Polarization independent and temperature tolerant AWG based on a silicon nitride platform

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Polarization tolerant optical receiver is a key building block for the development of wavelength division multiplexing (WDM) based high-speed optical data links. However, the design of polarization independent demultiplexer (DEMUX) is not trivial. In this work, we report on the realization of a polarization tolerant arrayed waveguide grating (AWG) on a 300-nm silicon nitride (SiN) photonics platform. By introducing a series of individual polarization rotators in the middle of the waveguide array, the polarization dependence of the AWG has been substantially reduced. Insertion losses below 2.2dB and a crosstalk level better than -29dB has been obtained for TE and TM polarizations on a four channel coarse AWG. The AWG temperature sensitivity has also been evaluated. Thanks to the low thermo-optical coefficient of SiN, a thermal shift below 12pm/°C has been demonstrated.

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1. Introduction

Leveraging the low cost and industrial manufacturing infrastructure of CMOS electronics, silicon photonics (SiPh) appear as a promising technology for the realization of efficient optical data links [1]. In particular, the integration of hundreds of optical components on a single chip can support the development of low cost coarse wavelength division multiplexing (CWDM), enabling the transmission of several high-speed data channels on a single optical fiber [2]. However, polarization management on the receiver side is a critical functionality, as commercially deployed optical fiber does not maintain the injected polarization state. A common solution consists of using a polarization splitter – rotator [3] at the receiver input to separate the transverse electric (TE) and transverse magnetic (TM) polarizations as well as rotating the TM(TE) signal into TE(TM). Therefore, two identical single polarization demultiplexer (DEMUX) can be used [4]. This approach simplifies the DEMUX design, but leads to a significantly larger footprint and increasing circuit complexity due to the multiplication of the components. Otherwise, a simpler solution is to use polarization tolerant DEMUX. Among all types of DEMUX, the arrayed waveguide grating (AWG) is particularly attractive with its potential for low insertion losses [5] and high channel count capacity [6]. Few

methods have been proposed to reduce the polarization sensitivity of AWGs. The simplest strategy is to use a custom waveguide geometry in order to equalize the TE and TM effective indexes in the waveguide [7]. Another possibility exploits the intrinsic dependence of the waveguide birefringence to the waveguide width in order to reduce the polarization dependence of the AWG [8,9]. Despite the ease of implementation (no additional fabrication steps), these techniques critically rely on the precision of the patterning, any inaccuracies quickly lead to increased insertion losses as well as higher crosstalk levels. Moreover, due to material and waveguide dispersion, birefringence tailoring is only valid for a narrow spectral range prohibiting the use of such methods for large bandwidth devices such as coarse wavelength division multiplexing based AWGs ($\Delta\lambda > 100\text{nm}$) [10]. Another interesting approach consists of introducing a half-wave plate in the middle of the AWG [11,12]. By doing so, the optical path for both polarizations will be perfectly equalized despite the inherent birefringence of the waveguides and star coupler slab regions. However, the insertion of such a plate leads to complex additional fabrication steps as well as high radiation losses especially for small (i.e. high index contrast) waveguides.

Fig. 1. (a) Top view of the AWG with integrated polarization rotators. The evolution of the input signal TE and TM components through the device is also shown. (b) Top and cut view of the SiN polarization rotator with all of its dimensions.

In this work, we propose a novel interpretation of this latter concept. As presented in Fig. 1(a), the half-wave plate is replaced by a series of individual waveguide-type polarization rotators (PR). Due to the proximity between the waveguides in the array, the fabrication dispersion between the rotators has to be low. Taking benefits from the excellent optical properties of silicon nitride (SiN)

based waveguides (one order of magnitude lower thermo-optical coefficient and reduced index contrast compared to silicon [13]), a polarization independent four channel CWDM based SiN AWG targeting O-band operation has been experimentally demonstrated as a proof of concept.

2. Polarization rotator

Following the four channel CWDM standard, the proposed AWG is intended to operate over a large spectral range ($\sim 80\text{nm}$). Therefore, in order to ensure low loss and broadband operation, a mode-evolution based architecture has been chosen for the polarization rotator [14]. This device is presented in Fig. 1(b). Unlike other common geometries, this PR is always narrower than the standard waveguide guaranteeing that PRs in the dense waveguide array do not overlap. In order to obtain polarization rotation, a vertical asymmetry in the waveguide geometry is required. In our PR, this is implemented using a slab created by partial etching of the SiN film. The introduction of this additional level is justified since it can also be used on several other devices including star couplers [15], grating couplers [16] or rib waveguides [17]. As shown in Fig. 1(b), the SiN waveguide core is 600nm height while the slab thickness is 350nm .

