Blue light generation in photonic crystal fibers with 1-μm femtosecond laser pulses

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Using 300-fs 1039-nm Yb-doped fiber laser, we experimentally demonstrate blue light generation in a high-Δ and high nonlinear photonic crystal fiber (PCF). The zero dispersion wavelength of PCF is 793 nm, detuning 245.8 nm from the pump wavelength. PCF allows a frequency conversion exceeding the octave of pump wavelength. The visible component of the measured output spectrum occurs in the fundamental mode and spans from 391.3 to 492.3 nm. The peak wavelength of 441.8 nm has a frequency detuning of 390 THz from the pump wavelength of 1039 nm.

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Photonic crystal fibers (PCFs) have become the preferred media in nonlinear optics because of their capability to manage mode area and dispersion characters flexibly[1,2]. Combined with Yb-doped fiber laser, a variety of experiments based on PCF were performed for spectral broadening and frequency conversion[3]. Particularly, the whole visible spectral region produced considerable attention because of its important applications in fluorescence imaging microscopy, spectroscopy, biophotonics, and photochemistry[4]. However, the blue region is difficult to reach with common pump sources operating around 1 μm. Traditionally, the widest special broadening requires pumping in the anomalous dispersion regimes near zero, i.e., the zero dispersion wavelength (ZDW) is fixed around 1 μm. Moreover, the group-velocity matching condition between solitons in the infrared and trapped dispersive waves in the visible region imposed the short-wavelength edge of the supercontinuum. Based on the understanding of this mechanism, a variety of schemes have been proposed to deal with this issue. The dual-wavelength pumping is an attractive solution but requires additional nonlinear crystal or fiber to support the shorter pump[5]. The other route is engineering the PCF to improve the group velocity of fiber end face while fixing the ZDW of head face around 1 μm. One successful experiment was the use of ZDW decreasing PCF[6]. The output spectrum spanning from 650 to 1380 nm mainly depends on the end dispersion characters of fiber. Similar methods include cascading two PCFs[7] and PCF after processing[8]. A more direct solution is the use of the high-Δ PCF with relative low ZDW[9]. Recently, a PCF combined with low ZDW and high-Δ has shown a particularly striking result[10]. In all these demonstrations, the ZDW of PCFs is located around the pump wavelength, and the supercontinuum is generally flat. As a result, the visible component is not distinct.

In this letter, a different method is employed where the ZDW of fiber is much lower than pump wavelength. At the same time, the high-Δ is used to improve the group velocity. The abrupt blue radiation is obtained in fundamental mode.

The scanning electron microscope (SEM) image of the uniform PCF used in our experiments is shown in Fig. 1(a). The core diameter d is approximately 2.43 nm, and the ratio d/Λ exceeds 90% (Λ denotes hole pitch). The relative small core leads to a high nonlinearity and the high d/Λ reduces confinement loss. According to the SEM, we calculated the dispersion character and nonlinearity coefficient (at slow axis) using the full vectorial finite difference frequency domain[11,12]. As shown in Fig. 1(b), the ZDW is located at 793.2 nm detuning 245.8 nm from the pump wavelength of 1039 nm, and the nonlinear coefficient at the pump light is 54.8 $W^{-1}\cdot km^{-1}$. The PCF's $|\beta_2|/\gamma$ (β_2 is the GVD parameter, γ is the nonlinearity coefficient)[13] that should stay relatively constant with wavelength to allow the soliton red-shift changes from 0.93 at pump wavelengths to 6.7 at 1,600.0 nm. Beyond this wavelength, the value of $|\beta_2|/\gamma$ increases rapidly, preventing the soliton Raman shift.

The PCF is pumped with a linearly polarized Yb-doped fiber laser delivering T_0=300 fs pulses (full-width at half-maximum (FWHM)) at a repetition rate of 50 MHz. The laser is focused into 2-m PCF by an 8-mm aspherical lens, with a coupling efficiency of approximately 20%.

