Highly efficient Cherenkov radiation generation in the irregular point of hollow-core photonic crystal fiber*

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Highly efficient Cherenkov radiation (CR) is generated by the soliton self-frequency shift (SSFS) in the irregular point of a hollow-core photonic crystal fiber (HC-PCF) in our laboratory. The impacts of pump power and wavelength on the CR are investigated, and the corresponding nonlinear processes are discussed. When the average power of the 120 fs pump pulse increases from 500 mW to 700 mW, the Raman soliton shifts from 2210 nm to 2360 nm, the output power of the CR increases by 2.3 times, the maximum output power ratio of the CR at 539 nm to that of the residual pump is calculated to be 24.32:1, the width of the output optical spectrum at the visible wavelength broadens from 35 nm to 62 nm, and the conversion efficiency η of the CR in the experiment can be above 32%.

Keywords: Cherenkov radiation, hollow-core photonic crystal fiber, soliton self-frequency shift

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1. Introduction

Hollow-core photonic crystal fibers (HC-PCFs)[1,2] have opened up a new phase for high field physics and the nonlinear optics of ultrashort pulses[3,4] due to the strong field confinement in a small size fiber core, the tailed dispersion of guided modes by varying the fiber structures, and the unique propagation characteristics confining the light energy in air core by the Bragg scattering effect.[5,6] The supercontinuum (SC) constituted by a visible component and a broadband infrared component can be efficiently generated in PCFs.[7−18] The reported results show that the SC generation originates from the interaction of a series of nonlinear effects, such as self-phase modulation (SPM), four-wave mixing (FWM), Raman self-frequency shift (RSFS), and the paradigm of effective three-wave mixing (ETWM). The difference between the pump wavelength and the zero-dispersion wavelength plays an important role in the SC generation. Usually, the ultrashort pump pulse near the zero-dispersion wavelength is used in the anomalous dispersion region. It has been demonstrated that the infrared component of the SC is generated by the high-order soliton fission,[19] and the visible component is generated mainly by the Raman soliton self-frequency shift (SSFS).[20−23] When the soliton is perturbed by a higher order dispersion, Cherenkov radiation (CR), which is known as nonsolitonic radiation or dispersive wave generation, can be generated and enhanced.[24] The high efficiency at the visible wavelength is important for generating useful laser sources for applications in biophotonics, calibration of astrophysical spectrographs, and ultrashort pulses.

Chang *et al.* experimentally demonstrated the CR with the pump pulse of 10 fs in a PCF, and discussed the influences of the pulse parameters on the bandwidth and the conversion efficiency. However, if the width of the pump pulse was above 100 fs, the conversion efficiency and the bandwidth of the CR in the visible wavelength would be low and narrow, respectively.[24] Yuan *et al.* experimentally achieved CR with a pump pulse of 120 fs, and discussed the

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influences of the pump power and wavelength on the bandwidth and the conversion efficiency in the fundamental mode of the PCF. However, the influences of the higher pump power on the conversion efficiency of the CR in HC-PCF are not considered.

In this paper, highly efficient CR by the SSFS are generated in the irregular point of a HC-PCF with 120 fs pump pulse. When the average pump power increases from 500 mW to 700 mW, the Raman soliton shifts from 2210 nm to 2360 nm, the output power of the CR increases by 2.3 times, the maximum output power ratio of the CR at 539 nm to the residual pump is calculated to be 24.32:1, the width of the output optical spectrum at the visible wavelength broadens from 35 nm to 62 nm, and the conversion efficiency η of the CR in the experiment can be above 32%. Moreover, the influences of the other factors on the experiment process are also discussed.

2. The PCF properties and experiment

The beam propagation method (BPM)[25] has been used to analyze the properties of group velocity dispersion D of the irregular point of HC-PCF. Figure 1 shows the group velocity dispersion D, where $D = -(2\pi c)/\left(\lambda^2\right)\partial^2\beta(\omega)/\partial\omega^2$. The $\beta(\omega)$ is the fiber mode-propagation constant, and is calculated as a function of wavelength for the fundamental mode of the irregular point of HC-PCF with the zero dispersion wavelength at 754 nm. The cross-section structure of HC-PCF is shown in inset (i) of Fig. 1, where the average cladding air hole diameter is $d = 4.78$ μm, and the hole-to-hole pitch is $\Lambda = 5.69$ μm. The zooming irregular point of HC-PCF is shown in inset (ii) of Fig. 1. The diameter of the irregular point is $d_1 \approx 3$ μm, and the average cladding air hole diameter near the irregular point is $d_2 \approx 5$ μm.

