Analysis of Self-Pulsating Sources Based on Cascaded Regeneration and Soliton Self-Frequency Shifting

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Abstract—We characterize the operation of self-pulsating sources made of two optical regenerators in cascade, namely a first regenerator of the type self-phase modulation spectral broadening and offset filtering, followed by a second regenerator of the type supercontinuum generation and offset filtering. The range of operation of this laser is explored as the wavelength and bandwidths of the band-pass filters are adjusted. We also provide experimental evidence that soliton self-frequency shift emanating from modulation instability triggers bursts of pulses at the repetition rate of the cavity. The stochastic nature of sources based on this concept leads to shot-to-shot pulse fluctuations in the cavity, which on average result in a flat supercontinuum extending beyond 1900 nm. Finally, a seed pulse can be sustained efficiently via this laser architecture, and the cavity consequently generates subpicosecond pulses at one of its outputs.

Index Terms—Self-pulsating source, laser resonator, nonlinear optics, self-phase modulation, optical pulse regeneration, soliton self-frequency shifting, modulation instability.

I. INTRODUCTION

SELF-pulsating fiber lasers have become a topic of interest for their ability to combine a high beam quality, stability and compactness. In such lasers, the generation of short pulses enables imaging, spectroscopy or metrology as well as industrial application when operating at watt levels [1]. To generate pulses, a nonlinear transfer function favoring pulses over continuous wave (CW) operation must be added in the laser cavity. Within the category of pulsed lasers that are all-fiber, mode-locking with nonlinear polarization rotation [2] or nonlinear loop mirrors [3], [4] are the most common ways to generate ultrashort pulses of large bandwidths.

In 2008, pulsed lasers based on a pair of complementary regenerators of type self-phase modulation (SPM) and offset filtering (SPM-OF) regenerators was demonstrated [5]. This architecture has interesting features including aperiodicity, low polarization sensitivity, and multwavelength operation [6]–[8]. Pulses propagating in sources based on that concept undergo large changes in their spectral and temporal profile twice per cavity round trip. As a result, their output feature invariant eigenpulses which can be regarded as dispersion-managed solitons [9]. These sources do not belong to the class of mode-locked lasers, for which a fixed phase relationship is maintained between the spectral components of the propagating beam. Consequently, the repetition rate of the output pulses is not constrained to a pulse-to-pulse time interval dictated by the cavity free spectral range or one of its harmonics.

Based on cascaded regeneration, a new method for generating short pulses in fiber lasers was also proposed and demonstrated experimentally in 2012 [10]. Sources of that kind, referred to as SPM-soliton self-frequency shift (SPM-SSFS) sources, are composed of two distinct regeneration stages. In the first stage, regeneration based on SPM-OF is followed by a second regeneration stage in which SSFS occurs during the generation of a supercontinuum (SC). This SC is partially washed out by a red-shifted band-pass filtering (BPF), and the ring cavity is closed as the output of the second stage becomes the input of the first stage. Hence, the design of SPM-SSFS sources has similarities with self-pulsating sources based on cascaded SPM-OF regenerators, which also feature wavelength toggling and alternating offset filtering. A particular feature of SPM-SSFS sources is that they provide a broadband SC at one of their output, along with a tunable temporal burst duration which can be extended up to several hundreds of nanoseconds when the pump power is increased. Because of the presence of multiple and varying pump pulses, the SC generated by this type of sources may be compared to supercontinuum emanating from noise bursts [11], [12] or noiselike pulses [13]. SPM-SSFS sources therefore provide a flexible platform for ultrashort pulse generation, which results in a tunable output energy and SC width, without active optical elements such as optical modulators. Moreover, no saturable absorber is required to trigger and sustain the pulsed regime, which enables compact and robust all-fiber setups. Overall, SPM-SSFS sources compose an interesting new architecture, which so far has not been the subject of much investigation. In [10], numerical simulations were provided along with spectral measurements to support the possibility that a pulse originating from the first nonlinear stage is turned into several fundamental solitons, shifted in frequency by stimulated Raman scattering (SRS) during propagation in the anomalous dispersion region of a highly nonlinear fiber (HNLF). However, multishot spectral measurements have provided an averaged spectrum rather than a direct experimental observation of this process.
In this paper, we experimentally investigate the conditions for pulse ignition and SC generation from the influence of filters in the cavity. Results provide the optimal filter bandwidth that maximizes the output SC bandwidth as well as the total output power. Shot-to-shot spectral measurements indicate, as previously assumed in [10], that the observed SC originates from the time-averaging of multiple spectra. These SCs, seeded by picosecond pulses, are extremely sensitive to initial conditions, and therefore their output spectra are unique [14]. Finally, numerical simulations are conducted, and show that the architecture of SPM-SSFS sources can sustain pulses in a SC-free regime, by avoiding the generation of multiple solitons. In this case, the source efficiency is maximal, and subpicosecond pulses are readily available at one cavity output.

