Thinner and Faster Photodetectors Producing Lower Phase Noise

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***Abstract* — Design parameters of a high-performance photodetector are further optimized using the Nelder–Mead method minimizing the phase noise calculated with a logarithmic time evolution algorithm. The new design is thinner, faster, and has 6 dBc/Hz lower phase noise than the original design.**

I. Introduction

In the last decade, the availability of user-friendly machine learning and optimization tools along with the affordability of computing and storage devices has led to an unparalleled surge of interest in the topics of machine learning and optimization in all fields of science and engineering. In photonics, one of the major application areas is improving the performance of already existing devices. In this work, we extend these efforts to modified uni-traveling-carrier (MUTC) photodetectors.

In uni-traveling-carrier photodetectors [1] and their modified versions [2]–[4], electrons are the major carriers, making it possible to increase the bandwidth in high-current applications. Since their first experimental demonstration [1], these photodetectors have been widely used in RF-photonic applications. In metrological and some other applications, however, the phase noise becomes the critical limiting factor.

Designing a high-performance MUTC or even improving the performance of an already existing design is a challenging task due to the required computation time, difficulties in estimating sensitivity of the device to the design parameters, and the existence of design constraints, *e.g.* the electrical breakdown potential of the materials used in the device. Recently, a numerical method was proposed to calculate the phase noise of MUTCs by solving the drift-diffusion equations [4], which provides a faster solution than Monte Carlo simulators. In this work, first, we further lower the computation time by evaluating the impulse response of the photodetector with logarithmic integration, and then, we use this accelerated impulse response calculator in a bounded Nelder–Mead optimizer to minimize the phase noise in an iterative fashion.

II. Phase Noise Calculation

We use a one-dimensional (1-D) model of the MUTC photodetector [3], [4] to calculate the impulse response of the device. External loading, impact ionization, thermionic emission, and the Franz-Keldysh effect are all considered in the simulations. To calculate the impulse response, we first calculate the steady state output current. Then we perturb the generation rate by a small amount and calculate how output current changes as a function of time. For perturbation, we use a hyperbolic secant function, i.e. $\Delta G_{\text{opt}} = r\text{sech}(t/\tau)^2$, where $\tau = 1$ ps and r is the perturbation coefficient. The normalized impulse response, $h(t) = \Delta I_{\text{out}}(t)/\int_0^\infty \Delta I_{\text{out}}(t)\text{d}t$, is then calculated by logarithmic integration. Assuming that the electrons in each current pulse are Poisson-distributed [6], the mean-square phase fluctuation is given by

$$\left\langle \Phi_n^2 \right\rangle = \frac{1}{N_{\text{tot}}} \frac{\int_0^{T_R} h(t)\sin^2\left[2\pi n(t-t_c)/T_R\right]\text{d}t}{\left\{\int_0^{T_R} h(t)\cos\left[2\pi n(t-t_c)/T_R\right]\text{d}t\right\}^2}, \tag{1}$$

where n is the harmonic-number, N_{tot} is the total number of electrons in the photocurrent, t_c is central time of the output current, and T_R is the repetition time between optical pulses.

III. Iterative Nelder–Mead Algorithm

For an MUTC photodetector with N layers, where material and doping types are fixed, there are $M = 2N$ variables to be optimized: the doping density and thickness of each layer. In the Nelder-Mead algorithm [5], a simplex of size a is initialized at x_0 using $x_i = x_0 + (p-q)u_i + \sum_{k=1}^{M} qu_k$, for $i = 1, \cdots, M$, where u_i are the unit base vectors, $p = a(\sqrt{M+1} + M - 1)/M\sqrt{2}$ and $q = a(\sqrt{M+1} - 1)/M\sqrt{2}$. Then depending on the comparison of the function values calculated at $M+1$ vertices, the simplex vertices are changed through three operators—reflection, expansion, or contraction—in order to find a point minimizing the cost function, which is the phase noise in this case. The algorithm might not converge to a local optimum, which occurs for example when the simplex falls into a subspace. Hence, we implement the algorithm in an iterative fashion so that if the cost-function does not change significantly even with non-overlapping vertices, a new search is initiated by replacing x_0 with $x_i + \phi$, where ϕ is an array of M random numbers that are two of orders of magnitude smaller than x_i.