The evolution spectrum as a function of the average laser power is shown in Fig. 2. Below the pump power of 16.67 kW, spectral broadening is dominated by self-phase modulation (SPM) and the Raman-shift soliton. As the pump power increases, the anti-stokes radiation appears near the ZDW on the short-wavelength edge. This is known as anti-Stokes Raman spectra. Symmetric frequency shift from the pump wavelength on other side is observed. When the average laser power is beyond 40.00 kW, the distinct dispersive wave emerges. The power of soliton out-of-pump beam is high enough to permit its spectrum to extend to the phase-matching region in normal dispersion regimes when the temporal compression occurs. The phase-matching between a soliton and dispersion radiation is $\Delta\beta = \beta(\omega)-\beta(\omega_s)-(\omega-\omega_s)\beta_1(\omega_s)-\gamma P_s/2$[14,15], where β is the dispersion radiation propagation constant, β_1 is the first derivative of β with respect to ω, ω_s is the frequency of the soliton with power P_s,

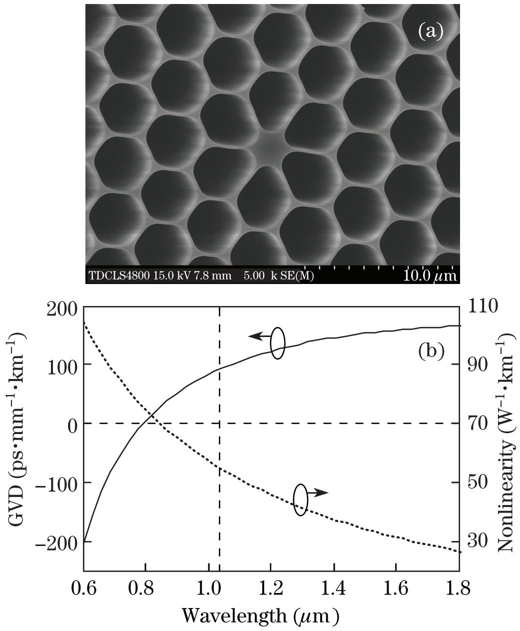

Fig. 1. (a) SEM images of the PCF; (b) calculated group-velocity dispersion as a function of wavelength for the fiber, where the solid line represents the GVD and the dotted line represents the nonlinearity coefficient. The vertical dotted line represents the pump wavelength.

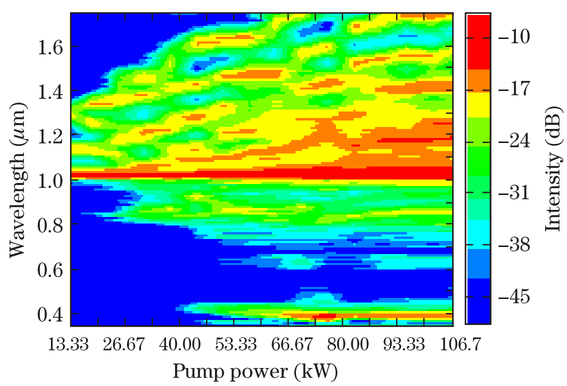

Fig. 2. Spectrally resolved output signal from a 2-m PCF measured as a function of the peak laser power.

and γ is the nonlinear coefficient at ω_{s}. In the case of 106.67-kW pumlp power (i.e., the launched peak power P_0=21.5 kW), the soliton number N with $N=(\gamma P_0 T_0^2/\beta_2)^{1/2}=45.3$, and each of the fundamental soliton has a peak power P_{k} with $P_{\mathrm{k}}=(2N-2k+1)^2/N^2 P_0$[16]. Thus, the first emitting soliton (k=1) has the peak power P_{s}=0.93 kW. The phase-matching curve for our PCF at the average laser pump of 106.67 kW is depicted in Fig. 3. The corresponding dispersive radiation is located at 496.7 nm. Subsequently, it blue-shifts progressively by trapping the red-shift soliton and finally reaches 441.8 nm after propagating 2 m. The measured spectrum is shown in Fig. 4 (bottom). This particular length of PCF is not necessary but ensures enough soliton red-shift. At the 20-dB level, the visible spectrum spans from 391.3 to 492.3 nm. In addition, the polarization of fiber is important for nonlinear phenomenon. In our experiment, pumping at slow axis

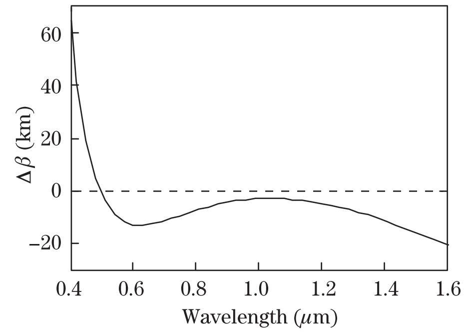

Fig. 3. Phase-matching curve between the pump soliton and the dispersion radiation. Nonlinear dephasing is taken into account.

