# Enhanced Supercontinuum Generation By Minute Continuous Wave Seed

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## ABSTRACT

It is well-known that the properties of the supercontinuum (SC) radiation depend critically on the initial pumping conditions. For instance, if the SC is initiated by noise, namely modulation instability (MI), statistically rare "rogue waves" can be observed with sizable spectral broadening and intensity enhancement in SC. Interestingly, such rouge events can be actively controlled by adding an external weak pulse or by modulating the pump-pulse envelopes. In contrast, we here present that a simple triggering mechanism using an extremely weak continuous wave (CW) can also achieve such "rogue" enhancement. We experimentally demonstrated that a weak CW trigger (~200,000× weaker than pump) can considerably broaden the SC bandwidth compared to the untriggered SC case (~100 nm wider). Such enhancement was found to occur when the CW trigger's wavelength falls roughly within the modulation instability gain bandwidth. CW triggering also significantly alters the SC amplitude statistics, i.e. from extreme-value statistics in the untriggered SC to almost normal distribution in the triggered SC. Interferometric measurements also revealed the improvement in the SC coherence when the SC is CW-triggered. The enhanced SC by minute CW triggering only requires the CW-wavelength tuning for optimization and eliminates the necessity of high-precision (down to picoseconds) timing between the pump and the seed as in the pulse-seeding case. It thus offers a more convenient and practical approach to realize an enhanced and stable SC for many applications, especially in which real-time, ultrafast and single-shot spectroscopic measurements are essential.

**Keywords:** Nonlinear optics, Supercontinuum generation

## 1. INTRODUCTION

As the salient field in nonlinear optics, supercontinuum (SC) radiation, which signifies an ultra-wideband spectrum, represents a ubiquitous light source for a myriad of applications, including frequency metrology, optical coherence tomography, molecular optical spectroscopy (e.g. fluorescence, absorption and vibrational spectroscopy), optical coherence tomography, and wavelength-division multiplexing (WDM) optical communications. The extensive spectral broadening in SC involves complex interactions among manifold optical nonlinear effects, each of which depends remarkably on many different parameters, namely the input light power and temporal pulse width, the fiber's nonlinearity and group velocity dispersion (GVD) and so on [1]. By far, a mechanism based on soliton-fission initiated by modulation-instability (MI) is one of the most effective approaches to generate ultrabroadband SC [2]. This process involves MI which creates spectral sidebands to the narrowband input pump light to an extent that Raman-induced self-frequency shift can break it into multiple red-shifted solitons. As MI grows spontaneously from noise, the subsequent soliton fission is triggered in a random fashion. Consequently, the SC generated by this approach is inherently incoherent and experiences significant pulse-to-pulse amplitude fluctuation [3]. In its extreme case, optical rogue waves can even be observed below the "threshold" for soliton fission [4]. Such degradation of SC stability, albeit the SC possesses an ultrabroadband spectrum, impedes the utility of SC in many practical applications, particularly where measurements of rapid dynamics and non-repetitive transient processes are essential, for instance, real-time, ultrafast and single-shot spectroscopy [5] and microscopy [6].

Fortunately, such random and extreme SC instability can be manipulated by adding an external weak pulse co-propagating with the pump light pulse [7] or by modulating the pump pulse envelopes [8]. These schemes show that such active controls can lead to drastic change in the SC's noise characteristics, especially are able to deliberately "stimulate"

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the rogue events in the SC [7]. We here present that a simple triggering mechanism using a separate, extremely weak continuous wave (CW) can also achieve such rogue enhancement and control the SC instability. By launching a CW CW trigger light (~200,000× weaker than pump) at a wavelength within the MI gain bandwidth together with the pump light, the MI growth process can be then initiated by such controllable CW trigger, rather than noise. Hence, the SC generation can be greatly enhanced in terms of both power and stability. We observed that introducing such minute CW trigger can considerably broaden the SC bandwidth (~100 nm wider), with more than 100-fold higher in average SC power compared to the untriggered SC case. . The CW triggering also significantly alters the SC amplitude statistics, i.e. from the extreme-value statistics in the untriggered SC to the almost Gaussian distribution in the CW-triggered SC. Interferometric measurements further revealed the improvement in the coherence of the triggered SC in contrast to the untriggered one.

