Experimental and Simulation Analysis of Two-Tone and Three-Tone Photodetector Linearity Characterizing Systems *

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Two measurement techniques are investigated to characterize photodetector linearity. A model for the two-tone and three-tone photodetector systems is developed to thoroughly investigate the influences of setup components on the measurement results. We demonstrate that small bias shifts from the quadrature point of the modulator will induce deviation into measurement results of the two-tone system, and the simulation results correspond well to experimental and calculation results.

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High saturation and high linearity photodiodes (PDs) are key components in high performance analog optical links to handle high optical and electrical power.[1] Surface normal photodiodes with a high output third-order intercept point (OIP3) of 52 dBm at frequencies less than 1 GHz have been reported.[2] Improvements in photodiode linearity create great challenges in linearity measurement. The OIP3 measurement is important due to the fact that the third-order intermodulation distortions (IMD3) appear very close to the fundamental signals and cannot be easily removed by filters. Many IP3 measurement systems have been employed including three-tone distortion measurement and two-tone setups.[3–5] The three-tone measurement system is considered to be the most precise measurement system. However, it requires numerous components and precision tuning in its complex setup. In contrast the two-tone measurement system setup is simpler. In the two-tone system, the nonlinearities of the optical modulators and the optical source can affect the measurement results because the second-order harmonics caused by the source or the bias drift from the quadrature point of the modulator will mix with other fundamental signals in the photodiode and contribute to the IMD3.

Previous works have demonstrated the study of the influence caused by the nonlinearity of the optical source.[6] In this work, a simulation model is developed to systematically investigate the influence of the bias shift from the quadrature point of the modulator in the two-tone setup. Additionally, we analyze the two-tone and three-tone measurements through mathematical calculations and experiments. The simulation results correspond well to our calculation and experimental observation. It is indicated that small bias shifts from the quadrature point of the modulator have large impacts on the result accuracy of the two-tone setup and establish the three-tone measurement technique as the preferred technique for accurately characterizing photodiodes with high linearity.

We assume that the bias shift of the modulator is $\lambda \times V_\pi/2$ in the two-tone measurement. When $\lambda \ll 1$ and the insertion loss for the modulator is t_x ($x = 1$ and 2), the output optical power of the modulator can be written as

$$P_{\rm out} = \frac{1}{2}P_{\rm in}t_x\Big[1+\cos\Big(\frac{\pi}{V_\pi}\Big(\frac{V_\pi}{2} + \lambda\frac{V_\pi}{2} + V_{\rm rf}\sin(\omega t)\Big)\Big)\Big]. \tag{1}$$

We use the Taylor formula to simplify Eq. (1) and calculate the optical power after the combiner

$$P_{\rm out} = \sum_{x=1}^{2}\frac{1}{2}P_{\rm in}t_x g_x\alpha\Big[1-\varphi_{\rm rf}\cos(\omega t) + \frac{\pi}{8}\lambda(\varphi_{\rm rf})^2\cos(2\omega t) + \frac{1}{24}(\varphi_{\rm rf})^3\cos(3\omega t)\Big], \tag{2}$$

where g_x is the gain of the EDFA, α is the optical attenuation set through the optical attenuator, and $\Phi_{\rm rf} = \pi/V_\pi \times V_{\rm rf}$.

We assume that the responsivity of the device is $\Re$ and the insertion loss of the combiner is $t_{\rm c}$. Then the output photocurrent of the fundamental rf signal is

$$I_{\rm fund} = \frac{1}{\sqrt{2}}\cdot\frac{1}{2}\cdot\Re\cdot t_{\rm c}(P_{\rm in}t_x g_x\alpha)\cdot\varphi_{\rm rf}, \tag{3}$$

Now we calculate the photocurrent of intermodulation terms caused by PD and MZM separately, ρ and ν are the constants representing the device nonlinearity due to the second and third order mixing,

$$i_{\rm IMD3}^{\rm PD} = \frac{1}{\sqrt{2}}\frac{1}{8}\nu\Re\alpha^3\cdot t_{\rm c}(P_{\rm in}t_x g_x)\cdot\varphi_{\rm rf}^3, \tag{4}$$

$$i_{\rm IMD3}^{\rm mzm} = \frac{1}{16\sqrt{2}}\rho\Re\alpha^2\cdot\frac{\pi}{2}\lambda\cdot t_{\rm c}(P_{\rm in}t_x g_x)\cdot\varphi_{\rm rf}^3, \tag{5}$$

$$P_{\rm IMD3}^{\rm PD} = 20\log\Big(\frac{5}{8}\upsilon\Re\alpha^3\cdot\frac{\pi}{2}\cdot t_{\rm c}(P_{\rm in}t_x g_x)\varphi_{\rm rf}^3\Big) + 20\log\lambda, \tag{6}$$