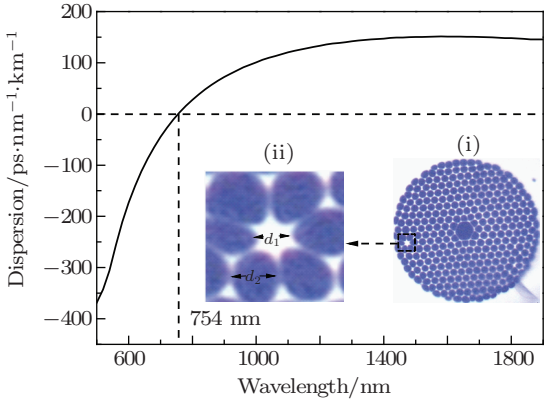


Fig. 1. (colour online) Group-velocity dispersion calculated as a function of radiation wavelength for the fundamental mode of the irregular point of HC-PCF. The vertical dashed line corresponds to the zero dispersion wavelength of 754 nm. Inserts (i) and (ii) show the whole and the zooming irregular point cross-sections of HC-PCF used in the experiment.

The experimental setup is given in Fig. 2. The light source is a mode-locked Ti:sapphire laser emitting a pulse train with the full width at half maximum (FWHM) of 120 fs at the repetition rate of 76 MHz. A variable attenuator is placed behind the laser to control the input energy, and an isolator is inserted to block the back-reflection from the input tip of the fiber into the laser cavity. A 40× objective lens with a numerical aperture of 0.8 is used for adjusting the input and output efficiency. CCD1 and CCD2 are used to observe the output mode field and check the coupling state of the input field, respectively. With the offset pumping technique, the fundamental mode can be selectively excited. The beam goes through the first split-beam mirror; one part is coupled into the power meter to monitor the input average power, and the other part is coupled into the HC-PCF span of 50 cm length. The coupling efficiency is above 70%. The transmission loss is 8 dB/m at 820 nm with the cutback method. The output spectra are monitored by two optical spectrum analyzers (OSA, Avaspec-256 and Avaspec-NIR-256) with measurement scopes from 200 nm to 1100 nm and 900 nm to 2500 nm and resolutions of 0.025 nm and 15 nm, respectively.

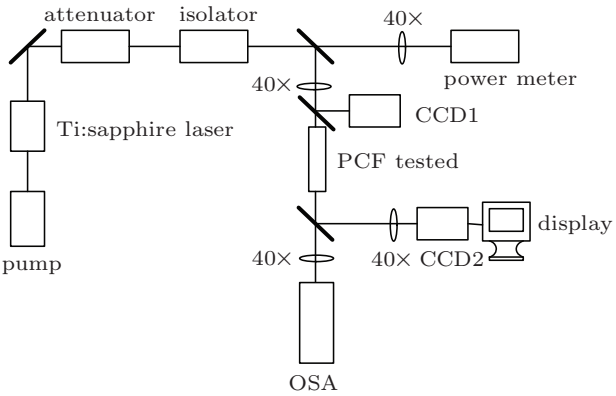


Fig. 2. Experimental setup.

3. Results and discussion

The experimental conditions and process are carefully optimized. The experiment is carried out by coupling fs pulses with working wavelengths of 820 nm

and 830 nm (lying in the anomalous dispersion region) and average power from 500 mW to 700 mW into the fundamental mode of the HC-PCF.

As shown in Fig. 3, when the pump wavelength is 820 nm, because of the interplay between the SPM and the negative dispersion, fundamental solitons are formed. Due to the intra-pulse Raman scattering (IRS), the Raman-type amplification appears. When the input pump power increases from 500 mW to 700 mW, the soliton shifts from 2210 nm to 2360 nm, and the second solution is generated in the range from 1210 nm to 1284 nm, as shown in Fig. 3. Subsequently, when the blue-shift waves and the red-shift solitons are phase matched, CR and high-order dispersion are generated. During the soliton shift process, the group velocity of the soliton continuously decreases, so the XPM traps the CR and results in the equal group velocities of the two waves. The pump power is greatly transferred into the CR and the solitons. As the large index contrast between the diffraction and the index-step guiding in the PCF can be well controlled, the SPM and the normal dispersion experienced by the femtosecond pulse broadens the CR.[20] Due to the nonlinear optical interaction of the laser pulses becoming weak during the radiation wavelength increasing and the absorption loss of the silica material being above 1800 nm, the Raman induced SSFS slows down.

