Mode Control in Planar Waveguide Grating Couplers With Double Surface Corrugation

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Abstract—Grating couplers with double surface corrugation are proposed to adjust the resonance behavior of both TE and TM modes simultaneously. Through proper selection of parameters, we designed a polarization-independent grating coupler operating at 1.55-μm telecommunication wavelength. Efficiency is achieved at around 55% for both TE and TM modes, and the polarization-dependent loss is <0.05 dB within the spectral window from 1544 to 1561 nm. Furthermore, a double-channel grating coupler is proposed to excite the TE and TM modes at 1.31 and 1.49 μm, respectively. The achievable efficiency is around 60% for both channels with good uniformity.

Index Terms—Coupler, grating, integrated photonics, planar waveguide.

I. INTRODUCTION

PLANAR waveguide grating coupler provides a practical and effective means for light coupling into photonic integrated circuit owing to its advantages on wafer-scale testing and multi-port package [1]–[4]. However, conventional grating couplers normally operate at single polarization, exciting either TE or TM mode into planar waveguides at specific working wavelength. The central resonance wavelength of TE mode is always longer than that of TM mode due to the asymmetric geometry of the grating region. Therefore, it is difficult to effectively tune and utilize the resonance behavior of both TE and TM modes, which limits its potential for novel applications. In order to extend the functionalities, we propose grating couplers with double surface corrugation (DSC) to adjust TE and TM mode excitation simultaneously. We observe that the diffraction effects of the two grating surfaces result in more resonance combinations compared with single grating, which enables the characterization of the resonance spectrum for both TE and TM modes. Based on the DSC structure, for the first time to our knowledge, we design a one dimensional (1-D) grating coupler which enables polarization-independent (POI) fiber-chip optical excitation. The operation principle of our proposed grating coupler is entirely different from the previously reported two dimensional (2-D) POI grating coupler [5], which works based on equal effective index of TE and TM mode through perturbation of the grating groove in lateral direction. The 1-D design is much easier to handle, and we also present a simple design procedure. Then, we further report the design work on a DSC based gating coupler to achieve double-channel (DCH) optical coupling at 1.31 μm (TE) and 1.49 μm (TM) wavelength. The coupling efficiencies of both channels are over 60%. The operation principle and design methods of the DSC based grating couplers are also theoretically discussed.

II. OPERATION MECHANISM OF DSC GRATING COUPLER

The typical spectral response of TE and TM mode excitation in a conventional 1-D grating coupler is illustrated in Fig. 1(a). TE mode is excited at wavelength longer than that for TM mode, and the achievable efficiency is usually different for each polarization. Provided that the wavelength space, Δrw, (in Fig. 1(a)) between TE and TM central mode resonance and the corresponding efficiencies and their difference, Δe, (in Fig. 1(a)) can be adjusted to desirable values, many potential applications can be exploited, for example, double-channel communication or polarization-insensitive excitation.
(ie. \( \Delta w = 0, \Delta ce = 0 \)). We observed that, by using the sophisticated diffraction and interference effect inside the grating couplers with double surface corrugation (DSC), it is possible to achieve such performance through a proper selection of parameters. DSC grating structures were previously used to enhance the coupling efficiency [6]–[8]. However, their investigations were based on analytical studies under rigid assumptions, such as the same pitch for both corrugations with 50% filling factor. Nowadays, the photonic device design relies heavily on numerical methods which enable more flexible modeling and parameter selection. Since the DSC structure has a constant lateral geometry, accurate calculations can be obtained by 2-D modeling which is more time-saving and easier to handle. In this letter, all the theoretical calculations are based on 2-D finite-difference time-domain (FDTD) algorithm. Consider the basic model of a DSC grating coupler which is periodically corrugated at both top and bottom surfaces, as shown in Fig. 1(b) and (c). Unlike in the single grating structure case, the mode diffraction inside the perturbed dielectric layer of the DSC structure is a result of superposition of both corrugation surfaces. The principle of operation is intuitively illustrated in Fig. 1(b). The incoming fiber beam (with incident angle \( \theta_0 \)) strikes the top corrugated surface and experiences the first diffraction. The diffracted lights with various angles \( \theta_1, \theta_2 \), then travel through the dielectric layer and reach the bottom surface where some of the lights are diffracted upward and travel back again to the top grating. The iterative process involves multi-diffraction and interference. In the DSC structure, the tangential wave vector \( K_{qp} \) of each diffracted light along the grating surface can be generally expressed by Eq. (1), which is applicable for both TE and TM modes

\[
K_{qp} = K_{in} - q \frac{2\pi}{\Lambda_1} - p \frac{2\pi}{\Lambda_2}
\]

