Appl. Phys. B (2016) 122:229
DOI 10.1007/s00340-016-6503-z

Applied Physics B
Lasers and Optics

Blue-enhanced supercontinuum generation pumped by a giant-chirped SESAM mode-locked fiber laser

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Received: 5 April 2016 / Accepted: 28 July 2016 / Published online: 6 August 2016

Abstract We report on a blue-enhanced supercontinuum generation pumped by a giant-chirped SESAM mode-locked 1064-nm fiber laser, in which the giant chirp is introduced by a piece of 3.5-km single-mode fiber outside of the cavity. The giant-chirped pump source with 2.2-nm spectral bandwidth and 186-ps pulse width is used to enhance dispersive waves generation in blue wavelength. An extremely wide optical spectrum with a broad 3-dB spectral bandwidth of 311 nm (from 446 to 757 nm) and a maximum spectral power density of 4 mW/nm at 464 nm is obtained.

1 Introduction

The broadband supercontinuum (SC) fiber sources with spectra from ultraviolet (UV) to mid-infrared offer a range of attractive applications [1–4]. In particular, the visible part (400–850 nm) of the sources is generally used as the excitation light for biophotonic fluorescence imaging, e.g., flow cytometry, coherent anti-stokes Raman scattering (CARS) microscopy and optical coherence tomography (OCT) [5]. Traditional SC sources are usually limited on the short wavelength edge to around 450–500 nm and difficult to cover blue band. Tapered or special designed photonic crystal fiber (PCF) is used to effectively enhance visible supercontinuum generation [6–9]. In a recent progress [10], we show that a giant-chirped pump source is helpful to increase the bandwidth of the SC generation and enhance the intensity of UV and visible wavelength range. When the average power of giant-chirped pump source is 1.4 W, we obtain a total power of 973 mW ultra-flat UV-enhanced supercontinuum spectrum, which has a high 3-dB spectral flatness from 431 nm to 798 nm and over 36 % (350 mW) of the total output power located in the visible and UV wavelength. However, the nonlinear polarization rotation (NPR) and ~1-km-long fiber cavity is adopted to generate the giant-chirped pulses in that work and the NPR mode-locking configuration is generally not self-starting. Furthermore, the method of NPR strongly depends on the polarization evolution and phase evolution of the pulse in the laser cavity, and mode locking can be easily affected by the environment-induced fiber birefringence and requires the adjustment of the polarization controllers for stable operation. On the other hand, an environmentally stable self-started mode-locked fiber laser can be achieved with a semiconductor saturable absorber mirror (SESAM) technology, which is superior to NPR mode locking because SESAM mode-locked laser is less sensitive to the temperature and to the birefringence of the fibers.

In this paper, we report on a blue-enhanced SC generation from a uniform PCF pumped by a giant-chirped SESAM mode-locked ytterbium-doped fiber laser, in which the giant chirp is introduced by a piece of ~3.5-km single-mode fiber outside of the cavity. An extremely wide and blue-enhanced SC spectrum spanning from 415 to 2400 nm with total power of 3 W is obtained, which has a broad 3-dB spectral bandwidth of 311 nm (from 446 to 757 nm). Over 30 % of the total SC power lies in the visible spectral ranges from 415 to 850 nm, corresponding to an output power of 900 mW and a maximum spectral power density of ~4 mW/nm at 464 nm. This kind of fiber source with enhanced blue spectral power density will find

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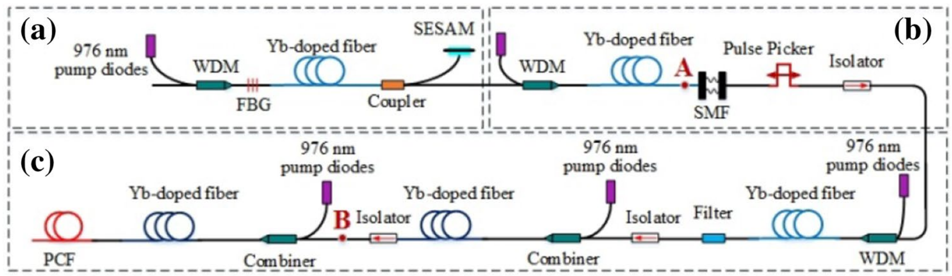

Fig. 1 Schematic setup of the UV-enhanced supercontinuum generation all-fiber system. SMF, single-mode fiber; WDM, 976-/1064-nm wavelength division multiplexer coupler

wide applications in biophotonic imaging, high-resolution microscopy and spectroscopy systems.

