All-Fiber Raman and Parametric-Assisted Spectral Talbot Array Illuminator for Mode Spacing Multiplication

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Abstract: An optical frequency comb with multiplied mode spacing of 94.5 GHz and up to 35 dB carrier-to-noise ratio is produced by a hybridly amplified spectral Talbot processor. The output supports frequency comb based coherent communications. © 2024 The Author(s)

1. Introduction

Optical frequency combs (OFCs) with large mode spacing are highly desirable for a wide range of applications such as spectroscopy and telecommunications [1,2]. However, the generation of widely spaced OFCs poses a challenge in various optical systems. Microresonators have demonstrated the ability to generate soliton Kerr comb with mode spacings in tens of GHz [3]. Despite their promising potential, challenges such as phase stabilization and limited output power remain [3,4]. An effective signal processing technique based on spectral Talbot array illuminator (S-TAI) has been proposed recently to enhance both the carrier-to-noise ratio (CNR) and the mode spacing of an OFC [5,6]. Unfortunately, the limited bandwidths of electrical waveform generators and modulation components make it difficult for the mode spacing to exceed a few tens of GHz [6,7]. Consequently, the potential applications in ultrahigh-data-rate telecommunications are limited. In a prior study, a parametric-assisted spectral Talbot amplifier has been demonstrated to enhance the CNR of an OFC by 11 dB while multiplying its mode spacing [8]. However, due to the limited conversion efficiency (CE) of the parametric four-wave mixing (FWM) process, the peak power of each frequency tone remains insufficient to support high-capacity coherent optical transmission.

In this work, we propose an all-fiber method for mode spacing multiplication by utilizing Raman and parametric-assisted S-TAI. The mode spacing is multiplied from 13.5 to 94.5 GHz, with each newly generated frequency tone exhibiting higher peak power and up to 35-dB CNR. Through the combination of distributed Raman amplification (DRA) and nonlinear parametric process, the performance of the all-optical S-TAI is significantly enhanced, resulting in substantial enlargement of the peak power and mode spacing of the OFC. The resulting widely spaced OFC achieves high quality and is suitable for application in coherent communications. To assess the practical use of the frequency comb carriers, the central 10 tones are filtered and modulated with 32-Gbaud PCS 64QAM signals for 80-km transmission. The normalized generalized mutual information (NGMI) tests on individual tones demonstrate similar performances at the 25% SD-FEC limit of 0.84. Apart from telecommunications, our OFC processing scheme paves the way for applications in other areas including microwave photonics and spectroscopy.

2. Principle of all-fiber mode spacing multiplication

The operation principle is illustrated in Fig.1. We here set the mode spacing multiplication factor m = 3 as an example. An input comb shown in blue with an initial free spectral range FSR = $1/T_r$ is allowed to propagate in a dispersion medium (D1) satisfying the Talbot condition $2\pi\beta_2 L = T_r^2/6$ [8,9], where β_2 and L are the second order dispersion and length of the medium, and T_r is the repetition period of the input. The power spectrum of the OFC remains unchanged, but the period of the corresponding optical pulse train decreases from T_r to $T_r/6$. After the propagation, a periodic discrete temporal phase pattern Φ_s is introduced to the multiplied pulse train. Next, the phase pattern Φ_s should be compensated to obtain an in-phase pulse train, corresponding to an OFC with boosted FSR. To achieve the ultrafast phase compensation, another OFC with the same initial FSR is used as a pump. It is directed to another dispersion medium (D2) satisfying the temporal Talbot condition $2\pi\beta_2 L = T_r^2/3$. The repetition rate of the pump pulses is then tripled, carrying corresponding discrete phase pattern Φ_p, where $\Phi_p = \Phi_s/2$ [8]. In the following FWM process, the pump pulses interact with half of the signal pulses in a nonlinear Kerr medium. Meanwhile, Raman amplification is implemented to enhance the parametric process and to improve the system sensitivity. Consequently, an in-phase idler (shown in purple) with the same repetition rate as the modulated pump (3x original repetition rate) is generated. In the frequency counterpart, energy redistribution among the frequency tones shapes the idler components into a 3x spacing multiplied OFC, resulting in enhanced mode spacing. A key advantage lies in the all-optical processing across the whole system, offering a potential operating bandwidth over a few THz. By harnessing the linear temporal Talbot effect and the nonlinear optical process, a temporal phase pattern (Φ_p) carried by the pump can be naturally generated to perfectly compensate for the ultrafast temporal phase pattern of the signal

