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Transmission characteristics of various bent periodic dielectric waveguides

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Abstract The transmission characteristics of various bent periodical dielectric waveguides (PDWGs) are analyzed by the finite-difference time-domain (FDTD) method in this work. The bending structures include a conventional 90° abrupt bend, a 90° transitional bend, and 90° circular arcs with different quantized radii of curvatures. The simulation results can make us to design a suitable bent PDWG in the photonic circuits.

Keywords Periodical dielectric waveguide (PDWG) · Finite-difference time-domain (FDTD) method

1 Introduction

The waveguide bending is an interesting subject of the researching guided-wave theory. And many phenomena have been investigated. In order to reduce the bending loss, the types of waveguides and bending structures should be carefully selected. For example, a conventional dielectric waveguide is not a good candidate for forming a wide-angle bend. It confines the propagating light wave within the core region by serial total reflections on the interfaces between the core and the cladding regions. In case a wide-angle bend exists, the condition of the total reflections on the core-cladding interfaces may be violated due to the bending section. It results in serious radiation loss. For this reason, we must seek other candidates to implement a wide-angle bent waveguide.

A periodical dielectric waveguide (PDWG) had been shown that it is a suitable structure to form an arbitrarily-shaped bend (Fan et al. 1995, Luan and Chang 2006). It consists of a linear array of cylinders/holes to build an optical channel. When the operating frequency is high, the theory of PDWG is very similar to a coupled resonator optical waveguide (Yariv et al. 1999; Mookherjea 2005). Each cylinder/hole can be seen as a coupled resonator with high quality

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factor. And the optical power can be successively coupled from one cylinder/hole to the next one. In this way, the light can be well guided along the desired optical path. On the other hand, in case the operating frequency is low enough (the wavelength becomes very long); the gap between the adjacent cylinders/holes may become negligible. In this case, the behavior of PDWG is just like a conventional dielectric waveguide (Luan and Chang 2006). Comparing with a photonic crystal waveguide (PCWG), the structure of PDWG is much simpler because the former is often implemented by building an optical channel within a large bulk region of photonic crystal. In modern photonic circuitry, all optoelectronic components and elements are as tiny as possible. Therefore, the application of PDWG in integrated optics is becoming more and more important because it occupies less area on a chip. Moreover, PDWG has another advantage. The bending structure of PDWG is more flexible than PCWG because a one-dimensional array of periodical cylinders/holes can be easily formed into arbitrary shape. However, PCWG is strictly limited by the lattice of photonic crystal. For example, a 60°-abruptly-bent PCWG can be easily implemented in the hexagonal-lattice photonic crystal (Fukaya et al. 2000; Frandsen et al. 2004; Rauscher et al. 2004). And a 90°-abruptly-bent PCWG is also easily fabricated in the photonic crystal of square lattice (Lee et al. 2006). If one wants to build the above two bending structures on the lattice-mismatching photonic crystals, the patterns are hardly designed. In other words, not only building a 60°-abruptly-bent PCWG in a square-lattice photonic crystal is difficult but fabricating a 90°-abruptly-bent PCWG in a hexagonal-lattice photonic crystal is also very hard.

Among basic integrated optical devices, a curved dielectric waveguide is a very common structure (Hunsberger 1982). It is superior to an abrupt bend because the latter often has larger bending loss. Another improvement method of reducing the bending loss of the abrupt bend is to replace it by a transitional bend. Although some other researchers had analyzed the arbitrarily-shaped bends based on PDWGs an earlier mention, their efforts were mostly focused on 2D cases (Fan et al. 1995, Luan and Chang 2006). In other words, the heights of cylinders in PDWG ware not taken into account in their studies. Therefore, their results may be not very suitable to the realistic 3D bent PDWGs. In this paper, we analyze a 90° transitionally-bent PDWG which comprises finite-height cylinders and the curved ones with various radii of curvatures. The heights of cylinders in these types of PDWGs have been considered in our simulation. And we compare their performances with a typical 90°-abruptly-bent PDWG. Their respective optical transmissions, incorporated with the effect of the height of cylinders, are investigated by the finite-difference time-domain (FDTD) method (Yee 1966). The simulation results can make us to determine the proper structural parameters of various bent PDWGs.

