Amplifier-free Low-CSPR Polarization-Division-Multiplexing Self-Homodyne Coherent Receiver for ZR Transmission

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Abstract *By utilizing the optical injection locking to regenerate remotely delivered LO, an amplifier-free low-CSPR polarization division multiplexing self-homodyne coherent system for ZR standard is proposed and demonstrated. Single polarization 240-Gbps (60GBaud-16QAM) transmission along 75km SMF has been achieved even without CPR algorithms. ©2022 The Author(s)*

Introduction

Compared to conventional intradyne coherent solutions, the self-homodyne (SHD) optical coherent transceivers reduce the cost and power consumption of digital signal processing (DSP), thus present tremendous advantages in intra-datacentre interconnections (DCI). due to its characteristics of simple configuration and low DSP complexity. With the progress of adaptive polarization controllers[1], lots of simplified DSP flows and novel subsystems are proposed [2]–[5]. However, to ensure received optical local oscillator (LO) power is sufficient, the launched remotely delivered LO power needs to be higher enough to overcome the transmission loss. That increases the carrier-signal power ratio (CSPR) and decreases the available signal power. With high power continuous-wave LO transmitting along the fibre, the SHD system suffers from the stimulated Brillouin scattering (SBS). Therefore, costly optical amplifiers must be applied if the SHD system is to be extended from intra-DCI to the medium-reach scenario. A LO-carrier regeneration technique with strong filtering effect is indispensable for extending the SHD infrastructure to metro-optical network like ZR standards. The injection locked lasers provide us a good choice to selectively amplify the carrier tributary and regenerate the optical LO with much lower costs. Leveraging by this feature, a polarization-division-multiplexing SHD (PDM-SHD) receiver with low CSPR can be achieved.

In this paper, we utilize the optical injection locking at receiver side to regenerate optical carrier, hence propose an amplifier-free low-CSPR PDM-SHD for medium-reach metro-optical network. Its performance of bit-error ratio vs. equivalent received optical power (BER-eROP) under different distances are presented and discussed. The feasibility of SHD based ZR transmission has been validated.

Principles of SHD

In SHD systems, the laser in the transmitter is split into two branches, one for optical signal modulation, and the other for the remote LO delivered to the receiver for coherent detection. Because of the homology of the modulated laser and LO laser, the phase noise (PN) induced by the laser linewidth can be reduced or eliminated.

$$\begin{aligned} E_{\mathrm{S}}(t) &= s(t)\cdot e^{j(\omega_0 t+\varphi(t))} \\ E_{\mathrm{LO}}(t) &= E_0\cdot e^{j(\omega_0(t+\tau)+\varphi(t+\tau_{\Delta L}))} \end{aligned} \tag{1}$$

As shown in Eq.(1), $E_{\mathrm{S}}(t)$ and $E_{\mathrm{LO}}(t)$ respectively denote the complex field of homogenous signal and LO at the Rx end. ω_0 denotes the central wavelength of the laser, and $\varphi(t)$ denotes the phase jitter induced by the laser linewidth. $\tau_{\Delta L}$ denotes the relative time delay (RTD) between signal and LO.

$$\begin{aligned} i_{\mathrm{I}}(t) &= R\cdot\left(E_{\mathrm{S}}E_{\mathrm{LO}}^* + E_{\mathrm{S}}^*E_{\mathrm{LO}}\right) \\ &= RE_{\mathrm{LO}}\Re\{s(t)\}\cos\left[\boldsymbol{n}_{\mathbf{p}}\left(\boldsymbol{t};\boldsymbol{\tau}_{\boldsymbol{\Delta}_L}\right)+\phi_0\right] \\ i_{\mathrm{Q}}(t) &= R\cdot j\left(E_{\mathrm{S}}E_{\mathrm{LO}}^* + E_{\mathrm{S}}^*E_{\mathrm{LO}}\right) \\ &= RE_{\mathrm{LO}}\Im\{s(t)\}\sin\left[\boldsymbol{n}_{\mathbf{p}}\left(\boldsymbol{t};\boldsymbol{\tau}_{\boldsymbol{\Delta}_L}\right)+\phi_0\right] \\ \hat{s}(t) &= R\cdot E_0\cdot e^{j\left(\boldsymbol{n}_{\mathbf{p}}(t;\tau_{\Delta_L})+\phi_0\right)} \\ \boldsymbol{n}_{\mathbf{p}}\left(\boldsymbol{t};\boldsymbol{\tau}_{\boldsymbol{\Delta}_L}\right) &= \boldsymbol{\varphi}(\boldsymbol{t}+\boldsymbol{\tau}_{\boldsymbol{\Delta}L})-\boldsymbol{\varphi}(\boldsymbol{t}) \end{aligned} \tag{2}$$

