

# Increasing tolerance in passive integrated optical polarization converters

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# Increasing Tolerance in passive integrated optical Polarization Converters

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**Abstract**— Integration of optical functions promises to be an important new technology, with applications in telecom, datacom, sensing, etc. Controlling the polarization in integrated circuits is needed to fully benefit from the use of light. Integrated polarization converters are required for this, but devices proposed so far have suffered from tight fabrication tolerances. It is shown here what the root of this intolerance is, and how critical fabrication errors can be compensated in a two-section polarization converter. The new device leads to doubling of the fabrication tolerances and wavelength range, and promises conversion efficiencies above 99% over a wide range of fabrication and operation parameters.

**Index Terms**— Indium Phosphide, fabrication tolerance photonic integration, polarization converter.

## I. INTRODUCTION

Polarization handling in photonics integrated circuits (PICs) is important for polarization independent operation of the chips, as well as for functionalities like polarization multiplexing and polarization switching. The central device for polarization handling is a polarization converter (or rotator). Preferably this should be a short and low-loss passive component, which can be realized within the standard fabrication of a PIC. A number of proposals have been made for polarization converters, mostly on InP-based materials [1-8] and on Silicon-on-insulator (SOI, [9-13]). The most promising of these seem to be the sloped sidewall devices. These converters operate as an integrated optical analogue of a half-wave plate. The tolerances to obtain an acceptable level of conversion are however relatively narrow; e.g. in [8] it is found that width deviations should be kept below 50 nm for a conversion efficiency above 95%. Similar tolerances can be found in [13] for a SOI sloped sidewall polarization converter.

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In this paper the origin of the relative intolerance of the polarization converter designs is investigated. It is found that the difficulty lies in maintaining the polarization angle of the modes close enough to the optimal  $45^\circ$  condition. A new converter structure will be introduced, which corrects for possible errors in this angle. Consequently the new polarization converter structure is more tolerant to fabrication errors, but also to ambient conditions and wavelength deviation. The tolerant converter makes use of two sections with sloped interfaces, whose cross sections are mirror images. The new device is doubled in length with respect to a single section device.

## II. PRINCIPLE OF OPERATION

Polarization conversion can be obtained with a narrow waveguide having one slanted interface (fig.1). In the converter which will be used as an example in the subsequent treatment, the tilted modes are not obtained with a sloped sidewall, but with a triangular top cladding. This has certain advantages in the realization of the device [14], as will be discussed below. Due to the electromagnetic boundary conditions the slanted interface rotates the polarization of the modes. With a careful design the rotation will be  $45^\circ$ . In that case a TE mode from a symmetric input waveguide equally excites the two rotated orthogonal modes. These modes propagate with different propagation constants  $\beta_1$  and  $\beta_2$ . After half of the beat length ( $L_{\lambda/2} = \pi / |\beta_1 - \beta_2|$ ) the rotated modes recombine to a TM mode in a symmetric output waveguide.

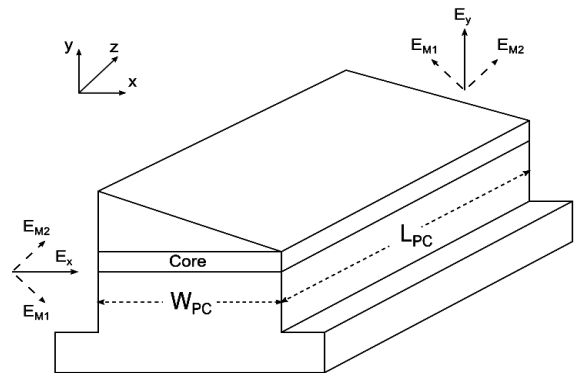


Fig. 1. Structure of the example polarization converter.

In this way full conversion between TE and TM is possible. Since the device is reciprocal, a full conversion from TM to TE can be obtained in the same way.

The operation of a polarization converter can be represented on the Poincaré sphere [16]. Every possible state of polarization (SOP) is described by a point on the surface of this sphere (fig.2). The two intersections with the x-axis are the TE and the TM points, the intersections with the z-axis are left-handed and right-handed circular polarizations, and the intersection with the y-axis are oppositely 45° tilted linear polarizations.