We note that SC coherence was shown to increase considerably as the pump pulse width is progressively narrower (< 50 fs). However, such ultra-short light pulses are drastically sensitive to ambient perturbation and hence are not practical in many applications. In addition, specialty dispersion-engineered fibers have also been demonstrated to be useful for reducing excess noise for SC generation. But the effect is static, not dynamically controllable. To this end, CW triggering offers a handy approach to provide a great degree of active control over the SC generation process and can also benefit the longer-pulse ( > ps) pumping scheme to generate a more stable and enhanced SC – expanding the scope of possibilities in SC generation. For instance, the longer pulse excitation (ps – ns) would be more desirable for the majority of the fluorescence and nonlinear optical microscopy techniques [9,10]. The present CW triggering scheme mainly only requires the CW-wavelength tuning for optimization and eliminates the necessity of high-precision (down to picoseconds) timing between the pump and seed as in the pulse-seeding case [7]. It thus offers a more convenient and practical approach to realize an enhanced and stable SC for many applications, such as real-time, ultrafast and single-shot spectroscopic measurements and high speed optical switching and signal processing in optical communication. We also demonstrate the utility of the present technique in the context of optical parametric amplification (OPA), in which the amplified signal quality showed significant improvement in the CW-triggered broadband pumping case versus the untriggered case.

## 2. EXPERIMENTAL SETUP

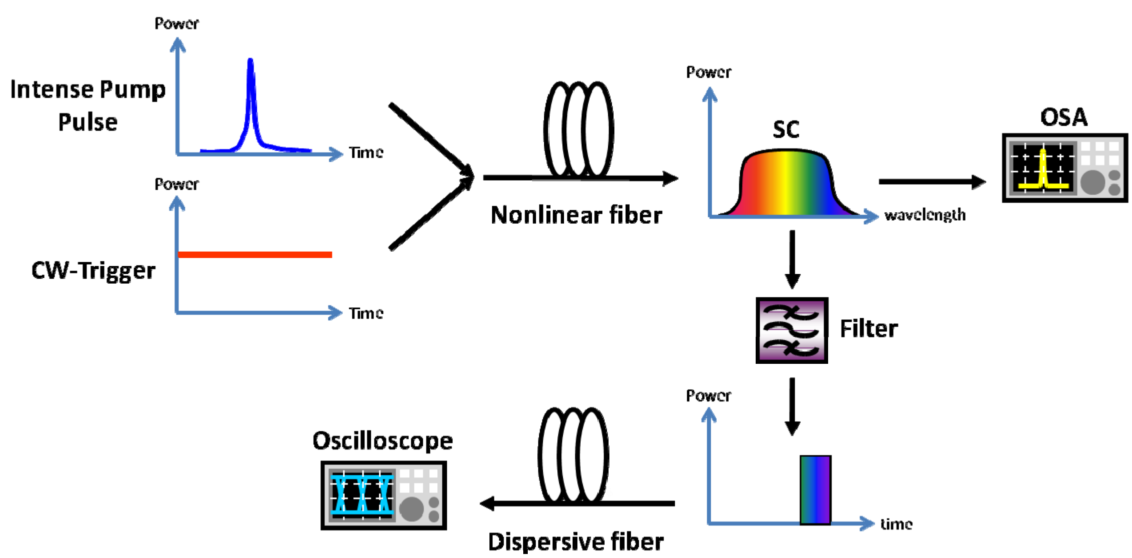


Figure 1. Schematic diagram of the experimental setup generating the CW-triggered SC.

