Picosecond supercontinuum generation seeded by a weak continuous wave*

Li Ying(李 荧), Hou Jing(侯 静)†, Leng Jin-Yong(冷进勇),
Wang Wen-Liang(王文亮), and Jiang Zong-Fu(姜宗福)

College of Optoelectronic Science and Engineering, National University of Defense Technology, Changsha 410073, *China*

(Received 11 October 2012; revised manuscript received 9 January 2013)

We experimentally investigate the spectral details of a picosecond supercontinuum pumped at 1064 nm and seeded by a weak continuous wave (∼20000 times weaker than the pulse peak power) at several power levels in photonic crystal fibers. Seeding at different wavelengths leads to different spectral details and the effects to the bandwidth of supercontinuum are also distinct. Spectra can be widened when seeded by a continuous wave at 1070 nm and narrowed by ∼ 100 nm when seeded at 1080 nm. The influence is enhanced by increasing the average seeded power.

Keywords: supercontinuum seeded by a weak continuous wave, modulation instability, four-wave mixing

PACS: 42.65.–k, 42.60.Fc, 42.65.Wi **DOI:** 10.1088/1674-1056/22/7/074205

1. Introduction

The study of supercontinuum (SC) generation in optical fibers[1–8] has been a field of intense research for decades, especially in photonic crystal fiber (PCF),[1–3,6,7] since 2000,[9] leading to a number of important advances in both fundamental and application sciences. SC generation can be achieved by using ultrashort pulses, long pulses, or even continuous wave (CW) signals. Different pump signals involve different spectral broadening mechanisms. For ultrashort pulses, signals usually pump in the anomalous dispersion regime of the PCF, and self-phase modulation (SPM), cross-phase modulation (XPM), stimulated Raman scattering (SRS), soliton fission, and soliton self-frequency shift broaden the spectra.[10,11] For long pulses or CW signals, modulation instability (MI), a four-wave mixing (FWM) process that is phase-matched by SPM and initiated spontaneously from noise, plays a crucial role in SC generation. At the beginning, the MI process creates spectral sidebands symmetrically on both sides of the central wavelength, in the time domain, a growing amplitude modulation is developed, leading to the formation of a train of ultrashort pulses. These pulses are not stable under higher-order dispersion and SRS effects, and they split into quasi-fundamental solitons, stretching SC to both long and short wavelength regions as dispersive waves.[2,12,13] This results in a dramatic enhancement in SC bandwidth and power.

With SC being successfully applied in optical coherence tomography,[14] coherent anti-Stokes Raman scattering microscopy (CARS),[15] optical frequency metrology,[16] and generation of ultrashort optical pulses,[1] the sensitivity to noise of the SC source from longer pulses has attracted a lot of scientific attention in recent years. Solli *et al*.[17] showed that a weak seed pulse is conducive to the control of spectra as well as improving the temporal coherence of SC. In 2011, Cheung *et al*.[18] used a weak CW light as the trigger to enhance and stabilize the SC generation. Afterward, the mechanism was also numerically studied.[19] Fernandes *et al*.[20] compared using a hybrid input with a CW only pump configuration.

Different from the experiments mentioned above, the wavelength of the pump signal in this work is changed to 1064 nm from communication wavelengths. We mainly investigate the influence to the expansion details of SC when a weak CW signal at two different wavelengths is seeded and the anomalous dispersion regime is pumped. We experimentally demonstrate that a weak CW signal can either increase or narrow the bandwidth of SC, which is largely dependent on the central wavelength of the CW signal seeded.

2. Experimental setup

The experimental setup used to generate SC is schematically illustrated in Fig. 1, in which a self-constructed continuous wave laser emitting at 1080 nm or 1070 nm (Fig. 2(a)), depending on the center wavelength of the fiber grating, and having 3 dB linewidth smaller than 0.1 nm and maximum optical power 100 mW supplies the input to the 40% port of the coupler through splicing. Another optical signal from an Nd:YAG *Q*-switched microchip laser (Teem Photonics, NP-10820) running at 1064 nm and emitting 0.6 nm (FWHM) pulses with 15 kW peak power at 7.3 kHz repetition rate is

*Project supported by the National Natural Science Foundation of China (Grant Nos. 61235008 and 61077076), the International Science & Technology Cooperation of China (Grant No. 2012DFG11470), and the Natural Science Foundation for Distinguished Young Scholars of Hunan Province, China (Grant No. 12JJ1010).

