Ultra-broadband supercontinuum generated in dispersion-flattened fiber

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With 4.28-km dispersion-flattened fiber (DFF), more than 254.9-nm 10-dB bandwidth on the right side of zero-dispersion wavelength and a 190.4-nm wide spectral region with the uniformity of within ±0.5 dB are obtained. While on the opposite side, 198.4-nm 10-dB bandwidth and 62.3-nm spectral region with the uniformity of within ±0.5 dB are obtained. More than 88 channels spaced at 2.52 nm on the long wavelength side are generated using Fabry-Perot (F-P) filter. The output supercontinuum (SC) characteristic is also analyzed by spectrum carving.

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The growth of the internet has led to the need for much larger capacity networks. Effectively utilizing the entire low loss transmission window of the silica fibers is one of the ways to answer this challenge other than using multiple fiber links. Practical and affordable multiwavelength picosecond pulse sources with large and uniform bandwidth, accurate wavelength spacing, high coherent, and high-power spectral intensity are therefore absolutely necessary. With the advent of high peak power picosencond lasers, a supercontinuum (SC) that can produce short pulses over a broad spectral range around 1550 nm has been generated in fibers. Short pulses generated based on spectral slicing of the SC also have been proved to be an excellent dense wavelength division multiplexing (DWDM) source. In 1999, Kawanishi *et al.* demonstrated propagation of 19 wavelength channels carved out of SC through 40 km of dispersion-shifted fiber (DSF) at 160 Gb/s[1]. F. Futami *et al.* generated 280-nm-wide flat SC with spectral-density fluctuation less than 10 dB in dispersion-flattened fiber (DFF) with normal group velocity dispersion (GVD)[2]. In 2000, H. Takara reported that more than 1000 optical frequency channels were generated with 12.5-GHz spacing from a single SC source[3]. Most recently, K. Mori obtained a SC source that emitted precise 50 GHz spaced optical carriers on ITU grid over a seamless spectral range from 1425 to 1675 nm covering the S-, C-, and L-bands[4].

In this paper, we report that ultra-broadband SC generated in DFF. On the right side of zero dispersion wavelength λ_0, more than 254.9-nm bandwidth at 10-dB is obtained with ±0.5 dB uniformity over 190.4 nm; while on the opposite side, 198.4-nm bandwidth at 10 dB is also achieved with ±0.5 dB uniformity over 62.3 nm. 88 channels spaced at 2.52 nm with flat top are obtained by using Fabry-Perot (F-P) filter.

The experimental setup used in SC generation is shown in Fig. 1, which includes picosecond pump pulse source, erbium-doped fiber amplifier (EDFA), SC fiber and a tunable filter. The generation of SC is modeled by the nonlinear Schrödinger equation, which describes the pulse propagation under the influence of nonlinear and linear effects in the fiber[5]. In short, SC occurs due to a combination of self-phase modulation (SPM), cross-phase modulation (XPM), four wave mixing (FWM), and the stimulated Raman effect (SRS).

In our experiment, the picosecond pump pulses are provided by a passively mode-locked erbium-doped fiber laser that generates a 13.9-MHz train of 1.5-ps hyperbolic-secant pulses centered at 1562 nm. High pulse peak power can be obtained due to its fairly short pulse width and the low repetition rate. So it is directly amplified by an EDFA without any compression. Following the amplifier, 4.28-km DFF with $\lambda_0 = 1450$ nm and dispersion slope of 0.015 ps/(nm^2·km) is used for SC generation and its dispersion at 1550 nm is 1.53 ps/(nm·km). The output result is sent into Ando AQ-6315A optical spectrum analyzer (OSA), HP 500MHz 54615B oscillator and FR-103MN autocorrelator for diagnostics.

Figure 2 shows the SC spectra generated with 1- and 2-mW average pump power, respectively. Their corresponding 10-dB bandwidths are 66 and 85 nm. At the beginning of SC evolution, since pump wavelength is in the anomalous dispersion region of DFF, GVD will enhance SPM to broaden the spectrum. So in this case, spectral broadening mechanism is dominated by SPM[6,7].

As increasing pump power, the spectrum broadens towards the normal dispersion region of DFF and even gets into the normal dispersion region, as shown in Fig. 3. In this case, XPM and FWM as well as SPM will play important roles in spectrum broadening. However, there is a deep dip between the short wavelength region and λ_0[8].

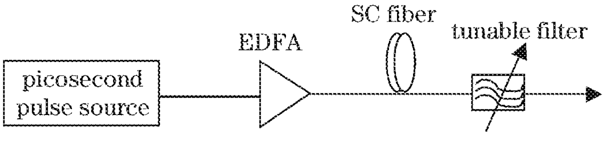

Fig. 1. Experiment setup for SC generation.

