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Effect of the CW-Seed’s Linewidth on the Seeded Generation of Supercontinuum

Xiaoming Wei, Chi Zhang, Shanhui Xu, Zhongmin Yang, Kevin K. Tsia, and Kenneth K. Y. Wong, Senior Member, IEEE

Abstract—We demonstrate numerically and experimentally the effect of the linewidth of the CW-seed on the seeded generation of supercontinuum. The qualitative simulation results, calculated from a numerical model based on the generalized nonlinear Schrödinger equation, show that the temporal coherence of the seeded supercontinuum benefits from a narrower linewidth of the CW-seed. In order to verify the numerical prediction, a CW-seed laser modulated by a phase modulator at different modulation frequencies is utilized to conduct the experimental analysis. With the increasing linewidth of the CW-seed, the contrast ratio of the interference fringe shows decreasing enhancement around the CW-seed and the corresponding four-wave mixing regions. Based on this, we employ four CW-seed lasers to enhance the temporal coherence of the seeded SC within the whole band.

Index Terms—Supercontinuum generation, nonlinear optics, four-wave mixing, temporal coherence.

I. INTRODUCTION

WITH a broadband optical spectrum, supercontinuum (SC) generated by the long pulses such as picosecond and nanosecond pulses, has been well demonstrated in the areas such as optical spectroscopy, optical frequency comb, pulse compression and ultrashort pulse source [1], [2]. The numerical simulation results have revealed that the nonlinear effects, including four-wave mixing (FWM), modulation instability (MI) and Raman scattering play a key role in the SC generation with long pulses [1]. In particular, MI is initiated from the noise, which would deliver the optical rogue wave in the extreme condition [2]. As a consequence, the SC exhibits large shot-to-shot fluctuations and poor temporal coherence outside the pump bandwidth, which does not support applications involving rapid transient dynamics. In addition, Nicholson and Yan [3] and Mussot et al. [4] have experimentally confirmed the coherence degradation of the generated SC by using cross-coherence and autocorrelation function measurements, respectively. In order to address these shortcomings, few optical techniques have been demonstrated, including triggering with a pulse-seed [5], introducing a feedback loop [6], and modulating the pump pulse train [7]. By tapering the photonics crystal fiber [8], [9], in addition, the significant reduction of the pulse-to-pulse fluctuation has been presented. Furthermore, we have shown that the SC generation can be manipulated by a weak CW-seed experimentally [10] and numerically [11], which eliminates the precise delay-time controlling and phase-locking with the intensive pump. With this approach, the MI growth arises alternatively from the controllable CW source, instead of the noise.

When it comes to the effect of the bandwidth of the seed source on the generated SC, Nguyen et al. [12] have recently studied the intensity noise of the stimulated SC by varying the seed’s bandwidth in a nanometer scale. For the coherence characteristic, Sørensen et al. [13] have numerically confirmed that a nearly coherent pulse-seed contributed greatly to the improvement of the coherence of the generated SC. Experimentally, although two individual CW lasers with three orders of magnitude difference in linewidth have been used to demonstrate the different stimulated effects on the SC generation [14], no detailed analysis of the coherence evolution of the stimulated SC has been presented yet, which would help to shed light on the noise degrading mechanism in the SC implementation. In this paper, we detailly investigate the influence of the linewidth of the CW-seed on the temporal coherence and pulse-to-pulse fluctuation of the seeded SC based on both numerical and experimental studies. Here, we will give a brief numerical investigation first. Then, by employing a CW laser phase-modulated by different frequencies, we demonstrate that the temporal coherence of the generated SC can be improved more with a narrower-linewidth seed. Finally, four CW-seeds are utilized to enhance the temporal coherence of the SC within the whole spectrum.

II. NUMERICAL STUDY

The generalized nonlinear Schrödinger equation (GNLSE) including the high order dispersions and the nonlinear effects of delayed Raman contribution, self-steepening and optical shock formation, has been successfully utilized to conduct the numerical study of the SC generation, and numerical results in excellent agreement with the experimental ones have been demonstrated [1]. Thus, we performed our numerical investigation
based on GNLSE:
\[
\frac{\partial A}{\partial z} = -\frac{\beta_2}{2} \frac{\partial^2 A}{\partial t^2} + \frac{\beta_3}{6} \frac{\partial^3 A}{\partial t^3} + i \gamma \left( 1 + i \tau_{\text{shock}} \right) \frac{\partial}{\partial t} A(z, t) \int_{-\infty}^{\infty} R(t') |A(z, t - t')|^2 dt'
\]

where \( A \) is the complex optical field envelope, \( \beta_2 \) and \( \beta_3 \) are the second- and third-order dispersions of the fiber medium, and \( \gamma \) is its nonlinear coefficient. The optical shock formation is introduced by the time constant \( \tau_{\text{shock}} = \lambda_0(2\pi c)^{-1} \), where \( \lambda_0 \) is the carrier wavelength, and \( c \) is the velocity of light in vacuum. The Raman response function is expressed as \( R(t) = (1 - f_R) h_R(t) + f_R h_R(t) \), where \( f_R = 0.18 \) is Raman contribution and \( h_R(t) \) is related to the experimental fused silica Raman cross-section. The GNLSE was solved by the well-known split-step Fourier method.