2 Descriptions of various bent PDWGs

Consider a typical PDWG consisting of a sequence of cylinders and the corresponding coordinate system, as shown in Fig. 1. The height and the radius of each cylinder are h and r, respectively. Let a (lattice constant) denote the distance between the centers of the adjacent cylinders. The refractive indices of the substrate and the cylinder are n_s and n_{cl}, respectively. On the other hand, the x-axis, the y-axis, and the z-axis are respectively directed in the upward direction, the lateral direction, and the direction of the input guide. The coordinate system is also adopted in the following PDWG structures. Figure 2a and b present the top views of a conventional 90° abruptly-bent PDWG and a 90° transitionally-bent one, respectively. Observing Fig. 2a, when the light of high frequency arrives at the bending corner, the lateral coupling from the corner cylinder A to the left nearest one B is very small. And hence the

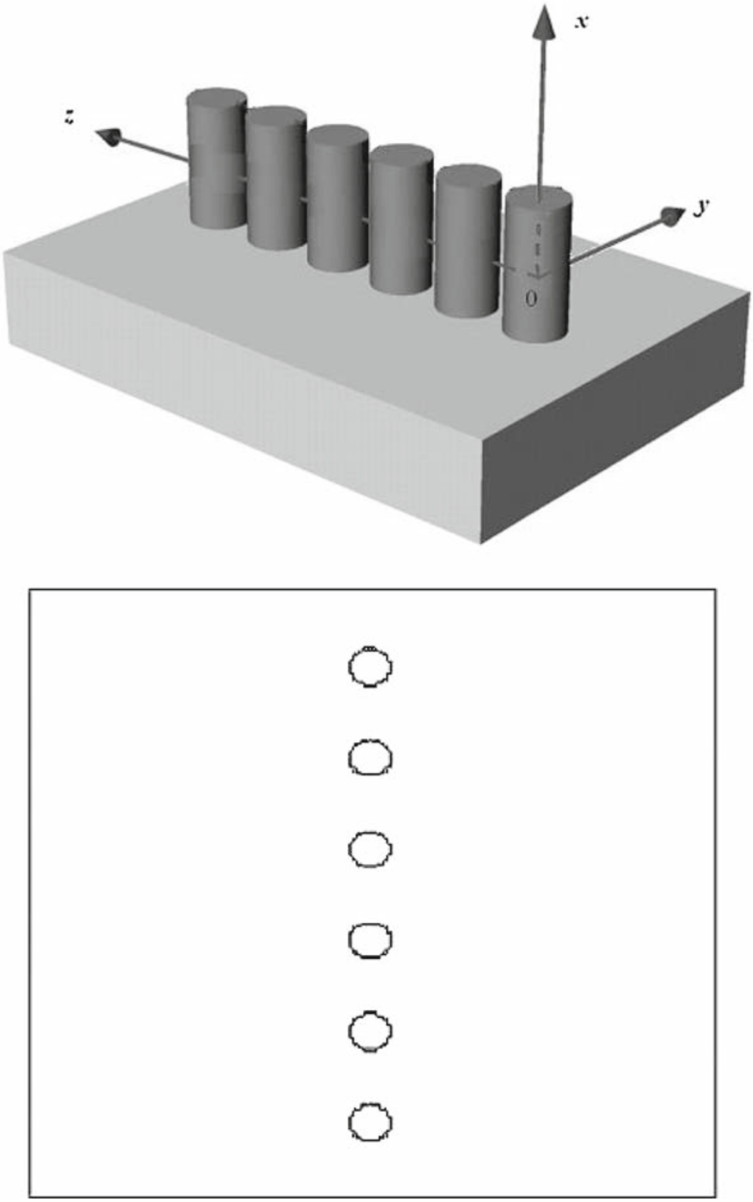

Fig. 1 A three-dimensional (3D) PDWG of height *h* and the relevant coordinate system

