IEEE Photonics Journal
An IEEE Photonics Society Publication

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Volume 9, Number 6, December 2017

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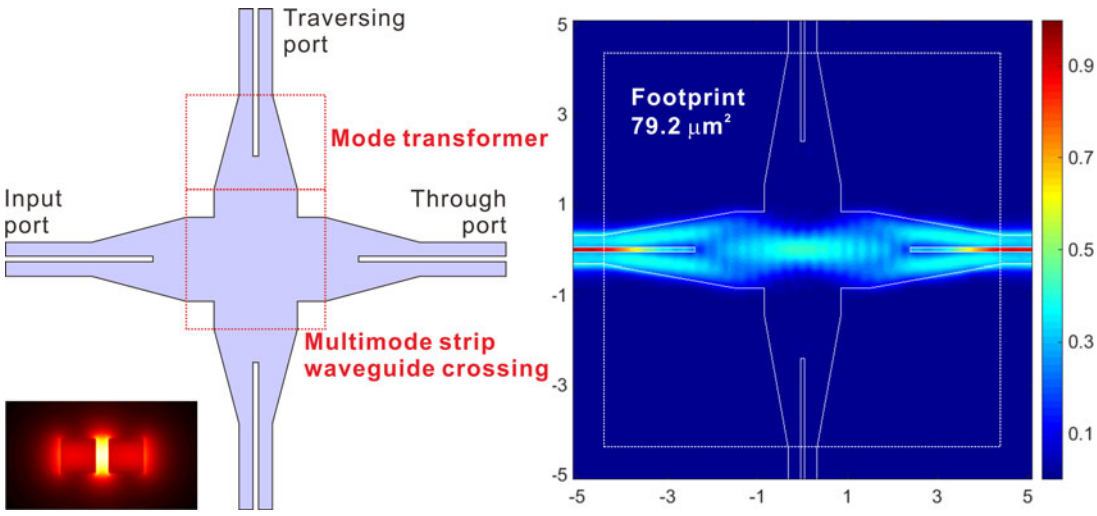

DOI: 10.1109/JPHOT.2017.2772888
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Compact Silicon Slot Waveguide Intersection Based on Mode Transformation and Multimode Interference

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DOI:10.1109/JPHOT.2017.2772888

Manuscript received October 14, 2017; revised November 4, 2017; accepted November 8, 2017. Date of publication November 13, 2017; date of current version November 21, 2017. This work was supported by Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Science, ICT & Future Planning (NRF-2017R1A2B4007143). Corresponding author: Min-Suk Kwon (e-mail: mskwon@unist.ac.kr).

Abstract: Silicon slot waveguide intersections are necessary for photonic-integrated circuits based on silicon slot waveguides. We theoretically investigate a compact silicon slot waveguide intersection, which consists of mode transformers and a multimode strip waveguide crossing. The mode transformer before the crossing converts the slot waveguide mode into strip waveguide modes with amplitudes and phases appropriate for efficient operation of the crossing, which is based on multimode interference. The reverse conversion happens in the mode transformer after the crossing. The investigated intersection has a throughput of -0.078 dB, a crosstalk of -41 dB, and a footprint of 79.2 μm^2. Its properties are better than those of previous silicon slot waveguide intersections, and especially its footprint is less than 33% of the previous ones. The intersection may be used for matrix switches based on silicon slot waveguides.

Index Terms: Silicon nanophotonics, optical interconnects, silicon slot waveguides, waveguide intersections.

1. Introduction

Silicon (Si) slot waveguides have strong field enhancement in the narrow low-refractive-index slot between two Si rails, which makes them very attractive as a platform for efficiently tunable devices [1]–[9] or sensors with high sensitivity [10]–[14]. Although the strong field confinement causes the propagation losses of Si slot waveguides to be larger than those of Si strip waveguides, fabrication processes have been improved to reduce the former to values comparable to the latter [12]. Up to now, there have been studies on a variety of discrete Si slot waveguide devices such as modulators using Si slot waveguides infiltrated with electro-optic (EO) polymer [1]–[3] or liquid crystal [4], [5], lasers [6], polarization splitters [7]–[9], ring-resonator-based [10]–[13] or Bragg-grating-based sensors [14], etc. By employing high-performance Si slot waveguide devices, efficient on-chip optical interconnection or photonic networks-on-chip (NoC) [15] may be implemented.

