Generation of Self-Pulsating source based on Regenerative SPM and Realizing High-quality Pulse source

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ABSTRACT
We analyze the operation of the self pulsating source based on the cascaded effects of soliton self frequency shift and SPM. The CW super continuum signal is generated based on erbium gain inside the cavity and single mode propagation of a strong Raman pump laser source through a highly nonlinear fiber. The generation occurs due to the nonlinear effects such as modulation instability and stimulated Raman scattering in HNLF. At one of the output that laser emits a supercontinuum extending beyond 1900 nm. Optical pulse compression stage is involved in this paper for realizing the remarkable high quality pulse source. Soliton is compressed using the single mode fiber (SMF) and dispersion shifted fiber (DSF). CDPF is made of two optical fibers in cascade, namely a first fiber of the single mode fiber (SMF) as high dispersion segments, followed by a second fiber of the type dispersion shifted fiber (DSF) as low-dispersion segments. This allows multiple channels to be placed on a single frequency where each channel can later be extracted for detection using a high-speed switch. Cascaded effects and compression stages are designed and evaluated in this proposed paper.

KEYWORDS: Modulation instability, nonlinear optics, optical pulse regeneration, self-phase modulation, Self-pulsating source, soliton self-frequency shifting.

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. To generate pulses, a nonlinear transfer function favoring pulses over continuous wave (CW) operation must be added in the laser cavity.

We have presented a self-pulsating laser source based on cascaded optical regeneration working at a wavelength of 1550 nm [2,3]. 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 [4]. Pulsed lasers based on a pair of complementary regenerators of type self-phase modulation (SPM) and offset filtering (SPM-OF) regenerators was demonstrated [5].

Sources of that kind, referred to as SPM-soliton self-frequency shift (SPM-SSFS) sources, are composed of two distinct regeneration stages. 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 \[6\], \[7\] or noise-like pulses \[8\]. 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. Results provide the optimal filter bandwidth that maximizes the output SC bandwidth as well as the total output power.

**Theoretical Basis:**
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). 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 filter offset is defined as \(\Delta\lambda = |\lambda_1 - \lambda_2|\). The 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.

![Fig. 1: Self-pulsating source based on cascaded regeneration.](image)

<table>
<thead>
<tr>
<th>Highly Nonlinear Fiber (HNLF)</th>
<th></th>
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<tbody>
<tr>
<td>(\tau)</td>
<td>12.5 w (^{-1}) km (^{-1})</td>
</tr>
<tr>
<td>(D_1)</td>
<td>-0.71 ps/(nm.km)</td>
</tr>
<tr>
<td>(D_2)</td>
<td>2.09 ps/(nm.km)</td>
</tr>
<tr>
<td>(S_1)</td>
<td>0.0074 ps/(nm(^2).km)</td>
</tr>
<tr>
<td>(S_2)</td>
<td>0.002 ps/(nm(^2).km)</td>
</tr>
<tr>
<td>(\Lambda_{seff})</td>
<td>6.3933 µm</td>
</tr>
</tbody>
</table>

**Insertion losses:**
- BPF\(_1\): 8 dBm
- BPF\(_2\): 5.5 dBm
- EDFA \(P_{sat}\): 15 dBm

Pulses propagating in HNLF\(_1\) at \(\lambda_2\) undergo spectral broadening by the conjugated effects of SPM and dispersion. After filtering at BPF\(_1\) and reamplification a similar spectral broadening is experienced by pulses in HNLF\(_2\), and finally BPF\(_2\) reestablished \(\lambda_2\) as the central wavelength for the next cavity round-trip. Dispersive waves are also emitted as a result of these interactions, and the observed spectrum is similar to spectra arising from supercontinuum seeded by pico second pulses.

\[ \gamma = 2\pi n_2 / (\Lambda A_{eff}) \]

Solitons resulting of the propagation in HNLF\(_2\) experience a significant amount of SPM when propagating in HNLF\(_1\). 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.

**Effect Of The Filter Bandwidths:**
The output properties of SPM-SSFS sources were studied in \[5\] 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. At one limiting case, BPF\(_1\) is a low-pass filter, and BPF\(_2\) is a high-pass filter. Self-pulsation occurs for a fixed EDFA pump power, by reducing the spectral separation between the BPFs, by red-shifting BPF\(_2\). For a BPF\(_2\) bandwidth of 3.5 nm, the continuum generated at the coupler is maximized, and reaches wavelengths past 1900 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.
In such a situation, the pulses filtered at BPF2 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 non optimal for SC generation. BPF2 is first shifted towards the longer wavelengths to trigger self-pulsation, and the output power at the coupler is recorded at that moment.

