}, a beam of a Ti:sapphire tunable laser was coupled into the TE_0 guided mode with a prism, and the measurements of the WDM characteristics were taken from the output edge of the waveguide. The diffraction efficiencies vary from 62% to 21%, while the FWHMs were around 3 nm. This is approximately 6 times broader than the theoretical values given by Eq. (6), whereas the cross talks are between -10 and -15 dB (Fig. 4). The broader than expected FWHMs prompted us to perform a secondary experiment to inspect the uniformity of the index modulation profiles. By illuminating the sample with a coherent visible beam from the top (nonguided light) we generated scattered beams corresponding to the different orders of the Raman-Nath diffraction through the thin layer of the grating. Because the intensity of each of them is proportional to the local index modulation, the use of a large-diameter incident beam allows the observation of the index modulation profile over the whole grating area. As suspected, highly nonuniform gratings were been observed in all fabricated samples. We attribute this to the nonuniformity of the excimer laser writing beam itself, which was working at barely above the threshold due to the intracavity etalons used in narrowing the linewidth of the laser. This nonuniformity of the index modulation over the grating area explains the broadening of the spectral response and the relatively high level of cross talk. It also partially explains the relatively low diffraction efficiencies, which should be improved with better control of the grating strength (i.e., of the exposure). However, as a proof-of-feasibility demonstration, the four-channel WDM implemented in silicon glass exhibited satisfactory functionality of wavelength demultiplexing.

References

1. M. Fallahi, K. A. McGreer, A. Delage, I. M. Templeton, F. Chatenoud, and R. Barber, "Grating demultiplexer integrated with MSM detector array in InGaAs/AlGaAs/GaAs for WDM," *IEEE Photonics Technol. Lett.* 5(7), 794-796 (1993).
2. B. H. Verbeek et al., "Integrated four-channel Mach-Zehnder multi/demultiplexer fabricated with phosphorus-doped SiO_2 waveguides on Si," *J. Lightwave Technol.* 6(6), 1115-1118 (1988).
3. H. Takahashi, K. Oda, H. Toba, and Y. Inoue, "Transmission characteristics of arrayed waveguides $N \times N$ wavelength multiplexer," *J. Light-wave Technol.* 13(3), 447-455 (1995).
4. V. Minier, A. Kevorkian, and J. M. Xu, "Diffraction characteristics of superimposed holographic gratings in planar optical waveguides," *IEEE Photonics Technol. Lett.* 4(4), 1115-1118 (1992).
5. V. Minier, A. Kevorkian, and J. M. Xu, "Superimposed phase gratings in planar optical waveguides for wavelength demultiplexing applications," *IEEE Photonics Technol. Lett.* 5(3), 330-333 (1993).
6. V. Minier and J. M. Xu, "Coupled-mode analysis of superimposed phase gratings guided-wave structures and integrating coupling effects," *Opt. Eng.* 32(9), 2054-2063 (1993).
7. H. Nishihara, M. Haruna, and T. Suhara, *Optical Integrated Circuits*, Chap. 4, McGraw-Hill, New York (1989).
8. R. L. Hyde, D. Barbier, A. Kevorkian, J. Bismuth, A. Othonos, M. Sweeny, and J. M. Xu, "Optical application lasing and wavelength division multiplexing integrated in glass waveguides," *Future Trends in Microelectronics*, NATO ASI Series, S. Luryi, J. M. Xu, and Zaslavsky, Eds., Kluwer, Holland (1996).
9. A. Othonos and X. Lee, "Narrow linewidth excimer laser for inscribing Bragg gratings in optical fibers," *Rev. Sci. Instrum.* 66(5), 3112–3115 (1995).



Andreas Othonos received his BSc, MSc, and PhD degrees in physics from the University of Toronto in 1984, 1986, and 1990, respectively. His doctoral dissertation research was conducted in the area of carrier and phonon dynamics in semiconductors. From 1990-I 996 he was with the Ontario Laser and Lightwave Research Center where he was actively involved in the research areas of optoelectronics and fiber Bragg gratings. Since 1996 he has been an assistant professor in the Department of Natural Sciences (Physics) at the University of Cyprus. He has published more than 40 papers in various refereed journals along with a number of invited chapters in books and invited review papers. His current research interests are ultrafast dynamics in semiconductors, nonlinear optics, fiber optics, and optoelectronics in general.

Biographies and photographs of other authors not available.