Measurement of intermodulation distortion in high-linearity photodiodes

Anand Ramaswamy[1*], Nobuhiro Nunoya[1], Keith J. Williams[2], Jonathan Klamkin[3,4], Molly Piels[1], Leif A. Johansson[1], Alexander S. Hastings[2], Larry A. Coldren[1,3] and John E. Bowers[1]

[1]*Department of Electrical & Computer Engineering, University of California Santa Barbara, Santa Barbara, C.A. 93106, USA*

[2] *Department of Naval Research Laboratory, Code 5650, Washington, D.C. 20375, USA*

[3] *Material Sciences, University of California Santa Barbara, Santa Barbara, CA 93106, USA*

[4] *Currently with Lincoln Laboratory, Massachusetts Institute of Technology, Lexington, M.A. 02420, USA*

**anand@ece.ucsb.edu*

Abstract: Accurately characterizing third order intermodulation distortion (IMD3) in high-linearity photodiodes is challenging. Two measurement techniques are evaluated–a standard two-tone measurement and a more complicated three-tone measurement technique to measure IMD3. A model of the measurement system is developed and used to analyze the limitations of the two techniques in determining the distortion of highly linear photodiodes. Experimental validation is provided by comparing the simulation trends with IMD3 results measured on two types of waveguide photodiodes: 1) an InP based uni-traveling-carrier (UTC) photodiode and 2) a Ge n-i-p waveguide photodetector on Silicon-on-Insulator (SOI) substrate.

OCIS codes: (230.5160) Photodetectors; (060.5625) Radio frequency photonics

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#119226 - $15.00 USD Received 29 Oct 2009; revised 6 Jan 2010; accepted 13 Jan 2010; published 21 Jan 2010

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1. Introduction

Microwave nonlinearities in photodiodes arise from the complex interaction of many different physical effects [1]. These nonlinearities in photodiodes are known to impact the performance of analog optical links [2]. High dynamic range links require very high optical powers which in turn places stringent requirements on the linearity and power handling capability of the photodiodes at the receiver [3]. Recent efforts to develop high current photodetectors with high linearity have resulted in surface illuminated photodiodes with over 700mA of photocurrent [4] and 3rd order Output Intercept Points (OIP3) in excess of 50dBm [5]. Improvements in photodiode linearity create significant measurement challenges. Interactions between non-linearities in the optical source and photodiode can lead to distortion cancellation or distortion enhancement and as such introduces errors into the measured photodiode OIP3. Currently, various techniques are used to determine the IMD3 of photodiodes [6–8]. The key issue is to ensure that when two closely spaced pure radio frequency (RF) tones are incident on the device, the resulting IMD3 measured should emanate entirely from the distortion of the photodiode. One way to get a harmonic distortion free sinusoidal signal with 100% modulation depth is through a two-laser heterodyne system [9]. However, generating a second tone that is closely spaced in frequency to the first tone would require an additional pair of lasers that are wavelength matched. Moreover, frequency and thermal drifts in the lasers would necessitate each pair being locked, further complicating the setup.

An alternative to optical heterodyning is using external intensity modulators to generate two RF tones by modulating the output of two c.w. lasers. Although this greatly simplifies the measurement setup, it introduces nonlinearities into the measurement through the intensity modulators and RF signal generators. An alternate approach to the two tone measurement technique is to use three tones to measure IMD3 [8,10]. In this technique, some of the third order non linear distortion components generated in the device under test (DUT) are independent of the harmonics originating in the optical modulators and signal generators. Recently, we developed a model for the above two modulator techniques and showed mathematically that as the OIP3 of a photodiode increases, the results from the two techniques diverge [11]. Also, it was observed that the two-tone technique is sensitive to non-linearities in the optical source whereas the same is not true of the three-tone technique. In this work we present the simulation model to show in detail the influence of modulator and signal source nonlinearities. Further, to validate the simulation results we use both measurement techniques to experimentally determine the IMD3 of two different types of waveguide photodetectors (with widely differing linearity) −1) Ge n-i-p waveguide photodetector on SOI [12] and 2) InP based UTC photodetectors [6]. In the case of the Ge n-i-p detector it is observed that the two approaches yield OIP3 results that are consistent with each other [11]. This is due to their relatively low linearity. However, the same is not true in the case of the high linearity (>40dBm) InP UTCs. This establishes the three-tone measurement technique as the preferred technique for measuring very linear photodiodes.