As shown in Eq.(2), after coherent detection, the received electrical signal $\hat{s}(t)$ is free of frequency offset, except for a random phase shift $\boldsymbol{n}_{\mathbf{p}}\left(\boldsymbol{t};\boldsymbol{\tau}_{\boldsymbol{\Delta}_L}\right)$, called phase noise. Specially, when RTD is relatively small, the variance or the magnitude of phase noise will approach 0 [6].

To reduce the RTD as far as possible, signal and LO can be multiplexed in polarization. When transmitted by two orthogonal polarizations, the RTD can be compressed to several picoseconds and the phase noise can be negligible. Hence, the lasers with wider linewidth can be used and the carrier phase recovery (CPR) algorithms can be simplified or even removed.

Injection Locked Lasers for Optical Carrier Regeneration under Low CSPR

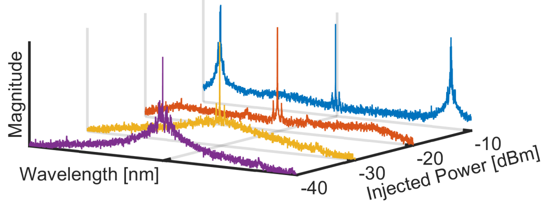

Fig.1: Regenerated LO spectrum in certain injection powers.

The injection locked lasers can regenerate the continuous-wave (CW) LO selectively, and can realize low-CSPR coherent receiving. With proper external light injection, the output laser of the injection locked DFB (IL-DFB) follows the wavelength and the phase of the injected light. To get the IL-DFB locked, the free-running output wavelength should be close enough to the injected light. What's more, the injected optical power also affects the locking state. As shown in Fig.1, unsuitable injected power makes the laser unlocked, i.e., typical low-cost DFB output (injected power too small) or chaotic output (injected power too high) [7]. When operating in a stable locked state, an IL-DFB laser can be used as an optical LO-carrier regenerator, outputting CW light with constant power and phase locked to the remotely delivered LO. The high-selectivity feature helps to realize the low-CSPR SHD system, and extend the transmission distances by suppressing the stimulated Brillouin scattering.

Experimental Setup

The experimental setup of the proposed PDM-SHD system is shown in Fig.2. For the transmitter side, a 60-GBaud 16-QAM electrical signal with a 0.15-factor roll-off is generated by the AWG (Keysight M8196A, 90 GSa). The light from ECL (~1 kHz) is firstly boosted to 20 dBm by an erbium-doped fibre amplifier (EDFA), and then the boosted laser is split into two branches with power ratio of 21 dB, by the PC1 and the PBS1. One branch is modulated by a single-polarization IQ-MZM (EOSPACE IQ-35G) with the electrical signal. The other branch is RTD-matched and used as the remote LO. After that, the modulated light and the LO are multiplexed to two orthogonal polarizations by a PBC. The CSPR of the launched light is approximately 0 dB, monitored by M1 and M2. For the fibre link, three different distances are tested, including the back-to-back (B2B), 50-km and 75-km SSMF transmission links. Because the amplifier-free system is power-limited, in order to test the receiver sensitivity, the VOA1 is applied to sweep the received signal optical power. For the receiver side, the PC2 and the PBS2 are used to demultiplex the signal and LO from two orthogonal polarizations. The OSA measures the crosstalk introduced by polarization misalignment and helps to adjust the PC2. The free-running wavelength of the IL-DFB is set very close to the wavelength of the remote LO, with less than 1-GHz frequency offset, using thermo electric cooler (TEC). The VOA2 clamps the maximum injecting LO power, avoiding IL-DFB jumping to chaotic states. The output power of the IL-DFB is 13.5 dBm. The M3 monitors the eROP, defined by Eq.(3). Finally, the regenerated remotely delivered LO from IL-DFB and RTD-matched signal light are sent to the ICR (NeoPhotonics ICR Class 40) for coherent detection, and captured by a digital sampling oscillator (DSO, Lecroy-10-36Zi, 80 GSa). The subsequent offline-DSP algorithms include electrical I/Q skew compensation, resampling, Gram–Schmidt orthonormalization processing (GSOP), coarse dispersion compensation, root-raised-cosine (RRC) match filtering, radius-directed constant modulus algorithm (RD-CMA) and constant phase rotation. In addition, the timing skew of the Tx (from PC1 to the fibre input end) and Rx (from PC2 to ICR) are aligned individually and statically, with a mismatch of less than 20 picoseconds.

