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Subpicosecond pulse compression in nonlinear photonic crystal waveguides based on the formation of high-order optical solitons*

Chen Xiong-Wen(陈雄文), Lin Xu-Sheng(林旭升), and Lan Sheng(兰 胜)†

Department of Physics, Shantou University, Shantou 515063, *China*

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We investigate by numerical simulation the compression of subpicosecond pulses in two-dimensional nonlinear photonic crystal (PC) waveguides. The compression originates from the generation of high-order optical solitons through the interplay of the huge group-velocity dispersion and the enhanced self-phase modulation in nonlinear PC waveguides. Both the formation of Bragg grating solitons and gap solitons can lead to efficient pulse compression. The compression factors under different excitation power densities and the optimum length for subpicosecond pulse compression have been determined. As a compressor, the total length of the nonlinear PC waveguide is only ten micrometres and therefore can be easily incorporated into PC integrated circuits.

Keywords: nonlinear photonic crystals, optical solitons, pulse compression
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1. Introduction

Photonic crystal (PC) has been considered as one of the most active research fields in the last decade.[1] By intentionally introducing defects into perfect PCs, one can create devices with various functions such as lasers, resonators, and waveguides, etc.[2−4] As one of the key components for PC integrated circuits, line-defect PC waveguides have been extensively studied. However, the previous investigations mainly focused on their linear properties and their nonlinear characteristics remain almost unexplored.[5,6] Recently, we have shown by theoretical analysis and numerical experiments that optical solitons can be generated in nonlinear PC waveguides of very short length (less than ~20μm) through the interplay of the huge group-velocity dispersion (GVD) and the enhanced self-phase modulation (SPM) near the band edge of the impurity band corresponding to the waveguide.[7] We also indicated that one of the potential applications of optical solitons in nonlinear PC waveguides is pulse compression. So far, the compression of optical pulses manly relies on devices based on optical fibres, for example, fibres with an external grating pair, Bragg gratings on fibres, nonlinear distributed filters, dispersion-decreasing fibres, and fibre arrays, etc.[8−12] Limited by the physical properties of optical fibres, however, such apparatuses generally need a total length of metres or even kilometres in order to attain an efficient pulse compression. For all-optical signal processing in the future, compact or ultra-compact pulse compressors are highly desirable in order to integrate them with other devices into a single chip.

It is well known that the guiding mechanism of light in PC waveguides is different from the total internal reflection in optical fibres. Another major difference between PC waveguides and optical fibres is that the GVD at the band edge of PC waveguides arises from the bending of the dispersion curves and its value is much larger than that in optical fibres originating from the GVD of SiO_2 material. The huge GVD implies that the dispersion length of line-defect PC waveguides can be extremely short as compared to that in optical fibres. As the balance between the GVD and SPM effects, optical solitons can be gen-

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†Corresponding author. E-mail: slan@stu.edu.cn

erated in nonlinear PC waveguides provided that the materials used for making PCs possess very large nonlinear coefficients. Thus, we have suggested that optical solitons can be created in nonlinear PC waveguides made of semiconductors with large nonlinear coefficients such as GaAs and AlGaAs. This has been confirmed by numerical experiments in which the parameters of PC materials and structures are set very close to their practical values.[7] In this article, we show that very efficient pulse compression based on the formation of high-order optical solitons can be realized by using nonlinear PC waveguides whose length is as short as ten micrometres.

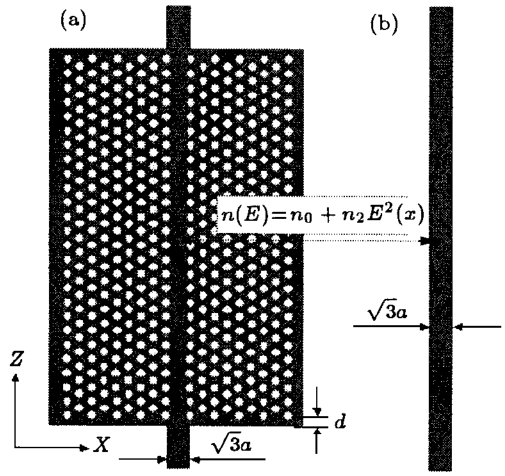

Fig.1. Schematic of (a) the nonlinear PC waveguide studied in this paper and (b) the slab waveguide used as a reference. The actual total length of the PC waveguide is $42a$.

