Programmable Tunable Coherent Supercontinuum Sources via Electro-optic Optical Frequency Combs

Minje Song[1], Hyunjong Choi, Youngjin Jung, Taehyun Lee, Gyudong Choi, Joon Tae Ahn, and Minhyup Song[*]

Photonic/wireless devices research division, ETRI, South Korea
mjsong@etri.re.kr[1], sminhyup@etri.re.kr*

Abstract *In this study, we present flexible flat-top coherent supercontinuum sources via electro-optic optical frequency comb and iterative line-by-line amplitude/phase shaping techniques. We demonstrate programmability and tunability in terms of repetition rate, bandwidth, and spectral range while maintaining stable spectral characteristics.*

Introduction

Supercontinuum (SC) generation based on electro-optic optical frequency comb (EO-OFC) is a powerful approach for generating programmable, tunable coherent wideband laser sources and ultra-short pulses [1]. Notably, in comparison to other SC generation methods, SC sources based on EO-OFC provide easy and fine tuning of line spacing and center wavelength [1-3]. Furthermore, the SC sources show remarkable spectral stability and robustness after programming and tuning in a flexible manner, and no additional active stabilization devices are necessary to maintain the stability [4-6]. These characteristics are highly desirable in applications requiring system flexibility such as microwave photonic signal processing and coherent optical communications [7].

The SC source based on EO-OFC is generated by spectrum broadening via self-phase modulation [4], and limited spectral bandwidth compared to other methods. The bandwidth and shape of the SC spectrum depend on the periodic pulse shape and power delivered to the highly nonlinear stage, leading to the development of various feedback pulse shaping methods to enhance spectrum properties such as the spectral bandwidth and the flatness [1, 8].

In this paper, we demonstrate a tunable and programmable coherent SC source based on EO-OFC with highly nonlinear stages. By applying the iterative line-by-line pulse shaping technique [1], we improve the flatness and bandwidth of SC sources. It enables precise and rapid spectrum apodization even during rapid repetition rate tuning. Additionally, we achieve spectral bandwidth programmability by managing pulse power at the entrance of the highly nonlinear stage using a high-power optical amplifier. We implemented a SC source with programmable repetition rates and spectral bandwidths up to 50 GHz and 92.5 nm at 20 dB, respectively. Moreover, we confirmed the frequency stability of the programmable and tunable SC sources through phase noise measurements.

Results

The EO-OFC offers the benefits of tunability in terms of center wavelength and repetition rate of the spectrum. Fig. 1 presents the schematic configuration of the EO-OFC, where a continuous wave laser output passes through the cascaded one intensity and three phase modulators. The modulators are driven by an RF signal generator that generates a single RF frequency tone between 250 kHz and 50 GHz. The RF frequency control enables the repetition rate of the OFC to be programmable. To efficiently broaden the spectrum in a highly nonlinear stage, a single-mode fiber (SMF) spool is employed to compress the pulse to its bandwidth limited duration by compensating for the dispersion in the EO-OFC stage. The dispersion compensation was demonstrated by monitoring the pulse width using an autocorrelator while adjusting the length of the SMF. To further enlarge the spectral bandwidth of EO-OFC, we applied a first highly nonlinear fiber (HNLF) stage, as shown in Fig. 2.

For SC generation, the pulse profile entering the highly nonlinear stage significantly decides

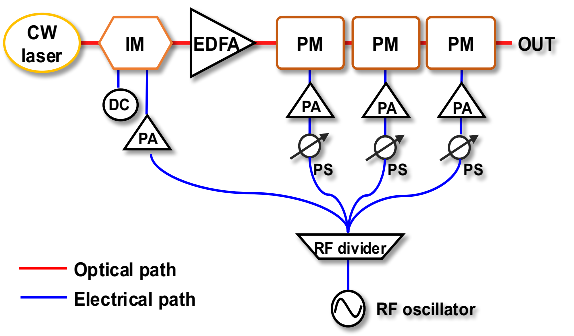

Fig. 1: Schematic configuration of EO-OFC generation. CW; continuous wave, EDFA; erbium doped fiber amplifier, IM; intensity modulator, PA; RF power amplifier, PM; phase modulator, PS; phase shifter.