The polarization rotator design process starts by selecting the width of its sections. The input and output waveguides width is set to 700nm , which corresponds to the standard waveguide width in our platform [18] in order to facilitate the connection with the AWG. The intermediate rib width is set to 450nm so that it is narrower than its height avoiding index crossing between the modes. During the first two sections of length L_1 and L_2 , the optical axis of the waveguide will gradually rotate thanks to the vertical and lateral asymmetry. Using long enough waveguide sections within the PR will prevent from high insertion losses due to parasitic coupling with other modes.

The polarization rotator has been simulated using an eigen mode expansion (EME) solver [19], which is well suited for such longitudinal structures as it requires less computational resources than the more commonly used finite difference time domain (FDTD) method. Firstly, the rotator has been optimized by varying the length of both tapered sections L_1 and L_2 while L_{out} is set to $20\mu\text{m}$. The results are presented in Fig. 2(a). Assuming a similar behavior for the opposite conversion, the graph shows the TM to TE rotation efficiency (i.e. transmission) as a figure of merit for the optimization. As it can be seen, a conversion efficiency higher than 99% is obtained for $L_1 = 26\mu\text{m}$ and $L_2 = 80\mu\text{m}$. As shown in Fig. 2(b) (dashed lines), this optimized PR demonstrates a wavelength tolerant behavior with an extinction ratio (ER) higher than 20dB over more than 80nm for both TE and TM polarizations.

The device was fabricated on the 300mm silicon photonics R&D platform in ST Crolles (France). More details about it can be found in [18,20]. Characterization has been performed using an edge coupling scheme as described in [21]. The control of light polarization state has been performed using standard fiber paddle polarization controller together with calcite-made polarizers and polarization maintaining optical fibers in order to properly reject the unwanted polarization states on a large wavelength range.

The accurate extraction of the insertion losses of the PR has been done using the cutback method using the transmission of waveguides containing 2, 4 and 6 polarization rotators. Thus, assuming a similar conversion efficiency, the measured insertion losses are an averaging of the rotator TE to TM and TM to TE

transmission. Since the fiber-chip coupling efficiency depends on the light polarization, we chose to use an even number of PR so that the light polarization at the input fiber-chip coupler and at the output one is the same, thus simplifying the normalization. As presented by the grey curve Fig. 2(b), the insertion loss of the rotator is better than -0.5dB over the whole O-band. The additional loss compared to simulation is attributed to fabrication variations.

Fig. 2. (a) Simulation (EME) of the TM to TE rotation efficiency as a function of L_1 and L_2 at a wavelength of 1300nm . (b) Simulated (dashed lines) and experimental (solid lines) spectral response of the polarization rotator. The solid grey line represents the experimental transmission of the PR. Vertical axis have been splitted with two different scales for better visibility of the top curves.

An extinction ratio higher than 7dB has been measured on a waveguide containing a single rotator. This deviation compared to simulation ($\text{ER} > 20\text{dB}$) is attributed to the poor extinction ratio of the measurement bench. Indeed, we believe that the PR has a higher ER than the measured value since there is no parasitic transmission peaks on the AWG spectrum (as can be seen in the next section) that could be attributed to residual non-rotated light.

3. Arrayed waveguide grating

The working principle of an AWG has been extensively described in the literature [22]. Here we present the simple design procedure that we followed for the four channel CWDM SiN based AWG.

