Cascaded second-order soliton for high-coherence supercontinuum generation

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Abstract
We propose the use of cascaded second-order soliton for high-coherence supercontinuum generation.

1. Introduction
Supercontinuum (SC) generation in optical fibers has attracted widespread interests in the past ten years. Particular attention has been focused on the SC noise properties because the stability of SC amplitude and phase are key factors in many applications, such as optical frequency metrology, generation of ultrashort optical pulses, photonic time stretch analog-to-digital conversion, optical coherence tomography, and multi-wavelength optical source for high-speed wavelength division multiplexed optical communication, etc. Although the stability of SC can be greatly improved in SC generation using femtosecond pulses, ultrashort pulses are sensitive to perturbations and hence are not practical in many applications. One of the ongoing research directions is to study SC properties when the pump pulses vary from picosecond to continuous wave regime. Modulation instability (MI) plays an important role in SC generation with long pulses. Since MI growth starts spontaneously from noise, the resulting SC has low coherence. The extreme case is the optical rogue wave, which shows the SC generated with picosecond pulses exhibits extreme value statistics with long-tailed probability distributions [1]. Active control of SC has been demonstrated by using a seed-pulse [2], a THz intensity modulation of the input pulse [3], or a minute continuous wave (CW) light [4]. Here, we propose the use of cascaded second-order soliton for SC generation, which is insensitive to noise and has high coherence.

2. Theoretical Model
The generalized nonlinear Schrödinger equation (GNLSE) which is widely used in the modeling of SC can be written as [5]:

\[ \frac{\partial A}{\partial z} + i \beta_2 \frac{\partial^2 A}{\partial t^2} + \frac{\beta_3}{6} \frac{\partial^3 A}{\partial t^3} + i \gamma R(t) A(z,t) A(z,t-t') dt' = \]

where \( A(z,t) \) is the field envelope, \( \tau_{\infty} = 1/\omega_l \) and \( \omega_l \) is the center frequency, \( \beta_2, \beta_3 \) and \( \gamma \) are the second-, third-order dispersion and nonlinear coefficient of the fiber respectively. The Raman response function is

\[ R(t) = (1-f_c) \delta(t) + f_c h_r(t) \]  

We use \( f_c = 0.18 \) and \( h_r \) determined from the experimental fused silica Raman cross-section [5]. We include the input random phase noise in the frequency domain through one photon per mode spectral density on each spectral grid in the simulation. The noise amplitude is chosen to be 1% of the pump amplitude.

3. Simulation Results
For the proposed scheme, the pump pulse is a hyperbolic secant pulse \( N_{\text{sech}}(t/T_0) \) with full width at half maximum (FWHM) = 5 ps. The parameter \( N_1 \) is the soliton order in the first fiber. The output of the first fiber is launched into a second fiber with a different
dispersion coefficient, and the soliton order in the second fiber is $N_2$. The output of the second fiber is launched into a third fiber with a different dispersion coefficient, and the soliton order in the third fiber is $N_3$. Here, we assume that the nonlinear coefficient $\gamma$ is the same for the three fibers, and $N_1=N_2=N_3=2$. Table 1 gives the detailed fiber design, when $\beta_{2i}$ and $\beta_{3i}$, $i = 1, 2, \text{and} 3$, are the second and third order dispersion coefficient in the $i$-th fiber, respectively. The parameters, $L_i$ and $z_{0i}$, $i = 1, 2, \text{and} 3$, are the fiber length and soliton period of the $i$-th fiber, respectively.

<table>
<thead>
<tr>
<th>fiber</th>
<th>$\beta_{2i}$ (ps²/km)</th>
<th>$\beta_{3i}$ (ps²/km)</th>
<th>$L_i$ (ps²/nm)</th>
<th>$z_{0i}$ (ps²/nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>first fiber</td>
<td>$-20$</td>
<td>$0.1$</td>
<td>$L_1$</td>
<td>$z_{01}=0.5$</td>
</tr>
<tr>
<td>second fiber</td>
<td>$-4.086$</td>
<td>$0.1$</td>
<td>$L_2$</td>
<td>$z_{02}=0.486$</td>
</tr>
<tr>
<td>third fiber</td>
<td>$-0.8236$</td>
<td>$0.01$</td>
<td>$L_3$</td>
<td>$z_{03}=0.487$</td>
</tr>
</tbody>
</table>

TABLE 1. FIBER DESIGN

Fig. 1(a) shows the input (blue) and output (black) of the first fiber. Fig. 1(b) shows the output of the second fiber. The solid curve and dashed curve in Fig. 1(c) represent the third fiber output and third fiber output after a nonlinear optical loop mirror NOLM (dashed curve). The NOLM is used for effective pedestal suppression. Fig. 1(d) shows the FWHM evolution in the first (solid curve), second (dashed curve) and third fibers (dot-dashed curve). The FWHM of the final output pulse is only 58 fs. Fig. 2(a) gives the average spectrum calculated from the 20 simulation runs with different realizations of input noise. Fig. 2(b) is the coherence diagram. Coherence is calculated using the method described in [5] and a value of 1 denotes perfect coherence. From Fig. 2, the coherence is almost 1 for the main part of the output spectrum. The average output spectrum is from 1425 to 1710 nm at $-20 \text{dBm}$ level.

4. Conclusions
The proposed supercontinuum generated with cascaded second-order soliton is insensitive to noise and has high coherence.

5. Acknowledgement
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6. References