where \( K_{in} \) is tangential wave vector of incident light along the top grating surface, \( \Lambda_1 \) and \( \Lambda_2 \) are the pitch of top and bottom surface gratings, and \( q \) and \( p \) are the diffraction orders for top and bottom gratings, respectively. The guided mode is excited when \( K_{qp} \) is equal to the wave vector of the guided mode in the grating region. For an infinite DSC structure, a combination of two corrugated grating surfaces can be defined into four different height sections (indicated in Fig. 1(c)). Then, the effective indices of the guided TE and TM mode in DSC structure can then be estimated approximately using Eq. (2) according to effective medium theory [9]

\[
n_{eff}^{TE/TM} = \sum_{i=1}^{4} n_{i}^{TE/TM} r_i
\]

where \( n_{i}^{TE/TM} \) stands for the effective index in each height sections for TE or TM mode, and \( r_i \) is the corresponding ratio of each height section in the grating structure. Compared with the diffraction effects in the single grating case (without the third item in the right hand side of Eq. (1)), the diffraction effects of the two grating surfaces have more resonance combinations, which enable the characterization of the resonance spectrum for both TE and TM modes simultaneously.

III. DSC-BASED POI GRATING COUPLER DESIGN

To verify the aforementioned mechanism, we first design the POI grating coupler. In our design, the light beam from single mode fiber (10.4 \( \mu \)m diameter) is incident on the grating at a tilt angle of 8°. We select a 660 nm thick unpatterned silicon layer as the basis to construct the DSC grating coupler. The thickness is not fixed and we can also achieve the POI behavior on thinner silicon layer (we will discuss this later). However, the silicon layer cannot be too thin, since thinner DSC structure has a lower refractive index contrast with the claddings which will result in the incident light traveling much easier through the DSC structure and leaking into the claddings. Moreover, thinner silicon layer will also limit the depth of grating grooves. According to Eq. (1) and Eq. (2), to allow the excitation of the guided mode, the selection of \( \Lambda_1 \) and \( \Lambda_2 \) should satisfy

\[
2\pi n_{Si}/\lambda \geq K_{qp} \geq 2\pi n_{SiO2}/\lambda,
\]

where, \( n_{Si} \) and \( n_{SiO2} \) are the refractive index of Silicon (3.48) and SiO2 (1.46), respectively. The tangential wave vector, \( K_{qp} \), is determined after the pitches are selected, then we can tune the etching depth \( d_1 \) and \( d_2 \) of both grating surfaces to adjust the effective index of the guided mode of the grating region, making the structure resonate at desirable wavelength. For the POI DSC coupler, 50% fill factor is adopted, and the initial pitch values \( \Lambda_1 = 800 \) nm and \( \Lambda_2 = 640 \) nm are chosen for the top and bottom grating surfaces. If necessary, they should be corrected by a little amount for a better PDL performance after tuning the etching depths. In order to enhance the coupling efficiency, a distributed Bragg reflector (DBR) is deployed at substrate side to reflect the transmitted light back into the DSC structure. The DBR consists of three pairs of cascaded 111 nm silicon and 269 nm silica layers, and the BOX layer thickness \( t_b \) is 1.5 \( \mu \)m. In our design, only the etching depths \( d_1 \) and \( d_2 \) at both grating surfaces are required to be swept simultaneously to optimize the POI performance (i.e. to make \( |\Delta ce| \) close to 0 at 1.55 \( \mu \)m wavelength). The sweep results in the form of contour profile as illustrated in Fig. 2(a). The area in the profile indicated by a circle has the minimum \( |\Delta ce| \), hence the
TABLE I

<table>
<thead>
<tr>
<th>TE mode</th>
<th>TM mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\lambda$</td>
<td>$q$</td>
</tr>
<tr>
<td>1.35 $\mu$m</td>
<td>1</td>
</tr>
<tr>
<td>1.55 $\mu$m</td>
<td>0</td>
</tr>
<tr>
<td>1.88 $\mu$m</td>
<td>0</td>
</tr>
</tbody>
</table>

Fig. 3. (a) Detailed spectral response for both TE and TM mode excitation in wavelength range of 1.5–1.6 $\mu$m. (b) PDL performance of the designed POI grating coupler.