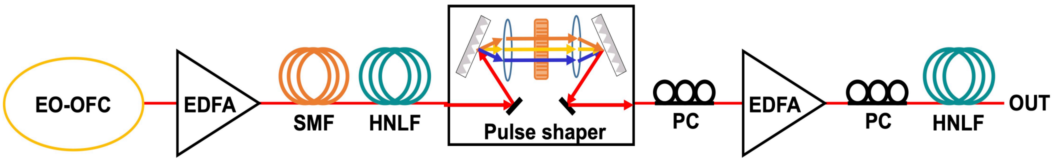

Fig. 2: Schematic diagram of the experimental setup for the programmable supercontinuum generator. HNLF: highly nonlinear fiber; PC: polarization controller. SMF: single-mode fiber;

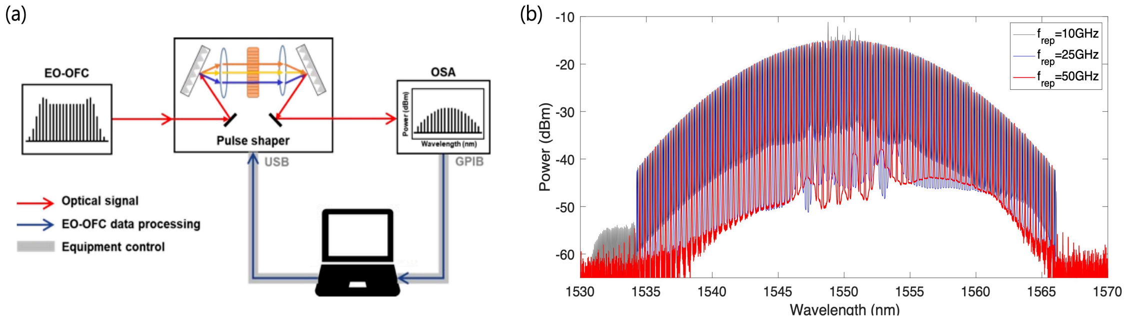

Fig. 3: Programmable pulse shaping (a) scheme, (b) gaussian apodized spectrum at repetition rates of 10, 25, and 50 GHz.

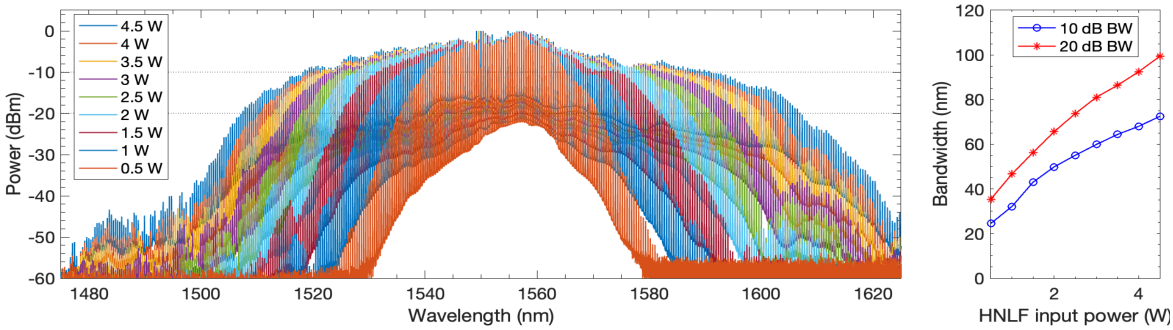

Fig. 4: Experimentally measured bandwidth programmable supercontinuum (a) spectrum, (b) 10 dB and 20 dB bandwidth according for HNLF input power.

the spectrum bandwidth and shape of SC sources. Self-phase modulation-induced spectral broadening with specific pulse shapes, such as periodic Gaussian pulses, has been reported to produce flat-top SC [1]. In this study, we generate these Gaussian pulses through pulse shaping based on the Fourier transform theorem [1].

As can be seen in Fig. 3(a), we constructed an iterative line-by-line spectrum shaping system suited for programmable SC sources. With a line-by-line optical pulse shaper, the EO-OFC is carved into a Gaussian shape with high accuracy. In order to minimize amplitude errors in each EO-OFC line, we iteratively control the spectrum intensity using a MATLAB program while monitoring the spectrum shape in real-time through an optical spectrum analyzer. Even during the repetition rate tuning of the SC sources, the attenuation levels of each EO-OFC tap can be recalculated to maintain the desired shape. To demonstrate the capability of the iterative pulse shaping technique with tunable repetition rates, we applied the same apodization to EO-OFCs with various repetition rates without making structural changes to our pulse shaping system. Fig. 3(b) illustrates the apodized EO-OFCs for 10, 25, and 50 GHz repetition rates while preserving the same Gaussian profile through the iterative pulse shaping process.

