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Efficient frequency upshift of 10 fs laser pulses propagating in a 5-cm length birefringent photonic crystal fibre*

Li Shu-Guang(李曙光)[a)b)†], Zhang Wei(张 炜)[a)], Wei Zhi-Yi(魏志义)[a)], Zhou Gui-Yao(周桂耀)[b)], and Hou Lan-Tian(侯蓝田)[b)]

[a)] *Laboratory of Optical Physics, Institute of Physics, Chinese Academy of Sciences, Beijing 100080, China*
[b)] *Key Laboratory of Metastable Materials Science and Technology, College of Science, Yanshan University, Qinhuangdao 066004, China*

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This paper reports that a 5-cm length birefringent photonic crystal fibre is used to tune the output frequency of unamplified 10-fs Ti:sapphire pulses. The zero dispersion of the fibre is at 823 nm and 800 nm for slow and fast fundamental modes, respectively. It is demonstrated that efficient upshift of the output frequency can be achieved when the pumped radiation is polarized along the slow axis of the fibre. When the average input power reaches 320 mW, about 60% of the output energy is located in one peak at 600 nm and is accompanied by depletion of the pulse inside the anomalous dispersion region.

Keywords: birefringent photonic crystal fibre, femtosecond laser pulses, frequency upshift
PACC: 7155J, 7830, 3320K

1. Introduction

The propagation of femtosecond laser pulses in photonic crystal fibres (PCFs) is attracting considerable research interest.[1−6] Birefringence in PCFs helps to maintain the polarization of guided modes, allowing a highly efficient generation of coherent supercontinuum radiation,[7,8] and frequency-tunable anti-Stokes line emission,[9−11] and results in nonlinear-optical spectral transformation of unamplified femtosecond Ti:sapphire laser pulses. Such supercontinuum radiation[12−15] has already found important applications, e.g., in the fields of optical metrology,[16] sensor technology,[17] optical tomography,[18] and coherent anti-Stokes Raman scattering microscopy.[19,20]

In this paper, we show that a birefringent PCF provides efficient frequency upshift of unamplified femtosecond Ti:sapphire laser pulses. In the experiments, the central wavelength 823 nm of the pump pulses is located at the zero-dispersion wavelength of the slow fundamental mode of the birefringent PCF, and located in the anomalous dispersion region of the fast fundamental mode. The experimental results and the analysis provide useful information that helps to convert the frequency of pulses to short wavelengths efficiently.

2. PCF and the laser system

The PCF used in the experiments was fabricated of fused silica with the use of standard technology described in detail elsewhere.[21] An elliptical core of the PCF (Fig.1(a)) with semi-axis sizes $\rho_x \approx 2.0\,\mu$m and $\rho_y \approx 1.5\,\mu$m gives rise to form birefringence, removing the degeneracy of the doublet of fundamental fibre modes. The modes of this doublet polarized along the x- and y-axes of the elliptical core of the fibre are referred to as slow and fast modes, respectively. We have calculated the group-velocity dispersion (GVD) for the doublet of fundamental modes of the PCF by the finite element method[22] as shown in Fig.1(b). The GVD for the two fundamental modes of the PCF passes zero at different wavelengths, and the dispersion of the fast (slow) axis is anomalous above the zero-dispersion wavelength (ZDW) of 800 (823) nm, i.e., the zero-GVD point for the guided mode polarized along the fast axis is blue-shifted with respect to the zero-GVD point for the mode polarized along the slow axis.

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†Corresponding author. E-mail: shuguangli@ysu.edu.cn
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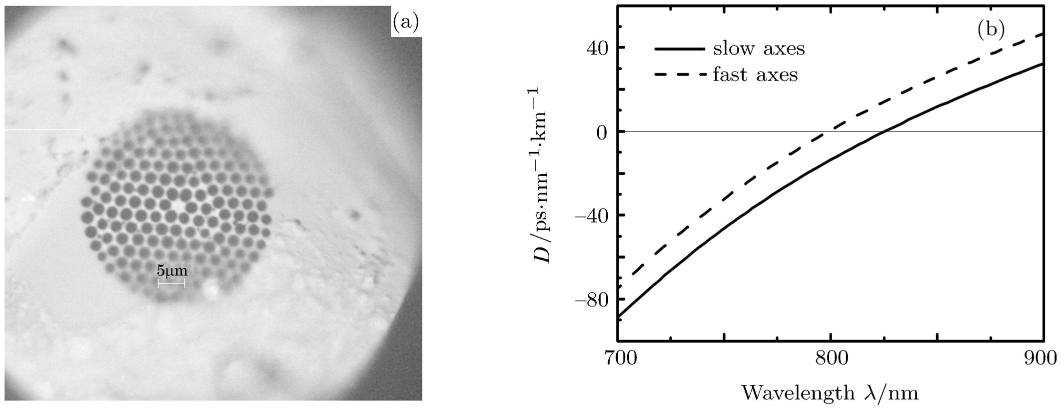

