Auto bias control technique for optical OFDM transmitter with bias dithering

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Abstract: In coherent optical communication systems, the transmitter usually employs an optical in-phase and quadrature (IQ) modulator to perform electrical-to-optical up-conversion. However, some environmental factors, such as temperature and mechanical stress, strongly influence the stability. To stabilize the quality of the transmitted signal, auto bias control (ABC) is essential to keep modulator in optimum bias. In this paper, we present a novel method of ABC for the optical orthogonal frequency division multiplexing (O-OFDM) signal. In the proposed scheme, a small cosine/sine wave dither signal is added on to the I/Q baseband signal, respectively. Based on the power monitoring of the 1st and 2nd harmonics of the dither signal, the biases of the optical IQ modulator for O-OFDM system can be adjusted very precisely. The simulation and experimental results show good performance on locating the optimum bias voltages for the IQ modulator with high precision.

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

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1. Introduction

In the last decade, the attention of both academia and industry in high-capacity transmission shifted to coherent optical communication due to rapid advances in semiconductor technology

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and electronic digital signal processing (DSP) [1–3]. Along with the rapid development of coherent optical single carrier, coherent optical OFDM (CO-OFDM) received much attention due to its excellent performance and flexibility, and has been considered as a promising technology for the future long-haul transmission and dynamic optical networks [4]. The optical IQ modulator is a key component for generation of the optical signals in coherent optical transmission system. However, some environmental factors, such as temperature and mechanical vibration, strongly influence the stability of IQ modulator [5,6]. To maintain the long-term quality of the transmitted signal, ABC is essential to trace the optimum bias conditions. In [7,8], the ABC was based on an asymmetric dithering and has been employed to monitor and control the bias drifting of signal carriers modulated with QPSK and 16-QAM, respectively. Differential phase information could also be used to control the biases for single carrier modulation [9]. However, only a few publications on bias controlling for O-OFDM have been reported, in [10], Cho analyzed the statistics of output optical power to control the bias of OFDM modulated signal.

In this paper, we propose a novel ABC approach for O-OFDM as an extension of [10]. In [10], within a small range ($\pm$ 10% of V_π) close to the optimum DC condition, the statistical analysis only offers a tiny distinguish ratio of the monitored power (< 0.5 dB). This may be a challenge for the practical implementation. In our proposed scheme, we add a small sine/cosine dither onto the OFDM I/Q signal. Based on the power monitoring of the 1st and 2nd harmonics of the dither signal, the bias of the optical IQ modulator for O-OFDM system can be finely controlled. A numerical simulation is first conducted to investigate the effect of the proposed bias control method. We then carry out a 10 Gb/s single-polarization CO-OFDM experiment to evaluate the system performance under the controlled bias condition. We will demonstrate that the proposed approach successfully enables us to control the system to the optimum bias condition with only negligible dithering penalty in the back-to-back configuration.

2. The principle of auto bias control technique

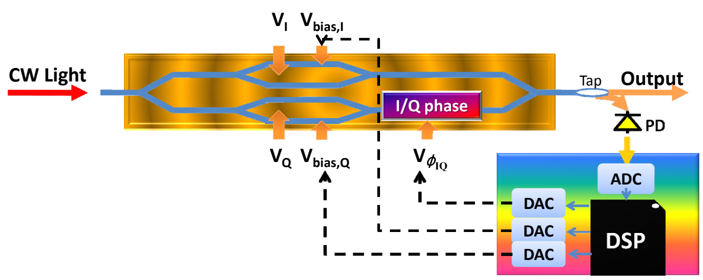

Fig. 1. The auto bias control configuration.

A typical ABC configuration for an optical IQ modulator is illustrated in Fig. 1. The IQ modulator comprises two parallel Mach–Zehnder modulators, with an I/Q phase shifter to define the phase difference of the two optical paths. In most of the current commercial optical IQ modulator, a photo-detector (PD) is integrated at the output end to detect a small proportion (usually ~5%) of the signal power. To monitor and control the biases, a low speed (tens of MHz) analog-to-digital converter (ADC) is employed to sample the detector signal. A digital signal processor (DSP) is then used to trace the optimum bias conditions. The calculated bias voltages are applied to the modulator after digital-to-analog conversion.