Figure 1 shows the schematic of the experimental setup for generating the minute-CW-triggered SC. Intense pump pulses are delivered by a picosecond mode-locked fiber laser (with repetition rate of 78-MHz, pulse width of 5.8-

ps and peak power at 22 W) and are launched into a 50-m highly nonlinear dispersive fiber (HNL-DSF) (with zero-dispersion wavelength (ZDW) at 1554 nm, dispersion slope of 0.035 ps/nm$^2$/km and nonlinear coefficient of 14 $W^{-1}km^{-1}$) to generate the SC. The center pump wavelength was 1554.5 nm which lies in the anomalous dispersion regime. On the other hand, we employed a tunable CW laser source with a power of ~80μW as the weak CW trigger which is also coupled into the HNL-DSF and co-propagate with the pump in order to observe the enhancement effect. A bandpass filter with a bandwidth of 10 nm was used to select the long-wavelength SC spectral region for further investigation, such as the real-time pulse-amplitude statistical measurements. The filtered SC output was dispersed by 200-m dispersion-compensating fiber (DCF) with dispersion of 18.5 ps/nm before detected by a real-time oscilloscope with a bandwidth and a sample rate of 4 GHz and 20 GSa/s, respectively. It is also possible to measure the individual pulse energy directly using a photodetector and a sampling oscilloscope while real-time spectral measurements are not required [11].

## 3. EXPERIMENTAL RESULTS AND DISCUSSIONS

### 3.1 Output SC power enhancement by the CW-trigger

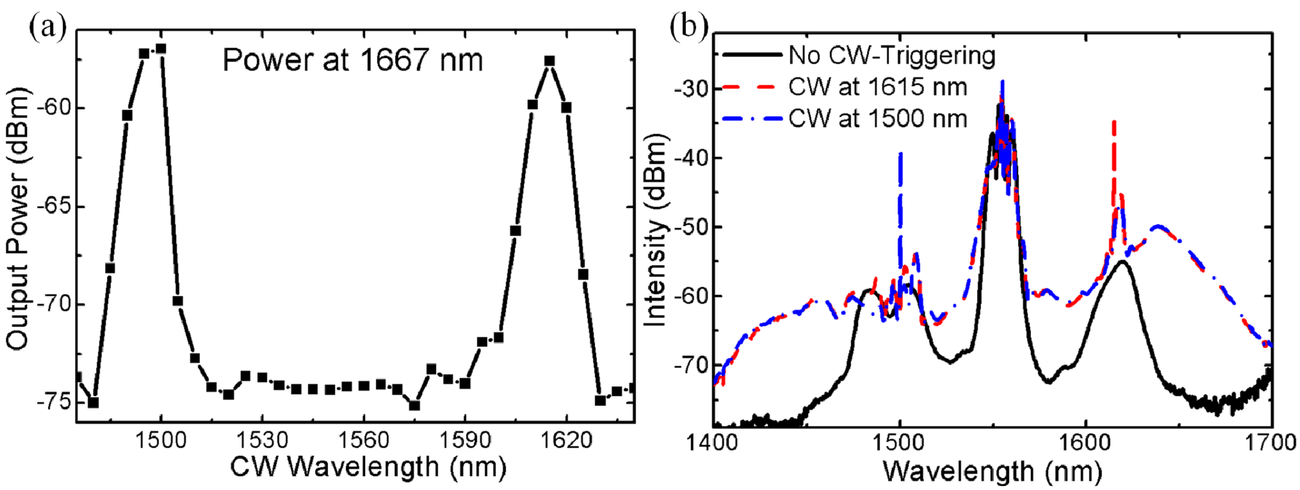


Figure 2(a). SC enhancement as the function of CW-trigger's wavelength. The peak power of the pump pulse at 22 W whereas the power of the SC trigger is 0.08 mW. (b) Untriggered SC spectrum (black line), SC spectrum with the CW trigger at at 1505 nm (redline) and SC spectrum with the CW trigger at 1614 m (blue line).

Figure 2(a) depicts the SC enhancement as a function of the CW trigger wavelengths. From the figure, it can be clearly observed that the enhancement effect manifests itself in the two main lobes, which roughly symmetrically straddled the pump wavelength, resembling the MI gain spectrum. The pronounced enhancement only occurs when the weak CW trigger has the wavelength match with the MI shift or in the other word, within the MI gain bandwidth – a region where the weak trigger experiences large MI gain. When the cumulative MI gain is sizable enough, soliton fission emerges and leads to substantial spectral broadening subsequently. The trigger wavelengths at 1505 nm and 1614 nm are at the peaks of the lobes and both give the greatest SC enhancement.

