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Sidelobes in the response of arrayed waveguide gratings caused by polarization rotation

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Abstract: Earlier it was observed that polarization rotation in an AWG built from birefringent waveguides can result in sidelobes in its response. This effect was measured in a polarization sensitive AWG with an orthogonal layout. Now we investigate through detailed simulation whether this effect also exists in polarization desensitised AWGs. It is shown that a dispersion compensated AWG does not suffer from a polarization sidelobe. Alternatively, the AWG can be designed to minimize polarization rotation to suppress the sidelobe.

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1. Introduction

Arrayed waveguide gratings (AWGs) are commonly used components in integrated optics. In most applications the crosstalk performance offered by these devices is very important, with large sidelobes adversely affecting crosstalk levels. Sidelobes in AWG responses have so far been reported to originate from finite array aperture sizes [1], phase errors due to fabrication imperfections [2], coupling between array waveguides [3], higher-order mode propagation [4], and unwanted scattering. Using relatively simple measurements, it can be shown that sidelobes can also be caused by polarization rotation in the AWG. We refer to these sidelobes as polarization rotation sidelobes or ‘PR-sidelobes’ for short.

In birefringent waveguides the TE and TM polarized modes have different propagation constants. An AWG constructed out of such waveguides will have different dispersion for either polarization. As such, the AWG pass band positions for different polarization will be shifted in frequency with respect to each other. There are several methods to make AWGs polarization insensitive. We will investigate whether these methods also reduce or eliminate the PR-sidelobes.

We first noticed PR-sidelobes experimentally in a device whose layout is shown in Fig. 1(a). It was discovered that the output signal of this AWG contained a mix of TE and TM polarization, whereas only one polarization state was launched at the input. It was further noticed that the main transmission peak had the same polarization as the input signal. The highest sidelobe however, had an orthogonal polarization with respect to the input signal.

The layout type of the investigated device uses the same bend radius and angle for all the tight bends in the array. This reduces the systematic phase errors associated with different bend radii and angles [5]. Unfortunately, this also causes the polarization conversion to be the same for every bend in the array, which creates a coherent effect. If the bends are different, averaging takes place, making the effect less pronounced. Here we will only discuss the effect in the orthogonal AWG layout of Fig. 1(a).

The work presented here expands on earlier work presented at a conference [6]. First we will discuss the devices in which the PR-sidelobes were observed. After that we continue in section 3 with a detailed description of the measurements. These are then compared in section 4 to simulations. A similar simulation is used in section 5 to see which polarization desensitising methods can remove the PR-sidelobe. We conclude in section 6.

2. Device design

The measured devices were manufactured in a well established process from the company Oclaro Ltd., based in the United Kingdom. The stack consists of a lightly doped 2µm thick p-InP top cladding and a 0.36µm thick MQW (Multiple Quantum Well) core on a n-InP substrate. The resulting slab index is 3.246 at a wavelength of 1.55µm. All waveguides were 1.5µm wide and deep-etched, with an etch depth of 3.6µm. The surrounding material is air. An SEM picture of the resulting cross-section is shown in Fig. 1(b). The indicated sidewall-angle in this figure equals 87 degrees.

Figure 1(a) shows the layout of the device. The used bend radius was 150µm for all curved waveguides. Lateral offsets of 16nm were applied at junctions between straight and curved waveguides. The designed four channel AWG had a free spectral range of 1600GHz and a channel spacing of 400GHz. The devices were processed by Oclaro.
3. Measurements

The devices were characterized and sidelobes on one side of the transmission peaks were observed. Figure 2 shows their location in the spectrum. Further measurements were carried out to determine the source of these sidelobes. The measurement setup used is shown in Fig. 3. In this setup the light from a broadband light source is TE polarized by the input polarizer. After the light has passed through the device under test, a second polarizer can be set to transmit either TE or TM polarized light, or be removed to allow any polarization to pass.

