Multiwavelength and Tunable Self-Pulsating Fiber Cavity Based on Regenerative SPM Spectral Broadening and Filtering

Martin Rochette, Lawrence R. Chen, Kai Sun, and Juan Hernández-Cordero

***Abstract*—We experimentally demonstrate the operation of a pulsed source based on self-phase modulation followed by offset spectral filtering. This source has three operation regimes: a continuous-wave regime, a self-pulsating (SP) regime where the source self ignites and produces pulses, and a pulse-buffering (PB) regime where no new pulse is formed from spontaneous noise but only pulses already propagating, or potentially pulses injected in the cavity, can be sustained. In the SP and PB regimes, the pulsed source is multiwavelength and continuously tunable over the entire gain band of the amplifiers. The output pulsewidth is quasi-transform-limited with respect to the spectral-width of the filters used in the cavity. Overall, this device is extremely simple to implement and is a strong candidate as a pulsed source and for signal buffering.**

***Index Terms*—Laser resonators, nonlinear optics, optical pulse generation, optical regeneration, optical signal processing.**

I. Introduction

OPTICAL regenerators have attracted a lot of attention to convert a collection of pulses with random amplitude variations into pulses with relatively uniform amplitude profiles. In this regard, a particularly simple and effective solution is the regenerator based on the principle of nonlinear spectral broadening followed by offset filtering [1], [2]. This regenerator design provides an output signal that is spectrally offset with respect to the input signal and, therefore, a cascade of two such regenerators with wavelength offsets of equal magnitude but opposite signs (paired regenerators) has been suggested as a means of regeneration without residual spectrum shift [3], [4]. Recently, it was predicted through numerical simulations that paired regenerators placed in cascade can support one or several eigenpulses (i.e., entering pulses that remain unchanged at the output of the paired regenerators) [5]. This research leads to the conclusion that paired regenerators placed in a loop configuration could potentially enable passive mode-locking.

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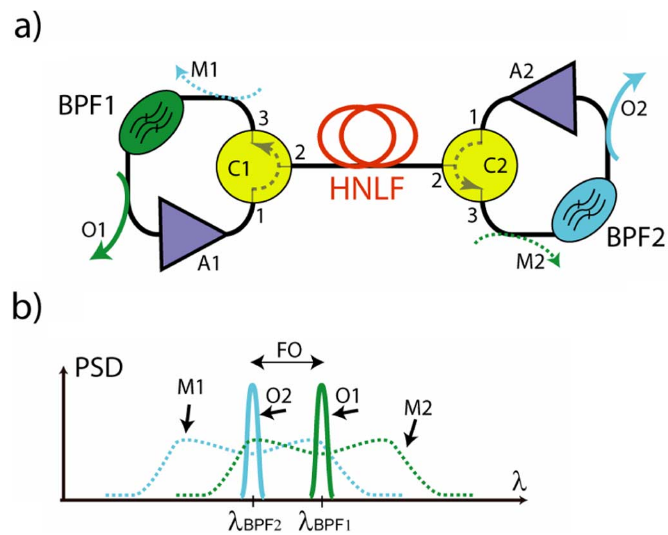

Fig. 1. (a) Experimental setup of the SP cavity and (b) schematics of spectra at various points of the setup to illustrate the operation principle of the pulsed source. O: signal output; M: monitor output; A: amplifier; C: circulator; PSD: power spectral density.

In this letter, we experimentally demonstrate the feasibility of self-pulsating action from paired regenerators in closed loop and distinguish among three operation regimes: continuous-wave (CW), self-pulsating (SP), and pulse-buffering (PB). In the SP operation, self-pulsation occurs spontaneously from the amplified spontaneous noise (ASE) of the amplifiers. In contrast, the PB regime does not allow pulses to ignite from ASE but can only support the oscillation of pulses that already circulate or that are being injected in the cavity. The SP regime could find applications where tunable and dual-wavelength pulsed lasers are currently required whereas the PB regime is particularly interesting for optical processing applications such as optical data buffering.

