EML-based Coherent Receiver for Low CSPR Single-Sideband Transmission Enabled by Injection Locking

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Abstract: We propose a novel single-sideband self-coherent detection scheme employing an EML-based receiver and demonstrate a 6.5-dB sensitivity improvement compared with Kramers-Kronig receiver for the SSB 16-QAM signal transmission over 40-km SSMF.

OCIS codes: (060.2330) Fiber optics communications; (060.4080) Modulation.

1. Introduction

The continuous growth of emerging technologies drives the need for high-capacity optical communication systems with low-cost optical transceivers. Due to the simple structure and excellent robustness against fiber dispersion, the single-sideband (SSB) direct-detection (DD) transmission using Kramers-Kronig (KK) receivers is a seriously considered candidate for data center interconnection (DCI) [1]. However, one major drawback of this system is the necessity for high carrier-to-signal power ratio (CSPR) to meet the minimum phase condition, resulting in a relatively low receiver sensitivity. In this regard, some researchers have worked on the modified KK receiver to reduce the required CSPR [2, 3]. Besides, optical carrier recovery based on stimulated Brillouin scattering allows low transmitted CSPR by boosting the carrier at the receiver [4]. To further reduce DSP complexity, a signal-signal beat interference (SSBI)-free system based on phase modulation is proposed without resorting to the KK algorithm [5]. Alternatively, the electro-absorption modulated laser (EML) serving as a self-coherent receiver provides an attractive solution in virtue of optical injection locking (OIL) technique. In recent years, the EML-based receiver has been proposed for radio-over-fiber and passive optical network scenarios, which can be co-integrated with a transimpedance amplifier (TIA) to further improve receiver sensitivity [6, 7]. For realistic deployment, a polarization-independent operation through a tandem-EML design has also been validated [8].

In this paper, we propose and demonstrate a low-cost EML-based coherent receiver in an 8-Gbaud SSB 16-QAM signal transmission system to relax CSPR requirement and improve receiver sensitivity. The nonlinear impairment induced by injection locking for the 16-QAM signal has been effectively eliminated through a neural network (NN)-based equalizer. The experimental results show that the proposed reception approach can provide a 6.5-dB sensitivity improvement with a 14-dB CSPR reduction compared to the standard KK receiver after 40-km fiber transmission.

2. Operation principle

Fig. 1(a) illustrates the operation principle of the direct detection and the EML-based coherent detection for the SSB signal. As shown in inset (ii), the SSBI is inevitable due to the square-law detection of the single-ended photodiode (PD). It is feasible to provide a sufficiently high CSPR or leave a frequency gap to mitigate the impact of SSBI, but at the expense of sacrificing receiver sensitivity or spectral efficiency, respectively. The SSBI iterative cancellation and KK algorithms also require a large CSPR of 6-10 dB. To further improve sensitivity, it is possible to replace the PD with an EML-based receiver, which consists of the electro-absorption modulator (EAM) and the distributed feedback (DFB) laser. After injection-locked to part of the incoming optical SSB signal, the DFB laser will lock and amplify the optical carrier with the same frequency and a fixed phase offset. The DFB-based LO is coupled with another part of the signal and detected by the EAM photodetector, which is reversely biased through a bias Tee [9]. As shown in inset (iii), the carrier-signal beating component is significantly amplified, and thus the impact of SSBI is effectively mitigated without the KK algorithm.

Fig. 1(b) shows the optical injection locking process for the unmodulated optical carrier and the optical SSB signal. To observe the electrical spectra of the DFB output detected by an EAM, two identical EMLs are employed to approximate an integrated EML-based receiver. When injecting a single carrier, the slave laser emission contains the weak injected component plus the very weak harmonic components at integer multiples of the beat frequency in the unlocked state [10], as shown in insets (i) and (ii). By analogy, when injecting an optical SSB signal, the unlocked signal sideband will pollute the LO with additional weak sidebands at the fundamental frequency and higher harmonics reflected from the DFB laser cavity, as shown in insets (iii) and (iv). The harmonic components are aliased in the signal spectrum and degrade system performance, which has a detrimental influence on the 16-QAM signal. To address this problem, we demonstrate a NN-based equalizer aimed to mitigate nonlinear distortion in the OIL process for the case of 16-QAM format.

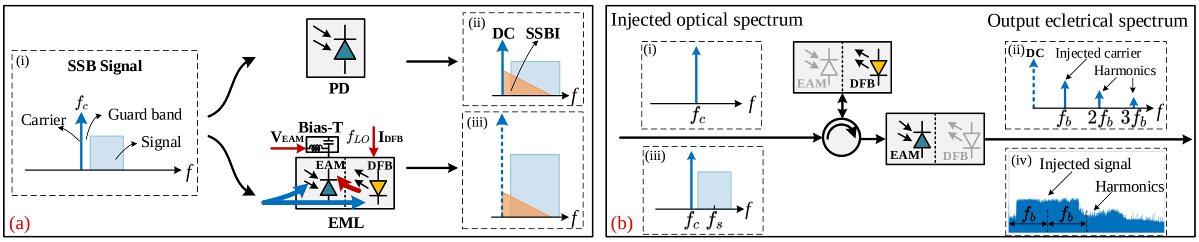

Fig. 1: (a) Schematic diagram of the direct detection and the EML-based coherent detection for the SSB signal. (b) Schematic diagram of optical injection locking for (i-ii) optical carrier in the unlocked state and (iii-iv) optical SSB signal with unlocked signal sideband.