The output optical field E_o can be written as:

$$E_o = \frac{E_i}{2}[\cos\left(\frac{\pi}{2}\cdot\frac{V_I + V_{bias,I}}{V_\pi}\right) + \cos\left(\frac{\pi}{2}\cdot\frac{V_Q + V_{bias,Q}}{V_\pi}\right)e^{-j\phi_{IQ}}] \qquad (1)$$

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where, φ_{IQ} is the phase difference between the IQ branches, V_π is the half-wave switching voltage, $V_{bias,I}$ and $V_{bias,Q}$ are the DC bias voltages for the real and imaginary components, respectively. The monitored electrical current of the coupled PD at the output end is proportional to the output optical power ($I_m \propto P_o = |E_o|^2$), given by [10]

$$P_o = \frac{P_i}{8}\left[2+\cos(\phi_I+\phi_{bias,I})+\cos(\phi_Q+\phi_{bias,Q})+4\cos\frac{(\phi_I+\phi_{bias,I})}{2}\cos\frac{(\phi_Q+\phi_{bias,Q})}{2}\cos\phi_{IQ}\right] \quad (2)$$

Where $\varphi_{I(Q)} = \pi V_{I(Q)}/V_\pi$, $\varphi_{bias,I(Q)} = \pi V_{bias,I(Q)}/V_\pi$, and P_i denotes the input optical power $P_i = |E_i|^2$.

To locate the optimum biases of the two MZM branches, we make the following obversions: biasing at the null point will suppress the optical carrier, and drive the RF signal in the most linear region of the IQ modulator; any drift from the null point will result a DC offset coupled onto the monitored electrical signal I_m. Thus, we can monitor the power of the monitoring signal I_m including both RF and DC components using an electrical low-pass filter, which we call 'current power' for brevity. Minimizing the current power by tuning the two biases suppresses the optical carrier, and forces the bias to the null point. Figure 2(a) shows the monitored current power as a function of both $\varphi_{bias,I}$ and $\varphi_{bias,Q}$ under the optimum φ_{IQ}. As shown in Fig. 2(a), for any given $\varphi_{bias,Q}$, we can minimize the current power to find the optimum $\varphi_{bias,I}$. Similarly, we can then find the optimum $\varphi_{bias,Q}$ under the optimum $\varphi_{bias,I}$. With a few rounds of tracing, the current power can achieve the minimum value, which indicates the two bias voltages are optimized. To observe the detailed simulation results, we plot the relative current power as a function of $\varphi_{bias,I}$ with varying φ_{IQ} and $\varphi_{bias,Q}$ in the Fig. 2(b). Here, we define the distinguish ratio (DR) as the maximum current power variation in a specified range of biases. Within the range of $|\triangle\varphi_{bias,I}| \leq 0.1\pi$, the DR is only 0.5 dB, where $\triangle\varphi_{bias,I} = \varphi_{bias,I}\text{-}\varphi_{bias,I\_optimum}$. As a result, $\varphi_{bias,I(Q)}$ would be easily affected by the electrical noise or resolution inaccuracy of sampling [10]. also analyzed the bias voltage for φ_{IQ} using the variance of I_m as a function of the phase shifter. Similarly, the optimum φ_{IQ} is hard to be precisely controlled.