2 Experimental setup

A schematic of the supercontinuum generation system used in this study is shown in Fig. 1, which consists of a SESAM mode-locked Yb-doped oscillator, a chirp-introduced device, a repetition rate modulation device (a pulse picker), three-stage fiber amplifiers and a piece of PCF. The SESAM mode-locked Yb-doped oscillator is constructed in a linear configuration depicted in Fig. 1a. The total length of the cavity is ~3 m, which includes a 1.5-m single-cladding Yb-doped fiber (YDF) (Nufern SM-YSF-HI-6/125) with group-velocity dispersion (GVD) of −35 ps/nm/km, a narrowband (full width at half maximum of 0.6 nm) and high reflectivity (99.9 %) fiber Bragg grating (FBG), and a 30 % fiber coupler is used to output the signal. One end of the Yb-doped gain fiber is fusion spliced to the FBG; the other end is fusion spliced to the fiber coupler of input end. The 70 % port of the fiber coupler is perpendicularly cleaved and butted to a SESAM. The YDF with ~250 dB/m absorption is pump in-core by a diode laser with a center wavelength of 976 nm and a maximum out power of 480 mW.

As shown in Fig. 1b, the chirp-introduced device includes a stage of core-pumped fiber amplifier and a ~3.5-km single-mode fiber with GVD of −30.8 ps/nm/km. The single-mode fiber is used to add chirp to the input pulse and stretch it with suitable GVD. A same kind of YDF with 2 m length is used as the gain medium, which is pumped by another single-mode diode laser operating at 976 nm. The pulse picker is used to reduce the repetition rate of the pulse.

As shown in Fig. 1c, three-stage fiber amplifiers include a core-pumped fiber amplifier and two stages of double-clad Yb-doped all-fiber amplifiers. The double-clad gain fiber has a 7/128 μm core/cladding diameter with 0.19/0.45 NA and cladding absorption about 5.4 dB/m at 975 nm. The isolator is used to prevent reflection back to the oscillator. The narrow bandpass filter is used to filter out amplified spontaneous emission (ASE) and stimulated Raman scattering (SRS) generated during the amplification. A short piece of single-cladding fiber is used to strip off pump light. The PCF of 1 m length has a core diameter of about 4.6 μm and a hole size to pitch ratio of about 0.6, with the ZDW around 1030 ± 20 nm. The dispersion coefficient at 1064 nm is 8.36 ps/nm/km, and the nonlinear coefficient at 1064 nm is 11.16 $W^{-1}km^{-1}$, identical to the PCF used in Ref. [10].

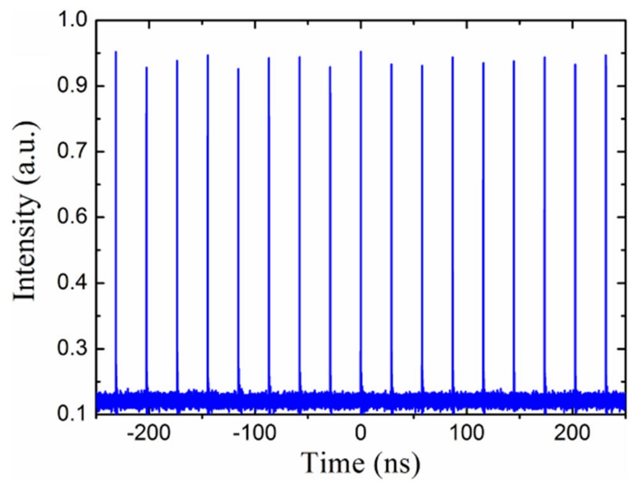

Fig. 2 Stable mode-locked pulse train at 34 MHz repetition rate

3 Results and discussion

3.1 Giant-chirped pulses generation and amplification

With proper adjustment of SESAM reflection coupling with the fiber end, stable self-started mode-locked pulses of the fiber laser occur at ~100 mW incident pump power and the repetition rate is 34 MHz (shown in Fig. 2), which agrees with the laser cavity length. The maximum output power is 3.7 mW for 100 mW pump power. As shown in Fig. 3a and b, the pulse FWHM width of the autocorrelation trace is 10 ps and the center wavelength is 1064.1 nm with spectral bandwidth of 0.46 nm. As shown in Fig. 1b, the first-stage preamplifier boosts up the output power to 66 mW (corresponding point A) under 343 mW pump power. Then,