corresponding etching depths, $d_1 = 80$ nm and $d_2 = 200$ nm, are selected. It should be noted that if there is more than one area with value close to 0, we need to check each area and select the one with highest efficiency for design. The spectral response of the POI grating coupler is given in Fig. 2(b), it can be seen that multiple resonances exist for both TE and TM polarizations. By considering the intrinsic property of the grating structure (i.e., no external DBR and substrate layers are deployed), we observe that the resonance centers basically remain unchanged. These mode resonance centers can be theoretically verified based on Eq. (1) and Eq. (2). The external waveguide of 660 nm thickness can support multimode, and we observe that the TM00 fundamental mode and TE01 mode are excited in the structure (TE$_{mn}$/TM$_{mn}$ stands for the TE/TM mode with field distribution which has $m$ “field zeros” in the y direction and $n$ “field zeros” in z direction). In Table I, we calculate the wavevector $K_{qp}$ of the effective diffracted light and the wavevector $K_{eff} = 2\pi n_{eff}/\lambda$ of the guided mode in the grating region at each resonance wavelength for a comparison. It can be seen that $K_{qp}$ is very close to $K_{eff}$ at each resonance wavelength $\lambda$, allowing the excitation of guided mode into the planar waveguide. In Fig. 2(b), it is also obvious that one central resonance at 1.55 $\mu$m wavelength is shared by both TE and TM modes. A clearer spectrum of the POI grating coupler is given in Fig. 3(a) for the wavelength range from 1.5 $\mu$m to 1.6 $\mu$m. The performance of the POI grating coupler for the TE and TM modes overlap quite well in the wavelength range of 1540–1580 nm, which implies good polarization independence. The PDL performance is shown in Fig. 3(b). The POI grating coupler exhibits a high performance of polarization-independence around 1550 nm wavelength and the PDL is about $4.1 \times 10^{-3}$ dB at 1550 nm. The PDL is less than 0.05 dB in the wavelength range of 1544 nm to 1561 nm, and less than 0.5 dB in a large range of 1535 nm to 1580 nm. The peak efficiency of 55% is achieved for both polarizations, and the 1 dB operation wavelength range is 1536–1563 nm for both TE mode and TM mode. We observe that each of the TE and TM diffractions will be primarily affected by one of the corrugated surfaces, and in our structure the top grating surface is primarily responsible for the TM mode and the bottom grating surface for TE mode. In addition, we also designed a POI grating on thinner silicon layer to excite both the fundamental TE and TM modes to the waveguide, the parameters are given as follows: $h_1 = 370$ nm, $d_1 = 125$ nm and $d_2 = 85$ nm, $h_1 = 1.75 \mu$m, $\lambda_1 = 595$ nm with 145 nm unperturbed region and $\lambda_2 = 800$ nm with 440 nm unperturbed region. The external waveguide thickness is 350 nm. The optimum efficiency is around 50%. If without backside DBR, the efficiency is around 36%, which is comparable with the previously reported result based on 2-D design [5].

IV. DSC-BASED DCH GRATING COUPLER DESIGN

Now we discuss the design of DCH grating couplers which are used to excite the TE and TM mode at two desirable wavelengths (1.31 $\mu$m for TE mode and 1.49 $\mu$m for TM mode). We choose 1.31 $\mu$m-band and 1.49 $\mu$m-band in our design since they are international standards for optical communication. The design approach of DCH DSC grating couplers is the same as that of POI grating couplers. It should be noted that, now in the sweep step, the target is to make $C_{TM,TE}^{1.49} + |C_{TM,TE}^{1.31}|$ close to 0, where $C_{TM,TE}^{1.49}$ is the coupling efficiency of TM mode at 1.49 $\mu$m wavelength and $C_{TM,TE}^{1.31}$ is the TE mode coupling efficiency at 1.31 $\mu$m wavelength. The parameters of the designed DCH grating coupler are listed as follows: $h_1 = 370$ nm, $d_1 = 80$ nm, $d_2 = 90$ nm, $\lambda_1 = 755$ nm with 355 nm unperturbed region and $\lambda_2 = 760$ nm with 400 nm unperturbed region. In this case, no DBR is deployed, and the BOX layer thickness is 2.2 $\mu$m. The spectral response of the DCH grating coupler is shown in Fig. 4(a). It can be seen that the TE mode is
excited at 1.31 μm wavelength, and the TM mode is coupled at 1.49 μm. The efficiencies for both TE and TM channels are achieved around 60%, which are better than the spatially-separat0d DCH coupler [10]. The 3-dB bandwidth for TE and TM polarizations is about 35 nm and 55 nm, respectively. In practical optical networks, the 1.55 μm wavelength channel is also popularly applied for data communication, so a broader bandwidth (or another resonance peak) around the working wavelength is necessary. Then, we also designed a DSC grating coupler with such behavior as illustrated in Fig. 4(b). It can been seen that the achievable efficiency for three channels at 1310 nm, 1490 nm and 1550 nm are 27%, 36% and 31%.

V. Conclusion

As a summary, the DSC based grating couplers were proposed to simultaneously adjust both the TE and TM mode excitation. Based on the structure, we designed a POI and a DCH grating couplers with good performance. The DSC structure has already been proven to be feasible for fabrication [8]. It may have wide applications in practical system.

REFERENCES