30-Gbps 100-km OFDM Transmission Using 10-GHz DML and Adiabatic-Chirp-Involved SSII Cancellation

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Abstract: We experimentally verified the influences of adiabatic chirp on DML-based OFDM transmission, including fading and nonlinear distortion. Employing the proposed SSII cancellation, the capacity over 100-km transmission was increased by 55% to record-high 30 Gbps.

OCIS codes: (060.3510) Lasers, fiber; (060.4080) Modulation; (060.4510) Optical communications

1. Introduction

Despite the advance of coherent detection, intensity modulation and direct-detection (IMDD) is still the most promising scheme in short-range ($<\sim$100 km) systems due to its cost-efficiency. While an electro-absorption modulated laser (EML) is widely used in different short-range systems, the applications of a directly modulated DFB laser (DML), which can provide higher output power, are limited to very short distance of $\sim$10 km and/or low data rate of $\sim$10 Gbps. Since both transient and adiabatic chirp would limit the transmission performance of DMLs, a chirp-managed laser consisting of a DML and an optical filter has been developed for extending the reach of 10-Gbps [1] and 25-Gbps [2] on-off keying (OOK) signals to $>$200 km and $\sim$40 km, respectively.

Combined with quadrature amplitude modulation (QAM), orthogonal frequency-division multiplexing (OFDM) signals can effectively achieve high spectral efficiency and ultimately lower the bandwidth requirements of components. Utilizing a stat-of-art digital-to-analog converter, 100-Gbps DML-based OFDM has been demonstrated [3], but the reach is limited to 10 km. There are two main issues to limit the transmission distance. First, detrimental dispersion-induced power fading could reduce available transmission bandwidth. Although positive transient chirp would deteriorate fading, it has been shown that fading might be eased by adiabatic chirp [4]. Second, nonlinear distortion, which is also caused by the interplay between dispersion and chirp, will deteriorate signal performance. For OFDM signals, the distortion has been modeled as subcarrier-to-subcarrier intermixing interference (SSII) [5, 6]. It should be noted that adiabatic chirp is omitted in [5]; there, it fits the case of using an EML, instead of a DML. By slightly modifying the model in [5], an SSII cancellation scheme has been proposed to eliminate the nonlinear distortion [7]. Although an alternative scheme, Voltera filtering, has been employed in a DML-based system [8], the effectiveness of SSII cancellation on DML-based transmission has not been experimentally confirmed and investigated.

In addition to experimentally confirming that adiabatic chirp can eliminate fading to enable more transmission bandwidth, this work realized and compared the SSII cancellation based on two models. One neglects adiabatic chirp [5], and the other takes it into account [6]. For OFDM signals after 100 km, the adiabatic-chirp-involved SSII cancellation can achieve the improvement of up to 7 dB in signal-to-noise ratio (SNR), but the other one can only achieve that of $<$3 dB, revealing that adiabatic chirp is critical to the nonlinear distortion. Without SSII cancellation, the maximum capacity over 100-km transmission is 19.5 Gbps using a 10-GHz DML, and it can reach 30.3 Gbps using the adiabatic-chirp-involved SSII cancellation, indicating 55% capacity improvement.

2. SSII model of a DML

As in [5], the output power of a DML can be expressed as $P = P_b(1+X)$, where P_b and X are bias power and a normalized driving OFDM signal, and its frequency chirp is $\Delta\nu = \frac{\alpha}{4\pi}\frac{\mathrm{d}}{\mathrm{d}t}\ln P + \frac{\alpha}{4\pi}\kappa P$, where the first and the second terms indicate transient and adiabatic chirp, respectively. α is the linewidth enhancement factor and κ is a constant related to optical gain compression [4], and α and κ of commercial DMLs are about 2–5 and 10–15 GHz/mW, respectively. Thus, chirp-induced phase modulation is $\phi = 2\pi\int\Delta\nu\,\mathrm{d}t = \frac{1}{2}\alpha\ln(1+X) + \frac{1}{2}\Omega\bar{X}$, where $\Omega = \alpha\kappa P_b$ and $\bar{X} = \int X\,\mathrm{d}t$. Then, the normalized optical field can be written as $E_n = \sqrt{P/P_b}\,e^{-j\phi} \approx 1 + S_1 + S_2$ [6], where $S_1 = \frac{1}{2}(1-j\alpha)X - j\frac{1}{2}\Omega\bar{X}$ and

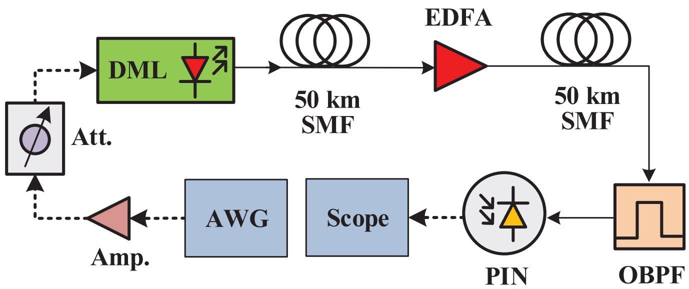

Fig. 1: Experiment setup of the DML-based 100-km transmission (Att.: attenuator; Amp.: amplifier; OBPF: optical bandpass filter)

