Parametric-Assisted Fiber-Optic Talbot Amplifier for Carrier-to-Noise Ratio Enhancement of Optical Frequency Combs

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Abstract: *We demonstrate an all-fiber optical amplifier based on parametric-assisted spectral Talbot effect to control the carrier-to-noise ratio (CNR) and the spectral spacing of optical frequency combs. The CNR is enhanced by up to 11 dB while the spacing is multiplied from 11 to 165 GHz.*

Introduction

Optical frequency combs (OFCs) are applicable for use in a wide range of research fields, including telecommunications, optical sensing, metrology, and optical computing [1-4]. OFCs can be generated via various approaches, ranging from fiber-based systems to chip-scale platforms. A critical figure-of-merit of OFCs is the optical carrier-to-noise ratio (CNR), which is defined as the power ratio of the carrier to the background noise. A high CNR ensures that the comb-based optical carriers can be readily used for telecommunications and other applications [1]. Another key property is the spectral spacing, often referred to as the comb tooth spacing of the OFCs. Flexible control of the spacing is of significance for reconfigurable wavelength-division multiplexing networks, parallel optical signal processing, and photonic computing [3]. Until now, improving the spectral quality of OFCs with wide tooth spacing has been a great challenge [5-7]. Stochastic noises introduced during amplification, transmission, and detection processes inevitably degrade the CNR and thus worsen the performance of the OFCs in different applications.

To address this challenge, we propose and demonstrate an all-fiber optical amplifier based on the parametric-assisted spectral Talbot effect. Our method combines the four-wave mixing (FWM) process and the Talbot effect to flexibly improve the CNR of an OFC and widen the tooth spacing. In our work, the repetition rates of a pump pulse train and a signal pulse train are first multiplied separately through the energy-preserving temporal Talbot effect. A nonlinear parametric process is then performed to naturally compensate the temporal variation of the phase profiles in the rate-multiplied signal pulse train. Thanks to the ultrafast amplitude and phase response of the parametric FWM process [8, 9], our approach can support large modulation bandwidths up to a few THz. Consequently, the discrete quadratic temporal phase variation of the rate-multiplied pulse train can be compensated effectively. An in-phase idler pulse train is thus generated, giving rise to a widely spaced OFC with improved CNR at the idler wavelengths.

The proposed all-fiber Talbot amplifier is experimentally verified to enhance the CNR of an input OFC by 8 dB and 11 dB, while increasing the comb tooth spacing from 11 GHz to 77 GHz and 165 GHz, respectively. This work represents a significant advancement in programmable generation and purification of OFCs with wide spacings, showing potential applications in various fields such as telecommunications, optical computing, and spectroscopy [2, 10].

Principle

Figure 1 depicts the operating principle of our proposed approach. A noise-dominated OFC is spectrally partitioned into two branches. The lower branch serving as an input signal is directed to a dispersive medium (D2) that satisfies the temporal Talbot condition [11]:

$$2\pi\beta_2 L = p/q * T_r^2 \quad (1)$$

where β_2 is the group velocity dispersion, L is the length of the dispersive medium, q represents the repetition rate multiplication factor and is set to 3 in this example, p is an integer coprime with q, and T_r is the period of the input pulse train. The power spectrum of the OFC remains unchanged but the period of the corresponding optical pulse train is reduced from T_r to $T_r/3$ by the Talbot effect. It should be noted that a periodic discrete temporal phase pattern Φ_s is introduced on the multiplied pulse train [11]. The upper branch acts as a pump and the temporal counterpart is a pulse train with the same period T_r as the original signal. In the following, the pump propagates through a dispersive medium (D1) and turn into another rate-multiplied pulse train with a deterministic temporal phase profile Φ_p. Through

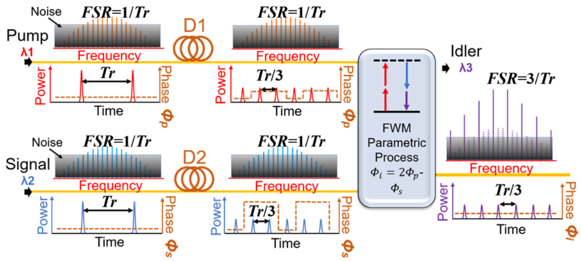

Fig. 1: Principle of all-fiber parametric-assisted all-fiber spectral Talbot amplifier. Brown dash lines: temporal phase pattern.

the design of D1 and D2, the temporal phases Φ_p can be used to completely compensate Φ_s via the FWM process in a highly nonlinear medium. Since the electrical field of the generated idler wave after the FWM is $E_i \propto E_p^2(t) \cdot E_s^*(t)$, the temporal phase relation between the pump and the signal should satisfy $\Phi_p = \Phi_s/2$. Consequently, the temporal waveform of the idler wave will consist of an in-phase optical pulse train at a high repetition rate. In the frequency counterpart, spectral energy redistribution of frequency lines shapes the idler components into a spacing-multiplied OFC with multiplication factor q, giving rise to enhanced CNR.