The simulation parameters match with the following experimental conditions: the nonlinear medium is a spool of 400-m highly-nonlinear dispersion-shifted fiber (HNL-DSF), whose zero dispersion wavelength (ZDW) is 1554 nm, the nonlinear coefficient is 14 W·km\(^{-1}\), and the \( \beta_2 \) and \( \beta_3 \) are \(-0.1707\) and \(0.0582\) ps\(^2\)·km\(^{-1}\) at 1557.8 nm, respectively. The Gaussian-shaped pump pulse at 1557.8 nm has a FWHM of 5.8 ps and a peak power of 6 W. The CW-seed is expressed as \( \sqrt{P_{\text{CW}}} e^{i\Phi} \exp[i\Phi(t)] \), where \( P_{\text{CW}} \) is the optical power of the CW-seed which is set to be \(-10\) dBm, and \( \Omega = 2\pi c(\lambda_p - \lambda_{\text{ZDW}}) / (\lambda_p \lambda_{\text{ZDW}}) \) is the normalized frequency relative to the pump. \( \Phi(t) \) is the random phase fluctuation with a zero ensemble average, and a variance related to the linewidth of the CW-seed through the phase-diffusion model [15]. The random background noise has also been introduced to the pump [16], of which the amplitude is \(~60\) dB lower than the pump.

For the sake of manageable computational time, the numerical frequency resolution in the simulation was set to 10 GHz. The wavelength of the CW-seed in the simulation was fixed at 1534 nm, consistent with the experimental value. As shown in Fig. 1(a), CW-seeds with different linewidths show a Lorentzian shape in the optical spectrum, which is characterized by the long tail. It is noted that the linewidth narrower than 10 GHz, but wider than 10 MHz, can still be partially resolved by the simulation system. It is because that the Lorentzian-shaped power spectrum of the CW-seed induced by the phase-diffusion model falls off slowly enough to be partly resolved. However, for the linewidth less than 10 MHz, their spectra fall off too fast to be distinguished by the simulation system, which can be seen from Fig. 1(b) that the CW-seed’s peaks with linewidths less than 10 MHz are overlapped.

To determine the trend of the influence of the CW-seed’s linewidth on the seeded SC qualitatively, we calculated the first-order temporal coherence with various background noise and phase noise of the CW-seed from shot to shot. For each set of parameters, 300 simulations were conducted, and the statistical results are shown in Fig. 1(c), where the SC spectrum with a 1-kHz CW-seed is also shown for the convenience of emphasizing the coherent component. It should be pointed out that the simulated spectra with different CW-seeds give a similar spectral shape, which is consistent with the experimental results shown in Fig. 3. It can be observed that the temporal coherence has been improved on both sides of the pump area with a CW-seed’s linewidth less than 1 GHz, i.e., the CW-seed and FWM areas marked with the red and green arrows, respectively.

It is because that the spectral broadening at these areas is induced by the coherent amplifications of the CW-seed and the FWM by-product, which is benefited from the MI effect. As the linewidth of the CW-seed increases, the coherence of the CW-seed and FWM areas is gradually decreased since the CW-seed becomes less and less coherent (i.e., has an increasingly growing phase noise). It should be pointed out that the results under different CW-seed’s linewidth cannot be well distinguished when the CW-seed’s linewidth is less than 10 MHz, which is much smaller than the frequency resolution of the simulation system as explained before. It is also consistent with the average optical spectra as shown in Fig. 1(a), where the curves with linewidth less than 10 MHz almost overlap with each other. Unlike FWM and MI effects, SPM does not build from noise and gives a coherent spectral broadening. In other words, the coherence at the area close to the pump wavelength is almost unchanged when the linewidth of the CW-seed is varied, as marked by the blue arrow in Fig. 1(c). It should be emphasized that the simulation analysis presented here is a qualitative one since the simulation resolution of the numerical system is limited to 10 GHz, which
is not comparable with the linewidth of the CW-seed used in the following experiments.

