Fiber and Integrated Optics, 25:29–40, 2006

ISSN: 0146-8030 print/1096-4681 online
DOI: 10.1080/01468030500332283

Transmission Characteristics of 90° Bent Photonic Crystal Waveguides

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There are several key factors that affect the transmission characteristics of the 90° (L-shaped) bent photonic crystal waveguides. The first factor is the direct coupling efficiency from the incident lights into the waveguides. The second one is the bandgap deviations of the photonic crystals. And the third factor is the optical reflections in the bent corners. In this article, we compare three types of L-shaped bent photonic crystal waveguides. One is the original type, which has an abrupt right-angle bend. Another is an improved 90° bend with a 45°-mirror. The other is an L-shaped bent photonic crystal waveguide with a 45°-transitional section. We investigate their respective frequency responses and observe the improvements in the total transmission efficiencies provided by the latter types.

Keywords 90° (*L*-shaped) bent photonic crystal waveguides, transmission efficiency

Introduction

A photonic crystal is often utilized in modern optoelectronic devices. It is a 2-D or 3-D periodical structure, and the period is identical to the order of the optical wavelength. Some important and interesting characteristics of the photonic crystal have been investigated. A common tool for obtaining the band structure diagram of the 2-D perfect (no lattice defects) photonic crystal is the plane-wave expansion method. The band diagram

Received 14 February 2005; accepted 14 May 2005.
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can be employed to select the appropriate operating frequency range of the photonic crystal devices. And the finite-difference time-domain (FDTD) method is often utilized to simulate the propagation of lightwave in the photonic crystal waveguide (PCWG). However, the analytical or quasi-analytical modal functions of the PCWG are difficult to derive. Thus the relevant characteristics, such as the coupling efficiencies from the incident lights to the PCWG, are seldom studied.

A PCWG is composed of linear vacancies (defects). These vacancies can trap photons and inhibit them from escaping into the bulk crystal. In this way, the PCWG has the better optical confinement than the conventional waveguides based on internal reflections of lights. Until now, many PCWG devices, including the wide-angle bent channel waveguides, the wide-angle Y-branches, the T-junctions, and the Mach-Zehnder interferometers, have been proposed [1–7]. Generally, the wavelength of the incident light is selected within the bandgap of the perfect photonic crystal, such that the whole lightwave propagates only along the channel waveguide created by the linear vacancies. Ideally, there should be no optical power losses. However, the reflections of lights caused by the air-to-PCWG interface and the bent corner may be generated. And the mismatches between the incident lights and the guided modes also result in optical losses. Moreover, the exact bandgap may deviate from the ideal one because of the lattice defects. Hence, the transmission efficiency of lightwave propagating along the wide-angle bent PCWG will degrade. For these reasons, a proper pattern of the bent waveguide for reducing the power losses is very important.

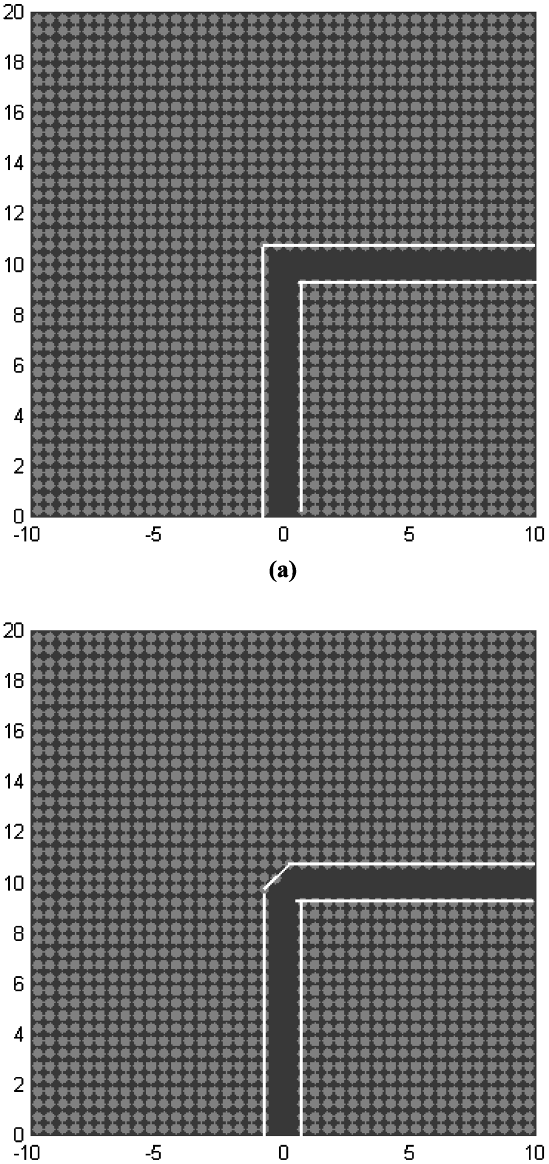
A 90° (L-shaped) bent channel waveguide is more significant than a small-angle bent one. It provides the more flexible layout of the photonic device because the total dimension of the device can be reduced. In this article, we investigate the optical performances of three different types of L-shaped bent photonic crystal waveguides and study their respective optical transmissions and other relative characteristics.