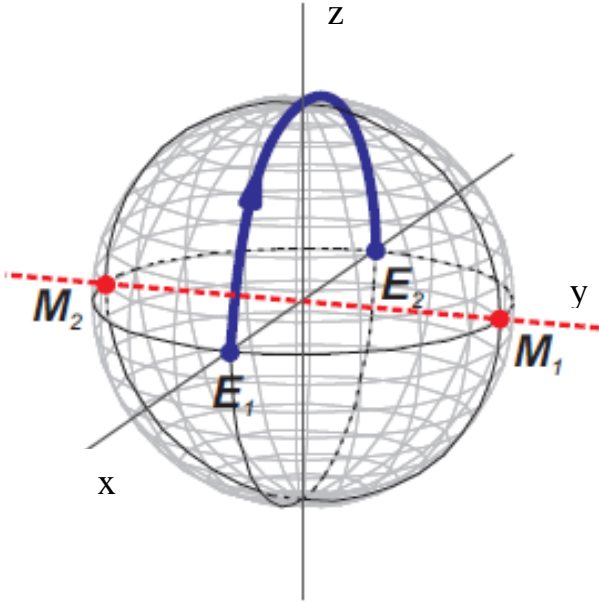


Fig. 2. The operation of a polarization converter depicted on the Poincaré sphere.  $M_1$  and  $M_2$  refer to the tilted modes.  $E_1$  and  $E_2$  refer to the start polarization state (in this case TE) and the target polarization state (TM), respectively.

The polarization conversion from TE to TM consists of a rotation of  $\pi$  rad around an axis through the two stable polarization states in the converter section (which are ideally the oppositely 45° tilted linear polarizations). The rotation angle is the phase shift between the two modes in the converter.

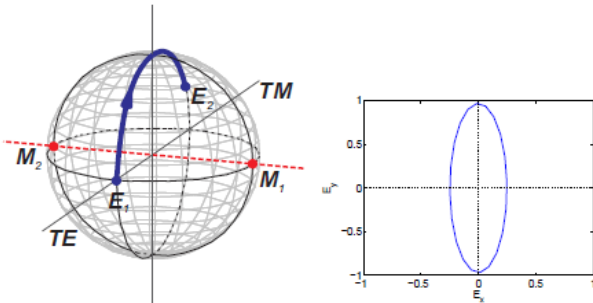


Fig. 3. The operation of a polarization converter if the phase shift  $\varphi$  is different from  $\pi$  rad.

For a deviation of a realized polarization converter from the optimal design two different errors can occur. The first is that the rotation (i.e., the phase shift) is different from the required  $\pi$  rad. This is shown in fig.3. The result is an elliptical SOP. The second possible error is that the tilting angle of the modes is different from 45°. In that case the final SOP is linear, (fig. 4, note that the linear polarization states are all on the equator of the Poincaré sphere), but it is rotated with respect to the TM polarization. Of course, in practice these two errors will appear together when the realized device deviates in some way from the design.

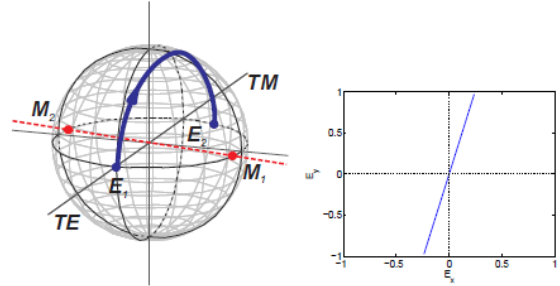


Fig. 4. The operation of a polarization converter if the tilting angle  $\Theta$  is different from  $\pi/4$  rad.

### III. THEORY

The conversion efficiency  $C$  of a polarization converter is given by the following formula[17]:

$$C = P_{Converted} / P_{Total} = 2[\cos(\theta)\sin(\theta)]^2 \{1 - \cos(\varphi)\} \quad (1)$$

In which  $\theta$  is the tilting angle of the modes and  $\varphi$  is the phase shift between them ( $\varphi=L(\beta_1-\beta_2)$ , with  $L$  the length of the slanted section and  $\beta_{1,2}$  the propagation constants). Clearly, for a perfect converter  $\Theta=\pi/4$  and  $\varphi=\pi$ . If deviations  $\Delta\Theta$  and  $\Delta\varphi$  occur with respect to these values, due to fabrication errors, changes in operational conditions or differences in material parameters, the change  $\Delta C$  in conversion is approximated by:

$$\Delta C = -4(\Delta\theta)^2 - 0.25(\Delta\varphi)^2 \quad (2)$$

(This is obtained with a Taylor series expansion. Since the first and third order expansion terms are zero, eq. 2 is correct up to the fourth order.)