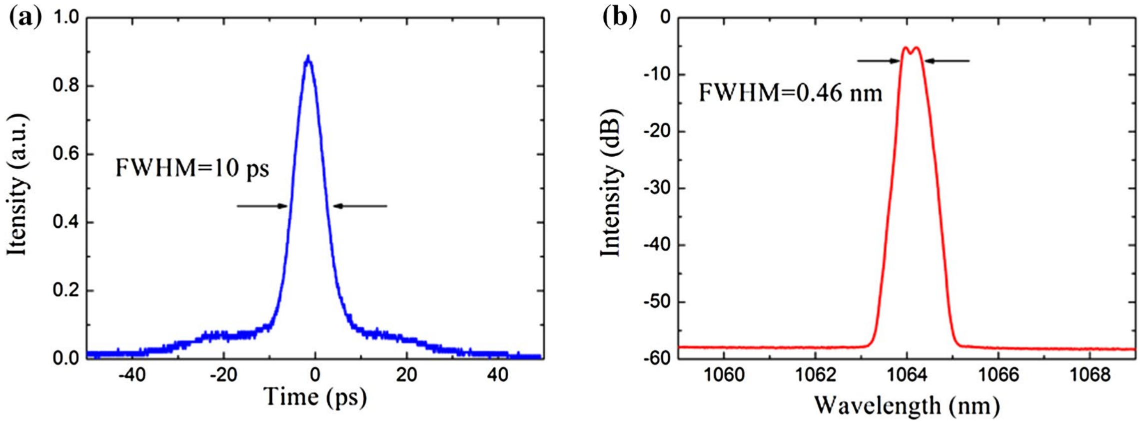

Fig. 3 **a** Autocorrelation trace and **b** spectral intensity of the SESAM mode-locked oscillator

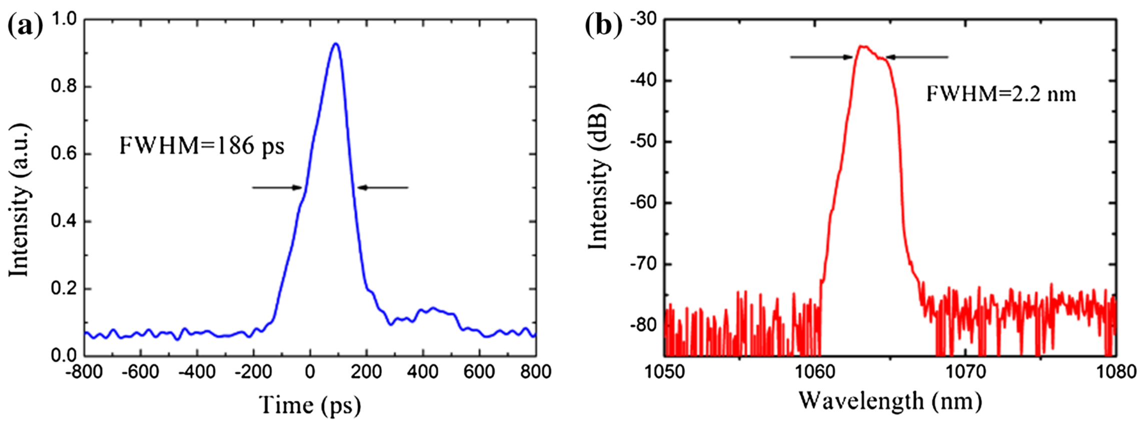

Fig. 4 **a** Temporal and **b** spectrum after ~3.5 km of single-mode fiber transmission

after ~3.5 km of single-mode fiber transmission, the pulse width of 10 ps is stretched to 186 ps (shown in Fig. 4a), and the spectral bandwidth is 2.2 nm (shown in Fig. 4b). The chirp is introduced using GVD, which causes different frequencies to propagate at slightly different speeds in the ~3.5-km length of a standard single-mode optical fiber. The time bandwidth product (TBP) is calculated to be 108, which is ~246 times the transform limit, assuming a sech2 profile, indicating that the pulses are highly chirped [11]. The 34 MHz repetition rate of the mode-locked pulse train is reduced to 400 kHz using the pulse picker, and the average power is reduced to 0.4 mW before launching into the fiber amplifiers.

