2 Tb/s Single-ended Coherent Receiver

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Abstract We demonstrate a single-ended coherent receiver with a record net data rate of 2 Tb/s in B2B, showing 3 dB OSNR advantage compared to the conventional coherent receiver at a LOSPR of 10 dB. Over 80 km, a net data rate of 1.872 Tb/s is achieved.

Introduction

Conventional coherent receivers (CR) utilize balanced photodetectors (BPDs) with high common-mode rejection ratios (CMRR) to mitigate the nonlinear signal-signal beat interference (SSBI) resulting from the square-law detection process. A high CMRR places stringent requirement on the balances of optical hybrid, RF circuitry and on the similarity of the two single-ended PDs in responsivities, polarization dependences and frequency responses [1]. As the symbol rate increases to 100 Gbaud and beyond for future 800 Gb/s and 1.6 Tb/s transponders, fulfilling these requirements in a cost-effective manner becomes challenging.

The abovementioned requirements can be eliminated by using single-ended PDs instead of balanced PDs [2-5]. A It has been shown at low baudrates that the SSBI can be mitigated using low-complexity DSP algorithms [4-5]. However, prior to SSBI cancellation, the Rx response must be accurately compensated [6-7]. For high baudrate systems, this separate calibration task becomes complicated and time-consuming. Recently, an effective DSP scheme which enables self-calibration of single-ended receivers (SERs) has been proposed in [8] and a capacity for SER of 882 Gb/s over 100 km has been demonstrated using the direct field reconstruction (DFR) and clipped iterative SSBI cancellation (CIC) schemes.

In this paper, we extend the developed techniques in [8] and demonstrate a 100 GHz SER for the reception of a 2×100 Gbaud dual-carrier PCS-256 QAM signal at a record capacity of 2 Tb/s in the B2B. At such high baudrate, due to the degraded performance of commercial 100 GHz BPDs at high frequencies, SER can provide a significant benefit over the conventional CR, showing a 3 dB OSNR advantage when the local oscillator to signal power ratio (LOSPR) was set to 10 dB. Over 80 km transmission, a capacity of 1. 872 Tb/s was achieved, which is the highest capacity of a CR demonstrated up to date.

Field reconstruction in SER

Considering a single-polarization SER [8], the received signals after ADCs are:

$$\begin{cases} R_1 = \boldsymbol{Y}_1 \otimes (A^2 + I^2 + Q^2 + 2AI) \\ R_2 = \boldsymbol{Y}_2 \otimes (A^2 + I^2 + Q^2 + 2AQ) \end{cases}, \qquad (1)$$

where $\otimes$ stands for convolution; $\boldsymbol{Y}_1$ and $\boldsymbol{Y}_2$ are the responses of PD 1+ADC 1 and PD 2+ADC 2, respectively; I and Q are the inphase and quadrature components of the optical field and A is the amplitude of the local oscillator (LO). After compensating the responses of PDs and ADCs, Eq. (1) effectively becomes a system of 2 quadratic equations with two unknowns. Using some simple manipulations, we have $I - Q = (R_1 - R_2)/(2A)$ and $(I + Q + A)^2 = \Delta = R_1 + R_2 - A^2 - (R_1 - R_2)^2/(4A^2)$. For typical LO to signal power ratio (LOSPR) values, we can assume $I + Q + A \geq 0$. Thus, when $\Delta\ \geq 0$, Eq. 1 have a unique solution:

$$\begin{cases} I = -A/2 + (R_1 - R_2)/(4A) + \sqrt{\Delta}/2 \\ Q = -A/2 + (R_2 - R_1)/(4A) + \sqrt{\Delta}/2 \end{cases}, \qquad (2)$$

Field reconstruction (FR) used Eq. (2) is called DFR. Eq. 1 can also be solved in an iterative manner in a similar way compared to the clipped iterative SSBI cancellation schemes for SSB DD transmissions [9]. The block diagram of the CIC

