Experimental Analysis of Two Measurement Techniques to Characterize Photodiode Linearity

Anand Ramaswamy, Nobuhiro Nunoya, Molly Piels, Leif A. Johansson, Larry A. Coldren and John E. Bowers
Electrical & Computer Engineering Department, University of California, Santa Barbara, CA 93106, USA

Alexander S. Hastings and Keith J. Williams
Naval Research Laboratory, Code 5650, Washington, D.C. 20375, USA

Jonathan Klamkin
Lincoln Laboratory, Massachusetts Institute of Technology, 244 Wood St, Lexington, M.A. 02420, USA

anand@ece.ucsb.edu

***Abstract*—As photodiodes become more linear, accurately characterizing their linearity becomes very challenging. We compare the IMD3 results from a standard two tone measurement to those from a more complex three tone measurement technique. A Ge n-i-p waveguide photodetector on Silicon-on-Insulator (SOI) substrate is used for the comparison. Additionally, we analyze, via simulation, the limitations of the measurement system in determining the distortion of highly linear photodiodes.**

I. INTRODUCTION

High performance analog optical links require photodiodes that have high power handling capability as well as high linearity [1]. Surface illuminated photodiodes with over 700mA of photocurrent [2] and 3rd order Output Intercept Points (OIP3) in excess of 50dBm have been reported [3]. UTC based waveguide detectors with OIP3's >40dBm have also been reported [4]. Improvements in photodiode linearity create significant measurement challenges. Namely, distortion from the measurement system influences and in some cases limits the measured third order intermodulation distortion (IMD3). Currently, various techniques are used to determine the IMD3 of photodiodes [3, 5, 6]. 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 pure RF tone with 100% modulation depth is through a two-laser heterodyne system [7]. However, generating a second tone that is close in frequency to the first tone would require an additional pair of lasers. Moreover, all four lasers need to be closely matched in wavelength and immune to thermal and other drifts. The latter requirement necessitates the lasers in each pair be locked to each other, further complicating the measurement 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 [6, 8]. 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.

In this work, we take a Ge n-i-p waveguide photodetector on SOI [9] and use both the above modulator techniques to measure its IMD3. It is observed that the two approaches yield OIP3 results that are consistent with each other. Next, we show mathematically that as the OIP3 of a photodiode increases the results from the two techniques diverge. We find 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. This establishes the three-tone measurement technique as the preferred technique for measuring very linear photodiodes.

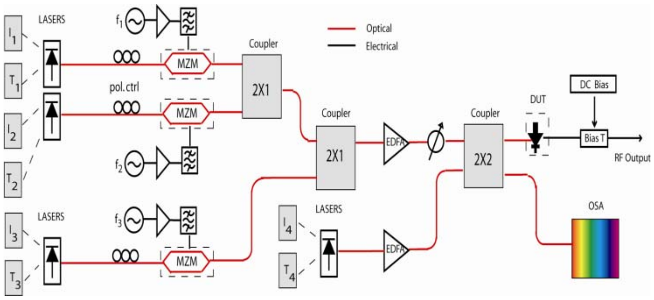

Figure 1. Experimental setup: three-tone measurement

II. EXPERIMENT

Figure 1 shows a schematic of the three tone experimental setup. 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. 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 [10]. However, in this experiment we use x-cut y propagating $LiNbO_3$ modulators whose chirp parameters are experimentally determined to be ~0.1[11]-a factor of 10 less than that of directly modulated semiconductor lasers [12]. Hence, the EDFA induced distortion can be 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. For this experiment the optical modulation index is varied between approximately 20-30%. The third order intermodulation distortion components are measured at frequencies $(f_1+f_2) - f_3$, $(f_1+f_3) - f_2$ and $(f_2+f_3) - f_1$ as shown in Figure 2. 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, in theory, distortion components can be observed at $2f_i - f_k$ (i,k={1,2,3} ; i≠k).

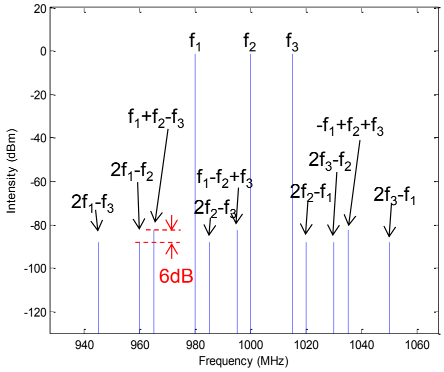

Figure 2. Ilustration of IMD3 components in a three-tone experiment

As outlined in [6] the three-tone IMD3 is 6dB larger than the ideally measured two-tone IMD3. This can be inferred from the expressions below:

Fundamental (f_i):
$$m + \frac{15h_3}{4}\left(\frac{m}{h_1}\right)^3 \approx m \tag{1}$$

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

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

As the power in the fundamental tone (1) goes up by 1 dB, the power in both the two-tone (2) and three-tone IMD3 components (3) 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 [6]. Hence, a factor of 3dB is added to the three-tone IP3 to relate this to the more commonly used two-tone IP3.