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IV. Numerical Results

We use the optimized design in [4] as the starting point in our optimization study. The materials, doping types and densities, and thickness values of each layer of this design and all the other simulation parameters can be found in [4]. The initial design's phase noise is -177 dBc/Hz. In the Nelder–Mead search, lower and upper boundaries are set to 90 and 110 % of the initial values. The number of iterations is set to 1000. At the end, we obtain new design parameters of a device with a phase noise of -183 dBc/Hz. These parameters are listed in Table I.

TABLE I. Material and doping types, doping concentrations, and layer thicknesses for the proposed design.

Layer No	Material and Doping Type	Doping Density (cm^{-3})	Thickness (nm)
1	InGaAs, p^+, Zn	8.1×10^{18}	11.3
2	InP, p , Zn	1.3×10^{18}	44.6
3	InGaAsP, Q1.1, p, Zn	1.8×10^{18}	12.2
4	InGaAsP, Q1.4, p, Zn	1.6×10^{18}	12
5	InGaAs, p, Zn	2.2×10^{18}	26.5
6	InGaAs, p, Zn	1.2×10^{18}	33
7	InGaAs, p, Zn	5.1×10^{17}	37
8	InGaAs, p, Zn	1.2×10^{17}	62
9	InGaAs, n, Si	5.8×10^{15}	188
10	InGaAsP, Q1.4, n, Si	9.5×10^{15}	15.6
11	InGaAsP, Q1.1, n, Si	8.1×10^{15}	18.8
12	InP, n, Si	9×10^{16}	34.7
13	InP, n, Si	1.6×10^{16}	447
14	InP, n^+, Si	8.6×10^{17}	78.7
15	InP, n^+, Si	6.9×10^{18}	634
16	InGaAs, n^+, Si	8.1×10^{18}	11
17	InP, n^+, Si	7.7×10^{18}	127
	InP (Substrate)		

Figures 1(a) and 1(b) show the electric field and carrier distributions at steady state inside the proposed MUTC photodetector, Fig. 1(c) shows its normalized impulse response. The optimized photodetector is 1.4 μm thinner than the initial design, which is 3.2 μm. The maximum value of the total current decays to 1% of its initial value in 25 ps, while the same process takes 56 ps for the original design. Hence, the proposed photodetector not only has less phase noise, but is also thinner and faster.

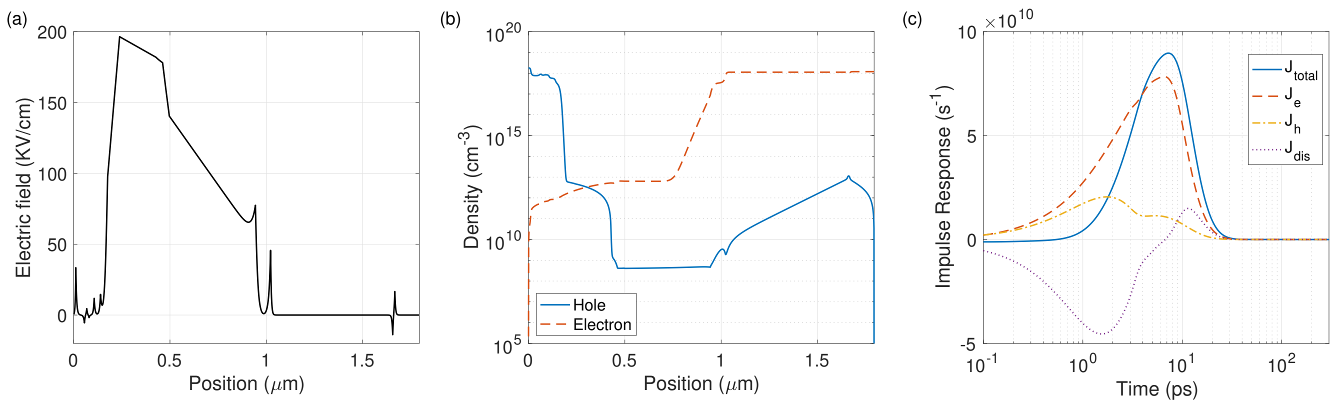

Fig. 1. (a) Electric field distribution and (b) density of electrons at steady state inside the MUTC photodetector, and (c) normalized impulse response of the MUTC photodetector for $f_R = 1/T_R = 2$ GHz and $n = 5$.

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