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T-shaped dielectric slot waveguides for efficient control of birefringence and polarization independent directional coupling

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ABSTRACT

A novel dielectric slot waveguide supporting strongly confined field in a T-shaped low-index slot region for both TE and TM polarizations is proposed and analyzed. Numerical simulations have demonstrated that quite different birefringent modal properties are achievable with tight optical confinement in the slot by tuning key geometrical parameters of the waveguide. Based on such a slot structure, the characteristics of directional couplers are investigated and the conditions for polarization independent coupling are also given. The presented T-shaped slot waveguide might be employed in integrated photonic systems as important building blocks enabling a number of potential applications.

1. Introduction

Silicon photonics technology has attracted considerable interest recently due to the high compatibility with standard complementary metal–oxide–semiconductor (CMOS) fabrication technologies and great potentials for guiding, manipulating and processing light signal at the diffraction-limited scale [1]. Among the most promising silicon-based structures, silicon slot waveguides offering the advantages of efficient guiding and confining light in the low-index region [2–4] have facilitated strong light-matter interaction and enabled a variety of applications ranging from sensing to nonlinear light interactions [5–13]. For instance, due to the capability of providing pronounced local field enhancement in the slot region, micro-ring resonators based on these slot waveguides have been employed for highly efficient biosensing [9] and gas detection [14]. On the other hand, slot waveguides have also found useful applications in the area of passive devices, enabling efficient waveguide bends [15], mode splitters [16] as well as other components [17].

In previous studies, both vertical slot waveguides [2,3,18] and horizontal structures [4,19] have been demonstrated to provide tight confinement of light for TE or TM polarization, respectively. To confine light strongly in the slot region for both polarizations, novel guiding mechanism is required. Among the recently proposed slot structures, the cross-slot waveguides formed by orthogonally positioned vertical and horizontal slot structures offer a good solution, and the optical properties have been well-studied both theoretically and experimentally in [20–22].

Here in this paper, we would like to present an alternative configuration to attain the above goal of strong confinement of light with different polarizations. The proposed slot waveguide consists of a vertical slot structure placed above a silicon slab, with a low-index buffer layer between them to construct a T-shaped slot region. Such a T-shaped slot waveguide could be realized by using similar fabrication methods of the conventional slot waveguides. For example, subsequent deposition of a thin silica layer and the upper silicon layer on a SOI substrate, followed by etching and filling of the slot region could be used to form such a slot structure. Theoretical analysis shows that the coupling between the upper vertical slot structure and the lower slab waveguide results in strongly confined fundamental TE and TM modes, with a large portion of the optical power effectively stored in the slot region. By tuning the geometrical parameters, very different modal birefringent properties from non-birefringent to highly-birefringent could be achieved while still maintaining high power confinement in the slot. We also carry out further investigations on the directional coupling between adjacent identical slot waveguides and demonstrate that polarization-insensitive couplers could be realized.

2. Properties of the proposed T-shaped slot waveguide

The schematic of the T-shaped dielectric slot waveguide is shown in Fig. 1, which consists of a vertical slot structure

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(slab width: w_1, slab height: h_1, slot width: t_s) separated from a silicon slab waveguide (width: w_2, height: h_2) by a low-index thin buffer layer (thickness: t_s). The substrate and the slot region are made of silica (SiO_2), and the high-index dielectric is chosen as silicon (Si). The modal properties are investigated at the wavelength of 1550 nm using COMSOL^{TM} with scattering boundary conditions. The refractive indices of the materials are $n_l = n_{s1} = n_{s2} = 1.444$ and $n_h = 3.476$, respectively.

The electric field distributions of the fundamental quasi-TM and quasi-TE modes of the slot waveguide with typical geometry are shown in Fig. 2(a) and (b), where the geometrical parameters are set as: $w_2 = 400$ nm, $h_1 = 200$ nm, $h_2 = 100$ nm and $t_s = 50$ nm. For the quasi-TM mode, light is mainly enhanced in the horizontal slot region (i.e. the buffer layer). While for the quasi-TE mode, tight confinement is observed mostly in the vertical slot region, while also exhibiting modal overlap with the lower silicon slab. Calculation results reveal up to 31% of the total power resided in the T-shaped slot for the quasi-TM mode while nearly 28% for the quasi-TE one. Simulations also show that due to the coupling between the vertical slot and the silicon slab modes, the hybrid quasi-TE mode supported by the T-shaped slot structure has a larger modal effective index than the conventional TE mode guided by vertical slot waveguide.