transmission efficiency of the 90° abruptly-bent PDWG may be poor. The 90° transitional bend in Fig. 2b is just moving the original corner cylinder *A* to the middle position of the both cylinders *B* and *C*. Like this, the total coupled power from cylinder *C* to cylinder *A* and then from cylinder *A* to cylinder *B* may be larger than that of the original structure. Like this, the transmission efficiency can be improved. On the other hand, in case the frequency of the light is low, the geometry of the 90° transitional bend is like that a short 45° transitional section

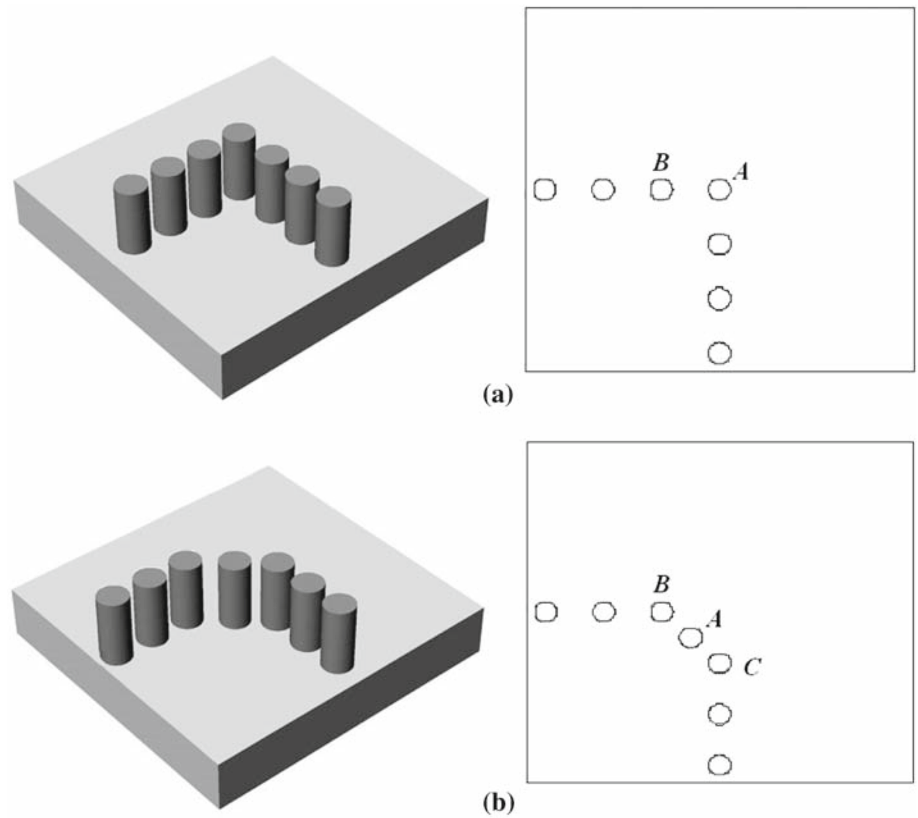

Fig. 2 **a** A 90° abruptly-bent PDWG. **b** A 90° transitionally-bent PDWG

was substituted for the abrupt bending corner. In this way, the transitional bending structure may decrease the radiation loss because the optical path looks not as sharp as that with an abrupt bend. According to the above statements, regardless of high or low frequencies, the 90° transitional bending structure should be preferable.

