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Asymmetric self-coherent detection with mitigated SSBI enhancement using partial pre-compensation

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Abstract *We propose a partial pre-compensation scheme to mitigate the SSBI enhancement induced by the non-ideal receiver response of double-sideband self-coherent detection systems. 1.2 dB enhancement of the power sensitivity is achieved based on optimized partial pre-compensation in a chromatic dispersion-based asymmetric self-coherent detection system. ©2022 The Author(s)*

Introduction

Self-coherent detection (SCD) has attracted extensive interest in recent years due to the capability of field reconstruction, which in conjunction with advanced digital signal processing (DSP) algorithms allows the compensation of a variety of impairments including chromatic dispersion (CD) and other channel imperfection [1,2]. In addition, the removal of the local oscillator leads to relaxed requirement for the remote wavelength management, which is beneficial for short-reach communications having a tight power consumption requirement.

Compared to single-sideband (SSB) SCD schemes [3,4], SCD schemes that are capable of detecting complex double sideband (DSB) signals can double the electrical spectral efficiency (ESE), which is defined as the ratio between the net data rate and the electrical bandwidth (bit/s/Hz). Thus, DSB-SCD schemes can approach the ESE of homodyne coherent detection in a single-polarization configuration. As such, different types of DSB-SCD schemes have been proposed to detect self-coherent DSB signals [5-9]. Single-carrier interleaved scheme [5] realizes the field reconstruction of SC-DSB signals by interleaving the CW-tone and signal into staggered time slots at the transmitter. However, the ESE is not improved since half of the time slots are not loaded with signals. Based on [5], the carrier-assisted differential detection (CADD) scheme is proposed and approaches the ESE of homodyne coherent detection by use of an additional direct detection branch [6]. We propose in [7] a different DSB-SCD scheme termed asymmetric self-coherent detection (ASCD), which can reconstruct complex DSB signals from the intensity of two signal portions, each experiencing a different optical transfer function. One embodiment of the ASCD scheme uses a CD element to induce disparate signal intensities in each reception path and a 100 Gb/s net rate has been demonstrated in a proof-of-concept experiment over 80 km of fibre. The ASCD scheme is subsequently extended to a Mach-Zehnder interferometer (MZI) based structure [8].

Despite varied receiver structures conceived in the DSB-SCD schemes such as the CADD and the ASCD, the transfer functions of the receiver in these schemes possess multiple null points in the spectrum that results in significant signal SNR degradation in a set of frequency intervals. Compensating the receiver response, as conventionally performed in these DSB-SCD schemes, leads to enhanced signal-to-signal beating interference (SSBI) [6-8], which also degrades the performance of the system.

In this paper, we propose a partial pre-compensation (PPC) scheme that mitigates the SSBI enhancement resulting from the non-ideal receiver response of DSB-SCD schemes. Without loss of generality, we assess the performance of the proposed PPC scheme in a CD-based ASCD receiver. The PPC scheme allows flexible control of the level of pre-compensation for the non-ideal receiver response based on a tunable parameter λ. We numerically evaluate the effectiveness of the proposed PPC scheme in a simulation setup where two independent SSB-PAM-4 signals with an aggregate symbol rate of 56 Gbaud are transmitted over 40 km of standard single-mode fibre (SMF). 1.2 dB enhancement of the power sensitivity is achieved at a BER of 3.8×10^{-3} with an optimized level of partial pre-compensation.

Working principle

Fig. 1 depicts the structure of the CD-based ASCD receiver, which consists of two reception paths each detecting a part of the received SC complex DSB signal. A CD element is employed in one of the branches in order to incur different optical responses between the two detection branches. Denoting the received signal as $T+s(t)$, the down-converted signals $p_1(t)$ and

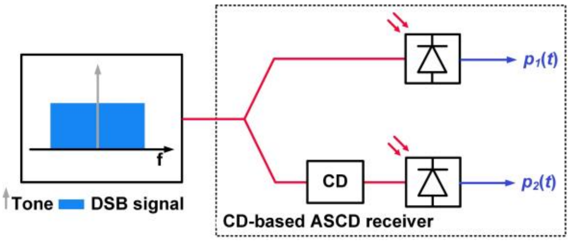

Fig. 1: Structure of the CD-based ASCD receiver.