2. Simulation

In this section we study the effect on OIP3 from the distortion in the optical source carrying the modulated RF tones. Figure 1 shows the model used for the three-tone (and two-tone) experimental setup. When the modulators are biased at quadrature, the output power (P_{out}) is related to the input power as follows:

#119226 - $15.00 USD Received 29 Oct 2009; revised 6 Jan 2010; accepted 13 Jan 2010; published 21 Jan 2010

$$P_{out} = \left(\frac{P_{in}}{2}\right)\left(1-\left(\frac{\pi}{V_\pi}\right)\left(c_1V_{RF}+c_2V_{RF}^2+c_3V_{RF}^3+...\right)\right) \quad (1)$$

In the above expression, we do not differentiate between the nonlinearities generated in the microwave source and optical modulator. The Taylor series expansion above takes into account the combined effect of all nonlinearities generated in the optical source.

Similarly, for the photodiode under test, the input optical power has two components: P_{DC} and P_{RF} and correspondingly, the output photocurrent has two components – a DC one given by $I_{DC} = a_1P_{DC}$ and an RF one given by:

$$I_{RF} = \left(a_1P_{RF}+a_2P_{RF}^2+a_3P_{RF}^3+...\right) \quad (2)$$

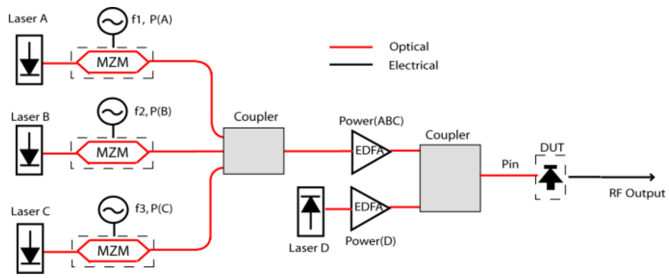

Fig. 1. Simulation Model: Three-tone measurement system

It should be pointed out that the Taylor series expansion in Eq. (2) implies memoryless non-linearities in the photodiode [7,8]. Figure 2 plots the IMD3 (both two-tone and three-tone) calculated using this model. In Fig. 2(a) the optical source is assumed to be linear ($c_2 = 0$ and $c_3 = 0$) and the non-linear coefficients assumed in the detector are indicated in the figure. From this calculation, the two-tone and three-tone OIP3 are found to be 42.218dBm and 39.208dBm. Since these OIP3 values are similar to experimentally observed values [6] the range of relative non-linear coefficients of the photodiode used in this calculation (and subsequent calculations) can be assumed to be reasonably close to the devices in [6]. Next, keeping the same non-linear coefficients in the photodiode, if we introduce nonlinearities in the modulators (c_2 = –0.01 and c_3 = –0.001) we observe that the two-tone OIP3 drops to 40.76dBm while the three-tone remains unchanged at 39.21dBm (Fig. 2(b)).