III. EXPERIMENTAL RESULTS

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. Details of the device design and fabrication can be found in [9].

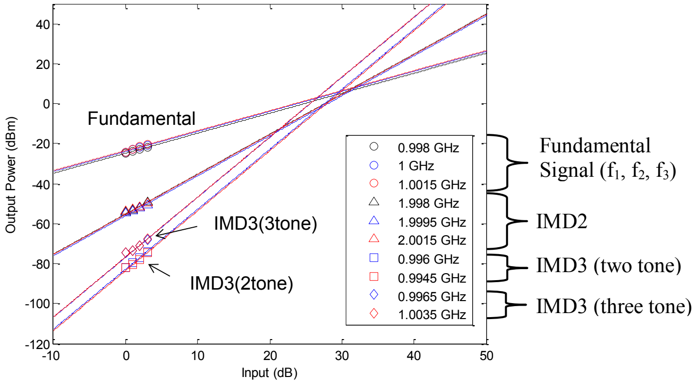

Figure 3. Sample experimental plot from a three-tone measurement (photocurrent =20mA; bias voltage across photodiode=2V)

Figure 3 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 20-30%. Note that for the first time, both the two-tone and three-tone characterization of a photodiode's IMD3 are simultaneously measured. This provides for an accurate comparison of the measurement techniques since the various experimental conditions (e.g. optical modulation index, input RF power etc.) in the measurement system remain relatively constant during the course of the measurement.

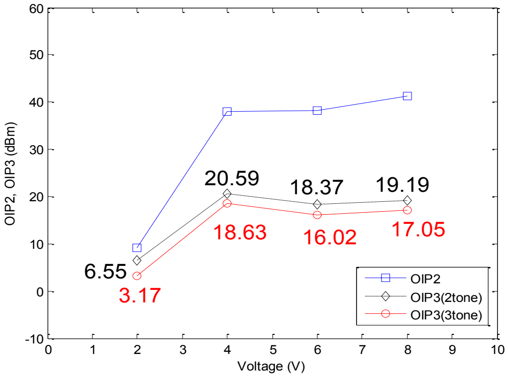

Figure 4. OIP2, OIP3 as a function of reverse bias (photocurrent=20mA)

Figure 4 summarizes the experimental OIP3 and OIP2 results as a function of reverse bias at a photocurrent of 20mA. 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 IV it will be shown via simulation that when the linearity of the device is very high (and the distortion of the measurement system begins to dominate), the two tone and three tone techniques yield very different OIP3 values.

IV. NON-LINEARITIES OF MEASUREMENT SYSTEM

In this section we study the effect on OIP3 due to distortion in the optical source carrying the modulated RF tones. A model is developed for the three tone experimental setup shown in Figure 1. If the input signal from the signal generator to the modulator is given as $V_{RF}=V_o(\sin\omega t)$ and we assume a Taylor series expansion for the phase shift in the modulator we get:

$$\varphi_{RF} = \left(\frac{\pi}{V_\pi}\right)\left(c_1 V_{RF} + c_2 V_{RF}^2 + c_3 V_{RF}^3 + \cdots\right) \tag{4}$$

where V_π is assumed to be 5.0V. Additionally, when the modulators are biased at quadrature, the output power (P_{out}) is related to the input power as follows:

$$P_{out} = \left(\frac{P_{in}}{2}\right)\left(1 - \varphi_{RF}\right) \tag{5}$$

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 $I_{DC}= a_1 P_{DC}$ and an RF one given by:

$$I_{RF} = a_1 P_{RF} + a_2 P_{RF}^2 + a_3 P_{RF}^3 + \cdots \tag{6}$$

Figure 5 plots the IMD3 and IMD2 calculated using this model. The modulator is assumed to be linear (c_2=0 and c_3=0) and the non-linear coefficients assumed in the detector are indicated in Figure 6. 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 [4] 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 [4].

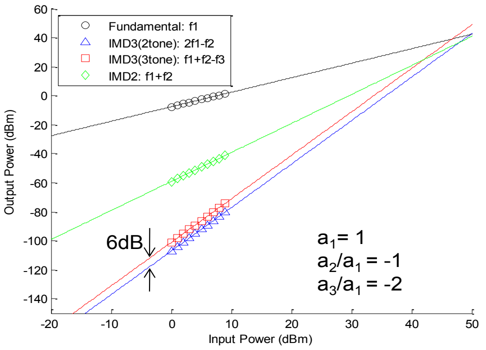

Figure 5. Calculated IMD3 and IMD2 (P_{dc}= 40mW)

Next, we introduce distortion in the optical source as follows: $c_2/\ c_1$=-0.01 and $c_3/\ c_1$=-0.001. Figure 6 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 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 Figure 7 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 3dB difference as given by equations (2) and (3).