†Corresponding author. E-mail: houjing25@sina.com

© 2013 Chinese Physical Society and IOP Publishing Ltd

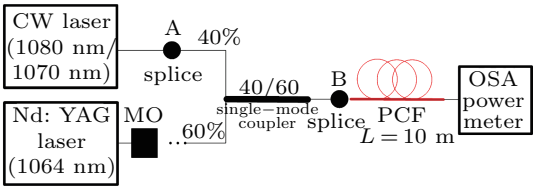


Fig. 1. (color online) Schematic diagram of the experimental setup.

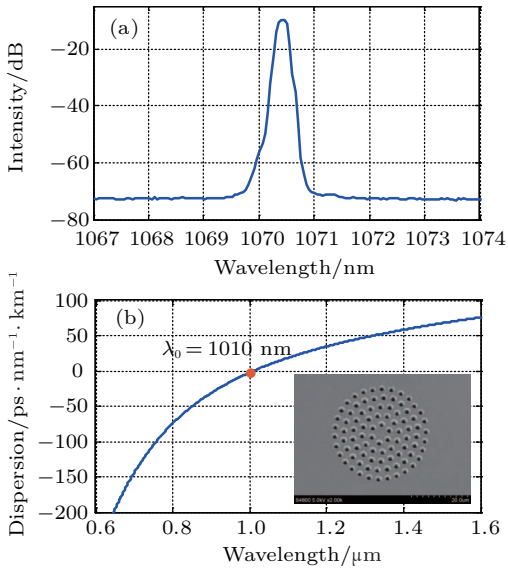


Fig. 2. (color online) (a) Output spectrum of the continuous wave laser at 1070 nm; (b) calculated dispersion curve and SEM (inset) of the PCF.

coupled to the 60% input of the coupler by a simple 25× microscope objective (MO) lens. Spliced with the output of the single mode coupler is a PCF with length 10 m, core diameter 4.6 μm, and small holes. The calculated dispersion curve and scanning electron microscope (SEM) image are shown in Fig. 2(b). As the zero dispersion wavelength is situated at about 1010 nm, both the pulse and the continuous lasers locate in the anomalous dispersion regime. The spectrum after the PCF is then monitored with an optical spectral analyzer (OSA). The power spectrum is measured with a wavelength resolution of 0.2 nm. In Fig. 2(a) we display the CW signal power spectrum measured with a resolution of 0.01 nm.

3. Experimental results and discussion

We start our experimental tests using only pulse laser signals at different peak power levels which are calculated according to the average power measured at the output end of the fiber. The output spectra are presented using dashed black lines in Figs. 3(a)–3(d). At least two pairs of sidebands (centered around 1075 nm, 1055 nm, and 1084 nm, 1045 nm) near 1064 nm arising from the spontaneous MI are notable (see the inset in Fig. 3(a)). MI leads to the breakup of a long pulse to multiple ultrashort pulses, which then evolve into optical solitons and soliton fission, leading to the spectral broadening