Consider another case of utilizing a curved bend to reduce the bending loss. A circularly-bent waveguide make the optical path smoother than the abruptly-bent one. Figure 3a shows the top view of a circularly-bent PDWG. Let a denote the distance between the centers of the adjacent cylinders in the straight sections. The radius of curvature of the circular bend is R. The circular bend shown in Fig. 3a can be utilized to replace the corresponding 90°-abruptly-bent PDWG presented in Fig. 3b for reducing the bending loss. Observing Fig. 3a, when $R = na$ holds ($n = 1, 2, 3, \ldots$), we have

$$\theta = \frac{\pi}{4n} \tag{1}$$

where n is an integer. The number of cylinders uniformly distributed within the arc of the circular bend in Fig. 3a is $2n-1$, which is equal to the number of the replaced cylinders within the corresponding 90° abrupt bend in Fig. 3b. In case the center of curvature of the circular bend is selected as an origin O', the centers of the cylinders occupied within the arc of the circular bend are ($R\cos\theta$, $R\sin\theta$), ($R\cos2\theta$, $R\sin2\theta$), ($R\cos3\theta$, $R\sin3\theta$),…, and

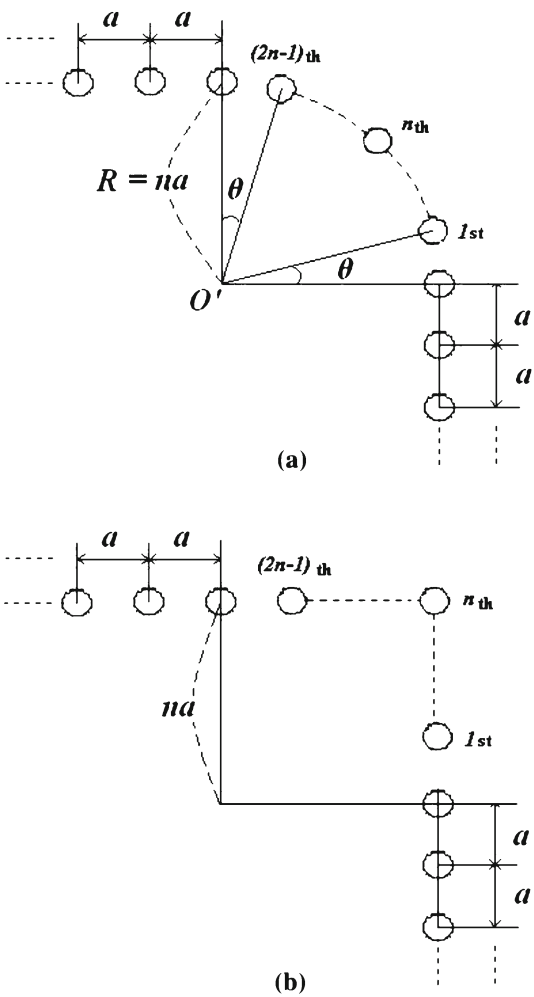

Fig. 3 **a** The top view of a circularly-bent PDWG of which circular bend has the radius of curvature $R = na$. **b** The top view of the 90° abruptly-bent PDWG corresponding to (**a**)

($R\cos[(2n-1)\theta]$, $R\sin[(2n-1)\theta]$), respectively. Note that the radius of our designed circular bend is quantized.

Figure 4(a–e) present the 3D 90° abruptly-bent PDWG and the 90° transitionally-bent one, the circularly-bent PDWGs with $R = a$, $2a$, and $3a$, respectively. We utilize FDTD method to simulate the propagation performances along these types of PDWGs and compute their respective transmission characteristics. And then the simulation results can make us to design a suitable bending structure. In the next paragraph, all the results are simulated by our developed FDTD software written in FORTRAN and MATLAB languages.