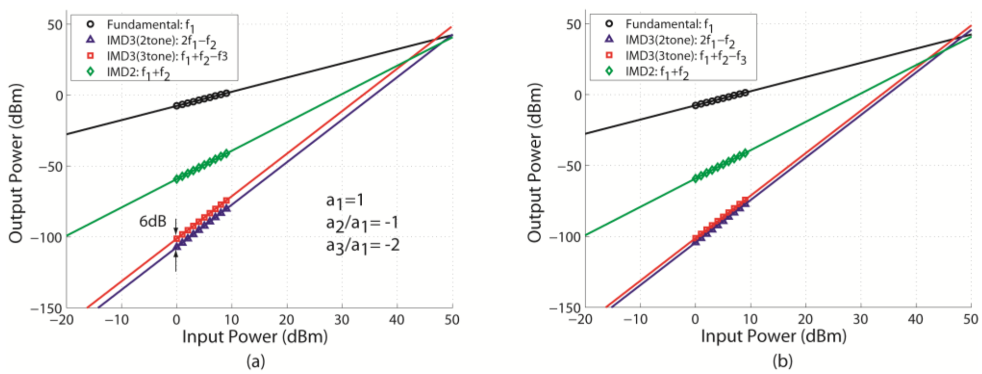

Fig. 2. Calculated IMD3 and IMD2 (P_{dc} = 40mW) (a). linear optical source (b) non-linear optical source (modulator: Vπ = 5V; c_2 = –0.01 and c_3 = –0.001)

It is observed that this discrepancy in two-tone OIP3 is very sensitive to the sign (i.e. phase) of the non-linear coefficients in the optical source as well as the photodiode. Figure 3(a) plots the OIP3 for both the two-tone and three-tone case as the second order non linear coefficient (a_2) in the photodiode is varied, while keeping a_3 fixed. It can be seen that

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depending on the magnitude and sign of a_2 of the photodiode the calculated two-tone OIP3 can be either be ~6dB greater or ~3dB less than its actual value. Further, the three-tone OIP3 remains constant even as a_2 is varied. In Fig. 3(b) the third order non-linear coefficient (a_3) in the photodiode is varied while keeping a_2 fixed. Again it can be clearly seen that the two-tone and three-tone OIP3 deviate from their theoretical 3dB difference [8].

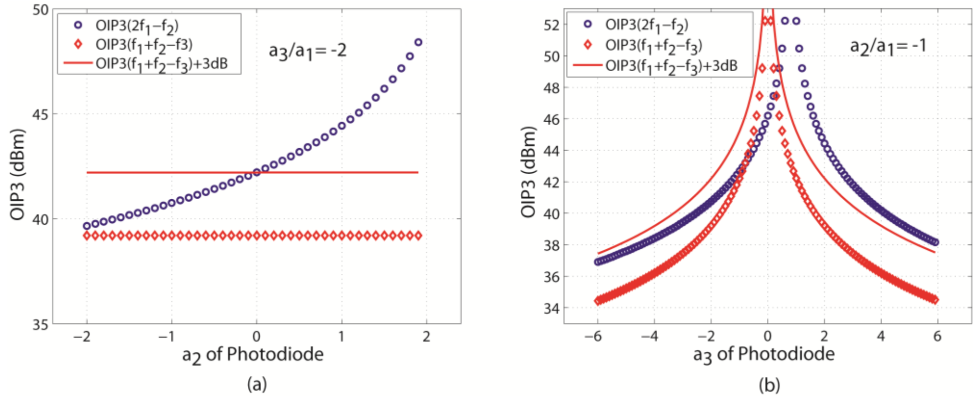

Fig. 3. OIP3 dependence on nonlinear coefficients of PD (a) a_2 dependence; (b) a_3 dependence

The deviation of the two-tone OIP3 from the actual OIP3 value is a result of the interaction between the non-linear coefficients of the optical source (c_2 and c_3) and the 2nd order non linear coefficient of the photodiode (a_2). To confirm this, in Fig. 4(a), $a_2/\ a_1 = -1$ is fixed and the OIP3 (both two-tone and three-tone) is plotted as a function of a_3 while keeping the optical source perfectly linear (c_2, c_3 = 0). Furthermore, in Fig. 4(b) we reintroduce the earlier distortion in the optical source, but set a_2 = 0, thereby eliminating any interaction between the photodiode 2nd order non-linearity and the modulator. In both cases, it can be observed that the two-tone and three-tone results maintain the 3 dB difference as expected. However, in reality there will be some second-order distortion coming from the optical source either due to a poor driver amplifier or improper biasing as well as non-zero modulation depth in the MZM. Even if the intensity modulators are biased at quadrature (to minimize c_2), there will still be some residual second-order distortion due to nonzero modulation depth. Additionally, having a_2 = 0 in the photodiode is not possible, so the two-tone measurement system will always add a certain nonlinearity (or at least an uncertainty) to the measurement.Thus the three-tone measurement system should be used to eliminate possible errors coming from nonzero a_2, c_2 and c_3.