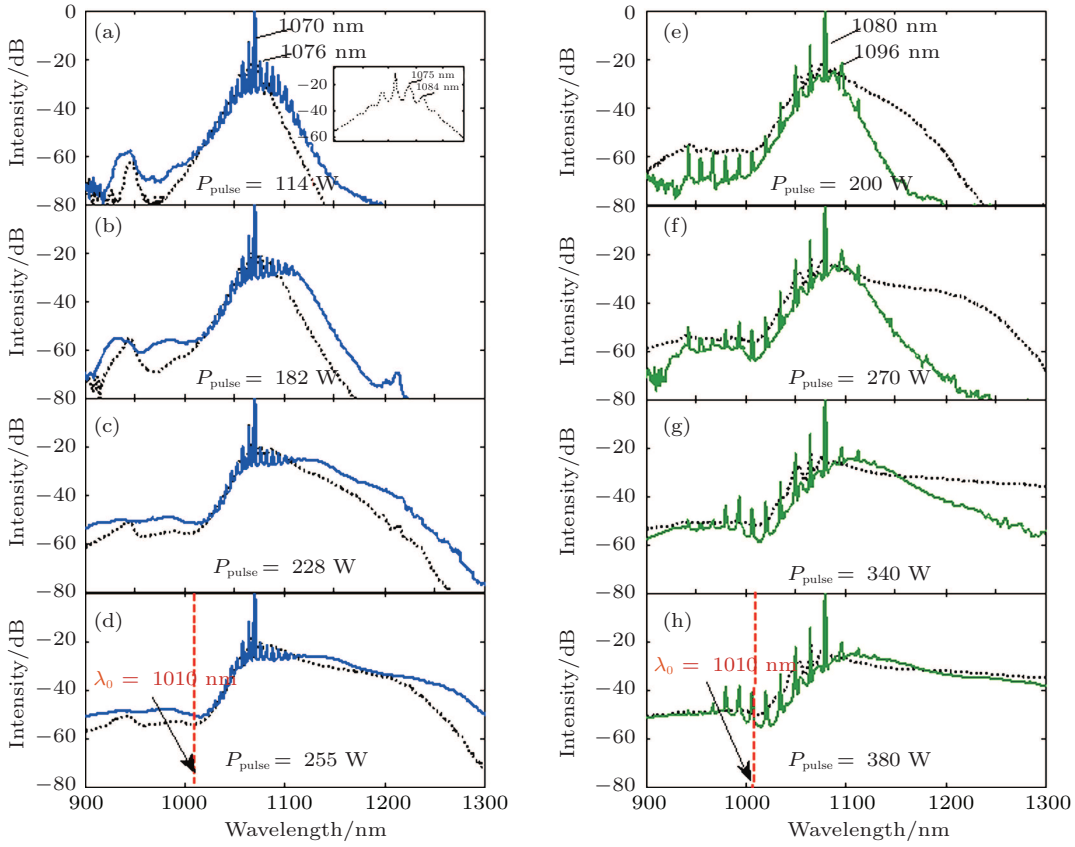


Fig. 3. (color online) Measured SC spectra for pulse pumping only (dashed black lines) and CW seeded pumping at 1070 nm (blue lines) or 1080 nm (green lines). Inset in panel (a) is the spectrum for pulse only pumping with pulse peak power 114 W. In panels (a)–(h), a different P pulse is used, where $P_{\rm pulse}$ is the calculated peak power of the pulse according to the average power. The 1070 nm CW signal power is fixed at 7.4 mW and the 1080 nm CW signal power is fixed at 10 mW. Dashed red lines in panels (d) and (h) indicate the location of zero dispersion wavelength.

in the long-wavelength region, as well as dispersive waves in the low-frequency region (see the hump centered around 947 nm in Fig. 3(a)). Then a weak CW signal ($\sim$ 7.4 mW) at 1070 nm is coupled with the pulse pump and launched into the PCF. Evidently, the MI wings of the spectrum evolve into a train of intensity peaks with much smaller frequency intervals (see blue lines in Figs. 3(a)–3(d)). In the long-wavelength region, the bandwidth is widened for 50 nm. In the short-wavelength region, the spectra are increased by several dB compared to those shown by the dashed black lines.

The spectra of pulse only pumping (dashed black lines) and 1080 nm CW signal seeded (green lines) configurations are also compared in Figs. 3(e)–3(h). Even though the seeded signal is $\sim$20000 times weaker than the pump pulse peak, the SC generation has a significant narrowing (almost 100 nm at each pulse peak power level). And the average intensity drops for 10 dB around 950 nm even with the efforts of higher intensity spikes nearby.

To eliminate the interference of the input power of the CW signal, we fix the power of the pulse signals and then investigate the spectral modification for various power levels of the CW signal. The results are shown in Fig. 4, which imply that the bandwidth of the SC increases with increasing power of the CW signal at 1070 nm; while SC exhibits the opposite trend as a function of power when the central wavelength is tuned to 1080 nm. However the enhancing and narrowing are not limitless. When the CW signals reach around 7.5 mW, the spectrum almost remains unchanged for these two cases.

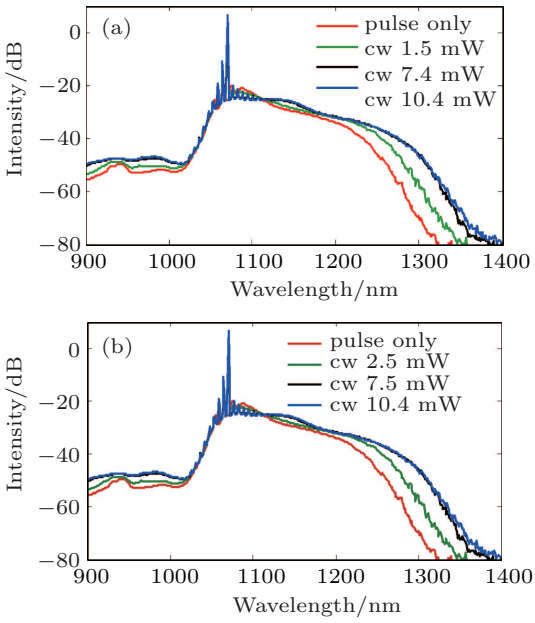


Fig. 4. (color online) Measured SC spectra with the CW seed at (a) 1070 nm or (b) 1080 nm for different seed power levels. The red lines show measured SC spectra without the CW seed. The peak power of input pulse is $P_{\text{pulse1}} = 230$ W in panel (a), $P_{\text{pulse2}} = 340$ W in panel (b).

