In-phase/Quadrature Skew Measurement for Optical Mach-Zehnder Modulator

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***Abstract*—We propose an accurate and robust in-phase/quadrature (IQ) skew measurement method for optical Mach-Zehnder IQ modulator based on image spectrum analysis. Numerical simulation and experiment results demonstrate 0.7ps measurement accuracy. The robustness to bias deviations and finite extinction ratios were also investigated.**

I. INTRODUCTION

Optical Mach-Zehnder (MZ) in-phase/quadrature (IQ) modulator is one of the most important devices in modern optical coherent communication system. It consists of two tributaries to modulate the in-phase and quadrature component of optical carrier. In high speed optical transmission system with several tens of giga-baud, a few picosecond (ps) of IQ skew that is defined as the delay difference between I and Q tributaries causes significant performance penalty [1,2]. Due to the fabrication error and/or variation in operating conditions, practical optical modulator, as well as digital-analog converter (DAC), driver and other possible devices in optical transmitter, usually exhibits such IQ skew. Fortunately, the IQ skew could be compensated by digital signal processing in modern optical transmitter, but it is necessary to accurately measure the IQ skew. Recently several methods has been proposed to measure the IQ skew [2-4]. Delay-interference method is used to measure IQ skew in [2], which requires high timing precision digital communication analyzer. Adaptive pre-equalizer using indirect learning architecture is used to model and measure the IQ skew in [3], which requires additional detection in the transmitter to monitor the pre-equalization error and feedback. Receiver multiple input multiple output equalizer is introduced to measure the transmitter IQ skew in [4], which requires feedback control from receiver to transmitter.

In this paper, we propose a simple, accurate and robust IQ skew measurement method based on image spectrum analysis. Numerical simulation and experiment results show that the method accuracy were 0.7ps and that the accuracy is consistent under bias deviations and finite extinction ratios of the optical modulator.

II. PRINCIPLE OF IQ SKEW M `EASUREMENT

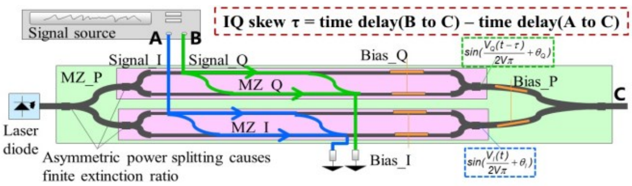

Fig.1 Optical IQ modulator with IQ skew. MZ: Mach-Zehnder

Schematic diagram of optical IQ modulator with IQ skew is shown in Fig.1. Optical phase modulation occurs in each arm of the MZ interferometers based on e.g. quantum confined stark effect in indium phosphide modulator. Bias deviations come from the imperfect optical phase bias control of the MZ interferometers. Finite extinction ratios come from the asymmetric power splitting of the input light. Taking those imperfections into consideration, the output optical field is given by

$$E(t) = sin(\frac{V_I(t)}{2V\pi} + \theta_I) + ie^{i\delta} \cdot sin(\frac{V_Q(t-\tau)}{2V\pi} + \theta_Q) \qquad (1)$$

where τ is IQ skew, $V_I(t)$ and $V_Q(t)$ are AC-coupled electrical signals on I and Q tributaries, θ_I, θ_Q and δ are bias deviations for MZ I, Q and P. Optimum values for θ_I, θ_Q and δ are all zero.

Single sideband (SSB) comb signal which only has either positive or negative frequency component should be useful in detecting the image spectral components by a simple monitoring method. It can be expressed by

$$V_I(t) = \sum_n A_n \cos(2\pi f_n t + \varphi_n), \quad V_Q(t) = \sum_n A_n \sin(2\pi f_n t + \varphi_n) \qquad (2)$$

where A_n, f_n and φ_n are amplitude, frequency and phase of the n^{th} component of comb signal, respectively.

Substituting (2) to (1) and considering small bias deviation and fundamental component of Bessel function extension for triangle function, the output optical field is:

$$E(t) \approx \sum_n J_1(\frac{A_n}{2V\pi}) \cos\theta_I \{ e^{j(2\pi f_n t + \varphi_n)} (1 + \frac{\cos\theta_I}{\cos\theta_Q} e^{j(\delta - 2\pi f_n \tau)}) + e^{-j(2\pi f_n t + \varphi_n)} (1 - \frac{\cos\theta_I}{\cos\theta_Q} e^{j(\delta + 2\pi f_n \tau)}) \} \qquad (3)$$

Where $J_1(\cdot)$ is the 1st order Bessel function of the first kind. The first term in bracket is the main signal at f_n, and the second term is the image signal at $-f_n$.

By sending the SSB comb signals with positive and negative frequency separately and using (3), the image-to-main signal power spectrum (IMPS) can be measured individually at each frequency, and expressed by

$$IMPS(f_n) = \frac{Pimag(f_n)}{Pmain(f_n)} = \frac{1 - \cos(\delta - 2\pi f_n \tau)}{1 + \cos(\delta - 2\pi f_n \tau)}$$
$$IMPS(-f_n) = \frac{Pimag(-f_n)}{Pmain(-f_n)} = \frac{1 - \cos(\delta + 2\pi f_n \tau)}{1 + \cos(\delta + 2\pi f_n \tau)} \qquad (4)$$

From (4), the frequency domain shape of IMPS or the image spectrum is fully determined by the IQ skew value, which will be flat when IQ skew is zero. Reorganizing (4), IQ skew τ can be expressed as a function of IMPS by

$$\tau = \frac{1}{2\pi}\frac{\partial}{\partial f}\arccos\left(\frac{1-IMPS(f)}{1+IMPS(f)}\right) \quad (5)$$

From (5), IQ skew can be easily measured based on the image spectrum shape denoted by IMPS.

