Ultrabroadband SCG with quasi-continuous wave nanosecond-long pump pulses in PCF

Qin Wang (王 琴)[1], Yaxian Fan (樊亚仙)[1*], Yuqiang Li (李玉强)[1], Jianping Ding (丁剑平)[1], and Huitian Wang (王慧田)[1,2]

[1]*Nanjing National Laboratory of Microstructures and Department of Physics, Nanjing University, Nanjing 210093, China*

[2]*School of Physics, Nankai University, Tianjin 300071, China*

[*]*Corresponding author: yxfan@nju.edu.cn*

Received November 2, 2010; accepted March 3, 2011; posted online May 18, 2011

An ultrabroadband supercontinuum (SC) is demonstrated in a pure silica photonic crystal fiber (PCF) pumped by quasi-continuous wave nanosecond-long pulses at 1,064 nm. The generated SC spectra extending from 450 to at least 2,400 nm have the salient feature of a short wavelength regime below the pump wavelength, which is much higher in intensity than the long-wavelength over the pump wavelength. The influence of pump power and repetition rates on SC generation (SCG) is explored. Results suggest that this pump source has both the advantages of short-pulse and continuous-wave pumps for SCG.

OCIS codes: 140.0140, 190.0190.

doi: 10.3788/COL201109.071405.

Since the fabrication of photonic crystal fibers (PCFs, also named microstructured fibers) in 1996[1], PCFs have attracted great attention due to their novel properties and potential applications[2,3]. One of the most successful applications for PCFs is in supercontinuum generation (SCG)[4−6], which has been widely used in telecommunication systems, spectroscopy, confocal microscopy, and optical coherence tomography, among others[7−9]. For SCG, in addition to femtosecond, picosecond, and nanosecond pulses[10−13], continuous-wave (CW) lasers have also been used[14−17]. The short-pulse laser pump has the advantage of a broader supercontinuum (SC) spectrum and the disadvantage of lower average power. In contrast, the CW laser pump has the advantage of higher average power and the disadvantage of a narrower spectrum. Ultrabroadband (UBB) and high-power SCG has not only been an important subject in recent studies but also a huge challenge. To achieve this goal, the appropriate fiber and pump source should be chosen. For instance, the multi-wavelength pumping system was used to obtain the visible part of a SC spectrum[18,19]. For the fiber, Wadsworth *et al.* changed the conventionally used endless single-mode PCF to a large core high-delta fiber for enhanced visible to ultraviolet continuum generation[5,13]. On the other hand, Fang *et al.* designed an UBB-flattened dispersion PCF for SCG in the telecommunication window[20]. There are also a number of doped fibers which have been used as an alternative to pure silica PCFs in order to obtain broader and higher intensity SC spectrum[21−23].

In this letter, we chose quasi-CW nanosecond-long (over 20 ns) pulses as the pump source for SCG in the conventional pure silica PCF. This kind of source, which was used for the first time in this experiment, not only has the advantages of the short-pulse and CW pump, but is also more compact and cheaper than picosecond or femtosecond laser. We generated the UBB SC spectrum extending from 450 to at least 2,400 nm.

The experimental configuration is shown in inset (a) in Fig. 1. For the SCG, the pump laser (in dashed line rectangle) was a laser diode (LD) pumped Q-switched Nd:YVO_4 laser. Laser output from a fiber-coupled LD at 806 nm was coupled with a pair of lenses into the Nd:YVO_4 crystal 4×4×8 (mm) in size and with a Nd-doped concentration of 0.27%. The laser cavity was composed of a flat input mirror (M1) and a flat output coupler (M2). An acousto-optic (AO) modulator with a repetition rate tunable from 1 to 100 kHz was used as the Q switcher and inserted into the cavity. The quasi-CW pump laser pulses at 1064 nm with a pulse duration above 20 ns were coupled into an 18-m-long PCF using a microobjective (lateral magnification 40×). Propagation loss was considerable when the wideband continuum passed through a long PCF; hence, a 3-m-long PCF rather than the longer one was used in our system to estimate coupling efficiency. We measured the output power with CW laser at 1064 nm and a transmittance of $> 50\%$ was obtained. Thus, a coupling efficiency of over 50% was easily achieved. The scanning electron