$p_2(t)$ can be expressed as

$$p_1(t) = |T + s(t)|^2 \\ = |T|^2 + 2T\,\mathrm{Re}(s(t)) + |s(t)|^2 \quad (1)$$

$$p_2(t) = |T + s'(t)|^2 \\ = |T|^2 + 2T\,\mathrm{Re}(s'(t)) + |s'(t)|^2 \quad (2)$$

$$s'(t) = s(t) \otimes h_{CD}(t) \quad (3)$$

where *T* is the CW-tone, *s*(*t*) is the complex DSB signal, h_{CD}(t) is the transfer function of the CD element. In the frequency domain, the linear part $2T\,\mathrm{Re}(s'(t))$ in (2) can be decomposed as

$$2T\left(S_I(\omega)\cos(\beta_2 L\omega^2/2) + S_Q(\omega)\sin(\beta_2 L\omega^2/2)\right) \quad (4)$$

where S_I and S_Q are the Fourier transform of the real part and imaginary part of $s(t)$, respectively, β_2 is the second derivative of the propagation constant, and L is the length of the CD element. Thus, $s(t)$ can be reconstructed based on the analytic relation between $p_1(t)$ and $p_2(t)$ as detailed in [7]. It is found from Eq. (1)-(4) that the retrievable information from the real and imaginary part of the received signal is unequal, because S_Q is retrieved from Eq. (2) and is filtered by a sinusoidal transfer function $\sin(\beta_2 L\omega^2/2)$ having multiple null points in the spectrum, whereas S_I retrieved from Eq. (1) experiences a *relatively flat* receiver response.

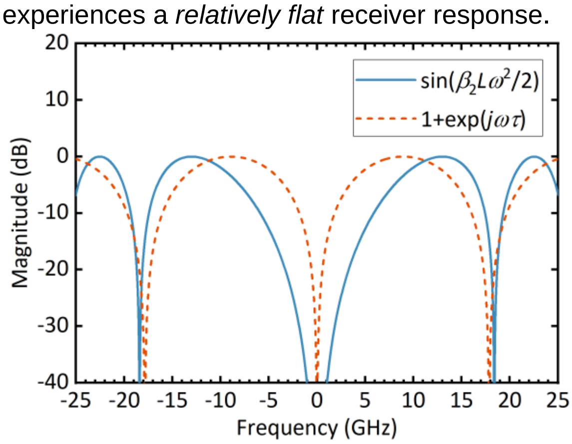

Fig. 2: Magnitude response of $\sin(\beta_2 L\omega^2/2)$ and $1-\exp(j\omega\tau)$.

To visualize the spectral null points, Fig. 2 shows the magnitude response of $\sin(\beta_2 L\omega^2/2)$ at a CD of 370 ps/nm. Note that non-ideal receiver responses are seen for other types of SCD schemes such as the CADD scheme. The signal in CADD is filtered by the transfer function $1-\exp(j\omega\tau)$ having similarly multiple null points in the spectrum. The response of $1-\exp(j\omega\tau)$ is shown by the dashed curve in Fig. 2 with τ set to 56 ps.

Compensating the non-ideal receiver response, as performed conventionally in the ASCD and CADD receiver DSP leads to enhanced SSBI since the spectral nulls are inverted and become singularities in the spectrum [4,5]. Since only the imaginary part of the signal is significantly degraded by the receiver response in the CD-based ASCD scheme, i.e. $\sin(\beta_2 L\omega^2/2)$, we pre-compensate for the imaginary part of the signal in order to mitigate the enhancement of SSBI terms $|s(t)|^2$ and $|s'(t)|$. The pre-compensated signal can be expressed in the frequency domain as below

$$S_I(\omega) + jS_Q(\omega)/\left[\sin\left(\lambda\beta_2 L\omega^2/2 + (1-\lambda)\pi/2\right)\right] \quad (4)$$

where λ is a coefficient that controls the level of pre-compensation. Fig. 3 shows the magnitude response of the transfer function in Eq. (4), i.e. $1/\sin(\lambda\beta_2 L\omega^2/2 + (1-\lambda)\pi/2)$. As λ changes from 0 to 1, the level of pre-compensation transits from no pre-compensation performed toward complete pre-inversion of the receiver response. Note that the residual receiver response due to partial pre-compensation is post-compensated in the receiver DSP for ISI removal.

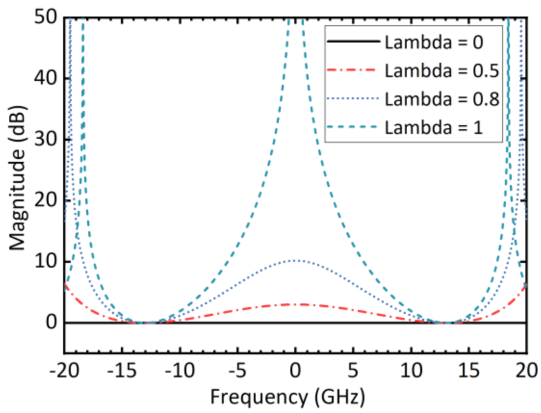

Fig. 3: Magnitude response of the pre-compensation transfer function.

