6.48 Tb/s Transmissions Using 50 GHz Integrated Lithium Niobate Flat-Top Electro-Optic Combs

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Abstract: We demonstrate 6.48 Tb/s transmission using 50-GHz integrated lithium niobate flat-top electro-optic (EO) combs over a 53-km field-deployed link and show their flexibility in generating combs with variable frequency spacing and using multiple laser sources. © 2024 The Author(s)

1. Introduction

Frequency combs are important for various applications including optical communications. It is envisioned that good combs with high power and low ripples can replace traditional lasers to reduce cost and form factors in WDM systems for long-haul as well as short-reach transmissions. Transmissions using dissipative Kerr solitons have been demonstrated [1]. However, Kerr combs suffer from large tone ripples due to their dispersion-restricted roll-off spectrum [2] and hence equalization techniques are required, leading to much waste of comb lines power and excessive losses. Besides, they have limited flexibility for their resonator-restricted free-spectral range and pump frequency. Moreover, they rely on complicated pump sweeping and feedback control techniques for soliton generation and stabilization. Alternatively, EO comb is a promising technology with high flatness, flexibility, and stability. We have previously demonstrated a power-efficient multi-pass EO comb generator on thin film lithium niobate (TFLN) [3], which is a promising photonic integrated circuits platform owing to its low loss, strong Pockels effect, and wafer-scale fabrication feasibility. However, a system-level investigation of EO combs and its advantages in a practical optical transmission system have yet to be undertaken.

In this paper, we demonstrate, to the best of our knowledge, the first 50 GHz EO comb on integrated LN platform and an 18-channel WDM transmission with a total bit rate of 6.48 Tb/s (net rate 5.4 Tb/s) over a 53-km field-deployed link. We further show the flexibility of EO combs such as allowing different RF driving frequencies (in our case 25 GHz and 50 GHz RF frequencies on 2 EO combs fabricated on the same chip) to produce combs with different frequency spacing as well as the ability to simultaneously generate two combs using two laser sources.

2. EO Comb and experimental setup

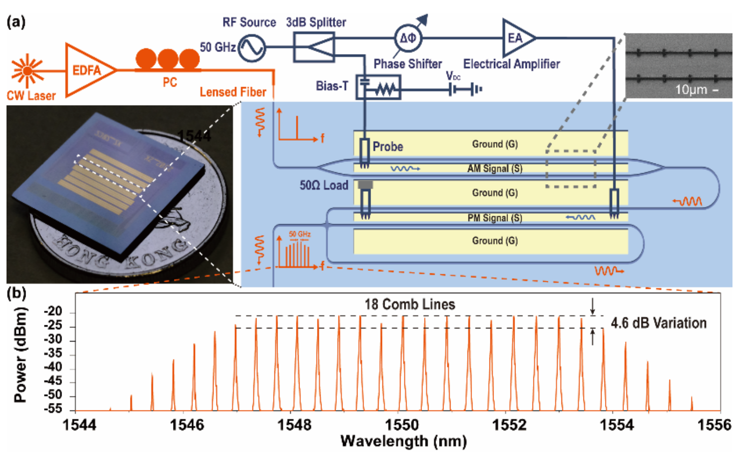

Fig. 1. (a) Schematic of flat-top EO comb generation; (b) Generated tone spectra with 50 GHz spacing.

