Light confinement in a 90° double high mesa slot bend waveguide

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Abstract. In this work, we propose a technique to enhance the confinement of light at 90° sharp bend of a double high mesa slot (DHMS) waveguide based on Silicon on Insulator (SOI). These waveguides deliver high electric field and optical power density in low refractive index Nano-metric slot. The slot is displaced to the inner and outer periphery of the bend and explores the deviation in the relative power. The maximum relative power is attained by shifting the slot towards the outer periphery of the bend. This is only conceivable by choosing the precise slot position where the two evanescent tails of the high index waveguide modes have maximum overlap.

1. Introduction

Slot-waveguide is a light guiding structure that has a property to boost the optical field in a Nano-metric scale void of low refractive index material inserted between higher refractive index material rails. Considering a high index-contrast interface, Maxwell’s equations suggest that in order to fulfil the continuity of the normal component of electric flux density D, the correspondent electric field (E-field) has to undergo a large discontinuity with much higher amplitude in the low–index side[1, 2]. Usually, slot waveguides are fabricated from high refractive index inorganic dielectrics or semiconductors such as silicon or silicon nitride [3, 4, 5]. These waveguides are capable of operating in the near-infrared (NIR) wavelength region. In recent years, a number of structures have been suggested to guide the light in low-index materials [6, 7, 8, 9, 10, 11, 12, 13]. Their mechanism relies on the external reflections provided by interference effects. Contrary to total internal reflection in case of conventional waveguides [14, 15, 16], the external reflection cannot be perfect unity. Consequently, the modes in these structures are intrinsically leaky modes. Besides, interferences are involved which make these structures strongly wavelength dependent.

In [17], DHMS waveguide is proposed for optical absorption sensing. In our paper, we presented a scheme to enhance the confinement of light in a 90°-bend DHMS waveguide based on SOI. These waveguides are attractive because it provides a high electric field and optical power densities in low refractive index nano-metric slot. The electric field propagating in the slot goes through an interruption at the high refractive index contrast interface which makes the electromagnetic (EM) wave to confine intensely in the slot than in the SiO₂-Si-SiO₂ rail [18,19,20]. The schematic and an E-field profile of the DHMS waveguide is shown in figure 1. Two single high mesa waveguides are separated by the slot region forming a DHMS waveguide. The waveguide core is sandwiched between
SiO$_2$ cladding. The waveguide core and cladding (upper and lower) has a refractive index of $n=3.4$ and 1.4 respectively. Simulations assume a wavelength of $\lambda=1.52 \, \mu$m. All simulations shown here are for the TE-polarization.

![Figure 1](image)

**Figure 1.** 2-D DHMS waveguide. a) The electric field (Ex) distribution of the fundamental TE mode, b) Normalized E-field profile.

To enhance the confinement of light in a DHMS waveguide we propose an asymmetric waveguide design. In our design, the core, lower and upper cladding height is fixed at 200 and 300 nm, respectively. The total width of the structure is fixed at 650 nm, where the gap is constant at 50 nm in all the simulations. The slot was displaced towards and away from the bend by keeping the total width of the waveguide constant and observes the deviation in the field power as shown in figure 2.

![Figure 2](image)

**Figure 2.** The DHMS waveguide structure with total width fixed at, $W=650$ nm. The slot is fixed at $G=50$ nm. a) The slot is placed in the centre of the waveguide b) The slot is shifted by “$x$” towards the outer periphery of the bend. c) The slot is shifted by “$x$” towards the inner periphery of the bend. In (a), (b) and (c), the total width of the waveguide is maintained.

Figure 2 a) represents the symmetric DHMS waveguide where the slot is placed in the centre of the waveguide. Figure 2 b) and c) represents the displacement of a slot towards the outer and inner periphery of the bend, respectively. Maximum light confinement is obtained when the two evanescent tails of the high refractive index waveguide modes have maximum overlap in the slot region. Simulations are performed by using Comsol Multiphysics software which solves the Helmholtz equation with the finite element method (FEM).

2. Study of normalized E-field versus slot displacements

The influence of slot displacement in a 90°-bend DHMS waveguide on E-field confinement is quite evident. The normalized E-field distribution over the output cross-section of numerous slot waveguides is presented in figure 3. Figure 3a) shows the E-field distribution at the cross-section of
the waveguide. The field in the slot is significantly reduced when travelling around a tight bend. Moving the slot towards the outer periphery of the bend reduces the losses due to the bend and re-establishes the power in the slot as shown in figure 3 (b, c, d, e). We have to precisely shift the slot at the region where the maximum overlap between the two evanescent tails of the high index waveguide modes occurs for the TE-polarization. Shifting the slot towards inner periphery of the bend has no substantial role in the enhancement of the E-field in the slot region as can be seen from figure 3 (f, g, h, i).

Figure 3. Normalized E-field distribution at the output of the double high mesa slot waveguides with 0.975 µm bend radius. a) Symmetric configuration. When the slot is shifted b) 10 nm away from the bend, c) 20 nm away from the bend, d) 30 nm away from the bend, e) 40 nm away from the bend, f) 10 nm towards the bend, g) 20 nm towards the bend, h) 30 nm towards the bend, i) 40 nm towards the bend.

3. Study of the relative power in the slot at various slot positions
The phenomenon of light confinement in a 90°-bend DHMS waveguide due to the asymmetric geometry is presented in this section. We calculated the power in the slot region relative to the total power of the waveguide for numerous slot positions. The relative power in the slot of a symmetric waveguide with 90°-bend is measured at 48.3 % as shown in figure 4. When the slot displaces towards the outer periphery of the bend, the percentage of power in the slot increases. For instance, the maximum relative power of 59.1 % is obtained at 40 nm of slot displacement. However, further displacement of the slot can increase the power in the cladding region as compared to the slot which drops the relative power in the slot. Furthermore, the slot displacement towards the inner periphery of the bend doesn’t boost the confinement of light in the slot.
4. Calculation of bending losses in a DHMS waveguide with 0.975 µm radius of curvature
By moving the slot from the centre of the waveguide not only maximizes the E-field inside the slot but also diminishes the bending losses in the structure due to the improved confinement of light in the slot. The bending losses for various slot displacements are plotted in figure 5.

As it can be seen from the figure that in case of symmetric waveguide structure (slot is placed in the centre), the losses are quite high, for instance, 1.98 dB for 0.975 µm radius 90° bend. The losses tend to reduce as the slot shifts toward or away from the bend but there is a finite limit to displace the slot. However, the minimum losses of 0.31 dB were obtained at 20 nm slot displacement towards the outer periphery of the bend but as we keep moving the slot in the same direction, the losses increase again. This happens due to the maximum overlap of the two evanescent tails of the high index waveguide in the left cladding region. Moreover, the bending losses can be cut by displacing the slot towards the bend but the impact is not so high as compared to the slot displacement towards the outer periphery of the bend.

5. Conclusion
In this work, we investigate the degree of confinement of light in a double high mesa slot waveguide with 90° bend. An asymmetric design of the waveguide is proposed by shifting the slot towards or away from the centre. This allows the maximum light confinement due to the overlap of two
evanescent tails of the high refractive index waveguide modes in the slot region. As a result bending losses are reduced from 1.98 dB to 0.31 dB for 0.975 µm radius 90° bend by just shifting a slot 20 nm towards the outer periphery of the bend.

6. References

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