Fig.1. (a) A microscopic cross-sectional image of the photonic crystal fibre. (b) Group-velocity dispersion calculated for the slow and fast fundamental modes in an elliptical-core photonic crystal fibre as shown in Fig.1(a).

The femtosecond laser system used in our experiments (Fig.2(a)) was based on a 532 nm-laser pumped Ti:sapphire laser, which generated 10 fs linearly polarized pulses of radiation with a central wavelength of 823 nm at a pulse repetition rate of 525 MHz. The spectrum of the initial pulses is shown in Fig.2(b). The output power of the laser was 480 mW at 4.15 W pump power (Verdi-5, Coherent), with an instability less than 1% over a few hours. The laser pulse was coupled into the fibre by a 40× standard microscopic objective lens that was mounted on a stable three-dimensional translation stage with 50 nm resolution. A half wavelength plate centred at 800 nm was used for tuning the polarization state of the input pulses. An optical spectrometer (HR2000CG-UV–NIR, Ocean Optics) was used to measure and record the spectra of radiation at the output of the PCF.

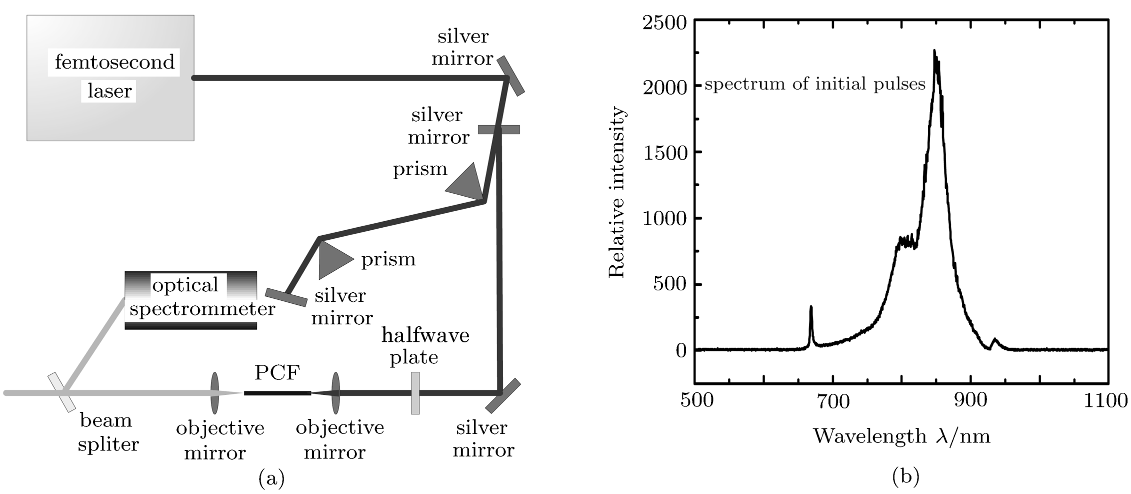

Fig.2. (a) Diagram of the experimental setup. (b) Spectrum of initial pulses.

3. Results and discussion

Propagation of unamplified Ti:sapphire laser pulses through the birefringent PCF was accompanied by nonlinear optical effects, leading to spectral broadening of the pump pulses and frequency conversion. First, we adjusted the polarization of the input pulses to match the direction of the fast polarization of the 5-cm length PCF. The ZDW for the mode polarized along the fast axis is 800 nm, and the central wavelength 823 nm of the input pulses is located in the anomalous dispersion region. From Fig.3(a) we can see that the spectra of radiation measured for different energies of the input pulses at the output of the PCF indicate spectral transformation features of soliton effects. Figure 4(a) shows the high-order dispersion. β_3 and β_4 correspond to the slow (solid lines) and fast (dotted lines) fundamental modes as a function of wavelength λ, and Fig.4(b) shows the effective area S and nonlinear coefficient γ corresponding to the fundamental mode as a function of wavelength λ, in which lines corresponding to the slow and fast fundamental modes are superposed. The nonlinear coefficient of the PCF is $\gamma = 0.05286\ \mathrm{m}^{-1}\cdot\mathrm{W}^{-1}$ at a wavelength of 823 nm. For the mode polarized along the fast axis, the fibre dispersions β_k at 823 nm are: $\beta_2 = -4.70785\ \mathrm{ps}^2\cdot\mathrm{km}^{-1}$, $\beta_3 = 0.07016\ \mathrm{ps}^3\cdot\mathrm{km}^{-1}$, $\beta_4 = -6.54371\times10^{-5}\ \mathrm{ps}^4\cdot\mathrm{km}^{-1}$. When the average input power is 320 mW, according to the formula

