Simultaneously Calibration of Tx/Rx Frequency Response and IQ Skew for Coherent Optical Transceiver

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Abstract: We report a calibration method that can simultaneously characterize frequency-response and IQ-skew of coherent optical transceivers with laser frequency offset and phase noise. 50/40GBaud Nyquist-16/64QAM signals transmission is achieved using 22GHz commercial coherent optical transceiver.

OCIS codes: (060.2330) Fiber optics communication; (060.1660) Coherent communications

1. Introduction

To support the increasing demands for high-capacity optical networks, coherent optical communication systems with high baud-rate and high modulation formats such as 100GBaud-64QAM are widely studied. One of the major challenges for transmitting such high-speed signal is to compensate for the intrinsic impairments of the coherent transceiver, especially for bandwidth limitation and in-phase and quadrature (IQ) skew. The over-bandwidth transmitted signal will suffer from the impairment from high attenuation in the high-frequency domain, for instance, transmitting a 50GBaud Nyquist signal in the optical transceiver (TRx) with 25dB bandwidth of 25GHz. However, the high cost for large bandwidth optical/electrical devices forces people to carry out over-bandwidth transmission therefore greatly increases the burden for the post-equalizers. Besides, the calibration for IQ skew is another important item. It has been reported that at the bit error rate (BER) of 1e-2 when no compensation algorithm is used in the receiver, the IQ skew tolerance for 16QAM and 64QAM signal with 1 dB signal to noise ratio (SNR) penalty is less than 11% and 4.2% of the symbol period respectively [1]. It means the effect of IQ skew will become larger with the increase of symbol rate and modulation format. Therefore, the research on precise calibration for optical transceivers becomes popular recently. Lots of calibration methods target for bandwidth or IQ skew measurement have been studied. However, these calibration methods are usually restricted to the transmitter (Tx)/receiver(Rx) calibration and require many training/iteration processes [2-5]. The implementation of simultaneously calibrating the bandwidth and IQ skew for the whole optical transceiver is still challenging especially by using just one measurement process.

In our previous work [6], a precise calibration method that can simultaneously characterize both frequency response and IQ skew of self-homodyne coherent optical transceivers has been proposed. However, the measured frequency response of the coherent optical transceiver cannot be separated. This will limit the application scenarios as the laser frequency offset will affect the real transmission frequency response. In this paper, we extend our previous work with an additional ability to separate the Tx/Rx amplitude-frequency response and therefore can be used in a coherent optical transceiver in the presence of laser frequency offset and phase noise. Two specially designed multi-tone signals are utilized to capture both the Tx/TRx amplitude-frequency response and Tx/Rx skew. With the easily obtained laser frequency offset value, the Rx amplitude-frequency response can also be obtained. Note that our proposed calibration method only needs an additional low-bandwidth ($<1\text{GHz}$) photo-diode (PD) and still can capture all these imperfection parameters by just one measurement process. With the proposed calibration method, the 40GBaud Nyquist-64QAM signal and 50GBaud Nyquist-16QAM signal can be obtained in a commercial coherent optical transceiver with a 15dB bandwidth of 22GHz.

2. Operation principle

The main idea of this calibration method is to obtain the Tx amplitude-frequency response by a low-bandwidth PD and get the TRx frequency response besides the Tx/Rx skew by the target optical transceiver. To realize these functions, two specially designed multi-tone signals are generated at the Tx side and can be described as $I(t)=\sum_{k=1}^{N}\{\cos[(k+1/2)\omega_0 t+\phi_{I1,k}]+\cos[((k+1/2)\omega_0+\Omega_I(k))t+\phi_{I2,k}]\}$ and $Q(t)=\sum_{m=1}^{N}\{\cos[(m\omega_0)t+\phi_{Q1,m}]+\cos[(m\omega_0+\Omega_Q(m))t+\phi_{Q2,m}]\}$, where 2N is the number of transmitted tones and it is set according to the target calibration bandwidth. ω_0 is the frequency interval of each two tones, $\Omega_i(j)$ $(i=\text{I or Q}, j=1\text{~N})$ is the sub-frequency interval between two adjacent tones based on the number j, and ϕ is the random phase to reduce the peak to average power ratio. Fig. 1(a) shows the schematic diagram of the designed I and Q signals. It is clear to see that the I and Q signals are interleaved in the frequency domain and thus they can be separated by the coherent

