J. Phys. D: Appl. Phys. 23 (1990) 1298–1301. Printed in the UK

# A novel technique for making grating demultiplexers in integrated optics

**Lotfi Rabeh Gomaa†, G H Chartier‡ and A S Samra§**

LEMO, INPG-CNRS, Ecole Nationale Supérieure d'Electronique et Radioélectricité, 23 avenue des Martyrs, BP 257, 38016 Grenoble Cédex, France

Received 14 November 1989, in final form 9 May 1990

**Abstract.** A new technique is proposed for making phase diffraction gratings for integrated optics. The ion-exchange technique in glass is used, the grating is obtained by performing the ion exchange through a periodic mask photolithographically printed in aluminium. The required modulation of the index of refraction is obtained by introducing consecutively two different ions, $Ag^+$ and $K^+$, inside the glass slide. The opto-geometric parameters of the phase diffraction grating are theoretically determined to obtain good wavelength demultiplexing properties at $\lambda_1 = 0.6328\ \mu m$ and $\lambda_2 = 0.5145\ \mu m$. An experiment is performed where an incident light beam with two wavelengths, $\lambda_1$ and $\lambda_2$, is directed on the grating with an angle of incidence such that all the diffracted energy is transferred to the first order of diffraction for $\lambda_1$ and to the zeroth order for $\lambda_2$. The same device could easily be designed for wavelengths of interest in telecommunications systems.

## 1. Introduction

Diffraction gratings are among the most important components for integrated optics. In the past few years, they have been studied theoretically and experimentally for many applications such as coupling, focusing, deflection and modulation of guided light beams. One of the most important characteristics of gratings is the dependence of their angular dispersion on the light frequency. It is this property which makes gratings useful for wavelength multiplexing and demultiplexing.

In planar guided optics a grating is a periodic line of discontinuity between two planar guides having different opto-geometric properties. When an incident light beam arrives on this periodic discontinuity, several diffracted light beams can be generated. Figure 1(*a*) shows the equivalent of what is called a ruled grating in conventional three-dimensional optics. Figure 1(*b*) shows a phase grating: two planar optical waveguides are separated by a zone where the effective index of the guide is periodically modulated. Here we will be concerned with integrated phase gratings. Several methods have already been used for inducing the refractive index modulation: (i) deposition of dielectric fingers on top of the guide surface [1]; (ii) using the electro-optic effect when the guide is made of an electro-optic material [2]; (iii) acousto-optic diffraction, via surface acoustic waves, is also a well known technique [3].

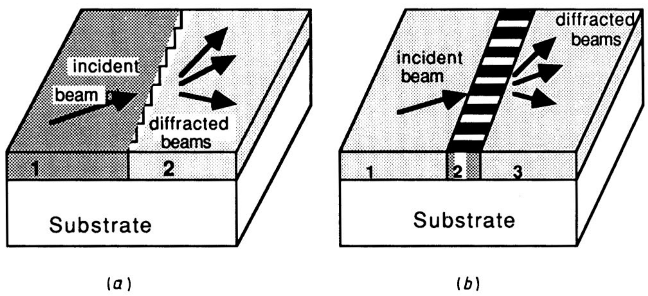


**Figure 1.** Integrated optical gratings. (*a*) Equivalent of a ruled grating; (*b*) phase diffraction grating.

In this paper we present a new fabrication technique of integrated optical phase gratings for planar optics. We make use of a recent fabrication procedure—double ion exchange in glass substrates [4]. Then we demonstrate that such a device has interesting wavelength demultiplexing properties.

## 2. The double ion-exchange technique

When a slab of soda lime glass is immersed in a molten metallic salt $M^+A^-$, the $Na^+$ ions of the glass are exchanged against the $M^+$ ions inducing, in the glass, a change of the chemical composition and a correlated modification of the refractive index starting from the

† Current address: Zagazig University, Faculty of Engineering of Shobra, Cairo, Egypt.
‡ To whom all correspondence should be addressed.
§ Current address: Mansura University, Faculty of Engineering Mansura, Egypt.

