Two-Dimensional and Three-Dimensional Analysis of Taper Structures for Coupling into and out of Photonic Crystal Slab Waveguides

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(Received December 11, 2005; revised April 2, 2006; accepted June 13, 2006; published online October 6, 2006)

The appropriate technique for coupling light efficiently from the conventional silica waveguide (SWG) entrance and exit of a photonic crystal slab waveguide (PCSWG) in a square lattice of dielectric rods is determined by calculation using the two-dimensional (2D) and three-dimensional (3D) finite-difference time-domain method. Four types of taper structure as the interface between SWG and PCSWG have been investigated. Coupling efficiency is found to be highly sensitive to the taper structure, defect rod configuration, and slab thickness. We find that when the type D tapered structure with a pair of larger defect rods, which is more flexible during fabrication, is placed between input/output SWG and PCSWG, it alters the mode properties of the guide mode so that mode matching can be achieved by determining the optimum defect configurations. Also, detailed computations of the 2D device and 3D slab version are given. [DOI: [10.1143/JJAP.45.7746](https://doi.org/10.1143/JJAP.45.7746)]

KEYWORDS: coupling technique, photonic crystal slab waveguide, finite-difference time-domain, taper structure

1. Introduction

Photonic crystal (PC) guiding structures may lead to the development of compact and integrated optical circuits (IOCs), provided that the guiding structures can achieve low propagation losses and high transmission efficiencies in different configurations needed in IOCs. A PC of a square lattice of dielectric rods is one of the most likely platforms of such IOCs. As many optical functions require various photonic crystal waveguide (PCWG) widths, a suitable taper with some optimized procedures for mode matching allows one to optimize the PC guiding configuration. In actual samples, it is important to connect a PC waveguide to a conventional dielectric waveguide.¹⁾ In a two-dimensional (2D) photonic crystal slab waveguide (PCSWG), horizontal confinement is provided by an in-plane and light is confined vertically out-of-plane in the third dimension. For a high-index contrast, lossless guided modes can exist in these structures. Thus, an optimized tapered structure with some defect rods between PCWG and the conventional silica waveguide (SWG) is introduced to obtain efficient coupling. Most approaches use 2D structures to address this issue,^{2–6)} but they do not take the out-of-plane effect into account. Some approaches^{7,8)} do take into account the entire three dimensionality, but show some drawbacks that made their implementation difficult for fabricating in IOCs. As described in ref. 7, an adiabatic taper design using a two-stage input coupler is realized by tilting the taper structure and varying rod size in the waveguide direction. Although high transmittance is achieved at localized frequencies, some complexity in fabrication is taken into consideration to obtain the optimal schemes, and a longer taper ($>6\mu\text{m}$) is not suitable for realizing in a high transmittance compact area in IOCs. However, such structures are very sensitive to inaccuracies during manufacture, and the experimental realization of such structures is much more difficult because of the presence of too many defects and the variation of rod size required to achieve an artificial material with a gradient effective index and an adiabatic mode transformation shown in refs. 8 and 9, although a shorter coupling using a narrower wire

waveguide between SWG and planar photonic crystal waveguide (PPCWG) on a shared connection structure, tapering the wire adiabatically is needed to convert the spot size of modes in the wire and couple to the fiber.^{10,11)} Note that the dielectric waveguides in integrated circuits as well as optical fibers have sizes on the order of a few microns. The additional procedure adversely affects the requirement of an ultra small space in IOCs. Moreover, the measurement point inside PPCWG is not suitable because of the Bloch mode (with net forward energy flux) consisting of both forward and backward propagation field contributions (Fourier components).