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$$P_{\rm IMD3}^{\rm mzm} = 20\log\Big(\frac{5}{16}\rho\Re a_2\cdot\alpha^2\cdot\frac{\pi}{2}\cdot t_{\rm c}(P_{\rm in}t_x g_x)\varphi_{\rm rf}^3\Big) + 20\log\lambda. \quad (7)$$

We can see that the IMD caused by PD changes by 6 dB with α, while IMD caused by MZM changes by 4 dB. Thus as the photocurrent increases, the bias shift will have less influence on the measured OIP3. Moreover, from Eq. 6, the OIP3 deviation versus bias shift λ is not symmetric. When λ is negative, the measured OIP3 will increase due to the decrease of the total photocurrent $i_{\rm IMD}$, while a positive λ will decrease the measured OIP3.

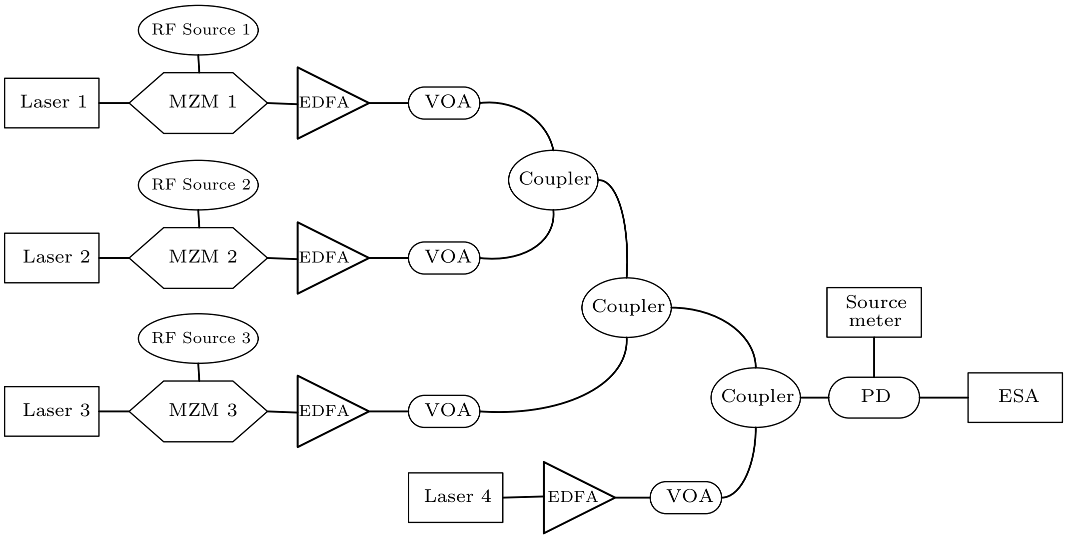

Fig. 1. Block diagram of three-tone OIP3 measurement setup.

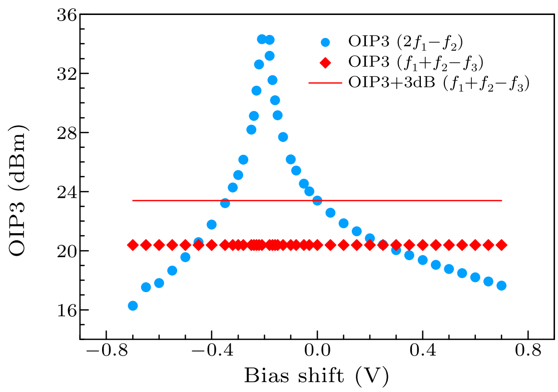

Fig. 2. OIP3 dependence on the bias shift.

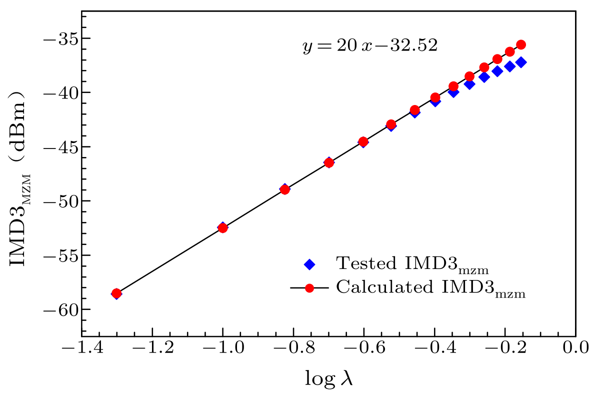

Fig. 3. IMD3$_{\rm MZM}$ (dBm) dependence on the bias shift (in log scale).