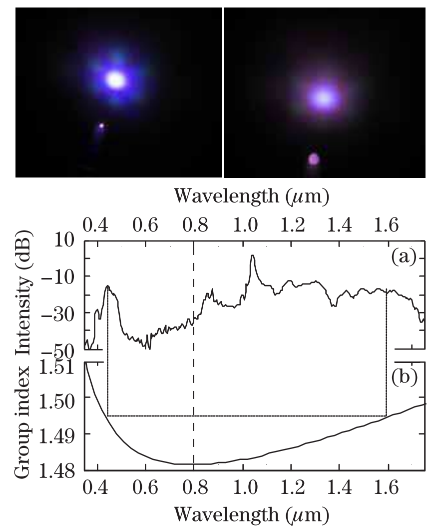

Fig. 4. Output field images of the modes at different polarization (top); left image indicates fast axis; right image, the slow axis. (a) Measured spectra out of 2-m PCF for 106.67-kW pump and (b) the calculated group index; dashed line indicates the ZDW.

achieved relatively good result. The upper part of Fig. 4 shows the field spots in the case of pumps at different polarization and illustrates that the visible light is generated in the fundamental mode, which is important for many applications.

The group index curve (at slow axis) is depicted to illustrate the group velocity matching between the dispersion wave and a corresponding soliton. Calculation result agrees well with experimental data. The contributive soliton for the blue light generation is located at 1,564.0 nm and does not shift as far as expected (typically beyond 2 μm).

In conclusion, we demonstrate experimentally the blue light generation from 1-μm femtosecond pulses in the high-Δ and high nonlinear PCF. The low ZDW allows the phase-matching dispersion wave deep in blue, and the group index has also been improved for the dispersion wave blue shift. The white light is observed in 1.6-W average pump power and performs in the fundamental mode.

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References

1. W. H. Reeves, D. V. Skryabin, F. Biancalana, J. C. Knight, P. S. Russell, F. G. Omenetto, A. Efimov, and A. J. Taylor, Nature **424,** 511 (2003).
2. W. Wang, L. Hou, Z. Liu, and G. Zhou, Chin. Opt. Lett. **7,** 768 (2009).
3. L. Fang, J. Zhao, and X. Gan, Chin. Opt. Lett. **8,** 1028 (2010).
4. A. M. Zheltikov, Phys. Usp. **49,** 605 (2006).
5. C. Xiong, Z. Chen, and W. J. Wadsworth, J. Lightwave Technol. **27,** 1638 (2009).
6. A. Kudlinski, A. K. George, J. C. Knight, J. C. Travers, A. B. Rulkov, S. V. Popov, and J. R. Taylor, Opt. Express **14,** 5715 (2006).
7. J. C. Travers, S. V. Popov, and J. R. Taylor, Opt. Lett. **30,** 3132 (2005).
8. C. Xiong, A. Witkowska, S. G. Leon-Saval, T. A. Birks, and W. J. Wadsworth, Opt. Express **14,** 6188 (2006).
9. J. M. Stone and J. C. Knight, Opt. Express **16,** 2670 (2008).
10. A. Kudlinski, M. Lelek, B. Barviau, L. Audry, and A. Mussot, Opt. Express **18,** 16640 (2010).
11. Z. Zhu and T. G. Brown, Opt. Express **10,** 853 (2002).
12. S. Guo, F. Wu, S. Albin, H. Tai, and R. S. Rogowski, Opt. Express **12,** 3341 (2004).
13. J. C. Travers, A. B. Rulkov, B. A. Cumberland, S. V. Popov, and J. R. Taylor, Opt. Express **16,** 14435 (2008).
14. A. S. Gouveia-Neto, M. E. Faldon, and J. R. Taylor, Opt. Lett. **13,** 770 (1988).
15. J. C. Travers, Opt. Express **17,** 1502 (2009).
16. T. Schreiber, T. V. Andersen, D. Schimpf, J. Limpert, and A. Tünermann, Opt. Express **13,** 9556 (2005).