To realize the optimal design of the terminals of the system for maximal optical transmittance and a shorter tapered structure ($<2\mu\text{m}$) of the system, it is necessary to search for the ideal patterns of the terminals of PPCWGs, which plays a critical role. In our recent investigation,¹²⁾ coupling efficiency was found to be highly sensitive to the taper structure and the geometrical parameters of defect rods. To construct efficient IOCs, coupling efficiency needs to be as high as possible, since loss can occur at any interface between local components and are integrated throughout the entire system. Furthermore, the sensitivity of geometrical parameters during manufacture can be a disadvantage in fabrication. It is the aim of this paper to present better coupling structures of the connecting point to obtain a higher coupling efficiency and a fabrication tolerant structure.

In this paper, the dependence of the tapered structure and defect rods for coupling will be presented in detail. On the basis of these previous works and to address the challenges, structures tapered in a stepwise manner and placed at the input and output terminals of PPCWGs are proposed. The structures presented here are simulated by the finite-difference time-domain (FDTD) method and shown to be quite simple and easy to fabricate because only one pair of in-axis defects set between SWG and PPCWG tapers is required. The most important result is that the suggested structures can considerably improve the transmittance efficiency of the coupling of light waves between SWG and PPCWGs.

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2. Waveguide Structure

The PPC structure consists of square lattices of dielectric rods embedded in a homogeneous dielectric medium of SiO₂ in a slab with the finite thickness h . For 2D PC, the radius of a rod is set to be $r = 0.2a$ (where a denotes the lattice constant of PC, the thickness of the slab to be h , and the refractive index of the dielectric rods to be $n = 3.45$ (GaAs), which corresponds to GaAs at a wavelength of $1.55 \mu\text{m}$. The surrounding medium in PPCWGs has an index of 1.45, which corresponds to that of silica (SiO₂) at a wavelength of $\lambda = 1.55 \mu\text{m}$. The lattice constant a is set to be 465 nm . SWG is on a SiO₂ clad, because it is structurally robust and shows single-mode behavior. SWG has a dielectric index of 1.45 and the surrounding dielectric medium is air ($n = 1$). The background material between the input/output terminals of PPCWG and SWG is air. In the conventional case, we set the distance from the terminals of SWG to the center of the nearest dielectric rod to be $a/2$ (it means SWG connected to silica surrounding PC) and the height of SWG is the same as that of PPCWG. The reason why the air-bridge PC slab is used, is that the waveguide mode over a wide frequency range below the light line of the air clad can be used. The band structures of PPC are calculated by the plane wave expansion method.¹³⁾

For 2D calculation, there is one gap for the transverse magnetic (TM) mode with electric fields parallel to the rod symmetric axis; it is located in the normalized range of $\omega(a/\lambda) \in [0.26, 0.36]$ (it corresponds to the range of wavelengths in free space from 1.29 to $1.79 \mu\text{m}$), with a midgap of $\omega_g = 0.30a/\lambda$ when the radius of rods is $R = 0.2a$, where a denotes the lattice constant and λ is the wavelength of light in free space, $\lambda = 1.55 \mu\text{m}$ when $a = 465 \text{ nm}$. This lattice constant is appropriate for transmission at the standard optical communication wavelength of $\lambda = 1.55 \mu\text{m}$. PPCWG is fabricated in the W1 direction (one row of dielectric rods removed in the $(1, 0)$ direction of PC) and its ending parts are specially designed by removing some rods to form four different types of the taper structure for analysis, as shown in Figs. 1(a)–1(d).

For three-dimensional (3D) calculation, a common photonic crystal slab (PCS) is a structure that is periodic in two dimensions. In the third dimension, light is confined by conventional index guiding. Typical examples given in this paper include waveguide slabs with a periodic set of a lattice of rods of finite vertical extent. These structures have attracted considerable interest since they possess many of the features of completely 3D photonic crystals, but are substantially easier to manufacture. Figure 2 shows the band gap diagram obtained by 3D calculation using the plane wave expansion method with a supercell technique. In the simulation, the height of the rods is $h = 4a$ in the y direction. As discussed in ref. 14, if a structure possesses one or more planes of reflection symmetry, the modes can be classified as either even or odd. These modes are similar to the transverse electric (TE) and TM modes. As a result, it is possible that a band gap exists between the even and odd bands of a PCS. Note that for the odd band, there is a clear band gap in the range of $\omega(a/\lambda) \in [0.353, 0.437]$, as shown in Fig. 2 whereas for the even band we find that no such band gap exists. This means that there is a quasi-TM band gap for this