$$\mathrm{eROP} = \mathrm{ROP} - 10\lg\left(1 + 10^{\mathrm{CSPR}/10}\right) \qquad (3)$$

Experimental Results

The CSPR of signal light is mainly controlled by PC1 and PBS1. When the output CSPR is 0 dB, the power splitting ratio of PBS1 approaches 21

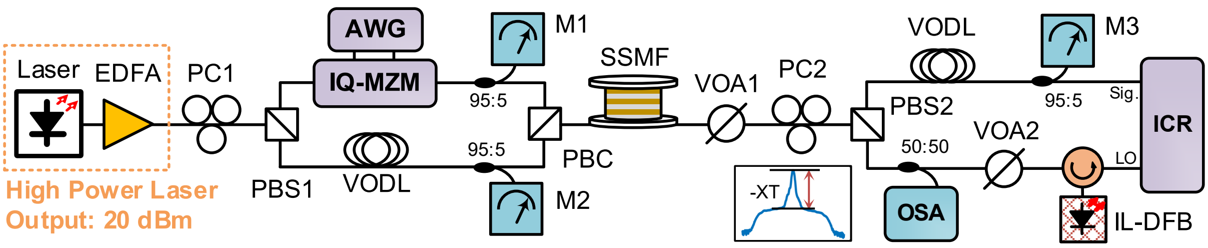

Fig.2: Experimental set-up. (**PC**: Polarization Controller; **AWG**: Arbitrary Waveform Generator; **IQ-MZM**: I/Q Mach-Zendel Modulator; **VODL**: Optical Delay Line; **PBS:** Polarization Beam Splitter; **PBC:** Polarization Beam Combiner; **SSMF**: Standard Single Mode Fiber; **VOA**: Variable Optical Attenuator; **OSA**: Optical Spectrum Analyzer; **IL-DFB**: Injection-locked Distributed-Feedback Laser; **ICR**: Integrated Coherent Receiver; **M1,2,3**: Optical Power Meter; **XT:** Crosstalk by Polarization-Misalignment).

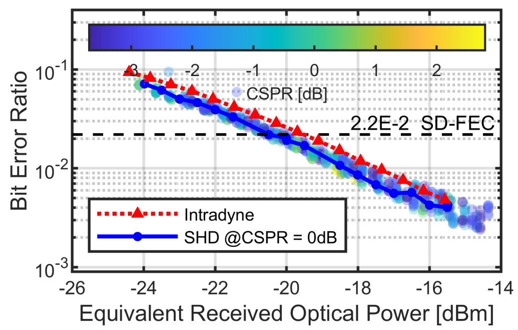

Fig.3: Varying CSPR, the BER-eROP relationship of SHD system remains constant, better than that of the intradyne.

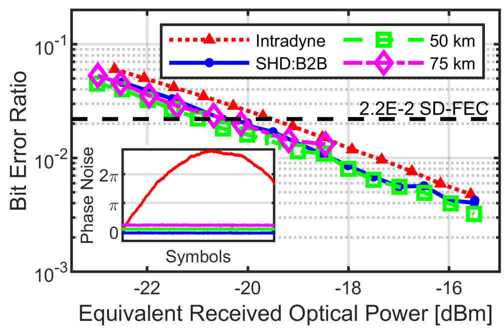

Fig.4: The BER-eROP relationship remains constant at different distances, because of amplifier-free.

