Low polarization dependent diffraction grating for wavelength demultimlexing

E. Popov [1], J. Hoose [2], B. Frankel [2], C. Keast [3], M. Fritze [3], T.Y. Fan [3], D. Yost [3], and S. Rabe [3]

[1]*Institut Fresnel, U.M.R. CNRS 6133, Faculté des Sciences et Techniques de St-Jérôme, 13397 Marseille Cedex 20, France*

[2]*Chromaplex, Inc., 150 Lucius Gordon Dr., Suite 115, West Henrietta NY 14586, USA*

[3]*Lincoln Laboratory, Massachusetts Institute of Technology, 244 Wood Street Lexington, MA 02420-9108*

e.popov@fresnel.fr

Abstract: A low polarization dependent, high diffraction efficiency grating for wavelength demultiplexer is proposed, manufactured by standard crystallographic etching of Si surface. Light is incident and diffracted inside the wafer, which is covered with reflecting metal. Optimized groove form results in a flat spectral response for TE and TM polarizations.

OCIS codes: (060.4230) Multiplexing; (050.2770) Gratings; (050.0050) Diffraction and gratings

References

1. J.-P. Laude, *Le multiplexage de Longueurs d'Onde* (Masson, Paris, 1992)
2. E. Loewen and E. Popov, *Diffraction Gratings and Applications* (Marcel Dekker, New York, 1997)
3. M. Sabeva, E. Popov, and L. Tsonev: "Reflection gratings in the visible region: efficiency in non-polarized light," Opt. Commun. **100**, 39-42 (1993)
4. K. Yokomori: "Dielectric surface relief gratings with high diffraction efficiency," Appl. Opt., 23, 2303-2310 (1984)
5. E. Popov, B. Bozhkov, and M. Nevière: "Almost perfect blazing by photonic crystal rod grating," Appl. Opt. **40**, 2417-2422 (2001)
6. RGL Cat#35-53-*-466 (www.gratinglab.com)
7. J. Hoose, "Optical diffraction grating structure with reduced polarization sensitivity," US patent no. 6,487,019 (2002)
8. M. Nevière and E. Popov, *Light Propagation in Periodic Media, Differential Theory and Design* (Marcel Dekker, New York, 2003)
9. J. Hoose, R. Frankel, and E. Popov, "Diffractive structure for high-dispersion WDM applications," US patent no. 6,496,622 (2002)

1. Introduction

Despite the boom in telecom at the late 1990s, the problem of manufacturing low-polarization dependent high-efficiency diffraction gratings for wavelength-division demultiplexing remains an open scientific, design and manufacturing question, which shows that in science, funding is not the sufficient condition. The design of gratings with desired properties has found several theoretical solutions, confirmed experimentally, but the problem lies in the feasibility and repeatability of these properties in the manufacturing process. The interested reader can find many excellent designs that have never been used commercially in Refs. [1] and [2]. Some of these possibilities are reviewed in Section 2.

#3237 - $15.00 US Received 3 November 2003; revised 6 January 2004; accepted 12 January 2004

The aim of this communication is to present a design that combines high efficiency and low polarization dependence with photolithographical manufacturing on Si wafer, which ensures high-precision repeatability.

2. Classical diffraction grating efficiency

Despite the existence of many new types of diffracting structures aimed at WDM, the classical echelette gratings still attract attention mainly due to the well-developed manufacturing process and well-known properties. In TM polarization one can chose a plateau-like region in the spectral dependence [2]. For example, a 600 gr/mm grating efficiency exceeds 90% in TM polarization in the spectral interval between 1.3 and 2 µm. However, the main drawback comes from the fact that the corresponding maximum in TE polarization lies at shorter wavelength, namely around 1.15 µm. This can be overcome by increasing the groove spacing, but the price to pay is the lower dispersion and the appearance of higher orders, leading to reduced overall efficiency and enhanced level of parasitic light.

Sinusoidal gratings have similar behaviour. There are several possibilities to shift the TE peak to longer wavelength, where only two orders propagate. The most typical are to use deep gratings in reflection [3] or transmission [4], or photonic crystals [5]. However, to make of them something more than an object of academic interest, it is necessary to advance the technological processes involved in the production of gratings and photonic crystals.