Three Types of 90° Bent Photonic Crystal Waveguides

Consider a 2-D photonic crystal comprising circular dielectric pillars in air on a square array. The lattice constant of the photonic crystal is a and the radius of the pillar is R_c. In this study, we omit two rows of pillars to create a channel waveguide. Figure 1a shows an original type of 90° bent PCWG, Type (I), which has an abrupt right-angle bend, and we depict the shape of the bent channel waveguide in solid lines. Figure 1b presents a modified pattern, Type (II), in which an additional pillar was placed in the left corner of the L-shaped bent channel region. Its topology is like a 45°-mirror as depicted as in solid lines. Figure 1c describes another modified bent structure, Type (III), in which a pillar was added in the left corner but another pillar was removed in the right corner. The bent region is similar to a 45°-transitional section, as depicted in solid lines. For improving the transmission characteristics of the wide-angle bent PCWG, adding or removing some pillars in the corners is common [1, 4, 7]. In our study, the fewest pillars were added or removed for simplicity.

Simulation Results

In our simulation cases, we select lattice constant as $a = 0.5\ \mu$m. The radius and the refractive index of the pillar are $R_c = 0.225\ \mu$m and $n = 3.16227766$, respectively. The space between the pillars is air-filled. Figure 2 is the band-structure diagram of the 2-D square-lattice photonic crystal obtained by the plane-wave expansion method. There exist



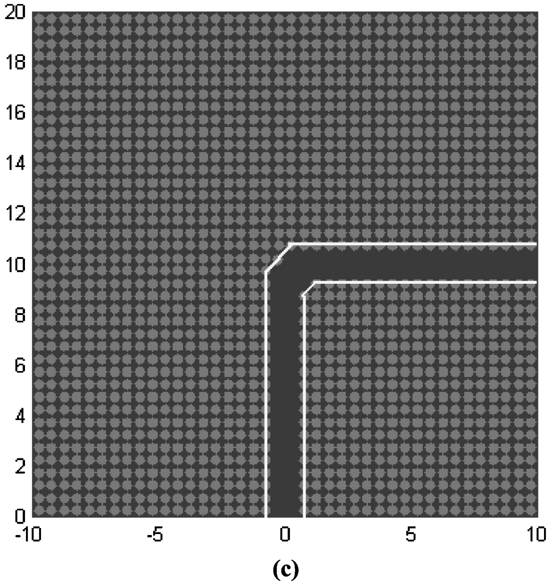
(a)

(b)

Figure 1. (a) Type (I) 90°-bent PCWG with an abrupt-right-angle corner. (b) Type (II) 90°-bent PCWG with an additional pillar placed in the left corner of the bent channel.

two band gaps for the TE modes. The bandgap in the higher normalized frequency (a/λ) range is much narrower than the other. It is between 0.551267916 and 0.568181818; the wider band gap is from 0.317368724 to 0.406173842.

