

Compact and monolithic coarse wavelength-division multiplexer–demultiplexer fabricated by use of a high-spatial-frequency transmission grating buried in a slab waveguide

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A compact and monolithic four-channel demultiplexer with 20-nm spacing was fabricated by use of a high-spatial-frequency transmission grating buried in a silica waveguide. The grating was successfully buried in a silica slab waveguide by overcladding by plasma-enhanced chemical-vapor deposition. The device's size was approximately $5.1\text{ mm} \times 9.2\text{ mm}$. The average insertion loss was 13 dB. The average cross talk was -15 dB for adjacent channels and -19 dB for nonadjacent channels. The polarization-dependent loss was estimated to be as low as 0.7 dB. © 2004 Optical Society of America

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Dense wavelength-division multiplexing (DWDM) has become a standard technique for managing high-bit-rate traffic in long-distance networks. Recently, cost-effective coarse wavelength-division multiplexing (CWDM) systems have begun to be applied to short distance, metropolitan, and access networks.¹ CWDM systems require compact and inexpensive demultiplexers that can separate 4–16 channels with 20-nm spacing.

Thin-film filter technology has been widely used for fabricating wavelength filters. However, a demultiplexer based on thin-film filters is less advantageous for higher channel numbers because discrete optical components, such as objective lenses and multilayer filters, have to be arranged for each channel. Arrayed waveguide gratings have characteristics with excellent applicability to dense wavelength-division multiplexing systems.² An arrayed waveguide grating device, however, requires a large chip size, which is not cost effective for CWDM systems with 16 or fewer channels. Recently a monolithic demultiplexer that uses a conventional grating and ridge waveguides was reported for wavelength-division multiplexing with 6.4- or 3.2-nm channel spacing.³ The device was successfully fabricated upon a millimeter-scale silica substrate by integration of a coarse grating in high diffraction order, collimating mirrors, and channel and slab waveguides by use of a deep etching technique.

In this Letter we describe the design, fabrication, and characteristics of a four-channel demultiplexer with 20-nm spacing that uses a high-spatial-frequency

transmission grating buried in a silica waveguide. The high-spatial-frequency transmission grating, which has a period comparable to an operating wavelength, can be designed to produce a first-order diffraction efficiency of more than 90% for both TE- and TM-polarized light.^{4–6} We successfully buried such a grating in a silica slab waveguide by overcladding without filling the grating grooves, which should be an advantageous technology for the achievement of a compact and reliable demultiplexer with low insertion loss and low polarization-dependent loss (PDL).

Figure 1 illustrates the layout of the four-channel demultiplexer with 20-nm wavelength spacing, which was designed to operate near 1550 nm. The demultiplexer consists of a high-spatial-frequency transmission grating, a pair of parabolic mirrors, and channel waveguides. These elements were fabricated

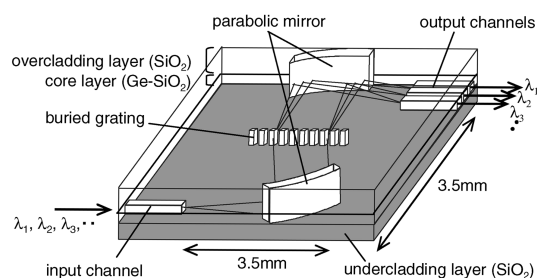


Fig. 1. Schematic layout of the proposed demultiplexer.

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by deep etching into a silica layer deposited onto a silica substrate. The input light expands horizontally from the input channel waveguide to the slab waveguide, depending on the numerical aperture of the waveguides. The first parabolic mirror, with an interface between the vertical etched silica and the air gap, reflects and collimates the expanded light toward the high-spatial-frequency transmission grating by total internal reflection. The first-order diffraction efficiency of the grating is more than 90% across a bandwidth of 200 nm centered at 1550 nm. The diffracted light is reflected and focused onto the focal plane at the ends of the output channel waveguides by the second parabolic mirror.

The light path in the slab waveguide was designed by calculation with OSLO (v. 6.1, Lambda Research) software. The dimensions of the grating were optimized by use of software based on rigorous coupled-wave analysis, GSOLVER (v. 4.20, Grating Solver Development). The refractive indices of the cladding and the core layers used for the calculation were 1.454 and 1.460, respectively, at 1.55 μm . The cross-sectional dimensions of the input and output channel waveguides were 5 μm $\times$ 5 μm . The device size was approximately 3.5 mm $\times$ 3.5 mm, not including the input and output channel waveguides, and 5.1 mm $\times$ 9.2 mm when both waveguides were included.

