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Design of a compact mode and polarization converter in three-dimensional photonic crystals

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Abstract: A mode and polarization converter is proposed and optimized for 3D photonic integrated circuits based on photonic crystals (PhCs). The device converts the index-guided TE mode of a W1 solid-core (SC) waveguide to the band-gap-guided TM mode of a W1 hollow-core (HC) waveguide in 3D PhCs, and vice versa. The conversion is achieved based on contra-directional mode coupling. For a 25μm-long device, simulations show that the power conversion efficiency is over 98% across a wavelength range of 16 nm centered at 1550 nm, whereas the reflection remains below –20dB. The polarization extinction ratio of the conversion is in principle infinitely high because both W1 waveguides operate in the single-mode regimes in this wavelength range.

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References and links

Three-dimensional (3D) photonic crystals (PhCs) offer a promising platform for photonic processing and communications, etc. [1–8]. Micro-cavities embedded in 3D PhCs can achieve ultra-high quality factors because of the confinements by the 3D photonic band-gaps (PBGs), making them well-suited for nonlinear optics and quantum optics [9]. Hollow-core (HC) waveguides or cavities, not achievable in PhC slabs, can be constructed in 3D PhCs. Similar to the devices based on HC PhC fibers [10], these HC devices may enable various chip-level applications, such as gas or liquid material sensing, high power transmission, and low-threshold oscillation or lasing, when they are filled with materials of desirable nonlinearities.

Among various designs of 3D PhCs [1–8], the one made of alternating layers of air-hole and dielectric-rod slabs (Fig. 1) is selected for the following two advantages: similarity in device design to PhC slabs, and flexibility in polarization control [5, 6]. The radii and heights of each air hole and dielectric rod are set as $r_H = 0.293a$, $h_H = 0.224a$, $r_R = 0.115a$, and
Fig. 1. A schematic of a 3D PhC consisting of alternating layers of air-hole and dielectric-rod slabs in the same triangular lattice. Six such layers form one period along z.

\[ h_R = 0.353a \ (h_H + h_R = a/\sqrt{3}) \]

where \( a \) is the fcc lattice constant, and the subscripts H and R denote hole and rod, respectively. With such settings, a complete band-gap of 21% is achieved in silicon PhCs [5]. It has been proved that the modes of the line-defect waveguides (with defect radius \( r_H' \) or \( r_R' \)) in individual layers of the 3D PhC have strong similarities in mode profiles and polarization to those in 2D PhCs or PhC slabs [11]. Thus, extensive device designs in 2D PhCs and slabs [12, 13] can be transferred to 3D PhCs with minor changes.

Fig. 2. (a) The band diagram of a W1 SC waveguide in a hole layer. The inset shows the x-y cross section of the waveguide. The red markers denote two index-guided TE modes, which are in the second and third Brillouin zones, respectively. The lower branch is of interest in this paper. (b) The mode profiles of selected components of the fundamental TE mode through the x-y and x-z mid-planes of the W1 SC waveguide, calculated at \( k_y = 0.05(2\pi/a) \) \((\omega=0.55(2\pi/a))\). 
(c) The band diagram of a W1 HC waveguide in a rod layer. (d) The mode profiles of selected components of the fundamental TM mode of the HC waveguide, calculated at \( k_y = 0.20(2\pi/a) \).

The building blocks of the devices and circuits in the 3D PhC are the W1 solid-core (SC) \((r_H' = 0)\) waveguide in a hole layer and the W1 hollow-core (HC) \((r_R' = 0)\) waveguide in a rod layer, as shown in the insets of Fig. 2(a) and 2(c), respectively. Their fundamental modes are attractive for their robustness to fabrication imperfections [14, 15]. The waveguide band diagrams are calculated and plotted in Fig. 2 [16], where the in-plane period \( \bar{a} \) is related to the fcc lattice constant \( a \) through \( \bar{a} = a/\sqrt{2} \). In Fig. 2(a), the red and black curves represent the
index-guided fundamental quasi-TE mode and higher order modes of the SC waveguide, respectively [12, 17]. The mode profiles of $H_z$, $E_x$, and $E_z$ components of the fundamental TE mode through the $x$-$y$ and $x$-$z$ cross sections of the waveguide are drawn in Fig. 2(b), where $H_z$ and $E_x$ dominate. In Fig. 2(c), the blue curve represents the PBG-guided fundamental quasi-TM mode of the HC waveguide, which is dominated by $E_z$ (Fig. 2(d)). In the overlap frequency range of the two fundamental modes, both waveguides operate in the single-mode regimes. Thus, one can construct low-loss devices that operate in desirable polarizations based on these fundamental modes, i.e., TEs in rod layers and TMs in hole layers.