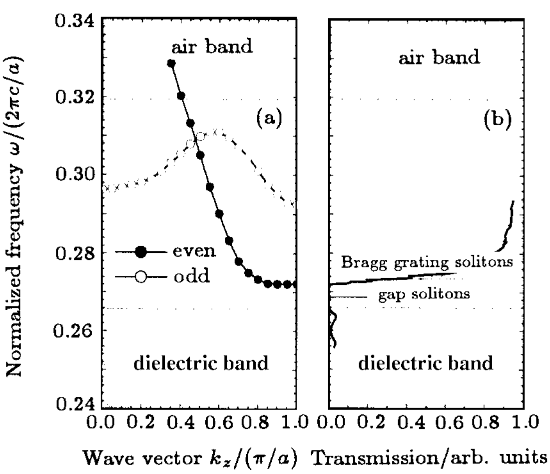

Fig.2. (a) Calculated dispersion curves for the TM mode of the PC waveguide. (b) Simulated transmission spectrum for the PC waveguide using a continuous wave source.

2. Structure of nonlinear PC waveguides

The schematic of the nonlinear PC waveguide is shown in Fig.1(a), in which a line-defect is created in a two-dimensional (2D) PC GaAs by incorporating a triangular lattice of air holes. The radius of the air holes is $0.3a$, where a=0.4μm is the lattice constant. Since it has been confirmed that the simulation of a pure 2D structure is a very good approximation of the practical 2D PC slabs,[13] we perform numerical simulations on a 2D nonlinear PC waveguide with a linear effective refractive index of ~2.87 using nonlinear finite-difference time-domain (FDTD) technique. In FDTD simulations, the grid sizes in the X and Z directions are chosen to be $\sqrt{3}a/10$ and $a/10$ respectively. Two slab waveguides of width $\sqrt{3}a$ are used to couple light into and out of the PC waveguide and direct coupling configuration (i.e. d=0 in Fig.1(a)) is employed in order to achieve a maximum coupling efficiency. For comparison, a slab waveguide with input and output waveguides of identical width is used as a reference, as shown in Fig.1(b).

The dispersion curves for the line-defect waveguide can be obtained by either plane wave expansion or FDTD methods. The calculated dispersion curves for transverse magnetic (TM) mode whose electric field lies in the 2D plane are shown in Fig.2(a). In general, the odd mode will not be excited in the case of normal incidence. In this article, we will focus on the low-frequency band edge of the even mode where very large GVD exists. The transmission spectrum obtained by numerical simulation using a continuous wave source is presented in Fig.2(b).

With the dispersion curve, the group velocity (v_g) and the GVD (characterized by β_2) near the band edge can be readily derived, as shown in Fig.3. It is remarkable that β_2 is extremely large (of the order of 10^7ps^2/m) at the band edge (f=0.2721c/a or λ=1.47μm). Even at 1.46μm, which is 10nm from the band edge, β_2 is still six orders of magnitude larger than that in conventional optical fibres. Meanwhile, v_g at this wavelength is only ~0.06c, where c is the speed of light in vacuum. This value is ~1/5th of that in the reference waveguide. According to the previous study concerning the enhancement of nonlinearity in nonlinear PCs, it is expected that an enhancement factor of ~25 would be achieved in the PC waveguide.[14]