0022-3727/90/101298 + 04 $03.50 © 1990 IOP Publishing Ltd

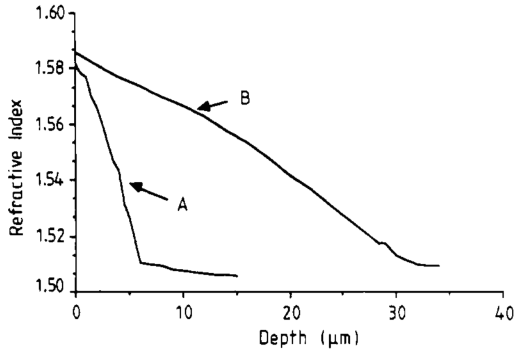


**Figure 2.** Effect of a potassium exchange on a subsequent silver exchange. A, $KNO_3$ at 370 °C for 24 h, and then $AgNO_3$–$NaNO_3$, 380 °C for 1 h; B, $AgNO_3$–$NaNO_3$ only, 380 °C for 1 h.

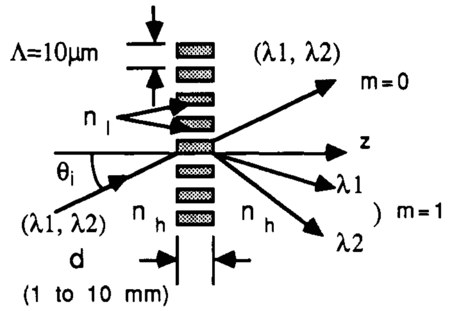


**Figure 3.** Top view of a phase diffraction grating illuminated by a parallel beam with two different wavelengths $\lambda_1$ and $\lambda_2$. Only the zeroth and first orders of diffraction have been drawn.

surface. When the refractive index is increased, which is often the case, an optical guide is made. Its opto-geometric properties are determined by the nature of $M^+$ and the temperature and duration of the exchange. One of us has shown [4] that if two different ions, $M^+$ and $M'^+$, are used successively then the result of the ion exchange can be significantly changed. The first exchange introduces $M^+$ ions inside the glass, which may halt a further exchange of $M'^+$ ions, or significantly reduce its rate.

$Ag^+$ and $K^+$ have been chosen for the ion exchange process since previous qualitative experimental investigations [4] have shown that potassium ions, when exchanged in a glass substrate, halt a subsequent silver exchange. A $K^+$ for $Na^+$ ion exchange is first performed in a soda lime glass microscope slide, using a molten bath of $KNO_3$ at 370 °C for 24 h. The slide is then immersed in a dilute melt of $AgNO_3/NaNO_3$ at 380 °C for one hour: curve A of figure 2 shows the refractive index profile. To demonstrate the effect of the $K^+$ exchange (which is done before the $Ag^+$ exchange) we compare the profile in curve A with the profile that has been obtained in another glass slide only immersed in the $AgNO_3/NaNO_3$ (380 °C, 1 h). The comparison of the two profiles shows clearly that, at a certain depth, the index of refraction resulting from the double ion-exchange process (potassium and then silver) is less than the single (silver) ion-exchange process. This means that the potassium ions halt a subsequent exchange with silver ions.

## 3. The phase grating fabrication

A constant-periodicity grating mask consisting of equally spaced parallel slots (5 µm width, separated by 5 µm) is transferred onto an aluminium coated glass microscope slide, using conventional photolithographic methods. The length $d$ of each slot is of the order of 1 to 10 mm, and will be determined from theoretical considerations in order to have good demultiplexing properties. We start from the aluminium-coated glass substrate, and the aluminium is removed below the previous slots.

We first perform a $K^+$ exchange in a molten bath of $KNO_3$ at 370 °C for 2 h. The resulting guide, in the uncoated areas, is single mode and has a low $\Delta n_s$ (the difference between the refractive index of the substrate and the maximum value of the refractive index profile at the surface of the guide). The effective index of the guided mode in the previous areas is measured using the $m$-line method. It is found that at 0.6328 and 0.5145 µm ($\lambda_1$ and $\lambda_2$) the effective indices are 1.5115 and 1.5135 respectively. The measurements are made on the back surface of the glass microscope slide (uncoated with aluminium).

