Polarization-insensitive 40-channel 100-GHz spacing fold-back planar echelle grating Mux/Demux for photonic integrated wavelength-selective switches

Citation for published version (APA):

General rights
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal.

If the publication is distributed under the terms of Article 25fa of the Dutch Copyright Act, indicated by the "Taverne" license above, please follow below link for the End User Agreement:
www.tue.nl/taverne

Take down policy
If you believe that this document breaches copyright please contact us at:
openaccess@tue.nl
providing details and we will investigate your claim.
We present and numerically demonstrate a novel polarization-insensitive (PI) 40-channel 100-GHz spacing fold-back planar echelle grating (PEG) multiplexer/demultiplexer (Mux/Demux) to realize the compact $1 \times 2$ crossing-less photonic integrated wavelength-selective switch (PIC-WSS). The PI operation is achieved by a polarization splitter to feed the TE and TM modes into the PEG via two waveguides with different incident angles so that the two diffracted modes combine at the same output waveguide. By optimizing the design of different input/output angle combinations and sharing the same blazed angle, a single compact PI PEG with fold-back configuration can simultaneously work as twice the Demux and Mux required. The footprint of the single fold-back PI PEG is only $\sim 40 \text{ mm}^2$. The numerical results show that the 40-channel 100-GHz spaced PI fold-back PEG has $< 2.4 \text{ dB}$ insertion loss, $< -60 \text{ dB}$ cross talk, zero polarization-dependent wavelength shift (PDWS), $0.3 \text{ dB}$ polarization-dependent loss (PDL), $< 0.5 \text{ dB}$ loss variation and $< 0.01 \text{ nm}$ wavelength shift between Mux and Demux.

Many advanced applications like 5G and edge cloud services steadily boost the growth of data traffic in metro networks. Innovative programmable metro network sub-systems are required to efficiently switch and route the large, heterogeneous, and dynamic data traffic. PIC-WSSs are promising and efficient solutions to implement a programmable network by routing wavelengths from any input to any output without electrical–optical–electrical (E/O/E) conversion [1,2]. The PIC-WSS has the potential to provide optical switching with a compact footprint, high stability, low cost, and low power consumption. Reported $1 \times N$ PIC-WSSs have a configuration consisting of an integrated Mux/Demux for the wavelength separation/combiner, broadcast splitters and many waveguide crossings, and photonic switches/gates for wavelength bypass/dropping/blocking [see the configuration in Fig. 1(a)] [3]. The conventional Mux/Demux in PIC-WSSs employ arrayed waveguide gratings (AWGs) on different photonic platforms. In previous work [4], we have demonstrated a hybrid integrated WSS consisting of InP semiconductor optical amplifiers (SOAs) as optical gates (OGs) with nanosecond switching operation and two silicon AWGs (one for Mux and the other for Demux), but it was limited to a 12-channel AWG and required wavelength registration to match the central wavelengths of the two AWGs. Another 40-channel 100-GHz spaced PIC-WSS approach on a silica platform [5] exploited a single AWG in a fold-back configuration as both a Mux and a Demux to eliminate the wavelength mismatch, but at the cost of larger chip size ($\sim 11,000 \text{ mm}^2$) and higher losses/cross talk due to numerous waveguides crossing. A fold-back PEG is an alternative solution to the fold-back AWG as the PEG can provide a smaller footprint to implement an ultra-compact PIC-WSS design by reusing the free propagation region (FPR) and the grating facets for implementing simultaneously multiple Muxes/Demuxes within the same photonic circuit. However, for a practical implementation of a PI PIC-WSS, the PEG should also have PI operation. Several PI PEG designs have been proposed. In Ref. [6], Zhu suggested the TE and TM were separated by a Bragg grating and demultiplexed by two different PEGs to achieve polarization insensitivity, but two PEGs could lead to wavelength mismatch and thus high insertion losses. In Ref. [7], Zhu et al. compensated for the PDWS with an extra-etching in the FPR, but the second lithography step increases fabrication complexity and brings extra insertion loss as well as the edge channels’ high PDWS (0.15 nm).