$$N = \sqrt{\frac{L_{\mathrm{D}}}{L_{\mathrm{NL}}}} = \sqrt{\frac{\gamma P_0 T_0^2}{|\beta_2|}}$$

the order of solitons in the fibre is $N = 3.97$. $T_0\left|\frac{\beta_2}{\beta_3}\right| = 0.38 < 1$, $T_0\left|\frac{\beta_3}{\beta_4}\right| = 6.08 > 1$. It is obvious that the second order dispersion β_2 and the third order dispersion β_3 play an important role in the process of frequency conversion. For a pump wavelength located in the anomalous dispersion region, the extension of the spectra into the infrared is due to the initial breakup of the pulses into multiple solitons followed by a soliton self-frequency shift. In propagation these solitons can lose some of their energy as they become coupled to phase-matched dispersive waves, giving rise to blue-shifted radiation.[1] With the increase of power, the outer edges of the spectra shift further in agreement with observations reported earlier.[1,2]

Second, we adjusted the polarization of the input pulses to match the direction of the slow polarization of the PCF. The central wavelength 823 nm of the input pulses is located at the zero-dispersion point for the mode polarized along the slow axis in the birefringent PCF. From Fig.3(b) we can see that when the average input power reaches 320 mW, efficient frequency upshift occurs, and about 60% of the output energy is located in the main peak at 600 nm, accompanied by almost complete depletion inside the anomalous dispersion region. For the mode polarized along the slow axis, the fibre dispersion β_k at 823 nm are: $\beta_2 = 0$, $\beta_3 = 0.06525\ \mathrm{ps}^3\cdot\mathrm{km}^{-1}$, $\beta_4 = -5.92\times10^{-5}\ \mathrm{ps}^4\cdot\mathrm{km}^{-1}$. When the average input power is 320 mW, according to the formula

$$N' = \sqrt{\frac{L'_{\mathrm{D}}}{L_{\mathrm{NL}}}} = \sqrt{\frac{\gamma P_0 T_0^3}{|\beta_3|}}$$

the order of solitons in the fibre is $N' = 2.54$. $T_0\left|\frac{\beta_3}{\beta_4}\right| = 6.25 > 1$.

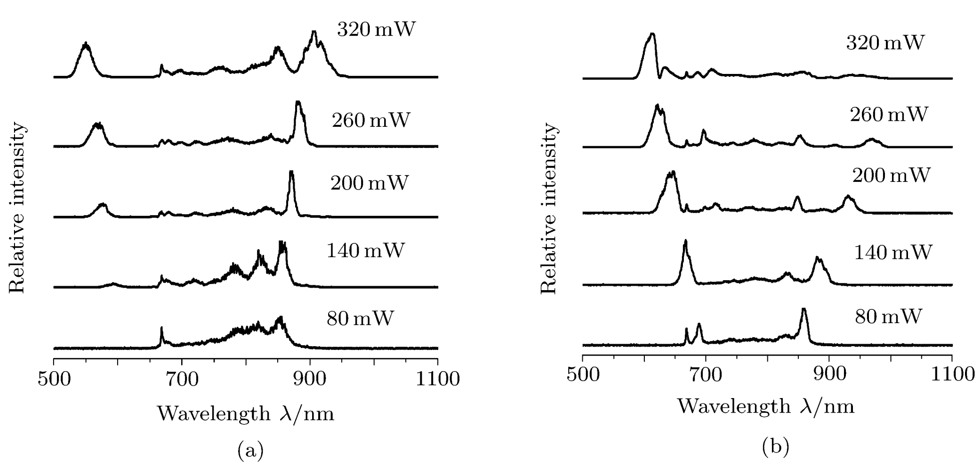

Fig.3. The spectra of radiation at the output of the 5-cm length PCF measured for different input powers of 10-fs 823-nm pump pulses polarized along (a) the fast and (b) the slow axes of the fibre core. The average input power is 80 mW, 140 mW, 200 mW, 260 mW, and 320 mW, respectively.