The aluminium is then removed all around the slots and an $Ag^+$ exchange is done in a dilute melt (2.5% mol. of $AgNO_3$ in $NaNO_3$) at 360 °C for 2 min. The resulting guide is also single-mode, but with a higher $\Delta n_s$. The measured effective indices are 1.5158 and 1.5175 respectively.

A single-mode guide now exists all over the glass substrate, but it has a different effective index according to the place where the light propagates. This planar guide is made of three different regions (see figure (1*b*)): regions 1 and 3 have the same opto-geometric properties, they are separated by region 2 where there is a periodic variation of the effective index of refraction. In this way we have made an integrated phase diffraction grating.

## 4. Theoretical analysis

Figure 3 is the top view of a transmission phase diffraction grating, where the spatial periodicity $\Lambda$ is equal to 10 µm. Two parallel guided light beams, of wavelengths $\lambda_1$ and $\lambda_2$, are incident with the same angle $\theta_i$ on the grating. Let $n_l$ and $n_h$ be respectively the effective indices in the slots and in the interslots areas. The dimensionless factor $Q$ is used to determine which regime of diffraction exists for our model:

$$Q = 2\pi\lambda d/\Lambda^2 n_h \quad (1)$$

Kogelnik [5] has shown that, for $Q < 1$, a Raman–

Nath-type of diffraction takes place and several orders of diffraction occur. The case when $Q > 10$ corresponds to a Bragg-type of diffraction, then only two significant orders of diffraction are to be found—the zeroth and the first order. If we take $d = 1$ cm, $\lambda = \lambda_1 = 0.6328\,\mu$m and $n_h(\lambda_1) = 1.5127$, $Q$ is found to be equal to 265 and we are definitely in the Bragg situation.

Kogelnik's theory [5] also gives the diffraction efficiency $\eta$ of the first order:

$$\eta = [\sin(\xi^2 + \nu^2)^{1/2}]^2/[1 + (\xi^2/\nu^2)] \qquad (2)$$

with

$$\xi = Ed/(2\cos\theta_i) \qquad (3)$$

$$\nu = K_c d. \qquad (4)$$

$E$ is a dephasing factor that is introduced if the angle of incidence $\theta_i$ is not equal to the Bragg angle $\theta_B$:

$$E = (2\pi/\Lambda)(\sin\theta_i - \sin\theta_B). \qquad (5)$$

Finally the parameter $K_c$ in equation (4) is called the coupling coefficient and is given as:

$$K_c = \pi\Delta n/(\lambda\cos\theta_i)$$
$$= 2(n_h(\lambda) - n_l(\lambda))/(\lambda\cos\theta_i) \qquad (6)$$

where $\Delta n$ is the amplitude of the refractive index modulation which is assumed to be sinusoidal. In our case the modulation is nearer to a rectangular one, varying from $n_h$ to $n_l$, over a period of $\Lambda = 10\,\mu$m; so, for a given wavelength $\lambda$, $\Delta n$ will be approximated [6] by the fundamental sinusoidal component of a rectangular refractive index modulation:

$$\Delta n = 2(n_h(\lambda) - n_l(\lambda))/\pi. \qquad (7)$$

It is clear that when $\theta_i = \theta_B$, the phase mismatch equals zero, and hence the efficiency for the first order of diffraction at wavelength $\lambda$ is

$$\eta(\lambda) = \sin^2[2(n_h(\lambda) - n_l(\lambda))/\lambda\cos\theta_B]. \qquad (8)$$