The polarization-selective nature of the W1 SC and HC waveguides helps suppress the crosstalk between them [18]. However, this hampers their inter-layer communication, which is of fundamental importance for functional 3D photonic integrated circuits. Moreover, if 3D PhC photonics are integrated with planar photonics, only the index-guided SC waveguide modes can be coupled to channel waveguides at low losses [19, 20], whereas the PBG-guided HC waveguide modes will suffer severe coupling losses due to the large mode mismatches. Therefore, the construction and integration of future 3D photonic circuits call for ways of efficient communication between the index-guided W1 SC waveguides and PBG-guided W1 HC waveguides. Here we propose a PhC mode and polarization converter that can convert the TE mode of a SC waveguide to the TM mode of a HC waveguide, and vice versa.

Based on the dispersion curves in Fig. 2, we list the following design guidelines: (i) the working frequency range of the converter, $\Omega$, covers most of the overlap frequency range of the TE and TM modes, but it excludes the slow-light region of the TM mode. $\Omega$, shown by the shaded areas in yellow in Fig. 2(a) and 2(c), centers at $\omega_k = 0.55(2\pi/c)$ and has a bandwidth of $\Delta \omega = 0.015(2\pi/c)$, where $c$ is the speed of light in the vacuum; (ii) the conversion efficiency approaches unity throughout $\Omega$; (iii) the mechanism is based on contra-directional coupling, which is indicated by the opposite slopes of the two dispersion curves; (iv) the device has a small footprint. In the rest of this paper, we will first discuss the W1 waveguide mode properties, followed by the converter design principles. Then, FDTD simulations of the device and optimization strategies will be covered. Finally, the device performance will be evaluated.

2. Mode evolution of W1 waveguides

In 3D PhCs, polarizations can no longer be identified as pure TEs or pure TMs because of the breaking of symmetry. Intuitively, we can characterize the polarization purity of a waveguide mode by calculating the energy ratio of each electric field component

$$RU_{i j} = \frac{\iiint_{\text{unit-cell}} dV \left( \varepsilon E_j E_i^* \right)}{\iiint_{\text{unit-cell}} dV \left( \varepsilon E_i E_i^* \right)},$$

where the integral is performed over one unit cell instead of at one cross section as in [11] ($i = x, y, z$). For the TE mode of the W1 SC waveguide ($r_{H' \leftarrow H} = 0$), the energy ratio of the non-dominant $E_z$ is merely 1%, whereas the dominant $E_x$ has a ratio of ~81%, both of which are calculated at a fixed frequency of $\omega_k = 0.55(2\pi/c)$ (Fig. 3(a)). The energy ratios of the magnetic field components $RU_{ij}$ ($i = x, y, z$) are also defined and calculated for the same mode in Fig. 3(b), where $H_z$ dominates over other components with a ratio of ~76%. For the TM mode of the W1 HC waveguide ($r_{H \leftarrow H'} = 0$), the energy ratios of $E_z$, $E_x$, and $H_z$ are calculated as ~62%, ~26% and ~10%, respectively, as shown in Fig. 3(c) and 3(d). Yet the polarization purity of the two modes still remain high, the non-trivial energy ratios of the minor components in the TE and TM modes can lead to a non-zero mode overlap, which is proportional to the inner product of the two modal fields [21]. The overlay can be even increased when the two waveguides are constructed in different layers of the crystal.
Nevertheless, despite the minor mode overlap resulting from the breaking of symmetry in 3D PhCs, the very weak interaction between the fundamental modes of the W1 SC and HC waveguides is still prohibited in $\Omega$ due to the significant phase mismatch. From Fig. 2(a) and 2(c), if the two dispersion curves are overlaid with each other, they are found to be quite far away, except one crossing point in the slow-light region of the TM mode.

Fig. 3. (a) and (b) The energy ratio of each component of the TE mode is calculated for a series of W1 hole waveguides with different defect sizes. (c) and (d) The energy ratio of each component of the TM mode is calculated for a series of W1 rod waveguides with different defect sizes. All the calculations are done at a fixed frequency of $\omega_0 = 0.55(2\pi/a)$.

