

Multiwavelength coherent optical carrier generation based on resonant electro-optic frequency combs for DWDM applications

Marlon M. Correia, Leandro M. Fernandes, Tomas P. V. Andrade and Flávio C. Cruz

Abstract— We demonstrate a 20 GHz single mode fiber-integrated broadband resonant electro-optic frequency comb generated from an acetylene-stabilized continuous-wave laser at 1542.384 nm. The optical spectrum spans the S, C, and L optical communication bands through nonlinear spectral broadening in highly nonlinear fibers. Measurements in the optical and radio-frequency domains confirm low-noise comb operation. The repetition-rate phase noise was -90 dBc/Hz at a 10 kHz frequency offset, while heterodyne measurements yielded a comb-tooth linewidth of 3.6 kHz, indicating that high spectral coherence is maintained throughout the supercontinuum generation process. This work experimentally investigates the impact of nonlinear spectral broadening on the phase-noise behavior and spectral coherence of resonant electro-optic frequency combs and highlights their potential for dense wavelength division multiplexing, high-speed optical communication systems, and quantum key distribution.

Keywords— Frequency-comb, Electro-Optic, Spectral-broadening, Phase-noise, Supercontinuum, dense-wavelength-division-multiplexing.

I. INTRODUCTION

Optical frequency combs (OFCs) have emerged as key optical sources for modern photonic systems due to their ability to generate a large number of phase-locked optical carriers with precise frequency spacing [1]. In particular, GHz repetition-rate combs enable direct integration with microwave and optical communication technologies, supporting applications such as radio-frequency (RF) photonics and arbitrary waveform generation [2], optical signal processing [3], high-speed optical communications [4] and quantum key distribution [5].

Several technological platforms have been proposed for generating optical frequency combs with GHz repetition rates. Traditional mode-locked lasers can provide ultra-short pulses and broadband spectra, but achieving repetition rates from several to tens of GHz remains challenging due to cavity design constraints [6]. In contrast, electro-optic (EO) comb generators, based on the phase and/or intensity modulation of a continuous-wave (CW) laser, offer precise control of the comb spacing together with high stability and repetition-rate tunability [7]. Among these approaches, resonant electro-optic comb generators (REOCGs) [8] combine the flexibility of EO modulation with the efficiency of resonant cavity enhancement. In this architecture, a CW laser is injected into a Fabry-Pérot resonator driven at microwave frequencies corresponding to integer multiples of the cavity free-spectral-range (FSR). This resonant operation enables efficient comb generation with reduced RF drive power while also mitigating the transfer of microwave phase noise to the generated comb lines, resulting

in highly coherent and spectrally stable optical frequency combs [9].

In this work, we demonstrate a 20 GHz fiber-integrated broadband resonant electro-optical comb generator driven by an acetylene-stabilized continuous-wave laser at 1542.384 nm and fully implemented with commercial components. High-repetition-rate 107 fs pulse trains are generated through dispersion-engineered fiber stages. Using both numerical simulations and experiments, we optimize the nonlinear-dispersive dynamics leading to efficient and coherent spectral broadening that spans the S, C, and L optical communication bands. The phase-noise performance of the resonant electro-optic frequency comb under nonlinear spectral broadening is experimentally investigated. The phase-noise analysis confirms that REOCGs can provide broadband, low phase-noise, and highly coherent frequency combs suitable for dense wavelength division multiplexing (DWDM) and high-speed data transmission in optical communications.