II. Experimental Setup

Fig. 1(a) shows the experimental setup of the pulsed source under investigation. The device is assembled out of the following components: a highly nonlinear fiber (HNLF), two low-power erbium-doped fiber amplifiers, two optical circulators, two optical bandpass filters (BPFs), and four tap couplers to extract the signal output (O) and for monitoring purposes (M). Specifications of the components are the following: HNLF length = 1007 m, HNLF chromatic dispersion $= -0.9$ ps/nm $\cdot$ km, HNLF nonlinearity coefficient $= 11.5$ $\mathrm{W}^{-1} \cdot \mathrm{km}^{-1}$, BPF 3-dB spectral width $= 0.39$ nm, amplifiers saturated output power $= 16$ dBm. Overall, the assembly consists of two cascaded regenerators with tunable output signal wavelengths. Fig. 1(b) schematically illustrates the operation principle of the source from an optical spectrum processing viewpoint: A pulse propagating in the HNLF (from C2 to C1) experiences SPM broadening (as observed from M1) before offset spectral filtering with BPF1. The regenerated pulse (as observed by O1) is then amplified by A1 and propagates through the HNLF (from C1 to C2) before passing through the second regeneration stage.

The experiments are performed as follows: Both central wavelengths of BPF1 (λ_{BPF1}) and BPF2 (λ_{BPF2}) are superimposed to enable CW laser operation. Then λ_{BPF1} is wavelength-shifted while λ_{BPF2} is unchanged. The spectra and autocorrelation traces are measured at the outputs and monitoring outputs for various values of λ_{BPF1}.

III. Results

Fig. 2(a) and (b) shows the spectra measured at monitoring output M2, which corresponds to the laser signal filtered by BPF1 followed by the HNLF. The central wavelength filter offset (FO) $= |\lambda_{\mathrm{BPF1}} - \lambda_{\mathrm{BPF2}}|$ etermines whether the source will operate in a CW or in a pulsed regime. A CW laser spectrum is observed for small values of the filter offset FO $= |\lambda_{\mathrm{BPF1}} - \lambda_{\mathrm{BPF2}}|$ 1.1 nm (Fig. 2(a), trace A). As BPF1 is tuned towards longer wavelength, the source spontaneously ceases the CW regime to oscillate in a pulsed regime as witnessed by the typical spectrum broadening of short pulses experiencing SPM (Fig. 2(a), traces B–D) and the manifestation of short pulses on the autocorrelator and the oscilloscope as shown in Fig. 3. This pulsating regime remains for 1.1 nm $<$ FO $<$ 8.8 nm without noticeable difference on the pulsewidth and can be sustained over indefinitely long periods of time. For FO $>$ 8.8 nm, the pulsed source ceases to oscillate and the output spectrum only contains ASE noise filtered by BPF1 (Fig. 2(b), trace E). Then, we note the following important feature of this device: reducing FO from a point of no oscillation at FO $>$ 8.8 nm down to FO $<$ 8.8 nm does not spontaneously lead to a pulsed signal until FO is small enough to trigger the first pulses to oscillate from ASE (Fig. 2(b), traces E-F). Such spontaneous ignition of the pulsed source does occur only for 1.1 nm $<$ FO $<$ 1.3 nm (Fig. 2(b), trace G). This observation leads to the conclusion that no new pulses are being formed from ASE in the range of 1.3 nm $<$ FO $<$ 8.8 nm and only existing pulses (and potentially externally injected pulses) can be sustained in the cavity.

Fig. 2(c) shows spectra taken from the monitoring output M1, that is, the pulsed signal filtered by BPF2 followed by A2 and the HNLF. Although the central frequency of BPF2 is fixed (whereas BPF1 is tuned), the spectrum broadens gradually as a result of increasing FO so as to ensure a good overlap with BPF1 (Fig. 2(c), traces A-D). The pulsed source emits two distinct wavelengths (λ_{BPF1} and λ_{BPF2}) available from independent outputs O1 and O2. In addition, the pulsed source can be operated at any arbitrary central wavelength over the gain band