For studying the transmission characteristics of the 90° bent PCWG, we select the half beam width $w_0 = 4.0$ μm and a certain normalized frequency within the band gap, say $a/\lambda = 0.4$, for simulation. Firstly, combining the FDTD method [8] with



(c)

Figure 1. (c) Type (III) 90°-bent PCWG with a pillar was added in the left corner but a pillar was removed in the right corner of the bent channel.

the perfectly matched-layer (PML) boundary condition [9], we developed a MATLAB program to simulate that the Gaussian beam is incident on the Type (I) bent PCWG. The input port of our simulated PCWG is 10 μm long and takes a right-angle turn. And the length of the output port is also 10 μm. Figure 3 presents the power intensity contour of the TE-polarized light being coupled to the bent PCWG from air. The incident optical power is partially blocked by the bulk crystal, and only a fraction of the incident light enters the PCWG because of the beam width (8 μm) larger than the PCWG's aperture. The backward and incident lights interfere with each other and become a few ripples on the air-to-PCWG interface. On the other hand, owing to the short length (10 μm) of the input port, the modal conversion from the incident Gaussian beam into the guided mode is incomplete and results in the modal conversion loss. Furthermore, the strong reflection occurs in the abrupt bent corner. Therefore, the total transmission efficiency of the Type (I) bent structure is poor.

For intensively investigating the modal conversion loss and blockage of light, we utilize the FDTD method to compute the direct coupling efficiencies from the incident Gaussian beam into a 10 μm long straight photonic crystal waveguide. Our coupling efficiency is defined as the ratio of the power at the exit of the 10 μm long straight PCWG over the incident power. The length of the straight PCWG is the same as the input port of the previously simulated bent one. For a certain normalized frequency, $a/\lambda = 0.4$, Figure 4a describes that the coupling efficiency decreases from 0.4138 to 0.1750 as the half beam width increases from 0.5 μm to 4 μm. This results because the fraction of optical power into PCWG's aperture is decreasing. Mismatch between the incident Gaussian beam and the waveguiding mode also becomes more serious. In this figure, the starting value of w_0 is 0.5 μm. In fact, the incident light is hardly converged within the spot size of which radius is less than this value. Thus we fix $w_0 = 0.5$ μm and vary the operating wavelength from 0.85 μm to 1.75 μm by the increment $\Delta\lambda = 0.05$ μm. That is, the normalized frequency a/λ is scanned from

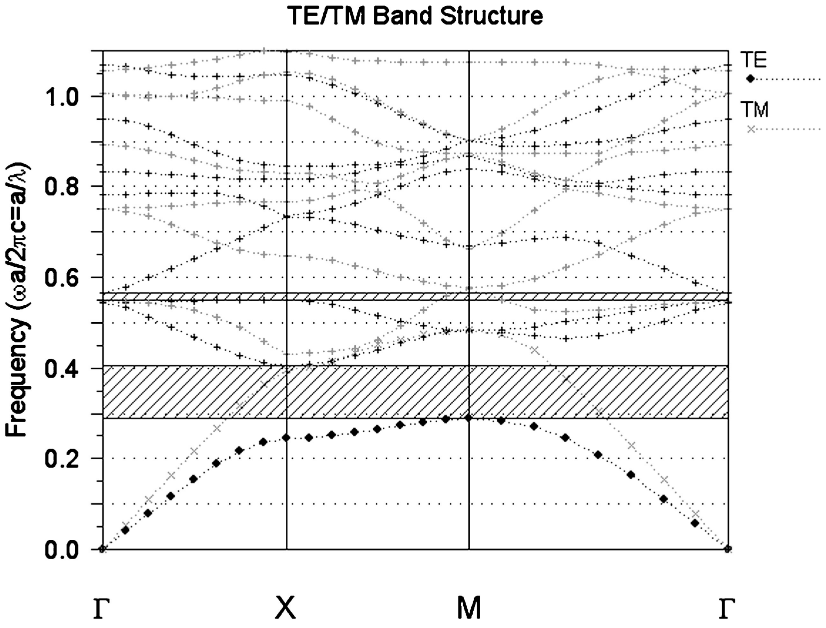


Figure 2. The band structures of the 2-D square-lattice photonic crystal with the lattice constant is $a = 0.5$ μm. The radius of the pillar is $R_c = 225$ nm. The refractive index of the pillar is 3.16227766.

