Non-Uniform Time-Stepping and Windowing for Fast Simulation of Photodetectors

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***Abstract*—Blackman-Harris time window is used as a broadband excitation to calculate the RF output power of a photodetector. A non-uniform time-stepping is implemented to capture rapidly changing fields and currents inside the photodetector. The comparisons of numerical results with experiments confirm the high accuracy of the proposed approach that yields a two-orders-of-magnitude reduction in computation time.**

***Index Terms*—drift-diffusion, photodetector, photodiode.**

I. Introduction

Photodetectors are essential components of opto-electronic, photonic, and optical communication systems. Today's modern high-power photodetectors consist of many layers of semiconducting materials with varying thicknesses and doping concentrations that are chosen to achieve desired output metrics such as output power, speed, bandwidth, and linearity. For analog photonic links, a key output metric is large RF output power, which is limited by the compression current in photodetectors that in turn limits the dynamic range of analog optical links. In addition to the structural complexity of photodetectors, their complex nonlinear response to the optical field makes their numerical modeling difficult.

To analyze photodetectors, one can solve the drift-diffusion equations. The standard approach includes a marching-on-in-time scheme implemented with sufficiently small time steps to obtain accurate results [1]. However, choosing very small time steps increases the overall computation time and memory usage. When simulating photodetectors that are used for detecting high-peak-power, ultra-short optical pulses, the use of extremely fine time steps can cause out-of-memory problems by requiring a memory that exceeds the physical memory capacity of a personal computer. In [2], we first proposed a novel non-uniform time-stepping (TS) approach that reduces the memory requirements and impulse response computation time by two orders of magnitude. To calculate RF output power, we recently proposed using window functions (such as Blackman-Harris, Nuttall, or Flat-Top [3], [4]) to represent broadband excitations [5]. When two methods are combined, we obtain an extremely accurate and efficient robust solver to analyze photodetectors.

II. Numerical Model

A. Non-Uniform Time-Stepping

In [1], we calculate the impulse response of a modified uni-traveling carrier (MUTC) photodetector under pulsed excitations in three steps as follows. First, we calculate the dark current. Then, the structure is excited with an ultra-short pulse defined by $y(t) = A\,\mathrm{sech}\{(t - t_c)/\tau\}$ where τ, t_c, and A are the optical pulse duration, pulse position, and pulse amplitude, respectively, and the output current, I_{out}, is calculated as a function of time. In the third step, the normalized impulse response, $h(t) = \Delta I_{\mathrm{out}}(t)/\int_0^\infty \Delta I_{\mathrm{out}}(t)\mathrm{d}t$ is calculated using a uniform time-step (TS), i.e. $t_{\mathrm{lin}}[i] = \Delta t \times (i-1)$, where t_R is the pulse repetition period, $\Delta t = t_R/(N-1)$, N is the total number of the time steps, and $i = 1, 2, \cdots, N$. However, the impulse response changes rapidly close to the pulse center. Based on this observation, a logarithmic TS was recently proposed to evaluate this numerical integration more efficiently [2], where the number of the time steps can be chosen much smaller than N. In this approach, $t_{\log,B}$, the time steps logarithmically distributed between t_c and t_R is determined with $t_{\log,B}[i] = t_R^{(i-1)/(M-1)} t_c^{(M-i)/(M-1)}$ for $i = 1, 2, \cdots, M$. Then, a similar formula is used to determine $t_{\log,A}$, the time steps from 0 to t_c, excluding t_c, i.e. $t_{\log} = t_{\log,A} \cup t_{\log,B}$. By doing so, the difference between consecutive time steps $\Delta t[i]$, decreases near t_c and increases farther away from t_c. With this approach, a factor of 20 reduction in computation time is achieved for the analysis of a photodetector under continuous excitations [2], in which the excitation strength is assumed to be moderate.