This suggests that the effect of errors in the tilting angle is more important than those in the phase shift. This will depend however on the actual value of the deviations. It will be shown in the next section, with simulations and general argumentation, that indeed the tilting angle deviation is dominant in reducing the conversion efficiency.

### IV. SIMULATIONS

The polarization converter is investigated with the structure depicted in fig. 1. As will be discussed below, the results

obtained for this converter are representative for all sloped sidewall polarization converters as well.

The first important issue is the relative impact of the two possible deviations; the error on the tilt angle  $\Delta\Theta$  and the error on the phase shift  $\Delta\phi$ . Previous work [15,17] has shown that the width of the converter section seems to be the most critical parameter. Hence the modes in the polarization converter section are analysed as a function of the width deviation  $\Delta W_{PC}$  with a FMM-mode solver [18].  $\Delta\Theta$  and  $\Delta\phi$  versus  $\Delta W_{PC}$  are shown in fig.5.

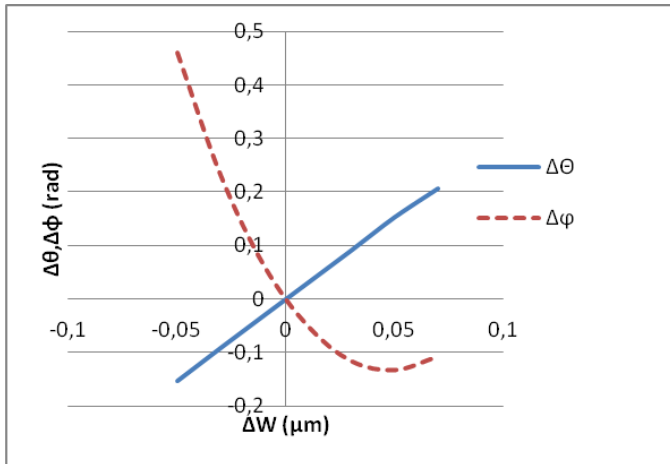


Fig.5. Dependence of the error in the tilt angle,  $\Delta\Theta$ , and the error in the phase shift,  $\Delta\phi$ , as a function of width deviation  $\Delta W_{PC}$ .

A linear dependence of  $\Delta\Theta$  with  $\Delta W_{PC}$  is found. The phase shift  $\Delta\phi$  however has a quadratic dependence, leading to a minimum close to the design point for  $W_{PC}$ . As a consequence, for large negative values of  $\Delta W_{PC}$ , i.e., when the converter waveguide is much smaller than designed, we can expect that  $\Delta\phi$  would become the dominant error (if  $\Delta\phi$  is larger than 4 times  $\Delta\Theta$ , according to eq. 2). However in the region close to  $\Delta W_{PC}=0$ , and for positive  $\Delta W_{PC}$  values, the tilting error clearly dominates.

This raises the question if a minimum in the  $\Delta\phi$ -curve close to the design width is a general property of sloped sidewall polarization converters. Simulations on other designs [15] show similar behaviour, thus confirming the generality. This can be understood by considering the mechanism behind the tilting of the modes. The polarization of the modes is determined by the electromagnetic boundary conditions at the material interfaces of a waveguide cross section. Since most of these are either horizontal or vertical, TE- and TM-like modes are generally found. In the polarization converters the interface that is placed under an angle induces the tilting of the modes. To obtain the desired  $45^\circ$  tilting angle, despite the presence of the horizontal and vertical interfaces, hybridization of the TE and TM modes is needed. Such hybrid modes require that the propagation constants of the modes are close together, which is therefore a necessary condition for a sloped sidewall polarization converter. Since the phase shift between the modes is proportional to the difference in the propagation constants, this implies that a minimum in the phase shift will

be found close to the optimal design of any sloped sidewall polarization converter

Figure 6 shows the effect of the two errors on the simulated conversion.