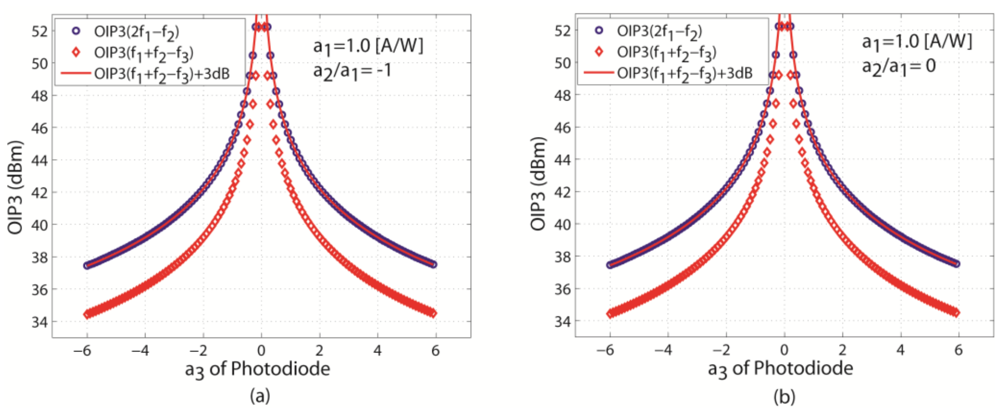

Fig. 4. OIP3 dependence on a_3 of photodiode with (a) perfectly linear optical source (c_2, c_3 = 0) ; (b) $a_2/\ a_1 = 0$ but not a perfectly linear optical source ($c_2/\ c_1 = -0.01$ and $c_3/\ c_1 = -0.001$)

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3. Experiment

Figure 5 shows a schematic of the experimental setup that is used for the three-tone measurement. As will be shown in this section, the same setup generates distortion components in the photodiode that are in essence the same as those generated by having only two tones.

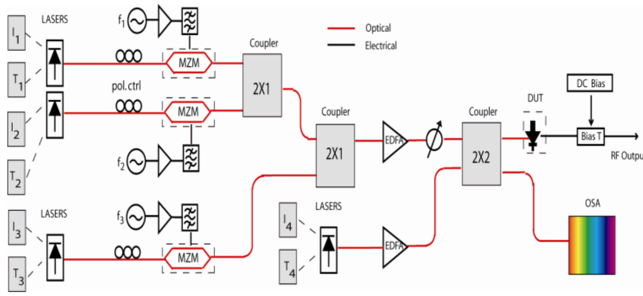

Fig. 5. Experimental setup: three-tone measurement

The output of three CW lasers with differing wavelengths (Δλ ~0.5-7nm) are modulated separately at frequencies f_1 = 980MHz, f_2 = 1GHz and f_3 = 1.015GHz. These are the same frequencies used in the simulations of the previous section. The modulators are biased at quadrature to minimize second harmonics. The three optical signals carrying RF modulation are combined and amplified by an Erbium Doped Fiber Amplifier (EDFA). Experimentally second order intermodulation distortion has been observed due to the coupling of the gain tilt of an EDFA with frequency chirp of the modulated input signal [13]. However, in this experiment we use x-cut y propagating $LiNbO_3$ modulators whose chirp parameters are experimentally determined to be ~0.1 [14] – a factor of 10 less than that of directly modulated semiconductor lasers [15]. Hence, the EDFA induced second order distortion is assumed to be negligible. An attenuator is used at the output of the EDFA to control the modulation index of the three tones. A fourth CW laser is used to ensure that the optical power and hence, photocurrent in the device remains unchanged as the optical modulation index is varied. Additionally, an optical spectrum analyzer (OSA) is used to monitor the spectral content of the optical signal to ensure that four-wave mixing does not occur.