As seen clearly in Figs. 3 and 4, the influence of the seeded CW signal has a remarkable dependence on its central wavelength; even both the 1070 nm and 1080 nm signals are in the gain bandwidth with MI. In the case with only pulse pumping, the largest gain (first order) of the spontaneous MI occurs at 1075 nm (see Fig. 3(a)), and the second order occurs at 1084 nm. The interval between the side lobes is $\sim$ 10 nm. When the CW signal centered at 1070 nm is seeded, the MI effect is enhanced (see Fig. 3(a)). This speeds up the processes of pulse breakup and soliton formation and then promotes the spectral broadening. When we add a 1080 nm CW signal, the interval between the side lobes is as large as $\sim$ 16 nm (see Fig. 3(e), if 1080 nm is defined as the first order, then 1096 nm is the second order) So only the fourth-order anti-Stokes side lobe (away from 1064 nm) generated from FWM is across the zero dispersion wavelength (see Fig. 3(h)). Besides, compared with the phase-matching conditions among the wavelengths in the normal dispersion regime, the ones in the anomalous dispersion regime are relatively easier to satisfy, as a result, a very considerable part of the pulse pump power is consumed to generate side lobes through FWM, leading to the spectral narrowing. By increasing the seeded power at 1080 nm, the effect of FWM is enhanced. The higher-order side lobe generation and higher side lobe intensity consume more pulse energy, making the spectrum further compressed.

4. Conclusion

In summary, we investigate the details of picosecond SC generation when a weak CW signal is seeded. By carefully selecting the central wavelength of the CW signal, picosecond SC can be considerably broadened or narrowed. When the CW signal (works like a seed for MI) centered at 1070 nm is seeded, the effect of MI is strengthened as its original way, making soliton fission easier and spectrum widened. While the width of SC is seriously narrowed when the wavelength of the seeded CW signal is around 1080 nm. Because more pulse power is used by FWM, which generates in the normal or anomalous dispersion regime. The enhancing and narrowing effects will be enhanced with higher seeded power.

References

[1] Dudley J M, Genty G and Coen S 2006 *Rev. Mod. Phys.* **78** 1135
[2] Wang Y, Xiong C L, Hou J, Cao J Q , Li Y, Song R and Lu Q S 2011 *Appl. Opt.* **50** 2752
[3] Chen H W, Chen S P, Wang J H, Chen Z L and Hou J 2011 *Opt. Commun.* **284** 5484
[4] Xia G, Huang D X and Yuan X H 2007 *Acta Phys. Sin.* **56** 2212 (in Chinese)
[5] Chen Y Z, Li Y Z and Xu W C 2008 *Acta Phys. Sin.* **57** 7693 (in Chinese)
[6] Li J F, Zhou G Y and Hou L T 2012 *Acta Phys. Sin.* **61** 124203 (in Chinese)
[7] Jin A J, Wang Z F, Hou J, Wang Y B and Jiang Z F 2012 *Acta Phys. Sin.* **61** 124211 (in Chinese)
[8] Song R, Hou J, Chen S P, Yang W Q and Lu Q S 2012 *Opt. Lett.* **37** 1529
[9] Ranka J K, Windeler R S and Stentz A J 2000 *Opt. Lett.* **25** 25

[10] Hori T, Nishizawa N, Goto T and Yoshida M 2004 *J. Opt. Soc. Am. B* **21** 1969
[11] Sakamaki K, Nakao M, Naganuma M and Izutsu M 2004 *IEEE Journal of Selected Topics in Quantum Electronics* **10** 876
[12] Cumberland B A, Travers J C, Popov S V and Taylor J R 2008 *Opt Express* **16** 5954
[13] Stone J M and Knight J C 2008 *Opt. Express* **16** 2670
[14] Povazay B, Bizheva K, Unterhuber A, Hermann B, Sattmann H, Fercher A F and Drexler W 2002 *Opt. Lett.* **27** 1800
[15] Lu F, Zheng W and Huang Z 2008 *J. Opt. Soc. Am. B* **25** 1907
[16] Washburn B and Newbury N 2004 *Opt. Express* **12** 2166
[17] Solli D R, Ropers C and Jalali B 2008 *Phys. Rev. Lett.* **101** 233902
[18] Cheung K K Y, Zhang C, Zhou Y, Wong K K Y and Tsia K K 2011 *Opt. Lett.* **36** 160
[19] Li Q , Li F, Wong K K Y, Lau A P T, Tsia K K and Wai P K A 2011 *Opt. Express* **19** 13757
[20] Fernandes G, Facao M, Carvalho M I, Rodrigues S, Heidarialamdarloo J, Pinto M F and Ferreira M F 2012 *Proc. SPIE* **8434** 1