In realizing photonic NoCs, waveguide intersections are an essential element. For example, they are required to make cross-grid matrix switches consisting of waveguide ring resonators coupled to a waveguide mesh [16]–[18]. When it comes to waveguide ring resonators, EO-polymer-filled slot waveguide ring resonators can have a larger modulation bandwidth than *pin*-type Si strip waveguide ring resonators since the former use the Pockels effect but the latter use the free electron plasma dispersion effect [1], [2]. In addition, the former may consume smaller modulation power than the latter [3]. Therefore, cross-grid matrix switches composed of Si slot waveguides may have better properties than those composed of Si strip waveguides. Although Si slot waveguide ring resonators have been actively studied, just three intersection structures for Si slot waveguides have been theoretically investigated [19]–[21]. One of them requires an additional Si strip waveguide vertically coupled to input and through Si slot waveguides separated by a traversing Si slot waveguide [19]. The realization of this structure seems difficult since the gap between the strip waveguide and the slot waveguide and the length of the strip waveguide have to be tightly controlled for a large throughput (*i.e.*, the transmission from the input waveguide to the through waveguide). The length of the strip waveguide is larger than 13 μm. Another structure consists of slot-to-strip waveguide converters in which one rail of a slot waveguide is logarithmically tapered up to become a strip waveguide, strip waveguide tapers, and a multimode strip waveguide crossing [20]. The throughput and crosstalk (*i.e.*, the transmission from the input waveguide to the traversing waveguide) of the intersection are -0.131 dB and -37.4 dB, respectively, at a wavelength $\lambda = 1.55\,\mu$m, and its footprint is 433 μm^2. The other structure is almost the same as the second one except that different slot-to-strip waveguide converters are used [21]. In the used converters, the rails of a slot waveguide are symmetrically tapered down toward a strip waveguide, and the strip waveguide is tapered down toward the slot waveguide between the rails. The throughput and crosstalk of the intersection are -0.086 dB and -35.6 dB, respectively, at $\lambda = 1.55\,\mu$m, and its footprint is 243 μm^2.

Compared to Si strip waveguide intersections with footprints down to about 23.4 μm^2 [22], the previous Si slot waveguide intersections have large footprints. This leads us to develop a compact intersection of Si slot waveguides. In this paper, we propose, design, and analyze such an intersection which has a throughput of -0.078 dB, a crosstalk of -41 dB, and a footprint of 79.2 μm^2, which is 18% of the footprint of the intersection in [20] and 33% of that in [21]. In addition, the intersection is quite tolerant to fabrication errors, which is important in its realization. The footprint is substantially reduced since the slot-to-strip waveguide converter and the strip waveguide taper are replaced by a *mode transformer* which is explained below. For the analysis, we have carried out three-dimensional simulations rather than two-dimensional simulations which were used for the previous intersections [20], [21]. Hence, there is no chance that approximate two-dimensional simulations result in overestimated intersection characteristics [23]. The intersection developed in this paper may play a key role in NoCs composed of Si slot waveguides.

2. Intersection Structure and Analysis Method

The Si slot waveguide intersection proposed in this paper consists of mode transformers connected to a simple multimode strip waveguide crossing, and its schematic diagram is shown in Fig. 1(a). It is assumed that the Si pattern of the intersection is embedded in silicon dioxide (SiO_2). The thickness of the Si pattern is set at 250 nm. The rails of the slot waveguide are 260 nm wide, and the slot is 100 nm wide. The multimode strip waveguides of the crossing have a width w_M and a length l_M. The mode transformer is the slot waveguide at one end and the multimode strip waveguide at the other end. In the mode transformer, the rails of the slot waveguide are linearly widened from 260 nm to ($w_M/2 - 50$ nm) over a distance l_T, and the slot terminates at a distance l_S from the slot waveguide end and it is filled with Si after the distance. The mode transformer is similar to the strip-slot waveguide mode converter in [24], but the latter is different from the former in two aspects: First, the slot exists in the whole taper region of the mode converter. Second, the multimode strip waveguide connected to the taper region, which is 1.24 μm wide, is narrower than that at the end of the mode transformer. As explained below, such differences are important to make the mode transformers function effectively for the intersection.