II. EXPERIMENTAL SETUP

The schematic diagram of the experimental setup is shown in Figure 1. We have used a commercial resonant electro-optical modulator (RES-EOM) [WR-250-03, OptoComb], comprising an integrated Fabry-Perot resonator with Finesse and free-spectral range (FSR) of 56.6 and 2.5 GHz, respectively. The device can be driven at multiples of the FSR, although with higher modulation efficiencies (> 3 rad/V) between 20-30 GHz ranges. The RES-EOM is temperature stabilized within 1 mK and excited by a single-frequency acetylene-stabilized laser source at 1542.384 nm (Stabilaser 1542ε, DFM). The laser has a short-term linewidth of 300 Hz and a specified long-term frequency drift of $\leq 2 \times 10^{-12}$ /year relative to its nominal frequency. The RES-EOM exhibits an optical transmission loss of 8.2 dB, which is compensated by a homemade erbium-doped fiber amplifier (EDFA) based on 1.3 m of highly doped erbium fiber. The amplifier provides an output power of 100 mW. The RES-EOM is driven by a 20 GHz RF signal generated by an amplified synthesizer (EXG N5173B, Keysight) referenced to a GPS-disciplined 10 MHz rubidium frequency standard, ensuring long-term stability and accurate locking of the comb repetition rate. We were also limited in frequency spacing (20-GHz) and microwave power (300 mW) by our available RF amplifier (8349B, HP). The RES-EOM can be driven with up to 1W of microwave power. The RES-EOM produces a symmetric comb with 2.0 nm BW (@3dB) in which the modes on the right and left of the input laser frequency have spectral phases with different slopes creating two interleaved pulse trains that effectively doubles the repetition rate to 40-GHz when the laser is in resonance with the Fabry-Perot cavity [8]. To recover a single 20 GHz