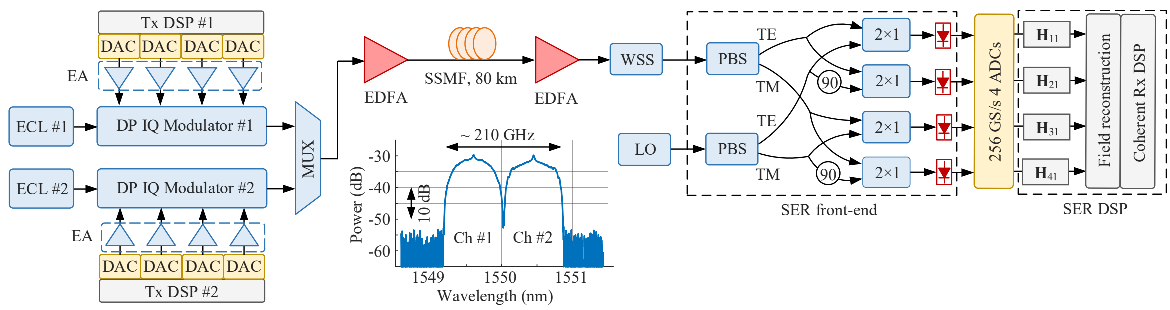

Fig. 1. Experimental setup for dual-carrier transmission at an aggregated baudrate of 200 Gbaud (2×100 Gbaud) PCS-256QAM over 80 km using a 100-GHz SER; inset shows the optical spectrum of the dual-carrier signal at the Tx

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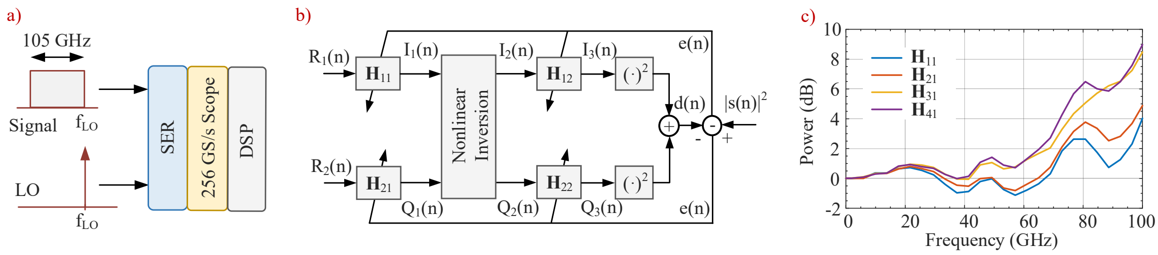

Fig. 2a) – Calibration mode with single-polarization 100 Gbaud 16 QAM signal for SER; b) – block diagram of the self-calibration mode; c) – frequency responses of the 4 obtained digital filters

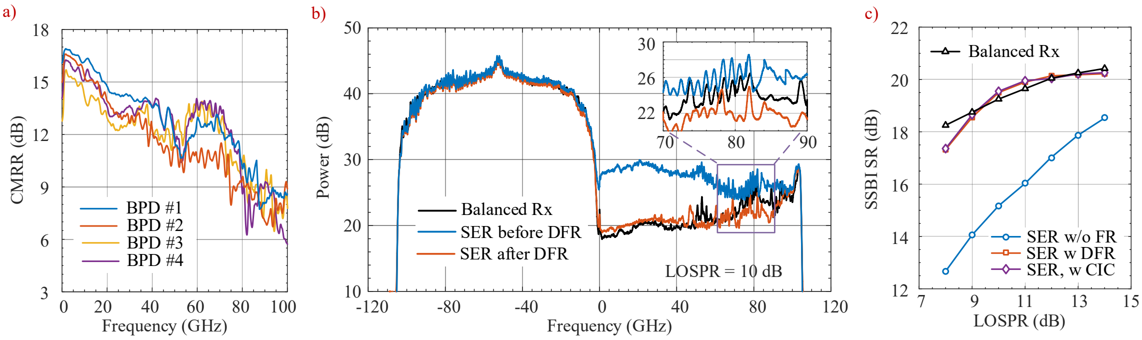

Fig. 3a) – Measured CMRR of 4 BPDs (with the optical hybrid); b) – Electrical signal spectra of the received 100 Gbaud signal in heterodyne reception mode with SERs with and without DFR and for balanced Rx when the LOSPR is 10 dB; c) – SSBI SR for SER with CIC with 4 iterations and DFR and balanced Rx as function of LOSPR.

algorithm and more detail on self-calibration of SER can be found in [8].