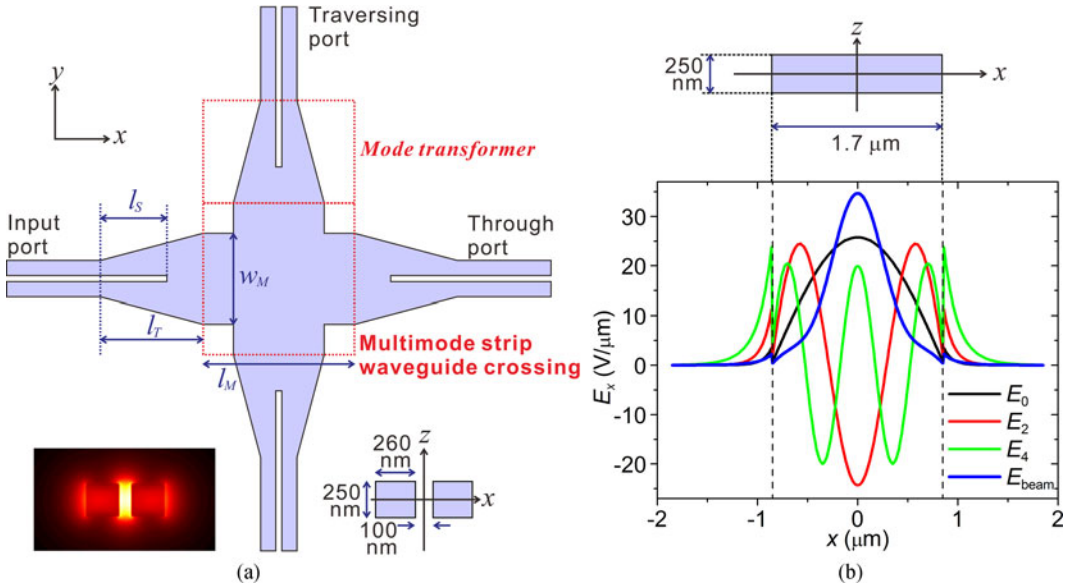

Fig. 1. (a) Structure of the Si slot waveguide intersection. It consists of four mode transformers and a multimode strip waveguide crossing connected to them. The right inset shows the cross-sectional structure of the slot waveguide, and the left inset shows the electric field profile of the slot waveguide mode (TE_s mode). The origin, i.e., $(x, y, z) = (0, 0, 0)$ is at the center of the intersection. (b) Distributions of E_0, E_2, and E_4, which are the x components of the electric fields of the TE modes of the multimode strip waveguide schematically shown together, along the horizontal line at $z = 0$. The distribution of E_{beam}, resulting from superposition of E_0, E_2, and E_4, is also shown.

The fundamental transverse-electric (TE) mode of the slot waveguide, which is denoted by TE_s mode, has the electric field distribution at $\lambda = 1.55\,\mu$m shown in the inset of Fig. 1(a). As well known, the major electric field component parallel to the x axis is symmetric about the z axis and highly enhanced in the slot. As the rail width increases, the electric field becomes more confined in the rails but weaker in the slot, and the slot waveguide becomes multimodal. Therefore, l_T is determined such that TE_s mode at the beginning of the mode transformer almost adiabatically evolves into that at the distance l_S, which is explained below. At the junction of the mode transformer, TE_s mode is transformed into even TE modes of the strip waveguide after the junction, and they evolve into the even TE modes of the multimode strip waveguide of the crossing, which are denoted by TE_{i0} mode for $i = 0$, 2, and 4. The reverse of this process happens in the opposite mode transformer. In this respect, the function of the mode transformer is different from that of the mode converter in [24], which converts TE_s mode to TE_{00} mode of a single-mode strip waveguide. When $E_i(x, z)$ represents the x component of the electric field of TE_{i0} mode, the distributions of $E_0(x, z)$, $E_2(x, z)$, and $E_4(x, z)$ along the central horizontal line (*i.e.*, $z = 0$) for $w_M = 1.7\,\mu$m at $\lambda = 1.55\,\mu$m are shown in Fig. 1(b).

While TE_{00}, TE_{20}, and TE_{40} modes are propagating along the multimode strip waveguide, they interfere with one another. As a result of the multimode interference, the beam determined by superposition of the three modes has its electric field distribution varying along the waveguide. If the values of l_T, l_S, and l_M are appropriately determined, the distribution of the beam becomes narrow at the center of the crossing, and the beam can pass through the crossing, being less affected by the traversing multimode strip waveguide. The multimode interference has been used for Si strip waveguide intersections, which usually employ TE_{00} and TE_{20} modes except TE_{40} mode [22], [25], [26]. The employment of TE_{40} mode is necessary for the Si slot waveguide intersection. If the multimode strip waveguide is too narrow to support TE_{40} mode, the multimode strip waveguide crossing does not work efficiently since the portion of TE_{20} mode in the crossing is larger than the optimal value required for the Si strip waveguide intersections [25]. For example, we confirmed