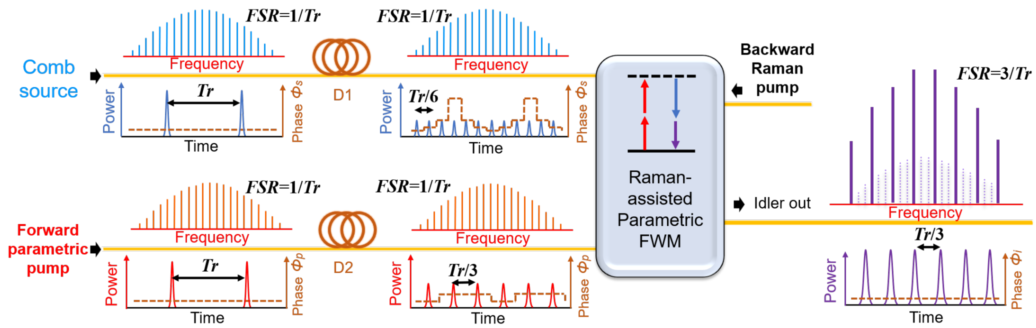

Fig. 1. Principle of all-fiber Raman and parametric-assisted spectral Talbot array illuminator for mode spacing multiplication.

(Φ_s). Leveraging the denoising property of the all-optical S-TAI in conjunction with DRA, the resulting wide-spacing comb exhibits sufficiently large CNR and power gain at each frequency tone, making it suitable for applications such as spectroscopy and high-speed coherent optical communication.

3. Experimental setup and results

Figure 2(a) shows the experimental setup while Fig.2(b) to (f) depict the measured results. We first generate a 13.5-GHz spaced OFC as a wideband comb source shown in Fig.2(b). Subsequently, two OFCs are filtered out using a WaveShaper. One of the filtered OFC, centered at 1548.5 nm, serves as the pump, and is directed to the upper branch. The other OFC, centered at 1558.8 nm, is directed to the lower branch. The pump propagates through a single-mode fiber (SMF) with a second order dispersion of ~100 ps^2/rad and is amplified to 23 dBm. The signal comb propagates through a SMF with ~50 ps^2/rad dispersion. To ensure precise temporal overlap of the pump and signal pulses, an optical tunable delay line (OTDL) is used in the signal branch. Subsequently, the pump comb and the signal comb with respective phase profiles are combined (shown in Fig.2(c)) and directed to a 200-m highly nonlinear fiber (HNLF) with nonlinear coefficient γ =30 W^{-1}·km^{-1}. A counter-propagating Raman pump at 1465 nm is launched from the opposite end of the HNLF and is filtered out after its propagation in the fiber. An optical spectrum analyzer (OSA) with a resolution of 0.02 nm is used to measure the spectra, and a 500-GHz bandwidth optical sampling oscilloscope (OSO) is utilized to measure the temporal traces. In Fig.2(d), the red trace shows the measured spectrum without the DRA, where an idler comb with enhanced mode spacing of 94.5 GHz centered at 1538 nm is generated, corresponding to a multiplication factor m = 7. Upon the use of DRA with an average input power of 36 dBm, the wide-spacing idler is significantly amplified (shown in blue curve in Fig.2d). Temporal traces of the pump, signal, and idler are captured via the OSO and are depicted in Fig.2(e). The repetition rates of the pump and idler are both 94.5 GHz, while the signal pulses exhibit a repetition rate of 189 GHz. The spectral gain is shown in Fig.2(f). The frequency tone at 1538 nm achieves a 21 dB gain, with higher gains (over 30 dB) observed at other

