Using Time-Domain Transient Simulation to Characterize Nonlinear Intermodulation Distortions in Photodetectors

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Abstract- **We propose a universal simulating solution to characterize the OIP3 of most kinds of photodetectors using Silvaco TCAD simulation tools. For a normal PIN photodetector and a uni-traveling-carrier photodetector, a fine agreement was observed in experimental results and simulation results. We believe that this solution could be useful in designing and optimizing high-power photodetectors.**

I. INTRODUCTION

High-power high-linearity photodetectors are very important for high-performance analog optical links [1]. The output third-order intercept point (OIP3) is a widely accepted figure of merit to characterize nonlinearities in high-power photodetectors [2]. Nonlinearities in high power photodetectors, especially third-order intermodulation distortions and saturated output RF power, have been modeled and simulated extensively in the past. The modeling of photodetectors was typically based on the drift-diffusion model [2-4], nonlinear equivalent circuit [5] or frequency-domain harmonic balance method [6]. These models have proven effective in predicting the linearity performance of photodetectors but mostly limited to specific types of photodetectors.

In this paper, we propose a simulating solution to characterize the OIP3 of any type of photodetectors using Silvaco TCAD tools. By combining physical models (e.g. drift-diffusion model, generation-recombination model, etc.), newton method and finite element method, photodetectors with complicate layers and different structures could be characterized in one simulation process.

II. SIMULATION PROCESS

i. The first step includes defining the layer structure of the device, drawing meshes, specifying material parameters and including solve methods in Silvaco Atlas. The cross section of a uni-traveling-carrier (UTC) photodetector defined in Silvaco Atlas is shown in fig. 1(a).

ii. The second step is to generate a modulated light waveform. Since the transient time simulation requires a large amount (typically 10,000 in our simulation) of time samples for a clear frequency spectrum, we wrote a Python script to generate the waveform file containing incident light with any power intensity and any modulation frequency automatically. A part of a sample of three-tone modulated waveform generated by the script is shown in fig. 1(b). The modulation frequencies are 1.0GHz, 1.1GHz and 1.3GHz, respectively.

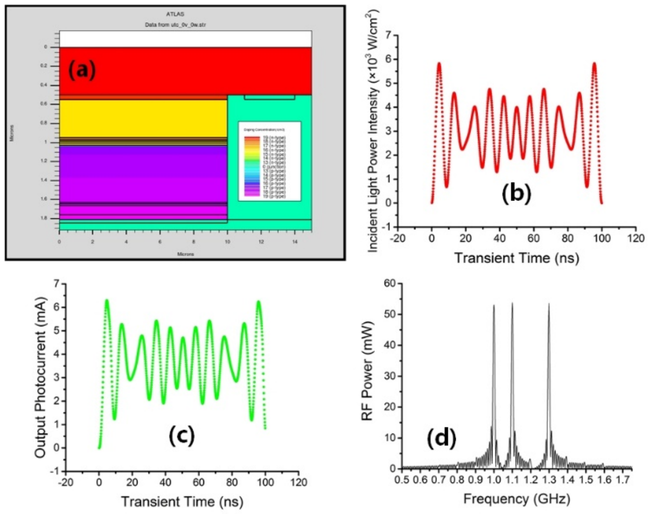

Fig. 1. (a) The 2D photodetector device modeled in Silvaco atlas; (b) script generated three-tone modulated illumination light waveform; (c) calculated output photocurrent of the photodetector; (d) frequency spectrum of furrier transformed simulation results.

iii. After the structure definition and waveform generating, the device was simulated in the Silvaco Atlas with appropriate physical models. In this work, the temperature of the device was kept at 300K to simulate the test environment with active cooling of the device. Due to Atlas' own calculation features, some time samples with uneven intervals would be added in the outcome results during the calculation process. These time samples were moved from the results to ensure a uniform time interval between the calculation results for the sake of further fast furrier transform. The modified output photocurrent corresponding to the waveform in fig. 1(b) is shown in fig. 1(c). A slight phase shift and minor distortions could be observed on the output current curve.

iv. The average photocurrent was calculated and extracted from the calculated photocurrent. The modified signal was then processed by fast furrier transform. Then the RF powers at fundamental and third-order intermodulation frequencies could be obtained. A sample of transformed RF spectrum in fig. 1(d).