In this paper, we present and numerically demonstrate—for the first time to the best of our knowledge—a $40 \times 100$-GHz spaced PI PEG with fold-back configuration that can simultaneously work as multiple Muxes/Demuxes for a compact and crossing-less $1 \times 2$ PI PIC-WSS design. By employing a $1 \times 2$ splitter to divide the input wavelength division multiplexing (WDM) data and two polarization beam splitters (PBSs) to feed two polarization states into different input waveguides with different angles [see the configuration in Fig. 1(b) and Fig. 2(a)], the single PI PEG with folded configuration prevents waveguides crossing to achieve low cross talk and low insertion loss as well as negligible PDL and PDWS. Numerical results show that for all the channels of the two PEG Muxes and Demuxes, the insertion losses are $1.5 \sim 2.1 \text{ dB}$ for TE and $1.8 \sim 2.4 \text{ dB}$ for TM; the cross talk levels are better than $-60 \text{ dB}$; the PDLS is less than $0.3 \text{ dB}$; the PDWS is zero at the central channel, 0.01 nm channel wavelength shift; and there is $< 0.5 \text{ dB}$ loss variation between Mux and Demux.
Fig. 1. (a) Schematic of conventional 1 × 2 M-channels WSS with separate PI/Demux. (b) Schematic of 1 × 2 40-channel crossing-less PI WSS employing a single PI fold-back PEG, PBSs, PBCs, and OGs.

WSS is explained as follows. The optical power of the input WDM channels with 100-GHz spacing is first split by a 50:50 power splitter to generate two copies of the input WDM channels. Each copy is fed into a PBS to separate the TE and TM modes. Then the TE and TM of the first copy (second copy) are launched into the TE and TM inputs of Demux 1 (Demux 2), respectively. The launching input angle of the TE/TM and the PEG are designed so that the 40 TE and TM channels diffracted by the grating are demultiplexed and then combined to the same 40 output waveguides of Demux 1 (Demux 2). The separated 40 channels are switched by the optical PI switch array and then guided back to the 40 inputs of Mux 1 (Mux 2). The switched channels are multiplexed to the TE and TM output ports of Mux 1 (Mux 2). The two polarizations are combined by the polarization beam combiner (PBC) to the first (second) output of the WSS. By programming the switch gates, any wavelength can be switched/multi-casted to the two WSS outputs.

The detailed method for PI and fold-back design is described as follows. The concave PEG is the projection of the straight diffraction grating on the waveguide plane. The input and output waveguides are placed on the imaginary Rowland circle (RC) with radius R. The injected multi-wavelength beam diverges in the FPR. Then the diffracted light beam, reflected by the grating facets, focuses to the output waveguides. Due to different refractive index and phase paths, different wavelengths are separated to different output ports. The relationship between the positions of incident light (input waveguide) and diffracted light (output waveguide) are determined by the diffraction equation [8,9]:

\[ d (\sin(\theta_{in}) + \sin(\theta_{out})) = (m \lambda)/n \]  

where \( d \) is the grating facet period, \( \theta_{in} \) is the incident angle, \( \theta_{out} \) is the output angle, \( m \) is the diffraction order, \( \lambda \) is the incident wavelength value in free space, and \( n \) is the effective refractive index of \( \lambda \) in the FPR. For the fixed input angle and grating period, the output angle of TE and TM modes are

\[ \theta_{out}^{TE} = \arcsin \left( \frac{m \lambda}{dn_{TE}} - \sin(\theta_{in}) \right) \]  

As TE and TM modes have different effective refractive indexes, the output angle is different for TE and TM, which leads to PDL and PDWS. To achieve PI operation, both the TE and TM signals should be directed to the same output waveguide. Therefore, we fix the output waveguide position \( \theta_{out}^{TE} = \theta_{out}^{TM} \) and design the input waveguides for TE and TM at different incident angles to diffract the two polarizations to the same output port. The design strategy is first to fix the diffraction order \( m \) and central wavelength \( \lambda \), then choose the input/output angle of the TE mode \( (\theta_{in}^{TE} \text{ and } \theta_{out}^{TE}) \). The grating period is calculated by

\[ d = (m \lambda)/(n_{TE} \sin(\theta_{out}) + \sin(\theta_{in}^{TE})) \]  

As the output angle of TM and TE should be the same, the input angle for TM mode is

\[ \theta_{in}^{TM} = \arcsin ((m \lambda)/(n_{TM}d) - \sin(\theta_{out})) \]  

and the physical spacing between the input TE and TM waveguide is

\[ \Delta s = 4 \pi R (\theta_{in}^{TE} - \theta_{in}^{TM}). \]  

By setting different input angles for TE and TM, the two modes can be diffracted and reflected to the same output waveguides without PDWS and PDL.