3 Losses of bent PDWGs

The total power loss of a bent PDWG comprising the finite-height cylinders results from two parts. One is the power attenuation and the other is bending loss. The power attenuation of PDWG is related to light scattering in the direction of propagation. Even PDWG is

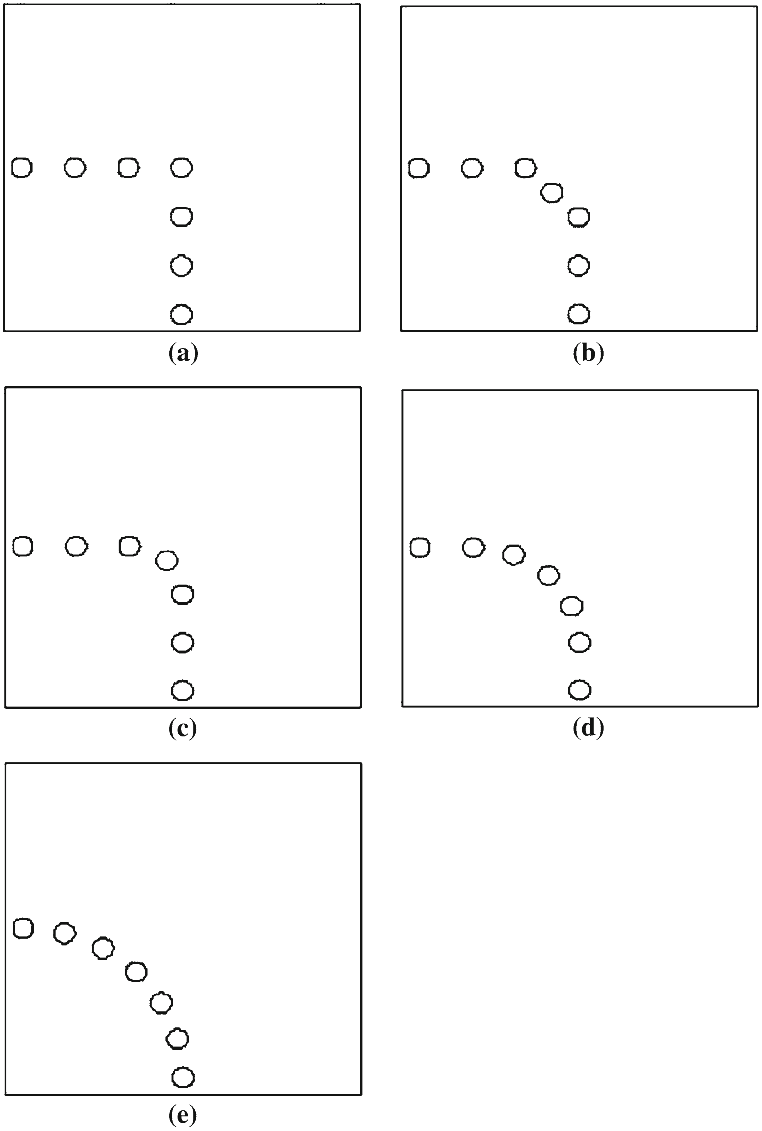

Fig. 4 **a** The top view of the 90° abruptly-bent PDWG. **b** The top view of the 90° transitionally-bent PDWG. **c** The top view of the circularly-bent PDWG with $R = a$. **d** The top view of the circularly-bent PDWG with $R = 2a$. **e** The top view of the circularly-bent PDWG with $R = 3a$

infinitely-long and straight, the power attenuation still exists. The attenuation constant can be obtained by the classical electromagnetic theory. Consider a long and straight PDWG, the attenuation constant at distance z can be expressed by