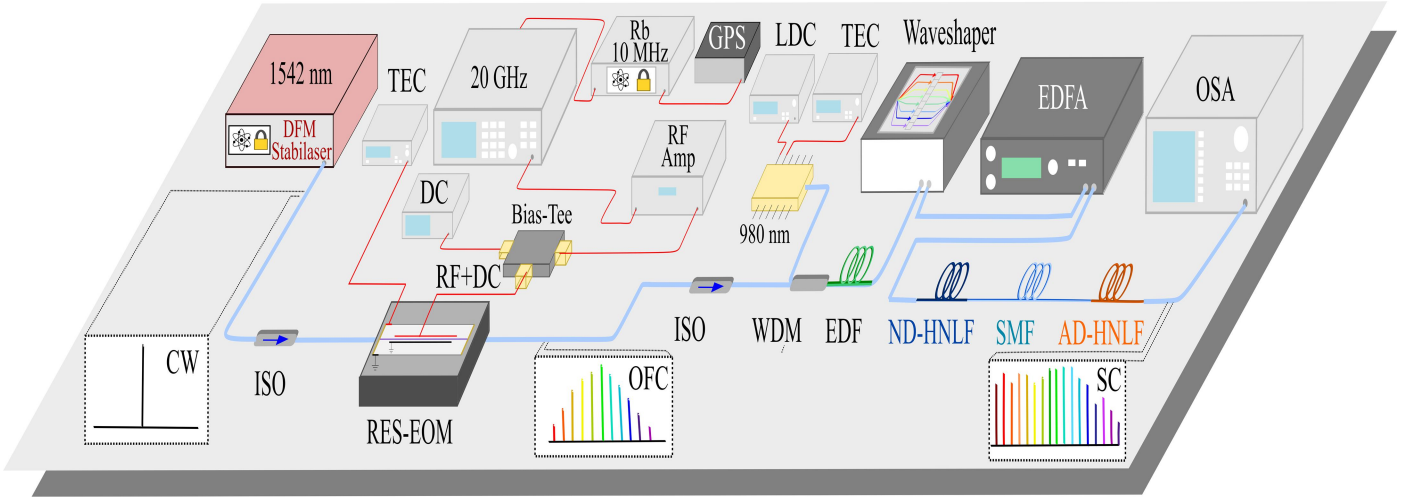


Fig. 1. Schematic diagram of the experimental setup for the 20-GHz fiber-integrated broadband resonant electro-optic frequency comb. 1542 nm: Acetylene-Stabilized Continuous Wave Laser, CW: Continuous Wave, ISO: Fiber Optical Isolator; RES-EOM: Resonant Electro-Optic Modulator, OFC: Optical Frequency Comb, GPS: Global Position System, Rb 10 MHz: 10 MHz Rubidium Frequency Standard, 20 GHz: 20 GHz Radio-Frequency Synthesizer; TEC: Temperature Controller, LDC: Laser Diode Controller, 980 nm: 980 nm Pump Laser, WDM: Wavelength Division Multiplexer, EDF: Erbium Doped Fiber, Wave-Shaper: Programmable Optical Filter, EDFA: Erbium Doped Fiber Amplifier; ND-HNLF: Normal-Dispersion Highly Nonlinear Fiber, SMF-28: Single Mode Fiber-28, AD-HNLF: Anomalous-Dispersion Highly Nonlinear Fiber; SC: Supercontinuum, OSA: Optical Spectrum Analyzer.

pulse train, the spectral phase of the comb was adjusted using a programmable optical filter (Wave-Shaper 1000A, Coherent), which introduced an optical delay of 25 ps to one side of the spectrum. This phase correction temporally realigned the interleaved sub-trains, yielding a uniform 20-GHz pulse sequence at the programmable optical filter output. The second EDFA (CEFA-C-PB-HP-PM, Keopsys) amplifies the pulse train to an average power of 2.5 W. The amplified output is then used for conventional pulse compression and spectral broadening based on dispersion management. The process employs a sequence of highly nonlinear single-mode fibers (HNLFs), as described in the next section. Finally, the optical spectra are measured at different stages of the system using an optical spectrum analyzer (OSA, AQ6374E, Yokogawa).

III. RESULTS AND DISCUSSION

To increase the optical bandwidth generated by the RES-EOM, we implemented a conventional pulse compression and spectral broadening scheme based on nonlinear propagation and dispersion management using a sequence of HNLFs, as illustrated in Figure 1. The pulse compression stage consists of a 56 m-long normal-dispersion highly nonlinear fiber (ND-HNLF, nonlinear coefficient $\gamma = 8.5 \text{ (W}\cdot\text{km)}^{-1}$, dispersion parameter $D = -1.28 \text{ ps/(nm}\cdot\text{km)}$, zero-dispersion wavelength $ZDW = 1566 \text{ nm}$), which generated spectral broadening through self-phase modulation (SPM), followed by pulse compression in a 10 m-long anomalous-dispersion (AD) fiber (SMF-28, $\gamma = 1.2 \text{ (W}\cdot\text{km)}^{-1}$, $D = +17 \text{ ps/(nm}\cdot\text{km)}$, $ZDW = 1310 \text{ nm}$). The lengths of both fiber stages were optimized through numerical simulations using publicly available codes from GitHub [10] in order to obtain the shortest achievable pulses at the system output. The corresponding experimental and numerical results are presented in Figure 2.

First, the optical spectrum generated from the RES-EOM output is presented in Figure 2(a). The spectrum exhibits a double-sided exponentially decaying profile, with a full width at half maximum (FWHM) bandwidth of approximately 2 nm. To characterize the temporal properties of the generated comb,

the pulse duration at the output of the second EDFA was measured using a homemade intensity autocorrelator. The corresponding autocorrelation trace is shown in Figure 2(b). The measured autocorrelation width is 1.8 ps, corresponding to an optical pulse duration of approximately 1.2 ps assuming a sech^2 temporal profile. At the output of the second EDFA, the pulses exhibit an energy of 125 pJ and a peak power of approximately 104 W. Following amplification, the optical pulses were launched into the ND-HNLF stage to induce nonlinear spectral broadening. Due to the combined action of self-phase modulation and normal dispersion, the pulses