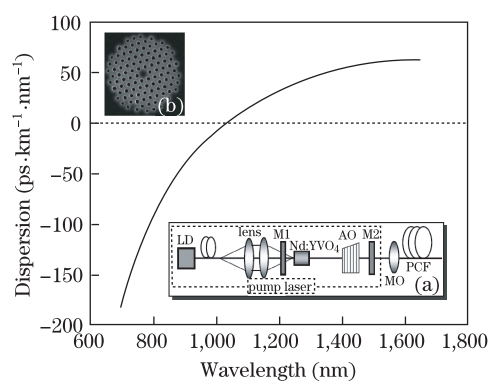

Fig. 1. Dispersion curve of the PCF (SC-5.0-1040). Insets (a) and (b) are the schematic diagram of the experimental setup and the SEM picture of the PCF cross section, respectively.

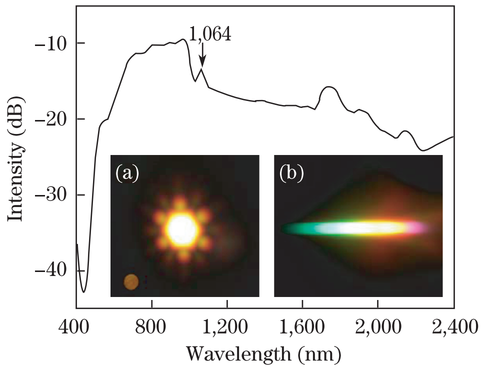

Fig. 2. SC spectrum from the PCF. Insets (a) and (b) are the output spot from the end of PCF and its spectral atlas obtained by a dispersive prism, respectively.

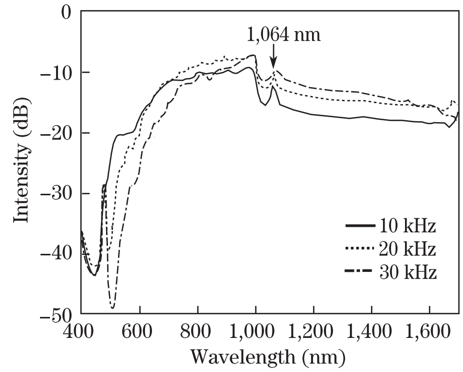

Fig. 3. Under the LD power of 8 W, the SC spectra at different repetition rates.

microscopy (SEM) picture of the PCF cross section (SC-5.0-1040, NKT Photonics A/S, Denmark) is shown in inset (b) in Fig. 1. The pitch (Λ), which is the distance between two most adjacent holes, was 3.2 ± 0.1 μm, and the ratio of average hole diameter to pitch was 0.53–0.56. The dispersion curve of the PCF, which was provided by the manufacturer, had a zero dispersion wavelength at 1040 ± 10 nm (Fig. 1). The nonlinear coefficient at 1060 nm was 1.1×10^{-2} $\mathrm{W^{-1}m^{-1}}$. The SC spectra generated from the PCF were recorded by two optical spectrum analyzers with measurement ranges from 350 to 1,750 nm (AQ6315, Ando, USA) and from 1200 to 2400 nm (AQ6375, Ando, USA).

Figure 2 shows an example of a SC spectrum from an 18-m-long PCF. It was generated by the 1,064 nm quasi-CW pump laser with an average power (P_A) of 1.48 W, a peak power (P_P) of 7.0 kW, and a pulse duration (τ) of 21.0 ns at a repetition rate of 10 kHz. It was measured by two spectrum analyzers with 10 nm accuracy. When each section of the spectrum was measured using a higher accuracy of 0.5 nm (because the measuring range was in conflict with precision), nearly the same results were obtained. For the generated SC light, its short-wavelength edge was at ~450 nm, whereas its long-wavelength edge was at least 2,400 nm. This is because the intensity of SC spectrum at 2,400 nm has no reduction trend and the long-wavelength edge of measured SC spectrum is limited by the measurement range of the spectrum analyzer. Intensity in the short-wavelength regime was observed to be very strong and capable of remarkably exceeding the long-wavelength regime. Although high peaks (generated by parametric processing or soliton fission) have also been reported[19,24], the SC spectra observed in our scheme have not only significantly high intensity but also more flatness in the short-wavelength regime. In addition, the output of the PCF was directly coupled into the spectral analyzer without any filters or other optical elements. The remaining pump at 1,064 nm was very small. As expected, the quasi-CW nanosecond-long pump pulses were superior for the ultrabroadband SCG. The average output power was also measured and was found to be more than 70 mW, which was still lower than that pumped by the CW laser, but much higher than other short-pulse pumps[10,13]. Moreover, the spectrum bandwidth was at times more than that of the CW pump source[14−17]. The output spot from the end of PCF is shown in inset (a) in Fig. 2. From the spectral atlas obtained by a dispersive prism, as shown in inset (b) in Fig. 2, we can find that the generated SC light covers almost the entire visible regime.