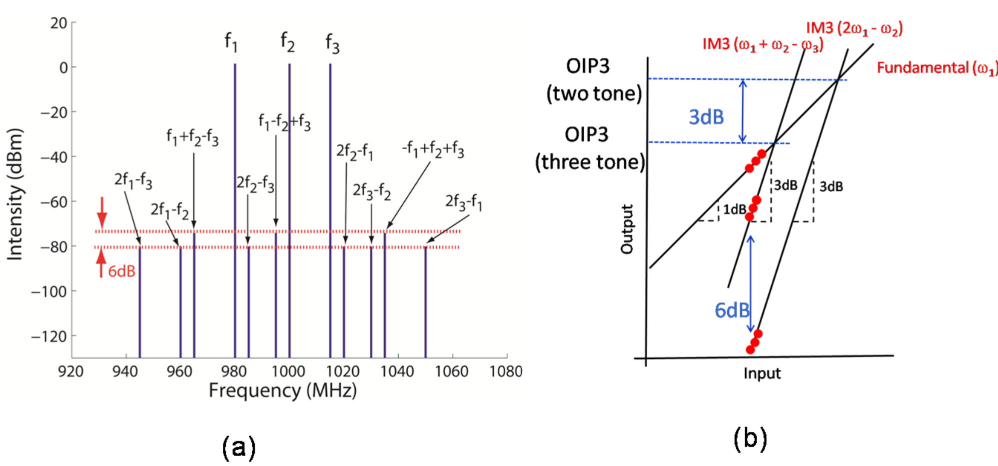

Fig. 6. (a). Ilustration of IMD3 components in a three-tone experiment (b) Relation between two-tone & three-tone IP3

For this experiment the optical modulation index is varied between approximately 20-30%. It is important to make sure that all three fundamental signals have the same power. The third order intermodulation distortion components are measured at frequencies $(f_1 + f_2) - f_3$,

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$(f_1 + f_3) – f_2$ and $(f_2 + f_3) –f_1$as shown in Fig. 6(a). It is important to note that in a three tone linearity measurement such as this, IMD3 from the interaction of two tones is also generated. In other words, distortion components can be observed at $2f_i –f_k$ (i,k = {1,2,3} ; i≠k). As outlined in [8] the three-tone IMD3 is 6dB larger than the ideally measured two-tone IMD3. This can be inferred from the expressions below:

$$\text{Fundamental}(\mathrm{f_i}): \quad m+\frac{15h_3}{4}\left(\frac{m}{h_1}\right)^3 \approx m \tag{4}$$

$$\text{IMD3}(2\mathrm{f_i}\text{-}\mathrm{f_k}): \quad \frac{3h_3}{4}\left(\frac{m}{h_1}\right)^3 \tag{5}$$

$$\text{IMD3}(\mathrm{f_i}\text{-}\mathrm{f_j}\text{+}\mathrm{f_k}): \quad \frac{6h_3}{4}\left(\frac{m}{h_1}\right)^3 \tag{6}$$

As the power in the fundamental tone (Eq. (4)) goes up by 1 dB, the power in both the two-tone (Eq. (5)) and three-tone IMD3 components (Eq. (6)) go up by 3dB. Note that the two-tone and three tone IMD3′s differ by a factor of 2 (or 6dB in Electrical Power). The three-tone IP3 is 3dB smaller than the two-tone IP3 [8]. Hence, a factor of 3dB is added to the three-tone IP3 to relate this to the more commonly used two-tone IP3. This is more clearly illustrated in Fig. 6(b).