Experimental setup and transmission results

The experimental setup is shown in Fig. 1. At the Tx, for each carrier, 100 Gbaud DP PCS-256 QAM signal with the entropy of 6 bits/symbol/polarization was generated using RRC filter with a roll-off factor of 5%. The generated signal after digital pre-emphasis (optimized for maximizing the SNR in the B2B) was then loaded into the memories of 4 CMOS DACs running at 120 GS/s. The 4 outputs of the DACs were amplified and then fed to a DP IQ-modulator which ~ 45 GHz of 3-dB bandwidth. The carrier frequencies of the two carriers were set at 105 GHz spacing and centered at 1550 nm. The two modulated optical carriers were then combined using a 3-dB coupler and then amplified using an EDFA before being launched into a single fiber span of 80 km of SSMF. At the receiver, the signal was amplified by another EDFA and then filtered using a WSS before being received by a SER with a LO at 1550 nm. The SER was effectively formed from a 100 GHz balanced Rx (BRx) by terminating the negative arms of the 4 BPDs. In this case, a fair comparison with the balanced CR can be made. The detected signals were then digitized by 256 GS/s 4-channel 110 GHz real-time sampling scope. The combined received signal power and LO power (both in dBm) was fixed at 16 dBm to maintaining the detected RF signal swing. After digitization, offline signal processing was performed for symbol detection, BER counting, GMI calculation.

The DSP first includes Rx front-end correction using 4 FIR filters ($\boldsymbol{H}_{11}, \boldsymbol{H}_{12}, \boldsymbol{H}_{21}, \boldsymbol{H}_{22}$) with 127 taps. These filters were obtained when the SER was operating at the calibration mode (heterodyne reception) by switching off the first carrier as illustrated in Fig. 2a using the developed self-calibrated routine in [8] (Fig. 2b). In the calibration mode, single-polarization 100 Gbaud 16 QAM signal was used as the training sequence and the LOSPR was set to 9 dB. The converged FIR filters for Rx front-end correction are shown in Fig. 2c. One can note that the PD #3 and PD #4 have lower bandwidths compared to the PD #1 and PD #2.

To illustrate the effectiveness of the SER, we further consider the heterodyne reception mode with 100 Gbaud DP PCS-256 QAM signal as illustrated in Fig. 2a. In this case, the SSBI which is a doubled sideband interference can be clearly observed on one side band of the Rx electrical spectrum as shown in Fig. 3b. We note that the Rx skews have been carefully calibrated to make sure that sideband image is dominated by the SSBI rather than the IQ imbalance. As shown in Fig. 3b for LOSPR of 10 dB, in the case of SER without FR, the SSBI can be clearly observed at the positive frequency region. After the DFR, the SSBI has been effectively removed. In fact, DSP can achieve better SSBI suppression compared to the BPD, especially at high frequencies (above 80 GHz, inset of Fig. 3b). This is because the CCMRs (measured considering both the BPDs

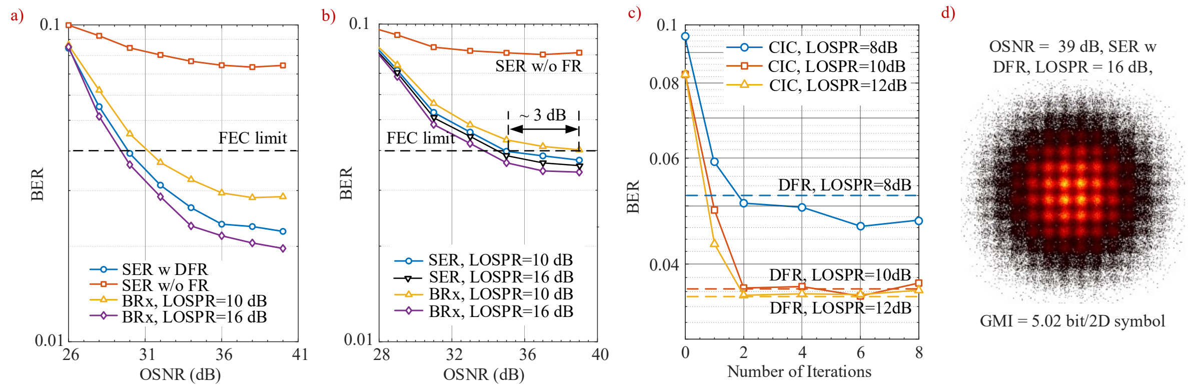

Fig. 4a) – The B2B performance of the single carrier transmission (100 Gbaud) in the heterodyne reception mode for SER and balanced Rx; b) – B2B performances of the dual-carrier transmission (200 Gbaud) for SER and balanced Rx; c) – Performance of the CIC in dual-carrier transmission mode at OSNR of 39 dB; d) – Received constellation for SER at OSNR of 39 dB