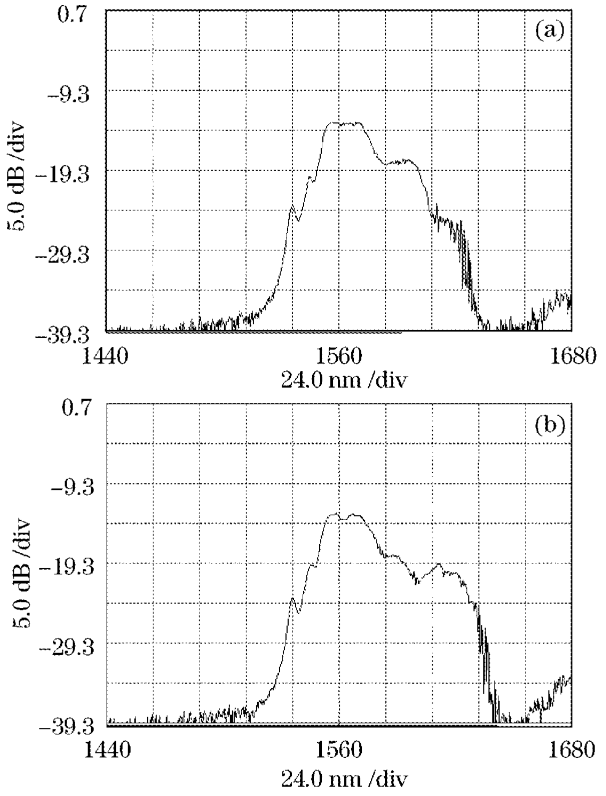

Fig. 2. SC generated at 1- (a) and 2-mW (b) average pump power.

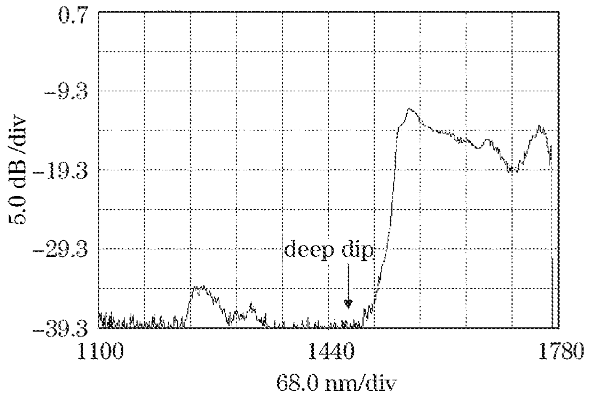

Fig. 3. SC generated at 8 mW average pump power.

If the pump power is further increased, the long wavelength side is quickly broadened and flattened due to SRS, as shown in Figs. 4(a) and 4(b) at the average pump power of 10 and 25 mW, respectively. The spectrum power of the right side of pump wavelength is higher than that of the opposite side due to the absorption of pump power. The SC generated by 55-mW average pump power is shown in Fig. 4(c). Data for wavelengths greater than 1780 nm cannot be obtained due to spectral limitation of the OSA. The SC has a 10-dB bandwidth of more than 254.9 nm on the right side of λ_0 and a 190.4-nm-wide spectral region between 1589.6 – 1780 nm that is flat within ±0.5 dB. On the left side of λ_0, 198.4-nm 10-dB bandwidth is obtained. Meanwhile, a 54.4-nm wide spectral region between 1195.2 – 1249.6 nm and a 62.3-nm-wide spectral region between 1270.0 – 1332.3 nm that is flat within ±0.5 dB are also obtained.

A F-P filter with 0.2-nm line width and 2.52-nm free spectrum region (FSR) is used to get multiple channels output as shown in Fig. 5(a) and the detail graph at long wavelength side is shown in Fig. 5(b). Figure 5 exhibits that more than 88 channels with flattened top at the right side of λ_0 are generated. While on the left side, this F-P filter failed to carve spectrum due to its coated film limitation. Due to the limitation of our laboratory, we have only this kind of F-P. Of course, to be suitable for DWDM application, a filter has FSR measure up to that ITU standard should be used.

To further see about the characteristic of SC, we use a Santec filter (1.95 ± 1 nm at 3 dB) to carve the SC. Due to the limitation of its tunable range (1530 – 1560 nm), we could only carve SC in this 30-nm range. The spectrum and autocorrelation of filtered pulses centered at 1556.08, 1554.16 and 1548.16 nm are shown in Figs. 6 – 8 as examples. Their pulse widths are 1.2, 1.05 and 1.35 ps, and the time-bandwidth products are 0.372, 0.326 and 0.422, respectively. These results show that the carved pulses have good coherence.

