Operation of regenerative sources based on alternating SPM and SSFS

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Abstract: We report on the operation of regenerative sources based on self-phase modulation (SPM) and soliton self-frequency shift (SSFS). Such stochastic sources generate a wide continuum spreading over 450 nm.

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The generation of short pulses has become a topic of interest for their applications in manufacturing, imaging, metrology and sensing. In fiber lasers, the most common way to trigger ultrashort pulses relies on additive pulse mode-locking. Moreover, favoring pulses over cw oscillation is also enabled by a pair complementary SPM regenerators in closed loop, leading to aperiodic pulse generation [1]. A new method for generating pulses in fiber lasers based on a pair of nonlinear stages was proposed and demonstrated experimentally in 2012 [2]. Sources of that kind are composed of two distinct nonlinear stages. In a first nonlinear stage, a supercontinuum (SC) is triggered by modulation instability (MI). This SC is partially washed out by a red-shifted band-pass filter (BPF). In a second stage, pulses incoming from this BPF are spectrally broadened by SPM, and a BPF selects the blue-most spectral components of the broadened pulses. This second stage corresponds to a SPM-offset filtering regenerator, as designed by Mamyshev in 1998 for telecommunication applications [3]. The ring cavity is closed as the output of the second stage becomes the input of the first stage with the addition of erbium-doped fiber amplifiers (EDFAs), as depicted in Fig. 1(a). This kind of self-pulsating lasers, referred to as SPM-SSFS sources, have similarities with self-pulsating sources based on cascaded SPM regenerators which also feature wavelength toggling and alternative offset filtering [1]. Fig. 1(a) depicts the experimental setup of a SPM-SSFS source, and insets (b) and (c) illustrate the nonlinear wavelength conversion that pulses circulating in the cavity undergo. To each nonlinear stage correspond a highly nonlinear fiber (HNLF) in anomalous and normal dispersion, as well as mismatched BPFs. As shown in the numerical simulations of Fig. 1(d) and (e), multiple solitons of different Raman shifts are generated during propagation in the HNLF with anomalous dispersion. On average, a wide and flat SC is generated at output C_3 of the cavity. At the other nonlinear stage, regeneration is performed with a HNLF in normal dispersion and an offset BPF. Pulses which have been subject to a large amount of SSFS are discarded by band-pass filtering.

In this paper, we experimentally investigate the conditions for pulse ignition and SC generation, as a function of the spectral bandwidth and separation of the two filtering stages. We demonstrate that this source enables SC generation in various configurations, leading to a wide spectrum spreading up to a wavelength of 1900 nm. We also report the first single-shot spectral measurements for this source, supporting the possibility that SC generation results from various Raman-shifted fundamental solitons providing a flat continuum on average. In Fig. 2(a) and (b), BPF_2 is adjusted to bandwidths in the range 0.2 to 20 nm, and its spectral position is shifted towards the short wavelengths until self-pulsation occurs. This position is reported in (b), and the corresponding continuum generated at C_3 is depicted in (a). Fig. 2(b) also indicates that the source still self-starts and produces a continuum when BPF_2 has a bandwidth of 0.2 nm. In fact, the bandwidth of BPF_1, in this case, can be decrease down to 0.5 nm without affecting the source operation. Conversely, a pair of low- and high- pass filters also enables pulsed operation, as shown in feature (h) of Fig. 2(b), thereby simplifying the experimental setup. Fig. 2(c) provides single-shot spectral measurement as measured using a time-to-wavelength mapping technique [4, 5]. These spectra reveal that pulses incoming to $HNLF_2$ separate into several subpicosecond solitons, experiencing different wavelength shifts by intra-pulse Raman scattering. The amount of circulating energy, contrary to traditional mode-locked sources, varies constantly because of the randomness induced by MI in the SC generation process. Supercontinuum-free operation is also investigated numerically. Although the source does not self-start in this regime, a seed pulse may lead to a highly efficient pulse-buffering regime. In this case, a single soliton with a duration of 300 fs accompanied with dispersive waves travels along $HNLF_2$. In conclusion, the operation of SPM-SSFS sources is characterized, and indicates their ability to trigger pulses at a large range of filter