4. Experimental results

4.1 Ge n-i-p detector on SOI

The device used for this experiment is a 7.4µm X 500µm evanescently coupled Ge waveguide photodetector that is grown on top of a Si rib waveguide. The 3dB bandwidth of the device is ~4.5GHz. However, the device design is not optimized for high current or high linearity operation. Details of the device design and fabrication can be found in [12]. Figure 7 plots the output RF power (in dBm) in the fundamental signals, third order distortion components (both two-tone and three-tone) and second order intermodulation distortion components (IMD2) versus the change in input RF power (dB) into the device. As mentioned in the previous section, the change in input RF power essentially corresponds to a change in optical modulation index, which is experimentally determined to be between 20 and 30%.

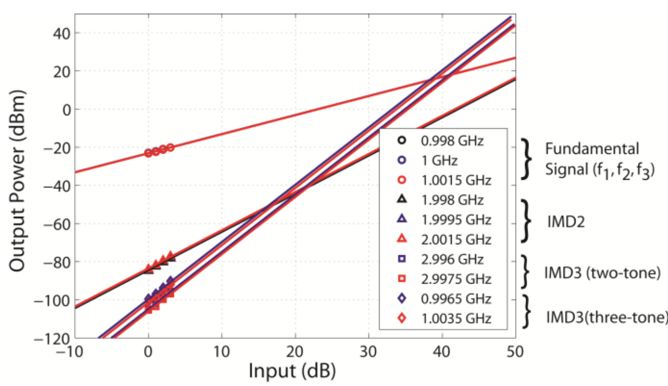

Fig. 7. Sample experimental plot from a three-tone measurement (photocurrent = 20mA)

Figure 8 summarizes the experimental OIP3 results as a function of reverse bias at a photocurrent of 20mA and 40mA. Although the difference between the two-tone OIP3 and three-tone OIP3 is not quite the theoretical 3dB, it clearly follows the theoretical trend. This is important because in Section 2 we observed that when the linearity of the device is very high

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(and the distortion of the measurement system begins to dominate), the two tone and three tone techniques yield very different OIP3 values.

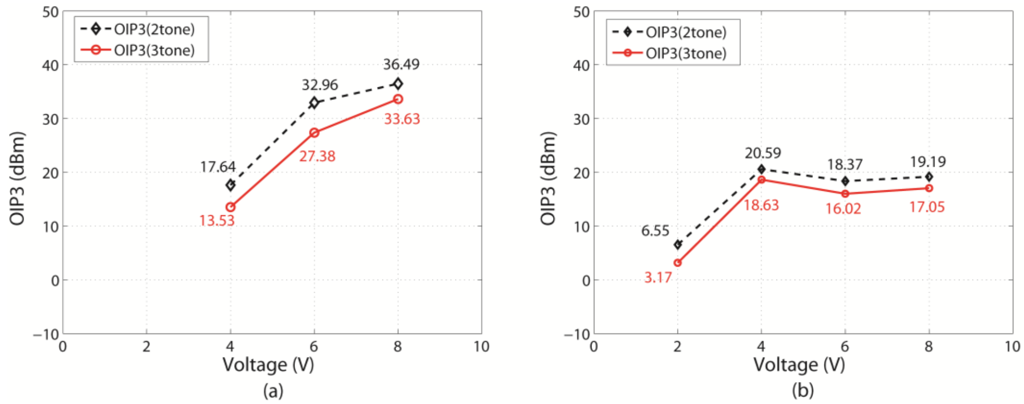

Fig. 8. OIP3 as a function of reverse bias (a) photocurrent = 20mA (b) photocurrent = 40mA

4.2 InP UTC detector

Uni-traveling carrier PDs (UTC-PDs), which were designed for high speed and high current operation, have shown very high output saturation and linearity characteristics [16,17]. We reported on waveguide UTC-PDs with OIP3s in excess of 40dBm for up to 80mA of photocurrent, measured at 1GHz [6]. For this experiment we use two UTC detectors which have similar 3dB bandwidth (~2GHz) and response but different absorption profiles. Device 1 is a UTC detector with a rectangular active area whereas Device 2 is a longer, tapered structure that reduces front-end saturation in the device. Hence, Device 2 is expected to a have a higher linearity. At a photocurrent level of 60mA Device 2 has a three-tone OIP3 of 43.2dBm as shown in Fig. 9(a). Taking into account the 3dB correction factor this translates into an OIP3 of 46.2dBm.