Three measurements were performed. In the first measurement the output polarizer was set to transmit the TE part of the output signal. In the second measurement the TM part of the output was transmitted. In the last measurement the output polarizer was removed and the total transmitted power was recorded. The results of these measurements are shown in Fig. 4. This figure clearly shows a sidelobe on the shorter wavelength side of the main transmission peak. This sidelobe is not present in the filtered, TE-only, output signal. However, it is present in the TM part of the output. Because only TE polarized light was launched, the TM output must be the result of polarization rotation in the sample.

On closer inspection of Fig. 2 it becomes clear that for TE input, the sidelobe is on the shorter wavelength side. For TM input, the sidelobe is on the longer wavelength side. This is consistent with polarization conversion taking place in the array. Suppose that the TE mode is launched and that it has a higher propagation constant than the TM mode ($\beta_{\text{TE}} > \beta_{\text{TM}}$), as is the case for our device. The phase of the light that is converted to TM then increases more slowly during propagation. The TM light thus experiences a virtual red-shift. This means that, to end up in the same output waveguide as the original TE light, its wavelength has to be shorter. The same argument holds for TM polarized input, but then a virtual blue-shift occurs. The rotated light in the output waveguide then has a longer wavelength. The sidelobe thus appears at shorter wavelengths for TE and at longer wavelengths for TM.

The layout of Fig. 1(a) can be divided into three general areas: the input waveguides, the array, and the output waveguides. Figure 2 shows that the distance in wavelength between the sidelobe and main peak ($\approx 2.4\text{nm}$) is less than the observed shift between the TE main peak and
Fig. 2. Typical response of the characterized devices for TE input (black) and TM input (grey). The arrows indicate the PR-sidelobes.

Fig. 3. Schematic of the experimental setup. The input polarizer is present in all measurement; in some measurements no output polarizer was used. ASE: Amplified Spontaneous Emission source, SMF: Single Mode Fiber, DUT: Device Under Test, OSA: Optical Spectrum Analyzer.

TM main peak (≈ 4.3 nm). If the rotation were to occur in the input waveguide, the full TE/TM shift should be observed. If the rotation occurred in the output waveguide, no effect should be observed. The rotation must therefore happen in the array itself. The rotation most likely occurs in the curved array waveguides, as curved waveguides have been reported to cause polarization rotation [7]. In the next section, the measurements will be compared to detailed simulations to further support this hypothesis.

4. Simulation

A transmission matrix based approach was used to simulate the device that was measured in the previous section. In the model, the AWG is split into two star couplers and individual straight and curved waveguides. For every part a transmission matrix is calculated. Concatenation of the transmission matrices then results in the transfer of the full AWG. The model includes polarization rotation.

The star-couplers are modelled using the “leading-order paraxial approximation”, as described in [8]. This approximation is valid for small angles in the star-coupler and allows the use of a Fourier transform to calculate the diffracted field. The mode field of the fundamental mode in the input waveguide of the star-coupler is approximated by a Gaussian. This allows for a fully closed analytical expression for the field at the other side of the star-coupler. The slab-index, that is necessary for this method, was calculated for each polarization independently and fitted with a second order polynomial. Using this method we calculated the coupling coefficients between the input and output waveguides to the array waveguides. It was assumed that
the coupling between array waveguides can be neglected. The array waveguides each have two inputs and two outputs; one for TE and one for TM. In the straight waveguides, the transmission matrix is as follows:

\[
T_s = \begin{pmatrix}
\exp(-j\beta_{\text{TE}} L) & 0 \\
0 & \exp(-j\beta_{\text{TM}} L)
\end{pmatrix}
\]  

(1)

with \(\beta\) the polarization dependent propagation constant. The propagation constant was calculated at several wavelengths by using a 2D Film Mode Matching method and then fitted with a second order polynomial for TE and TM separately. From Eq. (1) it is clear that we assume there is no polarization rotation in the straight waveguides. Instead, this is modeled in the curved waveguides.