$$\alpha = \frac{P_L(z)}{2P(z)} \tag{2}$$

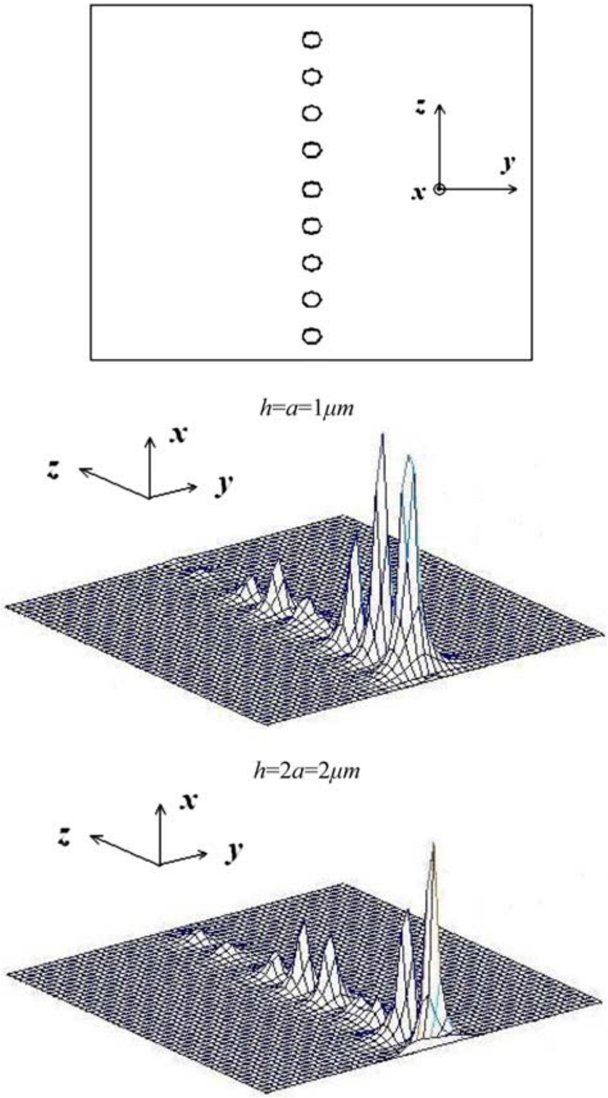

Fig. 5 Give the parameters: $a = 1\,\mu m$, $r = 0.2a$, $\lambda = 4a$, $n_s = 1.5$, and $n_{cl} = 3.4$, the calculated relative intensity profiles (on the *yz*-plane) of the TM-polarized (*x*-polarized) lights propagating along straight PDWGs in case of $h = a$ and $2a$

where $P_L(z)$ is the time-average power loss per unit length and $P(z)$ is the time-average power propagated along the waveguide. With no consideration of bending loss, the power attenuation loss is expressed by

$$\text{Power Attenuation Loss} = P_i \cdot (1 - e^{-2\alpha l}) \tag{3}$$

where P_i is the input power and l is the total length along the optical path from the input end to the output end. On the other hand, the total power loss is

$$\text{Total Power Loss} = P_i - P_o \tag{4}$$

where P_o is the output power. Because the total power loss of the bent waveguide is the sum of power attenuation and bending loss, we have

$$\text{Bending Loss} = P_i \cdot e^{-2\alpha l} - P_o \tag{5}$$

It is easily shown that the bending loss equals to the total loss if no power attenuation occurs by setting $\alpha = 0$ in (5). Unlike the power attenuation, the bending loss is due to the imperfect lateral confinement of PDWG within the bending region.

4 Simulation results

Given the typical parameters of 2D PDWG: $a = 1\,\mu\text{m}$, $r = 0.2a$, $n_s = 1.5$, and $n_{cl} = 3.4$, Luan and Chang had utilized Bloch's theorem and the FDTD method to show that the TM-polarized (x-polarized) light of wavelength $\lambda = 4a$ can be well guided by the PDWG and obtain the band structure diagram. Although the exact band gaps of 3D PDWG may be somewhat different from those of the simplified 2D cases, we still select $\lambda = 4a$ to simulate the optical performances of 3D PDWGs. In our 3D simulation, we choose an x-polarized circular Gaussian beam with half e^{-1}-width $w_0 = 2a$ as the input lightwave. After the Gaussian beam is incident on PDWG and then propagates a long distance, it gradually becomes the eigenmode of the periodical dielectric waveguide. Given $h = a = 1\,\mu\text{m}$ and $h = 2a = 2\,\mu\text{m}$, Fig. 5 shows the calculated relative intensity profiles (on the yz-plane) of the TM-polarized lights propagating along straight 3D PDWGs in steady states by FDTD simulation. Among all the figures of light propagations, only the relative power intensities on the yz-plane ($x = 0$) are depicted for simplicity. It is found that the both lights gradually decay. And the attenuation of PDWG with $h = 2a$ is more serious. On the other hand, for the y-polarized light of $\lambda = 4a$, the corresponding figures are omitted because they can not be well guided by the 3D PDWGs under the above structural parameters. Varying h from a to $3a$, Fig. 6 shows that the calculated attenuation constant is strongly dependent on h. And the relation between α and h is nonlinear.