3. Experimental setup and results

The experimental setup is depicted in Fig. 2. At the transmitter, an 8-Gbaud Nyquist 16-QAM signal based on Mersenne random sequence is generated by applying a 0.01 roll-off root-raised-cosine (RRC) filter and then up-converted to a center frequency of 5 GHz with a 1-GHz guard band. The digital signal is loaded onto a 25-GHz arbitrary waveform generation (AWG, Keysight M8195A) operating at 64 GSa/s and then amplified by two linear electrical amplifiers (EAs) before feeding into a 22-GHz I/Q modulator (IQM) biased at null point. The laser source (Santec TSL-710) at around 1575.4 nm is divided into two paths, one for signal modulation, and the other serving as the optical carrier. A variable optical attenuator (VOA) and a polarization controller (PC) are added to the lower path to control the CSPR and align the polarization of the two paths, respectively. As shown in inset (i), the modulated signal is combined with the optical carrier before an L-band erbium-doped fiber amplifier (EDFA) and 40-km standard single mode fiber (SSMF) transmission. At the receiver, an optical bandpass filter (OBPF) is used to suppress the out of band noise. Subsequently, the received optical signal is injected into an EML-based receiver through an optical circulator (OC) by adjusting the polarization with a manual PC. The inset (ii) shows the electrical spectrum of the detected signal. The measured frequency response and device schematic of the EML-based receiver are shown in insets (iii) and (iv), respectively. The electrical signal from the EML is captured by a 25-GHz real-time digital storage oscilloscope (DSO, Keysight DSOX92504A) at 80-GSa/s and processed offline. The output from port three of the OC is for locked state observation using an EAM and an electrical spectrum analyzer (ESA). In the receiver-side DSP, frequency down-conversion is firstly performed, and then matched filtering, down-sampling, equalization, and demapping are carried out in turn for signal recovery. Finally, the bit-error-rate (BER) is calculated for performance evaluation.

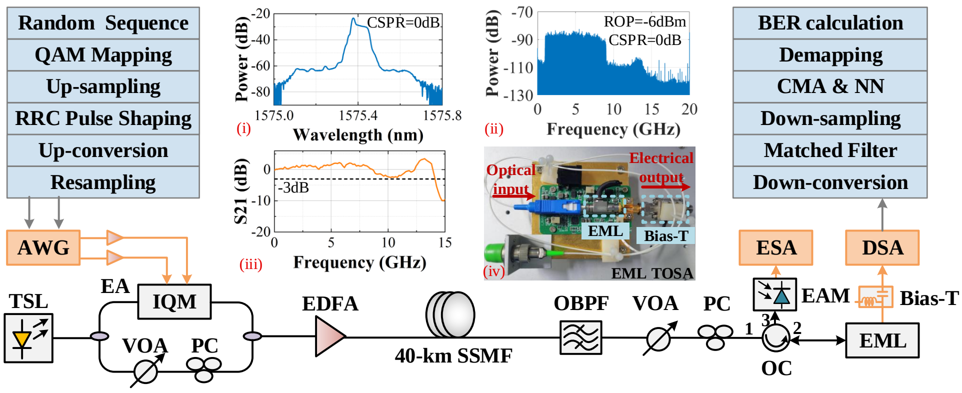

Fig. 2: Experimental setup for the proposed SSB transmission system with an EML-based coherent receiver.

To verify the effectiveness of the proposed EML-based receiver, we first measure the receiver sensitivity for the QPSK format in the OBTB case, as depicted in Fig. 3(a). For the EML-based receiver, a reduced CSPR leads to a higher receiver sensitivity due to relatively higher information-bearing signal power. With the optimum CSPR, the required received optical power (ROP) at the 7% hard-decision forward error correction (HD-FEC) threshold is -21 dBm when using the EML-based receiver, which outperforms the standard KK receiver with 10-dB sensitivity superiority. Since the required ROP is low, the DFB-based LO is not significantly affected by nonlinear impairment caused by OIL. However, higher ROP is require for the 16-QAM format, resulting in relatively larger leakage of the harmonic components into the LO. In addition, the 16-QAM signal is more susceptible to the nonlinear impairment than the QPSK signal. Therefore, a nonlinear equalizer based on neural network with one hidden layer (240 hidden neurons) is adopted to mitigate the impact of harmonic components on the 16-QAM signal, which is discussed as follows.

