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The junction of the straight and bent waveguide with small radiuses

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A model is provided to design the junction of a straight and bent waveguide, in which, a full vectorial finite difference model (FVFD), specifically suited for high index contrast and smaller size waveguides, for example, a waveguide in the silicon-on-insulator (SOI) technology, is used to obtain the electric and magnetic component of the field in a straight or bent waveguide. As a validation, a straight and bent waveguides in SOI technology are simulated using this model, the results show that the connection losses of junctions can be reduced using offsets. Also, experiments are implemented to testify the results, several typical width of SOI waveguides are fabricated to decide the optimum width, the bent losses for a bent waveguide with a radius of 2 μm are about 0.025 dB /90^0 with the optimum width of 450nm. And, the junction of a straight and bent waveguide with a radius of 2 μm are fabricated using 25 nm offset, the connection losses of the SOI waveguide junctions are reduced by about 20 percents, compared with the junctions without offsets.

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1. Introduction

Today's research push toward small, fast photonic circuits depends on the creation of small integrated optical interconnects [1]. The high integration density and low power consumption necessary for such a photonic circuit requires optical devices with smaller dimensions. Hence, the straight and bent waveguide junctions with low connection losses are always desired as the key structure of many optical integrated components [2-6] because of high integration density and low power consumption requirements.

Although there are some models for a straight and bent waveguides junction relied on approximations and simplified assumptions, for a bent waveguide with a radius smaller than 5 μm, the traditional algorithms show a little rough. Hence, in this paper, a model of a straight and bent waveguide junction is presented based on a FVFD method, which is specifically suited for smaller size waveguides. As an example, a junction of the straight and bent SOI waveguide is simulated using this model. Based on the simulation results, experiments are performed to explore the design.

2. The model of a straight and bent waveguide junction

The junction losses are mainly from the scattering losses due to a mismatch between the modal profiles of straight and bent waveguide at junctions when light propagate across the interface.

Hence, in order to reduce the connection losses (scattering losses), we should get a better match between the straight and bent waveguide mode profiles by making laterally offset the straight input waveguide at straight-bent waveguide junctions because the mode in the bent waveguide is located closer to the outer waveguide edge [2, 7].

Actually, the connection losses can be calculated by the relations:

$$\mathrm{loss} = 10\mathrm{Log}10\left(\frac{\iint\left(E_{x,v}(x,y).H^{*}_{y,g}(x,y)\text{-}E_{y,v}(x,y).H^{*}_{x,g}(x,y)\right)dxdy}{\iint\left(E_{x,g}(x,y).H^{*}_{y,v}(x,y)\text{-}E_{y,g}(x,y).H^{*}_{x,v}(x,y)\right)dxdy}\right) \tag{1}$$

where $E_{x,v}$ and E_{yv} are the electric component in the x and y direction of the field in the bent waveguide, $E_{x,g}$ and E_{yg} are the electric component in the x and y direction of the field in the straight waveguide, $H_{x,v}$ and H_{yv} are the magnetic component in x and y direction of the field in the bent waveguide, $H_{x,g}$ and H_{yg} are the magnetic component in the x and y direction of the field in the straight waveguide.

We can calculate the electric and magnetic component in x and y direction of the straight and bent waveguide using a full vectorial finite-difference (FVFD) mode solver [8], which is based on the Maxwell's equation for the complex amplitudes and a time dependence as $\exp(-j\omega t)$ to solve the optical waveguide.

The Maxwell's equation is,

$$\vec{\nabla}\times\vec{E} = j\omega\mu_0\vec{H} \quad \vec{\nabla}\times\vec{H} = -j\omega\varepsilon_0\varepsilon_r\vec{E} \tag{2}$$