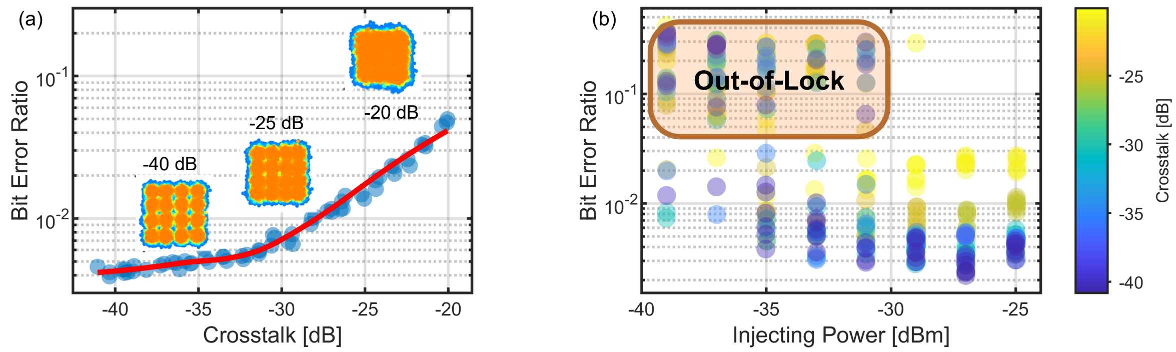

Fig.5: (a) The performance of the receiver is degraded by polarization crosstalk. (b) Out-of-lock happens when injecting optical power is not enough. The out-of-lock threshold is irrelevant with crosstalk, approximately -30 dBm.

dB and the launched remote LO power is approximately -2 dBm. For the polarization disturbance of EDFA and the 20-dB modulation loss of IQ-MZM, the LO branch power shifts quickly, but the signal power is stable. In back-to-back, as shown in Fig.3, the BER performances of signals with different CSPRs are nearly the same. For the conventional intradyne coherent detection system, the BER-ROP performance is tested with the standard DSP-flows with a 13.5-dBm LO from a heterogenous intradyne laser. It shows that the PDM-SHD system has better BER performance, even without CPR algorithms. To reach the 2.2e-2-FEC threshold, the minimum eROP of the SHD receiver is about -20 dBm. As shown in Fig.4, With longer fibre link, the BER-eROP performance of the SHD system remains constant. From the phase noise curves inserted, it can be seen the phase noise caused by PDM-RTD is negligible in the SHD system at distances less than 75 km. Also, owing to the ultra-low CSPR and high LO-regenerating sensitivity, the remotely delivered LO power can be less than 0 dBm, which is below the threshold of SBS at 75 km. Finally, we successful achieve single polarization 240-Gbps (60GBaud-16QAM) transmission along 75km SMF.

Discussion on Degradations by IL-DFB

The spectra of polarization-demultiplexed LO light is analysed by an OSA, under different crosstalk magnitudes. As shown in Fig.5(a), the polarizations misalignment causes crosstalk, leading to the signal-signal beat interference and degrading the performance of the receiver. Theoretically, the fluctuation of the LO light, i.e., the intensity envelope, is positively correlated to the crosstalk magnitude. With the intensity envelope signal as feedback, adaptive polarization controllers can work effectively [1]. Being in stable locked state is vital in the SHD system. Whenever the IL-DFB jumps to an out-of-lock state, the system fails immediately. The locking stability is related to injection optical power, when the wavelength of the free-running IL-DFB precisely matched. As shown in Fig.5(b), the out-of-lock threshold of the injection power is approximately -30 dBm. But crosstalk has no significant influence on the out-of-lock threshold.

Conclusions

Based on the injection locked DFB, an amplifier-free low-CSPR single-polarization PDM-SHD system for ZR transmission is proposed and verified experimentally. The transmitting distance reaches 75 km at a bit rate of 240 Gbps (60 GBaud, 16QAM).

Acknowledgements

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