The average power is boosted up to 217 mW (corresponding point B in Fig. 1c) by all the preamplifiers. Through the power amplifier, the average power of giant chirp pulse is amplified to 3.5 W at pump power of 14 W, corresponding to single pulse energy of 8.7 μJ. The pulse width of 186 ps (shown in Fig. 5b) has no obvious variation after fiber power amplifier. Figure 5c shows optical spectrum (FWHM = 2 nm) of the fiber power amplifier at 3.5 W with clearly ASE and SRS generated.

3.2 Supercontinuum generation pumped by the amplified giant-chirped pluses

Figure 6 shows the SC spectra measured by two different optical spectrum analyzers (Yokogawa, AQ6373 and AQ6375) with spectral resolution of 0.5 nm. The spectrum evolution accords with the typical theory of supercontinuum generation with picosecond pulse pump in the PCF anomalous dispersion region [12, 13]. In our previous work, the spectral broadening dynamics of the SC generation at the anomalous dispersive region of the PCF are carefully studied in the giant-chirped pulses pump regime [10]. At low pump power, the pulse is slightly compressed due to the positive initial strong chirp in the anomalous dispersion region of the PCF. As the pump power is increased, the pulse breaks up due to modulation instability (MI) caused in the anomalous dispersion. MI leads to temporal breakup