Figure 2 shows the calculated first-order diffraction efficiencies of the grating for TE- and TM-polarized light. A schematic of the light propagation and the dimensions of the grating are also shown in the figure. The grating consists of a periodic structure of silica and air (or vacuum), resulting in a high Δn of $>30\%$. Also, the optimized grating period and thickness were 1.5 and 3.4 μm , respectively. Therefore it was possible to design a grating that has a diffraction efficiency greater than 93%. The PDL should be minimized to less than 0.14 dB across the entire *S*, *C*, and *L* bands.

Silica glass was used as the substrate. An undercladding layer of SiO_2 and a core layer of Ge- SiO_2 were deposited by plasma-enhanced chemical-vapor deposition (PD160-SHR, SAMCO). The liquid sources of $\text{Si}(\text{OC}_2\text{H}_5)_4$ were vaporized at 80 $^\circ\text{C}$ and then introduced into a radio-frequency plasma of oxygen at a pressure of 53 Pa. The temperature and the rate of SiO_2 deposition were 400 $^\circ\text{C}$ and 100 nm/min, respectively. The refractive index was controlled by the $\text{Ge}(\text{OCH}_3)_4$ flow rate. The refractive-index contrast between the core and the cladding was estimated by a prism coupling method to be 0.7%. The thicknesses of the core and the undercladding layers were 5 and 10 μm , respectively. The channel and slab waveguides and the grating were patterned by use of a combination of electron-beam (EB) lithography and reactive ion etching. The EB resist (ZEP-520, Nippon Zeon) was spin coated onto the core layer and baked at 160 $^\circ\text{C}$ in a drying oven for 30 min. The EB resist was patterned by an EB writing apparatus (ELS5700, Elionix). The resist pattern was coated with a Ni layer (220-nm thick) by evaporation, and then a Ni mask pattern was formed on the core layer by a lift-off procedure. Induc-

tively coupled plasma reactive ion etching (ICP-RIE) (RIE-200IP, Samco) with C_3F_8 gas transferred the Ni mask pattern into the core layer. The residual Ni mask was removed by a FeCl_3 solution. Figure 3 shows scanning electron microscope (SEM) images of the high-spatial-frequency grating. The grating, with rectangular grooves of high aspect ratio, was successfully fabricated by ICP-RIE. Then the overcladding layer of SiO_2 was formed by plasma-enhanced chemical vapor deposition to bury the grating and the waveguides. Figure 4 shows a cross-sectional SEM image of the buried grating. Although a small amount of roughness remained, it was evident that grooves with high aspect ratios remained after the deposition.

The parabolic mirrors were fabricated in the following steps: (1) dc sputtering of a W-Si layer (1.5- μm thickness) onto the overcladding layer, (2) spin coating and patterning of the photoresist (AZ6130, Clariant), (3) transfer of the resist pattern to a W-Si layer by ICP-RIE with SF_6 gas, and (4) etching of both the overcladding and the core layers by ICP-RIE with C_3F_8 gas. Parabolic mirrors with a verticality of approximately 90 $^\circ$ could be formed by ICP-RIE. The roughness of the etched surface was less than 50 nm.

The device was characterized by use of a tunable laser diode (MG9638A, Anritsu) and an optical

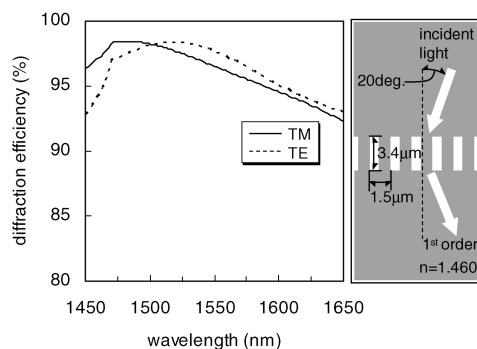


Fig. 2. Left, calculated first-order diffraction efficiencies of the high-spatial-frequency transmission grating for TE- and TM-polarized light near 1550 nm and right, schematic of light propagation and grating dimensions. The grating period and thickness are 1.5 and 3.4 μm , respectively.

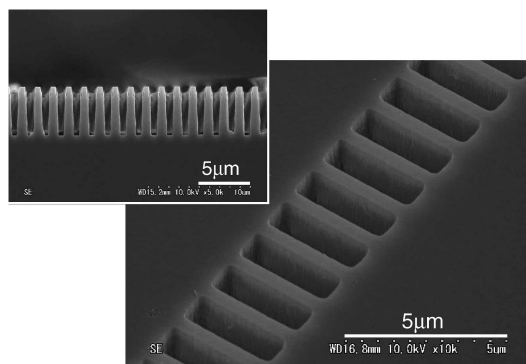


Fig. 3. SEM image of the top view of the high-spatial-frequency transmission grating etched by ICP-RIE. Inset, cross section of the grating. Grating period, 1.5 μm ; groove width, 0.60 μm ; groove depth, 4.9 μm .