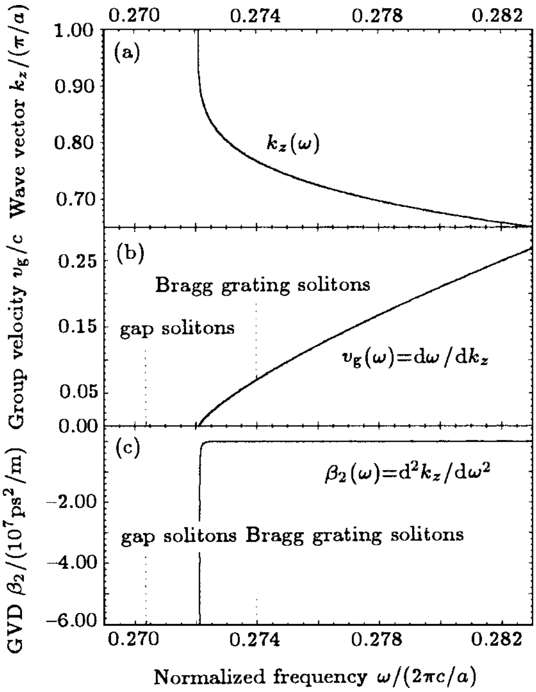

Fig.3. (a) Dispersion curve for the even mode of the PC waveguide. (b) Calculated group velocity as a function of normalized frequency. (c) Calculated group velocity dispersion as a function of normalized frequency.

It has been known that GaAs and AlGaAs possess very large nonlinear coefficients at their half-gap energies (∼500 times larger than silica) and the nonlinearity is of Kerr-type.[15] Therefore, the nonlinear refractive index change Δn is proportional to the local electric field intensity $|E|^2$, i.e.

$$\Delta n = n_2 |E|^2 , \quad (1)$$

where n_2 is the nonlinear coefficient of GaAs or AlGaAs. Similar to that in optical fibres, we can describe the GVD and SPM effects in the nonlinear PC waveguide with dispersion length ($L_{\rm D}$) and nonlinear length ($L_{\rm NL}$) defined as follows:[16]

$$L_{\rm D} = \frac{T_0^2}{|\beta_2|}, \quad (2)$$

$$L_{\rm NL} = \left(\frac{2\pi}{\lambda_0} n_2^{\rm eff} P_{\rm eff}\right)^{-1}. \quad (3)$$

In Eq.(2), T_0 is the half width of the input pulse at the $1/e$-intensity point. In Eq.(3), λ_0 is the wavelength of the input pulse in vacuum; $n_2^{\rm eff}=\alpha n_2$ represents the effective nonlinear coefficient and α is the so-called enhancement factor; $P_{\rm eff}=\eta P$ denotes the effective power density at the peak of the input pulse, P is the peak power density of the input pulse and η is the coupling efficiency.

In general, the interplay of GVD and SPM effects gives rise to optical solitons in the order of $\tilde{N}$ which is determined by $L_{\rm D}$ and $L_{\rm NL}$,

$$\tilde{N} = \left(\frac{L_{\rm D}}{L_{\rm NL}}\right)^{1/2} + \varepsilon, \quad (4)$$

where $\tilde{N}$ is an integer and $|\varepsilon| < 0.5$.[16] With respect to the initial pulse, the width of the fundamental solitons is narrowed for a positive ε and broadened for a negative ε.

3. Formation of high-order solitons and compression of subpicosecond pulses

3.1. Pulse compression based on the formation of high-order Bragg grating solitons

First, let us see how the formation of high-order Bragg grating solitons leads to the compression of subpicosecond pulses. The central wavelength of the input pulse is set to be 1.46μm, which is 10nm from the band edge. There, we have $|\beta_2| \approx 10^4$ps^2/m. If we consider a subpicosecond pulse whose width is ∼0.3ps ($T_{\rm FWHM}$ or 1.665 T_0), then $L_{\rm D} \approx$8.4μm. In order to satisfy the basic condition for the formation of solitons ($L > L_{\rm D} \approx L_{\rm NL}$), the total length of the nonlinear PC waveguide L is chosen to be $2L_{\rm D} \approx$16.8μm. The nonlinear coefficient n_2 for GaAs is assumed to be $1\times10^{-5}\mu$m^2/W (or 1×10^{-13}cm^2/W) which is very close to its practical value ((2–3)$\times10^{-13}$cm^2/W).

