Real-time In-field Automatic Bias Control and Self-calibration Module for High-baud Coherent Driver Modulator

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Abstract: We report a real-time in-field low-cost module that can simultaneously realize self-calibration and automatic-bias-control for coherent driver modulators. Precise frequency-response (<0.5dB) and IQ skew (<0.2ps) correction are achieved in experiments of 25/20GBaud 16/64QAM signal transmissions.

OCIS codes: (060.2330) Fiber optics communication; (060.4080) Modulation; (060.4510) Optical communications

1. Introduction

High-order quadrature amplitude modulation (QAM) with a high-baud rate is very sensitive to the imperfection of optical and electrical components such as limited bandwidth and in-phase and quadrature (IQ) timing skew. The IQ timing skew tolerance of 100GBaud 16/64QAM signal under the condition of the bit error rate of 2×10^{-2} is less than 1.1/0.42ps [1]. Therefore, accurate calibration is highly desired for the optical transceiver using a high symbol rate and high order modulation format technique. Recently many studies about optical transceiver calibration have been reported [2-3], which require the use of expensive equipment with a high sample rate and large bandwidth [4]. To cope with this problem, a low-cost transmitter calibration method is reported in [5], but it is difficult to achieve real-time precise calibration and it requires multiple measurements which will increase the measurement time and errors. Therefore, a precise low-cost technique for real-time and in-field measurement of IQ timing skew and frequency-response is highly desirable. At present, the technology of automatic bias control (ABC) of optical IQ modulators has been developed very well [6], which is essential in coherent optical transceivers. Therefore, it is a very good practical idea to realize the ABC and self-calibration simultaneously in one low bandwidth circuit board.

In this paper, we present a real-time in-field low-cost method that can simultaneously realize precise ABC and self-calibration for both transmitter frequency response and IQ timing skew characterization. The interleaved multi-tone signals of I and Q which is the high frequency with varying intervals are used for calibration. When I and Q are not orthogonal, high-frequency multi-tone signals of I and Q with varying intervals will beat as low-frequency multi-tone signals, and the frequency of this low-frequency multi-tone signal will be equal to the value of varying intervals. Compared with the reported schemes, the proposed self-calibration scheme can measure IQ skew and frequency response at one time and only needs to use the low-bandwidth components of the existing ABC module. Therefore, our scheme does not require any additional components, contributing to the integrity of the optical transceiver. The simulation results show that the measurement error of the frequency response and the IQ timing skew is less than 0.5dB and 0.2ps. Thanks to such highly precise calibration and ABC, the inter-symbol-interference induced by the limited bandwidth and the transceiver IQ skew can be effectively compensated in the experiments of 25/20GBaud 16/64QAM signal transmissions.

2. Operation Principle

Fig. 1(a) shows a typical coherent transmitter with an ABC module to be calibrated. To control the bias point and calibrate the frequency response and IQ timing skew of this coherent transmitter, a low-bandwidth (1.6GHz) photo-detector (PD) is used to detect a small proportion (about 10%) of the output optical power. Meanwhile, the output $|s(t)|^2$ of PD is sampled by a low-speed (250MSa/s) analog-to-digital converter (ADC) for signal processing, and the signal processing module includes the ABC module and self-calibration module (SCM). The ABC will output bias voltages with low-frequency dither signals, which are used to monitor the status of the bias point. It is worth noting that the correlation integration module, PD, ADC, and microcontroller unit (MCU) are shared by ABC and SCM, so we don't need to add any additional components for calibration. To ensure that ABC and SCM do not interfere with each other, the frequency of dither and the value of varying intervals of multi-tone are not equal.

For the ABC scheme, in our previous work [6], we use correlation integral (CI) degree of the dither signals and the optical signal by dither-correlation detection to realize real-time bias control of IQM. The CI of the branch I can be expressed as $CII = \int_0^T |s(t)|^2 \cdot \sin(2\pi f_I t)\, dt$, where $sin(2\pi f_I t)$ is the dither signal. Similar results CIQ and CIP can be obtained for the branch Q and phase difference of IQ. We can use these three parameters to control the bias point.