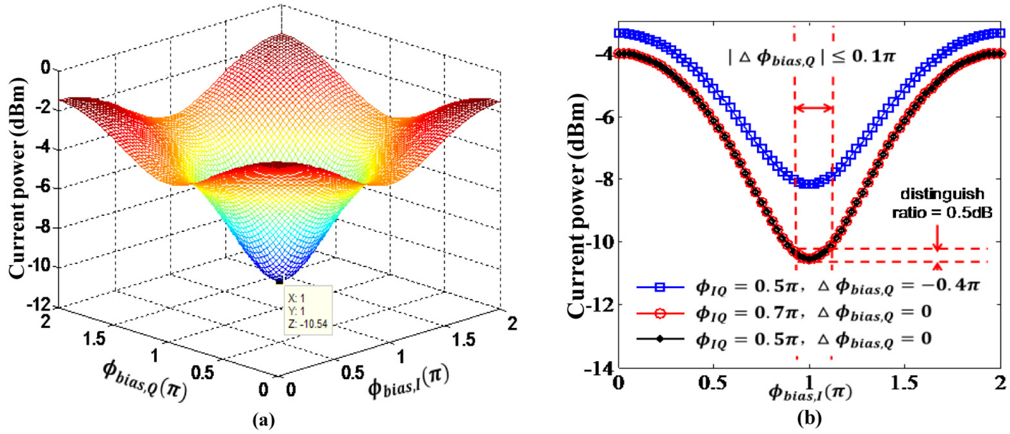

Fig. 2. The relative power as a function of (a)$\varphi_{bias,I}$ and $\varphi_{bias,Q}$, (b)$\varphi_{bias,I}$ with different $\varphi_{bias,Q}$ and φ_{IQ}.

In order to achieve precisely bias control, a small cosine/sine dither signal is added onto the OFDM signal. Note that the frequency of dither signal f_{dith} should be much smaller than the bandwidth of OFDM subcarriers. The detailed procedure of proposed ABC technique is described as following: I) We first monitor the minimum current power based on [10] to locate the biases in the range of ~0.1π. II) The optimum bias of φ_{IQ} is indicated by monitoring the overall minimum current power at the frequency of 2nd harmonic of dither signal. III) With numbers of iterations, the optimum bias of $\varphi_{bias,I/Q}$ can be estimated by monitoring the minimum current power at the frequency of 1st harmonic of dither signal. Next the fundamental and simulation results of proposed scheme will be introduced. The dither signal is expressed as $V_{dith}\cos(2\pi f_{dith}t)$ and $V_{dith}\sin(2\pi f_{dith}t)$ for the real and imaginary branches respectively, where $V_{drift,\,I}$ and $V_{drift,\,Q}$ are relatively small compared to V_π. In such a configuration, the biased signal can be expressed as:

$$\begin{aligned} V_{bias,I} &= -V_\pi + V_{drift,I} + V_{dith}\cos(\omega_{dith}t) \\ V_{bias,Q} &= -V_\pi + V_{drift,Q} + V_{dith}\sin(\omega_{dith}t) \end{aligned} \tag{3}$$

In the practical implementation, the OFDM subcarriers close to DC are commonly padded with zero to avoid DC interference [11].The OFDM RF signal V_I and V_Q can be written as Eq. (4), note that $2f_{dith} << f_s$:

$$\begin{aligned} V_I(t) &= \sum_2^{N_{sc}} \mathrm{Re}\{c_k\}\cos\left(2\pi f_s(k-1)t\right) \\ V_Q(t) &= \sum_2^{N_{sc}} \mathrm{Im}\{c_k\}\sin\left(2\pi f_s(k-1)t\right) \end{aligned} \tag{4}$$

First we set F1, F2 as following:

$$\begin{aligned} F_1 &= 2 + \cos(\phi_I + \phi_{bias,I}) + \cos(\phi_Q + \phi_{bias,Q}) \\ F_2 &= 4\cos\left(\frac{\phi_I + \phi_{bias,I}}{2}\right)\cos\left(\frac{\phi_Q + \phi_{bias,Q}}{2}\right)\cos\phi_{IQ} \end{aligned} \tag{5}$$

Then we substitute Eq. (3), Eq. (4) into F_1, F_2 and expand using a Taylor series expansion to second order, respectively:

$$\begin{aligned} F_1(t) &\approx 2 - 1 + \frac{\left(\phi_I + \phi_{bias,I} + \pi\right)^2}{2} - 1 + \frac{\left(\phi_Q + \phi_{bias,Q} + \pi\right)^2}{2} \\ &= \frac{\pi^2}{V_\pi^2}\frac{\left(V_I(t) + V_{drift,I} + V_{dith}\cos(2\pi f_{dith}t)\right)^2}{2} + \frac{\pi^2}{V_\pi^2}\frac{\left(V_Q(t) + V_{drift,Q} + V_{dith}\sin(2\pi f_{dith}t)\right)^2}{2} \\ &= \frac{\pi^2}{2V_\pi^2}\left(2V_{dith}\left[V_{drift,I}\cos(2\pi f_{dith}t) + V_{drift,Q}\sin(2\pi f_{dith}t)\right] + V_{dith}^2 + V_{drift,I}^2 + V_{drift,Q}^2\right) \\ &+ \frac{\pi^2}{2V_\pi^2}\left(V_I^2(t) + V_Q^2(t) + 2V_I(t)\left(V_{drift,I} + V_{dith}\cos(2\pi f_{dith}t)\right) + 2V_Q(t)\cdot(V_{drift,Q} + V_{dith}\sin(2\pi f_{dith}t))\right) \end{aligned} \tag{6}$$