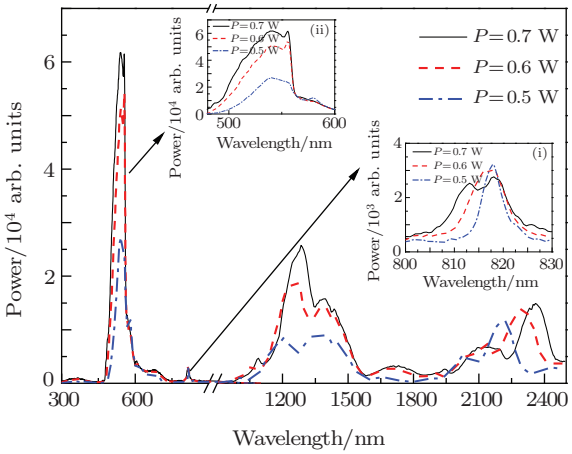


Fig. 3. (colour online) Output spectra from 300 nm to 2500 nm when the pump works at 820 nm and the input average power increases from 500 mW to 700 mW. Insets (i) and (ii) show the zooming output spectra of residual pump and CR.

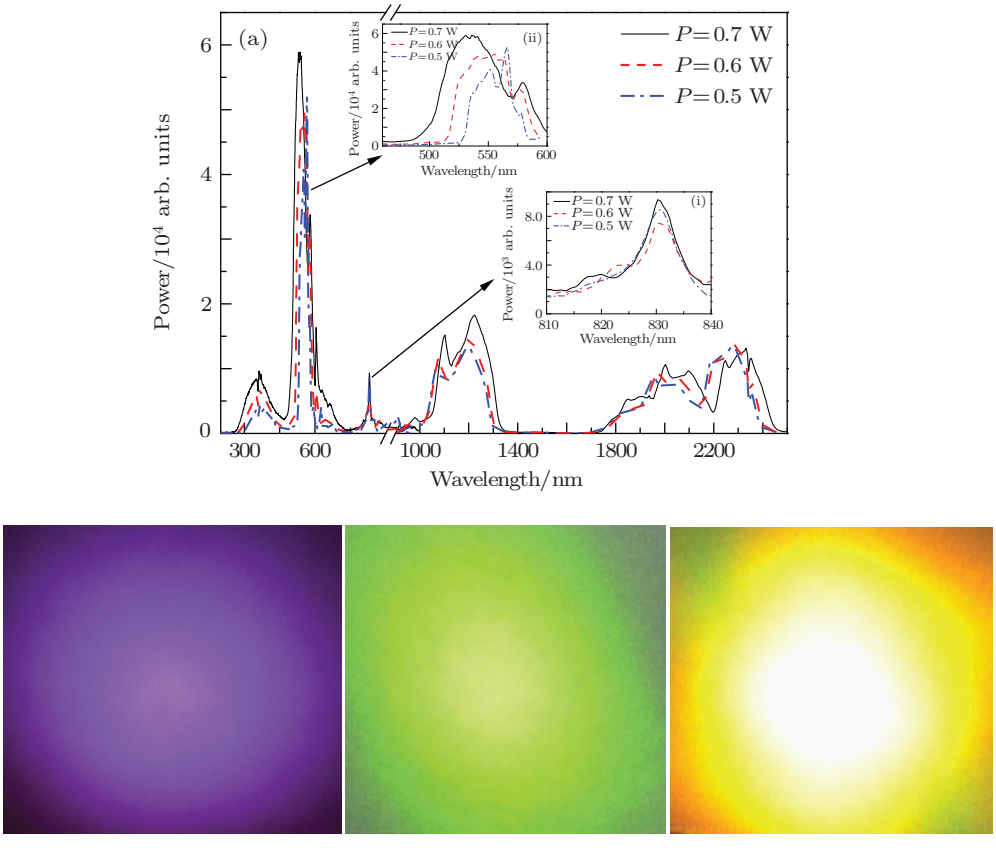


Fig. 4. (colour online) (a) Output spectra from 300 nm to 2500 nm when the pump works at 820 nm and the input average power increases from 500 mW to 700 mW. Insets (i) and (ii) show the zooming output spectra of residual pump and CR. (b) The corresponding far fields observed at different wavelengths (purple, green, orange-white).

