Mode Overlap Simulations for Quantification of Bend Loss in Silicon Nitride Strip Waveguides for Sensing

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Bent waveguides are not just essential for the connection of functional building blocks in photonic integrated circuits (PIC), but can be used to increase the sensitive area of a sensor based on optical waveguides. The bend loss of the investigated silicon nitride strip waveguides without top oxide cladding is about 2-4 times lower than with cladding. Such waveguide bends can be used for environmental or bio sensor PIC designs with increased sensitivity.
Keywords: *Silicon nitride, waveguide, bend, mode simulation, photonic sensors*

INTRODUCTION

Bent and straight waveguides are an important photonic element for connecting functional building blocks in a photonic integrated circuit (PIC). Unlike electrical connections with 90° corners, light cannot be transmitted in this Manhattan routing style. The radius of such bent connectors plays an important role in terms of losses. In addition, the loss for bent strip waveguides depends on essential parameters such as height and width. Another important function of waveguide bends can be found in many sensor applications. Silicon nitride strip waveguides are commonly covered with a top oxide cladding in order to prevent interference with the surrounding environment. In case of a sensor, this very interaction with the environment is the basis for most sensor effects and therefore the top cladding is removed within a dedicated area. The sensitivity of such photonic sensors is dependent on the interaction length with the analytes. Bent waveguides are used to increase the sensitive surface within the cladding-free area and exploit it as much as possible. For example, bent waveguides have been used in previous work to increase the interaction probability of a particle detector based on optical waveguides [1]. However, the total number of bends that can be integrated in a PIC is limited by the loss introduced by the bends. Besides roughness induced propagation loss along the bend, a major source of bend loss is mode mismatch between the straight and bent part of the waveguide [2][3]. Numeric simulations were carried out for 250 nm thick silicon nitride strip waveguides with and without top oxide cladding in order to determine the mode profiles and calculate the corresponding overlap for several bend radii and waveguide widths. The simulation results are compared with comprehensive measurements of dedicated test structures fabricated with a PECVD silicon nitride technology presented in previous work [4].

METHODS

We investigated the bend loss of silicon nitride strip waveguides with a height of 250 nm and widths from 450 nm to 750 nm for bend radii from 10 µm to 35 µm at a wavelength of 850 nm and TE polarization. The propagation loss of these waveguides was demonstrated previously to be as low as 1 dB/cm for the case with and 2-4 dB/cm without top oxide cladding [5]. Due to the short path length of the investigated waveguide bends and these low losses, propagation loss could be neglected. Lumerical MODE was used to compute the modal fields of the straight and the bent waveguide and an overlap integral was calculated to quantify the modal mismatch (cf. Figure 1).

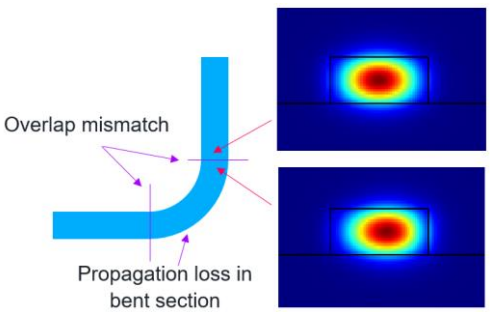

Figure 1: Sketch depicting loss sources of waveguides bends including mode overlap mismatch and propagation loss and two exemplary mode profiles.

Dedicated test structures were designed to compare the bend loss simulations with measurements. In order to compensate for the propagation loss of the entire test structure, a concept with spirals of identical total length but different bend radii was chosen. All measurements are referred to a spiral where the bend radius is such that the mode mismatch and thus the bend loss are negligible. Preliminary measurements have shown that a radius of 70 µm leads to negligible bend loss and can therefore be used as a reference. The losses of all other spirals refer to this reference spiral with the same waveguide width. Thus, it is a relative measurement, which provides good reproducibility as long as the coupled laser power remains constant during the measurement of a group of test spirals. Figure 2 shows an exemplary test structure for the bend loss measurement of one radius and one waveguide width. Grating couplers were implemented on each test structure to couple a power meter and a diode laser providing TE-polarized light at 850 nm wavelength. A dedicated set of spirals is required for each waveguide width with one spiral for each radius of interest.

Figure 2: Layout of an exemplary test structure for the measurement of bend loss on a test wafer with the reference spiral implemented on the right.

The total loss per spiral is defined by the number of bends and matches with the dynamic range of the applied power meter. The bend loss for a 90° bend BL is derived for each waveguide width with the following formula

$$\mathrm{BL} = \frac{P_x}{P_0 n_{bends}} \tag{1}$$

containing the transmitted power P_x of each spiral with bend radius x, normalized to the transmitted power of its corresponding reference spiral P_0 and divided by the number of 90° bends n_{bends}. An automatic wafer prober system was used to measure all dies on two test wafers, which lead to about 100 measurement values for each test structure.