Numerical validation

We numerically evaluate the effectiveness of the proposed PPC scheme in mitigating the SSBI enhancement in the CD-based ASCD scheme.

We transmit two independent SSB PAM-4 signals over 40 km of SSMF in the C band. Each of the PAM-4 signals operates at 28 Gbaud, thus forming an aggregate 56 Gbaud PAM-4 signal with a gross data rate of 112 Gb/s. The two SSB-PAM-4 signal are upconverted to an intermediate frequency with 2 GHz guard band from the signal edge to 0 GHz. Fig. 4 depicts the real and imaginary part of the dual-band SSB-PAM-4 signal with a different level of pre-compensation implemented by tuning λ at the transmitter. As Fig.4 shows, the proposed PPC only affects the imaginary part of the signal, whose edges are raised by the PPC filter as λ increases.

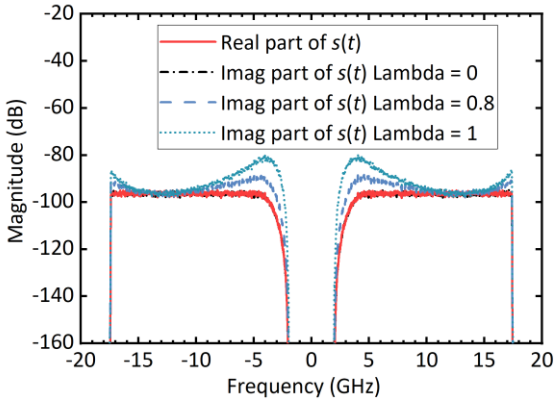

Fig. 4: Magnitude response of the real and imaginary part of the signal when different levels of the proposed pre-compensation scheme are applied depending on λ.

Next, we plot the BER versus the tuning parameter λ in Fig. 5 in order to assess the BER performance of the proposed PPC scheme. It can be seen from Fig. 5 that complete pre-compensation of the receiver response, i.e. $\lambda = 1$, leads to lower BER compared to complete post-compensation, i.e. $\lambda = 0$. However, the minimum BER is achieved when an intermediate level of pre-compensation is implemented, i.e. $\lambda = 0.8$.

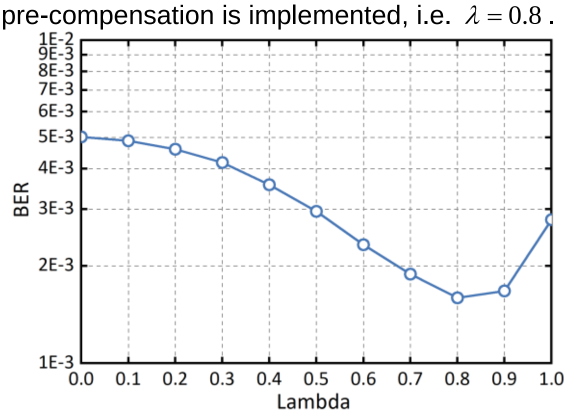

Fig. 5: BER versus λ.

The lower BER of an intermediate level of pre-compensation is achieved due to weaker SSBI as can be seen from the magnitude response of the SSBI contained in the reconstructed signal in Fig. 6, *before* the removal the SSBI using an iterative SSBI cancellation algorithm [7].

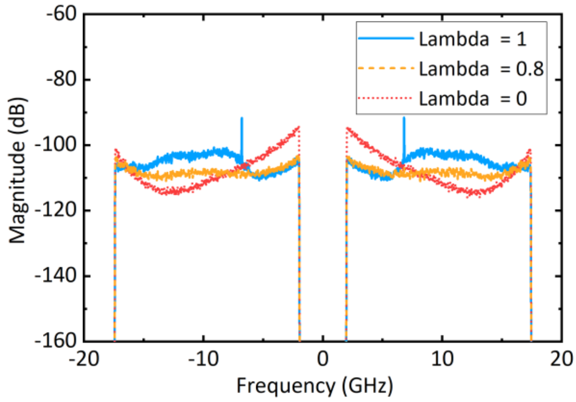

Fig. 6: SSBI spectra at different λ.