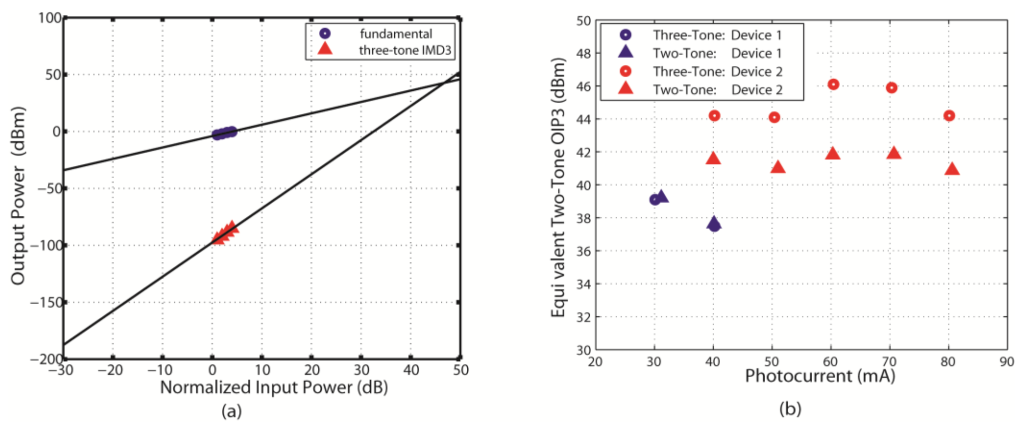

Fig. 9. (a) Three-tone IMD3 measurement at 60mA (b) Comparison of Two-Tone and Three-Tone OIP3(with the 3dB correction factor)

In Fig. 9(b) for the relatively lower linearity device (<40dBm), the two-tone OIP3 agrees well with the three-tone OIP3 (including the 3dB correction factor). However, for the higher linearity device (>40dBm) the two-tone and three-tone OIP3 differ significantly. From Section 2 we know that in certain cases optical source nonlinearities can play a significant role in limiting the measured IMD3. Here, we find experimental validation of this, even when highly linear $LiNbO_3$ modulators are used. As such this represents a clear situation in which the three-tone setup is essential to making an accurate OIP3 measurement.

#119226 - $15.00 USD Received 29 Oct 2009; revised 6 Jan 2010; accepted 13 Jan 2010; published 21 Jan 2010

6. Summary

In this paper we have we have modeled the influence of the measurement setup in two-tone and three-tone IMD3 characterization of highly-linear photodiodes. By introducing nonlinearities in the optical source and analyzing their interaction with the non-linear coefficients in a photodiode we are able to show that the three-tone technique is independent of harmonics in the optical source. We used two types of waveguide photodetectors to experimentally validate our simulation model. We showed that 1) the two-tone and three-tone techniques yield OIP3 results that are consistent with each other when the linearity of the photodiode under test is relatively low (<40dBm) and 2) OIP3 results diverge when the OIP3 of the device increases beyond 40dBm. Thus, as high linearity photodiode designs improve further it is necessary to use a measurement technique such as the three-tone system to accurately characterize photodiode nonlinearities.

Acknowledgments

The authors would like to thank useful discussions with Ronald Esman, Steve Pappert, Jim Hunter and Nadir Dagli. Further acknowledgment should be provided to Tao Yin from Intel Corp. for providing the SiGe detector on which these measurements were made. This material is based upon work supported by the DARPA-PHORFRONT program under United States Air Force contract number FA8750-05-C-0265.

#119226 - $15.00 USD Received 29 Oct 2009; revised 6 Jan 2010; accepted 13 Jan 2010; published 21 Jan 2010