# Low-loss adiabatic bend using minimised chip area

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**For the increasing complexity of integrated optical structures, there is a need of bends, which occupy a chip area as small as possible. The best results with respect to loss can be obtained by adiabatic bends with decreasing radius and variable waveguide width. Detailed simulations using 2D bend (mode) solver and adiabatic conformally-mapped 2D-BPM have been carried out in order to achieve a minimal size. Comparison is made with other approaches like standard bends with offsets.**

## Introduction

Since the demands on functionality of integrated-optic components for optical communication are growing, compactness of the devices, e.g. add-drop multiplexers, is a major concern. This compactness is determined mostly by the minimum bend radius that can be realised for low-loss optical channel waveguides. The aim is to design a bend, which has low loss and small dimensions. In this paper we concentrate on a rectangular waveguide structure having low polarisation dependence. This waveguide is fabricated using PECVD technology [1, 2]. Although the specific numerical results reported in this paper relate to this particular structure, the method used is valid for arbitrary waveguides. It is difficult to use an approximation to calculate the bend loss because of the high index contrast and buried channel waveguide (BCW) structure [3]. The Marcatilli and EIM approximation were used but failed. Therefore, we calculated the bend loss using a numerical bend mode solver [4], while varying two parameters, the channel width and bend radius. From a technological point of view these parameters can easily be varied.

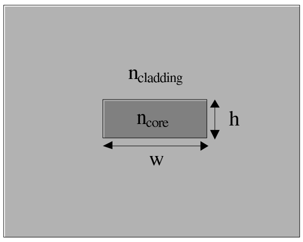

*Figure 1: Buried cannel waveguide structure.*

## Adiabatic bend

When a bent waveguide is connected to a straight waveguide two loss mechanisms occur. The first is the intrinsic radiation loss of the bend mode, which is called Pure Bend Loss (PB-loss). The second is transition loss (TL-loss) due to mismatch between the modes of the straight and the bend, the latter being shifted outwards and changed in shape. The modal shift can be compensated by an offset between channel and bend, but a change in mode profile shape cannot. Fig. 2 shows the 2D bend mode calculation result of the PB-loss of a 360-degree bend for different radii and channel widths. The PB-loss not only depends on the radius but also on the width. The PB-loss increases with both decreasing bend radius and decreasing channel width. The upper left region in Fig. 2 where the contour lines tend to run vertically is characteristic for the whispering gallery mode (WGM) regime, where a further increase of the width has no effect on the PB-loss.

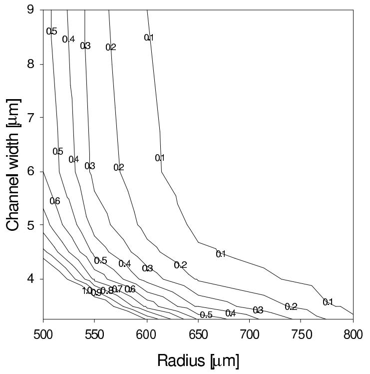

*Figure 2: Contour graph of the Pure bend loss as function of radius and waveguide width. The values at the contour lines are dB values*

This simulation result is the starting-point for designing an adiabatic bend. The assumption of the bend being adiabatic implies that the modal solution at a certain position in the bend is independent of the solution at any other position, so that the total bend loss can be calculated by simply integrating local losses. The bend starts with a large radius having a low transition loss. The bend radius decreases slowly during propagation in the bend until a minimum is reached. The simplest way to decrease the radius is linear as function of the arc length (or angle). A better way is the use of a function which has a large negative slope at large radii and low slope at small radii. A possible function is shown below (1) and a solution is shown in fig. 3. Here $R_{start}$ is the radius of the bend at the beginning of the bend. $R_{min}$ is the minimal radius and $A_{bend}$ is the rate of decrease of the radius. If the speed is too high the bend is not adiabatic anymore. If the decrease is too slow the bend size will be too large. $l$ is the arc length of the bend.