First, the array order has been set to $m = 6$ as a compromise between the channel transmission non-uniformity and the array diffraction efficiency (which ultimately defines the device footprint) [23]. Then, the path length difference between the arms of the array,

ΔL , can be calculated. Taking into account that the incoming light will pass through half of the array in TE(TM) and the other half in TM(TE), we found $\Delta L = 4.675\mu\text{m}$. The array waveguides and injection/collection waveguides are connected to the star couplers using tapers (width $W_{\text{ar}} = 3\mu\text{m}$, $W_{\text{inj/col}} = 6\mu\text{m}$). Thus, the index contrast between taper and star couplers is reduced, prohibiting back light reflection and noise. In order to minimize the insertion losses of the device, the spacing between the tapers in the array is set to 200nm that is the minimum feature size allowed in our fabrication process. Therefore, the waveguide pitch in the array is $d_{\text{ar}} = 3.2\mu\text{m}$. Using all these parameters, the array dispersion can be calculated [22]. A star coupler radius of $R = 500\mu\text{m}$ has been chosen so that the spacing between the output waveguides is large enough ($d_r = 12.4\mu\text{m}$) to avoid parasitic coupling. As depicted in Fig. 3(a), the same partial etching step as the one used for the polarization rotator has been performed at both end of the star couplers in order to reduce the index contrast between the slab mode propagating in the star coupler and the taper modes, which will further reduce the device insertion loss [15]. Using finite difference time domain (FDTD) simulations [19], the input waveguide diffraction angle has been estimated at 17° . From these parameters, the number of waveguides in the array has been fixed to $N = 48$ in order to collect all the light coming from the input waveguide. The AWG parameters are summarized in table 1. Due to the low array order, and therefore short ΔL , an “omega” array shape has been chosen in order to keep sufficient spacing between waveguides in the array. The fabricated AWG as well as the series of polarization rotators can be seen on Fig. 3(a).

Table 1. AWG parameters.

Symbol	Description	Value
m	Array order	6
ΔL	Path length difference	$4.675\mu\text{m}$
W_{ar}	Array taper width	$3\mu\text{m}$
$W_{\text{inj/col}}$	In/out taper width	$6\mu\text{m}$
d_{ar}	Array waveguide pitch	$3.2\mu\text{m}$
R	Star coupler radius	$500\mu\text{m}$
d_r	In/out waveguide pitch	$12.4\mu\text{m}$
N	Number of array waveguide	48
-	Footprint	$2200 \times 470\mu\text{m}$

The normalized experimental transmission of the AWG is shown in Fig. 3(b). First, the measured transmission of the AWG is normalized using the transmission of a straight SiN waveguide containing a single rotator. This will filter the different coupling losses (due to opposite polarizations) at the input and output fibre – chip couplers as well as the experimental setup transmission. The normalized insertion losses of the AWG is then obtained by adding the insertion losses of the PR. As shown on Fig. 3(b), the four channels present insertion losses below 2.1/1.4dB, 1.4/1.2dB, 1.9/2.1dB, 1.1/1.6dB for the TE/TM polarization and a crosstalk level higher than 30.3/31.4dB, 30.1/30.5dB, 31.3/29.7dB, 31.5/29.3dB. Furthermore, no significant spectral shift can be seen between the TE and TM response. As a reference, the transmission of a channel from a similar AWG without polarization rotators inserted in the waveguide array is also presented (dashed colored lines). As shown, such AWG presents $\sim 7\text{nm}$ peak shift between TE and TM polarizations.

Fig. 3. (a) Optical microscope top view of the AWG. (b) Experimental transmission of the four channels of the AWG for both TE and TM polarizations. The transmission of a channel from a reference AWG is also shown in colored dashed lines. The grey dashed lines correspond to the channel positions according to the CWDM standard.

In addition to polarization tolerance, demultiplexer designed for CWDM transceivers require temperature independent operation. Therefore, the temperature dependence of the AWG has also been evaluated using a Peltier element to control the chip temperature. As shown on Fig. 4(a), temperature was varied between 20°C to 45°C with 5°C steps. Using a linear interpolation, a low thermal drift of $11.9\text{pm}/^\circ\text{C}$ has been extracted (Fig. 4(b)), which corresponds to a shift below 1nm for $\Delta T = 80^\circ\text{C}$. This value is in good agreement with other SiN based devices reported in the literature [13,24].

4. Conclusion

By introducing an array of individual waveguide-type polarization rotators, a polarization independent CWDM silicon nitride based AWG has been demonstrated with interesting characteristics in terms of insertion loss and crosstalk. Compared to other methods, this technique allows for the reduction of the polarization dependence of an AWG over a large spectral range, paving the way to the realization of efficient polarization insensitive CWDM receivers.

Fig. 4. (a) Measured transmission of a central channel of the AWG at different temperatures in TE polarization. (b) Extracted AWG response drift with temperature.

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