II. Theoretical Basis and Experimental Setup

Self-pulsating sources based on cascaded regeneration rely on two or more nonlinear stages whose function is to convert the propagating signal from one wavelength to another. When there are two nonlinear stages, the initial signal is shifted from the wavelength $\lambda_{1,2}$ to the wavelength $\lambda_{2,1}$ via nonlinear wavelength converters (NWCs), as depicted in Fig. 1. These NWCs must feature intensity dependent transfer functions and hence favor high intensities, triggering pulses. Regenerative sources solely composed of cascaded SPM-OF regenerators at NWC$_{1,2}$ sustain pulses with a low amplitude jitter, due to the sharp transfer function that characterizes the SPM-OF regenerators placed in the cavity [6]. The temporal shape of the pulses is imposed by the spectral shape of the filters, via their Fourier transform plus an additional chirp, linear across the pulse. Fig. 2 depicts such a regenerator. In fact, a remarkable property of SPM-OF regenerators is that at the first approximation, the output pulse peak power is independent of the input pulse power. Given that the latter is above threshold, the output peak power $P_o$ is expressed as [15]:

$$P_o \sim \frac{P_p}{\Delta \omega_{SM}} = \frac{1}{\lambda} \Delta \omega_0 2\pi n_2 L.$$  \hspace{1cm} (1)

In equation (1), the output intensity is proportional only to the initial bandwidth $\omega_0$, as well as the nonlinear propagation length $L$ and the nonlinear coefficient $n_2$. The central wavelength is $\lambda$, $\Delta \omega_0$ is the input pulse bandwidth, $\Delta \omega_{SM}$ is the bandwidth of the pulses broadened by SPM, and $P_p$ is the input pulse peak power. Amplitude variations are, therefore, limited by this first nonlinear stage, which generates nearly chirp-free pulses at its output at small filter bandwidths, and linearly chirped pulses at larger spectral filter bandwidths [7].

In SPM-SSFS sources, the second NWC (NWC$_2$) is a HNLF with anomalous dispersion at the pump wavelength used in tandem with a BPF, as depicted in Fig. 3. Pulses input to this NWC undergo SSFS, induced by modulation instability (MI) when their temporal duration is in the picosecond range [16]. By joining both nonlinear stages with EDFAs, the source self-ignites pulses from amplified spontaneous emission (ASE), provided that the BPFs have an adequate relative spectral position, which is the subject of Section III.