Fig. 2. (a) Structure of PI fold-back PEG (twice Demuxes and twice Muxes) combining PBS and PBC for 1 × 2 crossing-less WSS. (b) Structure of 3-µm silicon slab waveguide. (c) Blazed angle for two input/output combinations. (d) Layout of the 1 × 40 PEG (gray part: area of light transmission).
In our design, the 3-μm thick silicon (waveguide core) on silica (substrate) platform is employed as the slab waveguide for guiding light [see Fig. 2(b)] [10]. The grating facets are coated with gold for reflection. The effective refractive index of TE and TM \((n_{TE} \text{ and } n_{TM})\) at the central wavelength of 1547.72 nm in the FPR are 3.4672 and 3.4664, respectively. The diffraction order \(m\) is set to 6 for both TE and TM, which results in ~258 nm free spectrum range (FSR). For TE mode, the input angle is set to 27° with an output angle of 20°, and the grating period \(d\) is calculated to be 3.36 μm. For TM mode, the input angle is 27.01° which results in an output angle of 20° (same as for TE). The physical distance of the TE and TM input is ~3 μm.

To achieve maximum diffraction efficiency and minimum loss, the grating facet is designed with a blazed angle \((\theta_b)\), which ensures the reflection direction to be the same as that of the zeroth diffraction [8,9]:

\[
\theta_b = (\theta_{in} + \theta_{out})/2. \tag{7}
\]

If the different combinations of input and output angles satisfy the same blazed angle condition (such as \((\theta_{in} + \theta_{out})/2 = (\theta_{in}^\text{TE} + \theta_{out}^\text{TE})/2 = \theta_b\)), namely that they share the same blazed angle, the same blazed grating can provide maximum diffraction efficiency for the different light beams injected from different input angles [see Fig. 2(c)]. The first input/output combination of TE mode \(((\theta_{in}^\text{TE} + \theta_{out}^\text{TE}))\) defines the grating period [see Eq. (4)]. Then the input angle of the other combination is set to \(\theta_{in}^\text{TE}\) following the rules set out by Lycett et al. in Ref. [9], and the corresponding output angle is calculated by

\[
\theta_{out}^\text{TE} = \arcsin((m \lambda)/(n_{TE}d) - \sin(\theta_{in}^\text{TE})). \tag{8}
\]

To achieve PI operation, the output angle of the TM is set to the same value as \(\theta_{out}^\text{TE}\), and the input angle of TM \(\theta_{in}^\text{TM}\) is calculated by Eq. (5). To reuse the single PEG four times for twice multiplexing and twice demultiplexing, our fold-back PEG is designed with four input/output angle combinations. The first input/output combination for TE is set to 27° and 20°, resulting in a 23.5° blazed angle; the other three combinations for TE are 28.5°/18.59°, 25.5°/21.44°, and 24°/22.91°. For TM, the four combinations are 27.01°/20°, 28.51°/18.59°, 25.51°/21.44°, and 24.01°/22.91°, respectively. Since the grating period \(d\) is fixed and calculated by the first input/output combination, the other combinations have a slight deviation compared with the blazed angle of 23.5°, which will result in extra negligible loss. By reusing the same PEG and sharing the same blazed angle, the fold-back configuration ensures zero wavelength shift between different input/output groups. Benefitting from the PEG’s bidirectionality, the input and output can be swapped, i.e., the light beams launched from the output waveguides can also be diffracted and reflected to the input waveguide. For the 1 × 2 WSS configuration, the single PEG works as twice Demux and twice Mux. Demux 1 uses the angle combination of 27° TE input, 27.01° TM input, and 20° as the same output for both modes. Mux 1 employs 18.59° as the input for both TE and TM, 28.5° as the TE output, and 28.51° as the TM output. For Demux 2, the waveguide positions are set with 25.5° TE input, 25.51° TM input, and 21.44° as the same output for both. For Mux 2, the input of both is 22.91° with 24° TE output and 24.01° TM output. The main design parameters are summarized in Table 1. The size of the single fold-back PEG, including grating facets and area of light transmission, is only ~40 mm² [see the layout in Fig. 2 (d)], which is much smaller than the AWGs used by Tesser et al. in Ref. [4] and Yoshida et al. in Ref. [5].