Transmitter IQ skew is usually induced by the delay difference of the used RF cables and electrical amplifiers (EA). For the proposed calibration scheme, the transmitted I and Q multi-tone signals are described as $I(t) = \sum_{n=1}^{N} cos[nw \cdot t + \phi_{n1}]$, $Q(t) = \sum_{n=1}^{N} cos[n(w+\Delta w) \cdot t + \phi_{n2}]$, where N is the number of transmitted tones for I

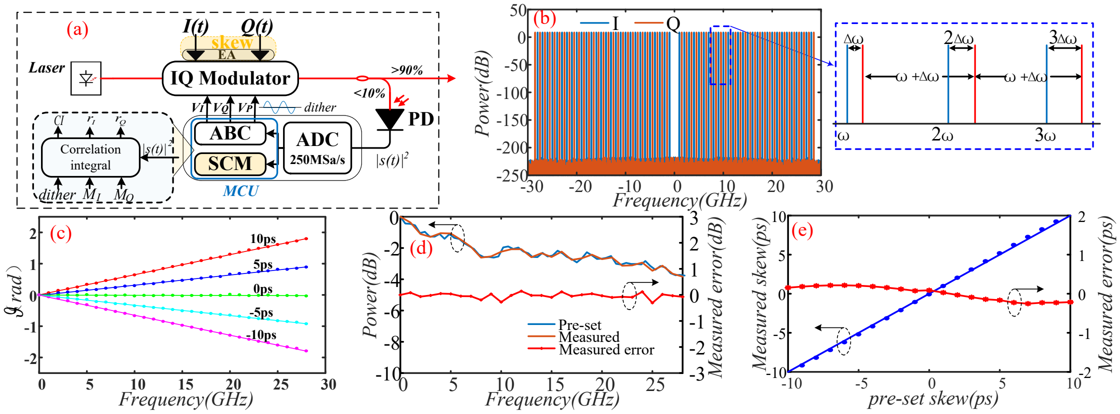

Fig. 1. (a) Coherent transmitter with ABC module to be calibrated, (b) spectrum of the transmitted interleaved I and Q multi-tone signals, (c) simulation comparison between the pre-set and measured amplitude response, (d) (e) transceiver IQ skew values using the proposed scheme.

and Q signal, Δw is the frequency of varying intervals, and w ($w \gg N \cdot \Delta w$) is the frequency point of transmitted multi-tone. And ϕ_{n1} and ϕ_{n2} are random phases to reduce the signal peak to average power ratio. The electrical spectrum of the I and Q transmitted signal is shown in Fig. 1(b). Multi-tone signals of I and Q are interleaved and intervals is varying in the frequency domain, and varying intervals could mark the frequency point of transmitted multi-tone. Optical IQ modulators are usually biased at the linear point $(\pi, \pi, \pi/2)$. With the help of our previous work [6], we can use the ABC module to offset the phase φ_p of parent modulator from $\pi/2$ to $(\pi/2+\theta)$. Therefore, the output of PD can be expressed as

$$|s(t)|^2 = |s_I(t)|^2 + |s_Q(t)|^2 + 2\Re\{s_I(t)s_Q^*(t)e^{j\theta}\}, \tag{1}$$

where $s_I = \sum_{n=1}^{N} \sin[\bar{a}_I(nw)\cos(nw(t+\Delta t))] \approx \sum_{n=1}^{N} \bar{a}_I(nw)\cos(nw(t+\Delta t))$, $s_Q = \sum_{n=1}^{N} \sin[\bar{a}_Q(nw)\cos(n(w+\Delta w)t)] \approx \sum_{n=1}^{N} \bar{a}_Q(nw)\cos(n(w+\Delta w)t)$, Δt is the IQ timing skew. And $\bar{a}_I(nw)$ and $\bar{a}_Q(nw)$ are the complex-valued frequency responses at the frequency of nw. Since low bandwidth of PD and ADC, high-frequency components of $|s_I(t)|^2$ and $|s_Q(t)|^2$ will be filtered out, and Eq. (1) can be modified as

$$|s(t)|^2 = \sum_{n=1}^{N} \bar{a}_I \bar{a}_Q^* \cos(nw\cdot dt - \Delta w\cdot t)\cdot\cos\theta. \tag{2}$$