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$$
\begin{aligned}
F_2(t) &= 4\sin\left(\frac{\phi_I+\phi_{bias,I}+\pi}{2}\right)\sin\left(\frac{\phi_Q+\phi_{bias,Q}+\pi}{2}\right)\cos\phi_{IQ} \\
&\approx 4\left(\frac{\phi_I+\phi_{bias,I}+\pi}{2}\right)\cdot\left(\frac{\phi_Q+\phi_{bias,Q}+\pi}{2}\right)\cos\phi_{IQ} \\
&= \pi^2\left(\frac{V_I(t)+V_{drift,I}+V_{dith}\cos(2\pi f_{dith}t)}{V_\pi}\cdot\frac{V_Q(t)+V_{drift,Q}+V_{dith}\sin(2\pi f_{dith}t)}{V_\pi}\right)\cos\phi_{IQ} \\
&= \frac{\pi^2}{V_\pi^2}\{V_{drift,I}V_{drift,Q}+V_{dith}[V_{drift,Q}\cos(\omega_{dith}t)+V_{drift,I}\sin(\omega_{dith}t)]+0.5\cdot V_{dith}^2\cos(2\omega_{dith}t)\}\cos\phi_{IQ}+ \\
&\frac{\pi^2}{V_\pi^2}\{V_I(t)V_Q(t)+V_I(t)V_{dith}\cos(2\pi f_{dith}t)+V_I(t)V_{drift,I}+V_Q(t)V_{drift,Q}+V_Q(t)V_{dith}\sin(2\pi f_{dith}t)\}\cos\phi_{IQ}
\end{aligned}
\tag{7}
$$

It can be proved that the cross terms including OFDM in Eq. (6) and Eq. (7) has negligible impact in the range of DC to f_s-f_{dither}. Because the frequency of dither signal f_{dither} is much smaller than the subcarrier bandwidth f_s, those cross terms can be digitally or electrically removed by employing a low-pass filter. Therefore, the F_1 can be approximately express as:

$$
F_1(t) \approx \frac{\pi^2}{2V_\pi^2}\left\{\underbrace{V_{drift,I}^2+V_{drift,Q}^2+V_{dith}{}^2}_{\text{DC harmonic component}}+\underbrace{2V_{dith}\left[V_{drift,I}\cos(2\pi f_{dith}t)+V_{drift,Q}\sin(2\pi f_{dith}t)\right]}_{1^{\text{st}}\text{ harmonic component}}\right\} \tag{8}
$$

Analogously, the summation of the F_2 can be also expressed as:

$$
F_2(t) \approx \frac{\pi^2}{V_\pi^2}\left\{\underbrace{V_{dith}\left[V_{drift,Q}\cos(2\pi f_{dith}t)+V_{drift,I}\sin(2\pi f_{dith}t)\right]}_{1^{\text{st}}\text{ harmonic component}}+\underbrace{0.5\cdot V_{dith}^2\cos(4\pi f_{dith}t)}_{2^{\text{nd}}\text{ harmonic component}}\right\}\cos\phi_{IQ} \tag{9}
$$

Then we monitor the signal power of dither harmonics applying a low speed ADC operated at tens of megahertz. From Eq. (9), the signal contains 1st and 2nd harmonics of dither frequency at $\varphi_{IQ}\neq 90°$. The 2nd harmonic component only vanishes when φ_{IQ} equals to 90°. Similarly, according to the Eq. (8) the 1st harmonic component vanishes when $V_{drift,\,I}$ and $V_{drift,\,Q}$ equal to zero. Thus, within the 0.1π range based on [10], we are able to control the three bias voltages just by monitoring the RF power of 1st and 2nd harmonic components. The first step is to tune φ_{IQ} to the optimum, which can be achieved by monitoring the power of 2nd harmonic component of dither signal using a narrow band pass filter. Minimizing this power will lead φ_{IQ} to 90°.

