

High confinement in silicon slot waveguides with sharp bends

P. Andrew Anderson, Bradley S. Schmidt and Michal Lipson

School of Electrical and Computer Engineering
Cornell University, Ithaca, NY 14853
lipson@ece.cornell.edu

Abstract: Slot waveguides allow for high optical confinement in a planar optical waveguide. Here we show a method for maintaining this high degree of confinement in slot waveguides with sharp bends. This high confinement can be achieved by using an asymmetric slot-based structure, where the mode in the bend remains localized in the slot region. We show that the relative power inside the slot can be as high as 28% for a 1 μm radius bend in an air-clad silicon waveguide.

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1. Introduction

Silicon waveguides provide a platform for highly integrated optical systems [1,2]. The high-refractive-index contrast in these systems allows for a high degree of confinement, therefore resulting in compact structures with extremely sharp bending radii. These include devices such as power splitters [3], couplers [4], bends [5], microcavities [6], and ring resonators [7-8]. While the high-refractive-index contrast of a silicon-based photonics platform provides high confinement of the optical field, there are still uses within the same platform for many materials with low indices of refraction, especially materials with either non-linear, electroluminescent, or photoluminescent properties [9].

Recently a silicon slot waveguide structure was demonstrated [10] that allows for a large portion of the optical mode to propagate through a low index region of the waveguide. It is not clear if these structures enable the same degree of high confinement for small bending radii, necessary for high-density integration on-chip [11]. This can become an important consideration for designing compact devices based on slot waveguides, such as recently demonstrated microring resonators [12], modulators [13,14], and polarizers [15], and directional couplers [16]. In this work we examine the effect on the performance of slot waveguides within sharp bends.

2. Slot waveguide principle of operation

The slot waveguide structure is based on a low-refractive-index sub- μm slot (such as air or SiO_2) formed between two silicon waveguides [10]. The principle of operation of this structure is based on the discontinuity of the electric field at the high-index-contrast interface. For an electromagnetic wave propagating in the z direction as shown in Fig. 1, the electric field component of the quasi-TE mode (which is aligned in the x direction) undergoes a discontinuity that is proportional to the square of the ratio between the refractive indices of the silicon and the low-refractive-index slot.

This discontinuity is such that the field is much more intense in the low-refractive-index slot region than in the silicon waveguides. Given that the width of the slot is comparable to the decay length of the field, the electrical field remains high across the slot, resulting in a power density in the slot that is much higher than that in the silicon regions. The percentage of power transmitted in a sub-100 nm wide slot can be higher than 40% of the total guided power [10]. The evanescent tails of the electromagnetic fields that are propagating in the silicon waveguides overlap in the central slot, which leads to a strong light confinement in the low index region. The net effect is a stronger intensity in the slot relative to the intensity in the silicon regions. As shown experimentally using these structures, light can be confined in low index regions as small as 50 nm in width [17]. The high confinement modes in the slot region

are part of the true eigenmodes of the waveguide and are therefore theoretically lossless assuming that there are no scattering points along the structures.

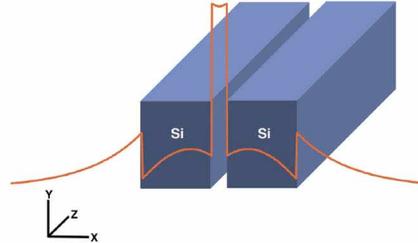


Fig. 1. The relative magnitude of the electric field quasi-TE mode along the x direction across the center of the waveguide. The waveguide is silicon and the slot and the surrounding cladding is air. The light propagates in the z direction.

Since the mechanism of confinement relies on a mode construction between two adjacent high index waveguide modes, it is not immediately apparent if the strong confinement in the slot is maintained in sharp bends where the modes in each high index waveguide differ strongly. Here we show a mechanism for maintaining the strong light confinement in the slot in structures with sharp bends. Such high confinement is achieved by using an asymmetric slot-based structure which has the slot placed at the region where the maximum overlap between the two evanescent tails of the high-refractive-index waveguide modes occurs.