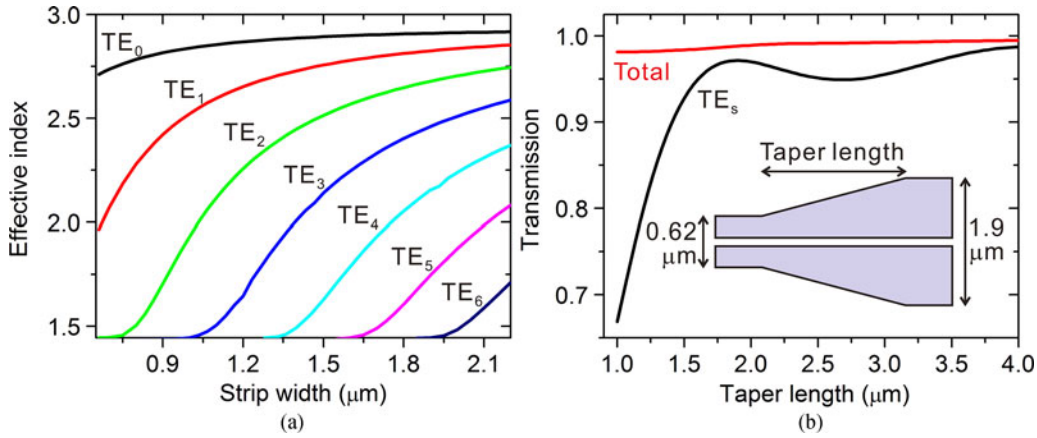

Fig. 2. (a) Effective indices of the TE modes of a strip waveguide as functions of the strip width of the waveguide. (b) Transmission from TE_s mode of the left slot waveguide to that of the right slot waveguide as a function of the taper length of the structure shown in the inset. The total power transferred to all the modes of the right slot waveguide is also shown as a function of the taper length.

that the portion of TE_{20} mode is larger than 10% when the multimode strip waveguide with $w_M = 1.25\,\mu$m does not support TE_{40} mode, and the portion is larger than the optimal value of ~5% in [25]. This is the reason why the multimode strip waveguide connected to the mode transformer is wider than that in the mode converter in [24]. When the amplitude and phase of TE_{i0} mode just after the mode transformer are denoted by A_i and ϕ_i, respectively, the x component of the electric field of the beam, E_{beam} is given by $\sum_{i=0,2,4} A_i E_i \exp(j\phi_i + j\psi_i)$, where ψ_i is the phase change of TE_{i0} mode due to its propagation over a distance in the multimode strip waveguide after the mode transformer. When the phase difference between TE_{00} and TE_{j0} modes is denoted by $\Delta\Phi_{0j}$, $\Delta\Phi_{0j} = \phi_0 - \phi_j + \psi_0 - \psi_j$ for $j = 2$ and 4. The distribution of E_{beam} for $A_0 = 0.933$, $A_2 = 0.341$, $A_4 = 0.118$, $\Delta\Phi_{02} = \pi$, and $\Delta\Phi_{04} = 2\pi$ is shown in Fig. 1(b). E_{beam} is almost completely confined in the 1.7-μm-wide interval. A method of determining the values of l_T, l_S, and l_M is discussed below.

The three-dimensional finite difference time domain (FDTD) method (FDTD Solutions, Lumerical Inc.) is used to carry out simulations related to the proposed intersection. As a source wave for the simulations, TE_s mode is launched in the slot waveguide. Electromagnetic fields are monitored at an observation point, and the monitored fields are expanded into the sum of the TE modes of the waveguide at the observation point by using the mode expansion method (the mode expansion monitor of FDTD Solutions is used for this calculation). The mode expansion coefficient of each TE mode is a complex number given by $A\exp(j\phi)$, and the transmission from TE_s mode to the TE mode is A^2. The dimensions of coarse meshes are 20 nm, 20 nm, and 20 nm, respectively, in the x, y, and z directions. The coarse meshes are gradually reduced to fine meshes in the slot region, which have dimensions of 10 nm, 10 nm, and 20 nm in the x, y, and z directions. We confirmed that the simulation results negligibly change even if the meshes are made smaller.

3. Design and Analysis of the Intersection

The design of the intersection is to determine the optimal values of w_M, l_T, l_S, and l_M for which the throughput is maximized at $\lambda = 1.55\,\mu$m. There are a few guidelines for the design. First, w_M is determined such that the multimode strip waveguide supports TE_{00}, TE_{20}, and TE_{40} modes around $\lambda = 1.55\,\mu$m. The effective indices of the TE modes of a strip waveguide at $\lambda = 1.55\,\mu$m are shown as functions of the strip waveguide width in Fig. 2(a). The cut-off widths of TE_{40} mode and TE_{60} mode are 1.3 μm and 1.9 μm, respectively. Consequently, w_M should be chosen between 1.3 μm and 1.9 μm. Second, the minimum value of l_T for a chosen value of w_M is determined as follows. We analyzed a tapering structure by which the rails of one slot waveguide are linearly widened to be