Fig. 1. Schematic diagrams of four types of taper structures, (a) type A (butt type), (b) type B (conventional type), (c) type D (tilt type) and (d) type D (stepwise without defect type). In these types, the distance from the end facet of SWG to the center of the nearest dielectric rod is given by $s + a/2$, where s is the shift parameter. The width of SWG is $2.4 \mu\text{m}$.

Fig. 2. Band gap diagram for odd band of photonic crystal slab, in which height of rods is $h = 4a$ in the direction of vertical extent (y direction).

structure because TM polarization parallels odd parity. The difference in normalized frequency range of $\omega(a/\lambda)$ between 2D and 3D calculations is that the 3D defect mode has smaller bandwidth and group velocity than the 2D defect mode.

3. 2D Coupling Analysis

A 2D calculation of this structure will be investigated, because the quantitative results will be applied directly to the

3D case and validate qualitatively many of the issues in the coupler design early at lower computational cost. Firstly, four types of taper configuration are illustrated for analysis, type A (the butt type), type B (the conventional type), type C (the tilt type), and type D (the structure tapered in a stepwise manner without a defect rod type), as shown in Figs. 1(a)–1(d), respectively. For these types, the distance from one end facet of the SWG to the center of the nearest dielectric rod is $a/2$. Transmittance is calculated using the FDTD¹⁵⁾ method at the terminal of SWG. The fundamental mode of the terminal of SWG is excited by a pulsed wave that propagates along the z -direction and is calculated with the overlap integral between the launched and measured fields at the output end of SWG [point B, see Fig. 1(d)]. The transmission spectrum is calculated from the Fourier-transformed time series and normalized with respect to the launched pulse. Perfectly matched layer (PML) conditions have been considered in the calculations to ensure no back reflection in the limit of the analyzed region¹⁶⁾ which is terminated by $0.5\mu\text{m}$ to realize perfectly absorbing boundary conditions. The input waveguide, we consider SWG with an optimized width of $2.4\mu\text{m}$ as obtained by the same procedure described in ref. 17. Our simulation results show a local optimum transmission when the SWG widths range from 1.44 to $3.028\mu\text{m}$. The reason why we adopt SWG wider ($<0.6\mu\text{m}$) a that outlined in refs. 7–9 is that a wider SWG is required for efficient mode profile matching to wider PPCWG taper. The larger the width of SWG, the smaller the length of the taper. That is, the PPCWG tapers are also short, allowing compact mode conversion blocks. In SWG, the field is concentrated in a region having a higher refractive index than its surroundings and the mode is guided by conventional total internal reflection. In PPCWG, the guiding mechanism is that the light in the defect region is channeled by two perfect mirrors formed by the adjacent bulk PC. The peak-to-valley ratio of resonant peaks is determined mainly by the coupling efficiency at the two input/output ends between SWGs and PPCWGs, respectively. Therefore, proper mode matching maybe achieved when the interfaces between SWG and PPCWG are controlled to avoid abrupt changes in reflectivity at the input/output interfaces between SWG and PPCWG. Thus, increasing the efficiency of coupling from SWG to PPCWG is needed.