We also investigate how the SC spectrum can be affected by the minute CW trigger. Figure 2(b) compares the CW-triggered and untriggered SC spectra. It is clearly observed that the SC spectrum is significantly modified and enhanced by an extremely weak CW trigger (> 200,000× weaker than pump). Notably, the CW trigger introduces ~20 – 25 dB increase in power on both the red-shifted (~ 1400 nm range) and blue-shifted (~ 1700 nm range) sides of the SC spectrum. The enhanced SC spectra spans from <1400 nm to >1700 nm, much wider than the untriggered SC which only has the bandwidth of ~200nm, i.e. from ~1450nm to 1650 nm. Interestingly, under the identical pump condition, the enhanced SC spectrum with a trigger at 1614 nm is remarkably similar to the one with a CW trigger at another wavelength of 1505 nm, in terms of the spectral shape and the undulation characteristics.

The results shown in figure 2 are significant that the enhanced SC can be realized by simply turning on a weak CW trigger, with a properly chosen wavelength within the lobe regions. Prior works showed that similar active control of SC can be realized by using a pulse-seeding mechanism or intensity modulation of the pump pulses at a frequency in the THz regime. Nevertheless, it is mandatory for the pulse-seeding scheme to maintain highly precise time-delay adjustment (down to ps) between the seed and the pump. While direct optical modulation technology at THz frequency is not readily available, special wavelength conversion techniques [8] are required to achieve the aforementioned modulation-enhanced SC. In contrast, the fact that the present CW-triggering technique requires only the wavelength tuning to achieve the enhanced SC with similar quality renders itself a much simpler approach to utilize the enhanced SC in a more practical way.

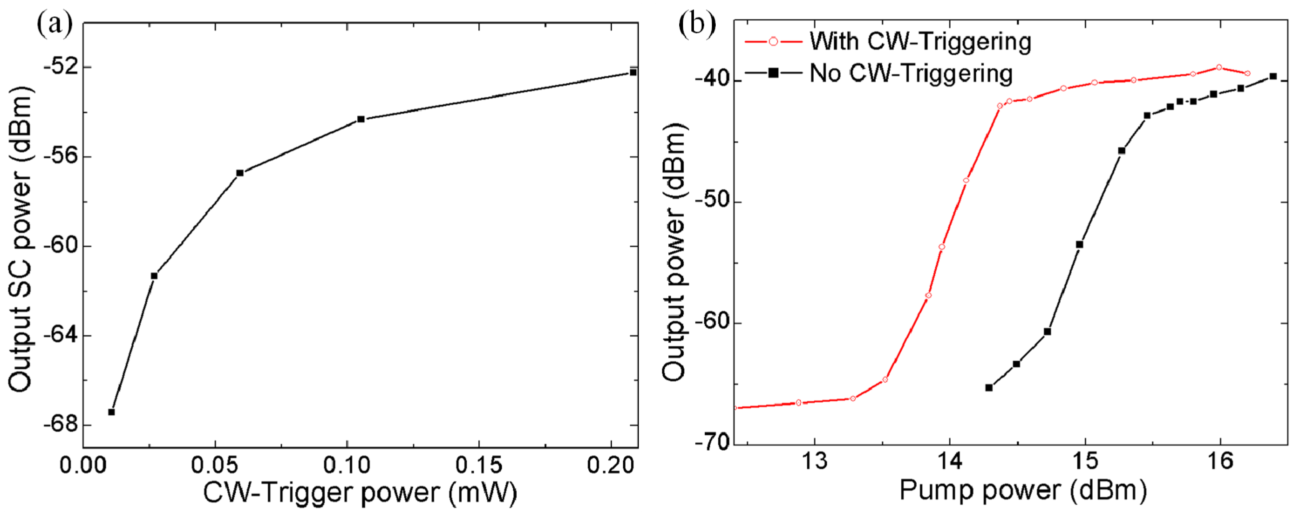


Figure 3(a). Output SC power as the function of CW trigger power at a fixed pump power. The CW-trigger wavelength is 1667 nm. (b) Filtered SC power as the function of pump power. Red-circle line represents the CW-triggered case while the black-square line represents the untriggered case.

