Efficient and Accurate Calculation of Photodetector RF Output Power

Ergun Simsek, Ishraq Md Anjum, Thomas F. Carruthers, Curtis R. Menyuk
Department of Computer Science and Electrical Engineering, University of Maryland Baltimore County
Corresponding Author: simsek@umbc.edu

David A. Tulchinsky and Keith J. Williams
U.S. Naval Research Laboratory, Washington, DC 20375 USA

Joe C. Campbell
University of Virginia, ECE Department, Charlottesville, Virginia 22904, USA

Abstract — **We present two different ways to calculate RF output power of today's complex photodetectors accurately and efficiently by solving drift-diffusion equations. Numerical results show a very good agreement with measurements.**

I. Introduction

Semiconductor photodetectors, which convert incident optical signals into electrical currents, are widely used in optical communication, opto-electronic, and RF-photonic applications that require large bandwidth, high efficiency, and low dark current [1]–[3]. However, designing photodetectors that meet all the requirements is a nontrivial task due to the design trade-offs [1]–[3], e.g., smaller photodetectors have a larger bandwidth but generate a weaker output current. In order to understand a photodetector's performance, it is necessary to find photodetector's RF output power spectrum either experimentally or numerically. Obtaining numerical results quickly can help to reduce costs and save time.

RF output power spectrum of a photodetector can be obtained numerically by solving the drift-diffusion equations [3], [4] assuming either a broadband or a monochromatic modulation. The former yields the entire spectrum in one run but it is not parallelizable. The latter gives an RF output power value at a single modulation frequency, but by it is possible to run the same code in parallel on many nodes, which significantly reduces the computation time.

II. RF Output Power: Numerical vs. Experimental Results

In this work, we study an InGaAs/InGaAsP/InP modified uni-traveling-carrier (MUTC) photodetector, which has 15 layers with varying thicknesses and doping levels as shown in Fig. 1(a). The photodetector is reverse-biased ($V_{\text{bias}} = -9$ V) and under a continuous wave laser illumination ($\lambda = 1550$ nm) that is modulated by an RF signal. The diameters of the incident beam and photodetector are 40 μm and 28 μm, respectively. The load resistance is 50 Ω. The output current and hence the output power of the photodetector can be calculated by solving the drift-diffusion equations in a similar fashion to the finite-difference time-domain method [4] in two different ways as follows.

Approach 1: Assume, we use the following expression to define a broadband modulation

$$P_{\text{in}}(t) = P_0 \left(1 + m \times \text{sinc}(2 \times f_{\text{mod}}^{\max} \times (t - T_{\max}/2))\right), \qquad (1)$$

where $\text{sinc}(x) = \sin(x)/x$ and $f_{\text{mod}}^{\max}$ is the highest frequency of interest, m is the modulation depth, t is time, and $T_{\max}$ is the largest t value. Figure 1(b) shows this non-uniform modulation in time-domain. The fast Fourier transform (FFT) of this signal gives almost a constant magnitude in frequency-domain for all the frequencies from 0 to $f_{\text{mod}}^{\max} = 100$ GHz, as illustrated in Fig. 1(c). Assuming an 8% modulation depth, $m = 0.08$, and a broadband modulation defined in (1), we can obtain the RF output power spectrum in one run by (i) solving the drift-diffusion equations to obtain the output current (I_{output}) and (ii) taking the FFT of the $I_{\text{output}}^2 R_{\text{load}}/2$ as shown with the blue curve in Fig. 1(d).

Approach 2: Assume we define a monochromatic modulation with the following expression

$$P_{\text{in}}(t) = P_0 \left(1 + m \times \sin(2 \times \pi \times f_{\text{mod},i} \times t)\right), \qquad (2)$$

where $f_{\text{mod},i}$ is i^{th} RF modulation frequency, where $i = 1, 2, \cdots, N_{\text{run}}$ and N_{run} is the total number of the simulations. Assuming same amount of modulation depth, we can obtain the RF output power at the modulation frequency of $f_{\text{mod},i}$ by (i) solving the drift-diffusion equations to obtain the output current (I_{output}) and (ii) calculating $I_{\text{output}}^2 R_{\text{load}}/2$.

At the modulation frequency, $f_0 = 1$ GHz, we can complete this computation with very high accuracy on a regular computer in 20 minutes. To calculate the output power at other modulation frequencies, $f_{\text{comp},i}$ for $i = 1, 2, \cdots, N_{\text{run}}$, we can scale the optical excitation duration ($T_{\max}$) and time-stepping (Δt) linearly with frequency to maintain the same accuracy level, e.g., $T_{\max} = 10 f_0/f_{\text{mod},i}$ guarantees the existence of 10 oscillations in the output current due to RF modulation. On a computer with M-nodes, we can benefit from parallel computing and achieve keeping the overall computation time to be around $20 \times N_{\text{run}}/M$ minutes.