0.588241 to 0.2857, which covers both bandgaps of the above perfect photonic crystal. It presents the direct coupling efficiency spectrum. All the efficiencies are less than 0.5. Figure 4b shows the serious modal conversion losses. The propagation distance of light along the PCWG is not long enough to make a complete modal conversion. There are two better coupling-efficiency windows in Figure 4b. The optimal coupling efficiency, 0.4138, is attained at $a/\lambda = 0.4$. In case a Gaussian beam of $w_0 = 0.5$ μm is injected

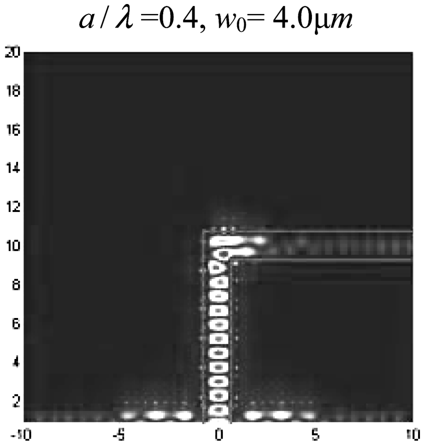
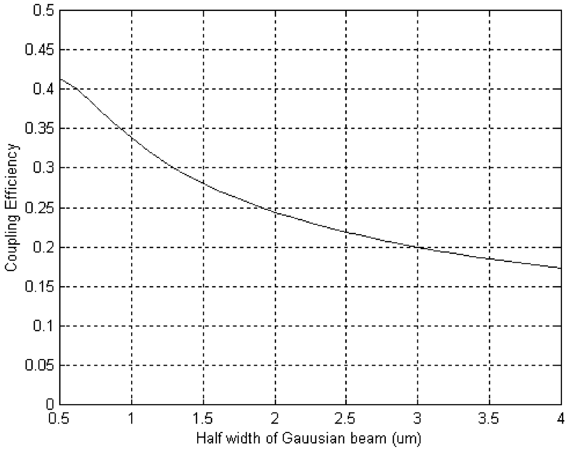
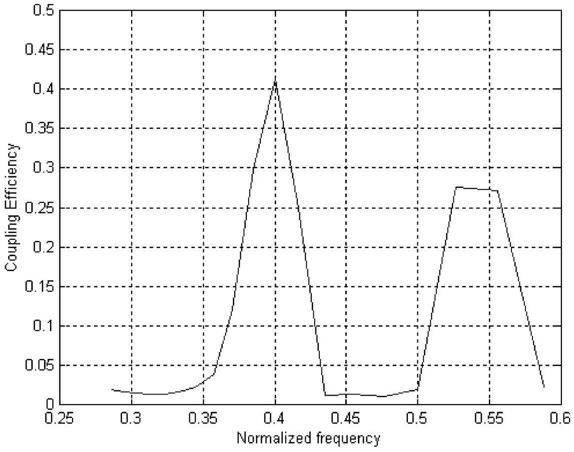


Figure 3. The power intensity contour of the light propagating along the 90°-bent PCWG with an abrupt right-angle bend.



(a)



(b)

Figure 4. A 2-D Gaussian beam is directly coupled into a 10-μm long straight PCWG. (a) The relation of the coupling efficiency and the incident half width. (b) The relation of the coupling efficiency and the normalized frequency.

into Type (I) bent PCWG of 10 μm long input port, the total transmission efficiency (output/input power ratio, P_O/P_I) should be less than 0.4138 because an extra bent-corner reflection occurs. On the other hand, Figure 4b also shows that the better coupling-efficiency window in the lower normalized frequency range is not in good agreement with the wider band gap ($0.317368724 < a/\lambda < 0.406173842$) of the perfect photonic crystal. The other better coupling-efficiency window is also different from the narrower bandgap ($0.551267916 < a/\lambda < 0.568181818$). This shows that bandgap deviations exist.