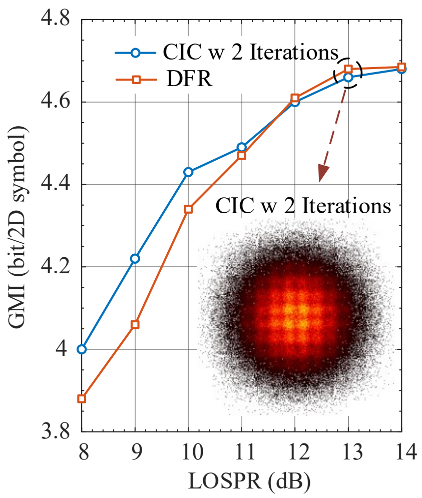

Fig. 5. Transmission over 80 km at 10 dBm of power for dual-carrier (200 Gbaud) system with 100 GHz SER

and the optical hybrid) drop to only ~ 7 dB on average for frequencies above 80 GHz (Fig. 3a). To characterize the effectiveness in SSBI suppression, we define the residual SSBI suppression ratio (SSB SR) over the full band (up to 100 GHz) and compare the SSB SRs with and without DF and BPD as shown in Fig. 3c. One can note that DFR can suppress the SSBI by more than 4 dB at LOSPR of 9 dB and outperforms the BPD when the LOSPR is from 9 dB to 12 dB. A better suppression of the SSBI consequently improves the system performance. The B2B performances of single carrier transmission (100 Gbaud in heterodyne reception mode) and of dual-carrier transmission (200 Gbaud) with 100 GHz SER are shown in Fig. 4a and Fig. 4b for LOSPR of 10 dB. For comparison purpose, we also include the performance of the conventional BRx at LOSPR of 10 dB and 16 dB in these figures. One can note that, without DF, the performance of SER is very poor due to the SSBI. When DFR is used, a BER below the commonly used 25% FEC limit of 0.04 could be achieved for dual-carrier transmission at a LOSPR of 10 dB. In addition, compared to the BRx at the same LO power, SER with DFR shows a 3 dB OSNR advantage at the FEC limit. This confirms the exceptional performance of the developed FR algorithm. When the LOSPR is increased to 16 dB, a GMI of 5.02 bit/2D symbol could be achieved (Fig. 4d). This leads to a record net data rate of 2 Tb/s. On the other hand, at LOSPR of 16 dB, BRx slightly outperforms SER. However, reducing the LO is desirable as it reduces the receiver's power consumption. At OSNR of 39 dB, we compare the performances of DFR and CIC techniques in Fig. 4c. One can note that CIC requires only 2-3 iterations and outperforms the DFR technique when the LOSPR is relatively low (e. g. 8 dB). This different behavior compared to [8] is due to the reduced ADC sampling rate to the symbol rate ratio (e. g. 256 GSas/200 Gbaud in comparison to 256 GSas/95 Gbaud in [8]). When the LOSPR is above 10 dB, CIC and DFR techniques show comparable performances.

For the transmission performance at a launched power to 10 dBm is shown in Fig. 5. Herein, due to the increase in the signal's PAPR, a LOSPR of ~ 13 dB was required for achieving the best performance. When the LOSPR is below 10 dB, CIC with 2 iterations outperforms the DFR technique. At LOSPR of 14 dB, CIC with 2 iterations and DFR show similar performance, achieving a GMI of ~ 4. 68 bit/2D symbol which effectively leads to a net data rate of 1.872 Tb/s.

Conclusions

We have shown that for high baudrate systems (e. g. 200 Gbaud), the SSBI can be cancelled more effectively in the digital domain (in SERs) rather than in the analog domain which is conventionally done using BPD. Using two effective FR techniques, we have demonstrated a 100 GHz SER with a record data rate up to 2 Tb/s. This indicates that SER can be more cost effective than BRx for future 1.6 Tb/s coherent transponders.

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