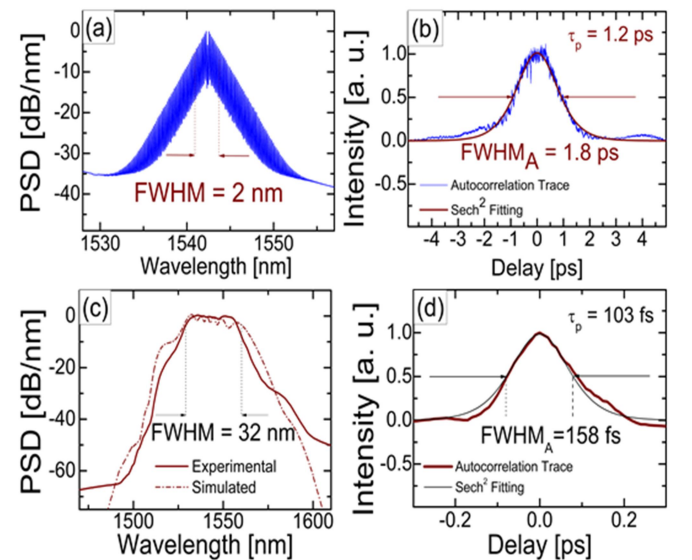


Fig. 2. Experimental and numerical simulation results of pulse compression in highly nonlinear fibers. (a) Optical spectrum at the RES-EOM output with 2 nm FWHM bandwidth. (b) Autocorrelation trace measured at the second EDFA output, corresponding to pulse duration of approximately 1.2 ps assuming a sech^2 profile. (c) Optical spectrum with 32 nm FWHM (wine solid line) at the output nonlinear broadening and pulse compression stage, showing good agreement with the numerical simulation (wine dashed line). (d) Autocorrelation trace of the compressed pulses, corresponding to pulse duration of approximately 103 fs assuming a sech^2 profile.