3. Numerical calculations of slot waveguide modes

In order to analyze the effect of the bend on the degree of localization in the slot region, we analyze the mode distribution in the structure for several slot positions in the waveguide. Simulations were performed using a custom complex modesolver and verified using 3-D FDTD simulations performed with a commercial FDTD simulation package [18]. The FDTD simulations were performed to verify that the mode profile matched the mode determined by the modesolver, while the modesolver was used to determine the propagation losses in the bends. The modesolver is 2-D Finite-Difference based and Full-vectorial. This method solves an eigenvalue problem for the propagation constant using the method of cylindrical perfectly matched layers [19]. The bend is simulated without any approximations or indirect methods beyond the restrictions of the simulation grid. Fig. 2(a) shows a schematic of the cross section of a slot waveguide with the slot placed at the center of the waveguide. Fig. 2(b) shows a similar schematic with the slot shifted in the direction away from the bend. The slot position x is defined as the distance (in nm) from the center of the waveguide to the center of the slot. A negative slot position refers to a slot placed towards the inside of the bend in the waveguide and a positive position refers to a slot placed towards the outside of the bend. The overall waveguide is assumed to be 450 nm wide and 250 nm tall, with a 50 nm wide slot. The complex mode solver uses variable grid spacing with a spacing of 5 nm within the region that includes the entire waveguide. This grid size was selected to decrease computational time based on a less than 0.03 difference in the percentage of power in the slot for the maximum difference when compared with grid sizes as small as 2 nm. The waveguide core has a refractive index of $n = 3.48$ and the refractive index of the cladding on all sides and within the slot is $n = 1.0$. Simulations assume a wavelength of $\lambda = 1550$ nm. As the method solves the eigenmode within the bend itself, losses due to transitions from straight to bent slot-

waveguides [20-21] are not considered here. All simulations shown here are for the quasi-TE polarization.

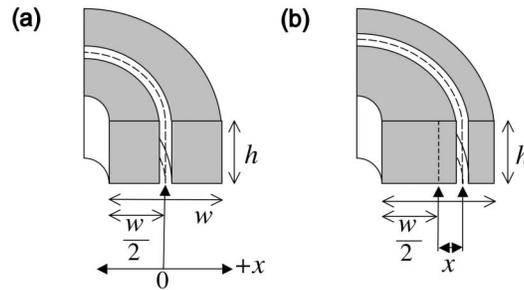


Fig. 2. The waveguide structure with dimensions $h = 250$ nm and $w = 450$ nm. (a) The slot is centered in the waveguide and (b) the waveguide slot is offset by x . The positive x direction is towards the outside of the bend.

The effect of placing the slot in an asymmetric position relative to the waveguide on the degree of power confinement is strong. Fig. 3 shows the normalized magnitude of the square of the electric field distribution ($|E^2|$) over the cross-section of several slot waveguides. When the slot is centered and the waveguide is straight, light is highly confined in the slot (a). The field in the slot is greatly diminished when traveling around a tight bend (b). Shifting the slot towards the outside of the bend reduces the loss due to the bend and restores the power in the slot (c). This is because shifting the slot ensures that the slot is placed at the region where the maximum overlap between the two evanescent tails of the high index waveguide modes occurs for the quasi-TE polarization.

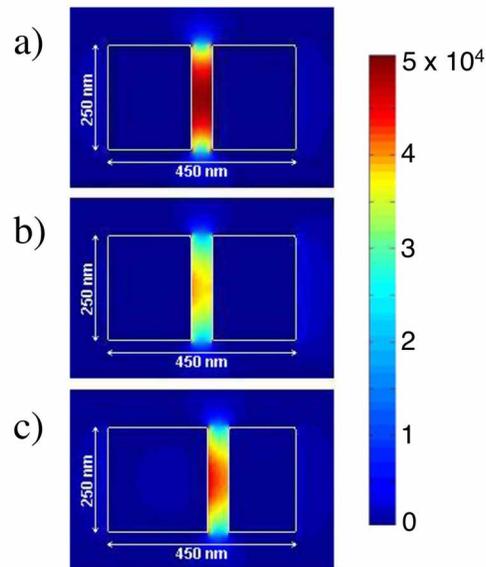


Fig. 3. $|E^2|$ distribution over the cross section of slot waveguides. (a) When the slot is centered and there is no bend, (b) a 1 micron radius bend with a centered slot, and (c) the same 1 micron radius bend with the slot moved by 40 nm towards the outside of the bend.