After some algebraic manipulation, the Maxwell's equation can be express as a linear system of two differential equations where the x and y components of the electric and magnetic fields are coupled,

$$\begin{cases} \dfrac{\partial}{\partial x}\left(\dfrac{1}{\varepsilon_r}\dfrac{\partial}{\partial x}\left(\varepsilon_r E_x\right)\right)+\dfrac{\partial^2}{\partial y^2}E_x+k_0^2\varepsilon_r E_x+\dfrac{\partial}{\partial x}\left(\dfrac{1}{\varepsilon_r}\dfrac{\partial}{\partial y}\left(\varepsilon_r E_y\right)\right)-\dfrac{\partial^2}{\partial x\partial y}E_y=\beta^2 E_x \\ \dfrac{\partial^2}{\partial x^2}E_y+\dfrac{\partial}{\partial y}\left(\dfrac{1}{\varepsilon_r}\dfrac{\partial}{\partial y}\left(\varepsilon_r E_y\right)\right)+k_0^2\varepsilon_r E_y+\dfrac{\partial}{\partial y}\left(\dfrac{1}{\varepsilon_r}\dfrac{\partial}{\partial x}\left(\varepsilon_r E_x\right)\right)-\dfrac{\partial^2}{\partial x\partial y}E_x=\beta^2 E_y \end{cases} \tag{3}$$

Using the finite difference schemes, Eq. (3) can be express in an eigenvalue matrix form as:

$$\begin{bmatrix} a_{xxE} & a_{xyE} \\ a_{yxE} & a_{yyE} \end{bmatrix}\begin{pmatrix} E_x \\ E_y \end{pmatrix} = \beta^2\begin{pmatrix} E_x \\ E_y \end{pmatrix} \tag{4}$$

where the matrix $\begin{bmatrix} a_{xxE} & a_{xyE} \\ a_{yxE} & a_{yyE} \end{bmatrix}$ is the expressions relatived with the finite difference schemes, $\beta = \dfrac{2\pi}{\lambda}N_o$, λ is free-space optical wavelength.

By solving the eigenvalue matrix Eq. (4), we can obtain the optical field mode profile E_o (E_x, E_y). Then, we calculate the connection losses using Equ. (1). In which, the radius of the curved waveguide is 2 μm, wavelength is 1.55 μm, and the size of the SOI waveguide is 450nm x 220 nm.

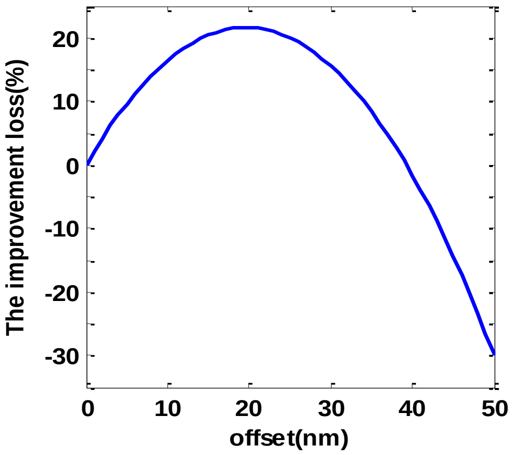

Fig. 1. The connection losses improvement varies with the junction offset between bent and straight waveguide.

Fig. 1 shows the calculated round-trip losses improvements as a function of the offset. The improvement is defined as the percentage change in losses between the connection with offset and without offset. One can observe the maximum improvement of 20 % was obtained theoretically for a junction offset of 25 nm. If the offset is off from 25 nm, the modal mismatch at the junctions worsens, hence, the connection losses become to be larger, and reaches one value where the losses are greater than the losses of the junction without offset.

3. The experimental demonstration of the connection losses reduction for the bent and straight SOI waveguide junction

Based on the above discussion, we design the bent and straight SOI waveguide junction with offset on 200nm CMOS line, also junction without offset as a comparison.

In order to increase the measurement accuracy, we design the measurement setup to test SOI devices shown in Fig. 3. In the measurement setup, light is injected with a tapered fiber in the input port, which will be splitted into two parts using 1x2 MMI by 50:50. One is of the reference waveguide as the normalization of the output port. The other will go to the measured devices. An output tapered fiber linked to an optical spectrum analyzer (Agilent 86140B) is used for the measurement of the output ports.

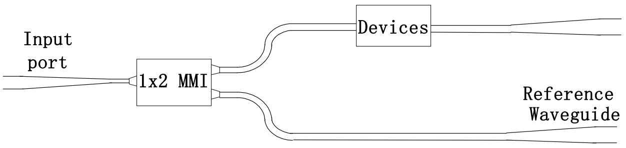

Fig. 2. The measured set-up of SOI devices.