Then, we investigate the BER as a function of CSPR for the 16-QAM format at different ROPs in the OBTB case, as shown in Fig. 3(b). Obviously, the NN-based nonlinear equalizer can effectively overcome performance limits of the 16-QAM signal, especially under the low CSPR condition. As expected, higher ROP enables better BER performance, simultaneously providing a wider locking range due to higher carrier power, as depicted in Fig. 3(c). We also evaluate the BER performance while varying the guard band at different CSPRs, as provided in Fig. 3(d). A wide guard band can reduce the undesired components aliased in the signal spectrum, but at the expense of spectral efficiency and bandwidth limitation, which is set to 1 GHz in the experiments.

Finally, we measure the receiver sensitivity for the 16-QAM format. Fig. 3(e) plots the BER curves at different CSPR values in the OBTB case. For the EML-based receiver, a lower CSPR allows for slightly higher sensitivity, but at the cost of a narrower locking range. At a CSPR of -4 dB, the BER performance get worse at high ROP due to larger harmonic components. For the KK receiver, the BER floor increases as the CSPR decreases owing to residual SSBI. The EML-based receiver improves the receiver sensitivity by 6.5 dB at the 7% HD-FEC threshold with a reduction of optimum CSPR up to 14 dB compared to the KK receiver. With the optimum CSPR, the fiber transmission performance is also depicted in Fig. 3(f), along with the recovered constellations as insets. The EML-based receiver exhibits a superior performance with a 6.5 dB sensitivity improvement in comparison with the KK receiver after 40-km fiber transmission, which can also reach a transmission distance of 80 km. If another L-band EDFA is available to compensate fibre loss at the receiver, the transmission distance can be further extended.

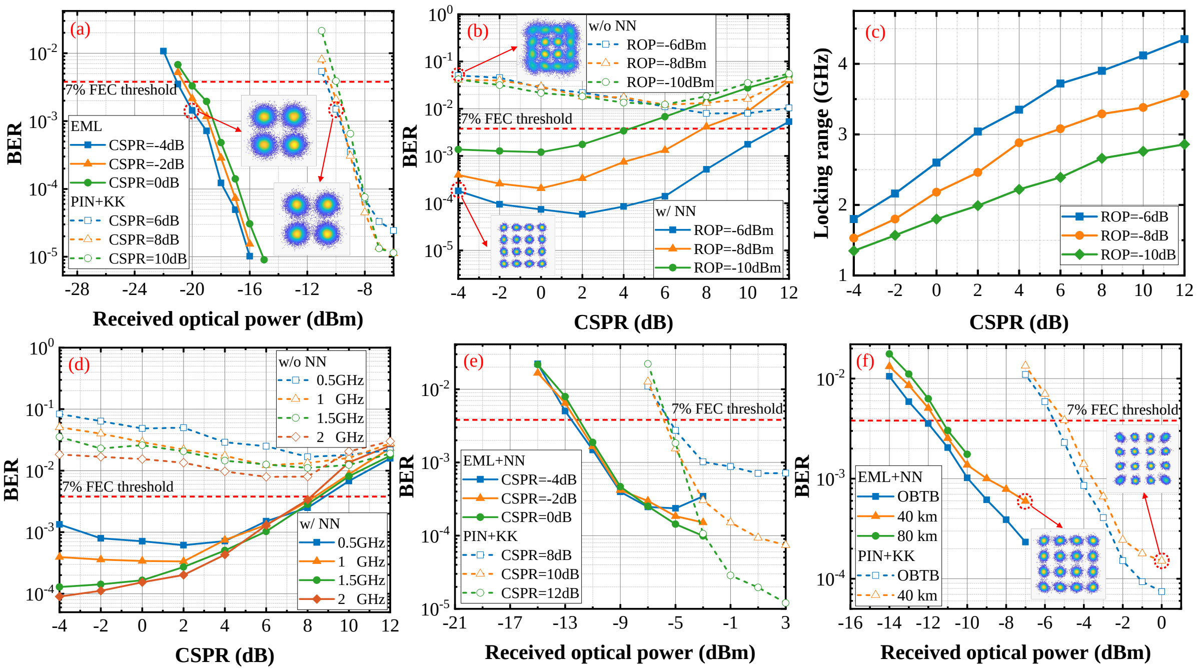

Fig. 3: (a) Measured sensitivity for the QPSK signal in the OBTB case. (b)-(c) BER and locking range versus CSPR for the 16-QAM signal at different ROPs. (d) BER versus CSPR for the 16-QAM signal at different guard bands. (e)-(f) Measured sensitivity for the 16-QAM signal in the OBTB and after fiber transmission cases, respectively.

4. Conclusions

In this work, the EML-based reception scheme is proposed to mitigate the impact of SSBI and reduce the required CSPR for the SSB signal transmission system enabled by an injection-locked DFB laser. Thanks to the NN-based nonlinear equalizer, a 6.5 dB sensitivity improvement is achieved for the 32-Gb/s SSB 16-QAM signal transmission over 40-km optical fiber in comparison with the standard KK receiver.

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