The schematic of our 50 GHz flat-top comb generation on LN platform is shown in Fig. 1, where an amplitude modulator (AM) and a phase modulator (PM) are cascaded as a time-lens system [4], generating a flat-top comb with 4.6 dB power variation within 18 comb lines. A continuous wave (CW) light from the CW laser is amplified and coupled to our x-cut LN chip through a lensed fiber, in between a polarization controller ensures quasi-TE mode coupling to align the LN z-crystal direction. We realize efficient EO modulation through carefully designed electrodes (right-top) with small gap (5μm) and capacitive-loaded structures for velocity-matching [5]. The CW light is first modulated by the AM to generate flat-top pulse in time domain, whose profile is then mapped to frequency domain by the cascaded double-pass PM (time-to-frequency conversion) [3], generating a flat-top EO comb. The radio-frequency (RF) source ensures the come line spacing (50 GHz), which can be flexibly tuned. The RF signal is split to two channels and applied to the AM and PM respectively by RF probes. An RF phase shifter aligns the relative phase of two modulators. For AM channel, a bias-T is used to control the bias point of the AM and the flat-top temporal pulse generation. For PM channel, the RF signal is amplified to ~33 dBm by an electrical amplifier, which can be flexibly tuned to control the comb line number (comb span). Fed with an amplified source ECL laser with power of 28 dBm and amplified RF sinusoidal signal, the TFLN chip generated 50 GHz-spaced comb tones with spectrum shown in Fig. 1. A tone ripple of 4.6 dB is achieved for the middle 18 tones of the comb spectra and information is modulated onto them for WDM transmissions. Our flat-top EO combs show much improved tone ripples compared with the roll-off pattern of Kerr combs and hence no power equalization technique is applied to the tones in our experiment. Fig. 2 shows the experimental setup. The comb tones are amplified and modulated by a polarization-multiplexed (PM) IQ modulator with 45 GBaud PM-16 QAM signal before amplified again and launched into fiber. The deployed fiber loop consists of three standard single-mode fiber links: green line (from Hong Kong Polytechnic University (HKPolyU) to a data center in Tseung Kwan O (TKO)), red line (from TKO to a data center in Chai Wan) and blue line (from Chai Wan to HKPolyU) as shown in Fig. 2. The transmitter and receiver are co-located in the lab at HKPolyU and the total length of this fiber loop is 53 km, which passes through the busiest streets in Hong Kong, rural mountainous areas as well as under the sea and along the cross-harbour tunnel. The received signal is then coherently detected and sampled by a digital oscilloscope (Keysight, Z594A, 80 GSa/s, 33 GHz) and processed offline. The sampled signal passes through a series of digital signal processing (DSP) consisting of CD compensation, polarization demultiplexing using constant modulus algorithm (CMA) + radius directed equalization (RDE), signal 4th-power based carrier frequency recovery (CFR), Kalman filter-based carrier phase recovery [6] (CPR) followed by decision and bit error counting for each channel.

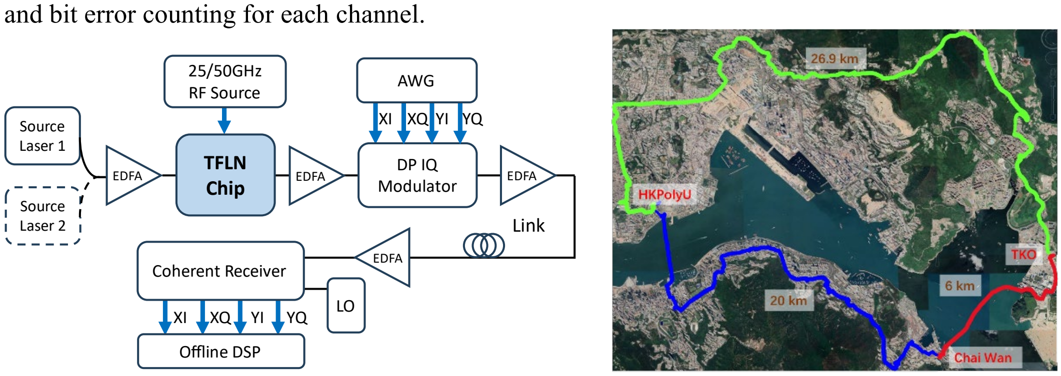

Fig. 2. WDM transmission experimental setup and the route of the field-deployed link across Hong Kong.

3. Results and discussions

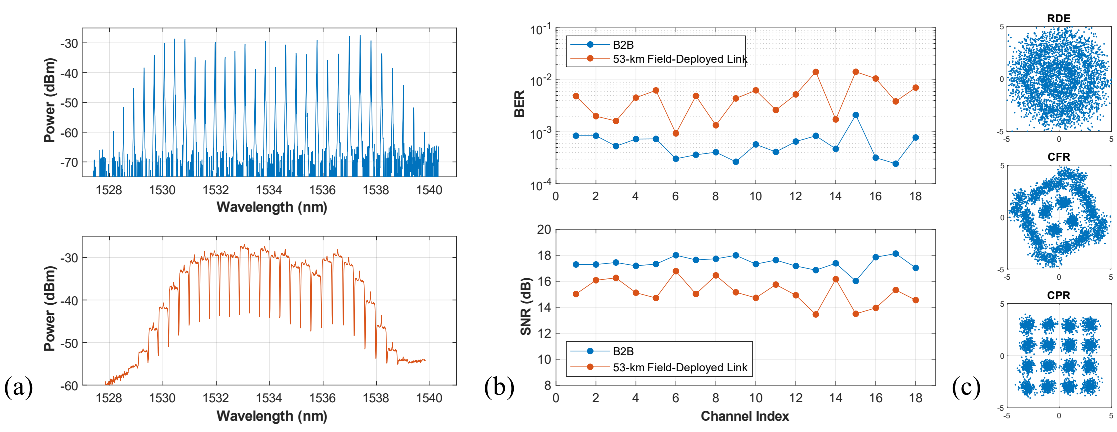

Fig. 3. (a) Spectrum of the 50 GHz EO comb and corresponding WDM signal; (b) SNR and BER of the 50 GHz EO comb WDM signal for B2B and 53-km field-deployed link transmission. (c) Received signal distributions at various stages of receiver DSP.