The curved waveguides are modeled by two hybrid modes with their principles axes rotated by an angle \(\phi\) with respect to the straight waveguide modes. The transmission matrix thus becomes:

\[
T_c = \begin{pmatrix}
\sin \phi & \cos \phi \\
\cos \phi & -\sin \phi
\end{pmatrix}
\begin{pmatrix}
\exp(-j\beta_0 R \theta) & 0 \\
0 & \exp(-j\beta_1 R \theta)
\end{pmatrix}
\begin{pmatrix}
\sin \phi & \cos \phi \\
\cos \phi & -\sin \phi
\end{pmatrix}
\]  

(2)

with \(\phi\) the polarization rotation angle, \(R\) the bend radius and \(\theta\) the bend angle. For the propagation constants of the hybrid modes, we assume that \(\beta_0 = \beta_{\text{TM}}\) and \(\beta_1 = \beta_{\text{TE}}\). Because these two propagation constants are different, the state of polarization will rotate during propagation through the curved waveguides.

To match the height of the polarization sidelobe in the simulation with the experimental results, a polarization rotation angle of 2.7° is needed. This is a reasonable value as the sidewall angle was measured to be 3°. As Fig. 1(b) shows, the sidewall angle increases closer to the substrate. The curvature of the waveguide causes the field to shift outward and slightly down. This increases the influence of the sidewall on the field profile.

An additional change was made in the simulation to better match the measurements. The fitted TE and TM mode indices were changed slightly to match the measured polarization dispersion of 4.3 nm in the array. This was done by subtracting 0.008 (around 0.25%) from the TM mode index. The need for this correction can be explained by the fact that the layer stack uses a MQW core, whereas a bulk model was used for the calculation. This difference can induce additional polarization dispersion.
A simulation was carried out with fully TE polarized light at the input on the same layout as shown in Fig. 1(a). In the simulation result the PR-sidelobe has shifted 2.2nm with respect to the main lobe. In the measured response this is 2.4nm. Please remember that only the polarization dependence of the whole layer stack was fitted to experimental results. The position of the PR-sidelobe was not matched to experimental results. Keeping this in mind, we obtain a very good match between the result of the simulation, shown in Fig. 5, and the measured response.

5. Eliminating the sidelobe

When using birefringent waveguides, an AWG is polarization sensitive. Several approaches exist for making such AWGs polarization insensitive. Smit names the following in [1]: insertion of a half-wave plate, compensating polarization dispersion, order matching, and launching TE and TM polarizations from different input waveguides (input polarization splitting). The discussion in this section strictly limits itself to AWGs with the same layout as shown in Fig. 1(a). It will be shown that, for this particular layout, only a specific form of dispersion compensation can eliminate the negative effect of the PR-sidelobe. The simulation method described in section 4 was used to show this. The simulation was modified to use one of the various polarization desensitising methods.

5.1. Decreasing polarization rotation

The PR-sidelobe will be reduced by decreasing the amount of polarization rotation taking place in the curved sections. This could be done by changing the waveguide geometry or by increasing the bending radius of the curved array waveguides. Alternatively, the length of the curved sections could be chosen in such a way that the hybrid modes have the same relative phase at both the end of the curve as at the beginning. In that case the state of polarization will be the same at the beginning and end of the curve. The curves then essentially become full-wave plates. For 90 degree bends in our InP layer stack, this condition is fulfilled by taking the bend radius equal to an integer multiple of 97µm. To meet minimum bend radius requirements, the radius would become 194µm.