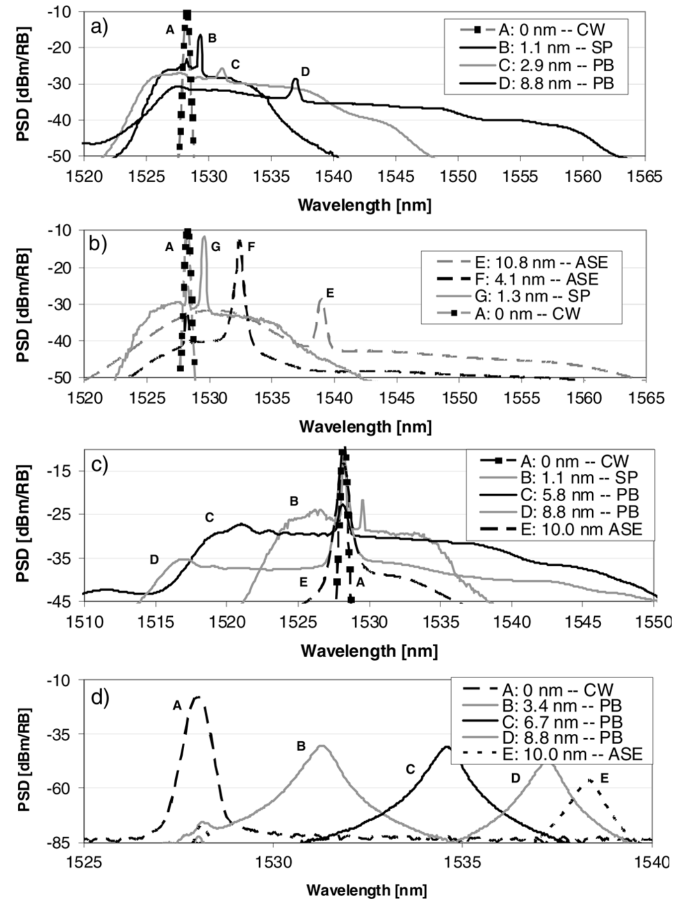

Fig. 2. Experimental results showing SP operation over a broad and continuous range of the filter offset parameter FO. In (a), spectra taken from the monitor output M2. λ_{BPF1} is tuned from 1528.3–1536.1 nm while λ_{BPF2} is maintained at 1528.3 nm. The source emits a CW signal when FO $= 0$ nm and self-pulsates when 1.1 nm $<$ FO $<$ 8.8 nm. In (b), λ_{BPF1} is tuned downwards from 1539.1–1528.3 nm while λ_{BPF2} is kept at 1528.3 nm. Only amplified spontaneous emission is observed until self-pulsation occurs when reaching FO $<$ 1.3 nm and CW oscillation occurs when reaching FO $<$ 1.1 nm. In (c), spectra taken from the monitor output M1, λ_{BPF1} is tuned from 1528.3–1539.3 nm while λ_{BPF2} is kept at 1528.3 nm. In (d) spectra taken from output O1. All spectra vertical axes represent power spectral density (PSD) in units of decibel milliwatts per unit of resolution bandwidth (RB $= 0.08$ nm) of the spectrum analyzer.

of the amplifier as long as FO enables a pulsating regime. The output spectra after BPF1 for different values of FO are given in Fig. 2(d). The eigenpulse width and spectra are determined from the filter profile and remain unchanged for different FO. This is also confirmed from pulse measurements on the autocorrelator.

Fig. 3 shows pulse profiles measured using an autocorrelator and an optical sampling module with 16-ps impulse response time connected to an oscilloscope. The oscilloscope is triggered from an electrical signal generated by a separate high bandwidth photodiode used to detect the output pulses. The pulsewidth extracted from the autocorrelator and retrieved from simulations is 5.6 ps. The oscilloscope shows the manifestation of pulses propagating with random relative delays. This can be expected from pulses generated from ASE. The round-trip time in the cavity is 10 μs as calculated from the $\approx$2-km fiber propagation length and from the observation of 100-kHz beating tones in the radio-frequency spectrum.