Figure 3 shows the transmission through these four types of tapered structure, types A–D, for PPCWGs of 16 periods. It can be clearly observed from these four types of structure that there is an imperfect conversion of the optical mode from SWG to PPCWG. One of the main reasons for the difficult achieving good coupling is the fundamental differences in the guiding mechanism and field profile between these two waveguides (SWG and PPCWG). In these tapered structures, the waveguide mode consists of the input and output terminals of SWG and the rod facets of tapered structures. This phenomenon is also due to Fabry–Perot resonances, in which a parasitic cavity is formed by refractions from the input/output end of SWG and the rod facets of tapered structure. The waveguide mode in PPCWG is a forward propagating Bloch mode, and there is strong scattering inside PPCWG. It can be observed in Fig. 3 that the coupling efficiency is higher for the type D than for the

Fig. 3. Transmission through four types of tapered structure, types A–D as shown in Figs. 1(a)–1(d), for PPCWGs of 16 periods.

other three types (types A, B, and C). As is shown in our previous study of a 2D triangular lattice PC structure,¹²⁾ a good tapered structure plays a critical role in achieving better matching between the fundamental modes of a wide dielectric SWG and those of a much narrower PPCWG. From the field patterns in the tapered region of PPCWG, one finds that the adiabatical reduction of the cross section of SWG occurs in a relatively short distance, while still retaining an almost perfect transmission throughout the structure. Figure 4 also shows the mode fields between SWG and PPCWG of types A–D. Because the mode field of type D is large, the matching with the PC waveguide mode is better than that of types A, B, and C.

According to the above analysis of the four types of PPCWG taper structure, type D is better than the others in terms of coupling field efficiently from input/output SWG to PPCWG, but shows some peak resonances in the transmission spectra. As reported in refs. 17 and 18 for the coupling technique in the case of a 2D PC of a triangle lattice, the introduction of localized defects within the PPC taper alters the modal properties of the guided mode so that mode matching can be achieved by setting some pairs of defect rods within SWG and PPCWG, as well as their optimum parameters (radii and relative position within the PPC taper), thereby, improving transmission efficiency. We intend to simply the patterns to allow easy design and fabrication. Therefore, parameters involved should be as few as possible. We propose a simple structure, with only one pair of defect rods separated at two ends, i.e., the entrance and exit terminals of SWG. For the type D taper structure shown in Fig. 1(d), one pair of larger single defect rods that are more flexible for fabrication is placed between the input and output terminals of SWG and PPCWG. The SWG width is $w = 2.4\mu\text{m}$. The distance from the end facet of the SWG to the center of the nearest dielectric rod is $a/2$. An optimized radius of defect pairs $r_{\text{opt}} = 0.622a = 0.289\mu\text{m}$, which is located at $(x, z) = (0, -9.7a)$ and $(0, +9.7a)$, is obtained by varying defect rod size. The maximum transmissions are 93% measured at point B and 90% at point A. The optimum relative position of the defect rod away from the origin point $(x, z) = (0, 0)$ along the z -axis $z_{\text{opt}} = 10.4a$

Fig. 4. Mode field patterns between SWG and PPCWG of types A, B, C, and D.

Fig. 5. Transmission against position along x -axis at output end of SWG ($z = 15 \mu\text{m}$).

is also obtained by varying the position of defect rod pairs with radii of $r_{\text{opt}} = 0.622a$ along the propagation direction (z axis). The transmission is above 80% for a range of defect position z values from $0.981a$ to $10.57a$. That is, there can be a large range of tolerance of manufacturing inaccuracies for the defect position. Figure 5 shows the transmission against the position along the x axis at the output end of SWG (at $z = 15 \mu\text{m}$). It is clearly shown that electric field intensity is well confined in the output end of SWG and the transmission is up to 90%.