5.2. Half-wave plate

By inserting a half-wave plate (HWP) at the center line, a polarization insensitive device was obtained in [9]. Its effect on the PR-sidelobe can be understood as follows. Suppose TE polar-
ized light is launched at the input. After propagating through the first curve, the polarization state is mixed. Dispersion then occurs in the straight waveguide, with the phase of TE increasing faster than that of the TM polarized light. At the center of the array the HWP interchanges the two polarizations. The phase difference between the two polarizations is then reduced again, until the second curve is reached. At that point the phase profile is the same as after the first curve. However, the main lobe is now TM polarized and the sidelobe is TE polarized. Propagation through the second curve causes additional polarization rotation. Applying the same reasoning as in section 3, dispersion in the last straight part of the array will cause a red shift of the sidelobe with respect to the main peak. The dispersion will now only occur in the last straight of the AWG. The shift of the sidelobe is therefore slightly smaller when using a HWP. We therefore expect to see a TM polarized mainlobe and a red shifted TE polarized sidelobe.

This behavior was verified using a modified version of the simulation described in section 4. The half-wave plate was modelled as interchanging the TE and TM content. In the simulation, the input was TE polarized. The results are shown in Fig. 6. As was expected, the mainlobe is now TM polarized and the TE polarized sidelobe is on the longer wavelength side.

![Fig. 6. Simulated response of an AWG with an inserted half-wave plate subject to polarization rotation in the curved waveguides. The PR-sidelobe is not removed by this method, but only displaced in frequency.](image)

5.3. Dispersion compensation

In a commonly used dispersion compensation method, a waveguide section with a different birefringence is inserted in the center of the array [10]. The section compensates for the polarization dispersion that occurs when propagating through the whole array. When polarization rotation occurs within the array, the required amount of dispersion compensation will be less. A single compensation section in the center of the array can therefore never both remove the PR-sidelobe and make the AWG polarization insensitive. The simulation result, shown in Fig. 7(a), confirms this. Another dispersion compensation method, described in [11], applies two compensation sections. The sections are positioned before and after the curved waveguides. The polarization rotated light now propagates through only one compensation section. Mixed polarized light at the input of the AWG propagates through both compensation sections. The amount of dispersion compensation is therefore different in the two cases. Figure 7(b) shows the result of a simulation, including polarization rotation, of such a dispersion compensated AWG. It can be seen that there is a PR-sidelobe, but its position is now the same as the main transmission lobe. This means that though the sidelobe exists, it does not have a negative influence on the AWG response.
5.4. Order matching

The response of an AWG is periodic, with every transmission peak being separated by one free spectral range. In the order matching approach, explained in [12], the free spectral range of the AWG is matched to the frequency shift between the TE and TM transmission peaks after propagating over the full length of the array. As mentioned in section 3, the observed frequency shift between the main transmission peak and the PR-sidelobe is less than that of the main TE and TM transmission peaks. The order matching method therefore cannot both eliminate the PR-sidelobe and make the AWG polarization insensitive at the same time.

5.5. Polarization splitter

In the polarization splitter approach, TE and TM polarized input light are launched from different positions in the input star coupler. The displacement between the two positions matches the frequency shift due to polarization dispersion. The spectral response of both polarizations thereby becomes the same. Launching from a different position can only be done if both polarizations can be separated at the input of the AWG, which cannot be done for polarization rotated light in the array.

6. Conclusion

It was shown through simulation and through measurements that polarization rotation in the curved waveguides of an AWG may cause a sidelobe in the response of the device, provided that the device is polarization sensitive. AWGs using the same curved waveguides in every arm seem particularly sensitive to this effect. Several methods exist for making AWGs polarization insensitive. The half-wave plate, order matching, and input polarization splitting methods will not remove the PR-sidelobe. When using certain variants of the dispersion compensation method, the PR-sidelobe is shifted to the same position as the main transmission lobe, cancelling negative effects. Reducing the amount of polarization rotation in the device will lower the PR-sidelobe level. The amount of polarization rotation can be reduced by choosing the length of the curves such that they become full-wave plates. For the discussed AWG layout and
layer stack, this would require a bend radius of 194\(\mu\)m. In practice, the best way to avoid a PR-
sidelobe may be to choose a different layout of the AWG, specifically a layout using different
bends in different array arms.

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