On the other hand, the breaking of symmetry in 3D PhCs indicates a way of achieving the desired mode conversion through the mode coupling between two intermediate waveguides: the mode profiles of a W1 hole or rod waveguide change slightly with the defect size, whereas the ever increased similarities in mode profiles and polarization between TE and TM modes lead to a moderate mode overlap; it then makes the effective mode interaction—i.e. the inter-layer power transfer possible, given that the phase-matching condition is satisfied. A general procedure for the TE to TM conversion could be: the SC waveguide mode is first converted to a TE mode of some intermediate W1 hole waveguide through a mode evolution; the power in the hole waveguide is then transferred to a W1 rod waveguide, given a sufficient mode interaction; finally, the obtained TM mode is converted to the desired HC waveguide mode through a second mode evolution. Thus, the key of the mode conversion process is to achieve efficient mode interaction between two intermediate W1 hole and rod waveguides, which requires both a considerable mode overlap and an accurate phase match.
For simplicity, we first discuss the phase-matching issue. From Fig. 2(a) and 2(c), phase-matching can be achieved if one can shift the TE and TM bands towards each other and cross them in $\Omega$. At the anti-crossing point, the Bragg condition is satisfied [21]. It is known that increasing the defect hole radius $r_{H}'$ can raise the bands of a W1 hole waveguide towards the air band, which results from the reduced refractive index of the waveguide [22]. Similarly, increasing the defect rod radius $r_{R}'$ can lower the bands of a W1 rod waveguide towards the dielectric band. In Fig. 4, at a fixed frequency of $\omega_0 = 0.55(2\pi/a)$, the wavevectors increase with the defect sizes for both waveguides. Accordingly, the phase mismatch between the two modes is significantly reduced. We can then identify a range on both $r_{H}'$ and $r_{R}'$, within which the two waveguides have common wavevectors, as indicated by the shaded area in grey in Fig. 4.

Along with the reduced phase mismatch, the similarities in mode profiles and polarization are also enhanced with the increased $r_{H}'$ and $r_{R}'$, which essentially promote the interaction between the TE and TM modes. For each point on the red curve in Fig. 4, the energy ratios are calculated correspondingly, as shown in Fig. 3(a). Based on both the electric and magnetic field calculations, it is found that the TE purity degrades with the increased $r_{H}'$. Interestingly, for the W1 rod waveguides, the trends are very different. As shown in Fig. 3(c) and 3(d), there’s no apparent degradation in polarization purity when $r_{R}'$ is increased. Nevertheless, the similarities between the TE and TM modes are still enhanced, according to the comparisons made between the energy ratios of corresponding components in Fig. 3.

Therefore, with properly designed waveguide parameters, the TE mode of a W1 hole waveguide can interact with the TM mode of a W1 rod waveguide efficiently, which can be utilized to achieve the desired mode conversion. Such mode interaction results from the breaking of symmetry in the 3D PhC. The crossing of the two dispersion curves in $\Omega$ guarantees the phase-matching condition, whereas it is the increased similarities in mode profiles and polarization that essentially strengthen the mode interaction.

### 3. Mode converter design

When the two waveguides with properly engineered parameters, i.e., $r_{H}'$ and $r_{R}'$, are placed in the adjacent layers, as shown in the inset of Fig. 5(a), power can be transferred from one waveguide to the other. In the language of the coupled-mode theory, such a waveguide pair forms a bi-layer compound waveguide, and the coupled modes constitute two super-modes [20, 23]. In the band diagram in Fig. 5(a), a mode-gap opens at the anti-crossing point of the “TE” (red) and “TM” (blue) super-mode bands, at which both modes display mixed TE and TM features. This can be seen more clearly from the mode profiles shown in Fig. 5(b).
Fig. 5. (a) The band diagram of a bi-layer compound waveguide consisting of a W1 hole waveguide with \( r_{H'} = 0.56r_H \) and a W1 rod waveguide with \( r_{R'} = 0.30r_R \). The inset is the \( x-z \) cross section of the waveguide. A mode-gap appears at the anti-crossing point of the TE (red) and TM (blue) bands. (b) The mode profiles of representative components of mode 1 and 2 in (a).