Fig. 4 depicts the experimental setup used in this work. This setup has similarities with the setup of Ref. [10], Fig. 1, but is improved with the use of tunable and adjustable filters for both BPF$_1$ and BPF$_2$, replacing the fixed filter formed by the conjunction of an optical circulator and a Bragg grating, thereby adding two degrees of freedom. This setup is composed of two HNLFs of length $L = 1007$ m, two adjustable and tunable BPFs, centered at the wavelengths $\lambda_{1,2}$, and with tunable 3 dB bandwidths $\Omega_{1,2}$, respectively. The filters have sharp edges, as shown in Fig. 4(d), and a modification of their bandwidth only alters the width of their flat top portion. The filter offset is defined as $\Delta \lambda = |\lambda_1 - \lambda_2|$. The nonlinear fibers HNLF$_{1,2}$ have a nonlinear waveguide coefficient $\gamma = 12.5$ W$^{-1}$ km$^{-1}$, and a chromatic dispersion coefficient $D_1 = -0.71$ ps/(nm km) and $D_2 = 2.09$ ps/(nm km), respectively. Their third-order dispersion coefficients are $S_1 = 0.0074$ ps/(nm$^2$ km) and $S_2 = 0.002$ ps/(nm$^2$ km). Insertion losses are of 1.7 dB for each HNLF, 8 dB for BPF$_1$, 5.5 dB for BPF$_2$, and 0.5 dB for each output coupler, in addition to the power drawn by their output port. Two EDFAs are inserted between each nonlinear stage, with a saturation power $P_{sat} \approx 15$ dBm. The cavity output is observed via the four output tap couplers C$_{1-4}$ with a 12.5 GHz photodiode and a standard optical spectrum analyzer (OSA). The 1% tap couplers are used for monitoring purposes. The extraction of 10% of the cavity power at C$_1$ and C$_2$ is sufficient to obtain output powers up to 10 dBm. The EDFAs are used below 50% of their capacity in terms of pump power, and higher coupling ratios could be used without altering the source operation.
Fig. 4. Closed-loop self-pulsating cavity. (a) Experimental setup of the SPM-SSFS source. (b) Spectrum at the first nonlinear stage, with SPM broadening and offset filtering at $\lambda_2$. (c) SSFS and filtering at $\lambda_1$, in the second nonlinear stage. (d) Illustration of the filter profiles. BPF: band-pass filter, BW: bandwidth, HNLF: highly nonlinear fiber, EDFA: erbium-doped fiber amplifier, NWC: nonlinear wavelength converter, OSA: optical spectrum analyzer, PD: photodiode, PSD: power spectral density.

Fig. 5. Propagation of pulses in the cavity of Fig. 4(a). (a) In the frequency domain and (b) in the time domain. The propagation length of the BPFs and EDFAs are increased for readability.

In Fig. 5, the propagation of pulses is shown in the spectral and temporal domain after 18 cavity round-trips. The limit case where BPF$_1$ is a low-pass filter and BPF$_2$ is a high-pass filter is illustrated. Pulses from EDFA$_2$ are launched into HNLF$_2$, and interact by the conjugated effects of MI and four-wave mixing (FWM). These interactions give birth to fundamental solitons, which experience SSFS as illustrated in Fig. 5(a), where a powerful soliton shifts to a wavelength of $\sim 1630$ nm. In the time domain, these solitons acquire a delay because of their different group-velocity in the anomalous dispersion regime. Dispersive waves are also emitted as a result of these interactions, and the observed spectrum is similar to spectra arising from supercontinua seeded by picosecond pulses. Solitons resulting of the propagation in HNLF$_2$ experience a significant amount of SPM when propagating in HNLF$_1$. This results in a large temporal broadening, as well as a weak emission of radiation from the blue-most wavelength components of these pulses, which now propagate slower than red-most wavelength components in normal dispersion. Low-pass filtering at BPF$_1$ do not extinct the significantly shifted solitons. However, they do not benefit from the gain of EDFA$_1$, nor pass through BPF$_2$. For other spectral components, SPM broadening occurs in the first few meters of the fiber, thereby shifting some energy towards the shorter wavelengths and resetting the central wavelength to $\lambda_2$, as depicted in Fig. 4(b). The numerical model used to generate Fig. 5 includes the effects of second- and third-order dispersion $\beta_2$, $\beta_3$, nonlinearity, and the Raman effect ($T_\text{R} = 3 \text{fs}$), and is implemented as described in [8].