We first generate a 50 GHz comb, and the spectra is shown in Fig.3(a). A 50 GHz RF tone is generated by a sinusoidal signal generator which is then amplified by electrical amplifiers and fed into the TFLN chip. Thanks to the good flatness of our as-generated EO comb, no wavelength selective switch (WSS) is used for equalizing the powers of the central 18 tones. We test the comb WDM signal in B2B and the 53-km deployed link transmission with a total loss of 30 dB. The SNR and BER of each channel are shown in Fig. 3(b). The SNR ripples for B2B transmission are 2 dB and it grows to 3.5 dB after fiber transmission due to the nonideal gain and noise figure spectrum of the EDFA. The BER obtained is below the soft decision-forward error correction (SD-FEC) threshold of $2.4\text{x}10^{-2}$ for all 18 channels and therefore the total bit rate is 18×45 Gb/s $\times 2 \times 4 = 6.48$ Tb/s or a net rate of 5.4 Tb/s over 53-km field-deployed fiber.

To illustrate the unique flexibility advantages of EO combs over other types of combs, we have also performed WDM transmission experiments using two 25 GHz combs simultaneously generated by pumping with 2 input lasers. The 25 GHz comb generator is fabricated on the same chip as the 50 GHz comb source using the same design strategy, but with an optical delay line in the loop structure designed for phase matching with a 25 GHz RF signal. The generated 2-comb spectrum is shown in Fig.4(a). The power ripple is higher than the case for single input laser, and we attribute it to the wavelength-dependent bias control values and non-flat EDFA gain, which can be addressed by using a balanced Mach-Zehnder interferometer structure and EDFA with flatter gain. The transmission performance and received signal distributions over the field-deployed fiber is shown in Fig. 4(b) and (c). 30 channels of 20 GBaud PM-16 QAM signal are successfully transmitted with BER below $2.4\text{x}10^{-2}$. The received signal distributions periodically exhibit nonideal IQ orthogonality over wavelength due to the nonideal bias control in the IQ modulator.

(a) (b) (c)

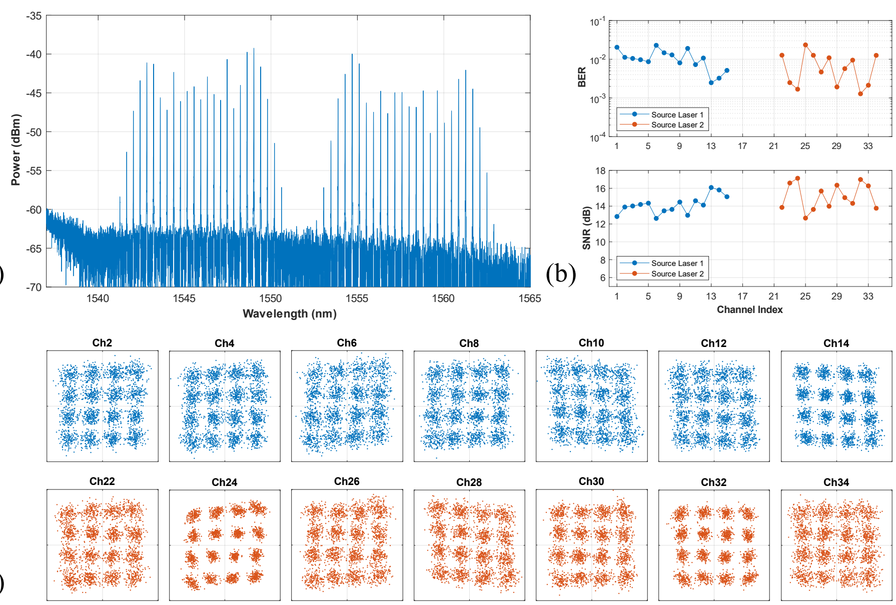

Fig. 4. (a) EO comb spectrum using 2 laser inputs with 25 GHz spacing; (b) SNR and BER of the 2-laser comb after transmission over 53-km field-deployed fiber; (c) Received signal distributions for sample channels of the 2-laser comb.

4. Conclusions

In this paper, we demonstrate the first 50 GHz EO comb on integrated LN platform and an 18-channel WDM transmission with a total bit rate of 6.48 Tb/s (net rate 5.4 Tb/s) over a 53-km field-deployed link. The flexibility advantages of EO combs such as variable comb frequency spacing and multiple comb generation using multiple laser sources are also shown.

5. Acknowledgements

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