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Low loss sharp photonic crystal waveguide bends

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ABSTRACT

In this paper we study slot structures in the 120° photonic crystal waveguide (PCW) bends. We find that the transmission characteristics of the slotted PCW bend can be simply predicted by analyzing the corresponding straight PCW. According to our mode analysis for straight PCW, the slot structure blue shifts the stopband of the fundamental mode, while enhances the light confinement at slot side. The experiment shows good agreements with the simulation. Furthermore, a low bending loss in broad bandwidth has been obtained in the capsule-shaped slot PCW bend, which is very useful for broadband application.

1. Introduction

Photonic crystal based device has been considered as one of the potential building blocks in photonic integrated circuit (PIC) for versatile applications [1]. Through photonic band gap (PBG) and slow light effect [2], various optical devices based on photonic crystals have been demonstrated with ultra-small footprints, such as waveguides [3], resonators [4], filters [5] and bends [6]. Among them, high efficient photonic crystal waveguide (PCW) bend can be achieved with the spatial extent on the order of the wavelength, which is a promising candidate for compact PICs [7–9].

In straight PCWs, guided modes perform less loss, as they are well confined by the PBG. For PCW bends, bending loss is introduced due to the discrete periodic structure. Hence structure modification should be adopted to reduce bending loss in a wide band. However, directly matching the dispersion relationship of the PCW bends with straight PCWs seems tough due to the non-periodical structure at the bending corner [10]. Thus extensive researches have been carried out to reduce the bending loss by means of resonance matching [6], impedance matching [11] and topology optimization [12–14]. Despite all this, treating the bend as a cavity or using impedance-matching can only explain the result of a single wavelength [13]. Moreover, most of these researches are based on complicated and precise structure designs, which are challenging for fabrication. To our knowledge, although the bending loss of 60° PCW bend has been reduced to as low as 0.05 dB/bend by Assefa, et al. [15], the bending loss of 120° PCW bend, which is much sharper, is still larger than 2 dB/bend in experiment [10]. Another way is adding slot structure at bending area to enhance the light confinement. Recently, Zhang, et al. theoretically obtained a 120° PCW bend with more than 90% transmission over 74 nm bandwidth with arc-shaped slots [16]; Chen, et al. achieved PCW bend with 2.81 dB bending loss at 1550 nm with capsule-shaped slots [10]. These two reported that PCW bends are both optimized with slot structures, which bring a new way to design the broadband and low loss PCW bends simply. However, the reported works for PCW bends mainly focus on the transmission and reflection, lacking of mode analysis.

In this paper, we use mode analysis to study the effect that the slot acting in the PCW bends. We measured the transmission spectra of the slotted PCW bends in SOI platform. A wide low bending loss has been obtained in the slotted PCW bend, which are useful for broadband application. The experiment result shows good agreements with simulation.

2. Detailed analysis and results

Introducing slot structures in PCW bends may have two effects: affecting the coupling between straight PCW and PCW bend, and radiation loss at the bending area. The radiation loss is masked with mode leakage, bandgap and other factors in transmission spectra, which is difficult to be individually extracted. On the other hand, the influence to coupling can be analyzed by studying the difference of mode profiles between original and slotted straight W1 PCW. Fig. 1(a) and (b) shows the schematic of the original and slotted W1 PCW, respectively. The slot in Fig. 1(b) replaces the inner holes at one side, and the slot width is the same as the hole diameter ($2r$). The dashed boxes present the supercells of the two PCWs.

We use three-dimensional (3D) PWE method to calculate the dispersion curves of the two PCWs in transverse electric (TE)