Further investigations on the mode birefringence are carried out with varied key geometrical parameters of the T-shaped slot waveguides. The birefringence is obtained using the equation: $\Delta n = n(TE) - n(TM)$, where $n(TE)$ and $n(TM)$ are the modal effective indices of the quasi-TE and quasi-TM modes, respectively. The mode confinement for each polarization is accounted by calculating the ratio of the power in the T-shaped slot region to the total power of the slot waveguide. The obtained results shown in Fig. 3(a), (c), and (e) illustrate that increasing the height of the vertical slot results in a shift from positive birefringence toward negative birefringence, indicating that the modal effective indices of the quasi-TM mode could exceed that of the quasi-TE one at relatively large h_1. High birefringence could be achieved with strong confinement in the slot for both polarizations when h_1 and w_2 are relatively large. Although similar high birefringence could also be realized using traditional slot waveguide, yet only one polarized mode is well confined in the low-index region in that case, unlike the strong confinement achieved for both polarizations using the proposed T-shaped slot structure. Besides, compared to the corresponding cross-slot waveguide (with additional

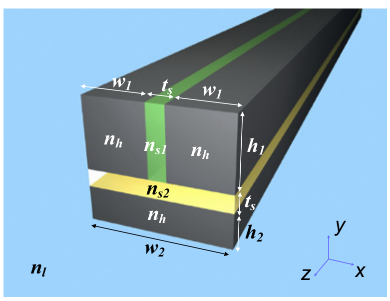

Fig. 1. Schematic of the proposed T-shaped dielectric slot waveguide.

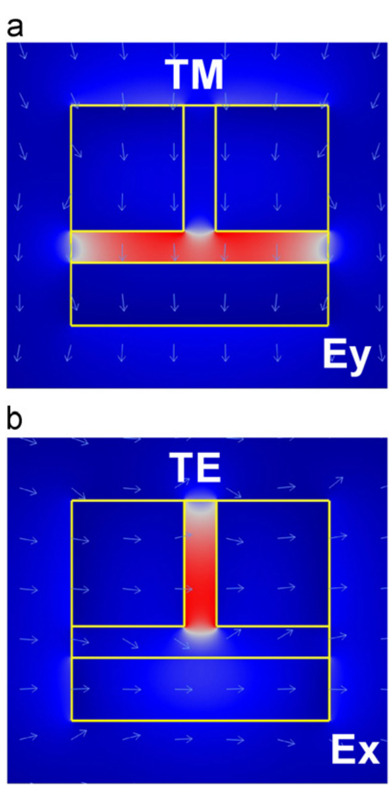

Fig. 2. Electric field profiles of the fundamental modes supported by the T-shaped slot waveguide ($w_1 = 175$ nm, $h_1 = 200$ nm, $w_2 = 400$ nm, $h_2 = 100$ nm, $t_s = 50$ nm): (a) E_y distribution of the quasi-TM mode and (b) E_x distribution of the quasi-TE mode.