Figure 3 (a) shows the SC output power (at 1667 nm) as the function of the power of the CW-trigger (at 1615 nm). We observe the output SC power enhancement essentially scales with the CW-trigger power except that such enhancement starts to roll-off for further increase in the CW-trigger's power .Moreover, we filter a portion of SC spectrum (1640 nm – 1650 nm) and measured the output SC power at that wavelength band as the function of the pump power (Fig. 3(a) and (b)). A threshold feature can be observed in both the untriggered SC and CW-triggered SC cases. Such threshold indicates the onset of the soliton fission in the SC generation process [3]. From Fig. 3(b), we can show that introducing the CW-trigger can effectively reduce the threshold pump power – making a more power-efficient SC generation process.

### 3.2 Coherence properties of stimulated SC

We study the SC amplitude statistics in both CW-triggered and untriggered SC situations using real-time wavelength-to-time mapping technique [12]. This technique has been employed for identifying ultrafast and rare event, such as capturing rogue waves in real-time [4], high-speed spectroscopy [13] and imaging [5]. Figure 4 shows the power histogram of 1562 filtered SC pulses (1640 nm – 1650 nm). It shows a clear long-tail distribution – a signature of the extreme-value statistics, resembling the key feature of the optical rogue waves [4]. However, when a weak CW at 1614 nm is added, it alters the SC amplitude statistics to an almost Gaussian distribution, and shows a ~60% reduction in the standard deviation. We attribute the observed pulse-amplitude variation to the relative intensity noise (RIN) and the finite coherence length (and hence the linewidth) of the CW source. Clearly, RIN can disturb the initial condition of soliton fission and thus deteriorates the SC stability. On the other hand, the coherence length of the CW source has to be long enough compared to the fiber length in order to preserve the phase coherence. In our case, the coherence length of the CW source is ~30 m compared to the fiber length of ~50 m. A narrow-linewidth CW source with low RIN is hence essential for maintaining high stability and coherence in the CW-triggered SC.

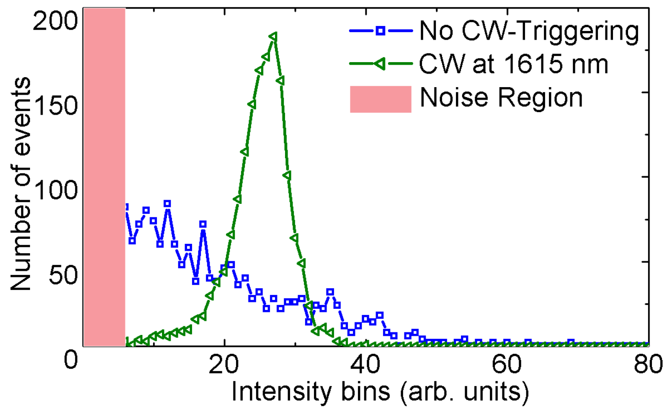


Figure 4. Filtered pulse-to-pulse amplitude histograms of the untriggered SC (blue) and the CW-triggered SC (green). The pump power is adjusted in order to compare the statistics under similar SC average power level. The red shaded region represents the noise floor of the measurement.

We further investigate the coherent properties of the SC based on the interferometric measurements. The filtered SC pulses are sent to an interferometer with unbalanced arm lengths. The coherence is evaluated by observing the interference fringes in the SC spectrum when consecutive coherent pulses are overlapped with a temporal delay. We quantify the coherence of the SC by a quantity called fringe visibility which is given by [14]:

$$V = (I_{\max} - I_{\min})/(I_{\max} + I_{\min})$$

where $I_{max}$ and $I_{min}$ corresponds the maximum and mininmum intensities of the fringes, respectively. For the untriggered SC, the MI growth starts spontaneously from noise and hence the SC is in general less coherent, especially in the red-shifted spectral regions. In contrast, when the SC is triggered by a weak CW light, pulse-to-pulse coherence is improved as shown in high visibility (Figure 5).