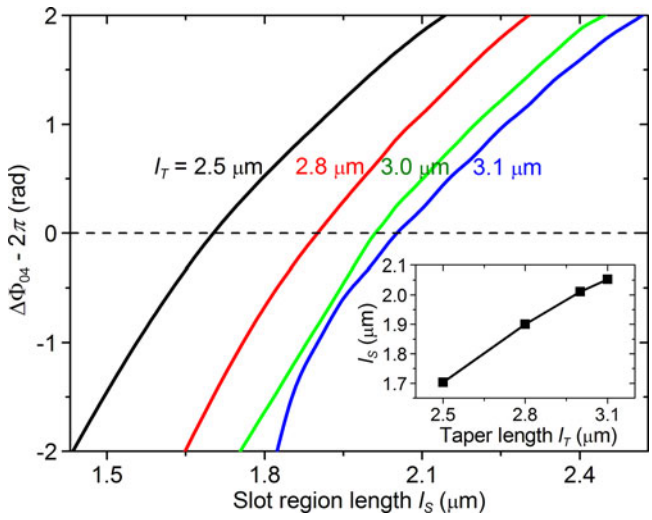

Fig. 3. Relations of the phase difference $\Delta\Phi_{04}$ between TE_0 and TE_4 modes to the slot region length l_S for a few values of l_T. The inset shows the relation of the value of l_S for which $\Delta\Phi_{04} = 2\pi$ to l_T.

connected to the other slot waveguide [see the inset of Fig. 2(b) for the tapering structure]. As the taper length increases, the transmission from TE_s mode of the left slot waveguide to that of the right one increases and saturates as shown in Fig. 2(b). The saturation happens if the taper length is larger than 2 μm. The rail width increase over this distance is 0.64 μm. Therefore, the maximum rate of rail width increase for efficient evolution of TE_s mode is given by 0.64 μm / 2 μm $=$ 0.32 μm/μm. Since the rail width increase rate in the mode transformer should be smaller than this value, the minimum value of l_T is given by (w_M $-$ 0.62 μm)/0.64.

As mentioned above, the throughput is maximized when the beam determined by the superposition of TE_{00}, TE_{20}, and TE_{40} modes is distributed in as a narrow region as possible at the center of the crossing. This happens if the following conditions are simultaneously satisfied in the middle of the multimode strip waveguide of length l_M: (1) $\Delta\Phi_{02} \approx \pi$, (2) $\Delta\Phi_{04} \approx 2\pi$, and (3) the values of A_i's are chosen for the beam to be confined in a small region. The propagation-induced phase change ψ_i is given by $\psi_i = \beta_i l_M/2$, where β_i is the propagation constant of TE_{i0} mode. Since the information about A_i's and ϕ_i's is required to check conditions (1) to (3), the mode transformer between the slot waveguide and the multimode strip waveguide should be analyzed with the rough ranges of l_T and w_M determined as explained above. The third guideline for a choice of l_M comes from condition (1): $\pi = \phi_0 - \phi_2 + (\beta_0 - \beta_2)l_M/2$, which results in $l_M = 2[\pi - (\phi_0 - \phi_2)]/(\beta_0 - \beta_2)$. It is necessary to check if condition (2) is satisfied for l_M determined by the third guideline. The relations of $\Delta\Phi_{04}$ to l_S are shown for $w_M = 1.7\,\mu$m and a few values of l_T in Fig. 3. For a given value of l_T, there is the value of l_S for which condition (2) is satisfied. The inset of Fig. 3 shows the relation between l_T and such a value of l_S. Therefore, using the value of l_S is the fourth guideline, and l_S should be smaller than l_T in the mode transformer while l_S is equal to l_T in the mode converter in [24].

Finally, it is necessary to confirm if condition (3) is satisfied when w_M, l_T, l_S, and l_M are determined following the four guidelines. Since conditions (1) and (2) are satisfied, $E_{\text{beam}}(x, z)$ in the middle of the multimode strip waveguide is given by $A_0E_0(x, z) - A_2E_2(x, z) + A_4E_4(x, z)$. To determine appropriate values of A_i's for which E_{beam} is confined in a small region, a field confinement factor is defined as $\int_{-f\cdot w_M/2}^{f\cdot w_M/2} |E_{\text{beam}}(x, 0)|dx / \int_{-\infty}^{\infty} |E_{\text{beam}}(x, 0)|dx$. It is a measure indicating how strongly E_{beam} is confined in the interval between $-f \cdot w_M/2$ and $f \cdot w_M/2$ for f between 0 and 1. The field confinement factor was calculated for various values of A_0 and A_2 under the assumption that $A_4^2 = 1 - A_0^2 - A_2^2$. The domains of ($A_0^2$,$A_2^2$) for which the field confinement factor is larger than 0.99 for $f = 0.8,\ 0.9,$ and 1.0 are shown in Fig. 4(a). Since the beam is likely to be confined in a smaller region for (A_0^2,A_2^2) in the domain for smaller f, (A_0^2, A_2^2) resulting from the guidelines should be close to such a domain. Fig. 4(a) also shows the traces of (A_0^2, A_2^2) obtained from the mode transformer