The principle of operation of the optical demultiplexer is as follows. Two optical light beams of wavelengths $\lambda_1$ and $\lambda_2$ (in our case 0.6328 and 0.5145 $\mu$m respectively) are incident at the same angle $\theta_i$ on the grating; $\theta_i$ is chosen equal to the Bragg angle of one of the wavelengths, for the moment $\theta_{B1}$ (Bragg angle for $\lambda_1$). The diffraction efficiency $\eta(\lambda_1)$ varies with the interaction length $d$ (the length of the slots of the grating mask) as $\sin^2(K_c d)$. This means that $\eta(\lambda_1)$ is an oscillating function of $d$ which reaches 100% whenever $K_c d = \pi/2$ (see figure 4). The diffraction efficiency for $\lambda_2$ is calculated in the same way, but equation (2) has to be used since the angle of incidence is not equal to the Bragg angle $\theta_{B2}$ for $\lambda_2$. Of course the diffraction efficiency for $\lambda_2$ will not reach 100% since there is a certain phase mismatch, however, $\eta(\lambda_2)$ will be an oscillating function of $d$, as shown in figure 4. From this figure it can be seen that, for $d' = 1.48$ mm as well as for $d'' = 4.25$ mm, the first-order diffraction efficiency is equal to 100% for $\lambda_1$ and equal to zero for $\lambda_2$.

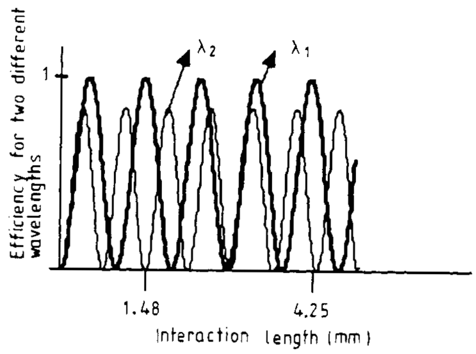


**Figure 4.** Diffraction efficiency as a function of the interaction length $d$, for two different wavelengths: $\lambda_1 = 0.6328\,\mu$m and $\lambda_2 = 0.5145\,\mu$m; the angle of incidence is the Bragg angle for $\lambda_1$.

We shall now calculate the angular separation $\Delta\theta$ between the zeroth order at $\lambda_2$ and the first order at $\lambda_1$:

$$\Delta\theta = \theta_1(\lambda_1) - \theta_0(\lambda_2). \qquad (9)$$

$\theta_1(\lambda_1)$ is the first-order diffraction angle for $\lambda_1$ and $\theta_0(\lambda_2)$ is the zeroth-order angle for $\lambda_2$. These angles are obtained [5] as follows:

$$\theta_1(\lambda_1) = \sin^{-1}(\lambda_1/n_h(\lambda_1)\Lambda - \sin\theta_i). \qquad (10)$$

$n_h(\lambda_1)$ is the effective index at $\lambda_1$ of the single-mode region outside the grating; its value can be measured using the standard $m$-line technique.

The angle of incidence $\theta_i$ is taken equal to the Bragg angle $\theta_{B1}$, which is given by $\theta_{B1} = \sin^{-1}(\lambda_1/2n_h(\lambda_1)\Lambda)$, in our case $\theta_i = 1.2°$. The angle $\theta_0(\lambda_2)$ is simply equal to $(-\theta_i)$, since we take the zeroth diffraction order for the beam with wavelength $\lambda_2$. At last we obtain $\Delta\theta = 2.4°$.

We can conclude that when two light beams with wavelengths $\lambda_1$ and $\lambda_2$ (0.6328 and 0.5145 $\mu$m) are incident at the same angle $\theta_i = \theta_{B1}$ on the phase diffraction grating described above, the diffracted energy at $\lambda_1$ and $\lambda_2$ will be separated by an angle of 2.4°. This means that these two wavelengths can be demultiplexed successfully.

## 5. Experimental results

The principle of the phase grating demultiplexer is given in figure 5. The length of the slots has been made equal to $d'' = 4.25$ mm. The experimental arrangement for grating demultiplexing is shown schematically in figure 6 where two laser beams (He–Ne and argon lasers) are aligned along the same direction and then focused on the base of a prism which couples the two beams into the single-mode planar waveguide. The input powers at $\lambda_1$ and $\lambda_2$ are measured by decoupling the two guided beams at these wavelengths (using a prism decoupler) just before the region of the grating.