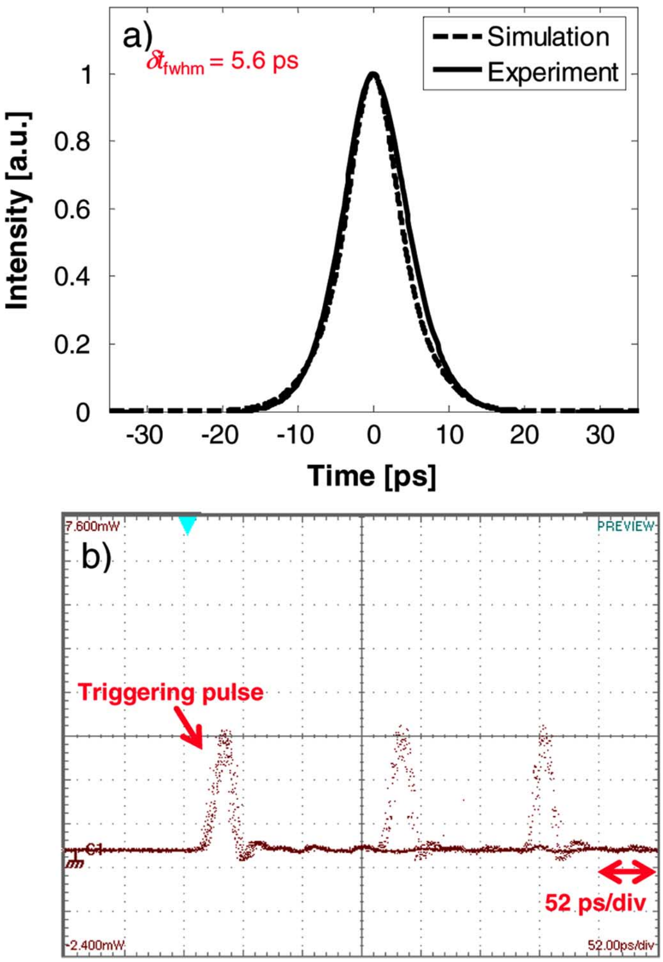

Fig. 3. Pulse profiles from (a) an autocorrelator and simulated autocorrelation and (b) from an oscilloscope. The autocorrelation provides a retrieved pulsewidth of 5.6 ps. The oscilloscope shows multiple pulse profiles. The first pulse on the left corresponds to the one that triggers the oscilloscope acquisition process.

IV. Discussion and Conclusion

The SP source operates in three regimes. The first regime is characterized by a wavelength offset of FO < 1.1 nm and produces a CW output. The second regime enable spontaneous ignition in an SP regime and occurs with 1.1 nm $<$ FO $<$ 1.3 nm. Pulses formed in this regime are eigenpulses that have a pulsewidth directly related to the spectral width of the BPFs. The PB regime is a third operation regime characterized by a wavelength offset comprised within 1.3 nm $<$ FO $<$ 8.8 nm and enables only the circulation of existing eigenpulses and potentially externally injected pulses in the cavity. When FO $>$ 1.1 nm, a pulsed regime dominates over a CW regime because a pulsed signal experiences less losses per cavity round-trip than a CW signal. The pulsed regime induces SPM spectral broadening in the HNLF that allows the signal to pass through the passband filters with an overall transmission loss lower than for any fixed wavelength in the cavity, which is the equivalent loss for the CW regime.

Another interesting mechanism involved in the PB regime is the following: an increase of FO from the SP regime is associated with spectrum broadening as can be seen in Fig. 2(a) and (b). This spectrum broadening ensures that pulses spectrally overlap passband filters and get through each round-trip without experiencing excessive losses. The spectrum broadening does not comes for free though. For constant pulse-shape, spectrum broadening requires that each amplified pulse is being provided with a peak power increase proportional to the induced chirp $\delta\omega$, that is $\delta\omega = -\gamma L_{\mathrm{Eff}} dP/dt$, where γ is the nonlinear fiber coefficient, L_{Eff} is the effective fiber length, P is the pulse power profile, and t is time [6]. Therefore, it is expected that the peak power of pulses after amplification must increase in order to get additional spectral broadening, as observed with increased FO. The amplifiers are providing a constant amount of power in the loop and for pulses to increase in peak power without changing profile involves that the number of pulses sustained in the loop is reduced as a consequence of increased FO. This was verified experimentally by first increasing FO in the PB regime without reaching the limit of FO > 8.8 nm. The spectrum then broadens as a result of an increase of FO. From this point, a reduction of FO did not modify the spectrum width until reaching the limits of the SP regime at FO $<$ 1.3 nm. This demonstrates that the spectral broadening is a good indication of the number of pulses oscillating in the cavity. Simulations to reproduce the spectral broadening of eigenpulses have led to the conclusion that up to 4500 pulses could be stored in the current cavity in the PB regime, with a decreasing pulse capacity as FO is increased. We believe that the PB operation regime can find applications for signal buffering, where pulses injected in the paired regenerators will oscillate indefinitely until a reset action is taken. Simulations show that the eigenpulses that oscillate in the cavity maintain their relative distance and keep a stable profile due to the operation of the regenerators. This dual-wavelength and continuously tunable pulsed source could also find applications as a mode-locked laser. The number of simultaneously pulsating wavelengths could be easily increased by increasing the number of regenerators in cascade.

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