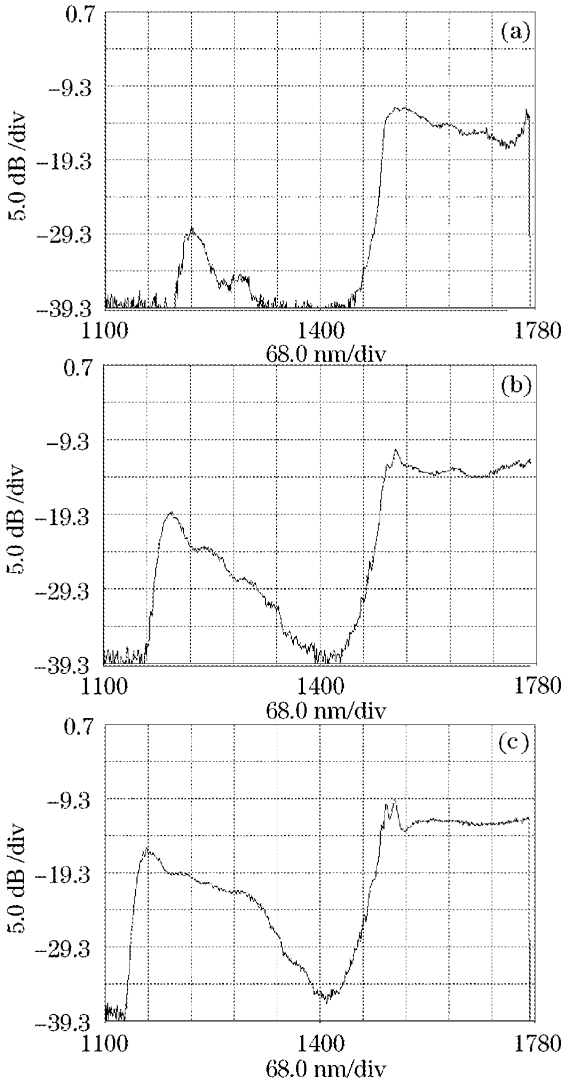

Fig. 4. SC generated at 10- (a), 25- (b) and 55-mW (c) average pump power.

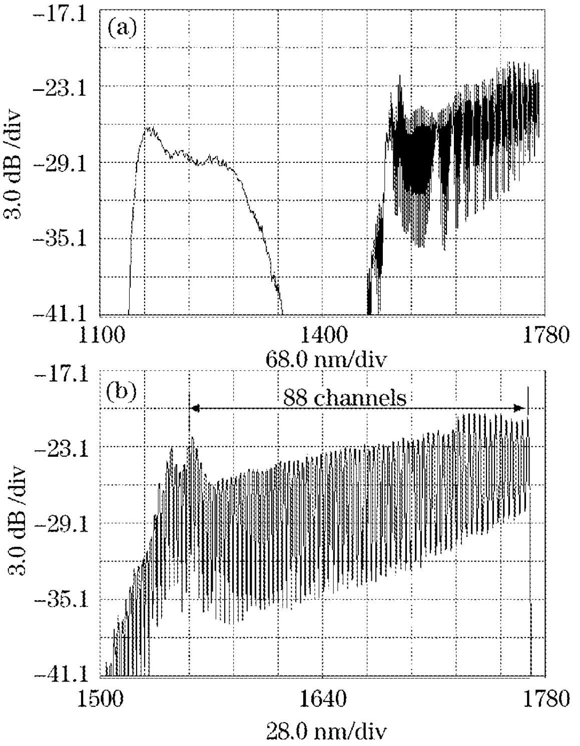

Fig. 5. Slices in the spectrum obtained by using F-P filter.

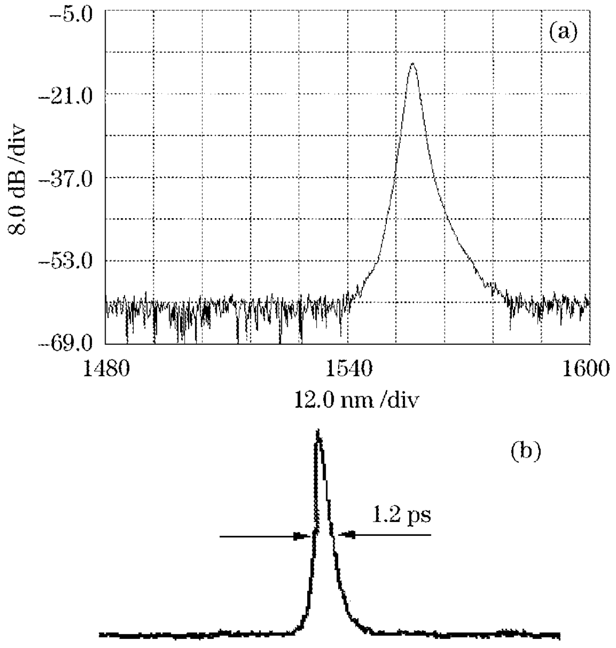

Fig. 6. Spectrum (a) and autocorrelation (b) of pulse carved from SC centered at 1556.08 nm.