Figure 4(a) shows the evolution of the output pulse as the power density for the input pulse is increased. For the comparison of pulse shape and width, we have normalized the peak intensities for the output pulses to one while the actual peak intensities are reflected in the numbers used for normalization, as indicated in the figure. From Fig.4(a), we can clearly see a significant narrowing of the pulse width with increasing of the power density of the input pulse. At 4×10^3W/μm^2, the width of the output pulse drops to 35fs, implying that a compression factor as large as 11.3 has been achieved. Meanwhile, the peak intensities of the compressed pulses are markedly enhanced. In addition, it is noticed that the group velocity of the output pulse is increased with the narrowing of the pulse width. This is reflected in the fact that the delay time between the reference and output pulses is reduced from 560fs to 200fs as the power density of the input pulse is raised from 1×10^3W/cm^2

to 4×10^3W/cm^2. This phenomenon arises mainly from the shift of the band edge towards the longer wavelength upon a positive nonlinear refractive index change. In Fig.4(b), we have summarized the compression factor and the delay time as functions of the power density of the input pulse.

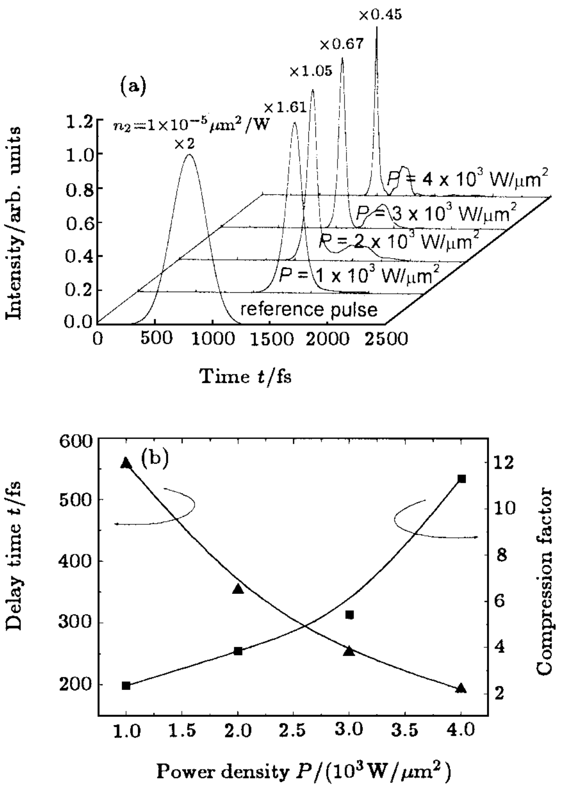

Fig.4. (a) Pulse compression due to the formation of high-order Bragg grating solitons with increasing the power density of the input pulse. (b) Compression factor and delay time of the output pulse with respect to the reference pulse as a function of the power density of the input pulse.

Utilizing the fact that the width of the fundamental solitons is very close to that of the initial pulse, the power density necessary to obtain the fundamental solitons (P_0) can be easily determined. For n_2=$1\times10^{-5}\mu$m^2/W, it is found to be 3×10^2W/μm^2. With this value, we can readily derive the soliton numbers $\tilde{N}$ for high-order solitons obtained at different input power densities by calculating the value of $(P/P_0)^{1/2}$. In optical fibres, the dependence of compression factor F_c on the soliton number $\tilde{N}$ has been derived based on the nonlinear Schrödinger equation. Without considering the high-order dispersion and nonlinear effects, the compression factor can be approximately expressed as[16]

