Relative timing jitter of Raman soliotns and its effect on nonlinear wavelength conversion

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Abstract: We demonstrate that shorter fiber length and the excitation pulse with shorter duration and higher energy can reduce a Raman soliton's relative timing jitter and leads to reduced noise in nonlinear wavelength conversion.
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When a femtosecond pulse propagates inside an optical fiber with anomalous dispersion, interplay between intra-pulse stimulated Raman scattering and soliton formation results in Raman soliton self-frequency shift; that is, the Raman soliton's center frequency red shifts continuously during propagation and maintains its transform-limited hyperbolic secant profile. Capable of providing wavelength tunable femtosecond pulses at the desired wavelengths that cannot be directly obtained from mode-locked ultrafast lasers, Raman soliton sources have found many important applications. As a particular example of nonlinear wavelength conversion, difference-frequency generation (DFG) between a Raman soliton and the pumping pulse that excites the Raman solliotn constitutes a powerful method to generate mid-IR femtosecond pulses [1]. Since the Raman soliton and its excitation pulse share the same repetition rate and the carrier-envelope phase (CEP) offset, the resulting DFG source—if the excitation pulse's repetition rate is stabilized—becomes a mid-IR frequency comb with its CEP offset automatically set at zero. Raman soliton's center wavelength can be tuned by varying the excitation pulse's energy, and therefore the relative intensity noise (RIN) of the excitation pulse causes the Raman soliton's center-wavelength fluctuation, which is then converted to timing jitter by fiber dispersion. In the subsequent DFG, this relative timing jitter between the excitation pulse and the Raman soliton will be transferred to the derived mid-IR comb source manifesting as broadened comb lines and increased RIN. In this paper, we carried out a detailed experimental study on optimizing Raman soliton's relative timing jitter and the resulting effect on nonlinear wavelength conversion.
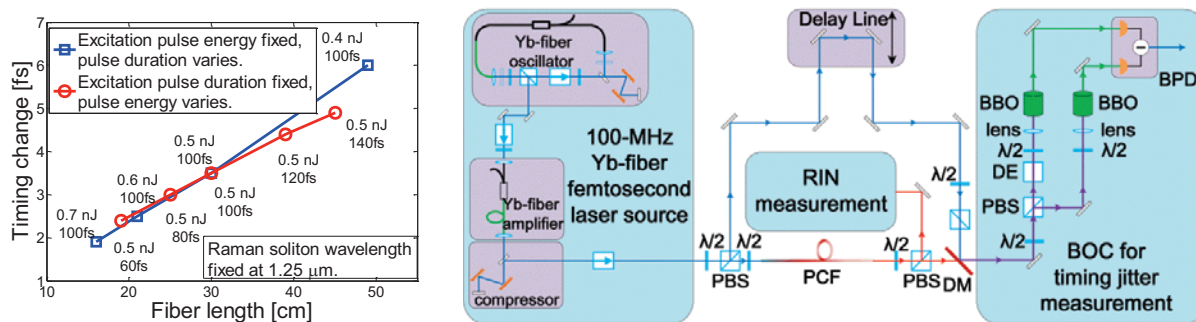

Fig 1. (left) Simulation results for Raman soliton's timing change due to 0.2% change of the excitation pulse energy. A 1.03 μm excitation pulse propagates in a photonic crystal fiber with zero-dispersion wavelength at 945 nm and the resulting Raman soliton's center wavelength is fixed at 1.25 μm. (right) Schematic setup to characterize relative timing jitter of a Raman soliton source. BOC: balanced optical correlator, PBS: polarization beam splitter, PCF: photonic crystal fiber, DM: dichroic mirror, DE: delay element, BPD: balanced photodetector.

Raman soliton centered at a desired wavelength can be achieved by different combination of fiber length and the excitation pulse's duration and energy. Figure 1(left) shows—by solving the generalized nonlinear Schrödinger equation—nine possible parameter-combinations that result in a Raman soliton at the same wavelength of 1.25 μm using a photonic crystal fiber (PCF) with its zero-dispersion wavelength at 945 nm. The excitation pulse's center wavelength is fixed at 1.03 μm. We vary the excitation pulse energy by 0.2% and record the corresponding timing change of the Raman soliton. As Fig. 1(left) illustrates, increasing excitation pulse energy (with duration fixed at