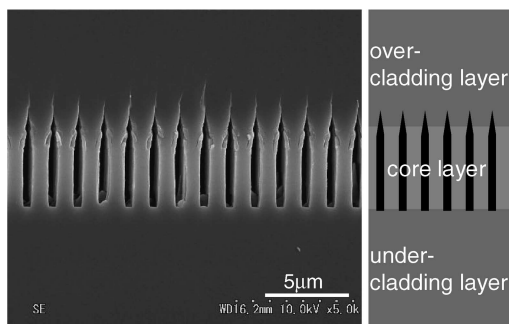


Fig. 4. Cross-sectional SEM image of the grating buried in a silica waveguide by plasma-enhanced chemical-vapor deposition.

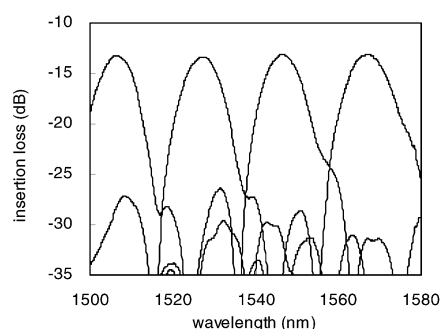


Fig. 5. Transmission spectrum of the 20-nm spaced four-channel demultiplexer.

spectrum analyzer (MS9710C, Anritsu) in the 1500–1580-nm wavelength region. Standard single-mode fibers were butt coupled to the input and output channels. Several subpeaks and shoulders that existed before annealing, which might have been caused by stress between core and cladding layers, made the spectrum noisy. Thus the waveguide was annealed.

Figure 5 shows the transmission spectrum of the device after annealing at 800 °C in air. The center wavelengths of the output signals were 1507, 1527, 1547, and 1567 nm. This device has good channel spacing (relative wavelength) accuracy. The average insertion loss of each channel was 13 dB, which includes both coupling losses to the fibers and on-chip loss. The average cross talk of this device was

16 dB for the adjacent channels and 21 dB for the nonadjacent channels, calculated within a bandwidth of ± 2.5 nm about each center wavelength. The on-chip loss is attributed mainly to scattering caused by roughness of sidewalls of the channel waveguides, which should be minimized by optimizing the mask patterning and the reactive ion etching. The PDL was

0.6–0.7 dB; we measured it by observing the changes in output power of the device for all possible polarization states generated with a polarization controller (11896A, Agilent). A 10% deviation of the fabricated grating profile from the optical design of the grating causes a PDL of approximately 0.5 dB. However, we consider that the PDL that is now commercially in demand (< 0.2 dB) can be achieved by improving the accuracy of fabrication.

A high-spatial-frequency transmission grating buried in a silica waveguide was used for a compact and monolithic four-channel demultiplexer with 20-nm spacing for CWDM networks. A pair of parabolic mirrors was used for collimation of input signals to the grating and for focusing of the diffracted signals onto the ports of output channel waveguides. All these optical components were successfully integrated upon a silica substrate by lithography and dry etching. The device size was approximately $5.1 \text{ mm} \times 9.2 \text{ mm}$ when input and output channel waveguides were included. The average insertion loss for four channels was 13 dB. The average cross talk of this device was 16 dB for adjacent channels and 21 dB for nonadjacent channels. The maximum PDL was 0.7 dB. Optimizing the procedures for device design and fabrication should improve these values. This device has great potential to satisfy the specification requirements for a CWDM data communication system.

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References

1. B. R. Eichenbaum and S. K. Das, in *Technical Proceedings of National Fiber Optic Engineers Conference* (Telcordia Technologies, Piscataway, N.J., 2001), pp. 1444–1448.
2. Y. Hida and Y. Hibino, in *Optical Fiber Communication Conference (OFC)*, Vol. 70 of OSA Trends in Optics and Photonics Series (Optical Society of America, Washington, D.C., 2000), pp. 399–401.
3. C. N. Morgan, S. Yu, and R. V. Penty, *IEEE Photon. Technol. Lett.* **14**, 1303 (2002).
4. M. G. Moharam and T. K. Gaylord, *J. Opt. Soc. Am.* **72**, 1385 (1982).
5. H. T. Nguyen, B. W. Shore, S. J. Bryan, J. A. Britten, R. D. Boyd, and M. D. Perry, *Opt. Lett.* **22**, 142 (1997).
6. T. Glaser, S. Schröter, R. Pohlmann, H. J. Fuchs, and H. Bartelt, *J. Mod. Opt.* **45**, 1487 (1998).