More importantly, the mode-gap size \( \Delta \alpha_{\text{gap}} \) directly reflects the amplitude of the coupling strength between the two modes [24], which is given by

\[
\kappa_{\text{HR}} = \frac{\Delta \alpha_{\text{gap}}}{4c} \left( |n_{\text{g,H}}| + |n_{\text{g,R}}| \right),
\]

where \( n_{\text{g,H}} \) and \( n_{\text{g,R}} \) denote the mode group indices of the uncoupled W1 hole and rod waveguides, and \( c \) is the speed of light in the vacuum. Light at any frequency within \( \Delta \alpha_{\text{gap}} \) that propagates in one waveguide can couple to the other after a certain mode interaction distance. Thus, the inter-layer power transfer can be realized with the aid of the bi-layer compound waveguide coupler that has a large mode-gap.

Based on this coupler, a schematic of the converter is depicted in Fig. 6, showing only the two engineered layers of the 3D PhC. Here we take the TE to TM mode conversion as an example: \( A, B \) and \( C \) denote the TE input, TM output, and TE residual ports, respectively. The red and blue arrows, representing the TE and TM waves, illustrate how the light propagates, evolves, couples, and re-evolves in the device. Along the propagation direction of the TE wave from port \( A \) to \( C \), the filled holes and the smaller holes at the bottom layer comprise, in sequence, the input W1 SC waveguide, the W1 hole mode-evolution waveguide and the bottom part of the bi-layer coupler. On the upper layer, along the propagating direction of the TM wave from port \( C \) to \( B \), the smaller rods in light green and the line of missing rods constitute, in order, the top layer of the coupler, the W1 rod mode-evolution waveguide, and the output W1 HC waveguide. In a general mode conversion process, the TE wave, which is sent into the converter from port \( A \), first propagates in the SC waveguide. It then evolves to the TE mode of a W1 hole waveguide with \( r_{H'} = r_{H0} \) through a slow taper. Right behind the defect \( D_1 \) in dark green, a uniform W1 rod waveguide with \( r_{R'} = r_{R0} \) emerges, which constitutes a bi-layer coupler with the W1 hole waveguide and harvests power from its neighbor through the contra-directional mode coupling. The obtained TM wave that propagates in \(-y\) direction is then in turn redirected by two 60° bends, and transformed into the W1 HC waveguide mode through a second taper. Two 60° bends are employed here to separate the output channel from the input one.
The first challenge in the converter design is to optimize for a wideband yet compact compound waveguide coupler. First, the bandwidth requirement can be satisfied if the coupler’s mode-gap size $\Delta \lambda_{\text{gap}}$ is larger than $\Omega$. Second, a short coupler length $L$ requires a large coupling strength $\kappa_{\text{HR}}$ for a fixed efficiency $CE$ [21], i.e.,

$$CE = \tanh^2 (\kappa_{\text{HR}} L).$$  \hspace{1cm} (3)

According to Eq. (2), $\kappa_{\text{HR}}$ is determined by both the group indices and the coupler’s mode-gap size $\Delta \lambda_{\text{gap}}$. By examining the dispersion curves of the fundamental modes of the W1 SC and HC waveguides in Fig. 2, we find that they remain quite straight throughout $\Omega$. It is further found that this conclusion holds for a wide range of $r_{H}$ (or $r_{R}$), i.e., dispersion curves of all these W1 hole (or rod) waveguides remain straight across $\Omega$, and their slopes change slightly with $r_{H}$ (or $r_{R}$). In this scenario, the group indices $n_{g,H}$ and $n_{g,R}$ can be both viewed as constants. As a result, $\kappa_{\text{HR}}$ is solely determined by $\Delta \lambda_{\text{gap}}$, which means the compact size and the wideband coupling can be achieved at the same time. As shown in Fig. 5, an optimized coupler design with $r_{H0} = 0.56r_{H}$ and $r_{R0} = 0.30r_{R}$ is found to have a large mode-gap of $\Delta \lambda_{\text{gap}} = 0.015(2\pi/a)$, centered at $\lambda_{\text{gap}} = 0.551(2\pi/a)$, which satisfies our requirements. At the anti-crossing point $k_{\text{y}} = 0.28(2\pi/a)$, two group indices are computed as $n_{g,H} = 6.17$ and $n_{g,R} = 6.06$ [16], and $\kappa_{\text{HR}}$ is calculated as 0.046(2$\pi/a$). Thus, a coupling efficiency of $CE = \tanh^2 (\kappa_{\text{HR}} L_{c}) = \tanh^2 (\pi) = 99.3\%$ is achievable within a distance of $L_{c} = 15.4a$. At this $k$ point, the two propagation constants, $|\beta_{H}| = 0.72(2\pi/a)$ and $|\beta_{R}| = 0.28(2\pi/a)$, also satisfy the Bragg condition, i.e., $|\beta_{H}| + |\beta_{R}| = 2\pi/a$.