3. Ruled grating with peculiar properties

Another possibility is to stay within the limits of classical commercial gratings (modulation depth-to-period ratio < 0.5) but to try to optimise the groove properties. A typical example of such a design is a grating ruled back in 1975 by Richardson Grating Lab and still available on order [6], master No. 1117, with the same groove frequency of 600 gr/mm. The peculiarity of this grating is that the TE peak is shifted to 1.6 µm instead of 1.15 µm. Low polarization difference could be obtained by combining the two gratings, presented in this and the previous section. The spectral dependence of efficiency of the two gratings glued together on the same substrate is flat, varying less than 3% within the spectral region 1.50 – 1.58 µm [7].

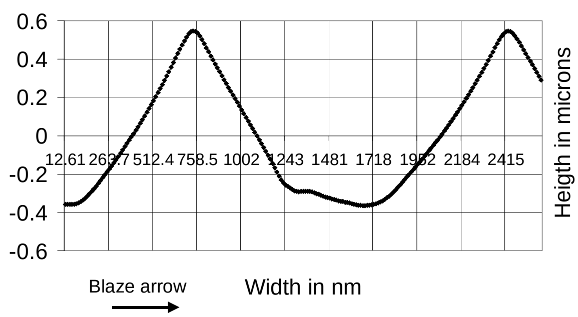

Fig. 1. Measured profile of the echelette grating (master no. 1117 ruled by Richardson Grating Laboratory, Spectronic Instruments, Inc., Thermo Optek Co.).

The explanation of this peculiar behavior has to be searched for in the groove form. The SEM profile of the groove structure is presented in Fig. 1. The numerical modelling of the efficiency behaviour using electromagnetic theory of gratings [8] shows a very good agreement with the experimental data. Moreover, it enables us to analyse the reason for such behaviour and, in particular, to answer to the question whether it is the sharp apex angle in Fig.1 which is responsible to the shift of TE peak to longer wavelengths.

Figure 2 presents the results of numerical modelling for three different profiles similar to the profile presented in Fig. 1. The first design is an echelette grating with 58° groove angle and 90° apex angle, with a TE peak at about 1.2 µm, as already discussed in Section 2. The

#3237 - $15.00 US Received 3 November 2003; revised 6 January 2004; accepted 12 January 2004

second grating has a sharp apex angle of 70°, corresponding to the apex angle of the profile given in Fig. 1. This grating is characterized by high TE efficiency, the peak shifted to 1.5 µm, but with very low TM efficiency. An increase in the TM efficiency could be obtained by introducing a flat region at the groove bottom, resembling the groove in Fig. 1.