Figure 1 shows the model used for the two-tone and three-tone experimental setups. For the two-tone measurement, the IMD3 power was taken from the electrical spectrum analyzer at the frequency of $2f_1 - f_2$. For the three-tone measurement, the IMD3 power was taken from the electrical spectrum analyzer at the frequency of $f_1+f_2-f_3$. For the photodiode under test, the input optical power has two components: $P_{\rm dc}$ and $P_{\rm rf}$. Correspondingly, the output photocurrent has two components: dc photocurrent given by $I_{\rm dc} = a_1P_{\rm dc}$ and rf photocurrent given by

$$I_{\rm rf} = a_1P_{\rm rf} + a_2P_{\rm rf}^2 + a_3P_{\rm rf}^3 + \ldots, \quad (8)$$

The effect of the bias shift on the OIP3 was studied using the optisystem simulation software with the help of Matlab. A nonlinear photodetector was defined with the nonlinearity function, as shown in Eq. (7). The two-tone and three-tone OIP3s were simulated to be 23.38 dBm and 20.38 dBm, respectively. Since these OIP3 values are similar to experimentally measured values, the range of relative nonlinear coefficients of the photodiode ($a_1 = -0.2$, $a_2 = -0.8$) used in this calculation (and subsequent calculations) can be assumed to be reasonably close to the device. Figure 2 shows the simulated OIP3 for both the two-tone and three-tone cases as the modulator bias shifts. It can be observed that the two-tone and three-tone results of the three-tone setup maintain the 3 dB difference as expected, while the two-tone setup is sensitive to the bias shift of the modulator. On the one hand, when the bias shift λ is negative, the OIP3 increases as the bias shift tends to be larger, and as λ arrives at a certain point, the measured OIP3 tends to decrease due to the great loss of the fundamental power, which can be derived from Eq. (5). On the other hand, when λ is positive, the OIP3 decreases with λ due to the decrease of fundamental power and the increase of the IMD3. Additionally, Fig. 3 shows that the IMD3 value changes by 20 dB with λ (from 0.05 to 0.35) in log scale, which is in good agreement with what we have obtained.

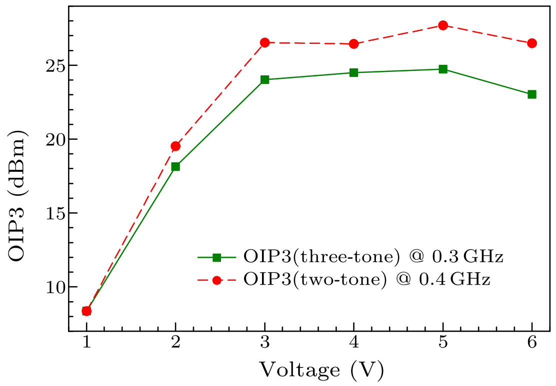

Fig. 4. OIP3 as a function of reverse bias tested at 0.3 GHz (three-tone) and 0.4 GHz (two-tone).

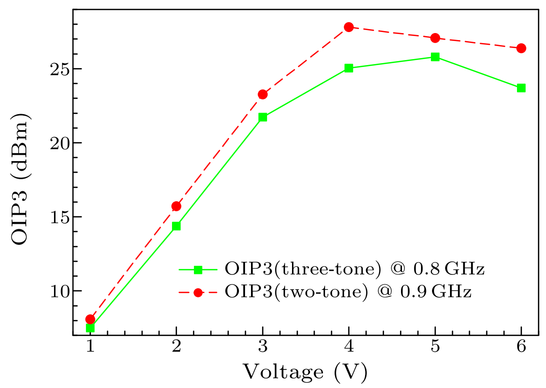

Fig. 5. OIP3 as a function of reverse bias tested at 0.8 GHz (three-tone) and 0.9 GHz (two-tone).