For studying the transmission characteristics of the three types of 90°-bent PCWG, we fix $w_0 = 0.5$ μm and vary a/λ. All the input and output ports of the PCWGs are 10 μm long. Figure 5 presents a comparison of the total transmission spectra among them. Table 1 lists the calculated P_O/P_I values. At $a/\lambda = 0.4$, the peak of the total transmission efficiency of Type (I) drops to 0.1298 due to strong optical reflection in the bent corner.

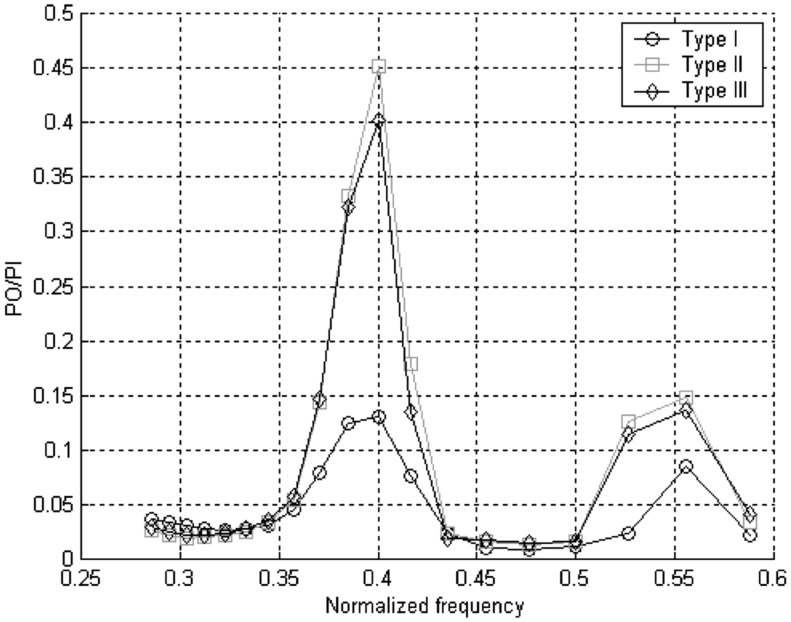


Figure 5. A comparison of the total transmission efficiencies (output/input power ratios, P_O/P_I) among the three types of 90° bent PCWGs.

Table 1
Output/input power ratio (P_O/P_I) of three types of L-shaped bends

Normalized frequency (a/λ)	P_O/P_I of Type (I) bend	P_O/P_I of Type (II) bend	P_O/P_I of Type (III) bend
0.28571	0.0367	0.0257	0.0288
0.29412	0.0342	0.0219	0.0242
0.30303	0.0303	0.0186	0.0213
0.31250	0.028	0.0198	0.0224
0.32258	0.0267	0.0215	0.0241
0.33333	0.0272	0.0249	0.0275
0.34483	0.0304	0.033	0.0355
0.36714	0.0457	0.0544	0.0574
0.37037	0.079	0.1439	0.1472
0.38462	0.1249	0.3335	0.322
0.40000	0.1298	0.4522	0.4024
0.41667	0.0758	0.1788	0.1351
0.43478	0.0234	0.0235	0.0197
0.45455	0.0108	0.0168	0.0176
0.47619	0.0093	0.0133	0.014
0.50000	0.0118	0.0157	0.0167
0.52632	0.0236	0.126	0.1142
0.55596	0.0844	0.1478	0.1365
0.58824	0.0215	0.0341	0.0408