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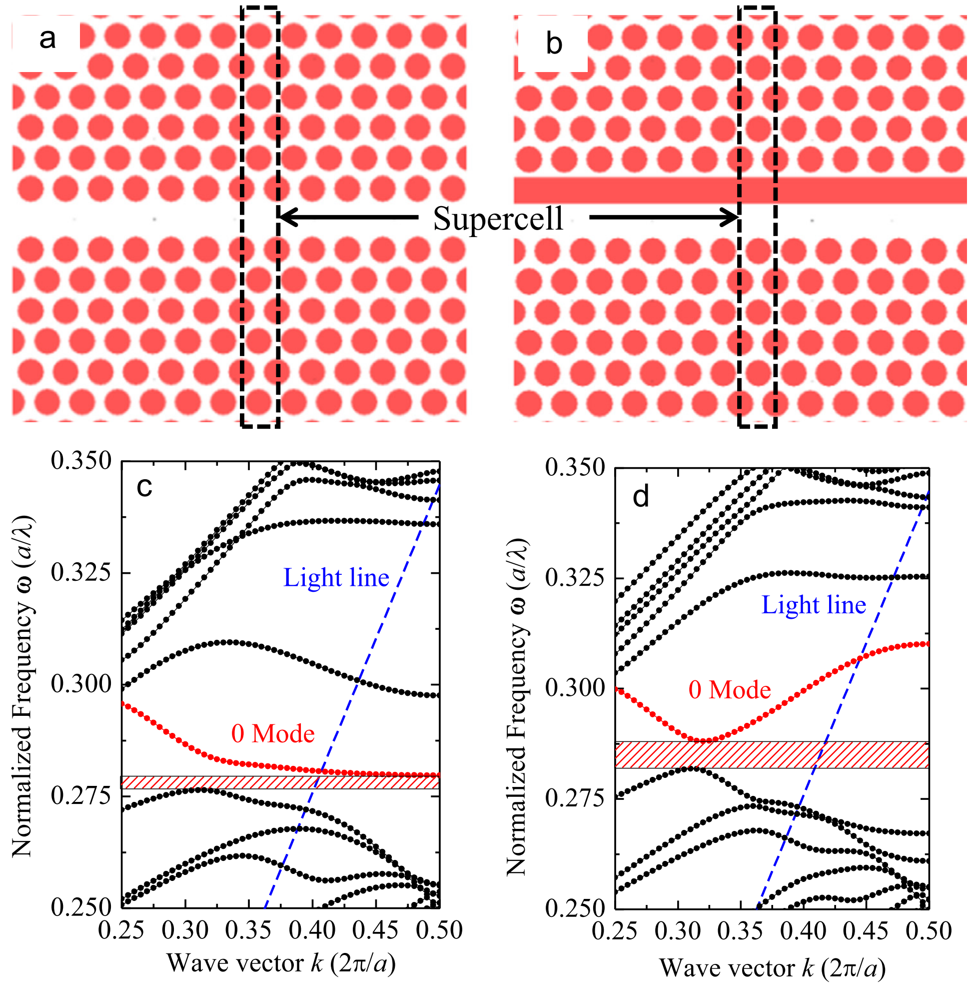

Fig. 1. Schematic of the (a) original and (b) slotted W1 PCW; (c) calculated dispersion curves of the original and (d) slotted W1 PCW. The dashed boxes present the supercells of the two PCWs. (For interpretation of the references to color in the text, the reader is referred to the web version of this article).

polarization. In simulation, we used a SOI platform with 220-nm-thick silicon (Si) slab and infinite oxide cladding [17]. The parameters are taken as following: the refractive index for Si slab $n_{Si}=3.43$, the refractive index for oxide cladding layer $n_{clad}=1.45$, the lattice constant $a=440$ nm, and the hole radius $r=160$ nm. Fig. 1(c) and (d) presents the dispersion curves of the original and slotted W1 PCW, respectively. It can be observed that the fundamental defect mode of W1 (plotted as red dot curves) located mainly above the light line (plotted as blue dashed curves) in oxide-silicon-oxide structure. The slots increase the ratio of the low index region, which reduces the effective index of the PCW. Thus blue shift occurs for the dispersion curves as well as the bandgap. As a result, the PCW with single side slot will stop at a shorter wavelength than that of the original W1 PCW.

The slot structure also affects the intensity of the defect modes.

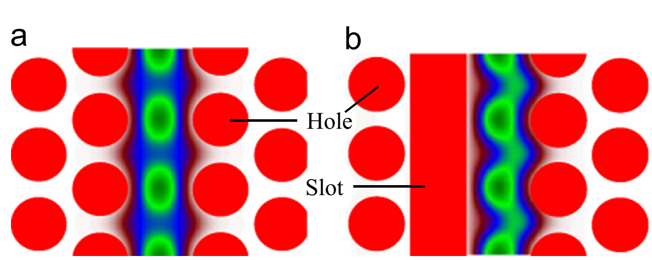

Fig. 2. Mode fields of the fundamental mode in (a) original and (b) slotted W1 PCW.

Fig. 2(a) and (b) shows the calculated mode fields of the fundamental mode in original and slotted W1 PCWs, respectively. The slot pushes the mode field to the opposite side, which indicates that the slot structure enhances the light confinement along the line-defect.

For the slot structures in PCW bend, directly calculating the dispersion curves of the bending area seems tough, because no periodical structure can be found at the bending corner [16]. Hence we analyze the slotted PCW bends via straight PCW. Fig. 3 (a) and (b) shows an arc-shaped slotted PCW bend [16] and a corresponding straight PCW with finite slot. Fig. 3(c) gives calculated results on the transmission spectra of the original W1 PCW, original PCW bend, straight PCW with finite slot and arc-shaped slotted PCW bend.

