Right-angle slot waveguide bends with high bending efficiency

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Abstract: Two right-angle bends for nanoscale slot waveguides with high bending efficiency based on a corner mirror and different resonant cavities are presented, one with a triangular cavity and the other with a square cavity. Through two-dimensional parametric scanning of the position of the mirror and the dimension of the cavity, a maximum bending efficiency calculated using mode overlap integral (MOI) of 94.3\% is achieved for the bend with the triangular cavity and 93.1\% is achieved for the bend with the square cavity. Although they both have similar bending performance, the position of the mirror is different between the two cases.

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References and links


1. Introduction

Optical waveguide bends are necessary structures in photonic integrated circuits (PICs) and planar lightwave circuits (PLCs). A few high efficiency microscale waveguide bending structures, including photonic crystal bends [1], circular and right-angle conventional waveguide bends based on resonant cavities and corner mirrors or air trenches, have been intensively researched [2-6]. However, it is not clear if a nanoscale slot waveguide [7], which is composed of two high-index layers and one nanoscale low-index layer in between can be
bent with a high efficiency at a right angle. Slot waveguides achieve high field confinement in the nanoscale low-index layer by taking the advantage of the electric-field discontinuity at the interface between high-index-contrast materials (e.g. silicon/silica) [7]. While it has been demonstrated that the bending efficiency of a circular slot waveguide bend can be improved using asymmetric slot waveguide [8], here we show for the first time two new right-angle slot waveguide bend designs with high bending efficiency based on a corner mirror and a resonant cavity. A symmetric slot waveguide structure is of more interest because a slot waveguide optimized to have highest confinement in the slot is symmetric when the width of the slot is given and when the two high-index layers and the two low-index cladding layers have same refractive index respectively [9].

2. Right angle slot waveguide bends

Figure 1 shows the proposed right-angle symmetric slot waveguide bends with silicon (refractive index \(n_H = 3.48\) at the wavelength \(\lambda = 1550\) nm) for the high-index regions and silica (refractive index \(n_C = n_S = 1.44\)) for the low-index slot and cladding regions. Two identical slot waveguides are laid perpendicular to each other forming a right-angle slot waveguide bend. For convenience purpose, we define the origin \(o\) of the coordinate system in Fig. 1 at the center of the crossing area of the two waveguides’ slot, with the \(x\)-axis horizontal and the \(z\)-axis vertical. At the outer corner of the bending area, a triangular air-trench area with the refractive index of \(n_a = 1\) is formed with its side AB tilted at the angle of 45 degrees with respect to \(z\) axis, serving as the total internal reflection (TIR) mirror. The positioning of the air-trench triangle is represented by the distance between line AB and line CD, which is parallel to line AB and passes the origin, in \(x\) direction, i.e., \(dx\), as shown in Fig. 1. Meanwhile, an isosceles right-angle triangular resonant cavity \(P_1P_2P_3\) and a square resonant cavity \(P_1P_4P_5P_6\) are introduced for two different designs respectively at the inner corner in the bending area, as is for conventional waveguide bends [2, 4]. The length of the sides \(P_1P_2\) and \(P_1P_3\) of the triangle \(P_1P_2P_3\) is \(t\) and the length of the square \(P_1P_2P_5P_6\) is \(s\). The refractive index of both cavities is \(n_H = 3.48\). In the following, we will show the bending efficiency optimization with
respect to the two geometric parameters \([dx, t]\) and \([dx, s]\) respectively. In the optimization, the width of the slot \(w_s\) is set to be 50 nm, for which the width of the high-index layers is optimized at \(w_H = 140\) nm for the light confinement in the slot [9]. The length of the two waveguides, i.e., the distance from the input line to the origin and from the origin to the output line, \(o_1 o\) and \(o_2 o\), are set to be 1.2 um.

The finite-difference time-domain (FDTD) method is used to optimize the bending efficiency of the structure, in which the input is the TM fundamental mode of the slot waveguide. The mesh size of 2.5 nm in both \(x\) and \(z\) direction is used throughout the work. It is known that there are more or less some non-modal parts in the output field of a sharp bending structure, which will radiate off the waveguide and further cause the power to change with propagation for a certain distance. Therefore, a power ratio of the output to the input is not an accurate measurement for comparing the performance of bending structures. Instead, we calculate the bending efficiency using the mode overlap integral (MOI) between the complex output electric field \(E_z(z)\) and the complex input modal electric field \(E_x(x)\), i.e.,