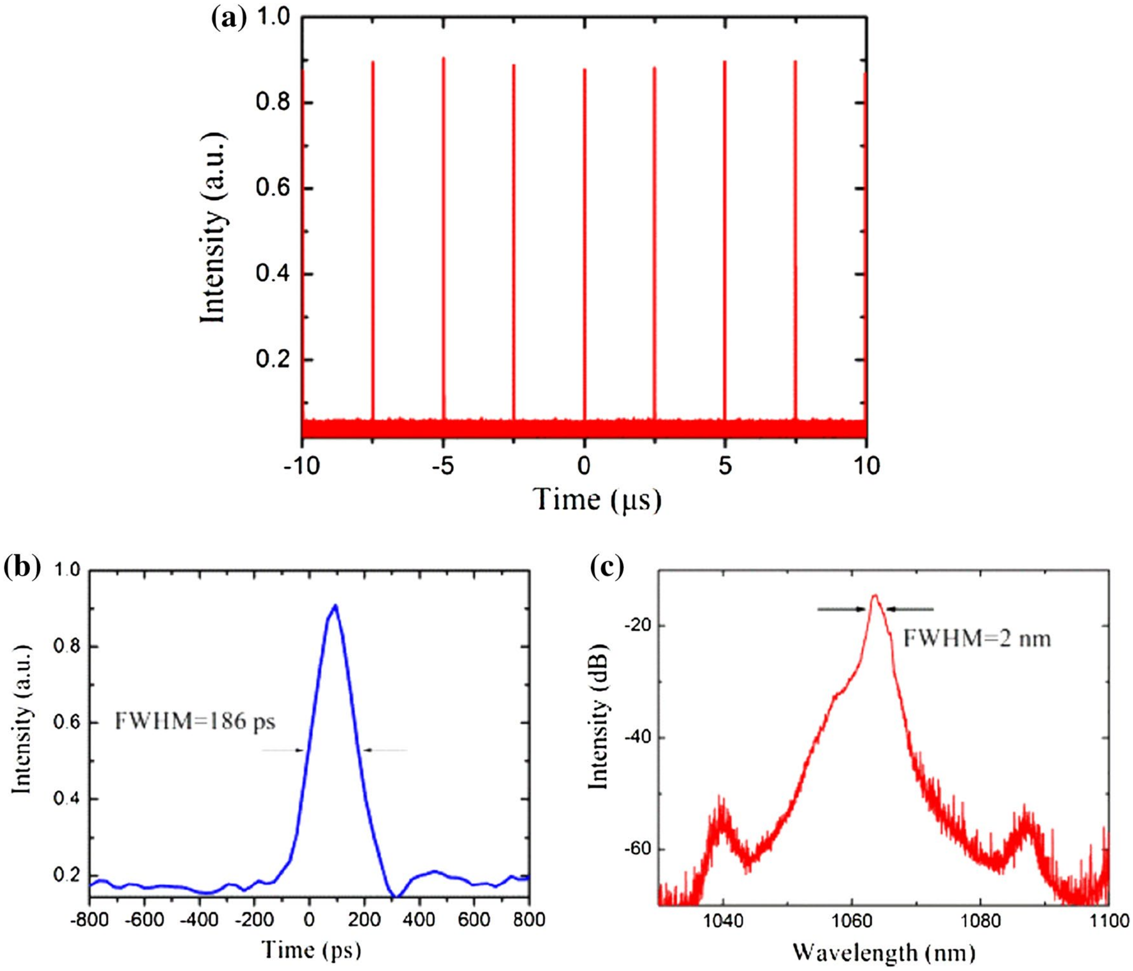

Fig. 5 **a** Pulse train of 400 kHz, **b** temporal and **c** spectrum after the fiber power amplifier at maximum average output power

of high power pulse into a distribution of soliton-like pulses and dispersive waves. Each of these solitons may furthermore resonantly transfer energy to the normal GVD regime if they have sufficient spectral overlap across the ZDW. In this process, MI provides the extremely smooth spectral features of continuum as each soliton and dispersive wave contributes to a slightly different region of the continuum spectrum. Once the MI dynamics breaks up the pump pulses into shorter duration sub-pulses, further spectral broadening follows the same mechanism as the case of femtosecond short pulses, whereby the long-wavelength generation is due to the Raman-induced solution self-frequency shift (SSFS) and the short-wavelength side is determined by the four-wave mixing (FWM) and dispersive wave generation in the normal dispersion region. While the soliton is being redshifted due to the self-frequency shift, it keeps a packet of dispersive waves trapped in a group-velocity-matched bound state, also known as soliton trapping of dispersive waves, so that the dispersive waves are blueshifted to maintain group-velocity matching. The spectrum exhibits a continuous broadening toward both sides of the pump wavelength in this process.

At the highest pump power of 3.5 W, a wider and flatter SC spectrum with total power of 3 W is obtained which spans over 1985 nm, ranging from 415 to 2400 nm (Fig. 6a blue curve and red curve). The spectrum generated at the highest output power is remarkably flat, with the 3-dB spectral bandwidth from 446 to 757 nm. The long-wavelength side of the spectrum is measured by the optical spectrum analyzer Yokogawa AQ6375 (1200–2400 nm), which has no order-sorting filters. Thus, a 1200-nm cut-on long-pass filter is used to prevent multi-order interference in the measurement. We also measured the output power of the SC in the visible wavelength region using a short-pass filter at 850 nm. Over 30 % of the total SC output power is located in the visible regime, corresponding to 900 mW output power. The measured maximum spectral power density is 4 mW/nm at the peak of 464 nm (shown in Fig. 6b), which corresponds to the enhanced blue-dispersive waves generation. In addition, the intensity of long wavelength is significantly weaker than

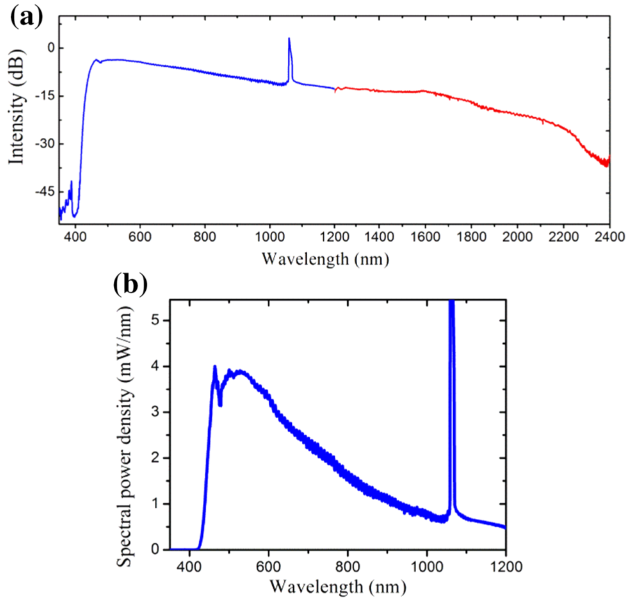

Fig. 6 **a** SC output spectrum at highest pump power level. Traces are measured with two OSAs. **b** Spectral power density of SC in the visible wavelength regime

