Low-noise, Flat-spectrum, Polarization-Maintaining All-Fiber Frequency Comb for Wideband Communications

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Abstract: We design and optimize a parametric frequency comb generator using all polarization-maintaining components, highly-doped PM fiber and PM highly-nonlinear fibers, obtaining 500 tones over 100nm with >-5dBm per tone and less than 40kHz linewidth. © 2022 The Author(s)

1. Introduction

Over the past 10 years, optical frequency combs have been increasingly explored in optical communications [1-5]. In long-haul transmission, the precisely spaced optical tones in a frequency comb enable high spectral efficiency [1] and improved signal-to-noise ratio for nonlinearity compensation [2]. In metro-distance systems, the phase coherence of frequency combs is exploited to reduce the complexity of digital signal processing for phase and frequency estimation [3]. In access and short reach systems, frequency combs provide parallel wavelength channels that massively increase the link capacity at low cost [4,5].

In contrast to applications in metrology and spectroscopy, optical communications do not necessarily require ultra-wide 'over-one-octave' bandwidths, but emphasize high power-per-tone, high optical signal-to-noise ratio (OSNR), narrow linewidth, flat spectrum, and insensitivity to environmental perturbation (e.g. vibration and temperature variation) [6,7]. These characteristics have made fiber-based frequency combs a promising solution for data transmission and signal processing [2,8]. Previous research has demonstrated fiber-based flat-spectrum comb with >0 dBm per tone and OSNR in excess of 40 dB over the telecom C band [7] for high spectral efficiency (>64QAM) high capacity (>2Pb/s) transmission [9]. Although remarkable performance has been achieved, there are still important challenges that have yet to be overcome. Firstly, the demonstrated combs so far are not polarization-maintained (PM) due to the use of non-PM components, such as standard single mode fiber and non-PM highly nonlinear fiber (HNLF), for pulse compression, shaping and parametric mixing. As a result, polarization control of each individual wavelength is needed for modulation. Secondly, the nonlinear processes that generate new optical tones significantly enhance the phase noise and linewidth of the tones at the spectral edges, limiting the usable bandwidth for transmission [9]. Thirdly, the nonlinear amplified loop mirror (NALM) based pulse shaper involves an erbium-doped fiber amplifier (EDFA) that adds tens of meters of fiber, which broadens the in-loop pulse width (due to dispersion) and, consequently, reduces the peak power of the pulses and the efficacy of the nonlinear mixer.

To address the above-mentioned challenges, we propose and improve the design of fiber-based frequency combs on three fronts. Firstly, we develop the comb generator using all-PM components, permitting an easy interface with wavelength demultiplexer and modulators. The all-PM system also allows for a stable output signal from the NALM based pulse shaper and a reduced noise of the expanded tones, whose signal to noise ratio (SNR) strongly depends on the state of polarization propagating through the highly nonlinear fibers [10]. In addition to the all-PM design, we engineered the optoelectronic comb generator to produce largely-chirped 1st stage comb signals, which are subsequently compressed to very short pulses (e.g. 470 fs) before entering any highly nonlinear fibers. This ensures strong nonlinear interaction in short fibers for high repetition rate signals, which empowers low nonlinear noise. Finally, we develop the NALM using a highly-doped PM erbium doped fiber (EDF), reducing the length of the EDFA to 1.6 m, significantly reducing the residual dispersion in the loop, ensuring high nonlinear efficacy and pedestal suppression ratio of the pulses for flat comb generation. The joint optimization results in a PM 25-GHz-spaced frequency comb with more than -5 dBm per tone and less than 40 kHz linewidth over 100 nm bandwidth.

2. Experimental Setup

Fig. 1a shows the system architecture of our frequency comb source, comprising an optoelectronic frequency comb generator followed by an all-PM-fiber-based NALM and a PM-HNLF-based nonlinear mixer. The optoelectronic comb was seeded by a 4-kHz-linewidth continuous wave (CW) laser emitting at 1550.12 nm. To achieve high OSNR, the CW light was amplified to 30 dBm before entering a $LiNbO_3$ Mach–Zehnder modulator (MZM) followed by two phase modulators. The MZM transformed the CW light into a repeated pulse train with the pulse period corresponding to each modulation cycle and the phase modulators added a quasi-linear chirp across each pulse, yielding flat-top pulses with relatively flat spectral envelopes for a tone spacing of 25 GHz [11]. A low phase noise RF source was employed to generate a 25 GHz sinusoidal signal that drove the modulators synchronously. The bandwidth of the optoelectronic comb signals is determined by the maximum phase deviation within each modulation cycle. Thus, to generate a wide bandwidth EO comb, we used two stages of phase modulators both driven with 36 dBm RF power, resulting in approximately 1.8 THz bandwidth as shown in Fig.1b. The strongly chirped signals were subsequently compressed to their transform limit using 50 m PM single-mode fibers (PM1550), resulting in 470 fs full-width half-maximum (FWHM) pulse width.

