A flat-topped etched diffraction grating demultiplexer with low polarization-dependent loss using a tapered MMI structure

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A flat-topped etched diffraction grating (EDG) demultiplexer with a low polarization-dependent loss (PDL) is designed. A design and simulation method based on the method of moment (MoM) is proposed. A 65-channel EDG demultiplexer with channel spacing of 100 GHz is considered as a design example. A tapered multi-mode interferometer (MMI) is used to flatten the passband of the EDG demultiplexer. The numerical results show that the exit width of the tapered waveguide impacts the loss of the TE case more than that of the TM case. Based on this fact, the exit width of the taper is optimized to obtain the lowest PDL. The tapering angle is also optimized where the minimal ripple is obtained. The designed EDG demultiplexer has an excellent flat-topped spectral response and a very low PDL.

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Wavelength division multiplexing (WDM) is an effective technology for increasing the capacity of an optical network. Planar waveguide demultiplexers, such as arrayed waveguide gratings (AWGs)[1] and etched diffraction gratings (EDGs)[2], may become the most potential and predominant components in WDM networks in the future due to their compact structures and excellent performances. Compared with an AWG, an EDG demultiplexer that is more compact and potential has a higher spectral finesse (since the total number of the grating facets of an EDG can be much greater with the modern semiconductor fabrication technology). These characteristics make EDG more suitable for high density communication systems.

The polarization-dependent loss (PDL) is an important performance of a demultiplexer, which can broaden and distort the signal bits (pulses) and ultimately lead to transmission errors together with the polarization mode dispersion (PMD)[3]. The method reducing the PDL of an EDG demultiplexer has been studied in some previous work with metallizing only one facet by Neviere[4] and with larger rounded troughs of grating by us[5]. However, the method based on metallizing only shaded facets is too difficult to fabricate although a perfect performance can be obtained. We have shown that appropriately rounded troughs of etched grating can reduce the PDL[5], which results in a large unnecessary insertion loss. In this letter, we give a design method, which reduces the PDL of the demultiplexer and obtains a flattened spectral response at the same time using a tapered multi-mode interferometer (MMI) structure at the end of the input waveguide with an appropriate exit width (d_1). Unlike any former work, the present design obtains both a flat-topped spectral response and a low PDL though some unavoidable loss is produced (which results from the flattened process instead of the attempt for reducing the PDL). The grating of an EDG demultiplexer is usually coated with a metal at the backside in order to improve the reflection efficiency. Therefore, the grating in such an EDG demultiplexer can be approximated as a metallic grating, which has been accurately analyzed using a method of moment (MoM)[6].

An EDG demultiplexer consists of an input waveguide, an array of output waveguides, a free propagation region (FPR), and an etched concave grating (see Fig. 1). The distribution of the surface current J on the metallic grating surface can be computed accurately with a MoM[6]. The grating curve is divided into N small straight-line segments. The length of the ith segment is S_i. The surface current J is represented in terms of pulse basis functions and can be obtained by solving the following $N \times N$ matrix equation for the TE case

$$W \cdot J = H, \quad (1)$$

where

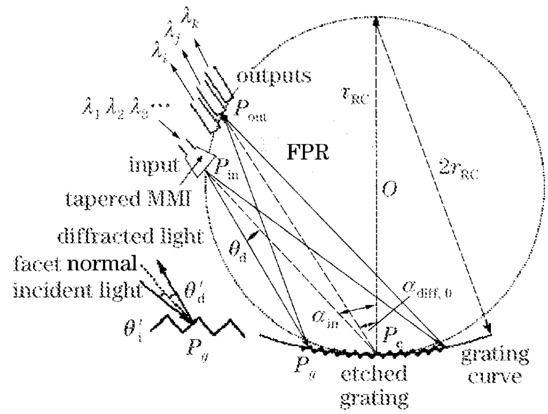

Fig. 1. Schematic diagram of an EDG demultiplexer based on a Rowland circle mounting.