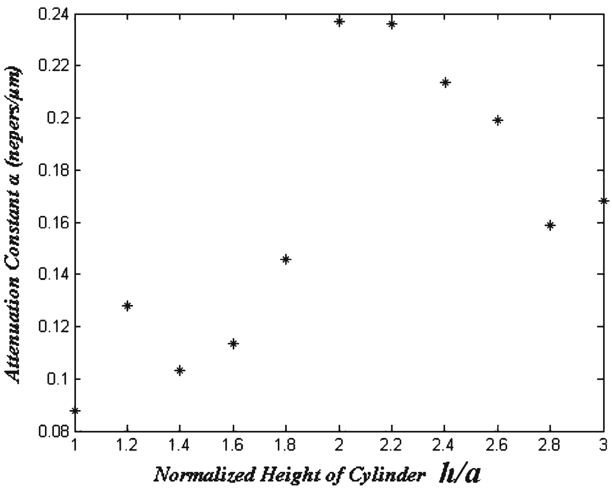

Fig. 6 Give the parameters: $a = 1\mu\text{m}$, $r = 0.2a$, $\lambda = 4a$, $n_s = 1.5$, and $n_{cl} = 3.4$, the relation of the calculated attenuation constant and the height of the cylinder

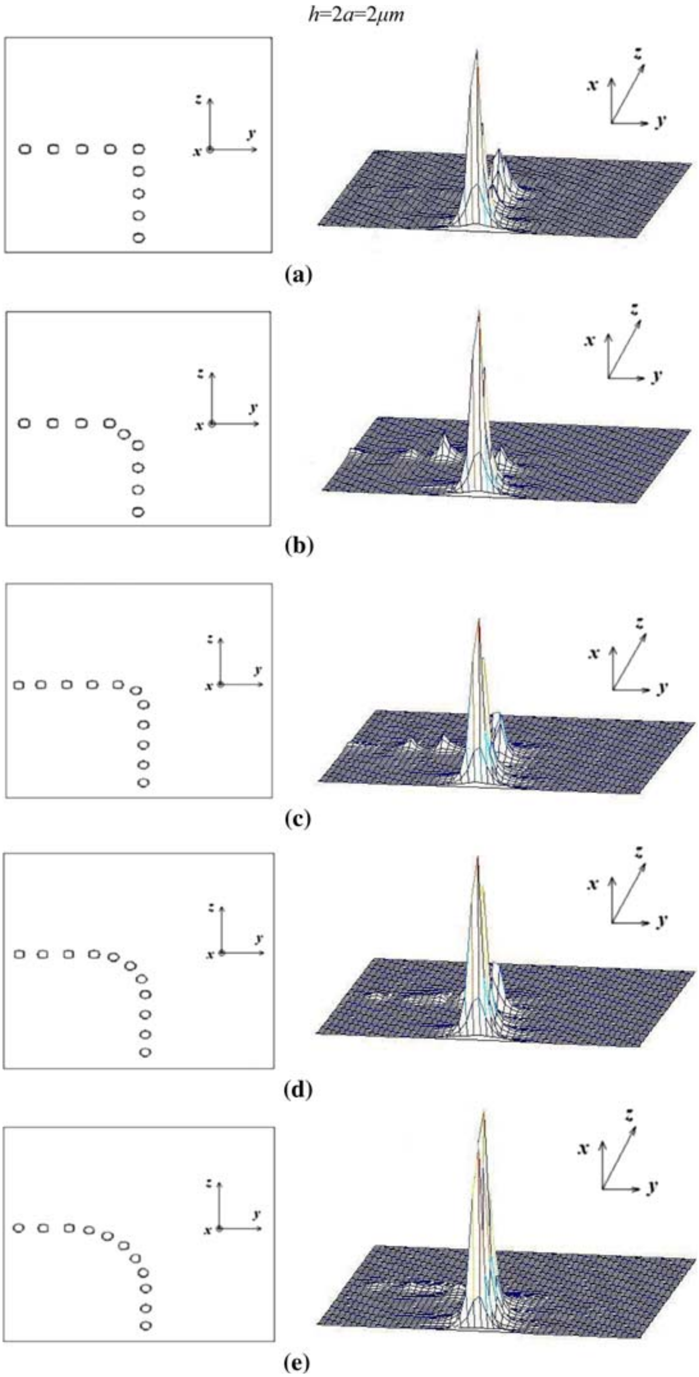

Fig. 7 Given $h = 2a$, the calculated relative intensity profiles of the x-polarized light along the various bent PDWGs. **a** The light propagates along a 90° abruptly-bent PDWG. **b** The light propagates along a 90° transitionally-bent PDWG. **c** The light propagates along a circularly-bent PDWG with $R = a$. **d** The light propagates a circularly-bent PDWG with $R = 2a$. **e** The light propagates along a circularly-bent PDWG with $R = 3a$

Table 1 Given $a = 1\,\mu m$, $r = 0.2a$, $n_s = 1.5$, and $n_{cl} = 3.4$, the bending losses of various bent PDWGs

	$h = a$	$h = 2a$	$h = 3a$
Bending loss of the 90° abruptly-bent PDWG (*d*B)	11.936	11.569	12.286
Bending loss of the 90° transitionally-bent PDWG (*d*B)	1.881	1.211	1.394
Bending loss of the circularly-bent PDWG with $R = a$ *(dB)*	2.999	7.498	2.731
Bending loss of the circularly-bent PDWG with $R = 2a$ (*d*B)	0.078	1.976	0.962
Bending loss of the circularly-bent PDWG with $R = 3a$ (*d*B)	1.306	4.667	4.935

Comparing the 90° abruptly-bent PDWG and the other bent ones, Fig. 7 presents the calculated relative intensity profiles of the TM-polarized lights of $\lambda = 4a$ propagating along these types of PDWGs for $h = 2a = 2\,\mu m$. All the other structural parameters are identical to those given in Figs. 5 and 6. It is found that the transmission efficiency of the 90° abruptly-bent PDWG is less than