Supercontinuum generation without residual pump peak through multiple coherent pump seeds

Dong Qiu1, Wei Lin2, Wen-Jing Liao1, Wei-Yi Hong1, Hong-Zhan Liu1, Wei-Cheng Chen3*, Hu Cui1, Zhi-Chao Luo1, Wen-Cheng Xu1, and Ai-Ping Luo1

1Guangdong Provincial Key Laboratory of Nanophotonic Functional Materials and Devices, South China Normal University, Guangzhou, Guangdong 510006, People’s Republic of China
2State Key Laboratory of Luminescent Materials and Devices, South China University of Technology, Guangzhou, Guangdong 510640, People’s Republic of China
3School of Physics and Optoelectronic Engineering, Foshan University, Foshan, Guangdong 528000, People’s Republic of China

E-mail: chenwch@fusu.edu.cn; luoaiping@sccnu.edu.cn

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We report an enhanced supercontinuum generation (SCG) in a conventional highly nonlinear fiber through injecting double bound-state solitons, which eliminates the residual pump peak existing in conventional SCG. The use of these phase-locked pulse pairs yields a novel multiple coherent pump technique. We further compare the SCGs pumped by conventional bound-state soliton and single-soliton. It confirms that the effective elimination of the residual pump peak in supercontinuum owes to higher transferring efficiency of the pump energy to newly generated frequencies in the multiple coherent pump scheme. The obtained results provide a new and simple method to obtain a flat supercontinuum source. © 2019 The Japan Society of Applied Physics

Supercontinuum sources attract a great deal of attention because of their important applications in diverse fields such as optical communication, frequency-comb, serial time-encoded amplified microscopy (STEAM) and optical coherence tomography (OCT). Supercontinuum generation (SCG), firstly reported in bulk medium, is known as a particular spectral broadening process in a nonlinear medium pumped by high-power pulse or continuous wave (CW). SCG research was further extended to optical fiber in 1976. The observed spectral broadening was attributed to cascaded stimulated Raman scattering (SRS) and self-phase modulation (SPM) effects. After that, SCGs in fibers were widely investigated. In order to obtain broadband supercontinuum, researchers adopted various pump seeds from soliton pulse, Q-switched pulse, noise-like pulse to dissipative soliton resonance, and special fibers from the ZBLAN fiber, photonic crystal fiber based on As2S3 chalcogenide glass to tellurite fiber with all-normal dispersion. The supercontinuum could cover the wavelengths from ultraviolet to infrared spectra, bringing wider applications. However, it is also found that the generated supercontinuum is not always flat due to the existence of a residual spectral peak at the pump wavelength which should be filtered in practical applications. So far, only a few techniques have been put forward, such as cascading specific optical fibers and designing special photonic crystal fiber to remove the residual pump peak in the supercontinuum. But they undoubtedly increase the cost and complexity of the supercontinuum sources. Thus, the elimination of residual pump peak in SCG is always an interesting and significant issue. It is necessary to propose an effective solution for eliminating the residual pump peak in supercontinuum without any special components and achieving a flat spectrum from a simple system.

In this work, we address this issue. We remove the residual pump peak in SCG by injecting double bound-state solitons in a conventional highly nonlinear fiber (HNLF). The use of the multiple sets of phase-locked pulse pairs yields a novel multiple coherent pump technique, which improves the transferring efficiency of the energy at the pump wavelength to newly generated frequencies. Moreover, for comparison, we use another two types of pulses as pump seeds, namely, conventional bound-state soliton and single-soliton. It is found that in these two cases, the generated supercontinuums still keep a strong residual pump peak. The double bound-state solitons served as the seed pulses of the multiple coherent pump scheme offer a simple, fresh and promising approach to obtain a flat supercontinuum.

Figure 1 depicts the schematic of the supercontinuum source. It consists of three parts: a mode-locked fiber laser acted as the seed source, a homemade erbium-doped fiber amplifier (EDFA) for amplifying the seed pulse and an 85-m long HNLF (YOFC, NL1016-B) with a nonlinear coefficient of 10 W−1 km−1 for broadening the pulse spectrum. The seed pulse laser is mode-locked by the nonlinear polarization rotation (NPR) technique, including a 5-m long erbium-doped fiber (EDF, Corning Er1550C3CT VHA) pumped by a 980 nm laser diode (LD), two polarization controllers (PCs), a polarization-dependent isolator (PD-ISO) and an output coupler (OC) with 30% output. Then the output pulse is transmitted into the EDFA, comprising a 2-m long EDF (Nufem SM-ESF-7/125) which is also pumped by a 980 nm LD with a pump protector (PP), for improving the power. Finally, the amplified pulse is injected into the HNLF to generate the supercontinuum. Note that for monitoring the pulse power input in the HNLF, we add an optical coupler to extract 1% output and measure it with an optical power meter (OPM).