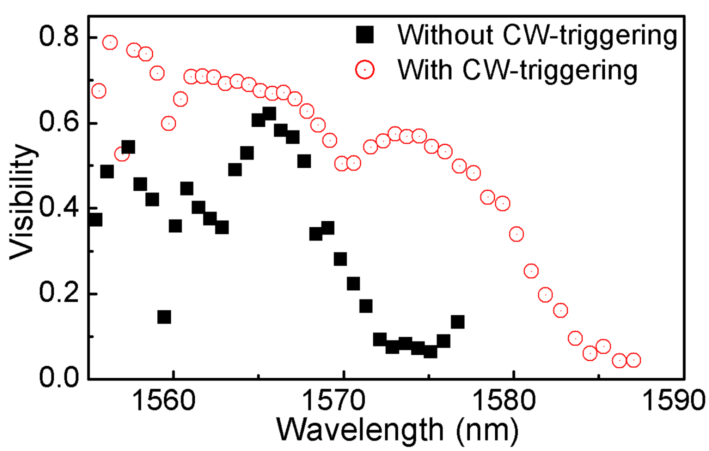


Figure 5. Fringe visibility of the SCs. The red circles represent the CW-triggered case while the black squares represent the untriggered case.

### 3.3 CW-triggered SC as a broadband pump for optical parametric amplifier

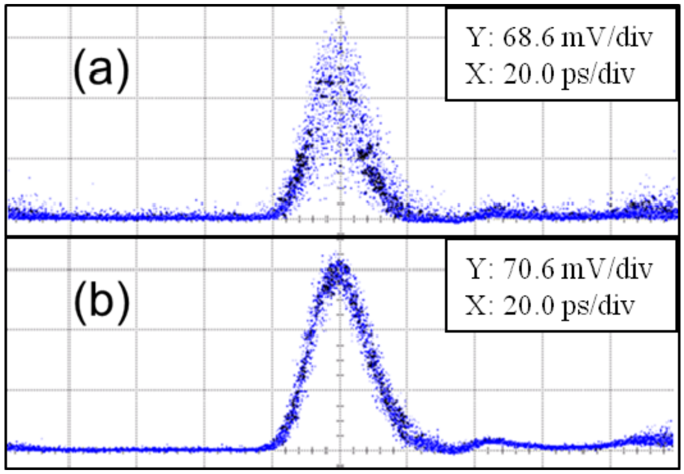

Figure 6. Output amplified signals of the FOPA (a) without CW-triggering. (b) with CW-triggering. The chirped pump wavelength range is 1561 nm – 1566 nm and the signal wavelength is 1554.5 nm.

The technique presented here will be applicable to in many applications, ranging from optical signal processing to high-speed biomedical diagnostics. As an example of the utility of the CW-triggered SC, we consider wideband-pumped optical parametric amplification (OPA). OPA is a nonlinear optical effect based on the third-order Kerr susceptibility of the material [15]. It has been recognized to be a versatile optical amplification approach in fiber-optics communication because of its ultra-wide gain bandwidth and flexibly-tunable gain spectrum [16]. In general, the amplified signal quality in OPA is critically related to that of the input pump pulse [16]. We employed a portion (1561 nm – 1566 nm) of the SC as the pump. The filtered pump is then temporally-chirped by a spool of dispersive fiber [17]. Such chirped pump pulse was then amplified and combined with a weak pulse signal at 1554.5 nm in a nonlinear fiber where OPA is taken place. Figure 6 clearly shows that the output amplified signal quality is greatly improved, in terms of intensity noise and timing-jitter, when the broadband pump is CW-triggered. When the broadband pump is CW-triggered, the timing jitter of the amplified signal is reduced from 6 ps to 1.1 ps. The timing jitter of the amplified signal with the CW-triggered SC is primarily attributed to group velocity dispersion (GVD) during the chirping of the pump pulse in a dispersive fiber. Such improvement in timing jitter and intensity noise by the CW-triggering scheme is of great importance to maintain the signal quality in all-optical signal processing applications.