To achieve the temporal phase compensation between the modulated pump and signal pulses, we carefully select the group velocity dispersion of both D1 and D2. We find that there are two possible solutions as illustrated in Fig. 2. The initial repetition rates for both the pump and the signal pulse trains are 11 GHz. In *solution one*, to achieve an amplification factor of 5, the repetition rate of the signal pulse is required to be double that of the pump pulse. Here, we set p = 1 and q = 5 in Eq. (1) for the pump branch and p = 1 and q = 10 for the signal branch. The modulated pump and signal are shown in Fig. 2a(i) and b(i), respectively. The temporal phase patterns are indicated by brown dashed lines, with restriction to a 2π basis. Despite that the pump pulses interact with only half of the signal pulses during the parametric process, the temporal phase patterns are effectively compensated, resulting in an in-phase idler as shown in Fig. 2c(i). The pulse rate of the idler is the same as that of the multiplied pump pulses. For *solution two*, to achieve an amplification factor of 5, we set p = 2 and q = 5 for the pump branch and p = 1 and q = 5 for the signal branch. The repetition rates in both the pump and signal are multiplied by 5 as shown in Fig. 2a(ii) and b(ii). By aligning the temporal traces of the pump and signal and performing the FWM parametric process, an in-phase idler is generated (Fig. 2c(ii)). For the comparison between the two solutions, an extra 3-dB loss occurs in the case of *solution one*. Nevertheless, *solution one* requires smaller

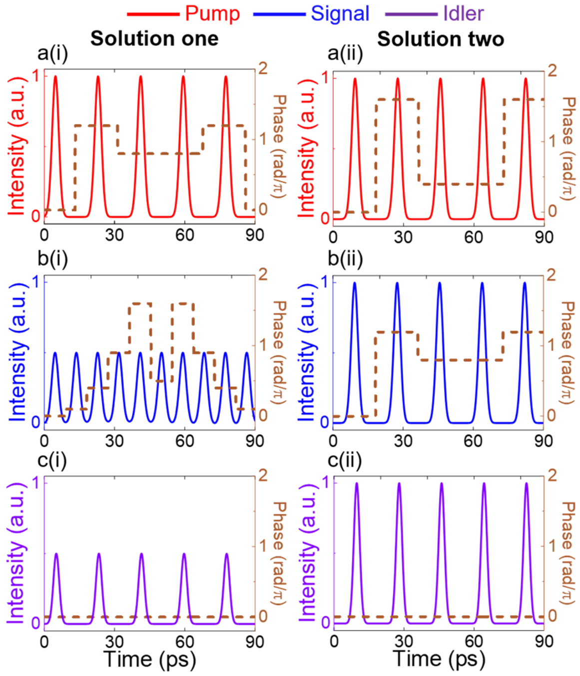

Fig. 2: Two solutions for generating in-phase high repetition rate idler. a(i) a(ii) temporal traces of pumps. b(i) b(ii) temporal traces of input signals. c(i) c(ii) temporal traces of in-phase output idlers after FWM.

group velocity dispersion for both D1 and D2. In the following experiments, we verify these two solutions collaboratively to achieve CNR enhancement of OFCs and widely spaced comb generation by using the proposed parametric-assisted Talbot fiber amplifier.

Experimental results

Figure 3(a) shows our experimental setup. Two optical frequency combs are filtered out from an 11-GHz spaced broadband comb source (BCS) using a programmable optical filter (POF). The BCS is intentionally loaded with ASE noise. The filtered noisy comb centered at 1545.5 nm is used as the pump and is directed to the upper branch, while the noisy signal centered at 1554.5 nm is directed to the lower branch. The optical spectra of the noisy pump and noise-dominated signal are shown in Fig. 3(b) and 3(c), respectively. The pump propagates through a single-mode fiber (SMF) with 148 ps/nm dispersion and is then amplified to 24 dBm by an erbium-doped fiber amplifier (EDFA). The noisy comb at the lower branch propagates through a SMF with 73 ps/nm dispersion. An optical tunable delay line (OTDL) is used to ensure precise temporal overlap of the pump and signal comb pulses. The pump comb and the noisy signal comb with discrete phase profiles are then combined by a 50:50 coupler and directed to a 200 m highly nonlinear fiber (HNLF) with nonlinear coefficient γ=30 $W^{-1}\cdot km^{-1}$. An optical spectrum analyzer (OSA) with a resolution bandwidth of 0.02 nm is used to