The software Epiprop is used as the simulator. The 100-GHz spaced 40-channel simulated output spectra and magnified spectra of Demux 1, Mux 1, Demux 2, and Mux 2 are illustrated in Figs. 3(a)–3(h), respectively. Figures 4(a), 4(b) and 4(c) show the overlapped detailed spectra of Demuxes and Muxes at central wavelength 1547.72 nm and C-band edge wavelengths 1531.90 nm and 1563.86 nm, respectively. The results show that from 1530 nm to 1565 nm for all Demuxes and Muxes, insertion losses range from 1.5 to 2.1 dB for TM and from 1.8 to 2.4 dB for TE. The PDWS at the central channel is zero, and is 0.009 nm at the edge channel, which is smaller than ~0.02 nm found by Zhu in Ref. [6] and 0.15 nm found by Zhu et al. in Ref. [7]. All channels have ~0.3 dB PDL, which is caused by polarization-dependent reflective coating and could be eliminated by removing the metal coating from the grating’s nonreflecting facets [11]. The cross talk levels are ~60 dB on average for all 40 channels. The loss variation of 0.04 to 0.5 dB between demultiplexing and multiplexing is observed due to slight deviation from the blazed angle. The wavelength shift between Demux and Mux is zero at the central channel and 0.01 nm at the edge channel. All simulated results are summarized in Table 2. The effect of TE/TM input distance variation on PI performance has also been studied by simulating a TM spectrum with distance variations up to ±200 nm in 50-nm steps (see Fig. 5). The variation of ±200 nm only results in a PDWS of 0.02 nm and a PDL of 0.4 dB. The fabrication tolerance could be further reduced by increasing the RC radius, i.e., increasing the distance between the TE and TM input. The typical refractive index variation after fabrication is in the order of ~1 × 10⁻⁵ which leads to ~0.005 nm central wavelength shift for both TE and TM. When the variation of blazed angle is < 1°, the increase of insertion loss is < 0.7 dB and the increase of cross talk is < 5 dB.

In summary, we designed and numerically demonstrated a novel PI fold-back PEG serving simultaneously as twice the Demux and Mux required in a PI PIC-WSS. The single PI fold-back PEG has 40 channels and 100-GHz spacing for Mux/Demux with low insertion loss of 1.5~2.4 dB, ~0.009 nm PDWS, ~0.3 dB PDL, low cross talk < ~60 dB, 0.04~0.5 dB loss variation, and 0~0.01 nm wavelength mismatching between Muxes and Demuxes, and compact footprint of ~40 mm². The flattop response of the PEG can be achieved by placing

<table>
<thead>
<tr>
<th>Table 1. Main Design Parameters of PI Fold-Back PEG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Period</td>
</tr>
<tr>
<td>Order</td>
</tr>
<tr>
<td>Central wavelength</td>
</tr>
<tr>
<td>Channel number</td>
</tr>
<tr>
<td>Blazed angle</td>
</tr>
<tr>
<td>FSR</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 2. PI Fold-Back PEG Performance Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Channel spacing</td>
</tr>
<tr>
<td>Channel number</td>
</tr>
<tr>
<td>Blazed angle</td>
</tr>
<tr>
<td>FSR</td>
</tr>
</tbody>
</table>

Letter 5270 Vol. 47, No. 20 / 15 October 2022 / Optics Letters
Fig. 3. Output spectra with TE mode (solid curve) and TM mode (dashed curve) of (a) Demux 1, (c) Mux 1, (e) Demux 2, and (g) Mux 2; magnified spectra at central channels of (b) Demux 1, (d) Mux 1, (f) Demux 2, and (h) Mux 2.

Fig. 4. Detailed output spectra at (a) 1547.72 nm, (b) 1531.90 nm, and (c) 1563.86 nm of Demux 1 (blue curve), Mux 1 (black curve), Demux 2 (green curve), and Mux 2 (red curve) with TE mode (solid curve) and TM mode (dashed curve).

Table 2. Simulated Results of the PI Fold-Back PEG

<table>
<thead>
<tr>
<th></th>
<th>Demux 1</th>
<th>Mux 1</th>
<th>Demux 2</th>
<th>Mux 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Losses (dB) (TE)</td>
<td>2.0–2.1</td>
<td>2.3–2.4</td>
<td>1.9–2.0</td>
<td>1.8–1.9</td>
</tr>
<tr>
<td>Losses (dB) (TM)</td>
<td>1.7–1.8</td>
<td>2.0–2.1</td>
<td>1.6–1.7</td>
<td>1.5–1.6</td>
</tr>
<tr>
<td>PDL (dB)</td>
<td>~0.3</td>
<td>~0.3</td>
<td>~0.3</td>
<td>~0.3</td>
</tr>
<tr>
<td>Loss variation (dB)</td>
<td>0.04–0.5</td>
<td>PDWS (nm)</td>
<td>0–0.009</td>
<td></td>
</tr>
<tr>
<td>Wavelength shift (nm)</td>
<td>0–0.01</td>
<td>Cross talk (dB)</td>
<td>~60</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 5. Detailed output spectra of original TE/TM design, and TM with distance variation of ±50nm, ±100nm, ±150nm, and ±200nm.

Data availability. Data underlying the results presented in this paper are not publicly available at this time but may be obtained from the authors upon reasonable request.

REFERENCES