### III. EXPERIMENTAL STUDY

As shown in Fig. 1(c), the overall coherence of the seeded SC has benefited from a narrower linewidth of the CW-seed. To study the effect of the CW-seed’s linewidth on the SC generation experimentally, we conducted the experiment based on the setup illustrated in Fig. 2(a). The pump pulse laser was provided by a wavelength-tunable pulse source, whose repetition rate and pulse duration are 10 GHz and 5.8 ps, respectively. An amplitude modulator (AM), together with a dc power supply and a RF pulse generator, was utilized to lower the pulse repetition rate down to 78 MHz. A polarization controller (PC) located between the pulsed laser and AM was used to match the polarization of the light with that of the transmission axis of the AM. After an isolator (ISO), the peak power of the 78-MHz pulse was boosted up by an erbium-doped fiber amplifier (EDFA). The amplified spontaneous emission (ASE) noise induced by the EDFA was filtered out by a tunable bandpass filter (TBPF) with a bandwidth of 3 nm. Then, the amplified pump pulse was combined with the CW-seed via a 10/90 optical coupler. The CW-seed laser was a single-longitudinal mode (SLM) laser with an original linewidth of about 100 kHz. The linewidth of CW laser was changed through a phase modulator (PM) with different modulation frequencies provided by a waveform generator (WG). To control the polarization of the CW-seed, another two PCs were inserted into the CW-seed branch. All the ISOs in the experimental setup were employed to protect the modulators from damaging by the back reflection light. Finally, the mixing light was injected into a 400-m HNL-DSF with a 1554-nm ZDW for the SC generation. The dispersion slope of the HNL-DSF is 0.035 ps/(nm⋅km), while the nonlinear coefficient is 14 W−1⋅km−1.

As discussed in [10], the stimulating effect on the generation of SC occurs when the weak CW-seed experiences large MI gain, which induces soliton fission and results in substantial spectral broadening subsequently [17]. Thus, we have to measure the MI gain spectrum first, and then find out the CW-seed wavelength ranges supporting the stimulated effect for SC generation. A wavelength-tunable CW laser and a bandwidth-variable filter at 1610 nm (Alnair Labs, BVF-100) were employed for this process: the optical power at 1610 nm filtered out by the filter mentioned above was measured with a power meter when the pulsed pump together with the wavelength-tuned CW laser were launched into the HNL-DSF for the SC generation. It is more sensitive to the CW-seed at the area close to the wing of the generated SC, which can also be testified by the SC spectra shown in the following experiments, i.e., Fig. 3. We thus fixed the center of the bandwidth-variable filter at 1610 nm, while the pump wavelength was fixed at 1557.8 nm [the vertical blue arrow in Fig. 2(b)]. The CW-seed was tuned over 1500–1640 nm to measure the MI-shaped “spectrum”. The measured results with different bandwidths of the filter are shown in Fig. 2(b), where the horizontal axis corresponds to the wavelength of the CW laser. It should be pointed out that the rightmost peak of the curves in Fig. 2(b) is owing to the contribution of the CW laser when its wavelength was tuned to around 1610 nm, just where the optical power was measured. As can be observed, the results under different filtering bandwidths give a consistent MI “spectrum” except the power level, which is because that a larger filter bandwidth would allow more power to be collected. With a MI gain spectral shape, Fig. 2(b) suggests that the wavelength of the CW-seed falling in the symmetrical lobes can provide stimulating effect for the SC generation pumped at 1557.8 nm. Therefore, we fixed the wavelength of the CW-seed laser at 1534 nm for the following stimulated SC studies [the red vertical arrow in Fig. 2(b)], which is consistent with the simulation conditions.

The optical power of the CW-seed was fixed at –10 dBm, and the spectra of the generated SC under different seeded conditions, where the CW-seed, pump and FWM areas are labeled as A, B and C, respectively.

![Fig. 2](image-url)  
(a) The experimental setup of our CW-stimulated generation of SC. (b) The power of the SC at 1610 nm as the function of the CW-seed’s wavelength with a tuning step of 1 nm, where different curves correspond to different bandwidths of the filter centered at 1610 nm. Here, the pump wavelength was chosen to be 1557.8 nm (the red arrow) and the seed wavelength will be chosen to be 1534 nm (the red arrow) for the following experiments.

Fig. 3. The experimental optical spectra of the generated SC under different seeded conditions, where the CW-seed, pump and FWM areas are labeled as A, B and C, respectively.