The measurement process of frequency response (FR) and IQ timing skew can be clearly observed in Fig. 1(a), where $M_I = \cos(n\Delta w\cdot t)$ and $M_Q = \sin(n\Delta w\cdot t)$ are low-frequency cosine and sine reference signals and the frequency of $n\Delta w$ is equal with the value of varying intervals in the frequency domain. Through the correlation integral module to calculate the correlation between the two low-frequency reference signal and $|s(t)|^2$, we can realize the process of marking the high-frequency (nw) multi-tone signal with value ($n\Delta w$) of varying intervals in the frequency domain. Therefore, the frequency response of the high-frequency signal corresponds to the frequency response of the low-frequency signal, and the frequency response of the low-frequency can be obtained from r_I and r_Q, which can be described as

$$\begin{cases} r_I = \int_0^T M_I\cdot|s(t)|^2\,dt = |\bar{a}(nw)|^2\cos\theta\cos(nw\cdot dt) \\ r_Q = \int_0^T M_Q\cdot|s(t)|^2\,dt = |\bar{a}(nw)|^2\cos\theta\sin(nw\cdot dt) \end{cases}, \tag{3}$$

where T is the period of M_I and M_Q, $\bar{a}(nw) \approx \bar{a}_Q(nw) \approx \bar{a}_I(nw)$ when the amplitude response of I and Q are close. Therefore, IQ timing skew of Δt and the amplitude response of $A_{dB}(nw)$ at each frequency point can be expressed as

$$\begin{cases} \Delta t = slope(angle(r_I + jr_Q), w) \\ A_{dB}(nw) = 5\log_{10}(|r_I|^2 + |r_Q|^2) \end{cases}, \tag{4}$$

where $angle(\cdot)$ is the function of solving the complex phase angle $\vartheta(nw)$, which can be expressed as $\vartheta(nw) = nw\cdot\Delta t$. And the $slope(\cdot)$ is the function of solving the slope, which can solve the slope Δt of $\vartheta(nw)$ corresponding to nw as shown in Figs. 1(c). Figs. 1(d) and 1(e) show simulation results of the frequency response and IQ timing skew. The pre-set frequency response and IQ timing skew of EA and the measured frequency-response and skew using our proposed method are both presented. The measurement error for amplitude response and IQ skew are also provided. It can be observed that a highly precise measurement of frequency response and IQ timing skew is achieved, and the maximum measurement error of frequency response and skew is less than 0.5dB and 0.2ps, respectively.