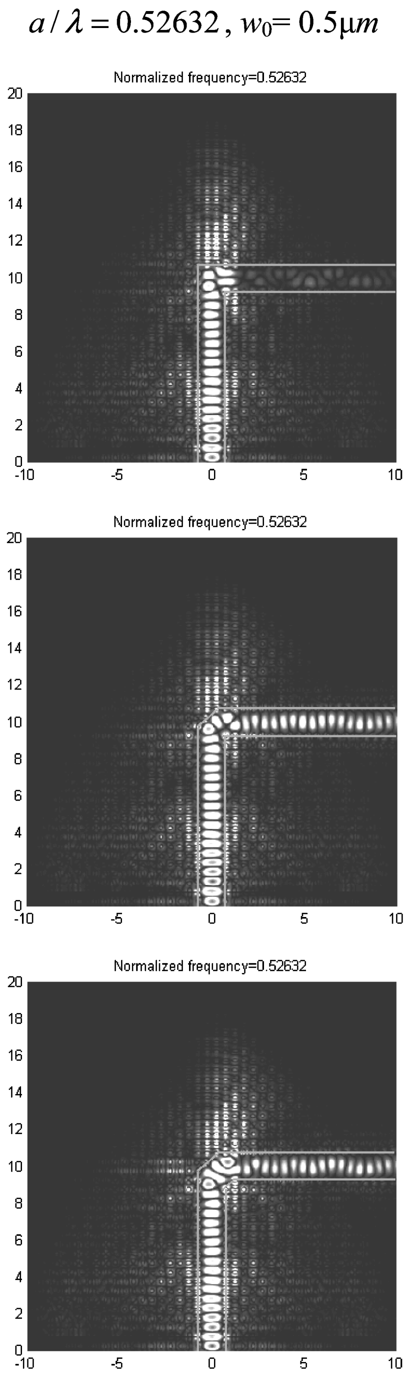
But the optimal P_O/P_I of Type (II) is as high as 0.4522 and that of Type (II) is 0.4024. It shows that Type (II) and Type (III) structures have the much better optical transmission characteristics than Type (I) bend, because the undesired bent-corner reflections can be lowered with assistance of the 45°-mirror or the 45°-transitional section. On the other hand, the performance of Type (II) structure is somewhat superior to that of Type (III).

Figure 6a describes the improvements provided by Type (II) and Type (III) 90° bent PCWGs. Given $a/\lambda = 0.52632$ and $w_0 = 0.5\ \mu$m, the upper diagram shows the power intensity contour of the TE-polarized light propagating along the Type (I) bent structure. It is obvious that very little power takes a turn along the bend. But both the middle and the lower diagrams describe much more power can be guided along the Type (II) and Type (III) bent structures. Although this normalized frequency is not within the two bandgaps of the photonic crystal ($0.317368724 < a/\lambda < 0.406173842$, and $0.551267916 < a/\lambda < 0.568181818$), it demonstrates that an extra 45°-mirror or the 45°-transitional section may compensate for power losses. Figure 6b shows a phenomenon similar to Figure 6a. At $a/\lambda = 0.4$, which is within one of the bandgaps but near its margin, the optical guidance of Type (I) PCWG seems not very good. But the same lightwave can propagate very well along the other types of bent PCWGs. It shows that the bent-corner reflections can be improved with assistance of the 45°-mirror or the 45°-transitional section. On the other hand, given a higher normalized frequency ($a/\lambda = 0.55596$), Figure 6c shows that all the three types of L-shaped bent PCWGs have good transmission characteristics. Comparing this figure with Figures 6a and 6b, the propagating paths of the lights along the waveguides become zigzag at this a/λ. According to classical theory of guided wave, it implies that the higher-order eigenmodes are excited, and the PCWG become a multimode waveguide at the higher normalized frequency.

Conclusions

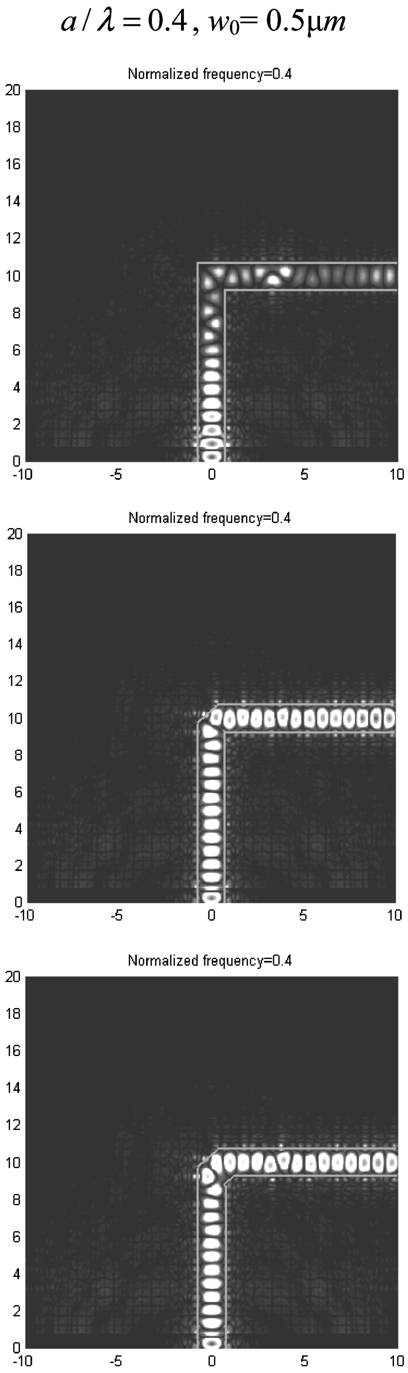
Some conclusions are drawn in our simulation as follows.