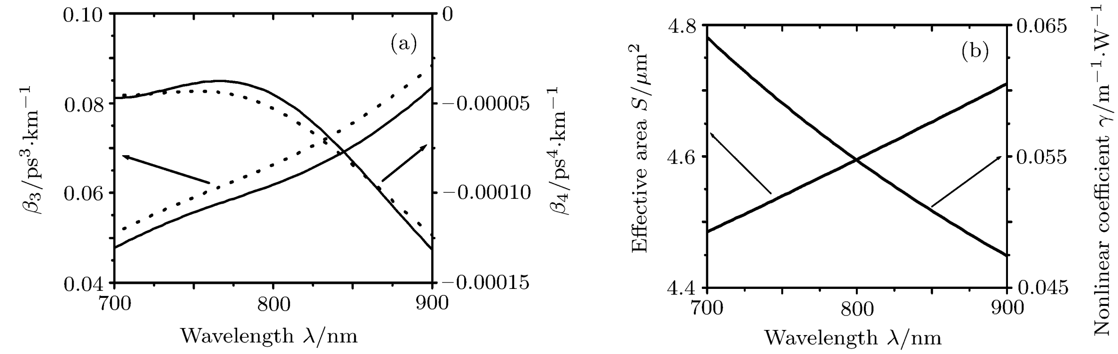

Fig.4. (a) The high-order dispersion β_3 and β_4 corresponding to the slow (solid lines) and fast (dotted lines) fundamental modes as a function of wavelength λ. (b) The effective area S and nonlinear coefficient γ corresponding to the fundamental mode as a function of wavelength λ, in which lines corresponding to the slow and fast fundamental modes are superposed.

To validate the experimental results, we repeated the measurement four times with an input power of 320 mW, and the other parameters of the pulses were the same as in Fig.3. From Fig.5 we can see that the results of the four repeated measurements for the input pulses match the direction of the fast (Fig.5(a)) and slow (Fig.5(b)) polarizations of the PCF, and the repetition of the experiments is acceptable.

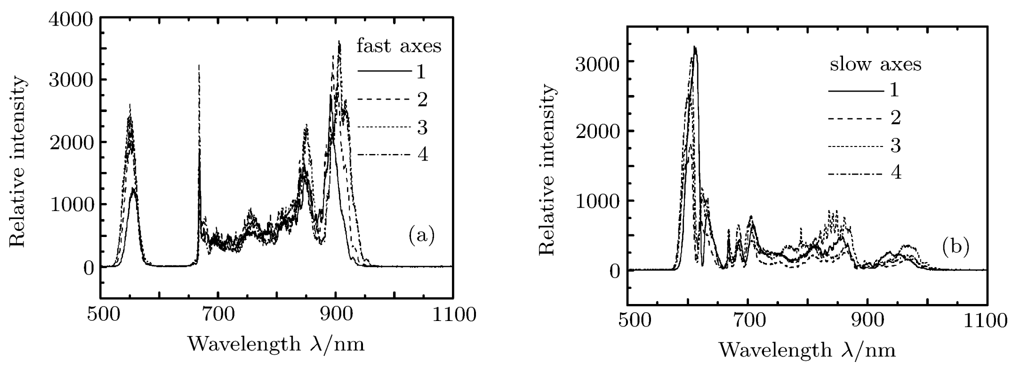

Fig.5. Spectrum of radiation at the output of the 5-cm length PCF measured for an input power of 320 mW, and 10-fs 823-nm pump pulses polarized along (a) the fast and (b) the slow axes of the fibre core. The curves 1, 2, 3, and 4 in the figure indicate the four results of the repeated measurement.

The comparison of the radiation spectra at the output of PCF is shown in Fig.6 for an input power of 320 mW, and the pump pulses are polarized along the slow and the fast axes of the fibre core, respectively. Comparison of the output radiation spectra suggests that, although the pump pulses polarized along the fast axis of the fibre can generate shorter wavelength blueshifted emission than the pulses polarized along the slow axis, the propagation of pump pulses polarized along the slow axis of the PCF can provide much higher efficiency of frequency upshift.