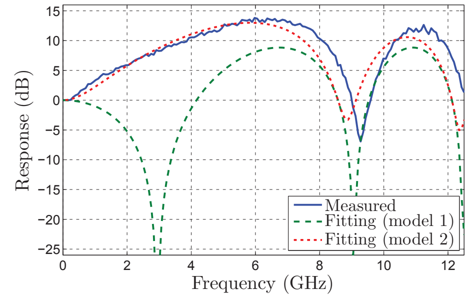

Fig. 2: Frequency response after 100-km transmission

$S_2 = -\frac{1}{8}(1+\alpha^2)X^2 - \frac{1}{8}\Omega^2\bar{X}^2 - j\frac{1}{4}\Omega(1-j\alpha)X\bar{X}$ are the 1st-order signal and the 2nd-order distortion. After dispersive fiber6 transmission and square-law detection, the detected signal is,

$$\left|\Theta[E_n]\right|^2 \approx 1 + 2\Re\{\Theta[S_1]\} + \left(\left|\Theta[S_1]\right|^2 + 2\Re\{\Theta[S_2]\}\right) \qquad (1)$$

where $\Theta[\cdot]$ indicates the dispersion effect, and $\Re\{\cdot\}$ gives a real part. Analyzing the signal $2\Re\{\Theta[S_1]\}$ in (1) yields the power fading at frequency f,

$$\gamma(f) = \left(1+\alpha^2\right)\cos^2\left(2\pi^2\beta_2 L f^2 - \tan^{-1}\alpha\right) + \frac{\Omega^2}{4\pi^2 f^2}\sin^2\left(2\pi^2\beta_2 L f^2\right) \qquad (2)$$

where β_2 and L are the dispersion parameter and the fiber length, respectively. It should be noted that, the last term in (1) denotes the received 2nd-order nonlinear distortion, referred as SSII. By regarding a demodulated OFDM signal as X, SSII (i.e., major part of nonlinear distortion) can be estimated in accordance with (1) to enable SSII cancellation [6].

3. Experiment setup and results

Fig. 1 exhibits the experiment setup of DML-based single-mode fiber (SMF) transmission. The electrical OFDM signal was generated by an arbitrary waveform generator (AWG, Tektronix® AWG70002A) with 40-GS/s sampling rate and 8-bit resolution. The 2nd–109th subcarriers were used to carry QAM data, and the bandwidth was 8.5 GHz. The 10-GHz DML (Gooch & Housego AA0701) was operated at the bias current (I_{bias}) of 50-90 mA and wavelength of around 1550 nm. The power of the driving signal was adjusted to keep the same carrier-to-signal power ratio (CSPR) for different I_{bias}. After 100-km transmission and direct-detection, the received electrical signal was recorded by a digital oscilloscope (Agilent DSO81204A) with 40-GS/s sampling rate, 8-bits resolution and 3-dB bandwidth of 12 GHz. An off-line DSP program was then applied to demodulate the OFDM signal, including the SSII cancellation. To verify the importance of adiabatic chirp, the SSII cancellation based on a model without considering adiabatic chirp [5] (i.e., $\Omega = 0$, referred as model 1) is compared with that based on a complete model, referred as model 2. The signal performance was evaluated by SNR and bit error rate (BER), which was determined by bit-by-bit comparison.

Fig. 2 plots the measured frequency response of 100-km fiber using I_{bias} of 90 mA. Fitting the measured data by (2) can estimate the chirp-related parameters, Ω and α. Using those parameters, the fitting curves based on model 1 (forcing $\Omega = 0$) and model 2 are also plotted in Fig. 2 for comparison. Without adiabatic chirp, the band at 2–3.5 GHz would suffer from fading of >5 dB; there, reconfirming the effect of adiabatic chirp to mitigate fading (i.e., the highpass behavior [4]). For the sake of simplicity, the modulation format was fixed as 16-QAM in the beginning of the experiment, and Fig. 3(a) shows the measured SNR of the 16-QAM OFDM signal, using various I_{bias}. Since Ω is proportional to P_b, lower I_{bias}, such as 50 mA in Fig. 3(a), could result in more fading and lower SNR at $\sim$3 GHz. The SNR after employing SSII cancellation is included in Fig. 3(a), and the corresponding improvement is shown in Fig. 3(b). Using model 1 to realize SSII cancellation, the improvement in SNR is limited to <3 dB because of omitting the contribution of adiabatic chirp. However, if I_{bias} is lowered to reduce Ω, the reduction of improvement in SNR caused by neglecting Ω would be smaller. For instance, the case of $I_{\text{bias}} = 55$ mA in Fig. 3(b) shows less difference between two models, as compared with the other cases.