Figure 3 shows the power of the 2nd harmonic component at the frequency of $2f_{dith}$ versus φ_{IQ} of different $\varphi_{bias,I(Q)}$. As shown in the figure, the 2nd harmonic component power reaches the minimum value when φ_{IQ} equals to π/2 with any settings of $\varphi_{bias,I(Q)}$. The DR within the range of $|\triangle\varphi_{IQ}|\leq 0.1\pi$ is larger than 15dB. Such a high DR signifies that the optimum bias can be accurately set.

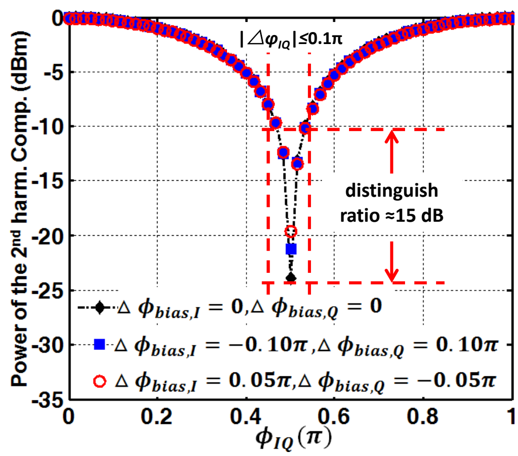

Fig. 3. The power of the 2nd harmonic vs. φ_{IQ} with different $\varphi_{bias,I}$ and $\varphi_{bias,Q}$;

Figure 4(a) shows the power of the 1st harmonic component as a function of $\varphi_{bias,I}$ and $\varphi_{bias,Q}$, where $\varphi_{IQ} = \pi/2$. The power of 1st harmonic component reaches the minimum when both of $\varphi_{bias,Q}$ and $\varphi_{bias,I}$ are optimum. Figure 4(b) shows the power of the 1st harmonic component as a function of $\varphi_{bias,I}$ with certain values of $\triangle\varphi_{bias,Q}$. From the Fig. 4(b) we find that the performance of proposed technique is dependent on the resolution of the adjusted bias votages provided by the DACs. For instance, DR is only 5 dB with resolution of 0.02π whereas DR of 17 dB can be achieved with resolution of 0.001π. Currently many commercialized DACs have a resolution up to 16 bits, which can give a tracking resolution of 2π/2^16 = 0.00003π. With such resolution the DR within range of $|\triangle\varphi_{bias,I}|\leq 0.1\pi$ is more than 20 dB. With a few iterations of tracing the minimum power, we can readily find and control the bias $\varphi_{bias,I(Q)}$ to be close to the optimum.

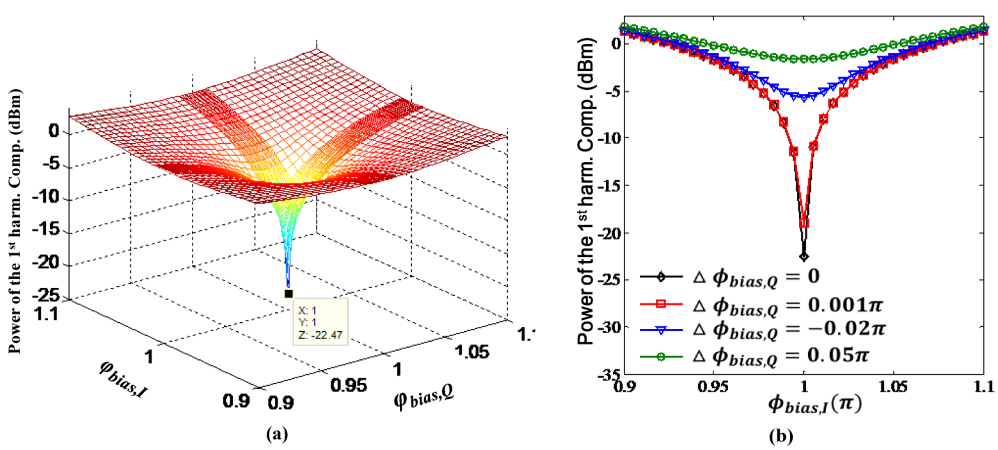

Fig. 4. The power of (a) the 1st harmonic versus $\varphi_{bias,I}$ and $\varphi_{bias,Q}$, (b) the 1st harmonic component versus $\varphi_{bias,I}$.

