Asymmetric double high mesa slot waveguide to enhance the light confinement in a 90° sharp bend

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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.

Keywords: Double high mesa slot waveguide, 90 degrees bend, Silicon, Silicon dioxide, 1.52 microns.

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. Usually, slot waveguides are fabricated from high refractive index inorganic dielectrics or semiconductors such as silicon or silicon nitride [1, 2, 3,4]. 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 [5, 6, 7, 8]. Their mechanism relies on the external reflections provided by interference effects. Contrary to total internal reflection in case of conventional waveguides [9, 10,11], 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 [12], 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 SiO_2-Si-SiO_2 rail. 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 are performed by using Comsol Multiphysics software which solves the Helmholtz equation with the finite element method (FEM). Waveguides are modelled for the wavelength of λ= 1.52 µm. All simulations are performed for the TE polarization because these waveguides are highly polarization dependent and can guide light in TE polarization only.

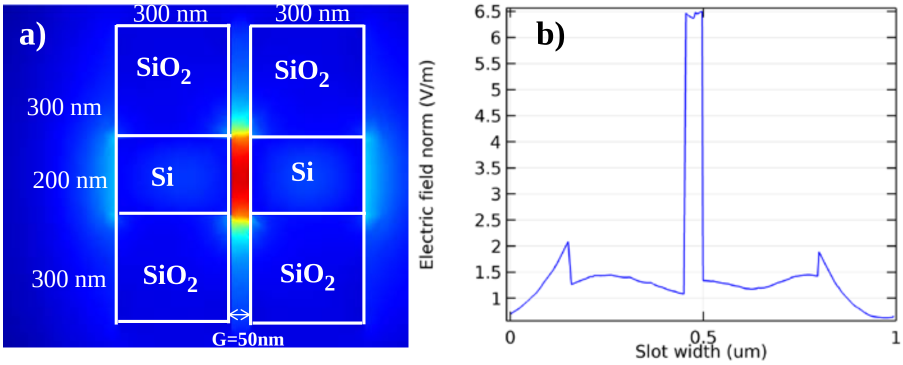

Figure 1. 2-D DHMS waveguide. a) The electric field (Ex) distribution of the fundamental TE mode, b) Normalized E-field profile.

2. Study of normalized E-field versus slot displacements

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 the inner and outer periphery of the bend by keeping the total width of the waveguide constant and observes the deviation in the field power. Maximum light confinement is obtained when the two evanescent tails of the high refractive index waveguide modes have maximum overlap in the slot region. The influence of slot displacement in a 90^o-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 2.

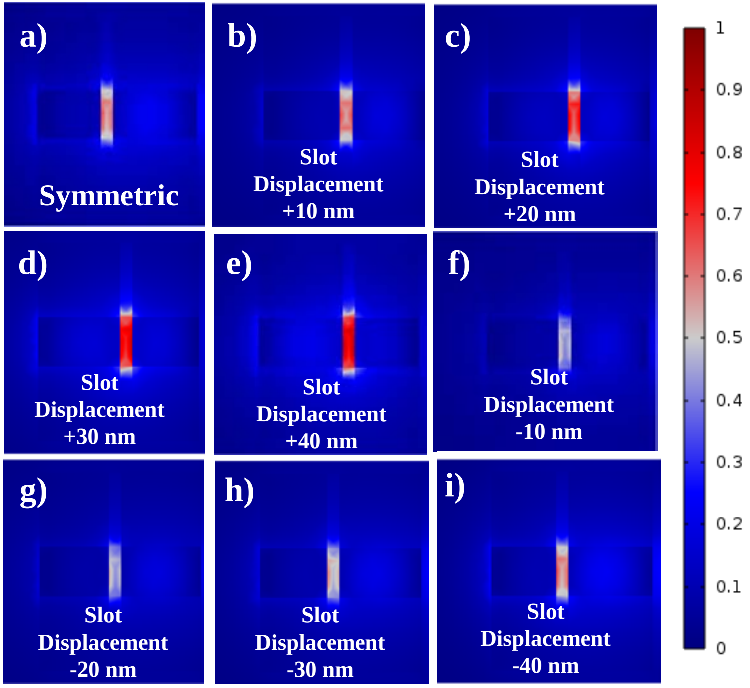

Figure 2. Normalized E-field distribution at the output of the double high mesa slot waveguides with 0.975 µm bend radius. a) Symmetric configuration, When the slot is shifted b) 10 nm away from the bend, c) 20 nm away from the bend, d) 30 nm away from the bend, e) 40 nm away from the bend, f) 10 nm towards the bend, g) 20 nm towards the bend, h) 30 nm towards the bend, i) 40 nm towards the bend.

Figure 2 a) 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 2 (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 significant role in the enhancement of the E-field in the slot region as can be seen from figure 2 (f, g, h, i).

3. Study of the relative power in the slot at various slot positions

The phenomenon of light confinement in a 90^o-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^o-bend is measured at 48.3 % as shown in figure 3. When the slot displaces toward the outer periphery of the bend, the percentage of power in the slot is increased. 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.