$$W_{mn} = \begin{cases} \frac{jk}{4} \sum_{n=1}^{N} \cos\Phi_{mn} \cdot H_1^{(2)}\left(k\left|\overrightarrow{r_m} - \overrightarrow{r_n}\right|\right) S_n & m \neq n \\ 1/2 & m = n \end{cases}$$

$$J_n = J\left(\overrightarrow{r_n}\right), H_n = H_g\left(\overrightarrow{r_n}\right).$$

Here W_{mn} is the (m,n)-th element of the $N \times N$ matrix W, k is the wave number in the FPR, $\overrightarrow{r}$ is position vector of an arbitrary point located on the grating curve, $H_g(\overrightarrow{r})$ is the incident magnetic field (calculated with the Kirchhoff-Huygens formula, which is similar to Eq. (2) below; cf. Ref. [6]) at point $\overrightarrow{r}$, $\cos\Phi_{mn} = (\overrightarrow{r_n} - \overrightarrow{r_m}) \cdot \overrightarrow{n_n} / |\overrightarrow{r_n} - \overrightarrow{r_m}|$, where $\overrightarrow{n}$ is the unit vector (pointing outward) normal to the grating curve, and $H_1^{(2)}$ is the first order Hankel function of the second kind.

Once Eq. (1) is solved for J, the diffraction field (produced by the surface current) at any point in the FPR can be calculated with the following explicit formula

$$E^{\mathrm{d}}\left(\overrightarrow{r_{\mathrm{d}}}\right) = \left\{\frac{k\eta \exp[-j(kr_{\mathrm{d}} + 3\pi/4)]}{\sqrt{8\pi k r_{\mathrm{d}}}}\right\} \cdot \sum_{n=1}^{N} S_n \cdot J\left(\overrightarrow{r_n}\right) \cdot \cos\Phi_n \exp[jk(x_n \sin\alpha_{\mathrm{diff},0} + z_n \cos\alpha_{\mathrm{diff},0})], \quad (2)$$

where (x_n, z_n) is the coordinate of point r_n on the grating curve, η is the free-space wave impedance ($\eta = 376.73031$ Ω), r_{d} is the distance from the origin to the output waveguide, and $\alpha_{\mathrm{diff},0}$ is the diffraction angle.

The field distribution $E_{\mathrm{image}}(x', z')$ at the image plane can be obtained by scanning over the surface of the output waveguide using Eq. (2) for a TE case.

The spectral response at a single-mode output waveguide can be obtained from the following overlap integral over the cross-sectional line where the starting facet of the output waveguide is positioned

$$I(f) = \frac{\left|\int E_{\mathrm{image}}(f, x') \cdot E^*_{\mathrm{outwg}}(f, x') \mathrm{d}x'\right|^2}{\int \left|E_{\mathrm{image}}(f, x')\right|^2 \mathrm{d}x' \int \left|E_{\mathrm{inwg}}(f, x)\right|^2 \mathrm{d}x}, \quad (3)$$

where E_{image}, E_{inwg}, and E_{outwg} represent the imaging field distribution, and the fundamental mode profiles of the input and output waveguides, respectively. Here the superscript " * " is for the complex conjugate.

As a numerical example, a 65-channel SiO_2 EDG demultiplexer with a flat-topped spectral response and a very low PDL is designed. We choose the following parameters: $n_{\mathrm{c}} = 1.445$ and $n_{\mathrm{r}} = 1.454$ for the effective refractive indices of the cladding and the core, respectively, the channel spacing is 100 GHz, the central wavelength is 1.55 μm, the width $d = 6$ μm for the input and output single-mode waveguides, and the separation between two adjacent output waveguides is 20 μm. The incidence angle is 30°, the diffraction order is 12, and the diameter of the Rowland circle is 10 mm. In the calculation of the surface current on the metallic grating surface with a MoM, each grating groove is divided into 15 segments.