3. Experimental Setup and Discussions

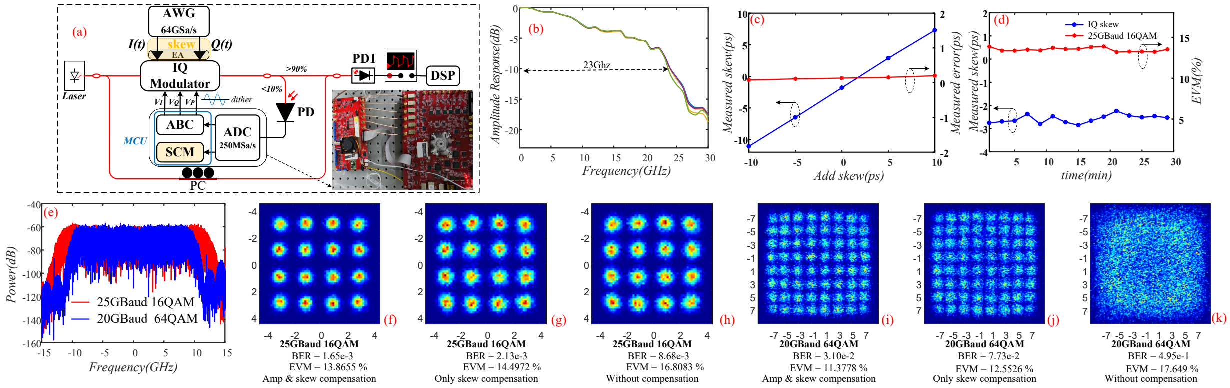

Fig. 2. (a) Experimental setup for 25/20Gbaud 16/64QAM signal transmission, (b-c) measured amplitude response, IQ timing skew using the proposed scheme, (d) the EVM and skew curve with time (e) electrical spectra of the received signals, and the constellation diagrams of recovered QAM signal using (f), (i) our proposed calibration method, using (g), (j) only IQ timing skew calibration, and without (h), (k) any calibration.

Fig. 2(a) shows the experimental setup of 25/20Gbaud 16/64QAM signal over optical back-to-back transmission using Kramers-Kronig (KK) receiver. A continuous-wave laser is used as the optical source with an optical power of 15.5 dBm, a wavelength of 1550nm, and a linewidth of 100kHz. An arbitrary waveform generator (AWG, Keysight M8194A) 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 (EA, Centellax OA3MHQM4) and an optical IQ modulator (Fujitsu FTM7977HQA) with 3 dB bandwidth of 23 GHz. A polarization controller (PC) is adopted to align the polarization states of the optical signal and the LO. The optical signal is received by a photo-detector (PD1) with 40GHz bandwidth, and electrical signals are captured by a digital sampling oscilloscope (DSO, Tektronix DPO 73304D) operated at 100GSa/s. During the implementation of our proposed calibration method, the frequency varying interval of the interleaved I and Q multi-tone signals is 250KHz, and the maximum frequency of multi-tone signals is 30GHz. Figs. 2(b) and 2(c) show the measured amplitude response and IQ timing skew, respectively. It can be observed that the maximum available bandwidth of this transmission system is 23GHz. Fig. 2(c) shows that the measured IQ timing skew is -2.6581ps. The fluctuation of amplitude response in multiple measurements within 23GHz is lower than 0.3 dB, and the fluctuation of IQ timing skew is less than 0.2ps, which means that our tests are fairly stable and repeatable.

Based on the control of ABC, the measured frequency response and IQ skew value, the Nyquist-QAM signal is pre-compensated at the transmitter. Fig. 2(d) shows the measured error vector magnitude (EVM) and IQ skew curve with time, which shows the stable performance of our ABC module and SCM. Fig. 2(e) shows the electrical spectra of the received 25GBaud 16QAM and 20GBaud 64QAM signals. The electrical spectra are flat thanks to the precise characterization and effective compensation. Figs. 2(f-k) show the constellation diagrams of recovered QAM signals using our proposed calibration method, using only IQ timing skew calibration, and without any calibration. It can be observed that the proposed calibration scheme is capable to improve the transmission performance, the measured bit error rate (BER) performance of 25 Gbaud 16QAM signals can be increased from 8.68e-3 to 1.65e-3. And even the 20 Baud 64QAM signals over optical B2B transmission can be achieved with the measured BER value below the 24% SD-FEC threshold of 4.5e-2 by using the 23GHz commercial coherent driver modulator.

4. Conclusions

We propose a real-time in-field low-cost method that can simultaneously realize precise ABC and self-calibration for both transmitter frequency response and IQ timing skew characterization. The measurement error of the amplitude response and IQ timing skew is less than 0.5dB and 0.2ps respectively. With the help of the proposed scheme, 25/20GBaud 16/64QAM signal is experimentally transmitted under the condition of B2B using KK receiver by using the 23GHz commercial coherent driver modulator.

5. Acknowledge

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6. References

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