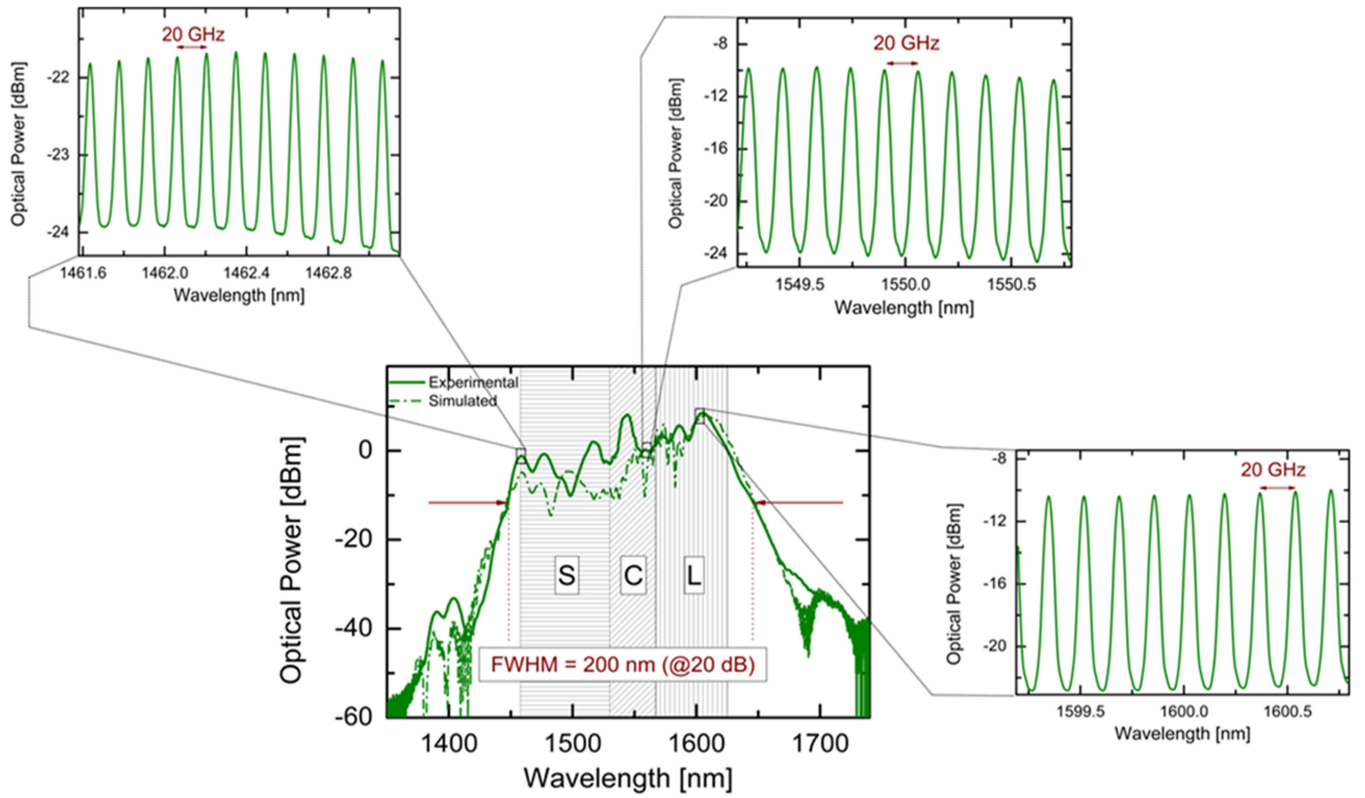


Fig. 3. Generated supercontinuum spectrum after the final anomalous-dispersion HNLF stage (ND-HNLF+SMF28+AD-HNLF). The spectrum spans approximately 200 nm (25.3 THz measured 20 dB below the peak level), covering the S, C, and L optical communication bands. The numerical simulation (green dashed line) shows good agreement with the experimental data. Insets show zoomed views of the S, C, and L optical communication bands, confirming the preservation of the frequency comb coherence across the broadened spectrum.

acquire a nearly linear positive frequency chirp while their optical spectrum broadens significantly (see Figure 2(c)). Pulse compression was achieved by propagation through the anomalous-dispersion (AD) SMF-28 fiber, which compensates the accumulated positive frequency chirp (normal dispersion) generated in the nonlinear stage. The resulting spectra after the temporal compression stage are presented in Figure 2(c), showing good agreement between the experimental data (wine solid line) and numerical simulations (wine dashed line). The optical spectrum exhibits a FWHM bandwidth of approximately 32 nm, corresponding to a substantial spectral broadening compared with the original RES-EOM output (FWHM = 2 nm). The temporal characteristics of the compressed pulses are presented in Figure 2(d), where the measured autocorrelation trace after the dispersion compensation stage is shown. The autocorrelation trace exhibits a FWHM of 158 fs, corresponding to a pulse duration of approximately 103 fs, assuming a $sech^2$ temporal profile. Therefore, the proposed nonlinear compression scheme achieved a pulse compression factor greater than 10 compared with the original 1.2 ps pulses generated at the EDFA output. At the output of the compressor stage (ND-HNLF+SMF28), the pulses exhibit an energy of 85 pJ and a peak power of approximately 825 W, demonstrating efficient nonlinear pulse compression while maintaining high peak power levels suitable for subsequent supercontinuum generation stages.

The final spectral broadening stage was implemented using an 9 m-long anomalous-dispersion highly nonlinear fiber (AD-HNLF, $\gamma = 9.3 \text{ (W}\cdot\text{km)}^{-1}$, $D = 0.51 \text{ ps/(nm}\cdot\text{km)}$), and ZDW = 1543 nm). The fiber length was optimized through numerical

simulations in order to maximize the generated spectral bandwidth while maintaining stable supercontinuum generation. In this stage, nonlinear effects such as self-phase modulation and soliton dynamics contribute to a significant spectral expansion [11]. The resulting supercontinuum spectrum is presented in Figure 3. The generated optical bandwidth spans approximately 200 nm (25.3 THz measured 20 dB below the peak level), demonstrating efficient nonlinear spectral broadening at a repetition rate of 20 GHz. The spectrum covers the S, C, and L optical communication bands, making the generated source attractive for DWDM high-speed data transmission systems. Furthermore, the experimental results exhibit good agreement with the numerical simulations (green dashed line), confirming the accuracy of the theoretical model used to optimize the nonlinear propagation stages. The insets in Figure 3 show zoomed views of the S, C, and L optical communication bands, demonstrating that the comb structure is preserved across the broadened spectrum and confirming the high coherence of the generated optical frequency comb.