The tested PD is a conventional uni-traveling carrier (UTC) photodiode. In our experiment, the three lasers were tuned at 1546 nm, 1547 nm, 1548 nm, respectively. The rf signals were tuned at different frequencies. The three optical signals carrying rf modulation were combined and amplified by an erbium doped fiber amplifier (EDFA) followed by an optical attenuator. The fourth laser was used to maintain a constant average optical power illuminated to the photodiode. When the third laser source is turned off, this three-tone measurement setup turns into a two-tone measurement setup. The OIP3 measured by the two-tone setup is assumed to be 3 dB larger than the three-tone setup.[7] OIP3 of the device was measured with both two-tone and three-tone measurements. Figures 4 and 5 show the measured OIP3 results in different measurements as a function of the reverse bias applied on the PD tested at 0.3 GHz (three-tone) and 0.4 GHz (two-tone) (f_1 = 0.5 GHz, f_2 = 0.6 GHz, f_3 = 0.8 GHz) and 0.8 GHz (three-tone) and 0.9 GHz (two-tone) (f_1 = 1 GHz, f_2 = 1.1 GHz, f_3 = 1.3 GHz). From the results, the OIP3 changes with the bias voltage due to the voltage swing effect and the voltage-dependent device capacitance.[8] The differences between the two-tone OIP3 and three-tone OIP3 are not quite the theoretical 3 dB due to the bias shift from the quadrature point of the modulator, which clearly follows the theoretical trend.

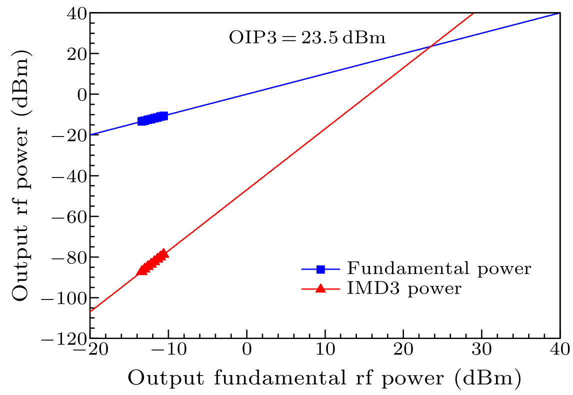

Fig. 6. Measured IP3 using the proposed two-tone setup ($\lambda = 0$ V, bias -3 V).

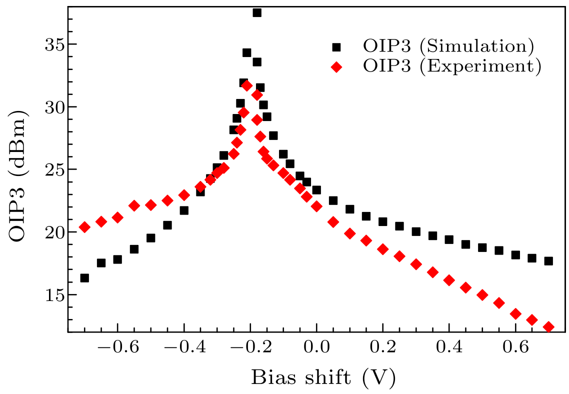

Fig. 7. OIP3 dependence on the bias shift based on experimental and simulation results.

To investigate the influence of the bias shift of the modulator on the OIP3 results, the bias of the modulator was precisely controlled with a feedback circuit by monitoring the output power. The bias was tuned away from the quadrature point by changing the dc voltage source with the step of 0.05 V, and all the instantaneous data of the dc voltage stabilized source and harmonics power of the ESA are monitored and recorded by a PC. The bias of the photodiode was -3 V and the frequencies of the rf resources were 0.3 GHz and 0.4 GHz, respectively. By incrementally sweeping the driven power of the MZMs, we measure the power of the fundamental tone (0.4 GHz) and the IMD3 tone (0.5 GHz). The output IP3 is calculated to be 23.5 dBm ($\lambda = 0$ V), as shown in Fig. 6. Figure 7 shows the experimental OIP3 results as a function of the bias shift of the modulator at a photocurrent of 20 mA. Though the experimental OIP3 values do not match with the simulation exactly, due to the different nonlinearity indices between the certain photodiode and the simulation one, it is clear that the experimental OIP3 results follow the same trend as the simulation, demonstrating that the bias shift of the modulator greatly affects the experimental results.

In conclusion, the influence of the bias shift from the quadrature point of the modulator on the OIP3 measurement has been systematically investigated through simulation, mathematical calculation and experimental comparison. The simulation and experimental results show that the bias shift has a great impact on the two-tone measurement system and the three-tone OIP3 remains unchanged, which corresponds to the calculation results. In the simulation and the experiment, when the bias shift is between 0 V and −0.2 V, OIP3 goes up as the bias shift becomes larger. When the bias shift exceeds 0.2 V, OIP3 drops off with the growth of negative bias shift. On the other hand, as the bias shift positively increases, the OIP3 falls off. Thus as the linearity of modified high power photodiodes continues to increase, it is necessary to use a measurement technique such as the three-tone system to accurately characterize the linearity of photodiodes.

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