The FDTD simulation shows that the slotted PCWs, no matter straight or bend, stop at a shorter wavelength than the corresponding original PCW. Such phenomenon conforms well to the hereinbefore described blue shifted bandgap of the infinite slotted PCW. The FDTD simulation also presents that the slotted PCW bend performs lower bending loss than the original PCW bend before 1400 nm, although a dip appears around 1450 nm. The low bending loss accords well with the enhanced light confinement by the slot. Considering there is no such dip in the transmission spectrum of the straight PCW with finite slot, it can be concluded that the dip is not induced from the coupling.

In experiment, we fabricated the original PCW bends and two shapes of slotted as PCW bends as presented in Ref. [16] and [10].

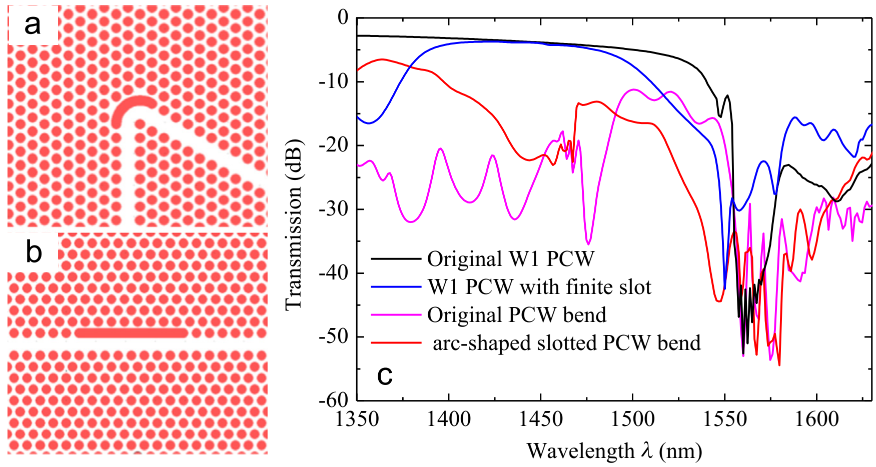

Fig. 3. (a) Arc-shaped slotted PCW bend; (b) straight PCW with finite slot; (c) transmission spectra of the original W1 PCW, original PCW bend, straight PCW with finite slot and arc-shaped slotted PCW bend.

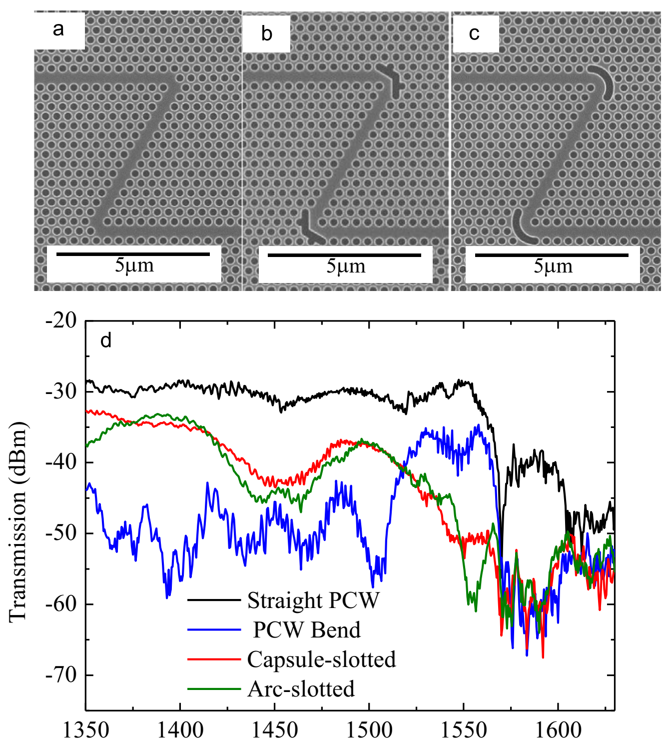

Fig. 4. Scanning electron microscope (SEM) images of the fabricated (a) original PCW bend, PCW bends with (b) capsule-shaped slot and (c) arc-shaped slot; (d) measured transmission spectra of the PCW bends. (For interpretation of the references to color in the text, the reader is referred to the web version of this article).