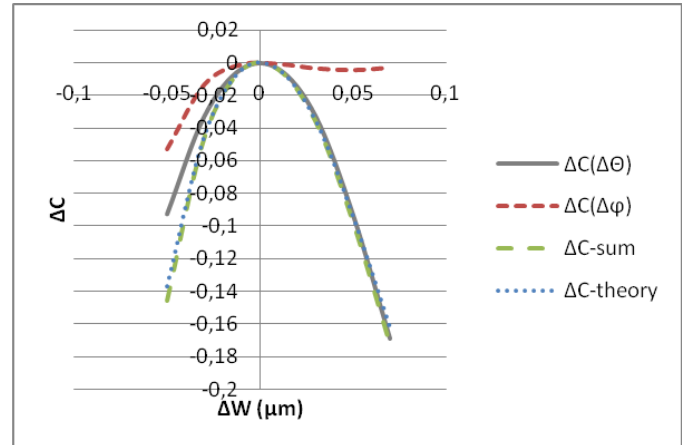


Fig. 6. Change in conversion efficiency  $\Delta C$  as a function of width deviation  $\Delta W_{PC}$ , from contributions of the error on the tilt angle  $\Delta\Theta$  ( $\Delta C(\Delta\Theta)$ ), the error on the phase shift  $\Delta\phi$  ( $\Delta C(\Delta\phi)$ ) and their sum ( $\Delta C$ -sum), as compared with the theoretical values ( $\Delta C$ -theory, according to eq. 2).

The theoretical result and added error contributions are very close together; underlining the validity of the analysis in section 3 (i.e., higher order terms in the Taylor expansion indeed have a small influence for these values of  $\Delta W_{PC}$ ). The contribution of the phase shift error  $\Delta\phi$  is negligible, except for widths which are more than 30 nm smaller. Over the whole investigated width range however the tilt angle error is dominant.

## V. IMPROVING TOLERANCES

The analysis above indicates that to improve the tolerance of the polarization converter a correction to the error in the tilting angle  $\Theta$  in particular must be made. It can be done by adding an extra section to the polarization converter, which corrects the tilting angle error. With the diagram in fig.7 this is illustrated. The diagram shows a top view of the Poincaré sphere, with the polarization conversions indicated by the axes (indicated with red dotted lines) around which the rotation of the SOP takes place, and the rotation trajectories (which show up as blue straight and dotted lines perpendicular to the rotation axes in this projection). Here we will use the conversion from TE to TM as an example. Since these devices are reciprocal, the conclusions will also hold for the reverse conversion (TM to TE). If we allow the rotation to go halfway, i.e. around  $\pi/2$  rad, the error in the tilting angle can be compensated with a rotation around an axis which is mirrored in the TE-TM axis. This second rotation would be on a circle that crosses the TM-point. To achieve this a second converter section is needed, in which the tilting angle is  $-\Theta$ , so the modes there are oppositely tilted. Exactly such a relation is obtained for two polarization converter sections which have mirrored cross-sections, as is illustrated in fig.8.

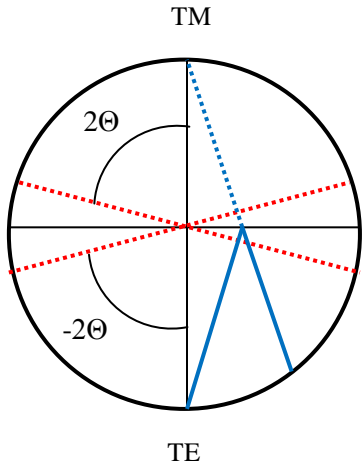


Fig. 7. Projection on the equator plane of the Poincaré sphere. Red lines indicate the rotation axes, blue lines the rotation trajectories.

In practical realizations it will be rather straight forward to obtain a mirrored cross section, as both sections will be simultaneously realized in the same material. Any deviation in width and material composition can therefore be the same in both (but of course this depends on the processing chosen, e.g. if the width of the two sections is defined in the same lithographic step, as is the case is [15,17]). However, because of the mirroring the second section will give a rotation of the SOP over the surface of the Poincaré sphere in the opposite direction, which means that a rotation angle of  $3\pi/2$  rad is required to reach the TM-point. The tolerant polarization converter thus consists of two sections of different length; one has a length  $L_{\lambda/4} = \pi/2(\beta_1 - \beta_2)$ , while the other has a length which is thrice as long:  $L_{3\lambda/4} = 3\pi/2(\beta_1 - \beta_2)$ . The total length of a device is therefore twice the length of a single section device. Fig. 9 shows the total path of the SOP on the Poincaré sphere upon propagation through a device consisting of two mirrored sections with lengths adjusted to the required phase shifts. Fig. 10 shows the schematic structure of the two-section polarization converter.