It can be seen that the SSBI is significantly enhanced without pre-compensation, i.e. $\lambda = 0$. On the other hand, complete pre-inversion of the receiver response leads to a non-marginal level of SSBI though the SSBI enhancement is avoided. Thus, our proposed PPC allows the flexibility to achieve significant mitigation of SSBI enhancement without incurring a relatively strong SSBI due to complete pre-compensation.

We also characterize the power sensitivity improvement by conducting partial pre-compensation for the receiver response. Fig. 7 shows the BER versus the received optical power (ROP) at different λ. At a BER level of 3.8×10^{-3}, the proposed PPC at $\lambda = 0.8$ achieves 1.2 dB improvement of the ROP sensitivity compared to the original scheme without pre-compensation.

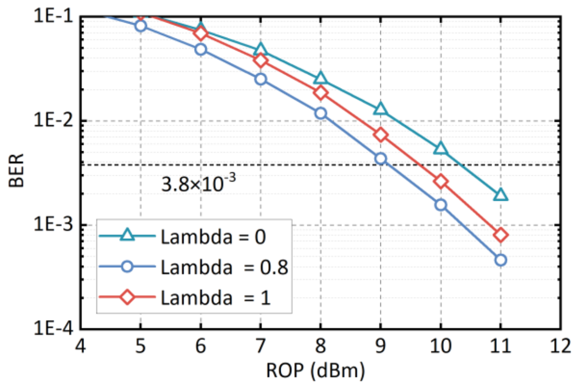

Fig. 7: BER versus ROP at different λ.

Conclusion

We propose a partial pre-compensation scheme in order to mitigate the SSBI enhancement for the CD-based ASCD scheme. We numerically validate the sensitivity improvement based on partially pre-compensated PAM-4 signals. This proposed transmitter-side pre-compensation scheme can be applied in other self-coherent detection schemes such as CADD and the MZI-based ASCD scheme with a similar receiver response containing multiple spectral null points.

References

[1] C. R. S. Fludger, T. Duthel, D. V. D. Borne, C. Schulien, E. Schmidt, T. Wuth, J. Geyer, E. D. Man, G. Khoe, and H. D. Waardt, "Coherent Equalization and POLMUX-RZ-DQPSK for Robust 100-GE Transmission," Journal of Lightwave Technology, vol. 26, no. 1, pp. 64-72, 2008, DOI: 10.1109/JLT.2007.912128.

[2] Ezra M. Ip and J. M. Kahn, "Fiber Impairment Compensation Using Coherent Detection and Digital Signal Processing," Journal of Lightwave Technology, vol. 28, no. 4, pp. 502-519, 2010, DOI: 10.1109/JLT.2009.2028245.

[3] S. Randel, D. Pilori, S. Chandrasekhar, G. Raybon and P. Winzer, "100-Gb/s discrete-multitone transmission over 80-km SSMF using single-sideband modulation with novel interference-cancellation scheme," *2015 European Conference on Optical Communication (ECOC)*, 2015, pp. 1-3, DOI: 10.1109/ECOC.2015.7341665.

[4] A. Mecozzi, C. Antonelli, and M. Shtaif, "Kramers–Kronig coherent receiver," Optica, vol. 3, no. 11, pp. 1220-1227, 2016, DOI: 10.1364/OPTICA.3.001220

[5] X. Chen, D. Che, A. Li, J. He, and W. Shieh, "Signal-carrier interleaved optical OFDM for direct detection optical communication," Optics Express, vol. 21, no. 26, pp. 32501-32507 (2013)

[6] W. Shieh, C. Sun, H. Ji, Carrier-assisted differential detection. Light Science & Applications, vol. 9, no. 18, 2020, DOI: 10.1038/s41377-020-0253-8.

[7] X. Li, M. O'Sullivan, Z. Xing, M. S. Alam, M. E. Mousa-Pasandi, and D. V. Plant, "Asymmetric self-coherent detection," Optics Express, vol. 29, no. 16, pp. 25412-25427, 2021, DOI: 10.1364/OE.421603.

[8] X. Li, M. O'Sullivan, Z. Xing, M. E. Mousa-Pasandi, and D. V. Plant, "Asymmetric Self-Coherent Detection Based on Mach-Zehnder Interferometers," Journal Lightwave Technology, vol. 40, no. 7, pp. 2023-2032, 2022.

[9] M. Matsumoto, "Optical Signal Phase Reconstruction Based on Temporal Transport-of-Intensity Equation," in Journal of Lightwave Technology, vol. 38, no. 17, pp. 4722-4729, 2020, DOI: 10.1109/JLT.2020.2995640.