In Fig. 4(a), when the pump wavelength is at 830 nm, due to the higher-oder dispersion and the IRS, the output spectrum spreads out asymmetrically as the input average pump power ($P_{\rm in}$) increases from 500 mW to 700 mW. The soliton shifts from 2275 nm to 2332 nm, and the CR is efficiently generated in the range from 566 nm to 530 nm. The observed far fields of the CR at different wavelengths are shown in Fig. 4(b). As seen from Fig. 5(a), when $P_{\rm in}$ is 600 mW, the bandwidth of the siliton ($B_{\rm S}$) can be up to 190 nm with the pump input wavelength (P_λ) being 820 nm. The maximum bandwidth of the CR ($B_{\rm CR}$) is 62.1 nm when $P_{\rm in}$ is 700 mW and P_λ is 820 nm. When P_λ is 820 nm, $B_{\rm S}$ and $B_{\rm CR}$ show the same shifting trend. When P_λ is 830 nm, $B_{\rm S}$ and $B_{\rm CR}$ show reverse shifting trends. Due to the intrinsic absorbing loss of the silica material and that the nonlinear optical interaction of the laser pulses becomes weak during the radiation wavelength increasing, the soliton energy is obviously attenuated. In Fig. 5(b), $\eta_{\rm S}$, $\eta_{\rm NI}$, and $\eta_{\rm CR}$ are the ratios of the output power of the soliton, the near-infrared waves, and the CRs to the output power of the residual pump, respectively. When P_λ is 820 nm, $\eta_{\rm S}$, $\eta_{\rm NI}$, and $\eta_{\rm CR}$ show the same shifting trend, and when $P_{\rm in}$ is 700 mW, $\eta_{\rm S}$, $\eta_{\rm NI}$, and $\eta_{\rm CR}$ are up to 5.89, 10.16, and 24.32, respectively. As 830 nm is much further away from 754 nm than 820 nm, $\eta_{\rm S}$, $\eta_{\rm NI}$, and $\eta_{\rm CR}$ of P_λ = 820 nm are much higher than those of P_λ = 830 nm. In the experiment, a conversion efficiency of 32% and a bandwidth of 62.1 nm are obtained. The nonlinear process depends on the pulse width, the pump power, the fiber, and a suitable P_λ,[7,23,24] so by choosing a more suitable condition, more remarkable CR can be generated.

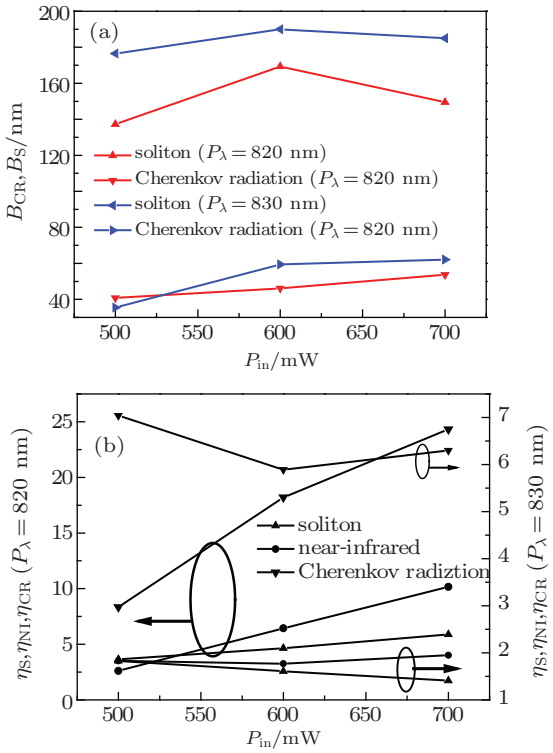


Fig. 5. (colour online) (a) Bandwidths (3dB) of pump at 820 nm and 830 nm each as a function of $P_{\rm in}$. (b) Ratios of the output power of the soliton, the near-infrared waves, and the CR to the output power of the residual pump each as a function of $P_{\rm in}$.

4. Conclusion

In summary, by coupling a train of femtosecond pulses with 120 fs pulse width at a repetition rate of 76 MHz into the HC-PCF, the highly efficient (> 30%) and broadband (> 60 nm) CRs are generated. The influences of pump power and wavelength on CR are investigated. This highly efficient and broadband visible CR is important to generate useful laser sources for applications in biophotonics, calibration of astrophysical spectrographs, and ultrashort pulses.

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