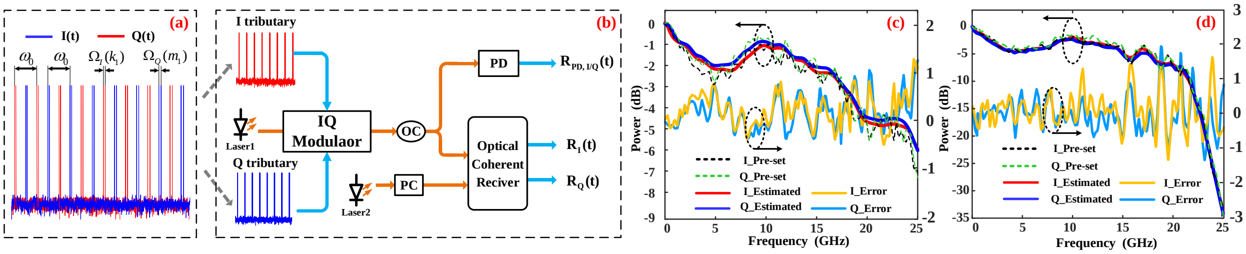

Fig. 1. (a) The schematic diagram of the special designed I and Q signals, (b) structure of the coherent system required to be calibrated, (c-d) the simulation results of the estimated Tx and TRx amplitude-frequency response.

optical transceiver. The sub frequency intervals Ω_I and Ω_Q of I and Q signals are also interleaved thus can be separated by the single PD. Fig. 1(b) shows the coherent back-to-back (B2B) transmission system to be calibrated. In our simulation, only a single polarization situation is considered for simplicity. The signal optical carrier and local oscillator (LO) are generated from different lasers thus will introduce the laser frequency offset and phase noise. We define $f_{I1}(k)=(k+1/2)\omega_0$, $f_{I2}(k)=(k+1/2)\omega_0+\Omega_I(k)$, $f_{Q1}(m)=m\omega_0$, $f_{Q2}(k)=m\omega_0+\Omega_Q(m)$. The optical IQ modulator is biased at the linear point, the Tx amplitude-frequency response can be obtained in a low bandwidth PD as long as the $\max\{\Omega\}\ll\omega_0$, and the low-frequency domain ($f<\omega_0$) of the received signals after PD detection can be expressed as

$$R_{PD,I}(\omega)=C_I\sum_{k=1}^{n}a_{TI}[f_{I1}(k)]\delta(\omega-\Omega_I(k)),\ \ R_{PD,Q}(\omega)=C_Q\sum_{m=1}^{n}a_{TQ}[f_{Q1}(m)]\delta(\omega-\Omega_Q(m)), \tag{1}$$

where $C_{I,Q}$ is a normalization constant, a_{TI} and a_{TQ} are the I and Q components of Tx amplitude-frequency response. As Ω is usually less than 100MHz, the approximate relationship $a_{TI}[f_{I1}(k)]=a_{TI}[f_{I2}(k)]$ and $a_{TQ}[f_{Q1}(m)]=a_{TQ}[f_{Q2}(m)]$ can be used in Eq. (1). The received signals after coherent detection are described as