III. EFFECT OF THE FILTER BANDWIDTHS

The output properties of SPM-SSFS sources were studied in [10] for fixed filter spectral positions and bandwidths. The source was started from ASE, as the pump power of EDFA$_{1,2}$ was increased beyond a given power threshold. In this section, the operation of the source is shown for a wide range of filter spectral bandwidths, and pulses are triggered by altering the filter offset. At one limiting case, BPF$_1$ is a low-pass filter, and BPF$_2$ has a variable bandwidth. Self-pulsation occurs for a fixed EDFA pump power, by reducing the spectral separation between the BPFs, by red-shifting BPF$_2$. The green zone of Fig. 6(a) represents the maximal filter offset that induces self-pulsation. This zone has a maximal $\Delta \lambda$ when $\Omega_2 = 3 \text{ nm}$. Fig. 6(b) illustrates the continuum observed at $C_3$ for some of these configurations. For a BPF$_2$ bandwidth of $3.5 \text{ nm}$, the continuum generated at $C_3$ is maximized, and reaches wavelengths past $1900 \text{ nm}$. For larger and smaller bandwidths, less energy is transferred towards the long wavelengths. Hence, there exist an optimal spectral bandwidth of BPF$_2$ for which the captured spectral power density contributes optimally to sustain the existing pulses in the cavity. This particular case was illustrated in [18], in the case of...
regenerative sources. In such a situation, the pulses filtered at BPF$_2$ exhibit long temporal duration due to the accumulated dispersion, or contain a broad pedestal if compression is achieved by chirp compensation. The pulse energy is high due to the large amount of spectral components captured by the BPF, but it is spread over a long duration, which is nonoptimal for SC generation.

In a second set of experiments, the filter bandwidths are changed, so that $\Omega_1 = \Omega_2$ at all times. In Fig. 7, the position of each BPF is depicted. BPF$_2$ is first shifted towards the longer wavelengths to trigger self-pulsation, and the output power at C$_3$ is recorded at that moment. Then, BPF$_2$ is shifted in the opposite direction, and the wavelength at which the source stops pulsating is recorded. For filter bandwidths of 4.7 nm, pulses are sustained in the cavity up to a filter offset of $\Delta \lambda = 3$ nm. Spectrally, the continuum at C$_3$ shows insignificant changing when altering the filters bandwidth. Even for filter bandwidths of 0.5 nm, which means large temporal pulse duration of $\sim 7$ ps from the SPM-OF regenerator, SC generation is initiated in HNLF$_2$.

Overall, SPM-SSFS sources self-start from thin filter bandwidths of 0.5 nm to ultra-large bandwidths in the limiting case, when reduced to a pair of low- and high-pass filters. Optimal filter bandwidths maximize the source efficiency by blocking the spectral content which does not contribute to the pulses.

IV. SINGLE-SHOT SPECTRAL MEASUREMENTS

A wavelength-to-time mapping technique is used to capture the power spectral density of pulses originating from HNLF$_2$ [19]. Used recently to analyze supercontinua induced by MI or noiselike pulses [20], [21], this technique relies on the fact that any pulse tends to turn into its Fourier transform when passing through a dispersive medium. When the third-order dispersion is small, the last term of Eq. (2) is negligible, and Eq. (2) provides a linear relationship between a time interval $\Delta \tau$, a wavelength interval $\Delta \lambda$, the chromatic dispersion coefficient $D$ and the fiber length $L$ [19]

$$\Delta \tau \approx D L \Delta \lambda + \frac{d}{d\lambda} D L (\Delta \lambda^2).$$

(2)