1. The coupling efficiency from an incident Gaussian beam to a PCWG will decrease by enlarging the beam width, because the less fraction of input power can enter the aperture of the PCWG. Another reason is the more serious modal mismatch between the incident lights and the guided modes. It often needs quite a long distance to convert the former into the latter to reduce the modal conversion loss.
2. Owing to the bandgap deviations of the linear vacancy photonic crystals, the better coupling-efficiency window is not in very good agreement with the bandgap of the perfect photonic crystal.
3. The transmission efficiency of the L-shaped bent PCWG can be improved by adding an extra 45°-mirror or a 45°-transitional section. And the improved structure with a 45°-mirror is somewhat superior to that with a 45°- transitional section.
4. At the higher normalized frequency, the higher-order eigenmode of the PCWG may be excited by the incident light. In this case, the propagating path of the eigenmode along the PCWG looks zigzag.
5. Adding or removing some pillars in the bent region is an easy way of improving the transmission characteristics of the bent PCWG. In the near future, other conventional types of bent structures, like a circular bend, an S-bend, and their respective modifications, can be proposed and analyzed according to the concepts shown in this article.



(a) $a/\lambda = 0.52632$

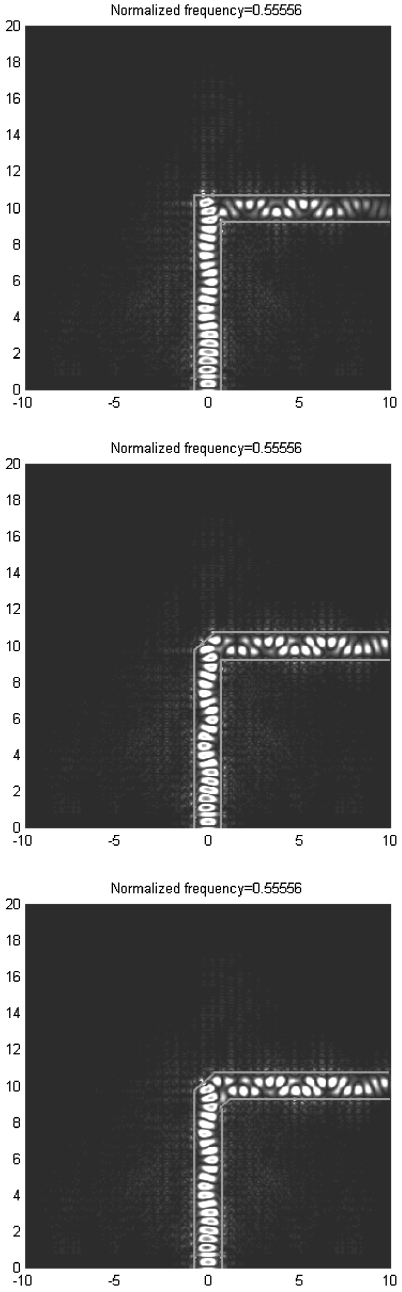
Figure 6. The total power intensity contours of the TE-polarized lights of propagating along the three types of 90° bent PCWGs. (*continued*)



(b) $a/\lambda = 0.4$

Figure 6. (*Continued*).

$a/\lambda = 0.55596$, $w_0 = 0.5\mu m$



(c) $a/\lambda = 0.55596$

Figure 6. (*Continued*).

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Biographies

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