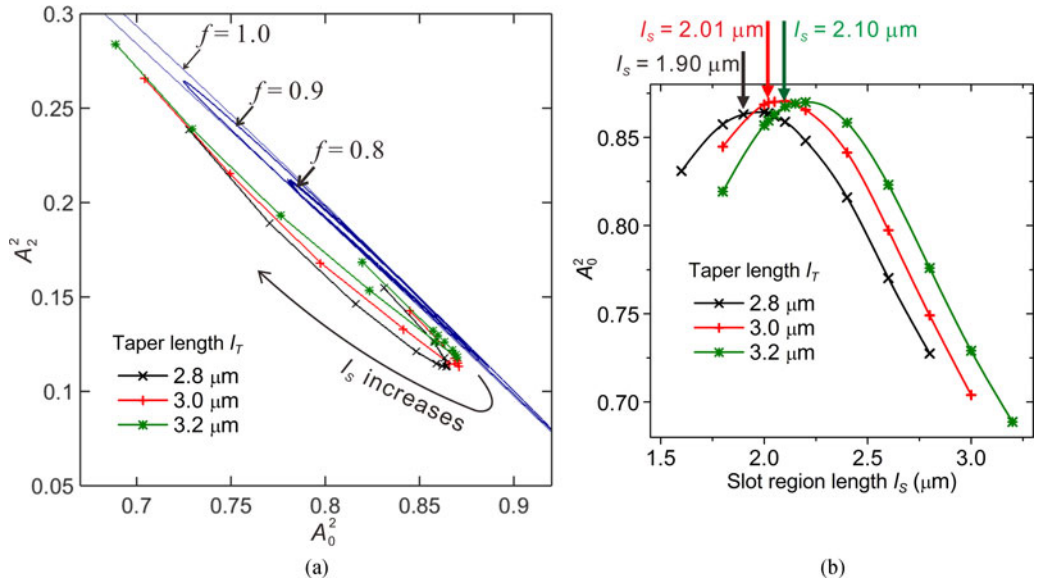

Fig. 4. (a) Domains of (A_0^2, A_2^2) for which the field confinement factor is larger than 0.99 for $f = 0.8$, 0.9, and 1.0. E_{beam} is confined in a narrower region for a smaller value of f. The traces of (A_0^2, A_2^2) of the mode transformer are also shown for $l_T = 2.8$, 3.0, and 3.2 μm. (b) Relations of A_0^2 to l_S for $l_T = 2.8$, 3.0, and 3.2 μm. The arrows indicate the values of A_0^2 related to the values of l_S satisfying condition (2).

TABLE 1
Parameter Values and Simulation Results for $w_M = 1.7\,\mu$m

l_T (μm)	l_S (μm)	l_M (μm)	$\Delta\Phi_{02}/\pi$	$\Delta\Phi_{04}/\pi$	Throughput
2.8	2.02	3.52	0.985	2.153	0.973
2.8	2.05	3.56	0.966	2.147	0.973
2.8	2.10	3.86	0.986	2.288	0.965
3.0	2.02	2.87	1.004	2.017	0.982
3.0	**2.05**	**2.90**	**0.981**	**2.001**	**0.984**
3.0	2.10	3.24	1.003	2.156	0.980
3.2	2.02	2.07	1.003	1.938	0.975
3.2	2.05	2.13	0.985	1.917	0.976
3.2	2.10	2.56	1.023	2.095	0.980

analysis for $l_T = 2.8$, 3.0, and 3.2 μm. The relations of A_0^2 to l_S are shown in Fig. 4(b). We can confirm that (A_0^2, A_2^2) determined by the mode transformer is close to the domain for $f = 0.8$ when l_S is around the value satisfying condition (2). Therefore, condition (3) is automatically satisfied when w_M, l_T, l_S, and l_M are determined following the four guidelines.

For many sets of (w_M, l_T, l_S, l_M), which were selected by following the guidelines, the whole intersection was analyzed at $\lambda = 1.55\,\mu$m. In some cases, a few values of l_S which are different from the guideline-based value were examined. In those cases, l_M was adjusted to make both $\Delta\Phi_{02}$ and $\Delta\Phi_{04}$ as close to π and 2π, respectively, as possible. For $w_M = 1.7\,\mu$m, Table 1 shows