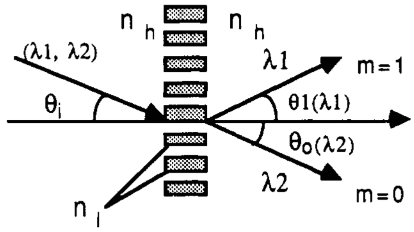


**Figure 5.** Principle of a wavelength demultiplexer. The interaction length *d* has been adjusted so that the efficiency in the first order of diffraction is maximum for $\lambda_1$ and equal to zero for $\lambda_2$.

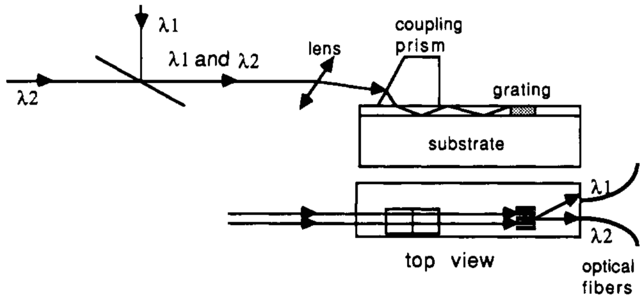


**Figure 6.** Experimental arrangement: two $\lambda_1$ and $\lambda_2$ beams are coupled using a coupling prism. The diffracted beams, which are well separated, are sent into two different optical fibres.

The guided beam at $\lambda_1$ is obtained from a 2 mW He–Ne laser, the other beam at $\lambda_2$ is obtained from an adjustable-power argon laser. The powers at $\lambda_1$ and $\lambda_2$ are 280 $\mu$W (measured with a calibrated wattmeter). After the passage of the beams through the grating, the powers at $\lambda_1$ (He–Ne) and $\lambda_2$ (argon) are well separated into two distinct beams, one green and the other red; the separation angle is approximately 2.5°, which is in good agreement with the theoretical calculations. The two beams have been coupled to two butt-joined multimode fibres at the well polished edge of the single-mode planar optical waveguide.

The output powers in both output beams are measured using a prism which decouples the two separated beams just after the region of the grating. The output powers at $\lambda_1$ and $\lambda_2$ are 170 and 150 $\mu$W respectively. In these measurements are of course included the power scattered in the region of the grating, the losses of the waveguide and the decoupling efficiency of the prism. This means that the diffraction efficiencies at $\lambda_1$ and $\lambda_2$ are higher than 170/280 = 60% and 150/280 = 53%.

## 6. Conclusion

In this paper we presented a new, efficient and simple grating demultiplexer suitable for integrated optics. The fabrication technique, by double ion-exchange in glass, allows an easy control of the opto-geometrical characteristics of the grating. A very simple experiment demonstrates the feasibility of such demultiplexers in the visible range, there is no reason why it could not be used in near infrared (0.85, 1.3 and 1.5 $\mu$m); both input and output beams could easily be coupled to single-mode fibres.

## Acknowledgment

We are most grateful to Gilles Clauss for efficient technical support.

## References

[1] Delavaux J M P and Chang W S C 1984 Design and fabrication of efficient diffraction transmission gratings on step-index optical wave guides. *Appl. Opt.* **23** 3004–9
[2] de Barros M A R P and Wilson M G F 1972 High-speed electrooptic diffraction modulator for baseband operation. *Proc. IEE* **119** 807–14
[3] Ushida N and Niizeki N 1973 Acousto-optic deflection materials and techniques. *Proc. IEEE* **61** 1073–92
[4] Chartier G H, Laybourn P J R and Girod A 1986 Masking process for double ion-exchanged glass optical waveguides. *Electron Lett.* **22** 925–6
[5] Kogelnik H 1969 Coupled mode theory of thick holograms gratings. *Bell Syst. Tech. J.* **48** 2909–47
[6] Su S F and Gaylord T K 1975 Calculation of arbitrary order diffraction efficiencies of thick gratings with arbitrary grating shape. *J. Opt. Soc. Am.* **65** 59–64