Bending optical solitons in nonlinear photonic crystal waveguides

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We investigate the propagation of optical solitons through nonlinear photonic crystal (PC) waveguide bends. Our studies focus on the waveguide bends in two-dimensional PC slabs which are widely used for the manipulation of photons. It is found that optical solitons are completely destroyed when trying to pass through the conventional waveguide bend. With appropriate modifications to the bend structure, however, perfect transmission of optical solitons can be realized. The criteria for the design of waveguide bends with low reflection loss are also generalized. © *2005 American Institute of Physics*. [DOI: 10.1063/1.1839650]

Optical soliton is considered to be the ideal form for the transportation of optical signals. In optical fibers, they originate from the balance between the effects of group velocity dispersion (GVD) and self-phase modulation (SPM).[1] In general, optical fibers of meters or kilometers are needed in order to generate optical solitons. In sharp contrast, it has been revealed very recently that optical solitons similar to those in optical fibers can also be created in nonlinear photonic crystal (PC) waveguides of only micrometers in length.[2] This phenomenon can be attributed to the huge GVD and the large nonlinear coefficient of nonlinear PC waveguides as compared to conventional optical fibers.[3] As the carriers of optical signals, it is required that optical solitons should be able to pass through the basic components in integrated PC circuits, such as waveguide bends, beam splitters, etc., with negligible loss in energy and tolerable distortion in shape.

Compact and low-loss waveguide bends are regarded as one of the key components for future integrated PC circuits. Since the demonstration of highly efficient transmission of light around sharp corners in PC waveguides theoretically by Mekis *et al.* and experimentally by Lin *et al.*,[4,5] this topic has received intensive studies.[6–11] So far, various methods have been proposed to suppress the reflection loss at the corners of bends, either by modifying the bend structure or through the control of modal pattern.[6–10] In device applications, it is required that the frequency range with high transmission covers the frequencies we are interested in. For instance, if a straight PC waveguide is employed to realize optical delay or to achieve enhancement of nonlinearity, then the operating frequency should be chosen to be at the edge of the impurity band corresponding to the straight PC waveguide. Thus, it is required that the PC waveguide bends involved should provide a near perfect transmission for the incoming pulses at near band edge frequencies.

In this communication, we investigate the propagation of the optical solitons generated in straight nonlinear PC waveguides through sharp corners. The investigation of spatial solitons in nonlinear PCs has been carried out by different researchers.[12,13] The optical solitons we studied belong to temporal solitons, similar to those generated in optical fibers or Bragg gratings.[1] A theoretical study for the transmission of discrete solitons through waveguide bends has been conducted by Christodoulides *et al.*[14,15] The elimination of reflection loss can be achieved by appropriately engineering the corner site of the bend. Although the PC waveguides are not formed by discrete cavities and the generated optical solitons are conventional Bragg grating solitons,[16] we think that the similar idea can be employed to minimize the reflection loss for the Bragg grating solitons at the bending corner.

To date, two-dimensional (2D) PCs made by patterning a triangular lattice of air holes in a high-index slab have been widely employed to realize three-dimensional control of photons. Therefore, our focus is directed to the line-defect waveguides as well as waveguide bends formed in such 2D PC slabs. Schematics of a straight waveguide and a conventional waveguide bend are shown in Figs. 1(a) and 1(b), respectively. The radius of the air holes is chosen to be $0.3a$, where $a=0.4$ μm is the lattice constant of the PC. For both structures, input and output waveguides are used to couple light into and out of the PC waveguides. In the following, the finite-difference time-domain (FDTD) method is utilized to simulate the transmission properties of the investigated structures.[17] For the sake of simplicity, we have chosen to

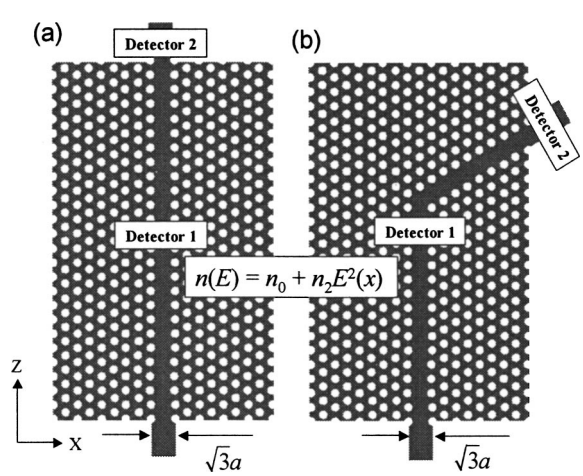

FIG. 1. Schematics of the straight waveguide (a) and the conventional waveguide bend (b).