The next issue is to design two lossless mode-evolution waveguides or adiabatic tapers for the two W1 waveguide families. By the adiabatic theorem, a long taper can guarantee a smooth mode evolution with a negligible transition loss [25]. On the other hand, both the requirements of a compact device size and the low material absorption necessitate short tapers. We investigate the propagation loss of tapers of various lengths, and find that a taper length of $20a$ is sufficient to achieve a loss below 1% for both types of waveguides.

The last design issue is regarding the 60° bends (see Fig. 6), which are used to separate the output channel from the input one. In principle, such waveguide bends are not needed in the conversion process and we can simply bring the two engineered waveguides to close proximity to construct the converter. However, in practical simulations, sources can excite not
only the desired polarization but also the other one when the two waveguides are placed in the adjacent layers. Introducing 60° bends can separate the SC and HC waveguides to be far away, which avoids the excitation of undesired modes and guarantees the simulations’ accuracies. In addition, the study of sharp bends in 3D PhCs also enriches the ways in which photonic integrated circuits are designed. Due to the 3D PBG confinement, an averaged transmission of ~95% is observed even in a bend without any engineering, across a range from 0.542(2π/a) to 0.556(2π/a). The transmission is further improved to ~99% through tuning the radii of $D_1$ and $D_2$ (in dark green in Fig. 6) to be $r_{D1} = r_{D2} = 1.6r_R$. It remains close to unity when $r_{D1}$ and $r_{D2}$ vary around these values. As shown later, the tuning of $r_{D1}$ and $r_{D2}$ plays a crucial role in improving the converter’s performance in the presence of defects in the hole layer.

4. Converter FDTD simulation and optimization

The first simulated structure is constructed through directly connecting each optimized waveguide element in succession. The calculation domain sizes of the FDTD simulations [26] are $5\sqrt[3]{3a} \times 276a \times 3\sqrt[3]{3a}$ ($x \times y \times z$), where a sufficient number of periods of crystals are used in the transverse plane and the large size in $y$ guarantees the complete separations of the pulses of interest during the simulations. Perfect-matched layers (PMLs) are used in $y$ directions, whereas the periodic boundary condition (PBC) is adopted in the transverse $x$-$z$ plane.

With a TE pulsed input in Gaussian temporal profile, the spectra for the converted TM wave at port $B$, TE/TM residuals at port $C$, TE reflection to port $A$, and their summation are plotted in Fig. 7. The conservation of power guarantees the accuracy of the simulation, despite the challenge in simulating pulse propagation at frequencies close to the slow-light region of the TM mode. We observe a conversion efficiency of 80% above 0.547(2π/a), which is, however, limited by the severe reflection throughout the full frequency range. Meanwhile, the rapid increase of the residual signal below 0.547(2π/a) raises another concern.

![Fig. 7. The TE to TM conversion spectra of the first converter design. The blue, green, black, and red curves represent converted TM, TE/TM residual, TE reflection, and their summation.](image)  

To meet the requirements of a high signal isolation and a low device insertion loss, the wideband reflection must be suppressed. Based on the fields’ snapshots, the strong reflection is attributed to the wave scattering by $D_1$, and to the waveguide impedance mismatch, i.e., the abrupt index change behind $D_1$. The problem of the scattering by $D_1$ is solved through tuning $D_1$’s radius from $1.6r_R$ to $1.4r_R$. To match the impedance, the entire W1 hole mode-evolution waveguide is shifted by $6a$ with respect to $D_1$, i.e., 14 out of the 20 tapered holes are placed before $D_1$ whereas the other 6 tapered holes replace the first 6 holes in the coupler.
Fig. 8. The snapshots of $E_z$ and $H_z$ fields through the mid-plane of each layer at different times show the TE to TM conversion process in an optimized converter. The red and blue arrows indicate the flow directions of the input TE and output TM, respectively.

