Noise Suppression in a 10 GHz Octave-Spanning Frequency Comb

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Abstract

We demonstrate a 10 GHz octave-spanning frequency comb from a 1550 nm resonant waveguide-type electro-optic comb generator. The impact of cavity filtering on the amplified spontaneous emission and shot noise is studied experimentally and theoretically.

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I. Introduction

Broadband, low-noise frequency combs at ∼ 10 GHz repetition rates are critical for a wide range of applications, including astronomical spectrograph calibration. Recent technologies like electro-optic modulation (EOM) [1], and microcombs [2] have been employed for astronomical applications, but still require amplification and dispersion-engineered nonlinear broadening to achieve octave-span supercontinuum for self-referencing or to cover the desired spectrograph bandwidth. However, amplification to high pulse energies is also associated with amplified spontaneous emission (ASE) and this amplitude noise on the input pulse dramatically increases during supercontinuum generation via modulation instability degrading the coherence and signal-to-noise ratio of comb lines [3]. High-Finesse Fabry-Perot cavities have been used to suppress this broadband noise [4]. However, there have not been quantitative measurements and theory of the effect of input relative intensity noise (RIN) on the coherence of the supercontinuum, particularly at the practically useful point of soliton fission.

Here we demonstrate a simple and robust approach to generating a coherent 10 GHz comb with a fiber-integrated waveguide EOM in a resonant Fabry-Perot cavity [5]. We show temporal compression of 10 GHz pulse train to ∼ 46 fs using an all-polarization-maintaining (PM) fiber design, followed by supercontinuum generation in a dispersion-engineered silicon nitride (SiN) waveguide. The remediation of broadband amplitude noise on the input pulse and its impact on the output supercontinuum coherence are investigated experimentally as well as through simulations.

II. Experiment and Results

Fig. 1(a) shows the experimental setup. The details of temporal compression have been described in [6]. A 10 GHz frequency comb generated after the 1550 nm resonant optical frequency comb generator (OFCG) is amplified to 3W using an erbium-doped fiber amplifier (EDFA), and propagated through 1.2 m of normal dispersion highly-nonlinear fiber (ND HNLF) and 22.5 cm of PM1550 to generate 46 fs pulses (Fig. 1(b) and 1(c)). The lengths of the fibers for this spectral broadening and temporal compression stage have been carefully designed by solving the nonlinear Schrodinger equation (NLSE) in PyNLO. The sub-50-fs pulses are then focused onto a 5 mm long SiN waveguide with a cross-section of 800 nm × 2500 nm to generate

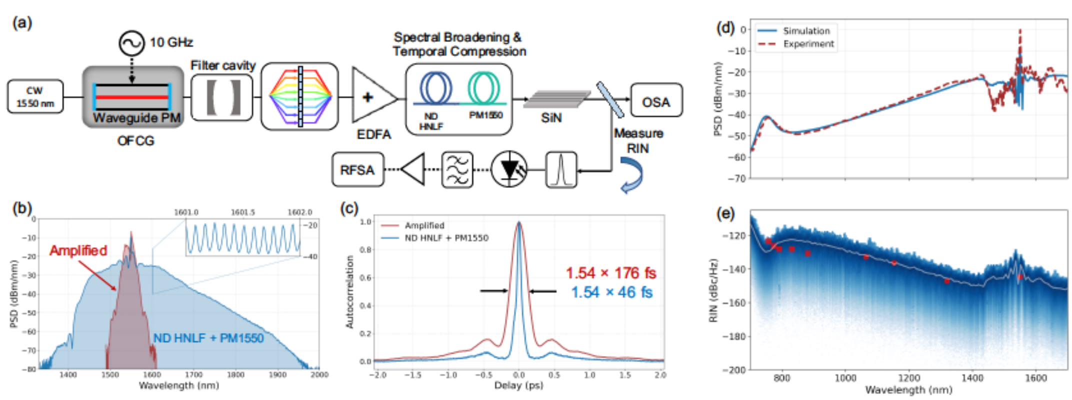

Fig. 1. (a) Schematic of 10 GHz supercontinuum generation and RIN measurement setup, (b) Optical spectra after EDFA (red) and propagation through ND HNLF and PM1550 (blue), (c) Corresponding autocorrelations and pulse widths, (d) Supercontinuum at the output of SiN waveguide, and (e) RIN in dBc/Hz across the spectrum in experiment (red) and simulation (blue). The white line corresponds to the mean value of 256 independent simulations.