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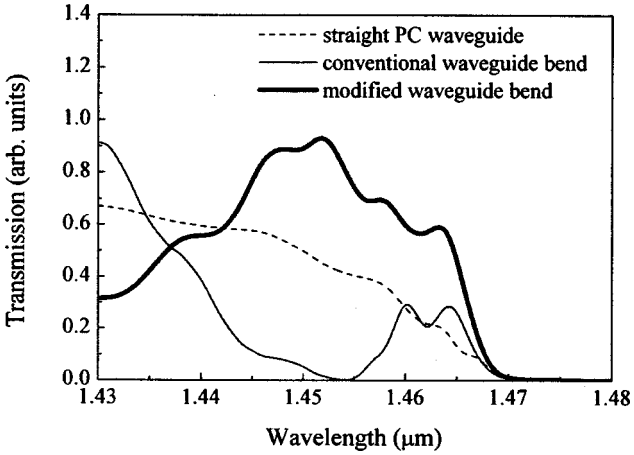

FIG. 2. Transmission spectra of the straight waveguide (dashed curve), the conventional waveguide bend (thin solid curve) and the modified waveguide bend (thick solid curve).

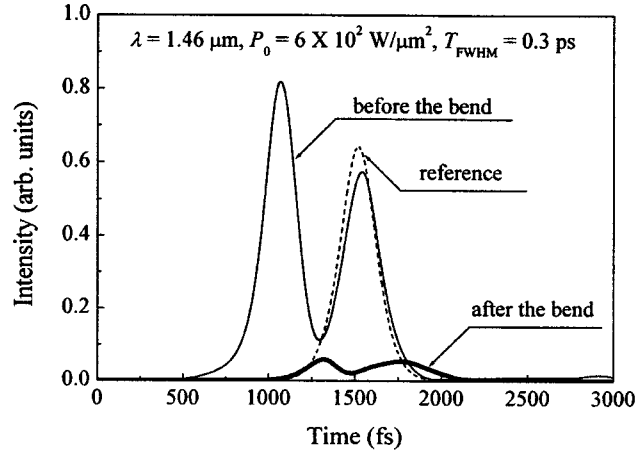

FIG. 3. Shapes of the optical soliton before (thin solid curve) and after (thick solid curve) the conventional waveguide bend. The shape of the soliton emerging from the straight waveguide (dashed curve) is plotted for reference.

simulate pure 2D PCs with an appropriate effective refractive index (here $n_{\mathrm{eff}}=2.87$) which has been confirmed to be a good approximation for the 2D PC slabs.[18] The grid sizes in the X and Z directions are chosen to be $\sqrt{3}\,a/10$ and $a/10$, respectively. Further reduction in grid size barely influences the simulation results. It should be noted that the material used to fabricate the PC slabs is nonlinear (e.g., GaAs or AlGaAs), that is its refractive index is proportional to the local electric field intensity ($n=n_{\mathrm{eff}}+n_2E^2$).

The linear transmission characteristic of the straight waveguide for electromagnetic waves with transverse magnetic polarization is shown in Fig. 2. It is apparent that the edge of the impurity band is located at ~ 1.47 μm. Previously, we have observed the formation of Bragg grating solitons by setting the wavelength of a 0.3-ps pulse at 1.46 μm where huge GVD is balanced by enhanced SPM effect.[2] For a nonlinear coefficient of $n_2=1\times 10^{-5}$ $\mu\mathrm{m}^2/\mathrm{W}$, the power density necessary for the formation of fundamental solitons in these straight waveguides is $\sim 3\times 10^2$ $\mathrm{W}/\mu\mathrm{m}^2$. In addition, the fundamental solitons are found to be generated at a waveguide length of ~ 8.4 μm.[2] Now we examine the propagation of the generated optical solitons through a waveguide bend of 60°. The power density for the input pulse is set at 6×10^2 $\mathrm{W}/\mu\mathrm{m}^2$ and the width of the generated optical soliton is slightly narrower than that of the input pulse. It is ensured that the optical soliton has formed before the input pulse arrives at the waveguide bend. The soliton shapes before and after the conventional waveguide bend are recorded for comparison, as shown in Fig. 3. Also, the shape of the soliton emerging from the straight waveguide is plotted as reference. Obviously, the optical soliton is completely destroyed after passing through the conventional waveguide bend. It is reflected in the severe distortion of the shape as well as the pronounced loss of the energy, as can be seen in Fig. 3. It clearly indicates that the optical solitons cannot pass through the conventional waveguide bend. In order to find out the origin of this phenomenon, we also simulated the linear transmission spectrum of the conventional waveguide bend and presented in Fig. 2. It is found that a significant drop in transmission appears at ~ 1.454 μm as a result of waveguide bending. Recalling that the material used for making the PC slabs is nonlinear, the linear transmission spectrum will shift to longer wavelengths when optical solitons containing strong energy reach the waveguide bend. Such a shift results in a dramatic decrease in transmission at ~ 1.46 μm which is responsible for the deterioration of the optical solitons. Therefore, we think that some modifications to the bend structure are essential to smoothly transmit the optical solitons to the other side of the bend.