In summary, we generated flattened ultra-broadband SC with DFF. Spectrum carving results are obtained by using two different filters. If the length of DFF is optimized, better results will be obtained. However, the repetition rate of pulses is too low to be used in DWDM system. To enhance the repetition rate, delay and multiplexing technology should be used. Meanwhile the F-P filter should be replaced by the one with FSR on the ITU grid. Now further experiments are under way.

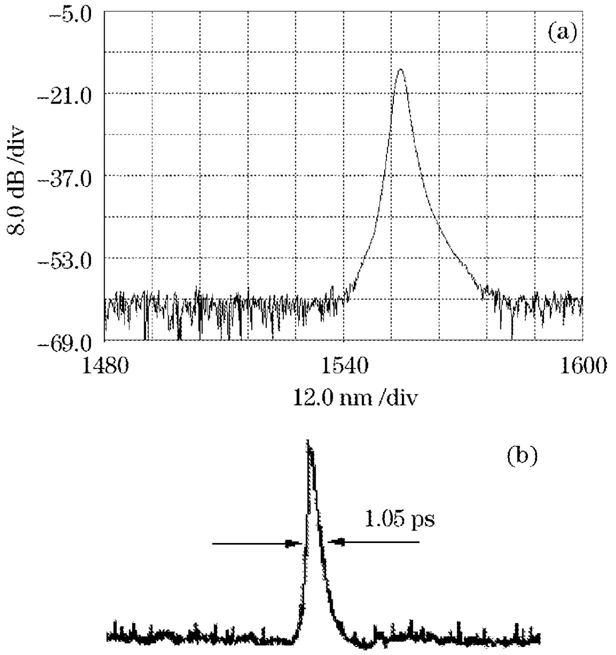

Fig. 7. Spectrum (a) and autocorrelation (b) of pulse carved from SC centered at 1554.16 nm.

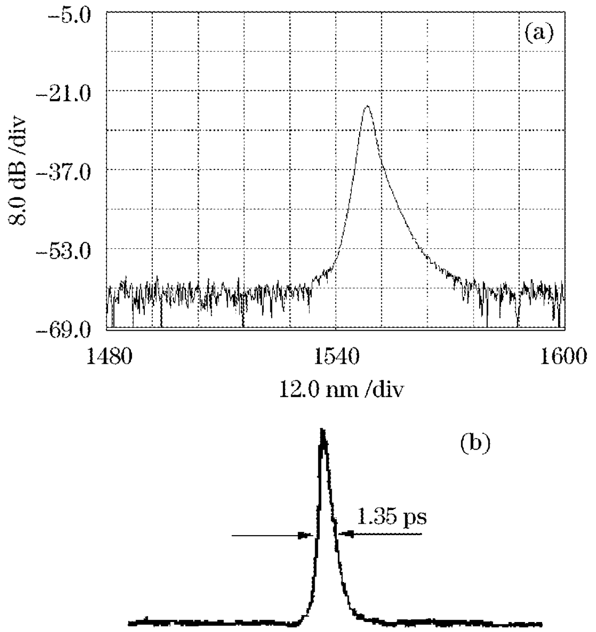

Fig. 8. Spectrum (a) and autocorrelation (b) of pulse carved from SC centered at 1548.16 nm.

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References

1. S. Kawanishi, H. Takara, K. Uchiyama, I. Shake, and K. Mori, in *Proceedings of OFC'99* PD1-1 (1999).
2. F. Futami and K. Kikuchi, IEICE Trans. Commun. **E82-B,** 1265 (1999).
3. H. Takara, T. Ohara, K. Mori, K. Sato, E. Yamada, Y. Inoue, T. Shibata, M. Abe, T. Morioka, and K. I. Sato, IEEE Electron. Lett. **36,** 2089 (2000).
4. K. Mori, K. Sato, H. Takara, and T. Ohara, IEEE Electron. Lett. **38,** 544 (2003).
5. G. P. Agrawal, *Nonlinear Fiber Optics & Application of Nonlinear Fiber Optics* (in Chinese) D. F. Jia, Z. H. Yu, B. Tan, Z. Y. Hu, and S. C. Li (translated) (Publishing House of Electronics Industry, Beijing, 2002).
6. K. Mori, H. Takara, and S. Kawanishi, J. Opt. Soc. Am. B **18,** 1780 (2001).
7. L. Xu, M. Y. Yao, Y. H. Li, J. Wu, M. H. Chen, J. F. Zhang, C. Y. Lou, and Y. Z. Gao, in *Proceedings of CLEO'99,* **P1.50,** 419 (1999).
8. N. Nishizawa and T. Goto, IEEE J. Sel. Top. Quantum Electron. **7,** 518 (2001).