## 4. CONCLUSION

In conclusion, we demonstrate an enhanced SC generation by introducing a minute CW trigger. The CW-triggered SC shows considerable spectral broadening (>100 nm wider), enhancement in output intensity (>20dB), and improvement in SC coherence. The present CW-triggering scheme only requires the trigger-wavelength tuning for optimization and thus makes it as an attractive and simple tool for realizing stable and enhanced SC, with a wide range of input pump conditions, namely from the shorter-pulse (~fs) to the longer-pulse (>ps) pumping schemes, in order to generate a more stable and enhanced SC – expanding the scope of possibilities in SC generation, especially for the applications in which single-shot, real-time spectroscopic measurements and imaging is required.

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## 6. REFERENCES


[1] R. R. Alfano, ed., " *The Supercontinuum Laser Source*," (Springer, 2006).

[2] J. M. Dudley, G. Genty and S. Coen, "Supercontinuum generation in photonic crystal fiber," *Rev. Mod. Phys*., **78**, 1135 (2006).

[3] G. Genty, S. Coen and J. M. Dudley, "Fiber supercontinuum sources,"*J. Opt. Sco. Am. B.,* **24**, 1771 (2007).

[4] D. R. Solli, C. Ropers, P. Koonath and B. Jalali, "Optical rouge waves," *Nature (London).,* **450**, 1054 (2007).

[5] K. Goda, K. K. Tsia and B. Jalali, "Serial time-encoded amplified imaging for real-time observation of fast dynamic phenomena," *Nature.* **458**, 1145 (2009).

[6] D. L. Marks, A. L. Oldenburg, J. J. Reylonds, "Study of an ultrahigh-numerical-aperture fiber continuum generation source for optical coherence tomography," *Opt. Lett.,* **27**, 2010 (2002).

[7] D. R. Solli, C. Ropers, P. Koonath and B. Jalali, "Active Control Rogue Waves for Stimulated Supercontinuum Generation," *Phys. Rev. Lett.,* **101**, 233902 (2008).

[8] G. Gently, J. Dudley and B. Eggleton, "Modulation control and spectral shaping of optical fiber supercontinuum generation in the picosecond regime," *Appl. Phys. B: Lasers Opt*., **94**, 187 (2009).

[9] D. Wildanger, E. Rittweger, L. Kastrup, and S.W. Hell, "STED microscopy with a supercontinuum laser source,"*Opt. Express*, **16**, 9614 (2008).

[10] A. Gambetta, V. Kumar, G. Grancini, D. Polli, R. Ramponi, G. Cerullo, and M. Marangoni, "Fiber-format stimulated-Raman-scattering microscopy from a single laser oscillator," *Opt. Lett.*, **35**, 226 (2010)

[11] C. Lafargue, J. Bolger, G. Genty, F. Dias, J. M. Dudley and B. J. Eggleton, "Direct detection of optical rogue wave energy statistics in supercontinuum generation," *Electron. Lett.,* **45**, 217 (2009).

[12] T. Jannson, "Real-time Fourier transformation in dispersive optical fibers," *Opt. Lett.,* **8**, 232 (1983).

[13] D. R. Solli, J. Chou and B. Jalali, "Amplified wavelength-time transformation for real-time spectroscopy," *Nature Photon*., **2**, 48 (2008).

[14] M. Born, E. Wolf, ed., "*Principle of Optics,"* (Cambridge University Press, 1999).

[15] G. P. Agrawal, "*Nonlinear Fiber Optics*", 4th ed., Elsevier (Singapore) Pte Ltd, (2009).

[16] M. E. Marhic, "*Fiber Optical Parametric Amplifiers, Oscillators and Related Devices*", 1st ed., (Cambridge University Press, 2008).

[17] C. Zhang, K. K. Y. Cheung, K. K. Tsia, and K. K. Y. Wong, "Fiber optical parametric with broadband chirped pump," *IEEE Photon. Technol. Lett.,* (to be submitted).


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