By tuning the pump power and carefully manipulating the PCs in the seed laser, we obtain the double bound-state solitons. The properties of the pulses are depicted in Fig. 2. As seen from Fig. 2(a), there is a modulation with a period of 0.68 nm across the spectrum. The regular spectral modulation is one typical characteristic of bound-state soliton. The corresponding pulse-train is presented in Fig. 2(b). The fundamental repetition-rate of 13.2 MHz. To confirm that the pulse is bound-state soliton, we measure its autocorrelation trace, as demonstrated in Fig. 2(c). Note that there are five pairs of solitons bounded together. Moreover, each pair
of solitons is also in a bound-state consisting of two solitons. Then, they form double bound-state solitons as a whole unit. The temporal separation between the main pairs of bound-state solitons is 12 ps, in accordance with the 0.68 nm modulation spacing on the spectrum. It should be noted that the separation between the two solitons in each sub-pair of bound-state is 1.81 ps, corresponding to the 4.52 nm modulation spacing on the spectrum. However, this modulation could not be clearly labeled on the spectrum, because it should coincide with the whole spectrum. Figure 2(d) gives the radio-frequency spectrum of the pulse. The signal-to-noise ratio is $\sim 52$ dB, indicating the stable mode-locked operation of the fiber laser.

Then the double bound-state solitons are amplified by the EDFA and injected into the HNLF to generate the supercontinuum. By tuning the pump power of the EDFA,
different stages of supercontinuum evolution are observed and summarized in Fig. 3. The whole excited spectrum finally covers the wavebands from 1100 nm to 2300 nm at the maximum pump power of 660 mW, with the 1-dB bandwidth reaching 1140 nm. Remarkably, there is no residual spectral peak at the pump wavelength.

Considering the pump wavelength and dispersion characteristic of the HNLF (zero-dispersion wavelength (ZDW) at 1550 nm), the broadening process of the spectrum could be expounded by SPM, four-wave mixing (FWM), soliton fission and SRS. In longer wavebands, soliton fission causes soliton self-frequency shift (SSFS). Then the generated red-shift Raman solitons act as a secondary pump source for continuously exciting SRS, which makes the spectrum greatly broaden. Meanwhile, in shorter wavebands, owing to the red-shift Raman soliton and dispersion, the blue-shift dispersive wave is observed together with anti-Stokes lasing lines. Because of the influence of Raman amplification, the intensities of anti-Stokes components are lower than those of Stokes components stimulated in longer wavebands, which makes the asymmetric intensity distribution at both sides of the pump wavelength in the early stage of the spectral broadening. In subsequent stages, the generated dispersive waves keep continuous blue shift, as presented in Fig. 3. This is because these dispersive waves can be further shifted by cross-phase modulation (XPM) initiated by infrared Raman soliton. In the meantime, diverse FWM (Bragg-scattering and phase-conjugated type FWM) processes permit subsequent interplay between distinct solitons and dispersive waves, which contribute to the generation of new red- and blue-shift components. Thus, the supercontinuum becomes wider and flatter. Noting that wavebands ranging from 1350 nm to 1420 nm and 1800 nm to 1940 nm display strong oscillation structures, which are caused by peak absorption loss of water and carbon dioxide.

In particular, we notice that when we keep boosting pump power of the EDFA, the spectrum always experiences continuous broadening without any apparent residual high intensity spectral peak around the pump wavelength as reported in references. The intensities of some broadening components even exceed that of the pump wavelength, indicating that strong nonlinear effects shift a large quantity of energy from the pump wavelength to new frequencies. We infer that it arises from the multiple coherent pump scheme of double bound-state solitons, i.e., two sets of coherent pulse pump mechanism. The sub-set of pulses have fixed phase difference between two solitons. At the same time, this sub-set of pulses as a unit forms the main-set of bound-state pulses with five “solitons” through locking their phases. These two sets of coherent pump pulses simultaneously participate in the SCG. Therefore, the double bound-state solitons could induce stronger nonlinear effects and make the energy at the pump wavelength efficiently transfer to the new generated frequencies. Consequently, the generated supercontinuum has no residual spectral peak at the pump wavelength. In addition, we increase the pulse number in the main-set bound-state from the seed pulse laser to generate the supercontinuum. It is found that the characteristics of the supercontinuum keep almost the same as those in Fig. 3. It is strongly inferred that the flat supercontinuum without residual spectral peak at the pump wavelength is decided by multiple coherent pump rather than pump pulse numbers.