III. Numerical simulation and experiment

A. Numerical simulation and results

Numerical simulation model was built for the system as shown in Fig.1. DAC with a sampling rate of 64Gsample/s and effective number of bits of 5.4 generates the SSB comb signals in a range 1~25GHz with 2GHz spacing. The extinction ratios of all MZ interferometers are set to 20dB. Bias deviations of three MZ interferometers I, Q and P are 10 degree.

Results of the image spectra denoted by IMPS are shown in Fig.2. The IMPS shapes are determined by the IQ skew as expressed by (4). The floor is caused by the additive noise and finite optical modulator extinction ratio. It will not affect the skew measurement because it does not change the IMPS shape. From Fig.2, bias I/Q deviations do not change the IMPS shapes, and bias P deviation only shifts the IMPS curve along the frequency and does not change the IMPS shape either. As a result, the skew measurement method is expected rather robust to the noise floor and the bias I/Q/P deviations. From Fig.2 and (5), the IQ skews are calculated out and shown in Fig.3. The achieved estimation errors are no more than 0.7ps in range of actual IQ skews from 0ps to 10ps under various bias deviations.

B. Experimental results

Experimental setup for the IQ skew measurement is shown in Fig.4. 64Gsample/s DAC were used to generate the same test signals as simulation. A 30G indium phosphide optical modulator was used to modulate electrical signals. The IQ skew could be from not only optical modulator, but also DAC, driver and connection cables. Light source was a 1546.5nm continuous wave laser with 13dBm output. An optical spectrum analyzer with a resolution bandwidth of 150MHz was used to collect the main and image signal spectra. In the experiment, different IQ skew values were emulated by adding delay to the Q tributary in the digital domain before the DAC.

Fig.5 shows the results of the measured IQ skews by the proposed method. The estimation error with respect to the actual value was identified to be less than 0.7ps for all the measurements in the diagram.

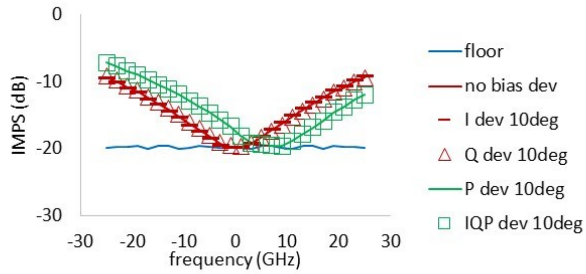

Fig.2 Image spectrum of 4ps IQ skew and various bias deviations

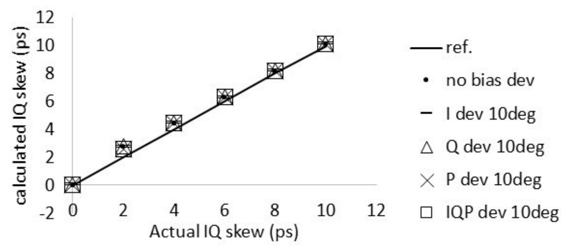

Fig.3 Calculated IQ skew by proposed method in simulation

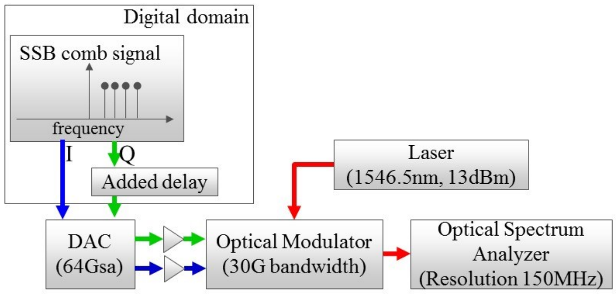

Fig.4 Experiment setup for IQ skew measurement

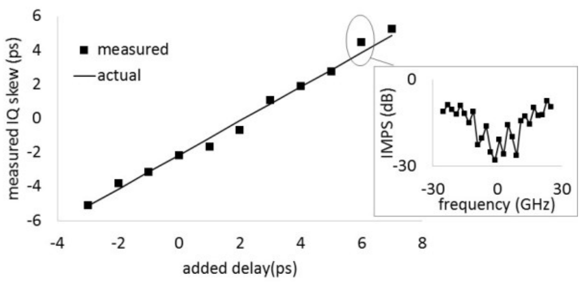

Fig.5 Measured IQ skew by proposed method in experiment. Inserted plot: measured image spectrum denoted by IMPS of 4ps IQ skew

IV. Conclusion

A simple, accurate and robust in-phase/quadrature skew measurement method for optical Mach-Zehnder modulator based on image spectrum analysis is proposed. Numerical simulation and experiment results show that the measurement accuracy is as high as 0.7ps and the method is robust to bias deviations and finite extinction ratios.

References

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