As discussed in [10], the stimulating effect on the generation of SC occurs when the weak CW-seed experiences large MI gain, which induces soliton fission and results in substantial spectral broadening subsequently [17]. Thus, we have to measure the MI gain spectrum first, and then find out the CW-seed wavelength ranges supporting the stimulated effect for SC generation. A wavelength-tunable CW laser and a bandwidth-variable filter at 1610 nm (Alnair Labs, BVF-100) were employed for this process: the optical power at 1610 nm filtered out by the filter mentioned above was measured with a power meter when the pulsed pump together with the wavelength-tuned CW laser were launched into the HNL-DSF for the SC generation. It is more sensitive to the CW-seed at the area close to the wing of the generated SC, which can also be testified by the SC spectra shown in the following experiments, i.e., Fig. 3. We thus fixed the center of the bandwidth-variable filter at 1610 nm, while the pump wavelength was fixed at 1557.8 nm [the vertical blue arrow in Fig. 2(b)]. The CW-seed was tuned over 1500–1640 nm to measure the MI-shaped “spectrum”. The measured results with different bandwidths of the filter are shown in Fig. 2(b), where the horizontal axis corresponds to the wavelength of the CW laser. It should be pointed out that the rightmost peak of the curves in Fig. 2(b) is owing to the contribution of the CW laser when its wavelength was tuned to around 1610 nm, just where the optical power was measured. As can be observed, the results under different filtering bandwidths give a consistent MI “spectrum” except the power level, which is because that a larger filter bandwidth would allow more power to be collected. With a MI gain spectral shape, Fig. 2(b) suggests that the wavelength of the CW-seed falling in the symmetrical lobes can provide stimulating effect for the SC generation pumped at 1557.8 nm. Therefore, we fixed the wavelength of the CW-seed laser at 1534 nm for the following stimulated SC studies [the red vertical arrow in Fig. 2(b)], which is consistent with the simulation conditions.

The optical power of the CW-seed was fixed at –10 dBm, and the spectra of the generated SC under different seeded conditions are illustrated in Fig. 3. As can be observed, the generated SC reveals weak FWM effect and intensity enhancement on both the blueshifted and redshifted sides of the generated SC when the CW-seed is introduced. CW-seeds phase-modulated by a sinusoidal waveform at different frequencies (from 100 kHz to
10 MHz) almost act like the same judging from the optical spectra, i.e., the spectra nearly overlap together as shown in Fig. 3. This means that the linewidth of the CW-seed has little influence on the intensity of the generated SC. It should be noted that, although the instantaneous variation of the CW-seed’s linewidth is relative small within the pump pulse duration, it would give an averaging effect owing to the mismatch between the repetition rate of the pump pulse and the modulation frequency of the CW-seed, as shown in the following averaged measurements.

In order to investigate the characteristic of the temporal coherence, we launched the SC pulse train into a homemade Mach–Zehnder Interferometer with a path difference almost equal to the separation of the adjacent pump pulses, i.e., separated by ~20 ps between the neighboring pulses. In this way, the interference fringes can be produced by the temporal overlap of the neighboring SC pulses if they are coherent. Under different seeded conditions, the interference spectra corresponding to the CW-seed region A are shown in Fig. 4(a). Without the CW-seed, no interference fringe can be obtained in this region, giving a bad temporal coherence. After adding the CW-seeds with phase-modulation frequency from 100 kHz to 10 MHz, the interference fringes have appeared in this area, which suggests that the CW-seeds have enhanced the temporal coherence of the generated SC around the seeded area. More importantly, the contrast ratio of the interference fringes is decreased as the phase-modulation frequency increases. It is because that the effective linewidth of the CW-seed is gradually broadened as the phase-modulation frequency increases, which results in a less coherent amplification by the MI gain as well as a less coherent spectral broadening [13].

To quantify the coherence, we introduce the fringe visibility, \( V = (I_{\text{max}} - I_{\text{min}}) / (I_{\text{max}} + I_{\text{min}}) \), where \( I_{\text{max}} \) and \( I_{\text{min}} \) are the maximum and minimum intensity of the interference fringe, respectively. The visibility of the wavelength marked by the green dotted line in Fig. 4(a) is calculated and shown in Fig. 4(b). Without the CW-seed, the visibility of the interference fringe is almost zero in this region. After introducing the CW-seed phase-modulated at 100 kHz, the visibility has been enhanced nearly from zero to ~0.5 (noted that the range of \( V \) is from 0 to 1). For the other phase-modulation frequencies, the visibility of the interference fringe is gradually degraded, i.e., from ~0.5 to ~0.1, when the linewidth of the CW-seed is increasingly broadened. This is consistent with the predication by the simulation results shown in Fig. 1(c).