$$\begin{cases} R_I(t)=\left\{\sum_{k=1}^{N}a_{II,k}\cos[f_{I1}(k)t+\phi_{I1,k}+\varphi_{II,k}+\psi_\theta]\right\}\times\cos(\theta)-\left\{\sum_{m=1}^{N}a_{QI,m}\cos[f_{Q1}(m)t+\phi_{Q1,m}+\varphi_{QI,m}+\psi_\theta]\right\}\times\sin(\theta) \\ R_Q(t)=\left\{\sum_{k=1}^{N}a_{IQ,k}\cos[f_{I1}(k)t+\phi_{I1,k}+\varphi_{IQ,k}+\psi_\theta]\right\}\times\sin(\theta)+\left\{\sum_{m=1}^{N}a_{QQ,m}\cos[f_{Q1}(m)t+\phi_{Q1,m}+\varphi_{QQ,m}+\psi_\theta]\right\}\times\cos(\theta)\end{cases}, \tag{2}$$

where θ is the initial phase difference between the carrier and the LO. a_{XY} and φ_{XY} (X,Y=I or Q) represent the channel amplitude-and phase-frequency response respectively, and they can be obtained by applying Fourier transform to $R_I(t)$ and $R_Q(t)$. ψ_θ is a constant phase term introduced by laser phase noise. In the presence of frequency offset $\Delta\omega$, the amplitude-frequency response can be expressed as $a_{II,k}=a_{TI}[f_{I1}(k)]\cdot a_{RI}[f_{I1}(k)-\Delta\omega]$. Here a_{RI} is the Rx amplitude-frequency response. Obviously, the real transmission frequency response will be changed by the dynamic laser frequency offset therefore the Rx frequency response cannot be compensated on the transmitter side. However, the laser frequency offset and phase noise will not affect the IQ skew estimation as they only contribute a constant phase term. Then the Tx and Rx skew can be calculated by analyzing the obtained φ_{XY} as

$$TX\_skew=\frac{d(\varphi_{II}-\varphi_{QI})/dw+d(\varphi_{IQ}-\varphi_{QQ})/dw}{2},\quad RX\_skew=\frac{d(\varphi_{II}-\varphi_{IQ})/dw+d(\varphi_{QI}-\varphi_{QQ})/dw}{2}. \tag{3}$$

Fig. 1(c-d) present the simulation results of the estimated Tx and TRx amplitude-frequency response. It can be observed that the absolute estimate error is within 1.5dB for both Tx and TRx amplitude-frequency response.

3. Experimental Setup and Discussions

Fig. 2(a) shows the experimental setup of a single-polarization 50GBaud B2B coherent transmission system to be calibration. Two ECL lasers with an optical power of 15.5 dBm and 10 dBm are used as the optical signal carrier and LO. The wavelength and linewidth of these lasers are 1550 nm and 100 kHz, respectively. An arbitrary waveform generator (AWG, Keysight M8195A) with a 3 dB bandwidth of 25 GHz is used to generate the electrical signal, and the output signal is then used to drive an electrical amplifier (CENTELLAX, OA3MHQM). The amplified signal is modulated onto the optical carrier by a single-polarization LiNO3 optical IQ modulator (Fujitsu, FTM7961EX). At the receiver, an integrated coherent receiver (ICR, Fujitsu FIM24706) with a 3 dB bandwidth of 22GHz is used to reconstruct the optical field. A polarization controller (PC) is utilized to align the polarization states of the LO and signal optical carrier. The detected electrical signals are captured by a 100 GSa/s digital