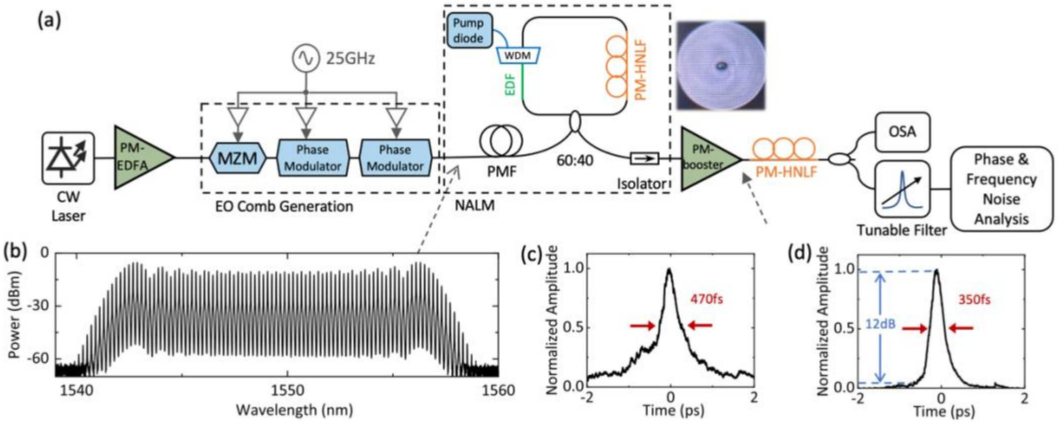

Fig. 1 (a) Experimental Setup. (b) spectrum of the EO comb; autocorrelator measurement of the compressed pulse before (c) and after (d) the NALM. Inset shows the cross-section image of the PM-HNLF.

As studied in [6, 7], the strong pedestal of the compressed pulses (see Fig.1c) due to the non-quadratic phase modulation at the edge of the pulses causes a large power variation in the broadened spectra. Therefore, a pulse shaping stage, either using nonlinear optical loop mirror (NOLM), NALM or waveshapers, has been employed to suppress the pulse pedestal. Here we focused on optimizing fiber-based NALM for higher OSNR and a higher pedestal suppression ratio compared to its passive counterpart, i.e. NOLM. To minimize the residual dispersion due to pigtails and EDF, we developed a bi-directional EDFA using a highly-doped PM-EDF with peak absorption of 80 dB/m (shown in green in Fig.1a) and pumped it with a laser diode emitting 600 mW at 980 nm. Compared to standard telecom EDFA that commonly has a much lower absorption of 5 to 8 dB/m, our design significantly reduces the length of the EDF and, therefore, the in-loop residual dispersion, ensuring short pulse width and high pedestal suppression ratio output. Due to nonlinear self-phase modulation, the output of the NALM is further compressed to a pulse width of about 350 fs. The PM-HNLF used in the NALM exhibits normal dispersion (-0.5 ps/(nm·km) at 1550 nm) and was spliced to PM1550 with <0.7 dB loss per splice.

In the final stage, the shaped pulses were amplified to 33 dBm using a PM booster EDFA before pumping a 50-m PM-HNLF, which has a normal dispersion of -1.3 ps/(nm·km) and a nonlinear co-efficient (effective gamma) of about 10.5 $\mathrm{W}^{-1}\cdot\mathrm{km}^{-1}$. Any dispersion due to the booster EDFA was compensated using a PM dispersion compensation fiber (DCF) for maximizing the peak power into the nonlinear mixer. The spectrum and OSNR were measured using optical spectrum analyzers (OSA). A 200 pm bandwidth tunable filter was employed to extract individual tones for phase noise characterization.