a smooth octave-spanning supercontinuum (SC) before soliton fission. The total throughput efficiency of the waveguide is 37%. The simulation results using 50 fs, 95 pJ input pulse are in good agreement with the experiment (Fig. 1(d)). However, coherence of the SC is lost around the 754 nm dispersive wave. We discovered this degradation in the signal-to-noise ratio of the comb lines was due to the 25 dB optical loss through the fiber-integrated comb generator and further amplification. The coherence of the supercontinuum at lower wavelengths is recovered by installing an additional 10 GHz Fabry-Perot (Finesse=60) cavity after the OFCG. The cavity suppresses excess RIN in the input pulse by 16 dB and improves the signal-to-noise ratio (SNR) of heterodyne beats between the CW lasers and the filtered supercontinuum at 1319 nm, 1156 nm, and 1064 nm by 18 dB as shown in Fig 2(a). This cavity also allows detection of the carrier-envelope offset frequency f_{CEO} in an f-2f interferometer with a SNR of 9 dB.

The noise properties of the supercontinuum were studied and quantified with a combination of RIN measurements and numerical simulations. In our setup, the output SC is filtered at multiple wavelengths using a 10 nm wide optical bandpass filter and then detected by InGaAs or silicon (Si) photodetectors (PD) for wavelengths above or below 900 nm. The resulting DC output voltage of the photodiode is noted. The time-varying photodiode signal is passed through an electrical bandpass filter (800 – 1050 MHz) to avoid saturation, and then amplified to observe the rise in noise floor with a radio frequency spectrum analyzer (RFSA). The total RF noise power density (in dBm/Hz) at 900 MHz after subtracting the detection noise floor is divided by the measured DC power to give RIN in dBc/Hz at the given wavelength (red circles plotted in Fig. 1(d)). To simulate the relative intensity noise of the supercontinuum, we considered 256 pulses with different random seeds of shot noise and ASE that amount to a measured RIN value of -151 dBc/Hz at 1550 nm. RIN (in dBc/Hz) as a function of wavelength is then calculated as the ratio of squared Fourier transform of intensity variations at each wavelength of the resulting 256 supercontinuua and its DC value squared [7]. We clearly observe an exponential growth of noise across the SC spectra from -151 dBc/Hz at the input to a value even as large as -123 dBc/Hz around 754 nm.

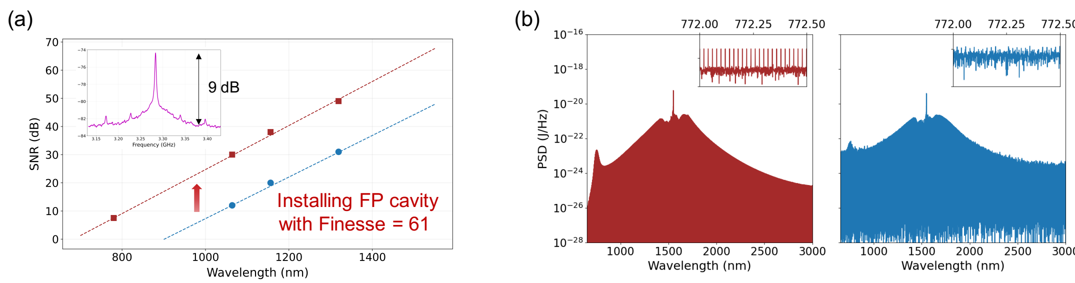

Fig. 2. (a) Comparison of SNR of heterodyne beats between the CW lasers and the filtered SC at 780 nm, 1064 nm, 1156 nm, and 1319 nm before and after installing Fabry-Perot (FP) cavity with FSR of 10 GHz. The inset shows the measured f_{CEO} signal, (c) SC spectra generated with 10 GHz pulse train as input to the simulations. Blue trace corresponds to 16 dB more RIN at the input as compared to the red.

We also investigate the growth of noise between the comb lines by giving 10 GHz pulse train as input to the simulations. This is done by concatenating the initial 256 pulses to generate a 10 GHz pulse train and this pulse train is given as input to the NLSE. The coherent supercontinuum measured after the filter cavity closely resembles the simulated red colored trace in Fig. 2(b). The blue colored spectrum in Fig. 2(b) corresponds to the same but with a multiple of shot noise added to the input pulse so that it amounts to 16 dB more input RIN. The loss of contrast of comb lines around 772 nm with more input RIN clearly demonstrates the importance of suppressing broadband amplitude noise for coherent supercontinuum generation.

In conclusion, for the first time, we achieved an octave-spanning 10 GHz frequency comb from a 1550 nm resonant electro-optic comb generator and experimentally and theoretically studied the excess amplitude noise generated in the supercontinuum. Future work will include the study of supercontinuum noise using high finesse cavities for larger RIN suppression. This work is important for understanding the noise limitations in multiple metrology scenarios with such combs, including the calibration of near-infrared astronomical spectrographs.

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