III. RESULTS AND DISCUSSION

The nonlinearity distortions of two types of photodetectors were measured and simulated to examine the effectiveness of the simulation method. We used a two-tone heterodyne measurement system to characterize the photodetectors. In the

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measurement system, two pairs of tunable lasers heterodyned two optical signals with different modulation frequencies (f_1=1.0GHz and f_2=1.1GHz) and modulation depths of ~100%. The IMD3 were measured at $2f_2$-f_1=1.2GHz. The simulations were performed with a three-tone (f_1=1.0GHz, f_2=1.1GHz, and f_3=1.3GHz) modulated light source, and the IMD3 were extracted at f_1+f_3-f_2=1.2GHz. Mathematically, the simulated three-tone OIP3 should be 3dB smaller than the measured two-tone OIP3 [7], e.g.

$$OIP3_{2t}=OIP3_{3t}+3(dBm),$$

and the simulated three-tone IMD3 should be 6dB bigger than the measured two-tone IMD3 [7], e.g.

$$IMD3_{2t}=IMD3_{3t}-6(dBm).$$

The first photodetector we used for comparison is a PIN photodetector with a 600nm absorption layer and a 300nm InAlAs electron blocking layer. The simulated and measured results can be seen in fig. 2(a) with the fundamental and IMD3 powers. The device was biased at -4V with a DC photocurrent of 10mA. The simulated and measured OIP3 in fig. 2(a) is 34.5dBm and 29dBm, respectively. Both IMD3s demonstrates a slope of ~3 which is nearly ideal. The OIP3 of the device was also simulated and measured over a range of bias voltages with the same DC photocurrent, as shown in fig. 2(b). The simulated OIP3s were typically 4~7dB higher than the measured data, but exhibit a similar trend versus bias voltage.

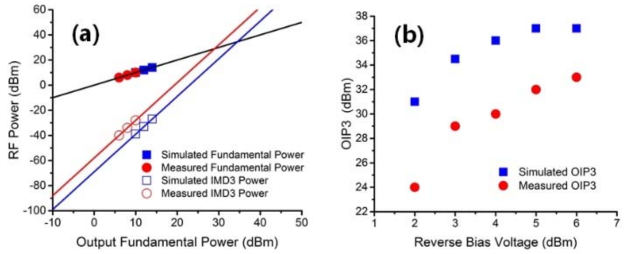

Fig. 2. Simulated and measured (a) output RF power of fundamental and IMD3 and (b) OIP3 versus bias voltage of an InAlAs PIN photodetector.

Another comparison was made on a UTC photodetector with a 600nm graded-doped absorption layer and a 15nm highly doped cliff layer. The device was also biased at -4V with a DC photocurrent of 10mA. As is shown in fig. 3(a), the IMD3s shows a slope of ~3 and the simulated and measured OIP3 is 37dBm and 31dBm, respectively. Fig. 3(b) exhibits the OIP3s simulated and measured over different bias voltages. The simulated OIP3s were also 4~7dB higher than the measured ones.

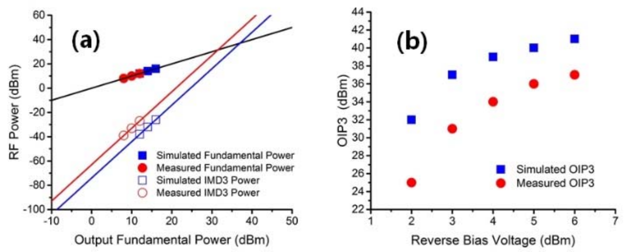

Fig. 3. Simulated and measured (a) output RF power of fundamental and IMD3 and (b) OIP3 versus bias voltage of an UTC photodetector.

The results in fig. 2 and fig. 3 indicates that the simulation could give relatively accurate results on the OIP3 of the two photodetectors. At 6V reverse bias, the simulated OIP3s are ~4dB higher than the measured OIP3s, which means they are only 1dB higher than the theoretical value. However, the simulated OIP3s at lower voltages were ~4dB higher than theoretical values. Still, the simulation gave a fine prediction on the OIP3's behavior versus bias voltage. And the simulated OIP3 of the UTC photodetector is higher than the PIN photodetector, which agrees with the measured results.

IV. Summary

We propose a simulating solution to characterize the OIP3 of most kinds of photodetectors using Silvaco TCAD simulation tools. The solution combines physical models (e.g. drift-diffusion model, generation-recombination model, etc.), newton method and finite element method to calculate the transient time response of photodetectors to modulated incident light source. The IMD3 and OIP3 of a normal PIN photodetector and a UTC photodetector were simulated and measured. A fine agreement was observed between experimental results and simulation results. We believe that this solution could be useful in designing and optimizing high-power photodetectors.

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