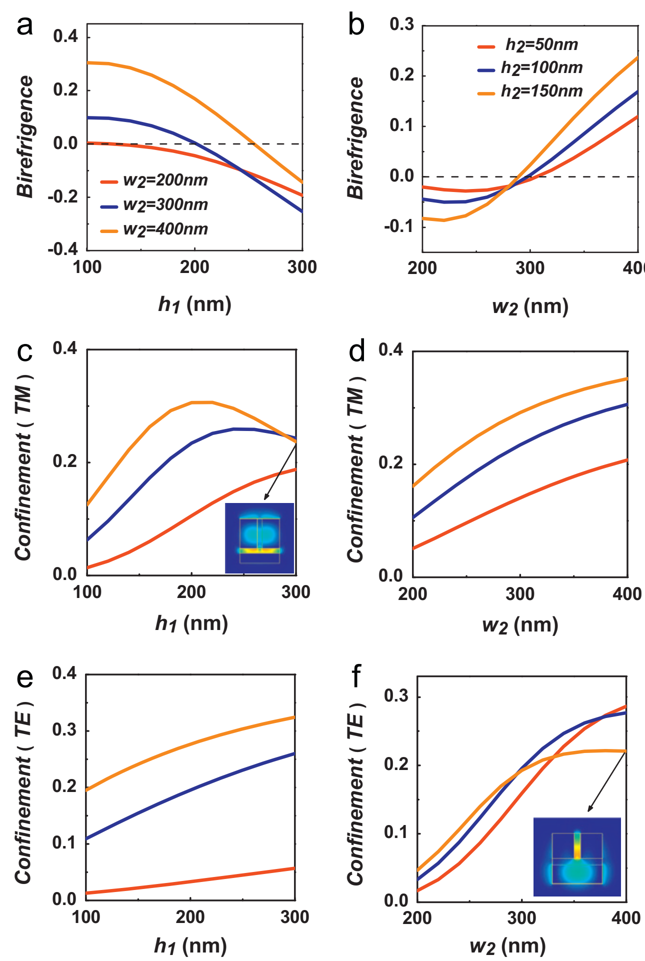

Fig. 3. (a)–(c) Birefringence of the T-shaped slot waveguide with various vertical slot heights (h_1) and the corresponding power confinement in the slot region ($h_2 = 100$ nm, $t_s = 50$ nm). The inset in (c) plots the E_y field distributions for $h_1 = 300$ nm, $w_2 = 400$ nm; (d)–(f) Birefringence of the T-shaped slot waveguide with various silicon slab widths (w_2) and the corresponding power confinement in the slot region ($h_1 = 200$ nm, $t_s = 50$ nm). The inset in (f) plots the E_x field distributions at $w_2 = 400$ nm, $h_2 = 150$ nm.

slot cut in the lower silicon slab), the birefringence can be tunable in a much wider range using our T-shaped structure. Furthermore, the T-shaped slot waveguide is able to allow for the transmission of two slot modes with quite different polarizations under a broadband geometrical parameter range, even for the case when the corresponding cross-slot waveguide is not able to support any guided mode or sustains only one polarized mode.

As seen in Fig. 3(a) and (b), zero birefringence may also be obtained with appropriate geometries, where the corresponding confinement could be still tight for a relatively wide silicon slab. On the other hand, Fig. 3(b) shows that increasing the silicon slab width w_2 (with w_1 increasing correspondingly and other parameters fixed) causes the birefringence shift from a negative value to a positive value. Both high-birefringence and non-birefringence could also be achieved with relatively tight field confinement, as indicated by Fig. 3(d) and (f).

Here, it is also illustrated in Fig. 3(c) and (f) that, regarding the confined power in the slot, an optimized vertical slot height (h_1) or optimized lower silicon slab width (w_2) exists for the quasi-TM or quasi-TE mode, respectively. This is due to the fact that the quasi-TM slot mode is more sensitive to the variation of h_1 and h_2 than other geometrical parameters while the quasi-TE mode is more dependent on the changes in w_2 and h_2. As w_2 or h_1 (h_2) gets relatively larger, the optical confinement in the silicon slabs will increase substantially, thus leading to the deteriorated confinement in the slot for the corresponding mode (also manifested in the field distributions shown in the inset).

Due to the relatively small overlap between the two polarized modes and enhanced regions occurring at different parts of the T-slot structure, the relatively independent control of the two polarization modal properties becomes possible. For example, the upper vertical slot region and/or the horizontal one can be filled with index-tunable materials. Changing the index of material inside one of the slots could lead to a relatively dramatic variation of the birefringence. Therefore such a property can be leveraged for sensing applications. On the other hand, if the vertical and horizontal slots are filled with different materials, the two polarized modes could be separately employed for sensing the index changes of the corresponding material.

The above features of different birefringence property along with strong optical confinement for both polarizations could also facilitate a number of other potential applications, such as birefringence control, polarization rotator, TE or TM pass polarizer, nonlinear control of light and many passive optical devices including directional couplers, mode splitters as well ring-resonators. In the following section, we carry out a numerical investigation of the directional couplers based on these T-shaped slot waveguiding structures.

3. Analysis of the polarization-independent directional coupler

Polarization-independent components are highly desired in many advanced photonic systems since they could eliminate the use of complex polarization diversity schemes with additional optical devices. Polarization independent directional couplers based on conventional vertical slots had been demonstrated in [23] by properly choosing materials and structural parameters. Here for the proposed T-shaped slot waveguide, we also investigate its properties when used for directional coupling, where the coupled system is schematically shown in Fig. 4(a). The output ports of the left and right waveguides are denoted as port 1 and port 2, respectively. The interaction length (i.e. length of the coupler) is defined as L, while the center-to-center (CTC) spacing of the waveguides is denoted as S. For a coupled system consisting