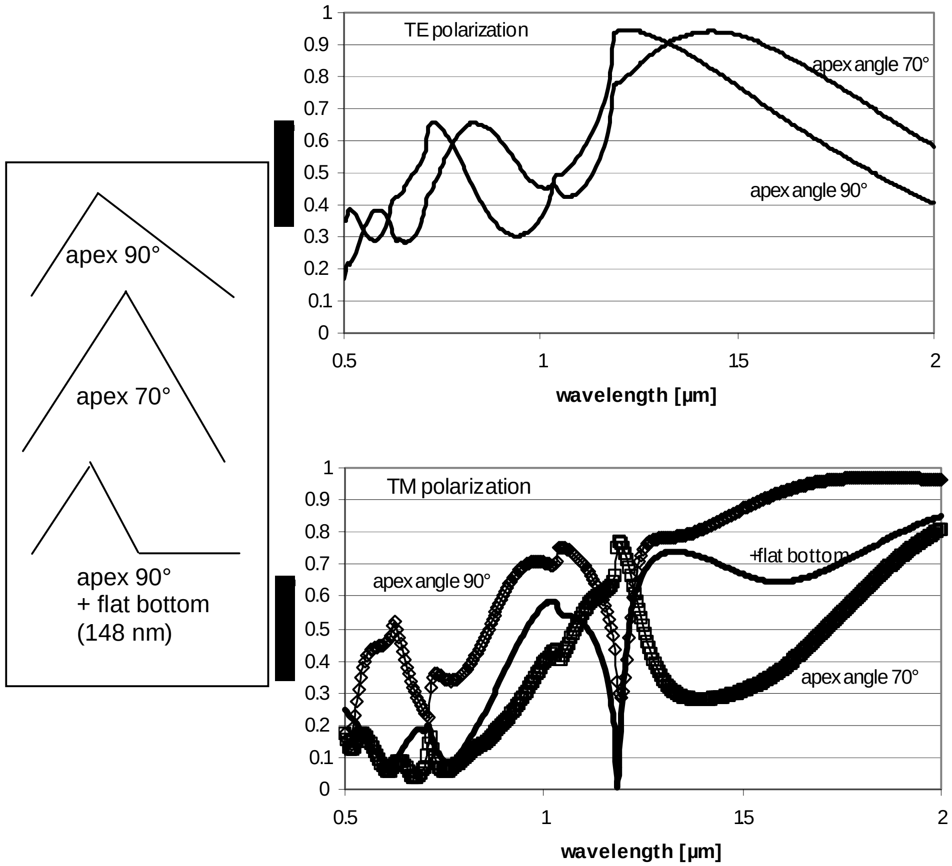

Fig. 2. Diffraction efficiency of three different echelette gratings with profiles presented in the inset. 600 gr/mm, measurements at 8° angular deviation (A.D.) (a) TE polarization, (b) TM polarization.

4. Silicon grating

It is possible to further improve the properties and to avoid use of two gratings, which requires precise alignment of the grooves and reduces the resolution by a factor of two due to the lack of phase synchronism between the grooves of the two gratings. Optimisation of the groove profile was carried out on the basis of the acquired knowledge that it is necessary to have a sharp apex angle and a flat region at the groove bottom. In addition, it was taken into account that such grooves could be naturally obtained by chemically etching crystalline silicon, which gives grooves with 70.5° apex angle. This combination should assure high-precision repeatability. The fact that Si is transparent above 1.35 µm led us to directly use bulk Si prisms with the grating etched wafer bonded directly to the prism. This avoids grating replication which can lead to groove distortions. The prism also allows the light to enter the silicon wafer at the Littrow diffraction angle without any angle induced losses.

The optimised groove profile consists of a symmetrical triangular groove with 70.5° apex angle and a flat region at the bottom. The manufacturing process consists of several processes:

#3237 - $15.00 US Received 3 November 2003; revised 6 January 2004; accepted 12 January 2004

1) thermal oxidation of <100> silicon surface to grow a 100 nm hard mask of oxide layer;
2) coat with antireflection coating and UV photoresist layer;
3) pattern grating using phase shifting mask with strip width equal to the flat region of the desired profile;
4) etching of photoresist and antireflection layers;
5) etching of the oxide hardmask;
6) removing of photoresist and antireflection coating;
7) TMAH (Tetramethylammonium Hydroxide) crystallographic etch;
8) strip the oxide hard mask;
9) deposition of aluminium cover.

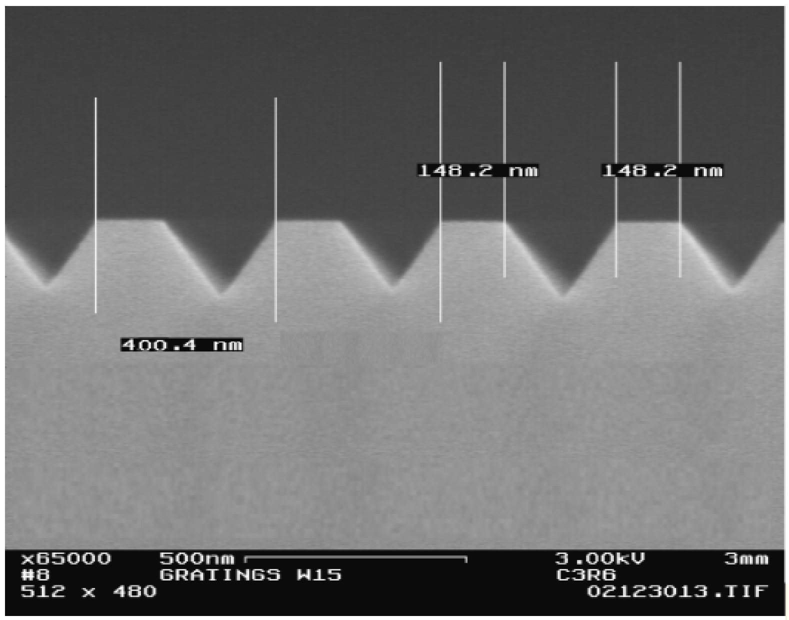

Fig. 3 SEM picture of a Si grating with triangular profile and flat top region.