Although the central wavelength of the Ti:sapphire laser pulses is close to the zero-dispersion point for the fundamental mode polarized along the slow axis in the birefringent PCF, the high-order dispersion

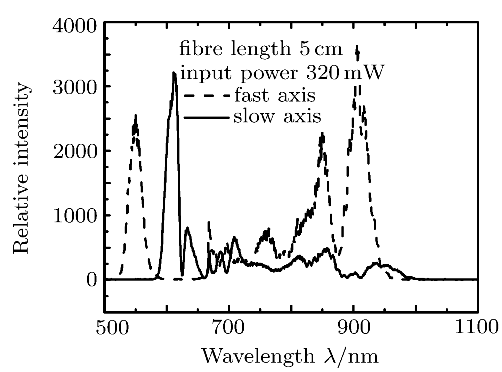

Fig.6. The comparison between output spectra at the PCF corresponding to pump pulses polarized along the slow and the fast axes of the fibre core.

corresponding to this mode is not equal to zero at the central wavelength of the input pulses. For pulses of 10 fs duration the spectrum of the initial pulses is broad (as seen in Fig.2(b)), and some of the spectral components fall within the range of anomalous dispersion of the PCF, in which these pulses can form high-order solitons. At the same time, there are solitons (the order of solitons is $N' = 2.54$) induced by third order dispersion β_3 in the fibre. High-order dispersion induces phase-matching resonances between these solitons and dispersive waves, giving rise to intense blueshifted emission.

Why can pulses polarized along the slow axis of the PCF provide much higher frequency upshift efficiency? The reason is that partially degenerate four-wave mixing (FWM) occurs relatively easily at the zero-dispersion wavelength of the PCF; at the same time, the interaction between solitons induced by third order dispersion β_3 and dispersive waves plays an important role for high-efficiency frequency upshift, too. In the process of FWM, the phase-matching condition can be written in the form[23]

$$\kappa = \Delta K + \Delta K_{\rm NL} = 0, \tag{1}$$

where ΔK, and $\Delta K_{\rm NL}$ represent the mismatch occurring as a result of dispersion, and the nonlinear effects, respectively. The wave-vector mismatches are given by $\Delta K = (\tilde{n}_3\omega_3 + \tilde{n}_4\omega_4 - \tilde{n}_1\omega_1 - \tilde{n}_2\omega_2)/c$, and $\Delta K_{\rm NL} = 2\gamma P_0$. The refractive indices $\tilde{n}_1$ to $\tilde{n}_4$ stand for the effective indices of the fibre modes. The FWM process becomes quite efficient if the phase-matching condition is satisfied. The wavelength conversion efficiency is

$$\eta = (\gamma P_0/g)^2 \sinh^2(gL), \tag{2}$$

where P_0 is the input power, γ is the nonlinear coefficient, L is the length of PCF, and g is the parametric gain which depends on the pump power and is defined as

$$g = \sqrt{(\gamma P_0)^2 - (\kappa/2)^2}. \tag{3}$$

From Eqs.(2) and (3) we can see that the maximum gain $g_{\rm max} = \gamma P_0$ occurs at $\kappa = 0$, and the wavelength conversion efficiency η will be improved when the input power P_0 increases. But the boosting of the wavelength conversion efficiency η will be restricted by the phase-matching condition. Consequently there should be an optimization between the conversion efficiency and the shortest upshift wavelength. The birefringence in PCFs helps to maintain the polarization of guided modes, and there is no direct relation between birefringence and the efficient frequency upshift.

4. Conclusion

We have studied the spectral properties of unamplified 10-fs Ti:sapphire pulses propagating through a 5-cm length birefringent PCF with an elliptically deformed core. When the pump pulses are polarized along the fast axis of the birefringent PCF, spectra of radiation measured at the output expand toward short and long wavelengths simultaneously. But when the pump pulses are polarized along the slow axis of the birefringent PCF, the central wavelength 823 nm of the input pulses is located at the zero-dispersion point, and efficient frequency upshift happens in the fibre. When the input average power is 320 mW, about 60% of the output energy is located in one peak centred at 600 nm accompanied by almost complete depletion inside the anomalous dispersion region. It is obvious that the partially degenerate FWM and high-order solitons induced by third order dispersion β_3 play important roles in the process of frequency upshift. The experimental results and the analysis provide useful information which is helpful for efficient conversion of the frequency of laser pulses to short wavelengths.

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