With these measures, the TE input is efficiently converted to a TM wave with a quite low scattering loss and a minor reflection. In Fig. 8, the snapshots of the dominant fields through the middle plane of each layer are drawn at different times, showing the mode conversion process. An efficiency of more than 98% is achieved throughout the frequency range from $0.5474(2\pi/a)$ to $0.5532(2\pi/a)$ (Fig. 9(a)). This corresponds to a bandwidth of ~16 nm centered at 1550 nm, if $a$ is chosen as 853 nm. In the same range, both the reflection and residual remain below -20dB, as plotted in Fig. 9(c). The bandwidth for a conversion efficiency of 95% is 20 nm. Given that the envelope of the TM wave in the coupler region is in a hyperbolic sinusoidal form, $\kappa_{HR}$ is retrieved as $0.05(2\pi/a)$, which is very close to the calculated value of $0.046(2\pi/a)$ by Eq. (3). This value suggests that the efficiency of 98% is achieved within a coupling distance of shorter than $20\lambda$, which leads to a total converter length of less than $40\lambda\approx25\mu m$. Moreover, the simulation for the TM to TE mode conversion is also performed, which clearly shows the reciprocal transmission of the device (see results in the linear scale in Fig. 9(b) and in the logarithm scale in Fig. 9(d), respectively).
Polarization rotators or converters, based on mode evolution, mode coupling or birefringence, have been proposed or demonstrated in compact sizes in planar photonic circuits [27–32]. Compared to these designs, our device has an infinitely high polarization extinction ratio, which is a consequence of the single-mode features of the W1 SC and HC waveguides throughout Ω. Moreover, the conversion here is between modes guided by different mechanisms, i.e., TE mode by total internal reflection and TM mode by photonic band-gap. Our device has a low insertion loss, yet is compact in size, both of which facilitate the integration of such devices with other functional modules. The converter bandwidth, which covers most of the targeted Ω range, is also sufficient for a wide range of applications in 3D PhC integrated circuits.

Comparing spectra in Fig. 9(a) with those in Fig. 7, we find that although the reflection is suppressed at the low frequencies by defect tuning and index matching, it is paid off by the raise of the reflection above 0.5532/(2π/λ). Further reduction on reflection might be possible if radius tuning is applied to individual rods and/or holes around D1. Moreover, the problem of rapid growth of the residual wave below 0.5474/(2π/λ) still exists, which limits the conversion efficiency and the operation bandwidth considerably. This growth is partially due to the insufficient coupling in the low frequency range, where kHR drops quickly from the value at \( k_{HR, \text{gap}} \). One solution is cascading another coupler with a lower center frequency, to cover a wider frequency range and to improve the overall value of kHR throughout Ω.

The 3D PhC converter could be fabricated using a layer-by-layer approach, where a bi-layer of rod and hole slabs is fabricated on a silicon-on-insulator (SOI) wafer and the 3D structure is stacked up using a wafer bonding approach. First, given a bi-layer structure, where a rod layer sits completely over a hole layer without any features underneath the rods, as that shown in Fig. 6, one can use a two-step etch process to define the two layers sequentially [33]. The precise alignment between the upper and lower layer can be achieved with electron-beam lithography. Then, another SOI wafer can be bonded to the fabricated bi-layer, and the substrate of the bonded SOI wafer can be wet etched away using the buried oxide as the etch-
The same process can be applied to pattern the bonded silicon layer to achieve another bi-layer, and to add another single crystalline silicon layer for patterning [34]. The whole PhC structure can be built up using multiple cycles of bi-layer patterning and wafer bonding processes.

5. Conclusion

In conclusion, a mode and polarization converter based on the contra-directional mode coupling is designed to realize the communication between the indexed-guided TE mode of a W1 SC waveguide and the PBG-guided TM mode of a W1 HC waveguides in 3D PhCs. Such conversion is essential for the construction of 3D photonic integrated circuits. An efficiency of more than 98% is achieved over a bandwidth of 16 nm centered at 1550 nm. In the same frequency range, both the reflection and residual remain below ~20dB. The polarization extinction ratio of the conversion is in principle infinitely high, because both the W1 SC and HC waveguides operate in the single-mode regimes in this wavelength range. The device is 25μm-long, including a compound waveguide coupler and two mode-evolution waveguides. In addition, a 60° rod waveguide bend is also studied, and incorporated into the converter design to separate the output channel from the input one, which demonstrates an efficient integration of sharp waveguide bends with functional modules in 3D PhCs.

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