$$F_c \cong 4.1\tilde{N}. \tag{5}$$

However, the high-order dispersion and nonlinear effects cannot be neglected in nonlinear PC waveguides. By carefully inspecting the dependence of compression factor on soliton number presented in Fig.4(b), it is found that the above relationship does not apply to the subpicosecond pulse compression in nonlinear PC waveguides. For instance, the soliton number at 3×10^3W/μm^2 is calculated to be about 3, but it actually gives rise to a compression factor less than 6. Apparently, the compression factor exhibits a nonlinear increase as the soliton number becomes larger. This phenomenon can be understood like this. With increase of the input power density, the band edge shifts towards longer wavelength. This results in a sharp decrease of the GVD (β_2) and thus a drastic increase of the dispersion length at the working wavelength. However, the nonlinear length does not change so much because the shift of band edge causes an increase in coupling efficiency η but a decrease in enhancement factor α. Therefore, we can expect a rapid increase in the soliton number defined in Eq.(4) with increasing of the input power density. On the other hand, the compression factor is mainly determined by the SPM-induced chirp or the nonlinear length. Consequently, we achieve compression factors smaller than that in optical fibres for small soliton numbers. As the input power density or the soliton number becomes larger, the situation will be different. The variation in GVD far from the band edge is rather gradual, both the dispersion length and nonlinear length are not sensitive to the shift of the band edge. The relationship between the compression factor and soliton number tends to approach the relationship described by Eq.(5), i.e. it becomes very similar to that in optical fibres where the high-order dispersion and nonlinear effects can be neglected. Therefore, the nonlinear dependence of compression factor on soliton number observed in nonlinear PC waveguides originates mainly from the higher order dispersion and nonlinear effects near the band edge.

3.2. Pulse compression based on the formation of high-order gap solitons

Now we examine the formation of gap solitons by setting the central wavelength of the input pulse at 1.48μm. This wavelength locates within the band gap and is also 10nm away from the band edge. Also, we examine the evolution of the output pulse upon the increase of the input power density. The simulation results are presented in Fig.5(a). The peak intensities are also normalized in order to compare the pulse width and shape. Apparently, we can observe a pronounced narrowing of the pulse width as the input power density is increased. The dependence of the compression factor and the delay time on the input power density is given in Fig.5(b). It is obvious that the compression factor increases almost linearly with the soliton number. A maximum compression factor of about 9 is achieved at $7\times10^3\mathrm{W}/\mu\mathrm{m}^2$. At $8\times10^3\mathrm{W}/\mu\mathrm{m}^2$, the compression factor becomes smaller. The reason for this phenomenon is not understood yet. More simulation results are needed in order to clarify this abnormal behaviour.

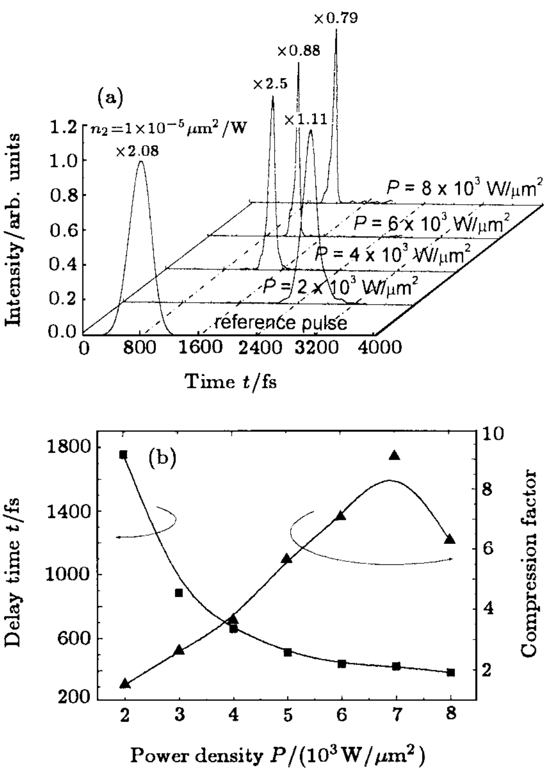

Fig.5. (a) Pulse compression due to the formation of high-order gap solitons with increasing the power density of the input pulse. (b) Compression factor and delay time of the output pulse with respect to the reference pulse as a function of the power density for the input pulse.

By carefully comparing Fig.4(a) and Fig.5(a), we can find two major differences in the pulse compression by utilizing Bragg grating solitons and gap solitons. First, much higher power density is needed for gap solitons in order to achieve the same compression factor. This is because the extra power density is needed to shift the band edge across the working wavelength in the formation of gap solitons. Second, the shape of the compressed pulses is more regular in the case of the Bragg grating solitons.