100 fs, blue curve) or reducing the pulse's duration (with energy fixed at 0.5 nJ, red curve) both lead to (1) a shorter required PCF length to generate a Raman soliton centered at 1.25 μm, and (2) a decreased timing change. It suggests that a combination of shorter excitation pulse, higher excitation pulse energy, and shorter fiber length can reduce the relative timing jitter between a Raman soliton and its excitation pulse. Guided by numerical simulations, we use the experimental setup shown in Fig. 1(right) to study the relative timing jitter of Raman solitons shifted to 1225 nm and 1275 nm using two PCF (zero-dispersion wavelength at 945 nm) lengths—38 cm and 205 cm. The home-built Yb-fiber laser system providing 3-nJ, 110-fs pulses includes a 100-MHz Yb-fiber oscillator centered at 1035 nm, an Yb-fiber amplifier, and a pulse compressor. We constructed a balanced optical correlator (BOC) [2] to measure the relative timing jitter between the excitation pulse and the Raman soliton.
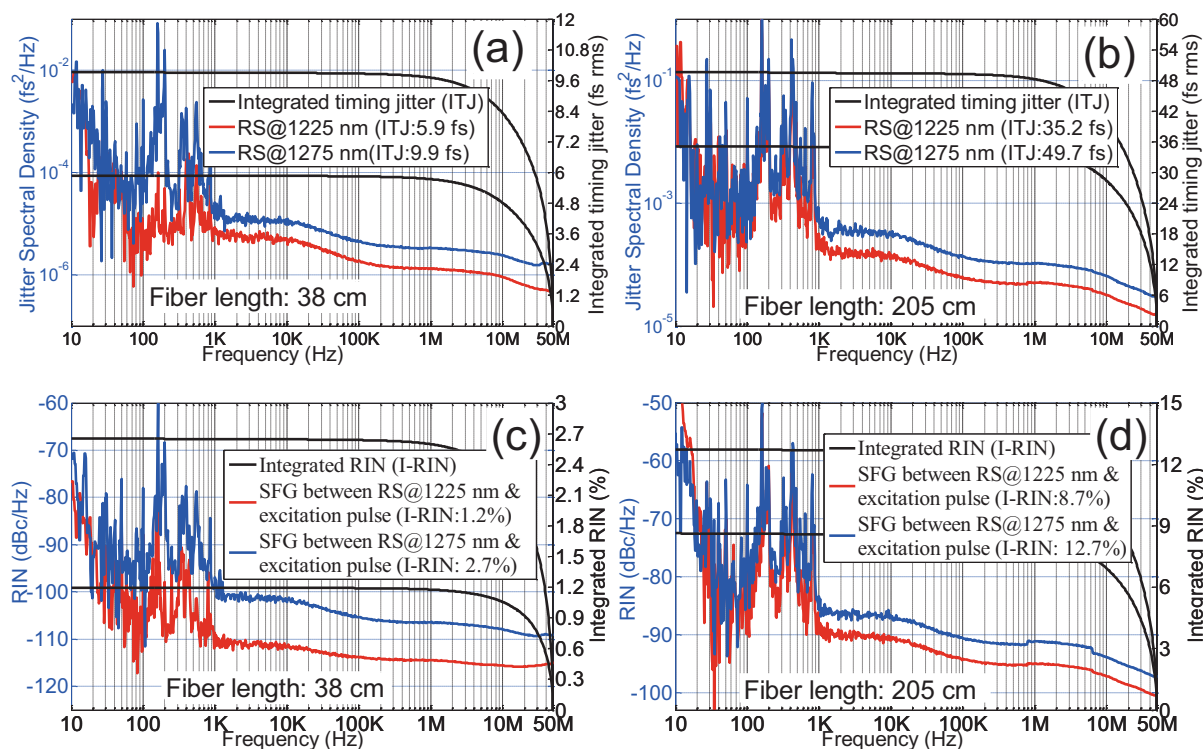

Fig 2. (a)(b) relative timing jitter of Raman solitons (RS) centered at 1225 nm (red curve) and 1275 nm (blue curve) using 38-cm PCF (a) and 205-cm PCF (b). Black curves are the integrated timing jitter (ITJ). (c)(d) RIN measurement of SFG pulse generated by mixing the excitation pulse with the 1225-nm Raman soliton (red curve) or with the 1275-nm Raman soliton (blue curve). (c) results from 38-cm PCF and (d) results from 205-cm PCF. Black curves represent the integrated RIN.

Figure 2(a) and 2(b) plot the relative timing jitter of two Raman solitons peaking at different wavelengths (1225 nm versus 1275 nm) generated by 38-cm PCF (Fig. 2(a)) and by 205-cm PCF (Fig. 2(b)). As expected from simulation, using shorter fiber length (i.e., 38 cm) with larger excitation pulse energy reduces timing jitter. More specific, the integrated timing jitter from 50 MHz to 10 Hz is 35.2 (49.7) fs for the 1225- (1275-) nm Raman soliton generated from 205-cm PCF; this value drops to 5.9 (9.9) fs when 38-cm PCF is employed. To study the effect of the relative timing jitter on nonlinear wavelength conversion, we measured the RIN of the sum-frequency generation (SFG) between Raman solitons and the excitation pulse. The SFG pulse exhibits an order of magnitude higher RIN (Fig. 2(c) and 2(d)) than the excitation pulse and the resulting Raman soliton, both of which have an integrated RIN around ~0.2%. Apparently it is the relative timing jitter that generates such a substantial increase of the RIN for these SFG pulses. As expected from Fig. 2(c)(d), a reduction of relative timing jitter using the 38-cm PCF reduces the SFG pulses' integrated RIN by a factor of ~5 compared with the results from the 205-cm PCF. Ongoing work is to reduce this relative timing jitter to the attosecond level by further optimization and achieve a low-noise femtosecond source derived from nonlinear mixing between a Raman soliton and the excitation pulse.

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