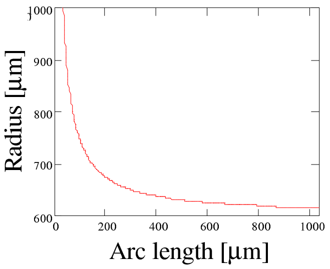

*Figure 3: Radius (mm) of the bend as function of the arc length. $R_{min}$ is 600 mm, $R_{start}$ is 3000 mm and rate of radius decrease $A_{bend}$ is 0.04*

$$R(l) = R_{min} \cdot e^{\frac{l}{ln\left(\frac{R_{start}}{R_{min}}\right)+A_{bend}\cdot l}} \tag{1}$$

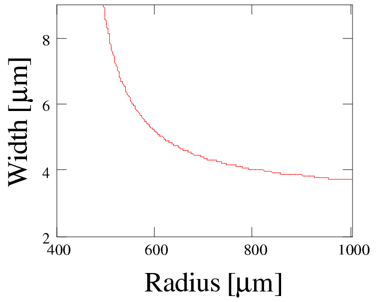

*Figure 4: Waveguide width (mm) as function of the radius of the bend (mm).*

Simultaneously with decreasing the radius, the channel width will be enlarged. Fig. 2 shows that widening the waveguide at constant radius results in lower loss. The function given in eqn. (2) approximates the contour lines of fig. 2 and a solution is shown in fig. 4. In this function $R_{start}$ is the radius of the bend at the starting point of the bend. $R_{tapmin}$ is the radius at which the width becomes infinite large. $A_{taper}$ is a constant that gives the rate of widening of the waveguide. $W_{wg}$ is the width of the straight waveguide. At the beginning of the bend the width is equal to $W_{wg}$.

$$W(R(l)) = W_{wg} \cdot e^{\frac{1}{A_{taper}\left(R(l)-R_{tapmin}\right)}} \cdot e^{\left(\frac{1}{A_{taper}\left(R_{tap\,min}-R_{start}\right)}\right)} \tag{2}$$

Further analysis is done on a 180-degree bend, which consists of two cascaded adiabatic 90-degree bends. So from 0 to 90 degrees the radius decreases and the waveguide widens, from 90 to 180 the opposite happens. Waveguide loss has not been taken into account because it depends on the quality of the fabrication process. As a measure for the size of a bend we take the surface area of a rectangle tightly enclosing the bend.

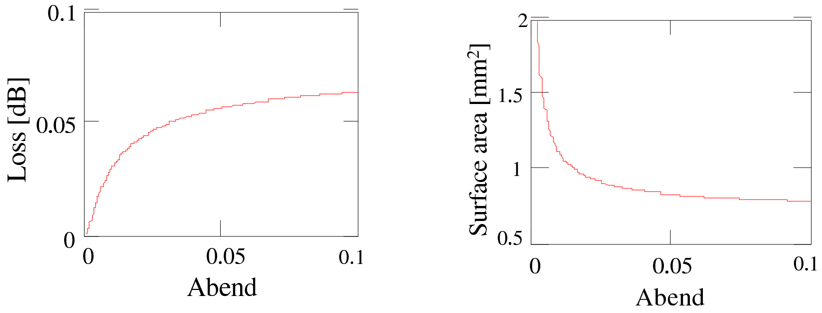

*Figure 5: (a) Loss of 180-degree bend versus the rate of radius decrease $A_{bend}$ and (b) Surface area of 180-degree bend versus $A_{bend}$. $R_{min}$ is 600, $R_{start}$ is 3000, $W_{wg}$ is 3.25, $A_{taper}$ is 0.01 and $R_{tapmin}$ is 400.*