Figure 6 also shows the steady state of electric field (E_y)

Fig. 6. Steady state of electric field (E_y) for input/output coupling using type D PPCWG taper structure with optimum defect ($w = 2.4 \mu\text{m}$, $r = 0.289 \mu\text{m}$ and $z_{\text{opt}} = 10.4a$). The wavelength of incident light corresponds to $\lambda = a/0.3 = 1.55 \mu\text{m}$. The size of the image plane shown is $30 \times 10 \mu\text{m}^2$.

for the input/output coupling in the case of using the type D PPCWG taper structure with the optimum defect ($w = 2.4 \mu\text{m}$, $r = 0.289 \mu\text{m}$ and $z_{\text{opt}} = 10.4a$). The wavelength of incident light corresponds to $\lambda = a/0.3 = 1.55 \mu\text{m}$. The size of the image plane displayed is $30 \times 10 \mu\text{m}^2$. In the simulations, we observe that the shape of the PPCWG taper structure plays a critical role in changing coupling efficiency between the conventional SWG and PPCWG taper structure; thus, we conclude that the type D PPCWG taper structure is superior to the other possible patterns of the PPC taper, particularly for our specified sample, i.e., Si dielectric rods embedded in the silica medium and set in 2D square lattices. On the basis of our simulations (the results is not shown here), the electric field (E_y) distributions for type D without defect rods show a standing-wave pattern in the input end of SWG. The coupling loss is due to the reflection at the junctions between SWG and the PPCWG taper; therefore, some parts are propagated back to the input end of SWG, and some parts decay on the sides of the input end of SWG. The electric field distributions exhibit a sinusoidal oscillation inside PPCWG. When light waves emerge from the output end of the PPCWG taper, some of them are coupled to the output end of SWG and most of them decay exponentially in air. The field distributions in the output end of the PPCWG taper are weaker than those in the input end. In contrast, the field distributions inside the input end of the PPCWG taper are nearly the same as those in the output end. From Fig. 6, it can be confirmed that designing appropriate PPCWG tapered structures of type D containing one pair of larger defect rods placed at optimal positions can significantly increase coupling efficiency and reduce reflection. In addition, the maximum transmission above 80% is not reduced markedly for a defect radius range from $0.578a$ to $0.656a$. Therefore, it is expected that the tapered structures of type D support a favorable environment for establishing suitable field distributions, and the introduction of defect rod pairs can efficiently hold the light waves and form a new diffraction center of light source (the scattering cross section results from a coherent superposition of individual amplitudes of light waves) in the cavity-like structures in PPCWG taper region. Consequently, a favorable coupling from SWG through the PPCWG taper to

Fig. 7. Transmission as function of distance from end facet of SWG to center of nearest dielectric rod s (in the unit of lattice constant a , where $a = 465$ nm). Transmitted optical power through the PPC waveguide is measured using two power monitors located at points A and B [see Fig. 1(d)].

PPCWG is achieved when the optimal defect configuration is employed. Note that the constructive interference in the input/output PPCWG tapers leads to an increase coupling efficiency mainly attributable to the use of the optimal design of the defect rod configuration.

Figure 7 shows transmission as a function of the distance from the end facet of the SWG to the center of the nearest dielectric rod s (in the unit of lattice constant of a , where s is a shift parameter). Transmitted optical power through PPCWG is measured using two power monitors located at point A (at the output end of PPCWG) and point B (at the output end of SWG) [see Fig. 1(d)]. In Fig. 7 it can be observed that the maximum transmissions (92.85% at point A, 90.78% at point B), are achieved for $s = 0.256a$ (119.04 nm). It should be emphasized that the transmission spectra measured at points A and B using PPC tapered waveguides at the SWG output end are very similar, which indicates that the defect at the output end only acts as a mode impedance matching which improves transmission without modifying the spectra. It can be observed in Fig. 7 that the maximum transmission shows a 2% difference measured at point B and point A, that is the coupling loss is merely 2%, which confirms that the introduction of localized defects can retain transmitted light efficiently emerging from the PPCWG along the z -axis and is realized resulting in a mode match that increases coupling efficiency and decreases reflection loss. It should also be noted that the transmission is above 80% for a range of parameter s values from $0.13a$ to $0.55a$. Namely, it can provide a large tolerance range of s between SWG and PPCWG for manufacturing inaccuracies.