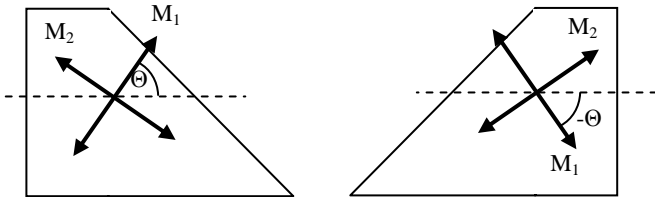


Fig.8. A mirrored cross section polarization converter leads to tilting angles of the modes with reversed sign. Note that the polarized modes  $M_1$  and  $M_2$  are always orthogonal.

Intuitively, one can view the increased tolerance of the two section polarization converter as follows. Ideally, in each of the two sections the tilting angle is  $45^\circ$ . Both section contribute equally to the polarization conversion (because the long mirrored section, with  $-3\pi/2$  phase shift between the modes, can be considered as having a  $\pi/2$  phase shift, so equal in magnitude to the phase shift in the short section). Thus, as any error on the tilt angle will be opposite in both sections, on average the tilt angle of  $45^\circ$  will be maintained in the full device.

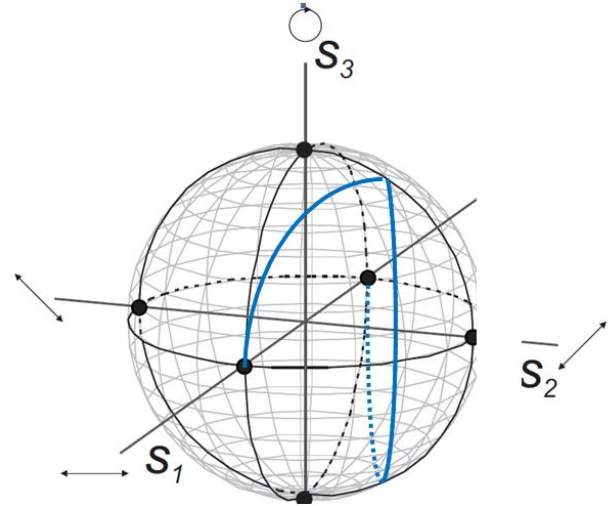


Fig.9. Trajectory of the SOP for conversion of TE to TM on the Poincaré sphere for the two section tolerant polarization converter. The dotted trajectory is at the backside of the sphere.

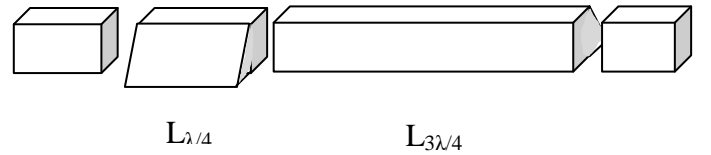


Fig.10. The construction of a tolerant polarization converter. For clarity some space is left between the different sections, which in reality will not be there. Input and output waveguides, as well as the two mirrored converter sections, are shown.

For the tolerant polarization converter, consisting of two sections, the conversion efficiency can be derived as:

$$\begin{aligned}
 C = & [\sin^6(\theta) \cos^2(\theta) + \sin^2(\theta) \cos^6(\theta)] \\
 & \cdot \{6 + 4\cos(\frac{\varphi}{2}) - 4\cos(\frac{3\varphi}{2}) + 2\cos(2\varphi)\} \\
 & + \sin^4(\theta) \cos^4(\theta) \\
 & \cdot \{-4 - 8\cos(\frac{\varphi}{2}) - 8\cos(\varphi) - 4\cos(2\varphi) + 8\cos(\frac{3\varphi}{2})\}. \quad (3)
 \end{aligned}$$

Again, for an optimal converter  $\Theta = \pi/4$  and  $\varphi = \pi$ . Performing a similar Taylor series expansion as before we can arrive at the change in C:

$$\Delta C = -0.25(\varphi)^2 \quad (4)$$

Which indeed shows that the error in  $\Theta$  is compensated for up to the fourth order, while only the error in  $\varphi$  remains. The dependence of the conversion efficiency as a function of  $\Theta$  (assuming a negligible error in  $\varphi$ ) can be plotted (from eqs. 1 and 3) for the original and for the tolerant version of the polarization converter (fig. 11):