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3. Experimental setup and results

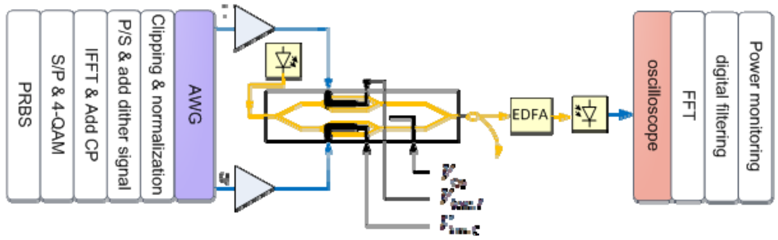

Fig. 5. Experimental setup for evaluation the proposed auto bias control technique.

A coherent optical OFDM back-to-back experiment is conducted to evaluate proposed ABC scheme. Figure 5 shows the experimental setup. The OFDM signal with 4-QAM mapping along with the dither signal (10MHz) is first offline generated with 4-QAM mapping, and then uploaded into a Tektronix arbitrary waveform generator (AWG) 7122B, operated at 10GS/s. The OFDM baseband signal is constructed with 80 subcarriers. The fast Fourier transform (FFT) size is 128. Two subcarriers are used to estimate the phase noise. 1/8 of the symbol period is used for cyclic prefix. The information rate is 10.6 Gb/s. The middle two sub-carriers are set to zero to avoid DC interference. The RF signal is fed into an optical IQ modulator (Suimitomo, T.SBX1.5-10-P-FA) to perform electrical-to-optical up-conversion. The half-wave switching voltage for the modulator used in the experiment is $5.8V$. A typical coherent receiver is used to detect the optical signal. The received base band signal is digitized by a real-time scope operated at 12.5 GS/s. In the digital signal processing, we use a digital band-pass filter with a bandwidth of 1MHz to remove other frequency components, in order to monitor the RF power which only includes the 1st or 2nd harmonic component.

Figure 6 shows the electrical current power as a function of one MZM bias voltage ($\triangle\varphi_{bias,I}$). The φ_{IQ} is set to $\pi/2$. There exists a power floor of the monitored RF power in the region close to the optimum bias, which matches well with the simulation results in Fig. 2. Some local minimum points can be found in the experiment, which is mainly due to the electrical/optical noise and the quantization error of ADC when detecting the small signal. However, by tracking the minimum current power in large variation range of $\varphi_{bias,I}$ and $\varphi_{bias,Q}$ with sufficient DAC resolution we can locate the biases in the range of 0.1π close to optimum.

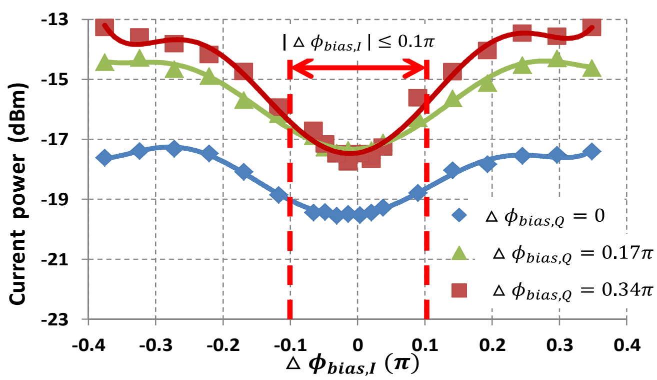

Fig. 6. The current power as a function of $\triangle\varphi_{bias,I}$.