Figure 8 shows the normalized transmission spectra of a type D tapered structure with defect pairs at the input/output end facets of PPCWG coupled to the entrance and exit terminals against a/λ for two cases: case (1) 2.4- μm -width of SWG, defect rod radius $r = 0.289\ \mu\text{m}$, defect rod position $z = 10.4a$, and central normalized frequency $a/\lambda = 0.3$, and case (2) the same as in case (1) except that the defect rod radius $r = 0.3\ \mu\text{m}$, defect rod position $z = 10a$, central

Fig. 8. Normalized transmission spectra of type D tapered structure with defect pairs at input/output end of PPCWG coupled to the entrance and exit terminals against a/λ for two cases: (1) 2.4 μm width of SWG, defect rod radius $r = 0.289\ \mu\text{m}$, defect rod position $z = 10.4a$, central normalized frequency $a/\lambda = 0.3$, (2) the same as in case (1) except that defect rod radius $r = 0.3\ \mu\text{m}$, defect rod position $z = 10.4a$, central normalized frequency $a/\lambda = 0.306$.

normalized frequency $a/\lambda = 0.306$. To obtain these results, an incident pulsed field was launched at the input end of SWG. The fundamental mode of SWG is excited by a pulsed wave that propagates along the z -direction and the transmission spectra field is calculated with the overlap integral between the launched and measured pulsed field at point B. The transmission spectra are calculated from the Fourier-transformed time series and normalized with respect to the launched pulse field. As compared with Fig. 3, the ripple in the transmission spectra shown in Fig. 3 is due to the mode mismatching at the interfaces between SWG and the PPC taper. When the proposed defect configuration is set, the response markedly diminishes because a better mode matching at the interfaces between SWG and PPCWG is achieved. It can be confirmed that an optimal defect rod pair can reduce the reflection at the boundary between SWG and PPCWG and can decrease the depth of the ripple in the transmission spectra in Fig. 3. According to case (1) shown in Fig. 8, an average transmission larger than 80% is achieved for a normalized frequency range from $0.294a/\lambda$ to $0.302a/\lambda$ and the maximum transmission is greater than 90%. However, in Fig. 8, it can be observed that the bandwidth for case (1) is smaller although it still satisfies bandwidth requirements for optical communications (in this case, $a/\lambda = 0.3$, corresponding to the wavelength of incident light of $\lambda = 1.55\ \mu\text{m}$ in free space). That is, high coupling efficiency is achieved at the sacrifice of bandwidth, which becomes more sensitive to the normalized frequency employed to optimize the parameters of the defects. It can be noted that for case (2) shown in Fig. 8 (a normalized frequency of $0.306a/\lambda$, corresponding to the wavelength of incident light of $\lambda = 1.52\ \mu\text{m}$ in free space), the central frequency can be controlled for optical communications by determining the optimal parameters of defect configuration in PPC tapers.