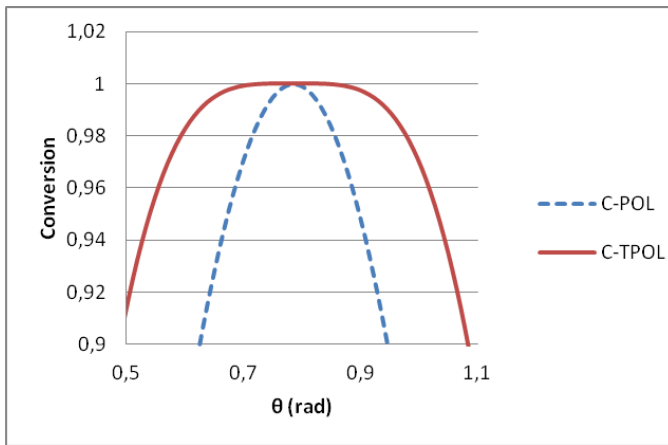


Fig.11. Conversion efficiency as a function of the tilting angle  $\Theta$  when the phase shift angle is  $\pi$  radians, for the single section (C-POL) and the two-section (C-TPOL) device.

These curves reveal the origin of the tolerant behaviour: for the two section device a plateau appears around the optimal value, indicating that the error in tilting angle can be compensated for relatively large deviations.

In order to investigate the tolerance of the new two-section device, we simulate the effect of width deviations on the conversion of the device introduced in fig.1. Before we do that, it is relevant to describe the fabrication of this example device, to show that it is indeed feasible to create mirrored sections.

The processing can be done as follows: The top cladding has a thickness which corresponds to the height of the top of the PC slopes. First, the sample is covered with silicon nitride. Two rectangular areas are etched in this nitride layer using an EBL-defined masking pattern. Inside these rectangles an HCl-etch creates the sloped top claddings, starting from the sides. The rectangles can have an arbitrary width, whilst the length defines the length of each section of the polarization converter. They are positioned with respect to each other, so that the opposite PC slopes are aligned. We deposit a new silicon nitride layer and then carefully dry etch it. Since the etch rate is lower on the slope than on a horizontal surface, by controlling the etching time we can remove the nitride except for a thin layer on top of the slope. (The silicon nitride is however maintained as an etching mask at the positions of the input and output waveguides to the converter, these being defined in a separate EBL-step.) The nitride layer on the slope acts as a mask, thus the PC straight sidewalls can be dry etched using an ICP or an RIE etch. In this way a two section polarization converter is obtained with mirrored cross-sections.

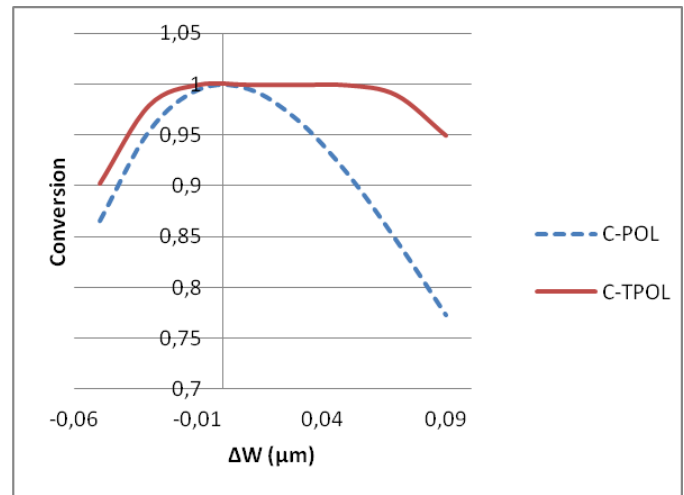


Fig.12. Dependence of conversion efficiency  $C$  as a function of width deviation  $\Delta W_{PC}$ . C-POL refers to a single section polarization converter, C-TPOL to the tolerant two section device.

Fig.12 shows the conversion for both a single and a two section polarization converter. It is seen that for the two section device a plateau appears, indicating that there is a wide width range for which a very high conversion can be obtained. If a width range of 100 nm is considered, the single section device would have a conversion above 90%, but the two section device would show a conversion  $>99\%$  for this range. For some applications [19] a 95% conversion efficiency is needed; the figure shows that in that case the width tolerance of the two-section polarization converter is doubled with respect to the single section converter.