Firstly, in order to design the optimum width of the SOI waveguide, we fabricate the different widths (380 nm, 400 nm, 450 nm, and 500 nm) on SOI technology. The measurement results of the bend losses are shown in Fig. 3, it is obvious that the optimum width of the rings is 450 nm, the bent loss is about 0.025 dB/90^0 for the radius of 2 μm in our measurement.

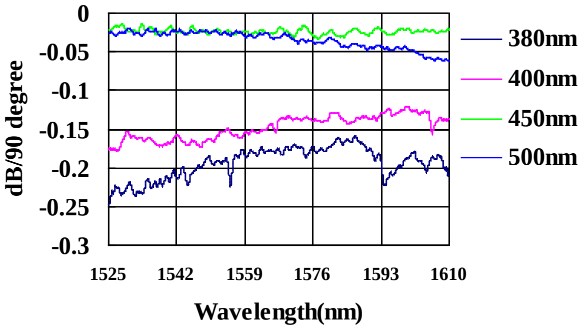

Fig. 3. Measured results of the bent losses for the radius of 2 μm with different widths (380 nm, 400 nm, 450 nm, and 500 nm) on SOI technology.

We fabricate the junction with the junction offset of 25 nm and without the offset as shown in Fig. 4. The measurements are performed for the junction with and without offsets. Fig. 5 plots the reduction loss percents with the offsets, compared the junction without the offsets. The reduction loss is defined as the percentage change in the connection losses between the junction with offset and without offset. It shows that an average reduction of about 20 percents reduction is obtained for a junction offset with 25 nm for wavelength range: 1250-1650 nm. The results show a good agreement with the theoretical results. There is a little bit of fluctuation in the loss lines because we use the high resolution in the optical spectrum analyzer.

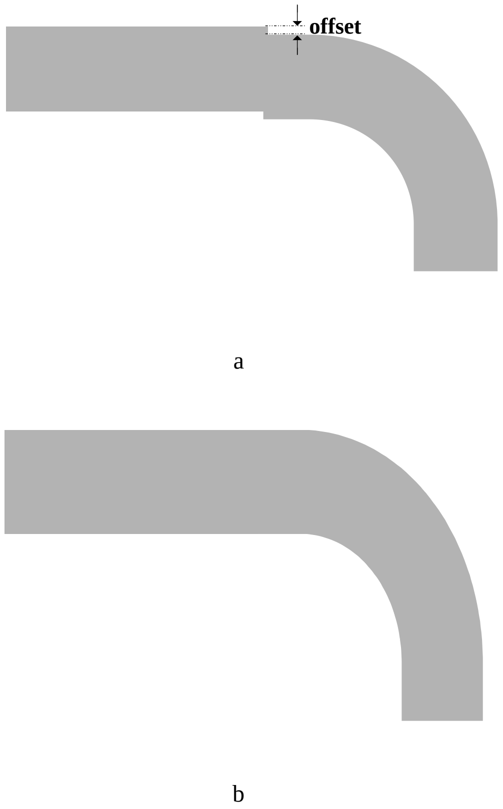

Fig. 4. Bent and straight waveguide junction (a) with offset; (b) without offset.

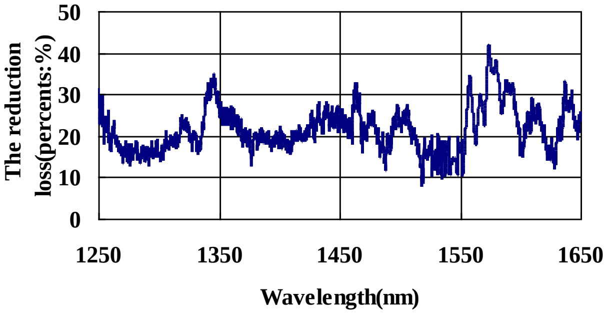

Fig. 5. The reduction junction losses (percents: %) with an offset, compared the junction without an offset.

4. Conclusion

A model of a straight and bent waveguide junction is developed. Using the model, an optimum design of a straight and bent SOI waveguide junction is provided to reduce the connection loss, which shows a reduction of about 20 percents reduction for the straight and bent waveguide junction using 25 nm offset with radii of 2 μm. An experiment is performed to validate the design.

Acknowledgments

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