We then explored the influence of the pump source at 1,064 nm. Firstly, we changed the repetition rate R_R when the LD power (P_LD) was fixed at 8 W. The output parameters (P_A, P_P, τ) of the pump source were (1.48 W, 7.0 kW, 21.0 ns) at $R_\mathrm{R} = 10$ kHz, (1.86 W, 3.8 kW, 24.5 ns) at $R_\mathrm{R} = 20$ kHz, and (2.39 W, 2.7 kW, 29.5 ns) at $R_\mathrm{R} = 30$ kHz, respectively. The influence to SCG is shown in Fig. 3. As R_R increased, the short-wavelength edge (~450 nm) slightly exhibited a red shift and the intensity in the long-wavelength regime (> 1,064 nm) was enhanced. Experiments at other repetition rates (from 5 to 50 kHz) were also carried out with the same phenomena observed. When the repetition rate was tuned, the average power, peak power, and pulse duration changed accordingly. As the R_R increased, the P_A also increased but the P_P dropped and the τ expanded. The results suggest that the high average pump power and high peak power are beneficial to the enhancement of intensity and the broadening of the spectral width of the SC spectra, respectively.

Second, we also investigated the influence of the pump power. We fixed the repetition rate at $R_\mathrm{R} = 10$ kHz and changed the LD power. The output parameters (P_A, P_P, τ) of the pump source were (0.74 W, 2.3 kW, 32.0 ns) at $P_\mathrm{LD} = 4$ W, (1.08 W, 4.2 kW, 26.0 ns) at

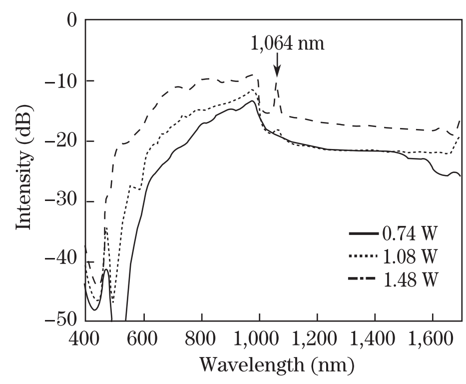

Fig. 4. At the same repetition rate of 10 kHz, the SC spectra at different pump powers (P_A).

$P_{LD} = 6$ W, and (1.48 W, 7.0 kW, 21.0 ns) at $P_{LD} = 8$ W. The increase of the LD power caused the enhancement of both average and peak powers, and the narrowing of the pulse duration of the pump laser at 1,064 nm. At an appropriate condition (the solid line in Fig. 4), the energy of the pump laser at 1,064 nm was completely converted to the SC light. As expected, both the spectral broadening and the increase in intensity of the SC light were realized as the P_A and P_P increased, as shown in Fig. 4. The results indicate the reason for the nanosecond-long pump source having the advantages of both the short-pulses and CW pump.

In conclusion, we have studied UBB (from 450 to 2,400 nm) SC generation in a conventional PCF using quasi-CW nanosecond-long pulses pumping. The effects of pump power and repetition rate on SCG are studied. The results suggest that the long-pulse pump scheme has both the advantages of the higher spectral power density for the CW pump and the broader SC spectra for the short-pulse pump. The results further indicate that the scheme especially benefits the generation of the high-intensity SC spectrum in the short-wavelength regime below the pump wavelength. Moreover, the quasi-CW nanosecond-long pulses pump source is more compact and cheaper than picosecond or femtosecond laser and is thus a promising candidate for SCG in PCF.