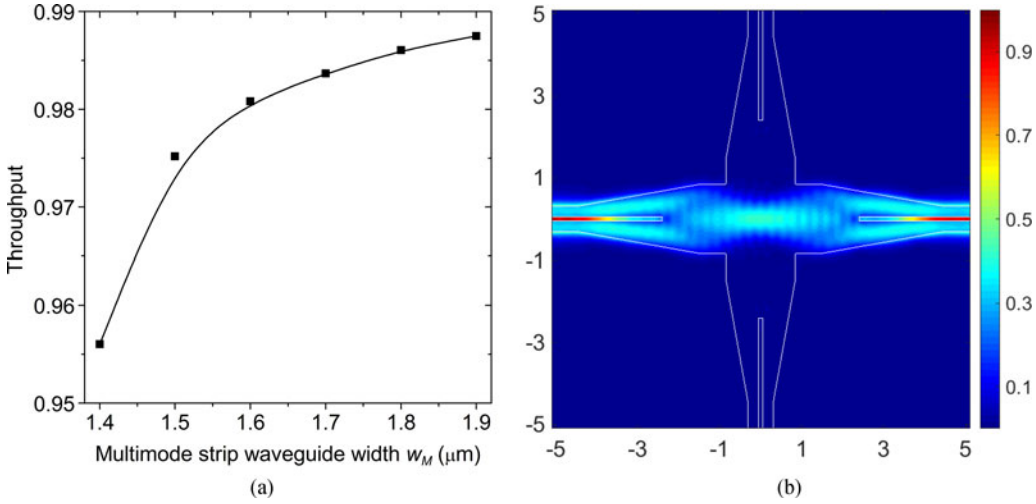

Fig. 5. (a) Peak throughput of the intersection as a function of the multimode strip waveguide width w_M. The parameter values resulting in the peak throughputs are found in Table 2. The line is a guide for eyes. (b) Electric field distribution in the intersection with $w_M = 1.7\,\mu$m, $l_T = 3\,\mu$m, $l_S = 2.05\,\mu$m, and $l_M = 2.9\,\mu$m.

TABLE 2
Parameter Values and Simulation Results Related to Fig. 5

w_M (μm)	l_T (μm)	l_S (μm)	l_M (μm)	$\Delta\Phi_{02}/\pi$	$\Delta\Phi_{04}/\pi$	Throughput
1.4	2.7	2.10	2.24	1.006	1.991	0.956
1.5	3.0	2.20	2.37	1.032	2.203	0.975
1.6	2.8	1.95	2.76	1.035	2.010	0.981
1.7	**3.0**	**2.05**	**2.90**	**0.981**	**2.001**	**0.984**
1.8	3.2	2.10	3.12	0.987	1.993	0.986
1.9	3.2	2.07	3.90	1.003	2.056	0.987

the throughput of the intersection, l_M, $\Delta\Phi_{02}$ and $\Delta\Phi_{04}$ with respect to l_T and l_S. The throughput is largest when $l_T = 3\,\mu$m, $l_S = 2.05\,\mu$m, and $l_M = 2.9\,\mu$m. In the same way, the peak throughput can be found for a given value of w_M. The peak throughput for each value of w_M is shown as a function of w_M in Fig. 5(a), and Table 2 shows the values of w_M, l_T, l_S, l_M, $\Delta\Phi_{02}$, and $\Delta\Phi_{04}$, which are related to the points in Fig. 5(a). The peak throughput for each value of w_M increases with w_M. For $w_M \geq 1.7\,\mu$m, l_T and l_M also increase with w_M. Hence, we focus on the case of $w_M = 1.7\,\mu$m to make the intersection have a large throughput and a small footprint. In this case, the throughput is -0.078 dB, the crosstalk is -41 dB, and the footprint is just 79.2 μm^2, which is less than 33% of those of the slot waveguide intersections in [19]–[21]. The properties of our intersection are compared with those of the previous intersections in Table 3. The electric field distribution in the intersection is shown in Fig. 5(b). It demonstrates that TE_s mode passes through the intersection with almost no loss.

With w_M, l_T, l_S, and l_M set at 1.7 μm, 3 μm, 2.05 μm, and 2.9 μm, the spectra of the throughput, crosstalk, and reflectance of the designed intersection were calculated and they are shown in Fig. 6(a). It can be confirmed that the properties of the intersection are maintained in the wide wavelength band between 1.5 μm and 1.6 μm: the throughput is larger than -0.18 dB, the crosstalk

TABLE 3
Comparison of the Slot Waveguide Intersections at $\lambda = 1.55\,\mu$m

	Throughput	Crosstalk	Reflectance	Footprint
[19]	−0.004 dB	N.A.[a)]	N.A.	13.4 μm [b)]
[20]	−0.131 dB	37.4 dB	−35.5 dB	433 μm^2
[21]	−0.086 dB	35.6 dB	−27.5 dB	243 μm^2
This work	**−0.078 dB**	**−41 dB**	**−30 dB**	**79.2 μm^2**

[a)] This value is not available.
[b)] Length of the strip waveguide vertically coupled to the slot waveguides.