Although broadband optical frequency comb generation based on RES-EOMs has already been demonstrated [8, 9], the impact of phase noise on supercontinuum generation and the preservation of spectral coherence in highly nonlinear single-mode fibers has not yet been investigated. Building upon the preliminary results reported in [9], this work provides a comprehensive experimental analysis of the noise performance of the generated 20 GHz broadband frequency comb and evaluates the influence of nonlinear propagation on the single-sideband (SSB) microwave phase noise, timing jitter, and

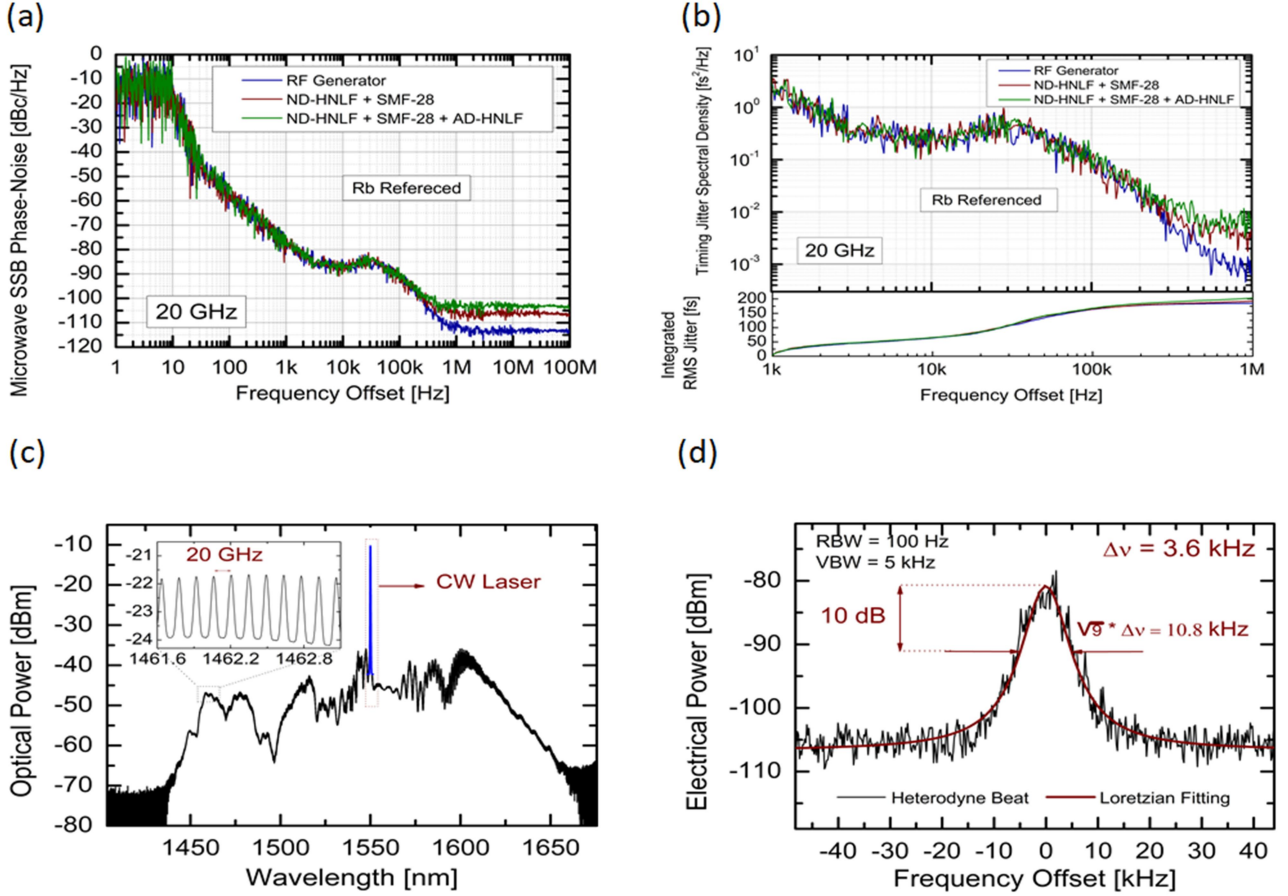


Fig. 4. Phase-noise, integrated timing jitter, and spectral coherence characterization of the generated frequency comb. (a) Single-sideband (SSB) phase-noise spectra measured for the 20 GHz RF synthesizer, at the output of the pulse compression stage (ND-HNLF + SMF-28), and after the final supercontinuum generation stage (ND-HNLF + SMF-28 + AD-HNLF). (b) Integrated RMS timing jitter calculated from the measured phase-noise spectra for the different stages of the system. (c) Optical spectra of the generated supercontinuum and the narrow-linewidth CW laser employed for the heterodyne beat measurements. The inset in (c) shows a zoomed view of the resolved 20 GHz comb lines. (d) Electrical spectrum of the heterodyne beat note measured using an ESA with RBW = 100 Hz and VBW = 5 kHz, showing 3.6 kHz linewidth assuming a Lorentzian profile.

spectral coherence of the resulting supercontinuum. Figure 4 presents the characterization of the phase noise and integrated timing jitter at different stages of the experimental setup, along with the spectral coherence measurements of the generated supercontinuum. The phase-noise performance of the system was experimentally characterized at different stages of the optical chain to evaluate the impact of nonlinear propagation on the phase stability of the generated frequency comb. For these measurements, the 20 GHz electrical signal was recovered using a 25 GHz BW photodetector (PD, 1414, New Focus) connected to a 26.5 GHz electrical spectrum analyzer (ESA, FPL series, Rohde & Schwarz) operated in phase noise analysis (PNA) mode. The corresponding results are presented in Figure 4(a), which compares the phase-noise spectra of the 20 GHz RF generator, the pulse compression stage output (ND-HNLF + SMF-28), and the generated supercontinuum after propagation through the complete nonlinear broadening stage (ND-HNLF + SMF-28 + AD-HNLF). The RF generator exhibits a phase-noise level of -111 dBc/Hz at a 1 MHz frequency offset, serving as the reference baseline for the system characterization. After spectral broadening and pulse compression through the ND-HNLF and SMF-28 fibers, the phase noise degrades slightly to -107 dBc/Hz (@1 MHz) and further increases to -102 dBc/Hz (@1 MHz) after propagation through the AD-HNLF for supercontinuum generation. This progressive degradation is primarily attributed to the

multiplicative phase-noise scaling in optical frequency combs, where the phase noise increases with the comb mode number. The frequency of each comb tooth is described by $(f_n = f_0 + m f_{rep})$, where f_n is the frequency of the comb tooth, f_0 is the carrier-envelope offset frequency, and f_{rep} is the repetition rate. As the comb bandwidth expands, additional comb lines are generated at larger mode numbers, leading to increased phase-noise contributions when the optical signal is converted back to the microwave domain. The relatively small additional degradation observed after nonlinear propagation indicates that the supercontinuum generation process introduces limited impact on the overall phase-noise performance. A similar behavior is observed in the integrated RMS timing jitter presented in Figure 4(b). The RF generator exhibits an integrated RMS jitter of 183 fs, which increases to 192 fs after the pulse compression stage and reaches 204 fs after the final supercontinuum generation stage. In all cases, the RMS timing jitter reaches a plateau at around 100 kHz frequency offset. These results demonstrate that, although a modest degradation in phase noise and timing jitter is observed along the optical path, the overall temporal stability of the frequency comb remains primarily limited by the RF synthesizer, with only a limited contribution from nonlinear optical effects.