4. Analysis of the power in slot waveguide bends

The plot in Fig. 4 shows the power inside the slot relative to the total guided power in the waveguide for various bending radii and slot positions. When the slot is centered, the percentage of power in the slot for a straight waveguide is 32.68%. For sharper bends, the power inside a slot that is centered drops for smaller radius bends. For a bend with a radius of 1 micron, this power drops to 23.40%. One can see, however, that by placing the slot towards the outer periphery of the bend, a higher power inside the slot can be obtained; for a radius of 1 micron, 28.12% of the power remains inside the slot, comparable to the power achieved in a slot waveguide that is straight.

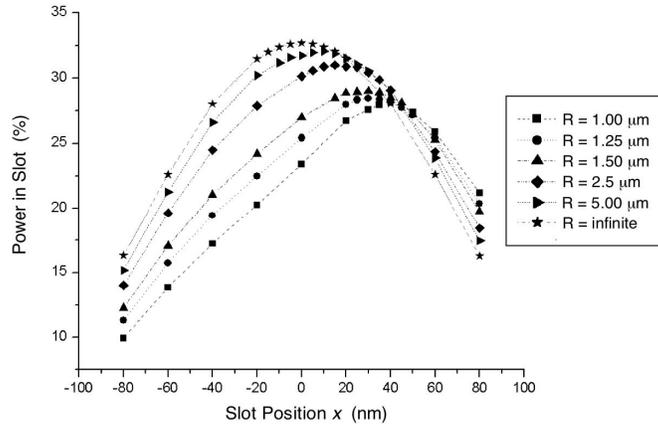


Fig. 4. The relative power in the slot for different slot positions and bending radii.

5. Analysis of bending loss reduction in slot waveguides

Displacing the slot region from the center of the waveguide not only maximizes the power inside the slot, but also reduces the bending losses in the structure. This is due to the increased confinement in the slot. The losses for various bending radii and slot positions are shown in Fig. 5. When the slot is centered in the waveguide, losses in the structure for sharp bends are relatively high, for example, 1.96 dB for a 1 micron radius 90-degree bend. One can see however that these losses drop for a slot placed away from the center of the waveguide. For example a total loss of only 1.23 dB can be achieved for a 90-degree bend with a 1 micron radius in a slot that is placed 30 nm away from the center, the position that maximizes the percentage of power within the slot. The losses of an optimized slot waveguide structure are approximately half of those of a single mode low-refractive-index silica waveguide which has a similar effective index ($n \approx 1.45$), while delivering a much higher peak intensity of at least an order of magnitude larger than in the silica waveguide [22]. Such a low-index-material single mode waveguide would have losses as high as 2.3 dB per 90-degree bend, with low peak intensity in the core.

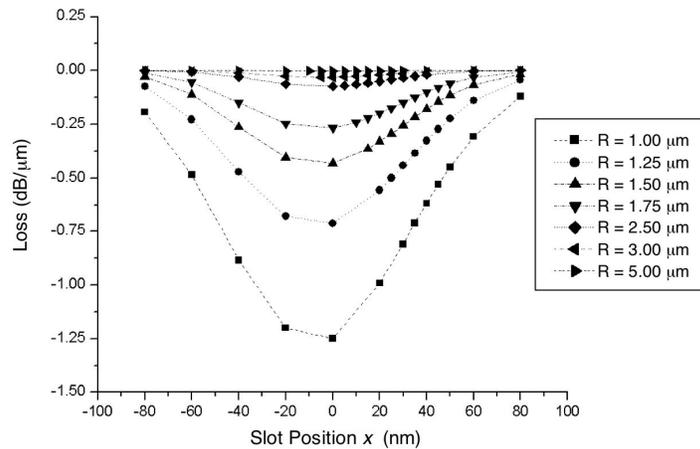


Fig. 5. Slot wave-guide losses due to bending for different slot positions and bending radii.

6. Conclusions

In conclusion we analyze the degree of confinement in slot waveguides with sharp bends. We show that high confinement can be achieved in waveguides with slots embedded asymmetrically relative to the center of the waveguides. Such high confinement in waveguides with bends enables the formation of novel photonic structures based on slot waveguides such as ring resonators, splitters, directional couplers, and demultiplexers, which rely on high field intensities for non-linear effects and are critical for high-density integration on-chip.

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