Fig. 4(a) presents the scanning electron microscope (SEM) images of the fabricated original PCW bends. A Z-bend PCW is constructed by two connected PCW bends in ΓK and ΓM directions [12]. Fig. 4 (b) and (c) shows the PCW bends with capsule-shaped slots and arc-shaped slots, respectively. The capsule-shaped slots and arc-shaped slots replace the innermost row of holes at outer corner of the bend. The length of each capsule slot is $\sqrt{3}a$, and the 120° arc slot has a bending radius of $\sqrt{3}a$. The lattice constant (a) and hole radius (r) of the fabricated sample stay the same as in simulation. The footprint of a single bend is 3 μm × 3 μm, and the total length of the PCW is 40a from port to port. The PCW bends were fabricated on a SOI wafer with 220-nm-thick top Si layer and 2-μm-thick buried oxide layer. The pattern was firstly defined by electron beam lithography (EBL) and then transferred through inductively coupled plasma (ICP) dry etching. After that, a 600-nm-thick oxide layer was deposited on the PCW by plasma enhanced chemical vapor deposition (PECVD) to provide protection and symmetric refractive index distribution in the vertical direction.

The transmission spectra of the PCW bends are measured by an auto-aligned system. Supported by a tunable laser, the measured wavelength range continues from 1350 nm to 1630 nm. Fig. 4 (d) shows the transmission spectra of the fabricated original PCW bends (blue curve), PCW bends with capsule-shaped slots (red curve) and arc-shaped slots (green curve) 120° W1 PCW bends. As a reference waveguide, the transmission spectrum of a straight W1 PCW with the same length and parameters is also measured as the black curve, which is cutoff at 1570 nm. The convex after the cutoff is due to the fabrication inaccuracy in dry etching process, which is sensitive in the bandgap area. Noticed that the light has propagated through the Z-bend, hence the transmission spectra contain twice the bending loss.

Different from the long straight access PCW waveguides demonstrated in Ref. [15], to measure the bending loss of the PCW modes above the light line, we design the access PCW with only a few microns long to alleviate the radiation loss. It can be observed that the reference straight PCW shows only a little change in transmission loss before cutoff, which means that the radiation caused by the mode above the light line can be omitted in straight PCW. Then we can find from Fig. 4(d) that the consistency between the experiment and simulation is very good. Firstly, the slotted PCW stops earlier than the original PCW bend, which is caused by the blue shift of the stopband. Secondly, the slotted bends perform lower loss than the original PCW bend before stop. Thirdly, the dips also appear at 1450 nm in both slotted bends. It is also worth noting that the two PCW bends show very similar spectra. Since the two shapes of slots are similar at interface with straight PCW but different in bending area, the similarity of transmission can be attributed to the effect of slot in coupling.

The bending loss is calculated as presented in Fig. 5. Since the bending loss in band gap is meaningless, we just focused on the spectra shorter than the cutoff wavelength. The slotted PCW bends show much lower bending loss than the original PCW bends at the wavelength far away from the cutoff wavelength, which can be applied for broadband application. For PCW bends with capsule-shaped slots or arc-shaped slots, the lowest bending loss is 1.64 dB at 1383 nm and 1.33 dB at 1359 nm, respectively. Furthermore, the capsule-slotted PCW bend performs bending loss lower than 2.5 dB in a wide range from 1350 nm to 1550 nm, which can be used in broadband application.

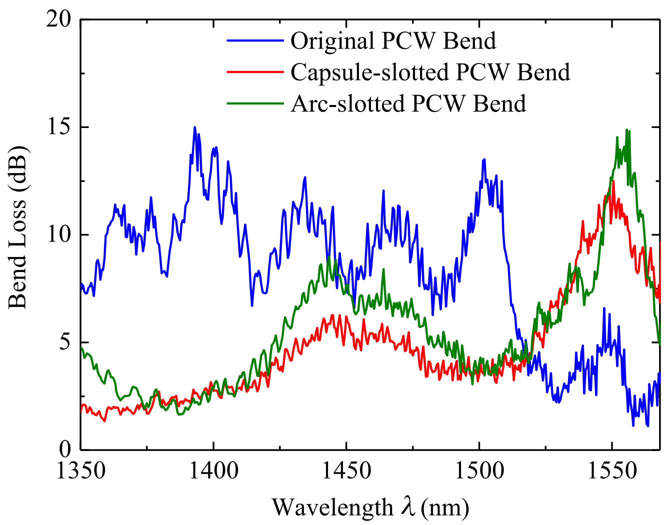

Fig. 5. Measured bending loss of the three PCW bends.

3. Conclusions

In summary, we have studied the influence of the slot structure on the 120° W1 PCW bends. It is found that generally introducing slot structure at the outer corner of the W1 PCW bend will both affect the coupling and radiation loss, which can be simply predicted by analyzing straight slot PCW. The slot structure blue shifts the bandgap as well as enhances the light confinement. The former effect causes the slotted PCW bend stops earlier than the original PCW bend, while the latter effect reduces the bending loss of the slotted PCW. The simulation agrees well with the experiment. The experiment also shows that the capsule-slotted PCW bends perform low bending loss in a wide wavelength range, which can be used in broadband application.

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