However, in an MUTC that is detecting high-peak-power, ultra-short optical pulses, the logarithmic TS does not provide a sufficient number of points around the pulse to capture the rapidly changing fields and currents along the photodetector. In order to address this issue, we proposed in [6] a novel nonuniform TS in which $\Delta t[i]$ is even further decreased near the pulse center and is further increased as $|t - t_c|$ increases, by using the expression

$$t_{\text{nu},B}[i] = t_c + \left(\frac{t_R - t_c}{\sum_{k=1}^{M} \xi(k)} \right) \sum_{k=1}^{i} \xi(k), \tag{1}$$

where

$$\xi(k) = \{t_{\log,B}[k] - t_{\log,B}[k-1]\} \left(\frac{k + c_1}{M + c_1} \right)^{c_2}, \tag{2}$$

and c_1 and c_2 are coefficients that we can choose to control the amount we shrink/enlarge $\Delta t[i]$. For the non-uniform TS, we define $t_{\log,B}[0] = t_{\log,B}[1]$, so that $t_{\text{nu},B}[1] = t_c$. This approach greatly reduces the number of time steps needed without sacrificing accuracy.

B. Blackman-Harris Time Window

A broadband excitation is defined with a Blackman-Harris window that is given by

$$F_{\text{mod}}(t) = \frac{1}{L} \sum_{n=0}^{3} a_n \cos \left(\frac{2\pi n (t - t_c)}{L} \right) \tag{3}$$

for $|t - t_c| \leq L/2$, where t is the time, t_c where the pulse is centered, $f_{\text{mod}}^{\max}$ is the highest frequency of interest, $T_{\max}$ is the largest t value, a_ns are some real constants determining the characteristics of the window function (for the four-term Blackman-Harris window, $a_0 = 0.35322$, $a_1 = 0.488$, $a_2 = 0.145$, $a_3 = 0.01022$), and $L = 1/f_{\text{mod}}^{\max}$. In a window function such as Blackman-Harris, the different frequencies are not represented at the same strength. Hence, we need to normalize the spectrum of output power, which is equal to output current squared times load resistance ($I_{\text{rms}}^2(t) \times R_{\text{load}}$) with respect to the square of the absolute value of the FFT of $F_{\text{mod}}(t)$, i.e.

$$P_{\text{out}}(f_i) = \frac{|\text{FFT of } I_{\text{rms}}^2(t) \times R_{\text{load}} \text{ at } f_i|}{|\text{FFT of } \mathrm{F_{mod}(t)} \text{ at } f_i|^2}. \tag{4}$$

C. Numerical Results

Our photodetector has 10 layers with different semiconductor materials and varying thicknesses and doping levels as listed in Table I. The photodetector is reverse-biased ($V_{\text{bias}} = -1$ 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 both 20 μm. The load resistance is 50 Ω.

Figure 1 shows a very good agreement between the experimental [7] and numerical results for the RF output power of the photodetector.

The overall computation takes less than two minutes on a desktop computer. A detailed analysis of the reduction achieved in computation time and memory usage will be provided at the conference.

TABLE I
SEMICONDUCTOR AND DOPING TYPES, THICKNESS, AND DOPING CONCENTRATION OF THE LAYERS FORMING THE PHOTODETECTOR.

Material	Thickness (nm)	Concentration (cm^{-3})
InGaAs, $p+$	50	2×10^{19}
InGaAsP, Q1.24, $p+$	20	8×10^{18}
InGaAs, $p+$	220	$5 \times 10^{18} - 3 \times 10^{17}$
InGaAs, $p+$	10	1.5×10^{18}
InGaAsP, Q1.24, n	12	1×10^{15}
InP, n	10	1.5×10^{18}
InP, n	350	1.5×10^{15}
InP, n	50	1×10^{17}
InGaAsP, Q1.24, $n+$	15	1×10^{18}
InP, $n+$	900	1×10^{19}

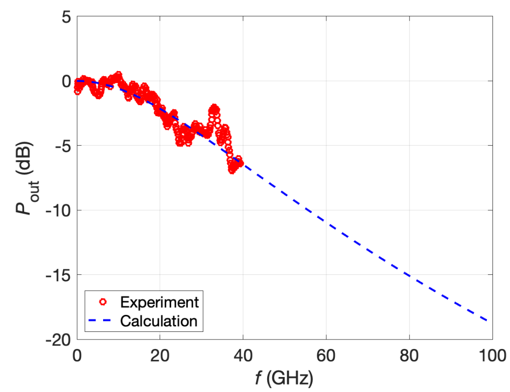

Fig. 1. RF output power spectrum of the photodetector described in Table I: experiment [7] vs. numerical results.

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