4. 3D Coupling Analysis

In this section, we will investigate the structure obtained by 3D calculation (for PCSWG) and the structure is the same as that obtained by 2D calculation, but in 3D calculation, the finite thickness h in the vertical direction is used. We observe the transmission spectrum for the type D structure using the 3D FDTD method. The computational space has a sampling rate of $\lambda/40$, where λ is the wavelength in free space. A continuous wave (CW) with the center wavelength $\lambda = 1.55 \mu\text{m}$, and a wavelength width of $\Delta\lambda = 2.4 \mu\text{m}$ to analyze structures with the finite length $h = 2a$ in the transverse plane. Using the optimal procedure for type D structure version obtained by 2D calculation, with optimal defect rods cannot obtain the same transmission as that in the case of 2D calculation. The detrimental effect of out-of-plane radiation arising from the defect is obvious and the transmission is less than 5% for this 3D calculation. A similar observation is made when the thickness of the slab of PCSWG is increased to $h = 4a$ (the transmission is up to 28.59%). To determine the optimal mode coupling conditions, we now change the thickness of the slab from $h = 1a$ to $18a$ with increments $1a$ using the type D taper structure with the optimum defect rod configurations ($w = 2.4 \mu\text{m}$, $r = 0.289 \mu\text{m}$ and $z_{\text{opt}} = 10.4a$). Figure 9 shows the normalized transmitted power as a function of the thickness h of the slab. From Fig. 9, one can observe that the thickness h of the slab is a parameter of prime importance for confining the entire light (primarily localized in the transverse direction) for the slab version obtained by 3D calculation. The structure of the slab with the thickness $h = 10a$ tested at $\lambda = 1.55 \mu\text{m}$ is shown in Fig. 10. Figure 10(a) shows the top view of the steady-state field distribution (x - z sectional plane, at $y = 0$) measured at the middle of the slab. Figure 10(b) shows the cross-sectional view of the steady-state field distribution as well as the location of dielectric rods (x - y sectional plane, at $z = 0$) measured at the output end of PCSWG. Figure 10(c) shows the lateral view of the steady state field distribution (y - z sectional plane, at $x = 0$).

Fig. 9. Normalized transmitted power as function of thickness h of slab. The thickness of the slab varies from $h = 1a$ to $17a$ with increments of $1a$.

Fig. 10. Structure of slab with thickness $h = 10a$ tested at $\lambda = 1.55 \mu\text{m}$, (a) shows the top of steady-state field distribution (x - z sectional plane, at $y = 0$) measured at the middle of the slab; (b) shows cross-sectional view of the steady-state field distribution as well as the location of dielectric rods (x - y sectional plane, at $z = 0$) measured at the output end of PCSWG. (c) shows the lateral view of steady-state field distribution (y - z sectional plane, at $x = 0$).

It is clear that the type D tapered structure with the optimum defect configurations can indeed effectively function using the 3D FDTD method if the thickness h of the slab is larger than $10h$. We find that the obtained results are similar to those shown in Fig. 6. The study of the coupling effects for the type D tapered structure in the case of 2D calculation allows us to validate qualitatively many issues regarding the design of couplers with lower computational cost and supports useful information directly appropriate for the corresponding 3D calculation. We find that as long as the size of the sample along the vertical direction, i.e., the y -axis, is sufficiently large, the detrimental effect of out-of-plane radiation caused by the defect can be neglected. As shown in Fig. 10, the electric field distributions are well confined in the propagation direction of PCSWG from the viewpoint of practical applications.

Additionally, because of resolution limitations, it is uncertain if the thickness h of the slab is greater than $20a$. For actual implementation and development in IOCs, thicker PCSWGs are not considered because compact size is required. For the sake of exploring the physical mechanism inside PCSWGs, the thickness of the slab version obtained 3D calculation needs to be increased significantly more gradually than our computational resources allow us to study.

5. Conclusions

We present a coupling technique using 2D and 3D calculations for coupling light efficiently from conventional silica waveguide (SWG) entrance and exit of a PCSWG in a square lattice of dielectric rods. Several important param-

eters were investigated to ensure a larger tolerance range for inaccuracy fabrication. The coupling dependence between conventional SWG and PCSWG shared a connecting facet for various taper geometries; we found that the structure tapered in a stepwise manner (type D) with optimized defect rod configurations for mode matching has high coupling efficiency and fabrication tolerance. The maximum transmittance can be up to 90% for a wavelength of 1550 nm in the case of 2D and 3D calculation in our investigation when the structure of the connecting facet is well designed. Also, we hope that the suggested structures possess other advantages, such as the shortness of the taper, the ease of fabrication, and its low cost.

Acknowledgements

This work was financially supported by the National Science Council of Republic of China under Grant No. NSC94-2112-M-231-001, and the Ministry of Economic Affairs, Taiwan, R.O.C., under Grant No. 94-EC-17-A-08-S1-0006.

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