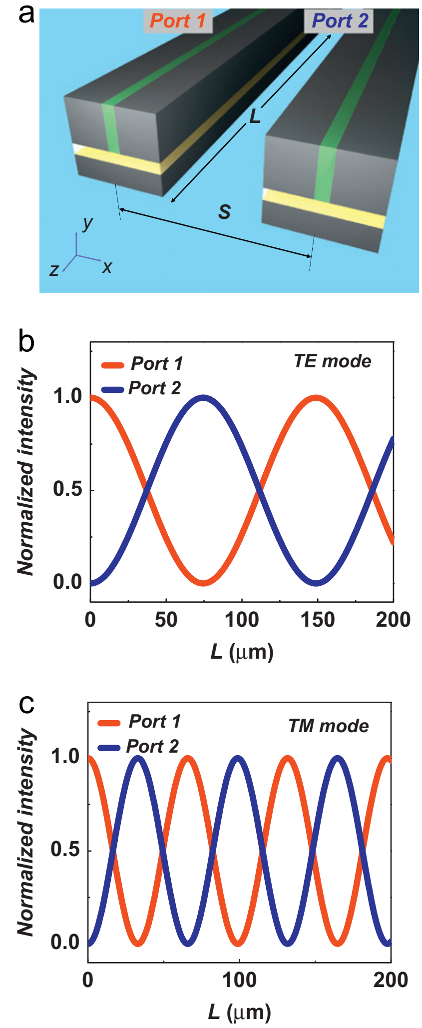

Fig. 4. (a) Schematic illustration of the coupled system consisting of two identical slot waveguide with center-to-center spacing S; (b)–(c) simulated normalized intensities at the two output ports with different coupler lengths (w_1=175 nm, h_1=200 nm, w_2=400 nm, h_2=100 nm, t_s=50 nm, S=1 μm) under the incident (b) TE mode and (c) TM mode. The red and blue curves are the output intensities from port 1 and port 2, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

of two laterally spaced slot waveguides (w_1=175 nm, h_1=200 nm, w_2=400 nm, h_2=100 nm, t_s=50 nm, S=1 μm), the output intensity versus the interaction length (L) are drawn in Fig. 4(b) and (c), where the input port is assumed at the left slot waveguide. It is shown that the oscillation period of the TM mode is shorter than the TE one, due to the relatively small coupling length (33 μm for TM and 74 μm for TE). Here the coupling length L_c is calculated using $L_c=\pi/|k_s-k_a|$, where k_s and k_a are the wavenumbers of the symmetric and anti-symmetric modes of two coupled slot waveguides, respectively. Fig. 5(a) shows the dependence of the coupling length on h_1, where S is fixed at 1 μm and w_2=400 nm. It is demonstrated that L_c increases as h_1 becomes larger. Due to the unique dependence of the modal behavior on special parameter for different polarizations, the magnitude of the increase in the coupling length is different for TM and TE modes, which is similar to the confinement properties discussed in the above section. With the increase of h_1, L_c exhibits a more rapid increase for the quasi-TM mode than the quasi-TE one. It is demonstrated that by choosing the appropriate parameters, the directional coupling between them could be tuned to be insensitive to the state of polarizations. Crossing points can be

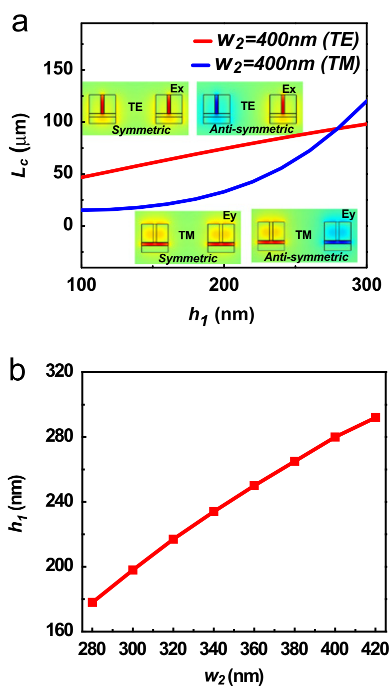

Fig. 5. (a) Dependence of the coupling length of the T-shaped slot waveguide couplers on h_1 ($w_2=400$ nm, $h_2=100$ nm, $t_s=50$ nm, $S=1$ μm). The upper insets plot the corresponding E_x field distributions of the symmetric and anti-symmetric quasi-TE modes in the coupled system ($h_1=280$ nm), while the lower insets show the E_y distributions of the symmetric and anti-symmetric quasi-TM modes for the same structure. (b) Polarization independent coupling condition for different w_2 and h_1 ($h_2=100$ nm, $t_s=50$ nm, $S=1$ μm).

seen in the two curves (around $h_1=280$ nm), where the coupling lengths for quasi-TM and quasi-TE modes are equal, indicating a polarization independent directional coupler may be realized in such cases. In Fig. 5(b), we show further the polarization independent conditions achieved for different combinations of parameters w_2 and h_1. It is indicated that the corresponding h_1 for polarization insensitive coupling condition exhibits a monotonical increase when w_2 grows from 280 nm to 420 nm. While for other slot waveguide configurations, the critical conditions with equal coupling lengths may also be met by carefully engineering the geometrical parameters.

4. Conclusion

We have presented and investigated a novel T-shaped dielectric slot waveguide to provide strong confinement of the light waves in the slot region for both TE and TM polarizations. By engineering the geometrical parameters of the waveguides, various birefringent properties with relatively a large portion of the power confined in the slot region could be achieved. We also investigated the coupling between adjacent slot waveguides and demonstrate directional couplers independent of polarizations.

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