![Fig. 4.](Color online) Characteristics of two types of seed pulses: (a) spectrum, (b) pulse-train and (c) autocorrelation trace of conventional bound-state soliton; (d) spectrum, (e) pulse-train and (f) autocorrelation trace of conventional soliton.
In order to highlight the elimination of the residual pump peak in supercontinuum generated using the double bound-state solitons as pump seeds, we adopt another two different types of pulses as pump seeds for comparison. One is conventional bound-state soliton generated from the same seed pulse laser. The other is conventional single-soliton produced by a mode-locked fiber laser with a similar structure as shown in Fig. 1. The spectra and autocorrelation traces of the pulses are presented in Fig. 4. Figures 4(a) and 4(b) show the typical characteristics of the conventional bound-state soliton, which consists of five sub-solitons with separation of 12 ps. Figures 4(c) and 4(d) are the representative features of conventional soliton with 1.43 ps pulse width. Both of the pulses are amplified by the same EDFA mentioned above. For better comparison the properties of the supercontinuum obtained with disparate seed pulses under the same conditions as far as possible, we set up the power of the pulses to be amplified to 100 mW. Then all of the pulses are separately transmitted into the same HNLF referred above. Finally, we get three different supercontinuums, which are shown in Fig. 5. As seen from Fig. 5, the supercontinuum pumped by the conventional soliton covers from 1200 nm to 2100 nm, including a deeper spectral dent in shorter wavebands. In longer wavebands, the broadened spectrum is narrower than the other two supercontinuums. More importantly, a strong residual spectral peak at the pump wavelength is presented with an exceeded intensity more than 20 dB, meaning a relatively low energy conversion in spectral broadening. Note that there is a CW component in the initial spectrum of the soliton, it may also contribute to the appearance of the spectral peak in supercontinuum. On the other hand, for SCGs pumped by the conventional bound-state soliton and double bound-state solitons, the two spectra have similar wavebands and intensities. The difference between them is that, for the conventional bound-state soliton pumped SCG, there is also an obvious spectral peak at the pump wavelength with a relative intensity of around 15 dB. It implies that both of the pump pulses undergo a similar nonlinear frequency shift, but there exists a distinct difference in SCG pumped by the double bound-state solitons. During the process of the SCG, for the conventional bound-state soliton, it is only one set of pump pulses, while for the double bound-state solitons, there are two sets of coherent pump pulses with fixed phase differences. In addition, we notice that on the spectrum of the conventional bound-state soliton, there is no CW component. But it still generates a distinct spectral peak in the excited supercontinuum. This suggests that the CW component in pulse spectrum is not the only ingredient responsible for the formation of the spectral peak in SCG.

In fact, according to previous reports, the spectral peak at the pump wavelength in the supercontinuum generally occurs in two cases. One is CW or long pulse pumping. In this condition, modulation instability dominates the initial stage and generates low energy solitons with relatively low peak power, which leads to the input energy to remain unconverted. Thus, the spectral peak emerges at the pump wavelength. The other is short pulse pumping (picosecond to femtosecond scale). In this condition, a part of the spectral peak comes from the original pump pulse, and the other is derived from the higher-order soliton compression in the initial stage, which generates wide temporal pedestals at both wings of the pulse and most of the pulse energy is preserved in temporal pedestals. Due to the low intensity of the temporal pedestals, it is unable to participate in nonlinear effects induced spectral broadening. In our experiment, we consider that the formation of the spectral peak in the generated supercontinuum pumped by conventional soliton and bound-state soliton arises from the inadequately converted seed pulse energy rather than soliton compression. Because in the case of the double bound-state solitons as the pump seeds, the pulses would also undergo higher-order soliton compression in the process of SCG due to the sub-pulses with narrower pulse widths. However, the generated supercontinuum is clear without a sharp spectral peak at the pump wavelength. Therefore, we speculate that the higher-order soliton compression is not the reason for the formation of the spectral peak in the supercontinuum in Fig. 5. If the energy of the original seed pulse could be adequately converted to the new generated frequencies, the supercontinuum would be flatter without the sharp spectral peak. In our experiment, since the double-bound state solitons possess two sets of pulses with fixed phase differences, they could enhance the nonlinear effects in the process of generating supercontinuum by much stronger interactions among the pulses. Thus, the transferring efficiency of the pump energy could be greatly improved and effectively eliminate the residual spectral peak in the supercontinuum.

In conclusion, we report that the residual pump peak in SCG is successfully eliminated through a novel multiple coherent pump scheme. The pump scheme is performed by double bound-state solitons. Furthermore, we compare the SCGs pumped by the conventional bound-state soliton and single-soliton. The physical mechanism of the residual pump peak elimination owes to higher transferring efficiency of

![Fig. 5.](Color online) SCGs from different pump pulses.)
multiple coherent pump seeds. Our experimental results provide an interesting and novel technique for further researching on mechanism of SCG and improving the flatness of the supercontinuum.

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