For a conventional EDG demultiplexer, the shape of the spectral response is of Gaussian type. Therefore, the transmission efficiency is sensitive to a slight wavelength shift and the device is not suitable for high-speed applications of planar waveguide modulation. To achieve a flattened spectral response, in this letter, we consider the method of connecting a tapered MMI section at the end of the input waveguide[8] since this method is simple and effective. The geometrical configuration of the tapered MMI is shown in Fig. 2. Based self-imaging principle, the four parameters of the tapered waveguide fulfil the following relation

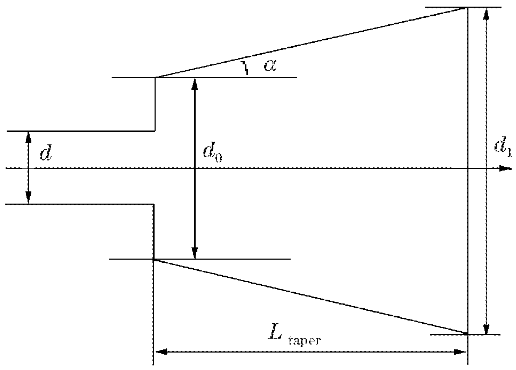

Fig. 2. The geometrical configuration for a tapered MMI.

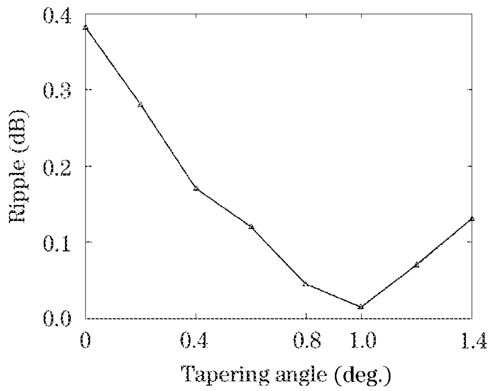

Fig. 3. The ripple varies with the tapering angle.

$$L_{\mathrm{taper}} = \frac{n_{\mathrm{r}}}{2\lambda} \cdot \frac{(d_1 + C)^2}{1 + n_{\mathrm{r}} \tan\alpha(d_1 + C)}, \quad (4)$$

$$d_0 = \frac{d_1 - n_{\mathrm{r}} \tan\alpha(d_1 + C)C}{1 + n_{\mathrm{r}} \tan\alpha(d_1 + C)}, \quad (5)$$

where $C = \frac{\lambda}{\pi}\left(\frac{n_{\mathrm{c}}}{n_{\mathrm{r}}}\right)^{2\sigma}\left(n_{\mathrm{r}}^2 - n_{\mathrm{c}}^2\right)^{-1/2}$ with $\sigma = 0$ (for the TE case) or 1 (for the TM case).

For a given exit width of the tapered MMI, an optimal tapering angle α can be obtained where the demultiplexer has a minimal ripple. Figure 3 shows the ripple as the tapering angle α varies when the exit width $d_1 = 14.9$ μm. From this figure, one can see that the demultiplexer has a minimal ripple 0.015 dB when the tapering angle is about 1.0°. When the tapering angle and the exit width are fixed, other parameters of the tapered MMI can be obtained using Eqs. (4) and (5).

The 1- and 3-dB passbands of the demultiplexer will be improved as the exit width of the tapered MMI increases. However, the loss will increase as d_1 increases (See Fig. 4), which confines the range of the exit width of the tapered MMI. Though the exit width cannot be selected, a

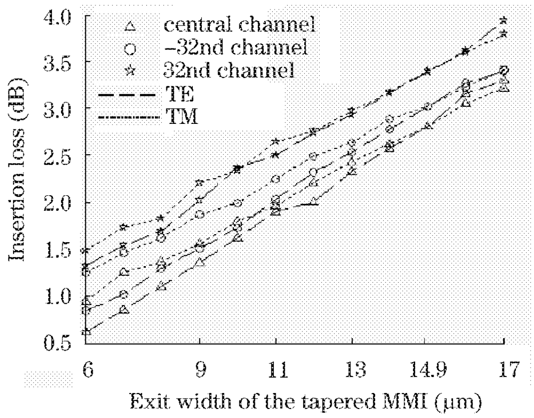

Fig. 4. The insertion loss as the exit width of the tapered MMI varies.