This work was supported by the National Nature Science Foundation of China (No. 60608006) and the New Century Excellent Talents in University (No. 08-0268).

References

1. J. C. Knight, T. A. Birks, P. St. J. Russell, and D. M. Atkin, Opt. Lett. **21,** 1547 (1996).
2. X. Ma and Y. Zhu, Chin. Opt. Lett. **8,** 983 (2010).
3. M. Chen, Y. Zhang, and R. Yu, Chin. Opt. Lett. **7,** 390 (2009).
4. J. K. Ranka, R. S. Windeler, and A. J. Stentz, Opt. Lett. **25,** 25 (2000).
5. W. Wadsworth, N. Joly, J. Knight, T. Birks, F. Biancalana, and P. Russell, Opt. Express **12,** 299 (2004).
6. J. M. Dudley, G. Genty, and S. Coen, Rev. Mod. Phys. **78,** 1135 (2006).
7. J. Swartling, A. Bassi, C. D'Andrea, A. Pifferi, A. Torricelli, and R. Cubeddu, Appl. Opt. **44,** 4684 (2005).
8. K. Shi, P. Li, S. Yin, and Z. Liu, Opt. Express **12,** 2096 (2004).
9. I. Hartl, X. D. Li, C. Chudoba, R. K. Ghanta, T. H. Ko, J. G. Fujimoto, J. K. Ranka, and S. Windeler, Opt. Lett. **26,** 608 (2001).
10. J. M. Dudley, L. Provino, N. Grossard, H. Mailotte, R. S.Windeler, B. J. Eggleton, and S. Coen, J. Opt. Soc. Am. B **19,** 765 (2002).
11. S. Coen, A. H. L. Chau, R. Leonhardt, J. D. Harvey, J. C. Knight, W. J. Wadsworth, and P. S. J. Russel, Opt. Lett. **26,** 1356 (2001).
12. V. Tombelaine, C. Lesvigne, P. Leproux, L. Grossard, V. Coudere, J. L. Auguste, and J. M. Blondy, Opt. Express **13,** 7399 (2005).
13. J. M. Stone and J. C. Knight, Opt. Express **16,** 2670 (2008).
14. J. C. Travers, R. E. Kennedy, S. V. Popov, J. R. Taylor, H. Sabert, and B. Mangan, Opt. Lett. **30,** 1938 (2005).
15. P. A. Champert, V. Couderc, and A. Barthelelmy, IEEE Photon. Technol. Lett. **16,** 2445 (2004).
16. T. Sylvestre, A. Vedadi, H. Maillotte, F. Vanholsbeeck, and S. Coen, Opt. Lett. **31,** 2036 (2006).
17. B. A. Cumberland, J. C. Travers, S. V. Popov, and J. R. Taylor, Opt. Express **16,** 5954 (2008).
18. P. Champert, V. Couderc, P. Leproux, S. Fevrier, V. Tombelaine, L. Labonte, P. Roy, C. Froehly, and P. Nerin, Opt. Express **12,** 4366 (2004).
19. E. Raikkonen, G. Genty, O. Kimmelma, M. Kaivola, K. P. Hansen, and S. C. Buchter, Opt. Express **14,** 7914 (2006).
20. L. Fang, J. Zhao, and X. Gan, Chin. Opt. Lett. **8,** 1028 (2010).
21. P. Domachuk, N. A.Wolchover, M. Cronin-Golomb, A. Wang, A. K. George, C. M. B. Cordeiro, J. C. Knight, and F. G. Omenetto, Opt. Express **16,** 7161 (2008).
22. A. Roy, M. Laroche, P. Roy, P. Leproux, and J. Auguste, Opt. Lett. **32,** 3299 (2007).
23. N. Nishizawa, H. Mitsuzawa, J. Takayanagi, and K. Sumimura, J. Opt. Soc. Am. B **26,** 426 (2009).
24. K. M. Hilligsoe, H. N. Paulsen, J. Thogersen, S. R. Keiding, and J. J. Larsen, J. Opt. Soc. Am. B **20,** 1887 (2003).