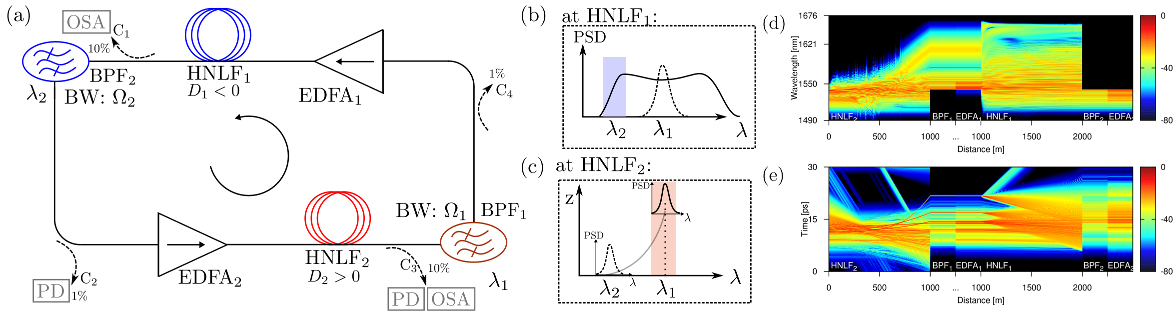

Fig. 1. (a) Setup of a generic self-pulsating source based on cascaded regeneration. Insets (b) and (c): nonlinear wavelength conversion schemes. (d) and (e): Map of pulse propagation in the spectral and temporal domains, when BPF$_{1,2}$ are a low- and high-pass filter respectively. BPF: band-pass filter; BW: bandwidth; EDFA: erbium-doped fiber amplifier; HNLF: highly nonlinear fiber. PSD: power spectral density; OSA: optical spectrum analyzer.

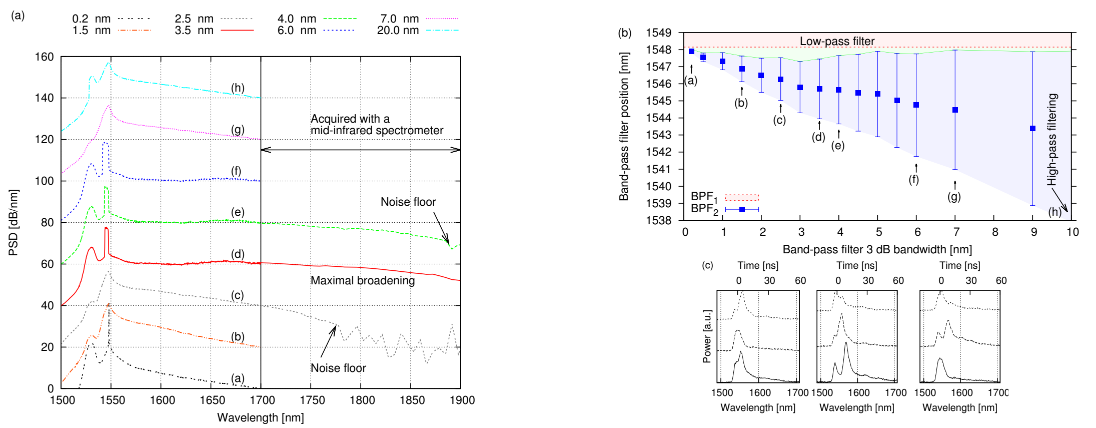

Fig. 2. (a) Supercontinuum observed at C_3 depending on the bandwidth of BPF$_2$. (b) Corresponding filter bandwidths and spectral offset triggering self-pulsation. (c) Single-shot measurements of the continuum.

bandwidths. A flat SC is observed at one of the cavity output, without optimization of the nonlinear medium carrying the continuum. Applications of SPM-SSFS sources include random number generation, chaotic LIDARs, imaging or sensing.

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