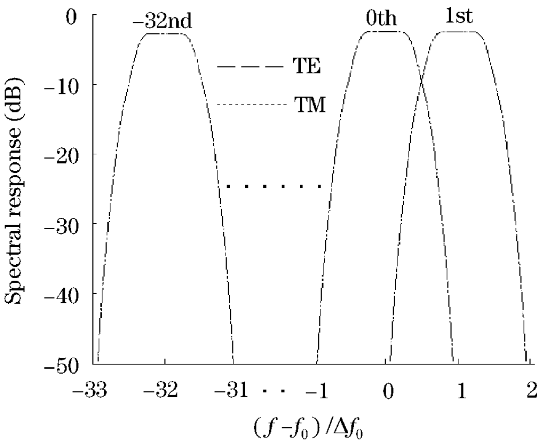

Fig. 5. Spectral responses at the −32nd, 0th, and 1st channels of the designed EDG demultiplexer.

too large value lest overlarge loss is produced. There are not other limitative conditions to help one select a fixed value of the exit width. In fact, one usually selects the exit width, roughly, which can make the additional loss less than 3 dB. Furthermore, Fig. 4 also indicates that the change in d_1 impacts the loss of the TE case more than it impacts one of the TM case. The fact can be used to minimize the PDL with the spectral flattened at the same time. In the numerical example, when $d_1 = 14.9$ μm, the loss of the TE polarization nearly equals to that of the TM polarization, where the minimal PDL may be obtained. Correspondingly, using Eqs. (4) and (5), one can obtain other optimal parameters of the tapered MMI: $d_0 = 9.3$ μm and $L_{\text{taper}} = 144.5$ μm. Using the present design parameters, the addition loss is still less than 3 dB for both polarizations at the central channel.

The spectral responses at the central, the first and the −32nd channels of the designed EDG demultiplexer are shown in Fig. 5. From this figure, one sees that the designed EDG demultiplexer satisfies the performance requirements very well. Our designs can give the following improved specifications: ripple $\leq$0.015 dB, 3-dB bandwidth $\geq$75 GHz, crosstalk $\leq$45 dB, and chromatic dispersion $\leq$6 ps/nm. For a conventional EDG demultiplexer of a Gaussian spectral response using other same structure parameters, 3-dB bandwidth is much less than 45 GHz, which makes the loss so sensitive to the wavelength shift that a slight change of temperature can induce a large increasing of the loss. Moreover, in this letter, a tapered MMI is used for obtaining a flat-topped spectral response instead of a conventional rectangle MMI. The taper can effectively reduce the ripple and the chromatic dispersion (using other same parameters expect a rectangle MMI at the end of the input waveguide, the ripple and the chromatic dispersion are 0.35 dB and 15 ps/nm at the central wavelength, respectively. Particularly, when the exit width of the tapered MMI is optimized, the maximal PDL throughout the total 65-channel is only 0.0096 dB. However, the specification will approach to 0.5 dB to a conventional EDG demultiplexer. Therefore, one only optimized the exit width of the tapered MMI by the way without increasing any additional loss when a flat-topped spectral response is carried out.

In conclusion, a design procedure based on a method of moment has been described for an EDG demultiplexer. The present method can simulate accurately the polarization characteristics, which cannot be treated with any scalar (polarization-insensitive) method. The present method has been illustrated with a numerical example of a 65-channel SiO_2 EDG demultiplexer with flat-topped spectral response and a very low PDL. We connect a tapered MMI at the end of the input waveguide to obtain a flattened spectral response. The exit width at the taper is optimized to obtain the lowest PDL. The simulation can be completed within an hour on a PC of Pentium IV (2.4 GHz). Note that the size of this EDG demultiplexer is too large (in terms of the wavelength) to simulate within a bearable time for other polarization-dependent numerical methods such as the FDTD method.

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