In Fig. 1(d), we compare the experimental results with the numerical ones obtained with both approaches briefly discussed above. For the broadband calculation, $f_{\mathrm{mod}}^{\max}$ is set to 100 GHz just to show the effectiveness of this approach. However, in order to keep the computation time moderate, Δt for broadband calculation is 5 times smaller than the Δt for the monochromatic calculations, even though the $f_{\mathrm{mod}}^{\max}/f_0 = 100$. It should be also noted that the accuracy of the broadband calculation depends on the number of periods included in the modulated signal. Having $T_{\max} = 20$ ns corresponds to 20 periods at the frequency of 1 GHz. The FFT of a sinc function with 20 periods shows slight differentiations (oscillations) for frequencies lower than $f_{\mathrm{mod}}^{\max}$. As a result, these two factors cause slightly different behavior in the output power spectrum as can be seen in Fig 1(d) but the difference is less than 1 dBm even in the worst case. Table I provides a comparison of the simulation parameters and run times.
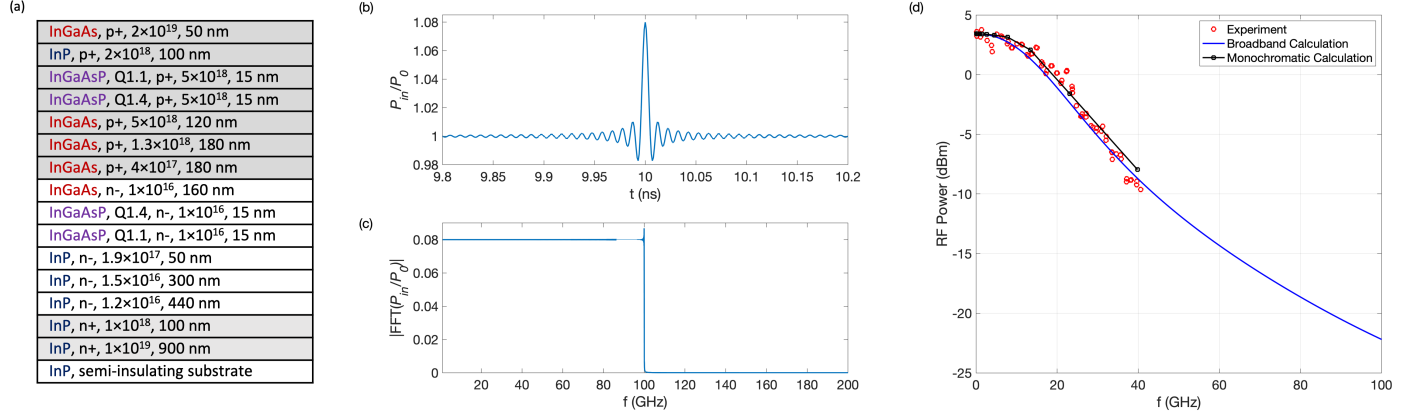

Fig. 1. (a) Structure of the MUTC photodetector. Broadband modulated signal in (b) time- and (c) frequency-domains. (d) RF output power spectrum: experiment (red circles) vs. broadband calculation (blue curve) vs. monochromatic calculation (black curve).

TABLE I. NUMERICAL SIMULATION PARAMETERS USED IN BROADBAND (MIDDLE COLUMN) AND MONOCHROMATIC (RIGHT COLUMN) CALCULATIONS. $T_{\max}$: DURATION OF THE OPTICAL EXCITATION. $n_{\mathrm{ts}} = T_{\max}/\Delta t$: NUMBER OF TIME-STEPS. N_{run}: NUMBER OF SIMULATIONS. $t_{\mathrm{comp},i}$: AMOUNT OF TIME SPENT TO COMPLETE ONE ITERATION.

	Broadband Calculation	Monochromatic Calculation
$T_{\max}$ (ns)	20	$10 f_0/f_{\mathrm{mod},i}$
Δt (ps)	1	$5 f_0/f_{\mathrm{mod},i}$
n_{ts}	20,000	2000
N_{run}	1	8
$t_{\mathrm{comp},i}$ (min.)	180	20

To lower the computation time of the broadband simulations, one might use other types of modulation expressions, such as the Blackman-Harris window function [5], which decays faster than a sinc function in the time domain. In that case, the output spectrum should be normalized with respect to the spectrum of the input modulation function. In such implementations, the computation time of the broadband calculation can be as low as the computation time of a single run in the monochromatic modulation. At the conference, we will provide a detailed comparison of the efficiency and accuracy of the calculations done with different broadband modulation functions and the rules to choose the optimum simulation parameters to assure the minimum computation time for the desired accuracy level.

REFERENCES

[1] Z. Li, H. Pan, H. Chen, A. Beling and J. C. Campbell, "High-Saturation-Current Modified Uni-Traveling-Carrier Photodiode With Cliff Layer," *IEEE J. Quantum Electron.*, vol. 46, no. 5, pp. 626–632, 2010.

[2] Y. Hu, B. S. Marks, C. R. Menyuk, V. J. Urick, and K. J. Williams, "Modeling sources of nonlinearity in a simple PIN photodetector," *J. Lightw. Technol.*, vol. 32, pp. 3710–3720, 2014.

[3] S. E. J. Mahabadi, S. Wang, T. F. Carruthers, C. R. Menyuk, F. J. Quinlan, M. N. Hutchinson, J. D. McKinney, and K. J. Williams, "Calculation of the impulse response and phase noise of a high-current photodetector using the drift-diffusion equations," *Opt. Express,* vol. 27, no. 3, pp. 3717–3730, 2019.

[4] E. Simsek, S. E. J. Mahabadi, I. Md Anjum, and C. R. Menyuk, "A Robust Drift-Diffusion Equations Solver Enabling Accurate Simulation of Photodetectors," PIERS 2021, Hangzhou, China, 21–25 November 2021.

[5] Q. H. Liu, "Transient electromagnetic modeling with the generalized K-space (GkS) method," *Microw. Opt. Technol. Lett.*, vol. 7, pp. 842 – 848, 1994.