Simultaneous Frequency-dependent Impairments Calibration for 96GBaud Coherent Optical Transceiver

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Abstract: We report a calibration method to simultaneously characterize all the frequency-dependent impairments of coherent optical transceivers. With calibration operation, dual-polarization 96GBaud Nyquist-16QAM signal transmission is achieved by using a silicon photonics-based 64GBaud-class coherent optical transceiver. © 2022 The Author(s)

1. Introduction

As high baud rate and high order modulation format signals are widely investigated for 400Gbps and beyond optical transmission systems, impairment calibration of high throughput coherent optical transceivers becomes indispensable [1,2]. Compared to frequency-independent impairment, the calibration of frequency-dependent impairments is more challenging [3-6]. Generally, the frequency-dependent impairments can be summarized as amplitude/phase frequency response (AFR/PRF) and skew for different transmitted tributaries, as they exhibit different gain, ripple, and phase characteristics in the variance of frequencies within the margin of device bandwidth. So far, transceiver IQ skews can be calibrated via either cascaded equalizers or complexed widely linear equalizers [3,4]. Transmitter (Tx) side AFR/PFR may also be captured by optical spectrum analyzers or by two-tone beating detection [5,6]. Nevertheless, the precise calibration for Rx PFR is not reported yet. Furthermore, existing methods treat the transmitter (Tx) and receiver (Rx) impairment individually and usually require training/iteration processes, making the calibration time-consuming and difficult to implement in real transceiver hardware.

In this paper, we extend our previous work in [7] with the capacity to simultaneously calibrate all the frequency-dependent impairments mentioned above. The specially designed multi-tone signals are utilized to capture both Tx and transceiver(TRx) side AFR/PFR/skew with the help of only an additional low-bandwidth (<1GHz) photo-diode (PD) which can be built in the Mach Zehnder modulator (MZM). Owing to the proposed calibration, a broader-band 96GBaud dual-polarization (DP) Nyquist-16QAM signal transmission is enabled with the 64GBaud-class 400Gbps silicon photonics-based optical transceiver.

2. Operation principle

The main idea of our proposal is to measure the Tx frequency-dependent impairment by multi-tone beating with a low-bandwidth PD implemented at the Tx side and to measure the overall TRx frequency-dependent impairment by field reconstruction with the assistance of the tested transceiver itself. To realize all these calibration functions, four specially designed multi-tone signals are loaded as the inputs $X_\eta(t) = \sum_{k=1}^{N}\{\cos[2\pi f_\eta(k)t + \Phi_\eta(k)]\}$, where $\eta = XI/XQ/YI/YQ$ and f_η means the frequency of the specific multi-tone signals, $\Phi_\eta(k)$ is the preset random phase used to reduce the peak-to-average power ratio, N is the number of transmitted tones in each tributary and is set according to the target calibration bandwidth, and $k = 1 \sim N$. More specifically, $f_{XI}(k) = kf_0 + \Omega(k)$, $f_{XQ}(k) = f_{XI}(k) + \frac{2}{4}(f_0 + \Omega(k))$, $f_{YI} = f_{XI}(k) + \frac{1}{4}(f_0 + \Omega(k))$, $f_{YQ} = f_{XI}(k) + \frac{3}{4}(f_0 + \Omega(k))$, f_0 is the primary frequency interval between each of two tones in the one tributary, $\Omega(k)$ is defined as the sub-frequency interval with the ability of $\Omega(k+1) - \Omega(k) = k\Delta f$, where Δf is the original value of $\Omega(k)$. Fig. 1(a) gives the schematic diagram of the simulation system and the specially designed multi-tone signals. It is clear to see that the four calibration signals are interleaved in the frequency domain and thus they can be separated by the coherent optical transceiver. The existence of sub-frequency intervals $\Omega(k)$ guarantees the interleaving characteristic of multi-tone signals after being detected by a single PD.