3. Results

Fig.2a shows the measured comb spectrum (blue lines) and the linewidth of individual tones. Considering a minimum -5 dBm power per tone, we obtained 100 nm comb bandwidth spanning from 1505 to 1605 nm, containing >500 tones with a maximum of power variation of 13 dB. The relatively large power variation between 1540-1557 nm originates from the non-ideal suppression of the pedestal, which could be further improved by a more careful compensation of the dispersion and dispersion slope in the NALM. Due to the coherent smooth broadening in normal dispersion region [11], less than 5 dB power variation can be obtained in the 1505-1532 nm and 1570-1600 nm wavelength region. Fig.2b-d show the zoom-in spectra measured using an OSA of 20-MHz-resolution at 1520, 1550 and 1590 bands, showing clean optical tones and an OSNR of 26-31 dB considering 1.25 GHz (0.01 nm) bandwidth white noise. The red square markers in Fig.2a display the measured linewidth of individual tones at 400 GHz intervals, showing less than 20 kHz linewidth over 65 nm and <40 kHz over 100 nm bandwidth.

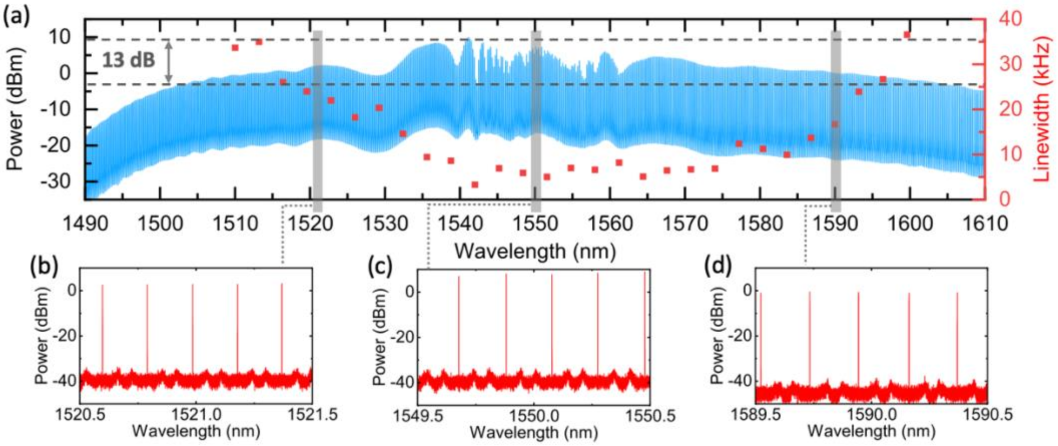

Fig. 2 (a) Measured spectrum (blue lines, 0.02nm resolution) and linewidth (red square markers). (b)-(d) Measured high resolution (20 MHz) comb spectra.

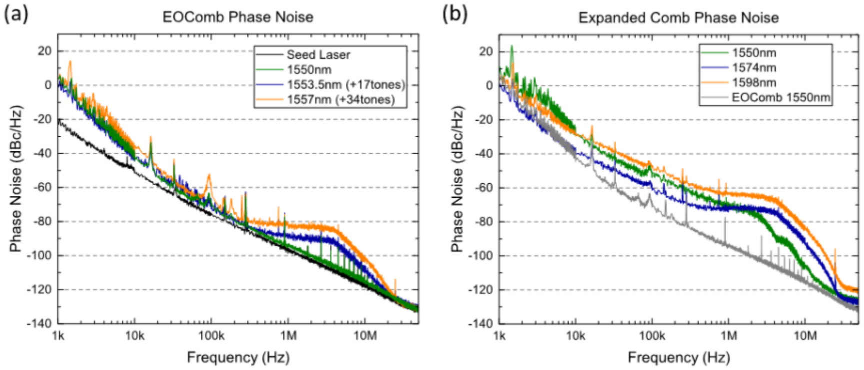

Fig.3 Measured phase noise of individual comb tones for (a) EO comb and (b) Expanded comb.

We further characterize the phase noise of individual tones for the EO comb (Fig.3a) and the expanded comb (Fig.3b). In our system, the low-frequency (<100kHz) phase noise degradation of the EO comb is primarily due to the RF amplifiers and the high frequency (200k-10MHz) white phase noise scales quadratically with the harmonic number. The expanded comb showed enhanced phase noise due to amplified spontaneous emission and the non-coherent interaction of phase noise as well as amplitude-phase noise conversion in the nonlinear process.

4. Conclusions

We demonstrate the first PM-fiber-based parametric frequency comb featuring 500 tones and <40kHz linewidth over 100 nm. We also characterize the phase noise of individual tones for EO comb and parametric comb for the first time, providing an insight of how phase noise scales in comb generators.

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