To investigate the preservation of spectral coherence after nonlinear spectral broadening, heterodyne beat measurements were performed between a comb tooth of the generated

supercontinuum output and a narrow-linewidth continuous-wave (CW) laser. A 100 Hz-linewidth CW laser operating at 1550 nm was used as an optical local oscillator to characterize the linewidth of comb lines located far from the central wavelength of the spectrum. The heterodyne signal was detected using a 25 GHz BW PD connected to an ESA. The corresponding optical spectra are presented in Figure 4(c), which shows both the generated supercontinuum and the CW laser employed in the experiment. In addition, the inset of Figure 4(c) presents a zoomed view of the resolved comb lines with approximately 0.16 nm spacing between adjacent modes. The heterodyne beat note is presented in Figure 4(d), measured using a resolution bandwidth (RBW) of 100 Hz and a video bandwidth (VBW) of 5 kHz. The measured beat-note linewidth at 10 dB below the peak level is 10.8 kHz, which corresponds to an estimated FWHM linewidth of approximately 3.6 kHz assuming a Lorentzian fit to the experimental data [12]. These results demonstrate that, even for comb lines located far from the spectral center, the generated supercontinuum preserves a high spectral coherence. Considering that the seed laser exhibits linewidths on the order of 300 Hertz, the measured results indicate only modest coherence degradation after the nonlinear broadening process, confirming the robustness and stability of the generated optical frequency comb across its entire spectral bandwidth.

These results demonstrate that the nonlinear spectral broadening process introduces only a moderate degradation in phase noise and spectral coherence, while preserving the overall stability of the generated optical frequency comb. Although the present implementation operates at a 20 GHz repetition rate due to the limited bandwidth of the available RF amplifier, the resonant electro-optic modulator architecture is inherently tunable and can be readily adapted to operate at 25 GHz comb spacing compatible with DWDM systems. Therefore, the proposed source represents a promising platform for multiwavelength coherent optical carrier generation, with potential applications in high-speed data transmission, optical communications and frequency-multiplexed quantum communication systems.

IV. CONCLUSION

In conclusion, we demonstrated a broadband resonant electro-optic frequency comb based on nonlinear spectral broadening in highly nonlinear single mode fibers, spanning the S, C, and L optical communication bands while preserving low phase-noise and high spectral coherence. Building upon the preliminary results reported in [9], this work demonstrates the generation of 103 fs pulses and a 200 nm (25.3 THz) supercontinuum bandwidth in standard single-mode fibers, while also investigating the impact of nonlinear spectral broadening on the phase-noise performance and spectral coherence of resonant electro-optic frequency combs. The optical and RF results confirm low-noise comb operation, with a phase-noise level of -90 dBc/Hz at a 10 kHz offset and a 3.6 kHz comb-tooth linewidth, demonstrating the preservation of high spectral coherence. The experimental results showed that nonlinear propagation introduces only a minimal degradation in temporal and spectral stability, confirming the robustness of the proposed architecture. Furthermore, the intrinsic tunability of the resonant electro-optic modulation scheme enables straightforward adaptation to repetition rates compatible with DWDM channel spacing (25-GHz), allowing the generation of multiple coherent optical carriers from a single laser source.

Future work will focus on channel power equalization across the broadened supercontinuum frequency comb spectrum, potentially employing nonlinear optical loop mirror (NOLM) or nonlinear amplifier loop mirror (NALM) techniques to improve spectral flatness for DWDM applications [13]. These characteristics make the demonstrated platform highly attractive for next-generation coherent optical communications, microwave photonics, and quantum photonic systems based on optical frequency comb technologies.

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