3.3. Optimum compression length

For high-order solitons in optical fibres, it has been recognized that the pulse width experiences a periodic variation with the period given by[16]

$$z_0 = \frac{\pi}{2} L_{\mathrm{D}}. \tag{6}$$

In order to gain a deep insight into the evolution of the high-order solitons formed within their period and to find the optimum length for pulse compression, we have recorded the variation of the pulse shape along the nonlinear PC waveguide. The evolutions of the formed Bragg grating solitons at P=$2\times10^3\mathrm{W}/\mu\mathrm{m}^2$ and the formed gap solitons at P=$6\times10^3\mathrm{W}/\mu\mathrm{m}^2$ are presented in Figs.6 and 7, respectively. In Fig.6, it is obvious that the formed soliton experiences an initial narrowing when it propagates from L=5.8μm to L=10.2μm. Then a slight broadening is observed and the soliton width is recovered at L=14.6μm. In the output waveguide where we recorded the pulse emerging from the entire nonlinear PC waveguide (L=19.2μm), the soliton width is slightly wider than the narrowest width achieved at L=10.2μm. This means that the optimum compression factor can be a little bit larger than that given in Fig.4(b). Also, it indicates that a nonlinear PC waveguide of only 10μm is adequate for achieving optimum compression of sub-picosecond pulses. This unique feature makes nonlinear PC waveguides very attractive for realizing ultra-compact pulse compressors which can be easily incorporated into PC integrated circuits in the future. The evolution of the formed high-order gap solitons shown in Fig.7 is very similar to that for the Bragg grating solitons. We can also observe a periodic change of the soliton width and determine an optimum compression length of about 10μm. The only difference is that the shape of the compressed pulses is not as good as that achieved by using Bragg grating solitons.

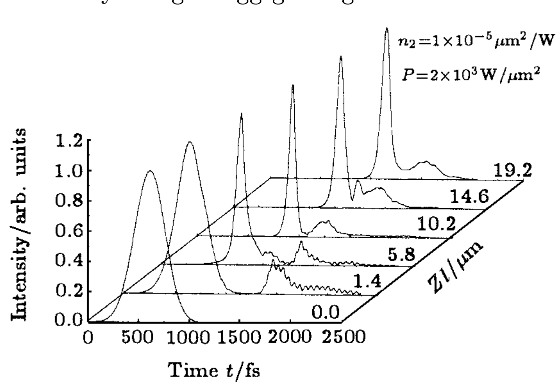

Fig.6. Evolution of the pulse shape for the formed high-order Bragg grating solitons along the nonlinear PC waveguide.

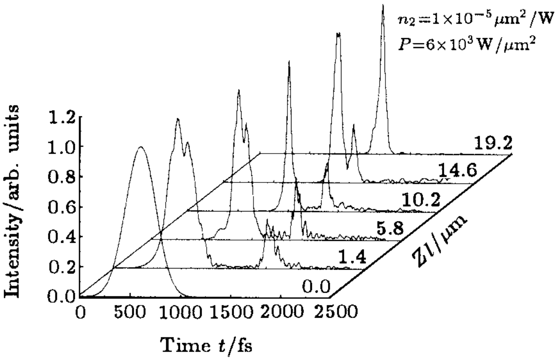

Fig.7. Evolution of pulse shape for the formed high-order gap solitons along the nonlinear PC waveguide.

4. Conclusion

In summary, we have proposed the use of nonlinear PC waveguides for the compression of subpicosecond pulses. The mechanism for pulse compression is based on the formation of high-order optical solitons due to the interplay of the GVD and SPM effects in nonlinear PC waveguides. It is shown by numerical simulation that both Bragg grating solitons and gap solitons can contribute to efficient pulse compression. Large compression factors of ~10 can be achieved even for subpicosecond pulses. Relying on the huge GVD and the enhanced SPM effects, the total length of the pulse compressors based on nonlinear PC waveguides can be as short as ~10μm. This implies that such compact compressors can be easily integrated with other PC-based devices for PC integrated circuits in the future.

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