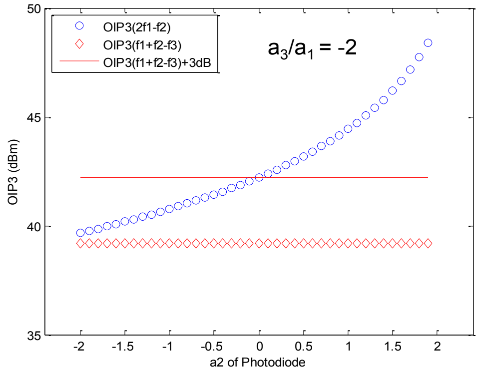

Figure 6. OIP3 dependence on a_2 of photodiode

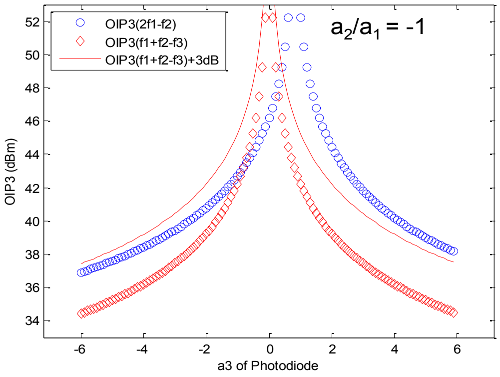

Figure 7. OIP3 dependence on a_3 of photodiode

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 Figure 8, $a_2/\ a_1$ =-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 Figure 9 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 from (2) and (3).

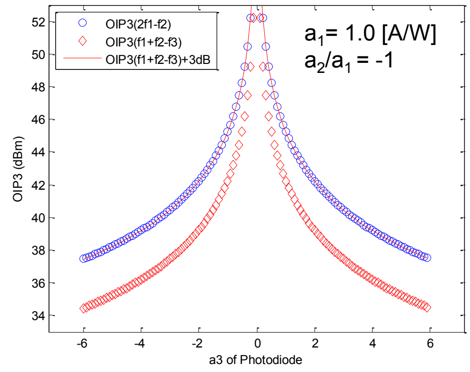

Figure 8. OIP3 dependence on a_3 of photodiode with perfectly linear optical source (c_2, c_3=0)

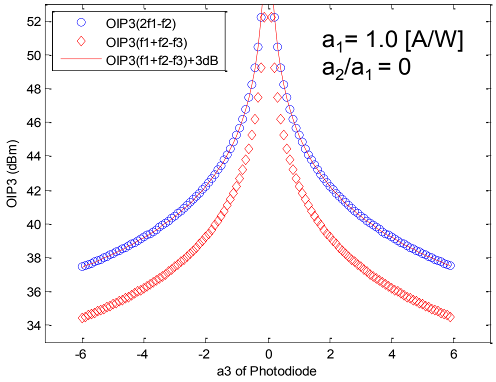

Figure 9. OIP3 dependence on a_3 of photodiode with a_2/a_1 =0 but not a perfectly linear optical source (c_2/c_1 = -0.01 and c_3/c_1 = -0.001)

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. Even if the intensity modulators are made out of a highly linear material (e.g. $LiNbO_3$), as in the case of this experiment, and the modulators are biased at quadrature (to minimize c_2), there will still be some residual second-order distortion due to thermal drift of the bias point. 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. This is particularly true as the linearity of detectors approach numbers in excess of 40dBm.

V. CONCLUSION

In this paper we have performed a detailed experimental characterization of two different linearity measurement techniques on the same photodiode for the first time. Using a Ge n-i-p waveguide photodetector on a Silicon-on-Insulator (SOI) substrate we have simultaneously measured both the three- tone OIP3 and the two-tone OIP3. Comparing these results, we find that at a photocurrent of 20mA, the difference between the two-tone and three -tone OIP3 is approximately 2-3dB, which is close to the 3dB predicted theoretically. Additionally, to show the need to adopt the more complex but more accurate three-tone measurement technique, we have modeled the measurement setup, introducing nonlinearities from both the optical modulator and RF signal generator. We find that the 2nd and 3rd order non-linear components (c_2, c_3) of the optical modulators affect the two-tone OIP3 measured in the detector because they interact with the photodiode non-linear coefficients (a_2 and a_3). On the other hand, the three-tone OIP3 remains unaffected by distortion in the optical source. Thus, as the linearity of photodiodes continues to increase, it is necessary to use a measurement technique such as the three-tone system to accurately characterize photodiode nonlinearities.

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