The resulting profile is shown in Fig. 3 before deposition of the aluminium reflection cover. The grating has to be used from the Si side so that the flat region remains at the groove bottom [9]. The comparison between the theoretical and experimental efficiency of the grating is presented in Fig. 4 and shows polarization difference less than 3%, mean absolute efficiency exceeding 80% with spectral variation which does not exceed 7% (Fig. 5).

#3237 - $15.00 US Received 3 November 2003; revised 6 January 2004; accepted 12 January 2004

(a)

(b)

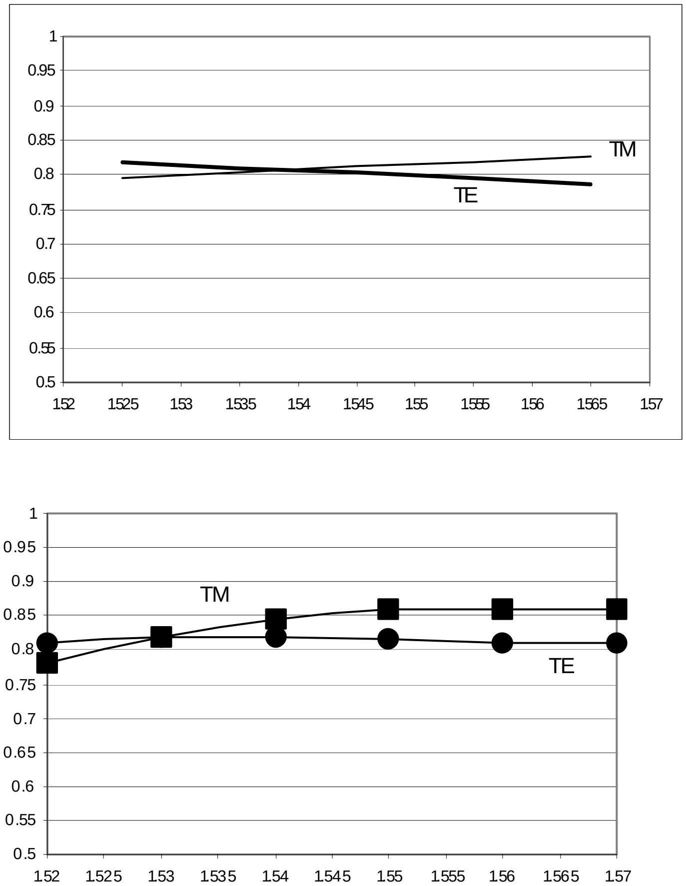

Fig. 4. Theoretical (a) and experimental (b) efficiency of a Si grating covered with Au layer and measured from the wafer side. Period 0.4 µm, flat region 148 nm, angle of incidence inside the wafer 33.7°.

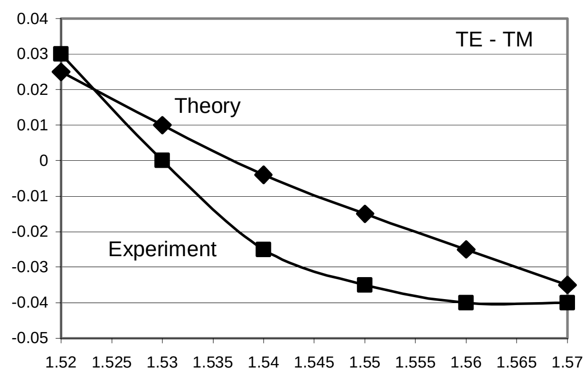

Fig. 5. Spectral variation of the polarization difference (TE minus TM efficiency).

#3237 - $15.00 US Received 3 November 2003; revised 6 January 2004; accepted 12 January 2004

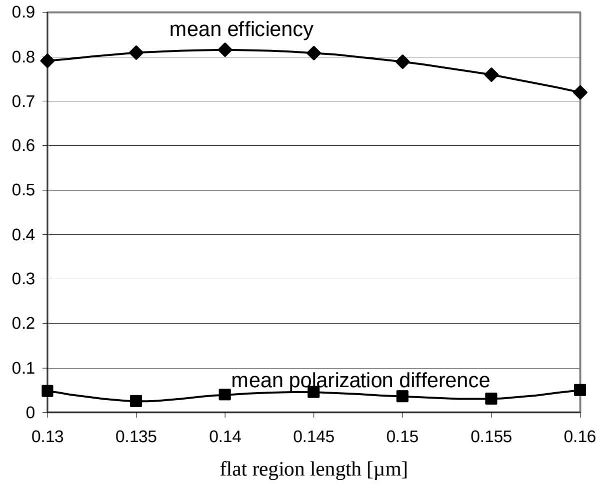

Fig. 6. Mean efficiency and mean polarization difference within the spectral region 1.52-1.57 µm as a function of the flat region width of the profile.