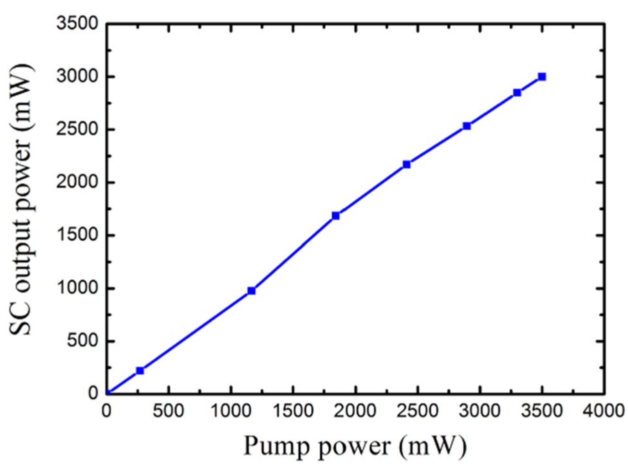

Fig. 7 Output powers of SC with different input pump powers

the intensity of short wavelength. This is because the initial pulses with giant chirp lead less energy for soliton formation in the anomalous dispersion regime and more energy transferred to the blue-dispersive waves. No sign of power roll-off is observed in Fig. 7, indicating that the supercontinuum output power can be further scaled as long as more powerful pump power is lunched.

4 Conclusion

In conclusion, we have reported experimental results on the blue-enhanced SC generation in a uniform PCF. The PCF is pumped by a giant-chirped SESAM mode-locked ytterbium-doped fiber laser, in which the giant linearly chirp is introduced by 3.5-km single-mode fiber outside of the cavity. At the pump average power of 3.5 W, a total power of 3 W blue-enhanced (maximum spectral power density of 4 mW/nm at 464 nm) SC with the spectrum range from 415 to 2400 nm is obtained, with the 3-dB spectral bandwidth from 446 to 757 nm and over 30 % (900 mW) of the total SC power locates in the visible regime.

Acknowledgments This work was supported by the National Natural Science Foundation of China (NSFC, Nos. 61235010 and 61527822), the Beijing Municipal Education Commission (No. KZ201110005011) and the Beijing University of Technology, China.

References

1. I. Hartl, X.D. Li, C. Chudoba, R. Ghanta, T. Ko, J.G. Fujimoto, J.K. Ranka, R.S. Windeler, A.J. Stentz, Opt. Lett. **26**, 608 (2001)
2. K. Lindfors, T. Kalkbrenner, P. Stolle, V. Sandoghdar, Phys. Rev. Lett. **93**, 037401 (2004)
3. P. Cimalla, J. Walther, M. Mehner, M. Cuevas, E. Koch, Opt. Exp. **17**, 19486–19500 (2009)
4. Y. Sun, C.F. Booker, S. Kumari, R.N. Day, M. Davidson, A. Periasamy, J. Biomed. Opt. **14**, 054009 (2009)
5. A. Labruyère, A. Tonello, V. Couderc, G. Huss, P. Leproux, Opt. Fiber Technol. **18**, 375 (2012)
6. U. Møller, S.T. Sørensen, C. Larsen, P.M. Moselund, C. Jakobsen, J. Johansen, C.L. Thomsen, O. Bang, Opt. Fiber Technol. **18**, 304 (2012)
7. J.M. Stone, J.C. Knight, Opt. Fiber Technol. **18**, 315 (2012)
8. J. Cascante-Vindas, A. Díez, J.L. Cruz, M.V. Andrés, Opt. Exp. **18**, 14535 (2010)
9. J.M. Stone, J.C. Knight, Opt. Exp. **16**, 2670 (2008)
10. S. Gao, Y. Wang, R. Sun, H. Li, C. Tian, D. Jin, P. Wang, Opt. Exp **22**, 24697 (2014)
11. E.J.R. Kelleher, J.C. Travers, E.P. Ippen, Z. Sun, A.C. Ferrari, S.V. Popov, J.R. Taylor, Opt. Lett. **34**, 3526 (2009)
12. B. Kibler, B. Barviau, C. Michel, G. Millot, A. Picozzi, Opt. Fiber Technol. **18**, 257 (2012)
13. V.V. Alexander, O.P. Kulkarni, M. Kumar, C. Xia, M.N. Islam, F.L. Terry Jr., M.J. Welsh, K. Ke, M.J. Freeman, M. Neelakandan, A. Chan, Opt. Fiber Technol. **18**, 349 (2012)