Figure 5a shows the loss of the adiabatic bend (in dB) as function of the parameter $A_{bend}$. When $A_{bend}$ is large (fast decay of radius) the loss will be the loss of a bend having radius $R_{min}$ (0.6 mm) which is 0.06 dB. But then the transition will not be adiabatic anymore and transition loss will occur. When $A_{bend}$ is close to zero, the loss is equal to loss $R_{start}$ (3 mm) that is almost zero. When we now look at the surface area (fig. 5b) of the bend as function of $A_{bend}$ we see that for large $A_{bend}$ (fast decay of radius) the surface is very small (equal to surface of bend with radius $R_{min}$). For small $A_{bend}$ the surface is large (equal to surface of bend with radius $R_{start}$). So $A_{bend}$ must be small for low loss and large for small size. A good compromise is $A_{bend}$ is 0.04.

## Comparison

In Table 1 the loss and size of different types of bends are compared. Type 1 and 2 are bends with constant radius (600 and 652 μm) connected to the straight channel without a shift, having a total loss (PB-loss + 2*TL-loss) of 0.76 and 0.47 dB respectively. Adding an optimal shift between bend and straight decreases the total loss (type 3, 4). However these two bends still suffer from the high PB-loss. Increasing the waveguide width lowers the bend loss but increases the transition loss due to modal shape mismatch between the straight and bend mode (type 5, 6). Type 7 is the adiabatic bend, which has the lowest total loss (0.054 dB).

*Table 1: Loss and size of different types of 180-degree bends.*

| Type | Offset | Radius (µm) | Bend width (µm) | Transition loss (dB) | Pure Bend loss (dB) | Total loss (dB) | Surface (mm$^2$) |
|---|---|---|---|---|---|---|---|
| 1 | no | 600 | 3.25 | 0.13 | 0.50 | 0.76 | 0.72 |
| 2 | no | 652 | 3.25 | 0.097 | 0.28 | 0.47 | 0.85 |
| 3 | yes | 600 | 3.25 | 0.06 | 0.50 | 0.62 | 0.72 |
| 4 | yes | 652 | 3.25 | 0.037 | 0.28 | 0.35 | 0.85 |
| 5 | yes | 600 | 6 | 0.19 | 0.06 | 0.44 | 0.72 |
| 6 | yes | 652 | 6 | 0.20 | 0.026 | 0.43 | 0.85 |
| 7 | - | variable | variable | - | - | 0.054 | 0.85 |

# Validity

Fig. 6 shows the conformally-mapped index structure [5] of the first half of the 180-degree bend and the BPM-simulation results [4]. The loss, thus calculated for this first half is 0.047 dB and the total 180-degree bend loss is 0.094 dB which is higher than expected (0.054 dB). This deviation can have two causes: the bend is not adiabatic or the EIM used to do the 2D-BPM simulation gives the wrong core index.

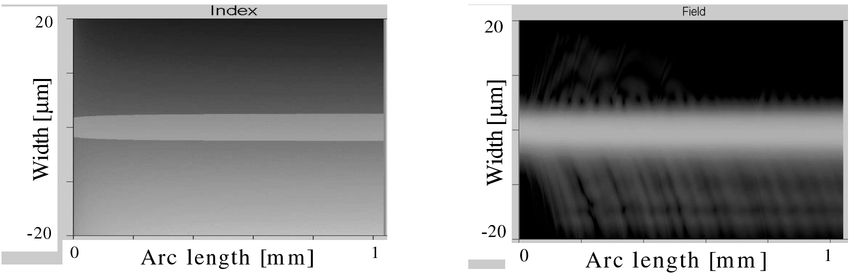

*Figure 6: (a) Conformally-mapped waveguide structure (the refractive index is indicated as a greyscale value); (b) 2D-BPM simulation result*

## Conclusion

An adiabatic bend having low loss and small size has been designed and optimised. The estimated loss for a 180 degree bend is 0.054 dB which is much less than a non-optimised bend 0.57 dB and the surface area is 0.85 mm$^2$. The 2D-BPM simulation gives a small deviation of the loss compared to the model.

## Acknowledgement

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## References

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