Although there exist gratings having higher efficiency (e.g., multilayered dielectric grating reaching 99% efficiency in a given spectral range), the silicon grating has two advantages. First, it is relatively cheap to produce due to the standard semiconductor technology used. Moreover, the tolerances with respect to the groove parameters are sufficiently large. The groove form can be easily controlled due to the crystallographic structure of Si. The only free parameter is the width of the flat region of the profile. Fortunately, its influence on the efficiency properties is rather weak, as observed in Fig. 6, which presents the mean efficiency (TE and TM case) and the mean polarization difference within the spectral range 1.52 – 1.57 µm.

The second advantage is the compactness of the device, combined with relativile high dispersion, due to the high optical index of Si, as discussed further.

A schematical representation of the device and its general view are given in Fig. 7. Light from the input fiber is collimated by a 15 mm focal length lens and enters normal to the large facet of the Si prism through an A.R. coating. It propagates further inside the silicon and is diffracted backwards (Littrow) from the wafer grating. Grating dispersion inside Si is not high, the angular interval of diffraction of 1.52-1.57 µm spectrum is about 2.5°.

However, due to the high index of Si, when exiting the Si prism into air, this angular interval grows to 8.7°. Diffracted light is then focused by the input/output lens into output fibers aligned in the lens focal plane. The linear dispersion is 48µm/nm, which is enough to separate about 50 channels inside the working spectral range. In addition, channel crosstalk drops to less than –20 dB within 0.5 nm wavelength change, which ensures packing at least 50 channels within the range of 1.52-1.57 µm.

Device passband characteristics in a 100 GHz mux testbed show very low scatter (< –40 dB) due to the atomically smooth groove surfaces and good crystal plane alignment.

#3237 - $15.00 US Received 3 November 2003; revised 6 January 2004; accepted 12 January 2004

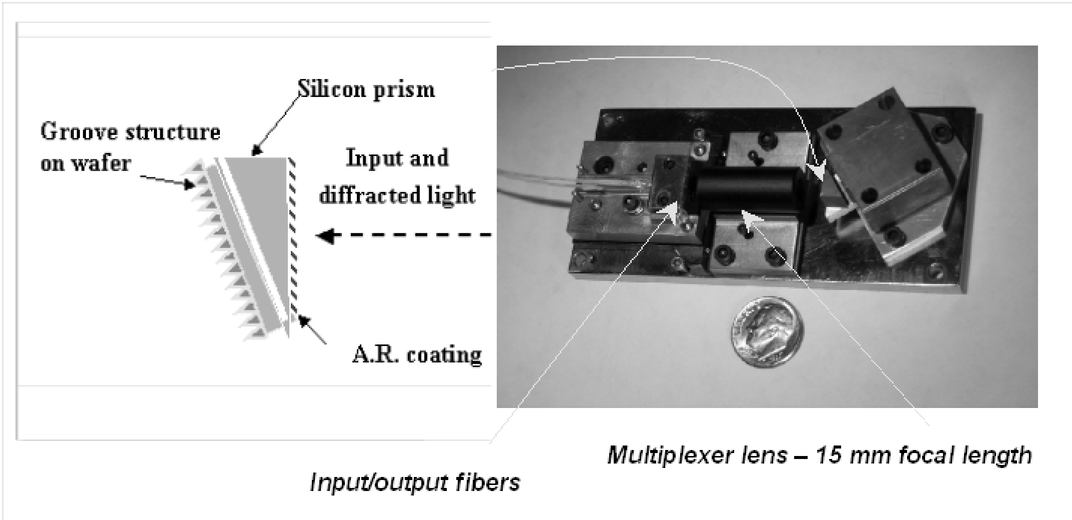

Fig. 7. Schematical representation and general view of the device.

Acknowledgments

We want to thank John Bowen and Gary Blough of Photon Gear, Ontario, NY who designed and made the lens, and took the picture of the complete MUX.

#3237 - $15.00 US Received 3 November 2003; revised 6 January 2004; accepted 12 January 2004