Then, BPF2 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 the coupler shows insignificant changing when altering the filters bandwidth. Optimal filter bandwidths maximize the source efficiency by blocking the spectral content which does not contribute to the pulses.

**Noise Bins:**
Noise bins represent the noise by the average spectral density in two polarizations using a coarse spectral resolution. The main advantage of using noise bins is to cover the wide spectrum of the optical signals or to represent the noise outside the sample signal bandwidths.

**Pulse Compression Stage:**
In this paper, a remarkable pulse compression is realized through utilizing soliton pulse. Fig. 2 represents the general block diagram of pulse compression stage. The comb-like dispersion profile fiber (CDPF) structure is used by SMF and DSF. In this work, and after an optimization, around 30 dBm launch into ten parts are chosen of alternately arranged 140 m SMF segments with a GVD value of $D=17$ ps/nm/km at 1550 nm as high-dispersion segments with a 140 m DSF segments with negligible low dispersion have zero dispersion at 1547 nm as low-dispersion segments with total length 1.4 km. Pulses in the CDPF are influenced alternatively by nonlinear effect and group velocity dispersion (GVD) effect in space and adiabatic optical soliton transmission can be maintained and evolved in anomalous dispersion region.

![CDPF diagram](image)

**Fig. 2:** Pulse compression stage and structure of CDPF

$$CR = \frac{FWHM_{output pulse}}{FWHM_{input pulse}} \times 100$$

**Results:**
**Supercontinuum generation:**
An optimal filter bandwidth leads to a broad SC extending beyond 1900 nm. A BPF2 bandwidth of 3.5 nm, the continuum generated at Coupler is maximized, and reaches wavelengths past 1900 nm. For larger and smaller bandwidths, less energy is transferred towards the long wavelengths. Hence, there exist an optimal spectral bandwidth of BPF2 for which the captured spectral power density contributes optimally to sustain the existing pulses in the cavity.

![Optical Spectrum Analyzer](image)

**Fig.3:** Generation of Supercontinuum
Fig. 4: Sampled signal spectrum

Table 1: Output Powers For Various BPF

<table>
<thead>
<tr>
<th>BPF: B/W in nm</th>
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<th>OUTPUT POWER Max in dB</th>
<th>OUTPUT POWER Min in dB</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>5</td>
<td>-40.9815</td>
<td>-102.81</td>
</tr>
<tr>
<td>0.2</td>
<td>1.5</td>
<td>-47.7304</td>
<td>-102.48</td>
</tr>
<tr>
<td>2.5</td>
<td>3.5</td>
<td>-42.4711</td>
<td>-102.73</td>
</tr>
<tr>
<td>4.0</td>
<td>6.0</td>
<td>-40.4233</td>
<td>-102.83</td>
</tr>
<tr>
<td>7.0</td>
<td>12.0</td>
<td>-41.7679</td>
<td>-102.77</td>
</tr>
</tbody>
</table>

Pulse Compression:

Fig. 5: Input optical pulse

Fig. 5: Pulse compression
A remarkable performance is achieved having a low pulse CR (8%).

\[ \text{CR} = \frac{0.9}{10.6} \times 100\% = 8\% \]

**Fig.6:** Pulse compression in 3D view

**Conclusion:**

The operation of self-pulsating sources based on SPM regenerators as well as SSFS followed by offset filtering is characterized temporally and spectrally. An optimal filter bandwidth leads to a broad SC which extends past 1900 nm, and potentially the HNLF pumped closer to the zero dispersion wavelength. All-optical pulse compression and reshaping are key stages for realizing a remarkable high-quality pulse source. Several techniques were proposed to realize effective pulse compression stage. Among all, recently a soliton based pulse compression stage and a self-phase modulation (SPM) based pulse reshaping stage become an optimum choice. This work presents a simple design for a soliton based pulse compression stage. A remarkable performance is achieved having a low pulse CR (8%). This design is a suitable candidate for realizing a remarkable pulse source for OTDM applications. Using soliton based compression, a very small pulse width can be produced but with pedestal which can be removed by an SPM based reshaping stage in future.

**REFERENCES**