A spool of 21.64 km of SMF-28, for which this assumption holds, is used along with a real-time oscilloscope. The temporal duration of the observed signal must be small with respect to the time-delay corresponding to the signal bandwidth. Because SPM-SSFS sources generate a burst of pulses at their output, it is necessary to reduce the burst duration to a minimal value. For this purpose, the EDFA pump power is decreased to shorten the duration of the temporal burst after the regeneration stage. Fig. 8 presents a set of unrelated 30 single-shot spectra, when BPF$_1$ and BPF$_2$ have a bandwidth of 5 nm and 6 nm, respectively. This set of spectra reveals several peaks at various wavelengths, red-shifted with respect to the pump, which correspond to powerful solitons shifted by SRS. Fig 5(a) indicates that co-propagating solitons exchange energy as they collide with others [22]–[24]. The soliton temporal duration can be retrieved from their bandwidth at the output C$_3$. From the solitons of Fig. 8(a) whose full width at half maximum (FWHM) is separated from other spectral components, the soliton temporal FWHM are of $\sim 120$ fs – 200 fs, for a spectral bandwidth of 12–21 nm. As
indicated by Fig. 8(a), a small amount of energy is nevertheless transferred to the longer wavelengths, up to 1700 nm, revealing the presence of solitons of short temporal duration whose frequency shift is proportional to $1/t_{\text{FWHM}}^4$ [25]. The shifting rate is also potentially raised by collisions with other solitons generated by MI [24]. The randomness characteristics of SC generation induced by MI imply that the energy contained in the cavity is not constant, contrary to mode-locked lasers or sources based solely on cascaded SPM-OF regenerators. The offset filtering periodically reduces the number of pulses, and the total pulse energy varies as depicted in Fig. 9.

V. SC-FREE OPERATION

In this section, we numerically investigate the potential of SPM-SSFS sources for SC-free operation, a regime in which a single pulse propagates in the cavity with a minimum energy loss. The operation of SPM-SSFS sources according to the setup of Fig. 4 is such that the pulse input to HNLF$_2$ is chirped, in the picosecond range, and energetic. This pulse is split into several fundamental solitons, drifting with various amounts of spectral shifts. Most of the time, these solitons are therefore rejected by BPF$_1$. If BPF$_1$ is a low-pass filter, the solitons are sustained in HNLF$_1$ but rejected at BPF$_2$, because their spectral broadening by SPM is insufficient to transfer energy back to $\lambda_2$. In this case, the source efficiency is limited as illustrated by the SC observed at $C_3$.

However, are SPM-SSFS sources able to generate and sustain a single pulse, which could undergo SSFS and transfer most of the energy from the short towards the long wavelengths? To answer this question, the setup of Fig. 4 is altered by the addition of a dispersion compensating fiber after EDFA$_2$. Chirp compensation therefore decreases the pulse input to HNLF$_2$ down to a FWHM duration of 300 fs. At such pulse duration, propagation in HNLF$_2$ enables SSFS of a single soliton, because the effects of MI and FWM do not prevail [26].

Simulations conducted with various filter bandwidths, gain and saturation indicate that single-pulse operation is supported by the cavity. However, the source is not self-starting in this configuration. To trigger pulses, the required saturation energy leads to higher order solitons of $N > 2$ input to HNLF$_2$, contradicting the requirement for single-pulse operation. Nevertheless, if a pulse seed is launched in a cavity with adequate amplifiers, the SPM-SSFS source reaches a steady-state, sustaining picosecond pulses in HNLF$_1$, and subpicosecond in HNLF$_2$. Fig. 10 illustrates the steady-state propagation of a single pulse inside the cavity, in the time and frequency domains, after 10 cavity round-trips. The BPFs are Gaussian, with a FWHM bandwidth of 5 nm, and their spectral separation $\Delta \lambda = 10$ nm. The saturation power of EDFA$_{1,2}$ are of 0.075 and 2.11 dBm, respectively. A length of 42 m of single-mode fiber compensates for the dispersion in HNLF$_1$. In this configuration, 37% of the power input to HNLF$_2$ passes through BPF$_1$. The SPM-OF regenerator is less efficient, and passes 14% of the resulting power. The experimental design of a cavity enabling SC-free operation would require a proper tuning of the doped-fiber lengths. The initial pulse can be seeded at $C_2$, and monitored at $C_3$ and $C_4$. By adjusting the pump power of the EDFAs, the required spectral shift which maximizes transmission can be reached at each nonlinear stage.
Finally, simulations indicate that SC-free operation can be sustained in SPM-SSFS sources, provided that a pulse seed is input to the cavity.

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REFERENCES


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