Assume the optical IQ modulator is biased at the linear point, the signal after PD detection can be expressed as:

$$R_{PD,\eta}(f) = \chi \sum_{k=1}^{N} a_{Tx,\eta}(k) \cdot p_{Tx,\eta}(k) \cdot \delta[2\pi(f - (f_0 + k\Delta f))], \quad (1)$$

where χ is a normalization constant, and δ is the Dirac delta function. $a_{Tx,\eta}(k)$ can be approximated as the amplitude response at the frequency $[f_\eta(k) + f_\eta(k+1)]/2$ and $p_{Tx,\eta}(k)$ can be approximated as the phase difference between the frequency $f_\eta(k)$ and $f_\eta(k+1)$. Consequently, the Tx PFR $\varphi_{Tx,\eta}(k)$ is calculated from the integral operation of $p_{Tx,\eta}(k)$, which can be expressed as $\varphi_{Tx,\eta}(k+1) = \varphi_{Tx,\eta}(k) + p_{Tx,\eta}(k)$. Noted that the group delay induced by the integration operation can be eliminated after obtaining the Tx skew.

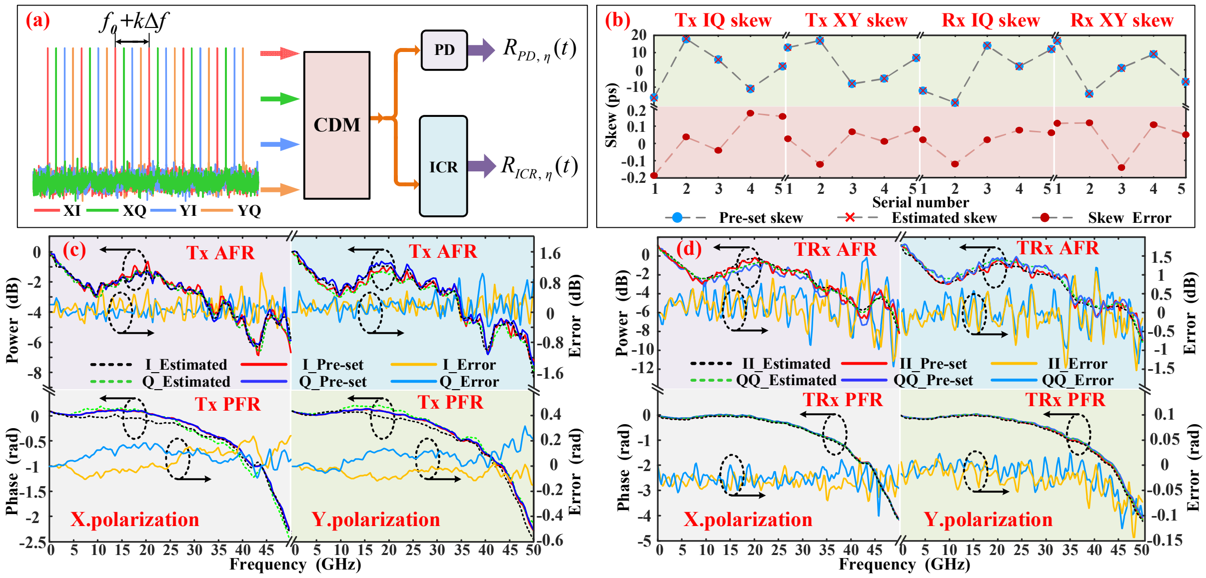


Fig. 1. (a) The schematic diagram of the specially designed multi-tone signals and simulation setup, (b) the simulation results of the estimated Tx/Rx side IQ/XY skew, (c-d) the simulation results of the estimated Tx/TRx side amplitude-frequency response and phase-frequency response.

The received signals obtained by different output ports of the receiver can be described as:

$$R_{ICR,\eta}(t) = \alpha_{pol.X}\{\chi_{XI,\eta}\sum_{k=1}^{N} a_{XI,\eta}(k)\cos[2\pi f_{XI}(k)t + \Phi_{XI,\eta}(k) + \varphi_{XI,\eta}(k)] + \chi_{XQ,\eta}\sum_{k=1}^{N} a_{XQ,\eta}(k)\cos[2\pi f_{XQ}(k)t + \Phi_{XQ,\eta}(k) + \varphi_{XQ,\eta}(k)]\}$$
$$+\alpha_{pol.Y}\{\chi_{YI,\eta}\sum_{k=1}^{N} a_{YI,\eta}(k)\cos[2\pi f_{YI}(k)t + \Phi_{YI,\eta}(k) + \varphi_{YI,\eta}(k)] + \chi_{YQ,\eta}\sum_{k=1}^{N} a_{YQ,\eta}(k)\cos[2\pi f_{YQ}(k)t + \Phi_{YQ,\eta}(k) + \varphi_{YQ,\eta}(k)]\}, \quad (2)$$