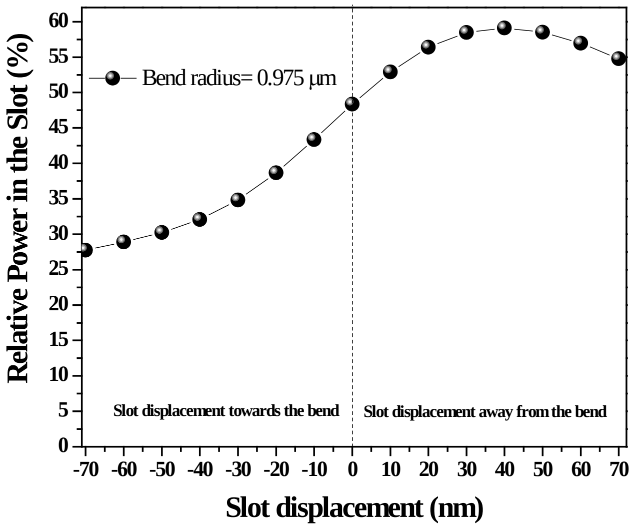

Figure 3. The relative power in the slot for various slot displacements.

4. Conclusion

In this work, we investigated the degree of confinement of light in a DHMS waveguide with 90^o sharp bend. An asymmetric design of the waveguide is proposed by shifting the slot towards the outer periphery of the bend. 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. For instance, the maximum increase of 11 % of relative power in the slot is obtained by shifting the slot at 40 nm from the center.

5. Acknowledgement

This work was supported by the Federal Agency of Scientific Organizations (agreement No 007-ГЗ/Ч3363/26) and Ministry of Education and Science of the Russian Federation and the Russian Foundation for Basic Research (grant No. 16-37-00241 mol_a).

6. References

[1] Xu, Q. Experimental demonstrations of guiding and confining light in nanometer-size low refractive index material / Q Xu, V.R. Almeida, R.R. Panepucci, M. Lipson // Optics Letters. – 2004. – Vol. 29(14). – P. 1626-1628.

[2] Almeida, V.R. Guiding and confining light in void nanostructure/ V.R. Almeida, Q. Xu, C.A. Barrios, M. Lipson // Optics Letters. – 2004. – Vol. 29 (11). – P. 1209-1211.

[3] Barrios, C.A. Demonstration of slot-waveguide structures on silicon nitride/silicon oxide platform / C.A. Barrios, B. Sanchez, K.B. Gylfason, H. Sohlstrom, M. Holgado, R. Casquel // Optics Express. – 2017. – Vol. 15(11). – P. 6836-6856.

[4] Butt, M.A. Silicon on silicon dioxide slot waveguide evanescent field gas absorption sensor / M.A. Butt, S.N. Khonina, N.L. Kazanskiy // Journal of Modern Optics. – 2018. – Vol. 65(2). – P. 174-178. DOI: 10.1080/09500340.2017.1382596.

[5] Saynatjoki, A. Low-loss silicon slot waveguides and couplers fabricated with optical lithography and atomic layer deposition / A. Saynatjoki, L. Karvonen, T. Alasaarela, X. Tu, T.Y. Liow, M. Hiltunen, A. Teronen, G.Q. Lo, S. Honkanen // Optics Express. – 2011. – Vol. 19(27). – P. 26275-26282.

[6] Preston, K. Slot waveguides with polycrystalline silicon for electrical injection / K. Preston, M. Lipson // Optics Express. – 2009. – Vol. 17(3). – P. 1527-1534.

[7] Sun, R. Horizontal single and multiple slot waveguides: optical transmission at λ=1550 nm / R. Sun, P. Dong, N. Feng, C. Hong, J. Michel, M. Lipson, L. Kimerling // Optics Express. – 2007. – Vol. 15(26). – 17967-17972.

[8] Degtyarev, S.A. Modelling of TiO_2 based slot waveguides with high optical confinement in sharp bends / S.A. Degtyarev, M.A. Butt, S.N. Khonina, R.V. Skidanov // International conference on computing, electronic and Electrical Engineering. – 2016. – P. 10-13. DOI: 10.1109/ICECUBE.2016.7495222.

[9] Butt, M.A. Fabrication of Y-splitters and Mach-Zehnder structures on (Yb, Nb): $RbTiOPO_4$/$RbTiOPO_4$ epitaxial layers by reactive ion etching / M.A. Butt, R. Sole, M.C. Pujol, A. Rodenas, G. Lifante, A. Choudhary, G.S. Murugan, D.P. Shepherd, J.S. Wilkinson, M. Aguilo, F. Diaz // J. Lightwave technol. – 2015. – Vol. 33(9). – P. 1863-1871.

[10] Butt, M.A. Channel waveguides and Mach-Zehnder structures on RbTiOPO4 by Cs+ ion exchange / M.A. Butt, M.C. Pujol, R. Sole, A. Rodenas, G. Lifante, J.S.Wilkinson, M. Aguilo, F. Diaz // Optical Materials Express. – 2015. – Vol. 5(5). – P. 1183-1194.

[11] Butt, M.A. An evanescent field absorption gas sensor at mid-IR 3.39 µm wavelength / M.A. Butt, S.A. Degtyarev, S.N. Khonina, N.L. Kazanskiy // Journal of Modern Optics. – 2017. – Vol. 64(18). – P. 1892-1897.

[12] Intekhab, A. Slot waveguide by using Double High-Mesa Structure for Optical absorption sensing / A. Intekhab, K. Hamamoto // Japanese Journal of Applied Physics. – 2010. – Vol. 49(12R). – P. 122503-122511.