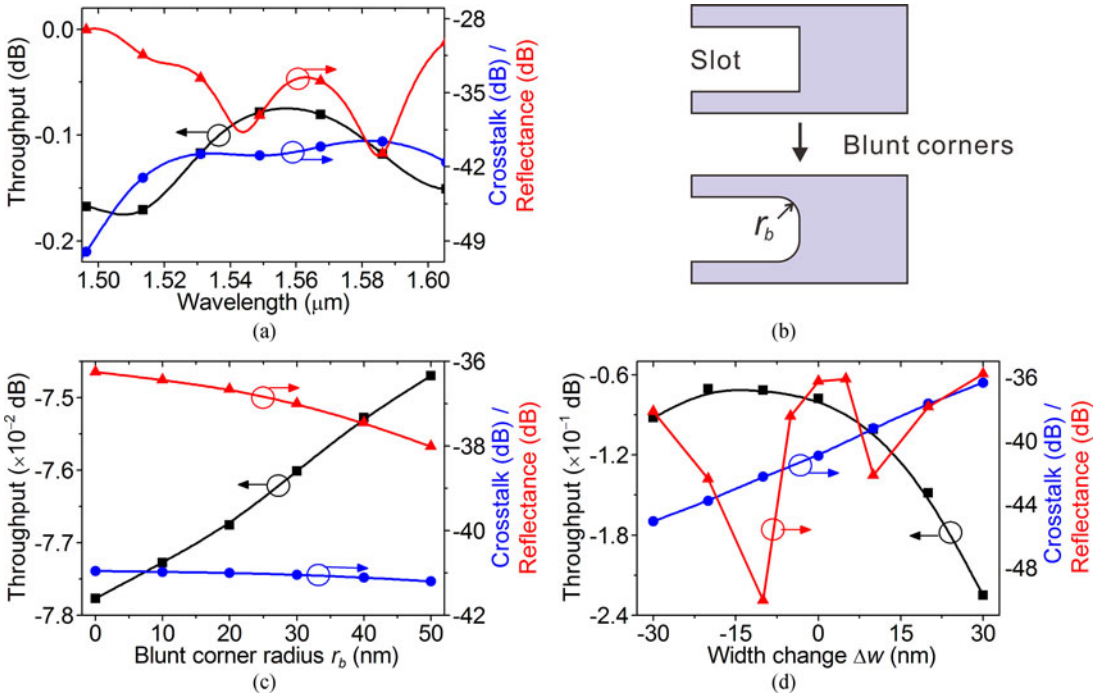

Fig. 6. Characteristics of the intersection with $w_M = 1.7\,\mu$m, $l_T = 3\,\mu$m, $l_S = 2.05\,\mu$m, and $l_M = 2.9\,\mu$m. (a) Spectra of the throughput, crosstalk, and reflectance of the intersection. (b) Slot termination region with the blunt corners. (c) Relations of the throughput, crosstalk, and reflectance to the blunt corner radius r_b. (d) Relations of the throughput, crosstalk, and reflectance to the width change Δw. The square, circle, and triangle symbols represent the throughput, crosstalk, and reflectance of the intersection, respectively.

is smaller than −40 dB, and the reflectance is smaller than −29 dB. In the narrower wavelength band between 1.52 μm and 1.57 μm, the throughput is between −0.15 dB and −0.078 dB. In addition to the wavelength dependence of the intersection, its fabrication tolerances need to be checked. First, we consider the influence of the blunt corners which can occur at the slot termination position. The intersection was analyzed after the 90° sharp corners in the mode transformer were replaced by round corners with a radius of curvature r_b [see Fig. 6(b)]. The analysis results are shown in Fig. 6(c). As r_b increases from 0 nm to 50 nm, the properties are rather improved: the throughput slightly increases by 0.003 dB, the crosstalk decreases by 0.25 dB, and the reflectance decreases by

1.8 dB. Hence, the blunt corners do not deteriorate the intersection properties. Next, we consider the influence of a change in the Si pattern widths. Changing the Si pattern widths by Δw, we analyzed the intersection. As shown in Fig. 6(d), if Δw is between -30 nm and 10 nm, the throughput is larger than -0.1 dB, and the crosstalk is smaller than -39 dB. However, as Δw becomes larger than 10 nm, the intersection properties become worse. Therefore, the fabrication tolerance of the Si pattern widths is set at ± 10 nm. The intersection can be fabricated by using 193 nm optical lithography and dry etching [27]. In the case of the best-in-class fabrication process based on 193 nm optical lithography and dry etching, the accuracy of the minimum feature size is ± 8 nm [28]. Consequently, the tolerance may be satisfied by the process.

4. Conclusion

In summary, we have developed the Si slot waveguide intersection which consists of the mode transformers and the multimode strip waveguide crossing. The design guidelines have been provided, and the designed intersection has been theoretically investigated by using three-dimensional FDTD simulations. The investigation has demonstrated that the intersection has a larger throughput and a smaller crosstalk than the Si slot waveguide intersections in [19]–[21]. The most prominent feature of the intersection is that its footprint is less than 33% of those of the previous intersections. Its performance is quite well maintained in the spectral range between 1.5 μm and 1.6 μm, and it is tolerant to fabrication errors such as blunt corners. In the future, the intersection may be combined with EO-polymer-filled slot waveguide ring resonators to realize high-performance matrix switches for NoCs.

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