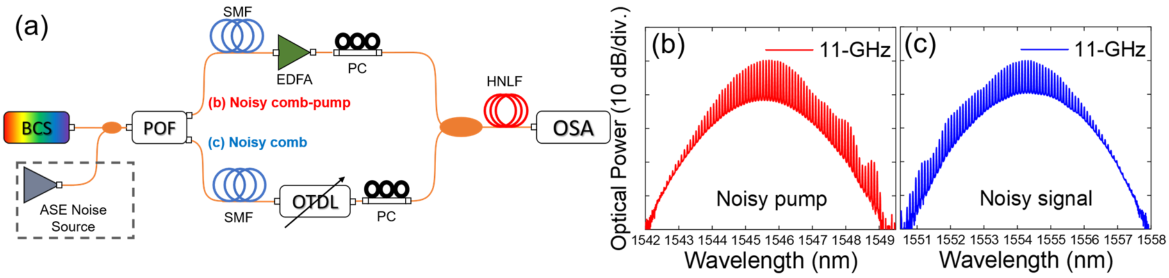

Fig. 3: (a) Experimental setup. (b) initial noisy pump with 11-GHz frequency spacing. (c) initial noisy signal with 11-GHz spacing. BCS: Broadband comb source. POF: Programmable optical filter. OTDL: Optical tunable delay line.

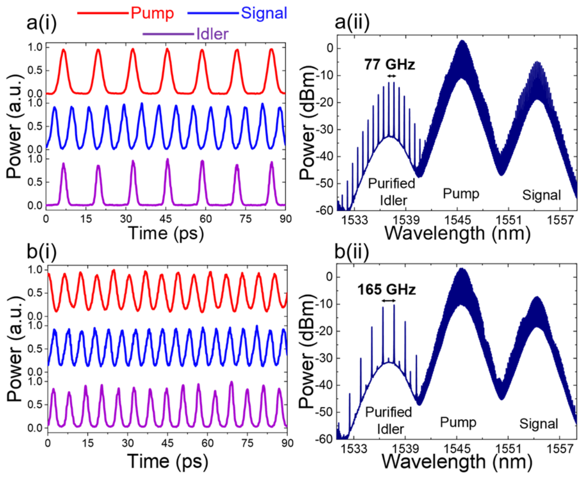

Fig. 4: Versatile OFC purifications. a(i) b(i) temporal traces of pump, signal and idler. a(ii) b(ii) purified OFC with amplification factors of 7 and 15.

measure the output spectra.

We present experimental demonstration of CNR enhancement of noise-overwhelmed OFCs and demonstrate tooth spacing multiplication for an 11-GHz spaced noise-dominated comb. As shown in Fig. 4a(i), the amplification factor q is set to 7. By applying the aforementioned *solution one*, a 154-GHz pump pulse train is used to interact with 77-GHz signal pulses to generate in-phase idler pulses at 77-GHz pulse rate. In the spectral domain, the comb tooth spacing is enhanced by a factor of 7 and the CNR is improved by ~8 dB, as depicted in Fig. 4a(ii). By managing the effective dispersions of the pump and signal branches through the POF, the pulse rate of the noisy pump and signal can be adjusted flexibly. In this way, the generated idler comb can exhibit programmable spacing and CNR improvement without introducing significant changes to the system configuration. In the experiment, we program the POF to introduce desired GVDs for the pump and signal branches to meet the Talbot conditions required by various amplification factors *q*. In addition, we also demonstrate the capability based on *solution two.* In this case, the repetition rates of the pulsed pump and the noisy signal are both set to 165 GHz. The generated idler is a 165-GHz in-phase pulse train as shown in Fig. 4b(i). In the corresponding optical spectrum, the comb tooth spacing is multiplied by 15 times to become 165 GHz. The CNR is improved by approximately 11 dB, as shown in Fig. 4b(ii).

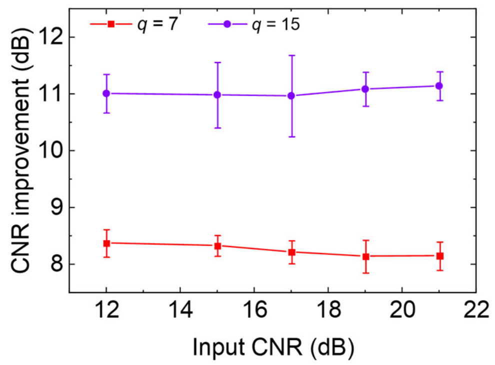

Fig. 5: CNR improvement against as the input CNR of both pump and signal. Red and violet marks indicate amplification factor q = 7 and q = 15, respectively.

We also investigate the CNR improvement as a function of the input CNR of the original pump and signal. The study is performed by programming the output power of the ASE source to control the input CNR. The result is shown in Fig. 5. It is observed that the CNR improvement is insensitive to the input CNR over the input range of 12 to 21 dB. This property favors the application of our scheme for enhancing the CNR of OFCs suffered from different degrees of degradation.

Conclusion

We present a parametric-assisted spectral Talbot amplifier for enhancing the CNR of OFCs. The all-fiber system is highly versatile and allows for noiseless spectral amplification and widely spaced optical frequency comb generation.

Acknowledgements

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