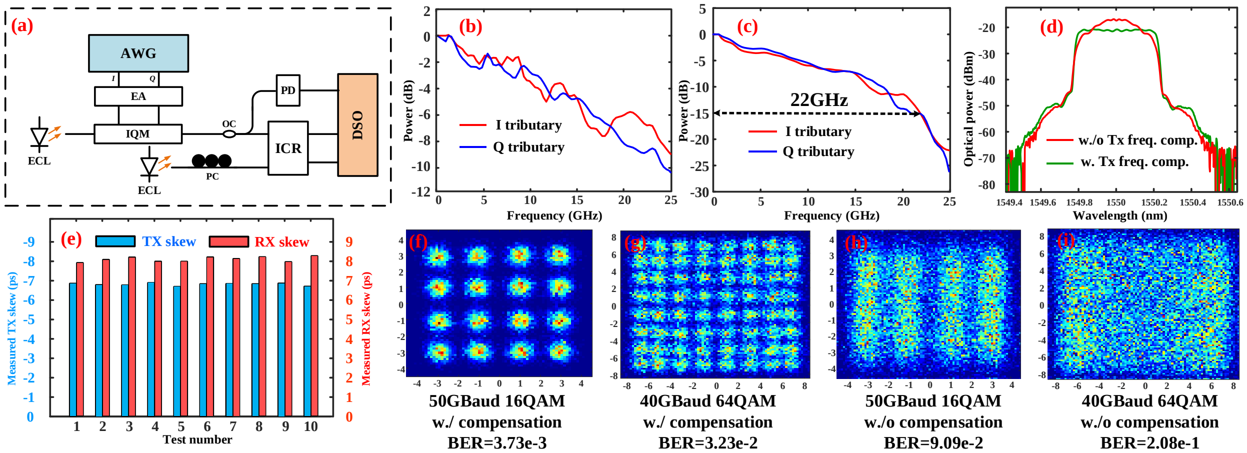

Fig. 2. (a) Experimental setup of 50Gbaud B2B transmission, (b-c) measured Tx and TRx amplitude-frequency response, (d) optical spectra from the output of optical IQ modulator with/without Tx amplitude-frequency response compensation, (e) measured TX skew, and RX skew by using the proposed scheme, the constellation diagrams of the received signal (f-g) with and (h-i) without the proposed calibration scheme.

sampling oscilloscope (DSO, Tektronix DPO73304D) with a 3 dB bandwidth of 33 GHz.

During the implementation of our proposed calibration method, the frequency interval ω_0 is set as 600MHz, $N = 45$ thus the calibration bandwidth is about 27GHz, $\Omega_I(k) = (3 + k * 4)$ MHz and $\Omega_Q(k) = (1 + k * 4)$MHz where $k = 1$~N. Figs. 2(b) and 2(c) show the measured Tx and TRx amplitude-frequency response, respectively. Obviously, the amplitude-frequency responses for I and Q tributaries are different. Meanwhile, the attenuation of this optical coherent transceiver is about 22dB at 15GHz. Based on the measured Tx amplitude-frequency response and Tx skew value, the Nyquist-QAM signal is pre-compensated at the transmitter and the Rx skew is compensated at the receiver by adding a time delay digitally. Fig. 2(d) shows the optical spectra of the 50GBaud Nyquist-16QAM signals at the output of the optical IQ modulator. The spectra are flat thanks to the proposed calibration method. Fig. 2(e) shows the measured Tx and Rx skew in 10 tests. The average value of measured Tx and Rx skew are -6.77ps and 8.04ps, respectively. The fluctuation of the measured IQ skew is within $\pm$ 0.2ps. Figs. 2(f-g) and 2(h-i) show the constellation diagrams of recovered Nyquist-QAM signals with and without our proposed calibration method. The used Rx digital signal process(DSP) include GSOP, CMA, DD-LMS, and phase recovery. The proposed calibration scheme is capable to improve the quality of the recovered QAM signal. Benefited from the calibration, 40GBaud Nyquist-64QAM signal can be obtained within the 24% FEC with BER of 4.5e-2 [7] and 50GBaud Nyquist-16QAM signal can be obtained within the 7% FEC with BER of 3.8e-3.

4. Conclusions

We propose a highly precise calibration method for a coherent optical transceiver in the presence of laser frequency offset and phase noise, with the capability of simultaneously characterizing both the Tx/TRx frequency response and Tx/Rx skew by a single measurement. Only a low bandwidth PD is used as the additional device. The absolute estimate error of the amplitude-frequency response and the Tx/Rx skew is less than 1.5dB and 0.2ps, respectively. Consequently, 50GBaud Nyquist-16QAM and 40GBaud Nyquist-64QAM signals are experimentally transmitted under the condition of B2B, by only use an optical coherent transceiver with a 15dB bandwidth of 22GHz.

5. Acknowledge

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6. References

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