Basically, a waveguide bend can be considered as a resonant cavity that connects two identical waveguides. According to the scattering theory, the transmission through the waveguide bend can be expressed as follows:[19]

$$T=\frac{4\Gamma_+\Gamma_-}{(\omega-\Omega)^2+(\Gamma_0+\Gamma_++\Gamma_-)^2}, \tag{1}$$

where ω and Ω denote the frequency of the incident wave and the resonant frequency of the cavity, respectively. Γ_+ and Γ_- represent the forward and backward decay rates of the electromagnetic wave along the two waveguides. Γ_0 is a decay rate that characterizes the intrinsic loss of the cavity. For PC waveguide bends, the radiation loss can be neglected and Γ_0 is taken to be zero.

From Eq. (1), there are two basic conditions to achieve perfect transmission through waveguide bends of any angle. They give rise to the design criteria for the bend structure. These two conditions are (1) $\Gamma_+=\Gamma_-$ and (2) $\omega=\Omega$. The first one requires that the bend structure or the cavity must be symmetric with respect to the two waveguides. The second one implies that we need to tune the resonant frequency of the cavity to the operation frequency.

Bearing these requirements in mind, we have tried various modifications to the conventional waveguide bend. One of the successful modifications is depicted in Fig. 4. Many more air holes are removed to form the cavity. Obviously, the modified bend fulfills the first requirement and is symmetric with respect to the two waveguides. Also, we can examine

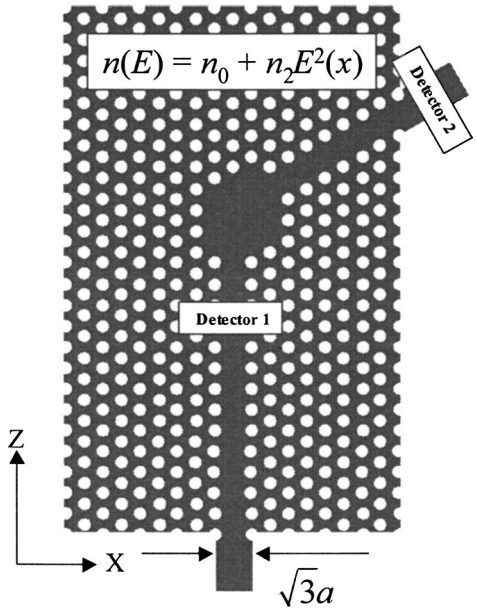

FIG. 4. Schematic structure of the modified waveguide bend.

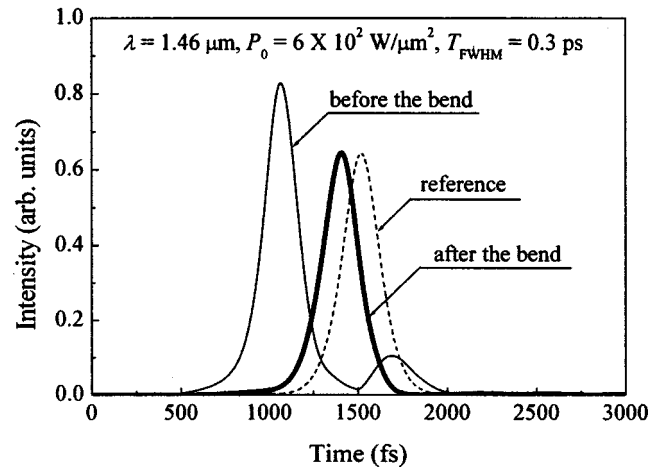

FIG. 5. Shapes of the optical soliton before (thin solid curve) and after (thick solid curve) the modified waveguide bend. The shape of the soliton emerging from the straight waveguide (dashed curve) is plotted for reference.

the transmission spectrum of the modified bend to verify the implementation of the second condition. It is also shown in Fig. 2. We can see that the transmission around 1.46 μm is markedly enhanced. The drop in transmission appearing in the spectrum of the conventional waveguide bend is replaced by a significant enhancement. Thus, the modified bend structure satisfies both the conditions necessary for perfect transmission.

As expected, perfect transmission of optical solitons is achieved by utilizing the modified waveguide bend. Figure 5 presents the soliton shapes before and after the modified bend. It is remarkable that no attenuation and distortion are observed with respect to the solitons emerging from the straight waveguide, indicating the successful transmission of Bragg grating solitons.

In summary, we have investigated the propagation of optical solitons through nonlinear PC waveguide bends. It is found that optical solitons are completely destroyed when trying to pass through a conventional waveguide bend. With appropriate modifications to the bend structure, perfect transmission of Bragg grating solitons has been realized. In addition, we have generalized the criteria for designing such PC waveguide bends based on the scattering theory.

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