According to the measured SNR of the 16-QAM OFDM signals, the bit-loading algorithm was then applied to estimate the maximum transmission capacity with and without SSII cancellation. Fig. 4 shows the estimated data rates to reach the FEC limit (i.e., BER of 3.8×10^{-3}) over the transmission of 0–150 km. Similar to the above discussion, relatively more improvement can be achieved by using the adiabatic-chirp-involved cancellation (model 2)

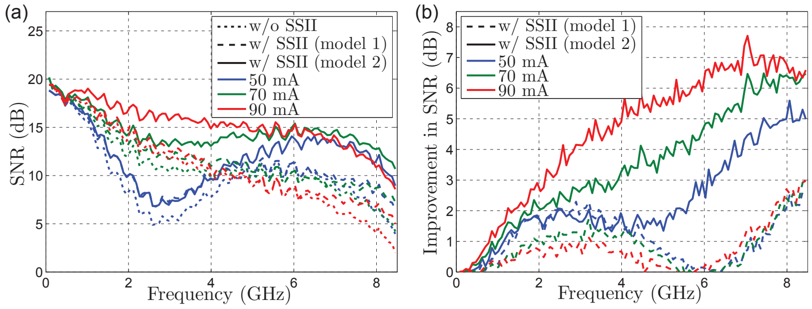

Fig. 3: (a) SNR and (b) improvement in SNR at different I_{bias} over 100-km transmission

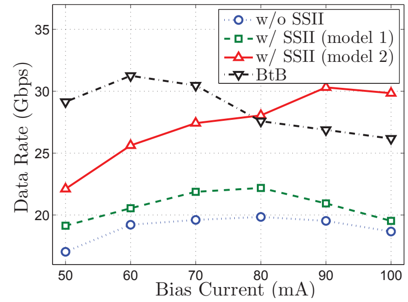

Fig. 4: The estimated data rate at different I_{bias} over 100-km transmission

at higher I_{bias}, while the adiabatic-chirp-irrelevant cancellation (model) 1 keeps similar improvement in data rate for signals at various bias currents. Specifically, the improvement in data rate is always less than $\sim$2.3 Gbps using the adiabatic-chirp-irrelevant cancellation. In contrast, the improvement of up to 10.8 and 11.2 Gbps can be achieved by the adiabatic-chirp-involved SSII cancellation at I_{bias} of 90 and 100 mA, respectively, leading to 55% and 60% improvement. Besides, the capacities at optical back-to-back (BtB) are also shown in Fig. 4 for comparison. Due mainly to the power saturation of the DML at high current, higher I_{bias} leads to lower data rate at optical BtB; however, higher I_{bias} also generates more adiabatic chirp and power gain (as in Fig. 2), such that the data rate could be increased after dispersive transmission. Furthermore, to confirm the feasibility of the estimated data rates in Fig. 4, we selected the case at $I_{bias} = 90$ mA, which can achieve the highest data rate after SSII cancellation, to experimentally demonstrate the bit-loaded OFDM transmission. In accordance with the SNR at $I_{bias} = 90$ mA in Fig. 3(a), the bit-loaded signals were generated and evaluated, and the data rates are 19.5, 20.9, and 30.3 Gbps for the cases without SSII and with SSII cancellation (model 1 and model 2), respectively. The measured SNR of the bi-loaded signals are shown in Fig. 5. The measured BERs are 1.4×10^{-3}, 1.2×10^{-3} (3.7×10^{-3} before the adiabatic-chirp-irrelevant cancellation), and 1.1×10^{-3} (2.7×10^{-2} before the adiabatic-chirp-involved cancellation), and all are lower than the FEC limit. In addition, selected constellations of the 30.3-Gbps signal before and after SSII cancellation are also shown in Fig. 5.

4. Conclusion

This work employs the SSII cancellation, which takes adiabatic chirp into account, in a DML-based OFDM system. Compared with the cases without SSII cancellation, the SNR improvement is up to 7 dB, and the data rate is improved by 55% to achieve a record data rate of 30 Gbps after 100-km dispersion-uncompensated fiber transmission.

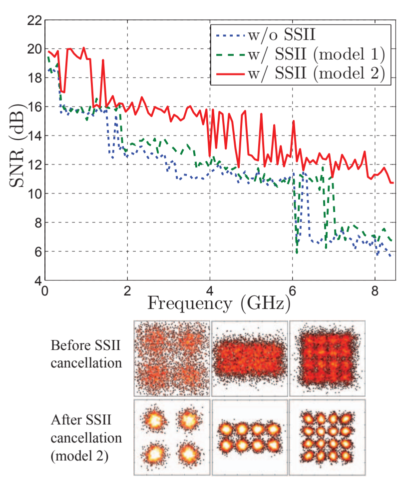

Fig. 5: The SNR of the bit-loaded OFDM signals at $I_{bias} = 90$ mA, and the selected constellations of the 30.3-Gbps signal

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