RESULTS

Measurements for four different waveguide widths and eight different radii per width were performed and compared with the simulation in Lumerical MODE. Figure 3(a) and 3(b) show the result for a 90° silicon nitride strip waveguide bend with and without top oxide cladding, respectively, together with the corresponding waveguide cross section.

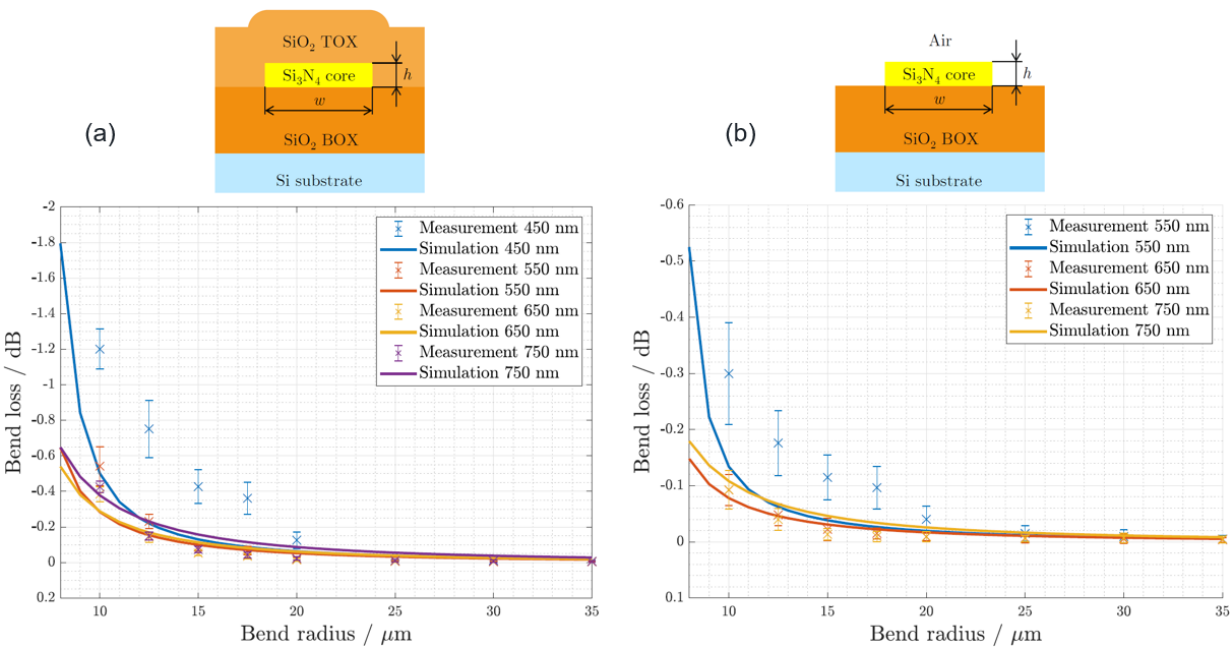

Figure 3: Measurement and simulation results of the loss of 250 nm thick strip waveguides (a) with and (b) without top oxide cladding (cross section on top) for a 90° bend at 850 nm wavelength dependent on bend radius for four and three waveguide widths w, respectively.

There are no results for the 450 nm wide waveguide without top oxide cladding, since there are no propagation modes in the bend. The trend of measurement and simulation is comparable and shows an increase of the bend loss at smaller bend radii up to -1.2 dB and -0.3 dB for a 90° bend with and without top oxide cladding, respectively.

DISCUSSION

The simulation results for the narrowest waveguide widths (450 nm with and 550 nm without top oxide) are significantly lower than the measured values. Presumably, for very small bend radii, the propagation loss along the waveguide bend is much larger than for the straight waveguide and is not negligible, because the mode field is pushed closer to the sidewall where it is scattered more by the rough surface. However, since the typical roughness size parameter is in the order of a few nanometers it is very difficult to take it into account in the simulation and will be explored in a future publication, currently in preparation. Hence, modal mismatch simulations are not suitable for very narrow waveguides close to the lower cut-off of the propagation condition.

Figure 3 shows another very interesting phenomenon for both configurations with and without top oxide cladding. Apparently, there is an optimum waveguide width, which provides the lowest bend loss. This is also confirmed by the measurements, although the difference is within the measurement uncertainty. Obviously, wider waveguides are more susceptible regarding mode field displacement, which correspondingly increases modal mismatch and bend loss.

A comparison between the two waveguide configurations shows that the bend loss for the waveguide without top oxide cladding is about 2-4 times lower than with top oxide cladding, which is also confirmed by the simulation. This is remarkable because, the propagation loss is about 2-3 times greater compared to the waveguide with top oxide [5]. Supposedly, the lack of the top oxide cladding is beneficial in terms of mode overlap and therefore reduces the bend loss significantly. This may be caused by the higher index contrast of the waveguide without top oxide cladding, which confines the modes in the bend region more to the silicon nitride waveguide core and reduces therefore the mode mismatch. These findings are very valuable for optimized designs of environmental or bio sensors based on optical waveguides with a large sensitive area and low limits of detection (LOD).

References

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