The interference spectra of the pump area B are shown in Fig. 5(a). Different from the CW-seed area, the spectral broadening is mainly dominated by the SPM of the pump in the pump region. Thus, the contrast ratio of the interference fringe in the SPM-dominated area is little influenced by the seeded conditions, which is consistent with the simulation results shown in Fig. 1(c). On the edge of the SPM-dominated area, as marked by the red dotted line in Fig. 5(a) where the SPM domination is weak, the CW-seed improves the pulse-to-pulse coherence slightly compared with the unseeded case.
In the FWM area C, the pulse-to-pulse coherence [as shown in Fig. 5(b)] shows the same characteristics as that of CW-seed area A, e.g., a wider CW-seed linewidth provides a smaller pulse-to-pulse coherence improvement. To investigate the pulse-to-pulse stability under different seeded conditions, a 20-nm bandpass filter with a fixed center wavelength of 1582 nm was utilized to filter out the redshifted spectral component. The corresponding pulse train was recorded by a 16-GHz real-time oscilloscope. For each seeded condition, 1500 pulses were used to calculate the ratio of the standard deviation to the mean (std/mean, also known as the inverse signal to noise ratio [12], [17]) of the pulse intensity, as shown in Fig. 5(c). Compared with the unseeded case, the CW-seed has reduced the std/mean from 0.15 to around 0.08, which is consistent with what has been found in [10] and [11]. It is noted that the std/mean has a small variation when the linewidth of the CW-seed was changed, which however would increase with an increasing seed’s bandwidth as shown in [12]. This can be attributed to the fact that, the variation of the seed’s bandwidth is in a nanometer scale in [12], i.e., from 1 to 36 nm. By using a PM with a megahertz modulation frequency here, the range of the linewidth variation is very small (i.e., much smaller than 1 nm) compared with that of [12], which prevents the observation of such a std/mean evolution.

The analysis presented above, such as Figs. 4(a) and 5(b), has shown that the participation of the CW-seed has efficiently enhanced the pulse-to-pulse coherence in the areas close to CW-seed and the corresponding FWM wavelength, respectively. With a CW-seed’s wavelength close to the MI peak, the coherent wavelength of seeded SC is discontinuous by using a single CW-seed, which is consistent with the numerical findings of [17]. To enhance the pulse-to-pulse coherence within the whole redshifted wavelength, we introduced four CW-seeds phase-modulated at 100 kHz to stimulate the SC generation. The CW-seeds were provided by four tunable CW laser modules (Photonetics TUNICS-OM). As shown in Fig. 2(b), MI effect occurs at spectral ranges of 1529–1548 and 1569–1588 nm. To achieve stimulated effect, the wavelength of the CW-seed should fall in the region with significant MI gain. We thus chose the wavelengths of four CW laser sources to be 1530, 1534, 1540 and 1545 nm, which almost cover the whole anti-Stokes side of the MI gain spectrum. It should be pointed out that the locations of the CW-seed’s wavelengths have been fine tuned to obtain the widest improved bandwidth of coherence. The interference spectra without and with the CW-seeds are illustrated in Fig. 6(a). It is clear that the multi-CW-seeds have enhanced the pulse-to-pulse coherence and spectral intensity within the whole redshifted spectral component. The histogram of the pulse intensity of the redshifted spectral component was calculated and shown in Fig. 6(b). As can be observed, the std/mean of the pulse intensity has been slightly reduced to 0.108. As a consequence, the improvement of the pulse-to-pulse stability by using four non-phase-locked CW-seeds is less obvious than that of single CW-seed. In this regard, detailed studies on the phase-locked multi-CW-seeded SC are under investigation.

IV. Conclusion

In summary, we have investigated the influence of the linewidth of the CW-seed on the noise property of the seeded SC. Based on the numerical model, the qualitative calculation results reveal that a narrow linewidth of the CW-seed facilitates the improvement of the temporal coherence of the SC.
Experimentally, a SLM laser, phase-modulated at different frequencies (from 100 kHz to 10 MHz), has been employed to verify the simulation studies. It is shown that a CW-seed with a narrower linewidth is more suitable for the improvement of the temporal coherence of the stimulated SC, while the pulse-to-pulse stability has no such a rigorous requirement as shown in Fig. 5(c). Regarding the fact that the controllable range by a single CW-seed is disconnected, which is usually confined to the CW-seed and FWM areas, we have introduced four CW-seeds to improve the temporal coherence within the whole redshifted component of the stimulated SC. The interference spectra show that the temporal coherence has been enhanced across the whole redshifted spectral component. We believe the present would be particularly relevant to practical stimulated SC design with the aim of not only enhancing the SC spectrum, but also improving its temporal coherence, especially which pumped by the long pulse (picosecond to nanosecond).

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REFERENCES

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