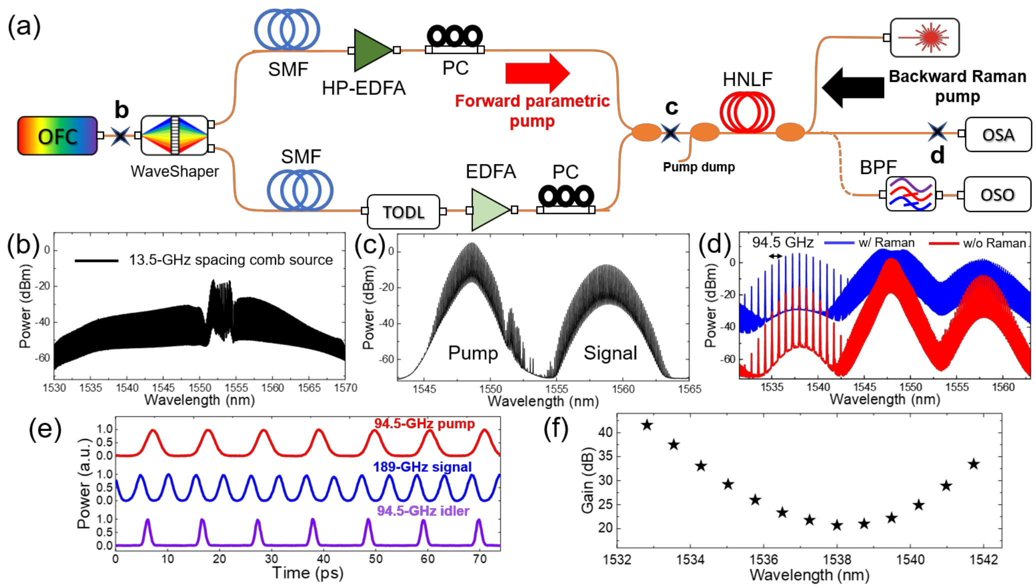

Fig. 2. (a) Experimental setup. SMF: single-mode fiber; TODL: tunable optical delay line; HP-EDFA: high power erbium-doped fiber amplifier; PC: polarization controller; BPF: bandpass filter; HNLF: highly nonlinear fiber; OSO: optical sampling oscilloscope; OSA: optical spectrum analyzer. (b) Spectrum of the 13.5-GHz spacing comb source. (c) Input spectrum of the pump and signal before the HNLF. (d) Output spectrum after Raman-assisted parametric process. (e) Temporal traces of the pump, signal, and idler. (f) Achieved gain at each frequency tone.

idler wavelengths. Apart from simplifying the setup by using the same HNLF for FWM and DRA, Raman amplification compares favorably to lumped fiber amplification owing to the reduced noise figure, widening of FWM gain spectrum, and suppression of its wavelength dependence [10].

To assess the quality of the generated 94.5-GHz wide-spacing OFC, we filter out each optical carrier to serve as a laser source for 80-km transmission. A probabilistic constellation shaped (PCS)-based coherent system is experimentally demonstrated, as shown in Fig.3. At the transmitter side, pseudo random bits sequence (PRBS) is generated and mapped to PCS signals with an entropy of 5.1 bits. Each optical carrier is modulated by an I/Q modulator (IQM) driven by an arbitrary waveform generator (AWG). After 80-km transmission, the signal quality is measured using a 22-GHz bandwidth coherent receiver followed by a 256 GSa/s real-time oscilloscope. The NGMI is plotted against the received optical power (ROP) that can be adjusted by a variable optical attenuator (VOA) in Fig.3(b). The highest NGMI at ROP of -10 dBm is 0.904 with DRA and 0.88 without DRA. With Raman and parametric-assisted S-TAI, all performances are above the 25% SD-FEC threshold at any ROP between -10 and -20 dBm. Meanwhile, to reach above the 20% SD-FEC threshold, a ROP of -17 dBm is required for the DRA case, as compared to -12 dBm without Raman amplification. Fig. 3(c) depicts the GMI against the carrier wavelength. High-quality performances are obtained for all the 10 carriers within the range of 1537.3 to 1541.0 nm. All of them exceed the 25% SD-FEC threshold, indicating the excellent transmission quality of the mode-spacing multiplied OFC.