Then, we add the dither signal onto transmitted signal, in which the frequency is 10 MHz, and the amplitude is 10% to the OFDM subcarrier. The insets of Fig. 7 show the electrical spectrum after PD. When $\varphi_{IQ} = \pi/2$, the 2nd harmonic component (~20MHz) vanishes. Hence, minimizing the 2nd harmonic component power will directly lead φ_{IQ} to $\pi/2$. The DR is as high as ~13 dB.

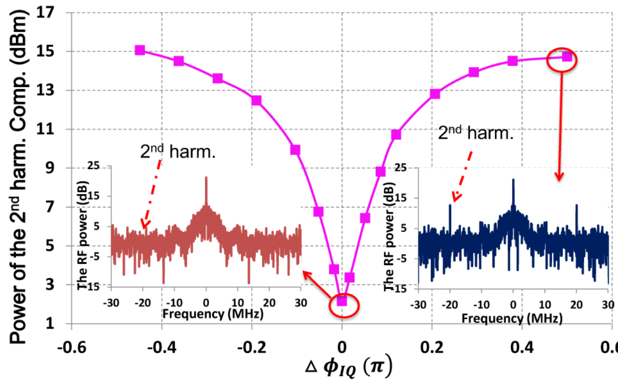

Fig. 7. The 2nd harmonic component power as a function of $\triangle\varphi_{IQ}$

Figure 8 shows the power of the 1st harmonic component as a function of $\varphi_{bias,I}$, where $\varphi_{bias,Q}$ and φ_{IQ} are set to optimum voltages. Similarly, the 1st harmonic component vanishes when $\varphi_{bias,I}$ reaches to the optimum point. The DR is up to 16 dB when $|\triangle\varphi_{bias,I}|\leq 0.05\pi$ (where the range of 0.29 V). The experimental results are well in agreement with the simulation results discussed in section 2.

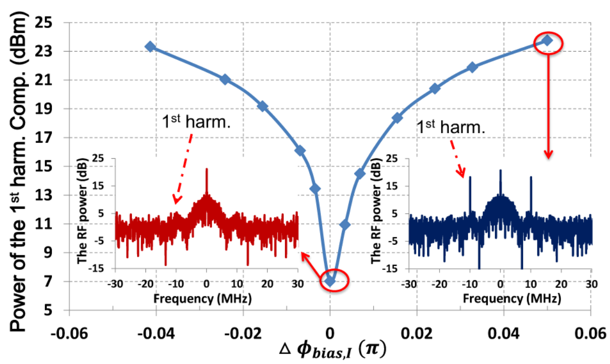

Fig. 8. The 1st harmonic power as a function of $\varphi_{bias,I}$

Furthermore, to evaluate the influence of the dither signal, we conduct a bit error ratio (BER) against OSNR measurement with and without dither signal in a back-to-back measurement, which is shown in Fig. 9. The theoretical required OSNR for the BER of 10^{-3} is ~3 dB. The required OSNRs with and without dither signal are 5.0 dB and 4.8 dB, respectively. The tiny difference is mainly due to additional power of the dithering signal. The inset shows 4-QAM constellation measured at high OSNR (~6 dB/0.1nm) under the dynamically tracked optimum biases.

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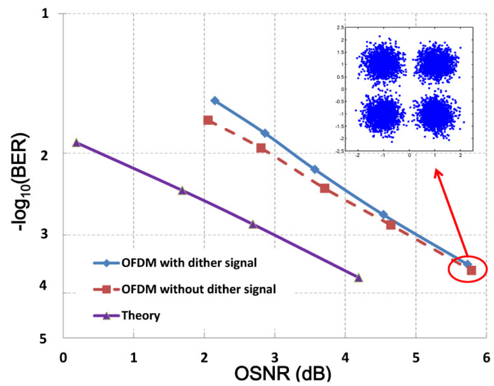

Fig. 9. The BER performance of a 10.6 Gb/s OFDM signals with and without dither signal

4. Conclusions

In this paper, we propose a novel ABC technique for O-OFDM based on power monitoring of 1st and 2nd harmonics of dither signals. The proposed scheme is easy to be implemented with low-speed optoelectronic devices. The theoretical analysis is given to illustrate the principle of the proposed scheme. The simulation and experiment results show good performance of an I/Q modulator with its biases set optimally according to the proposed scheme.

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