The tolerance region is especially extended to the positive side, i.e. for wider converters, while for narrower converters the improvement is less. The reason for this becomes clear from fig.6. For narrower converters the error in phase angle  $\phi$  comes into play. As the tolerance improvement depends on compensating the tilting angle error  $\Delta\Theta$ , the region where  $\Delta\phi$  has no influence (for wider converters) shows the best behaviour. The designer can make use of this by designing the width of the two section polarization converter a bit larger, in order to aim for the middle of the plateau.

The performance of the polarization converters is also determined by other fabrication errors, such as deviations in material composition and layer thicknesses, as well as by deviations in the operational conditions assumed in the design. The ideas explained above can be used to improve tolerance in those parameters as well. This is illustrated with the core layer composition and the wavelength dependence of the single section and the two section devices in figs. 13 and 14, respectively.



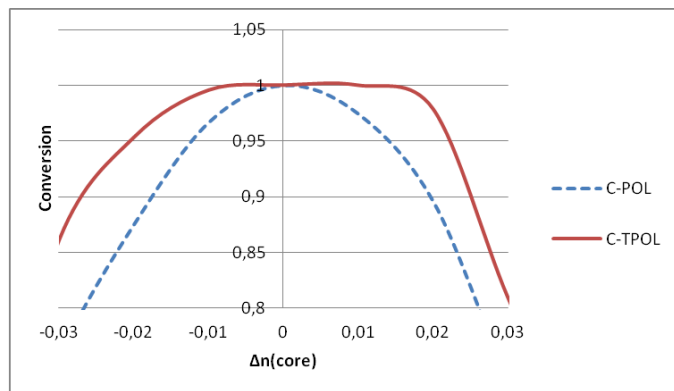


Fig. 13. Dependence of the converter on refractive index deviations of the core layer, for the single and the two section devices. C-POL refers to the single section polarization converter, C-TPOL to the tolerant two section device.

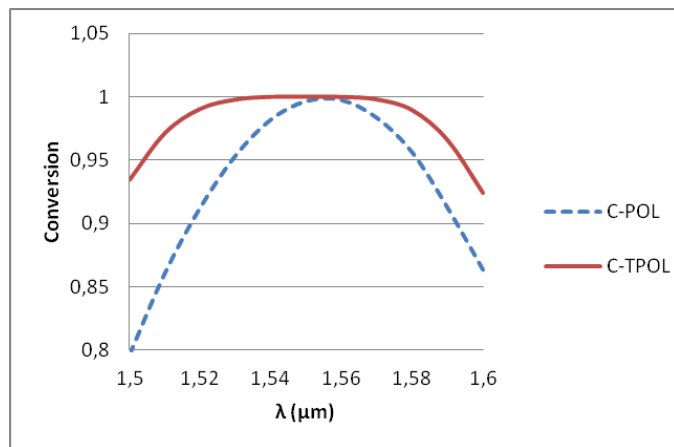


Fig. 14. Wavelength dependence of the single and the two section devices. C-POL refers to the single section polarization converter, C-TPOL to the tolerant two section device.

Also in these cases for the two section polarization converter a plateau is obtained, indicating that here too the error in the tilting angle is corrected. Both the core layer refractive index deviation and the wavelength range for conversion  $>95\%$  are almost doubled with respect to a single section device. For the important C-band the original polarization converter gives  $>95\%$  conversion, but the new tolerant device promises  $>99\%$ . This indicates that the performance of the converter improves dramatically, supporting applications in which polarization purity is important, like polarization multiplexing or polarization switching.

The coupling losses between the different sections are acceptable; the total simulated device loss is 0.5 dB.

## VI. CONCLUSIONS

The major origin of the limited tolerances in the fabrication of single section sloped side polarization converters is identified to be the difficulty in maintaining a  $45^\circ$  tilting angle for the modes in the converter waveguide. A new polarization converter is proposed to correct for deviations in this angle. It is a two section device, in which the two sections have modes with opposite tilting angles. The two sections are mirrored with respect to each other. This should be easily achievable in fabrication. The new two-section device shows a doubled width tolerance and wavelength range for more than 95%

conversion, and promises significantly higher conversion efficiencies. The tolerant polarization converter has twice the length of the one-section device, and includes one extra waveguide junction. The junction losses in these devices can be kept low ( $<1$  dB) with an optimized design ([5], [17]).

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