In order to maximize spectrum broadening in a second nonlinear medium, the periodic pulses into the highly nonlinear medium should be quasi-zero dispersion. We leveraged the pulse shaper's capability to control amplitude and phase simultaneously. The pulse shaper applied a spectral quadratic phase to the combs for fine dispersion compensation [1]. The dispersion and power of the input pulse were managed to exhibit maximum spectral bandwidth and flatness at the output.

Furthermore, we demonstrated the programmable control over the spectral bandwidth of SC sources by adjusting the optical power applied to the HNLF. We regulated the optical power applied to the HNLF by controlling the high-power amplifier in the second nonlinear stage in Fig. 2. Fig. 4 displays the SC spectrum with programmable bandwidth while varying the

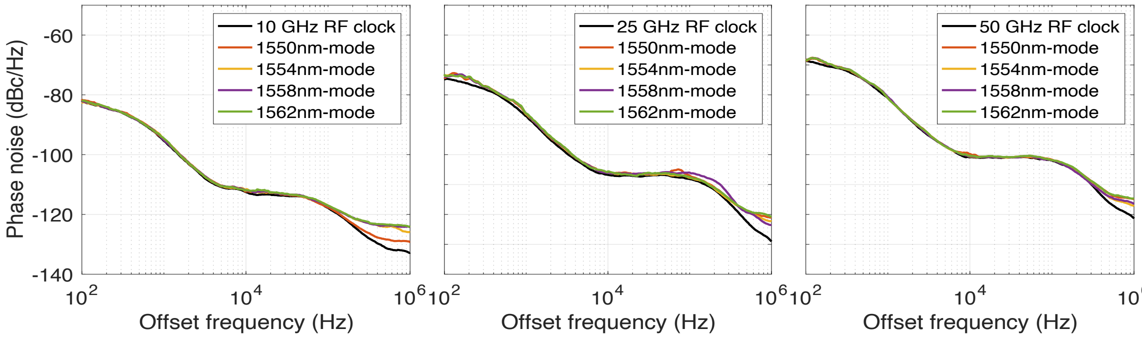

Fig. 5: Experimentally measured phase noise of supercontinuum at repetition rates of 10, 25, and 50 GHz.

optical input power from 0.5 W to 4.5 W. The measured spectrum shows a 10dB bandwidth of 72.5 nm and a 20 dB bandwidth of 99.39 nm with an optical input power of 4.5 W to the HNLF.

We also implemented phase noise measurements to demonstrate the coherence of our SC source. Fig. 5 presents the phase noise of the 10, 25, and 50 GHz SC sources. The phase noise was measured through a modified self-heterodyne method illustrated in Fig. 6, where the components of the SC source are converted to the RF domain by a 50 GHz photodiode after being mixed together. As shown in Fig. 5, the single-sideband phase noises of the noise spectrum at a 10 kHz offset frequency are -111.69 dBc/Hz, -105.59 dBc/Hz, and -99.86 dBc/Hz for the repetition rates of SC are 10 GHz, 25 GHz, and 50 GHz. We experimentally show that the phase noise of the SC is extremely close to the RF signal generator. It indicates that the SC generation processes do not substantially degrade the phase noise characteristics.

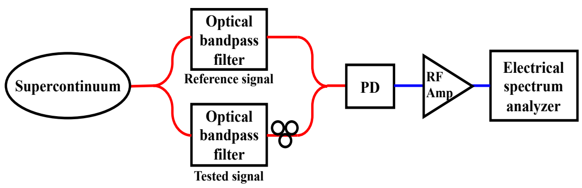

Fig. 6: Schematic configuration of modified self-heterodyne.

Conclusions

In summary, we implemented tunable and programmable flat-top SC sources based on EO-OFCs. The flatness and bandwidth of the SC spectrum enable to be improved through iterative line-by-line amplitude and phase shaping. Furthermore, by controlling the optical power input to the nonlinear medium, we achieved programmable bandwidth and repetition rates up to 99.39 nm at 20 dB and 50 GHz, respectively. Our SC source also offers tunable and programmable characteristics to the repetition rate, center wavelength, and bandwidth while maintaining spectral frequency stability. The remarkable flexibility of our SC source is expected to show strong applicability to various areas such as microwave photonics and optical communications.

Acknowledgements

This work was supported by the Institute for Information and Communication Technology Promotion (IITP) grant funded by the Ministry of Science and ICT, South Korea (2019-0-00008).

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