where $\alpha_{Pol,X/Y}$ is the distributed power from different polarization states. It can be observed from (2) that the impairments of the dual-polarization I and Q tributaries from the Tx/Rx side are all mixed. This effect will introduce inevasible crosstalk between all tributary signals and will greatly increase the difficulty of separating the non-ideal imperfection characteristics from each tributary and Tx/Rx side. $\chi_{\eta1,\eta2}$ represents the power from different transmitter ports, with detailed expressions in [2]. $a_{\eta1,\eta2}$ and $\varphi_{\eta1,\eta2}$ represent the AFR and PFR of the optical transceiver respectively, which can be obtained by applying the Fourier transform to the received signal. In the presence of frequency offset $2\pi f_O$, the AFR can be expressed as $a_{XI,XI}(f) = a_{Tx,XI}(f) \cdot a_{Rx,XI}(f - 2\pi f_O)$, and the PFR goes the same. Therefore, the AFR/PFR from Tx/Rx side can be separated. Then, if we define the skew from the XI and YI port as the XY skew, the Tx and Rx IQ/XY skew in X polarization can be calculated from $\varphi_{\eta1,\eta2}$ as :

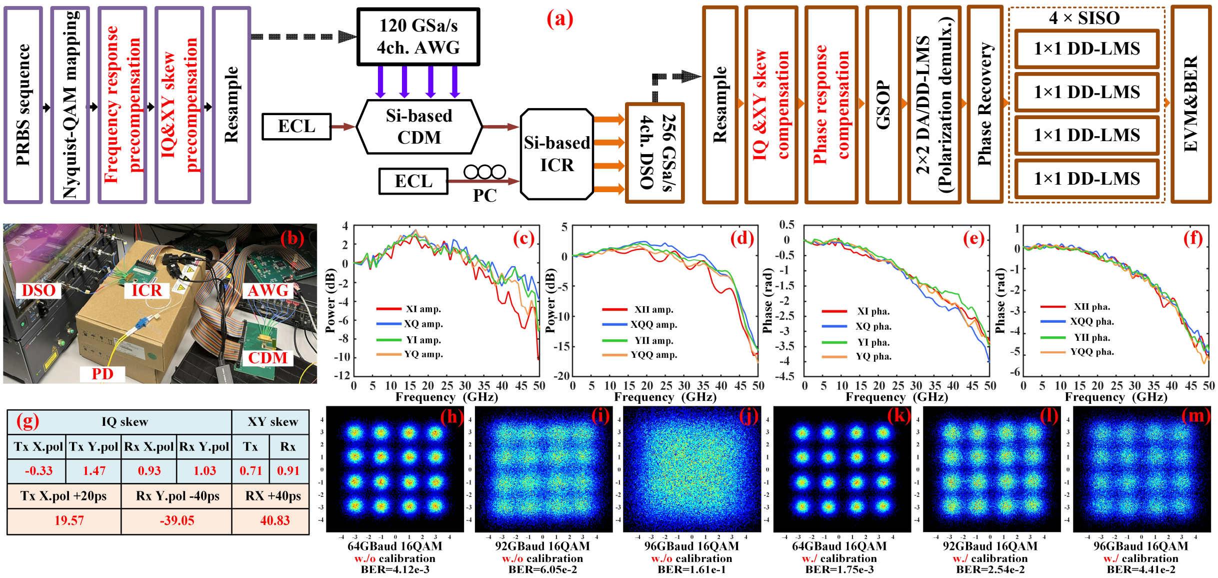
$$TxIQskew = [d(\varphi_{XI,XI} - \varphi_{XQ,XI}) + d(\varphi_{XI,XQ} - \varphi_{XQ,XQ})]/2df,\ RxIQskew = [d(\varphi_{XI,XI} - \varphi_{XI,XQ}) + d(\varphi_{XQ,XI} - \varphi_{XQ,XQ})]/2df,$$

$$TxXYskew = [d(\varphi_{XI,XI} - \varphi_{YI,XI}) + d(\varphi_{XI,XQ} - \varphi_{YI,XQ})]/2df,\ \ RxXYskew = [d(\varphi_{XI,XI} - \varphi_{XI,YI}) + d(\varphi_{XQ,XI} - \varphi_{XQ,YI})]/2df. \quad (3)$$

Fig. 1(b) shows the simulation results of the estimated Tx/Rx side IQ/XY skew, and five different values are preset to each skew impairment. The absolute estimate errors are within 0.2ps. Figs. 1(c-d) present the simulation results of the estimated Tx/TRx AFR and PFR. Noted that the Rx AFR/PFR is calculated by subtracting the TRx and Tx AFR/PFR. It can be observed that the absolute estimate error is within 1.5dB and 0.2rad for both Tx/TRx sides.