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\text{bending efficiency in MOI} = \left| \int_{-\infty}^{\infty} E_z(x)^* E_x(x) dx \right|^2 / \left| \int_{-\infty}^{\infty} E_z(x) E_x(x) dx \right|^2,
\]

with \(*\) being conjugation [10]. Note that in the above formula, we used \(E_z(x)\) instead of \(E_x(z)\) because only the shapes of the input and output modal field distributions are concerned here in the evaluation of the MOI. As a result, we can change the physical independent variable \(z\) to integration variable \(x\) for the output field \(E_z\). The bending efficiency calculated using MOI does not change with the propagation along the output waveguide. The bending efficiency calculated using MOI method will be simply referred to as bending efficiency in the paper unless otherwise explicitly stated. A two-dimensional parametric scanning of \(dx = [15\ nm, 70\ nm]\) and \(t = [165\ nm, 205\ nm]\) for the bend with the triangular resonant cavity, and a two-dimensional parametric scanning of \(dx = [-20\ nm, 20\ nm]\) and \(s = [150\ nm, 200\ nm]\) for the bend with the square cavity, are performed for the bending efficiency. Figure 2 shows the bending efficiency calculated using different \([dx, t]\)'s for the bend with the triangular cavity. It can be seen that for each different \(dx\), there is a corresponding value of \(t\) to reach a maximum bending efficiency, and the global maximum bending efficiency of 94.3% is at \([dx, t] = [55\ nm, 190\ nm]\), at which the power ratio is 96.2%, which is 1.92% higher than the bending efficiency in MOI of the bend with the triangular cavity for different \([dx, t]'s.\]
efficiency in MOI. A few of the maxima are very close to the global maximum but with different pairs of \([dx, t]\)'s. For example, the maxima at [50 nm, 185 nm], [60 nm, 190 nm], [45 nm, 185 nm] and [65 nm, 195 nm] are all 94.2%. Figure 3 shows how the light (power) is efficiently bent to the horizontal (output) branch from the vertical (input) branch at the global maximum bending efficiency. We can see that both the branches behave as slot waveguides with light well confined in the central layer. The positive \(dx\) value at the global maximum is to compensate the Goos-Hänchen shift at the mirror interface [11]. Each curve in Fig. 2 is relatively flat, resulting in good fabrication tolerance. Therefore, although a resonance cavity is introduced to improve the bending efficiency, the cavity is a relatively low Q-value cavity, which is similar to the case in conventional waveguide bending structures [2]. Note that when the bending efficiency is optimized at \(dx = 55\) nm, the slot layer is completely cut off by the mirror at the bending point.

Figure 4 shows the bending efficiency calculated using different \([dx, s]\)'s for the bend.

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Fig. 3. Beam (power) propagation of the bend with the triangular cavity at the global maximum point of \([dx, t] = [55\) nm, 190 nm].
with the square cavity. As in the case of the bend with the triangular cavity, for each different \(dx\) there is an corresponding value of \(s\) which achieves maximum bending efficiency, and the global maximum bending efficiency is 93.1\% at \([dx, s] = [10 \text{ nm}, 172 \text{ nm}]\), at which the power ratio is 94.8\%. Similar to the case of the triangular cavity bend, there are also several maxima that are very close to the global maximum, i.e., at \([10 \text{ nm}, 170 \text{ nm}], [15 \text{ nm}, 170 \text{ nm}], [5 \text{ nm}, 170 \text{ nm}]\) and \([20 \text{ nm}, 170 \text{ nm}]\). Although the curves in Fig. 4 are also flat, they are narrower than those for the bend with the triangular cavity, indicating that the Q-values of the square cavities are also low but higher that those of the triangular cavities. From the global maximum point \([10 \text{ nm}, 172 \text{ nm}]\), we see that the mirror is only 10 nm away from the line CD, indicating that the slot is not cut off but a little narrower than in the straight input or output slot waveguides. Figure 5 shows the beam (power) propagation in the slot waveguide bend with the square cavity at the global maximum. It can be seen that the light is efficiently transmitted to the horizontal branch from the vertical branch.

![Beam (power) propagation of the bend with the square cavity at the global maximum point of \([dx, s] = [10 \text{ nm}, 172 \text{ nm}]\).](image)

3. Conclusions

In summary, we have shown that two high efficiency right-angle slot waveguide bends can be realized with a corner mirror and a triangular or a square resonant cavity. According to our two-dimensional optimizations on the position of the mirror and the size of the resonant cavity, a maximum bending efficiency calculated using MOI of 94.3\% is achieved for the slot waveguide bend with the triangular resonant cavity, and 93.1\% is achieved for the bend with the square cavity. The major difference between the two designs is in the position of the mirror. In the bend with the triangular cavity, the mirror is 55 nm right to the reference line CD in Fig. 1 when the bending efficiency is optimized, causing the slot being completely cut off at the bending point, while in the bend with the square cavity, the mirror is only 10 nm right to line CD when the bending efficiency is optimized, by which the slot is not cut off. The proposed slot waveguide bending structures will facilitate the integration of slot waveguide in photonic integrated circuits.

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