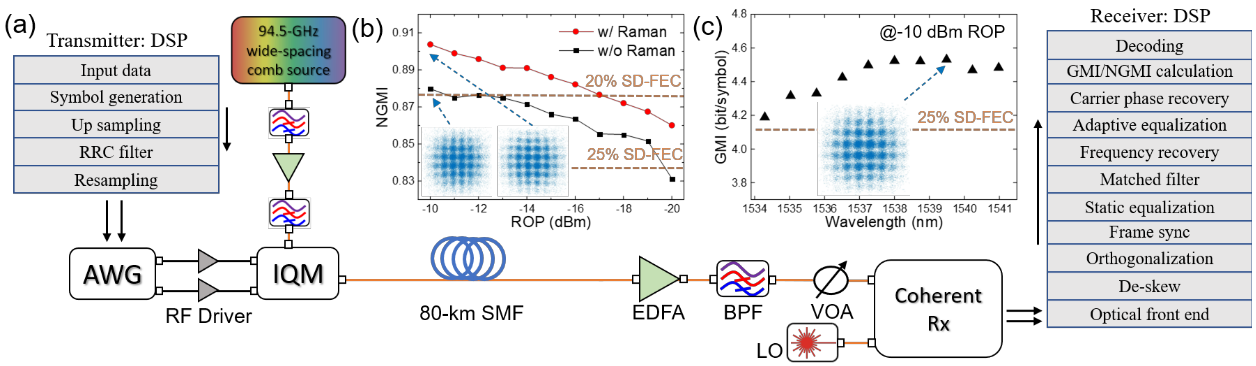

Fig. 3. (a) Schematic of the coherent optical transmission system using a 94.5-GHz wide-spacing comb source. (b) The system performance with varying ROP at the wavelength of 1538nm. (c) The system performance at different wavelength under -10 dBm ROP.

In conclusion, we demonstrate an all-fiber scheme for mode spacing multiplication of an OFC. By synergizing DRA and FWM in an all-fiber S-TAI, the mode spacing has been multiplied from 13.5 to 94.5 GHz, while the newly generated frequency tones feature high power and sufficiently large CNR. The wide-spacing comb is used as a multi-carrier source for 32-Gbaud PCS-64QAM modulation. After 80-km optical transmission, the measured performances of all channels are above the SD-FEC threshold with 25% overhead. It is anticipated that higher modulation rates can be effectively supported by the OFC carriers. Our demonstration paves an effective approach for widening the mode spacing and enhancing the power of OFCs, thus enabling their application in diverse disciplines.

Acknowledgments

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References

[1] S. A. Diddams, *et al.*, “Optical frequency combs: Coherently uniting the electromagnetic spectrum,” Science **369**, 6501, 2020.
[2] A. A. Jørgensen, *et al.*, “Petabit-per-second data transmission using a chip-scale microcomb ring resonator source,” Nat. Photon. **16**, 11, 2022.
[3] T. J. Kippenberg, R. Holzwarth, and S. Diddams, “Microresonator-based optical frequency combs,” Science **332**, 555-559, 2011.
[4] B. Y. Kim, *et al.*, “Coherent combining for high-power Kerr combs,” Laser Photonics Rev. **17**, 8, 2023.
[5] B. Crockett, L. R. Cortés, S. Konatham, and J. Azana, “Full recovery of ultrafast waveforms lost under noise,” Nat. Commun. **12**, 2402, 2021.
[6] L. R. Cortés, R. Maram, H. Chatellus, and J. Azana, “Subnoise detection and passive amplification of frequency combs through customized coherent spectral energy redistribution,” Phys. Rev. Appl. **9**, 6, 2018.
[7] Z. Li, Q. Xie, Z. Zhang, Y. Zhang, H. Zhang, and C. Shu, “All-optical purification of arbitrary spectral waveforms via cross-phase modulation based spectral Talbot amplifier,” in CLEO 2023, paper STh3N.2.
[8] Z. Li, Q. Xie, Y. Zhang, H. Zhang, C. Huang, and C. Shu, “Parametric-assisted fiber-optic Talbot amplifier for carrier-to-noise ratio enhancement of optical frequency combs,” in European Conference on Optical Communications (ECOC) 2023, paper P33.
[9] L. R. Cortés, R. Maram, H. Chatellus, and J. Azana, “Arbitrary Energy-Preserving Control of Optical Pulse Trains and Frequency Combs through Generalized Talbot Effects,” Laser Photonics Rev. **13**, 12, 2019.
[10] X. Guo, X. Fu, and C. Shu, “Gain-saturated spectral characteristics in a Raman-assisted fiber optical parametric amplifier,” Opt. Lett., **39**, 3658, 2014.