3. Experimental Setup and Discussions

As silicon photonics-based coherent transceiver has the advantage of compact size and ultra-low-cost, it is highly desirable for high data rate transmission. Therefore, a newly-developed 64GBaud-class silicon photonics-based coherent transceiver integrated with a CDM and ICR from CICT is used for the evaluation of our calibration proposal. Fig. 2(a) shows the experimental setup. Two ECL lasers with the power of 15.5 dBm and 10 dBm are used as the optical signal carrier and LO. The wavelength and linewidth are set as 1550 nm and 100 kHz, respectively. An arbitrary waveform generator (AWG, Keysight M8194A) with a 3 dB bandwidth of 45 GHz is used to generate the electrical signal, and to drive the CDM. The modulated signal is then amplified by an EDFA. At the receiver, the silicon photonics-based ICR is used to reconstruct the optical field. The detected electrical signals are captured by a 256 GSa/s real-time oscilloscope (Keysight, UXR0704A) with an operation bandwidth >70 GHz. Finally, conventional adaptive algorithms including GSOP, 2×2 DA/DD-LMS (data-aided for polarization de-muxing), phase recovery, and four blind 1×1 DD-LMS equalizers (single input single output, SISO) are used to demodulate the signal. Note that the algorithms we used do not compensate for any impairment between the I and Q tributary, and the static equalizers (in red) are activated with the impairment values from our calibration method.



(g) IQ skew				XY skew	
Tx X.pol	Tx Y.pol	Rx X.pol	Rx Y.pol	Tx	Rx
-0.33	1.47	0.93	1.03	0.71	0.91
Tx X.pol +20ps		Rx Y.pol -40ps		RX +40ps	
19.57		-39.05		40.83	

Fig. 2 (a) Experimental setup of 400Gbps optical coherent transceiver and the flow chart of equalization algorithms, (b) profile display of silicon photonics-based 400Gbps optical coherent transceiver, (c-d) measured Tx and TRx amplitude-frequency response, (e-f) measured Tx and TRx phase-frequency response, (g) the measured original IQ/XY skew and IQ/XY skew with additional values, the constellation diagrams of the received DP signal (h-j) without and (k-m) with using the proposed calibration scheme.

The profile display of the silicon photonics-based 400Gbps optical coherent transceiver is proposed in Fig.2 (b). During the calibration, the frequency interval f_0, Δf and N are set as 750MHz, 1.875 MHz, and 64 respectively to cover a 52GHz calibration bandwidth. Figs. 2(c-f) show the measured Tx/TRx AFR and PFR, respectively. The frequency response for each tributary is inconsistent. Meanwhile, the ripples on the response curves are also obvious. All of these may significantly degrade the system transmission performance. Based on the measured AFR/PFR and IQ/XY skew values, the pre-compensated Nyquist-QAM signal is sent to the calibrated optical transceiver. Fig. 2(g) shows the measured original IQ/XY skew values, and the additional skew values are applied in different input/output ports to verify the calibration accuracy. The fluctuation of the measured IQ skew is within ±0.2ps. Figs. 2(h-j) and 2(k-m) show the constellation diagrams of recovered Nyquist-QAM signals with and without our proposed calibration method. Thanks to our calibration, error-free transmission of both 64 and 96-GBaud DP Nyquist-16QAM signal is enabled with independent pre-FEC BER falling below the 7%/ 24%FEC threshold of 3.8e-3/4.5e-2 [8], by only using 64GBaud-class silicon photonics-based coherent optical transceiver.

4. Conclusions

We propose a highly precise calibration method for a 96GBaud coherent optical transceiver, with the capability of simultaneously characterizing both the Tx/Rx AFR/PFR and IQ/XY skew. The absolute estimate error of the AFR and PFR is less than 1.5dB and 0.2rad, and 0.2ps for IQ/XY skew respectively. Consequently, 96GBaud DP Nyquist-16QAM signal transmission is experimentally demonstrated with our silicon photonics-based optical coherent transceiver. The experimental results reveal the potential of the proposed calibration method being applied in beyond 100GBaud optical transceivers to achieve better transmission performance.

5. Acknowledge

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6. References

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