those of the other bends. Even the simplest modified bending structure (90° transitional bend) can improve the transmission characteristics very much. And the circularly-bent PDWGs with quantized radii of curvatures also reduce much more bending losses. Among these modified bends with different types and*h*, it is necessary to calculate the bending losses for comparing their respective performances.

For saving the computational time, we vary h from a to $3a$ with an increment of a. And Table 1 lists the calculated bending losses of the various bent PDWGs. In this table, it is obvious that the bending loss of the circularly-bent PDWG is a function of R and h. According to this table, the circular bend with $R = 2a$ has the least bending loss in case of $h = a$. Referencing to Fig. 6, $h = a$ also has the smallest attenuation constant. Thus $R = 2a$ and $h = a$ are the best structural parameters of the circularly-bent PDWG in our simulation.

5 Conclusions

Some conclusions are drawn from our descriptions and simulation as follows.

1. A periodical dielectric waveguide consisting of a sequence of cylinders can be easily fcformed into an arbitrary bend.
2. The total power loss of a bent 3D PDWG is the sum of the power attenuation and the bending loss. The attenuation constant is a nonlinear function of the height of cylinder.
3. The transmission efficiency of the circularly-bent PDWG is dependent on the quantized curvature radius R of the circular bend and the height h of the cylinder. And the 90° circular bend with $R = 2a$ and $h = a$ have the less bending loss in our simulation.

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