Designing Nonlinear Optoelectronic Devices with Numerical Optimization: Lessons Learned

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2023 Photonics & Electromagnetics Research Symposium (PIERS) | 979-8-3503-1284-3/23/$31.00 ©2023 IEEE | DOI: 10.1109/PIERS59004.2023.10221428

Abstract— Photodetectors are widely used in various applications with different requirements. Choosing the right group of semiconductor materials and adjusting the parameters of the layers that form the photodetectors are crucial for optimizing their performance. This paper investigates the suitability of four numerical optimization methods — genetic algorithm, particle swarm optimization, surrogate algorithm, and the Nelder-Mead simplex algorithm — for the design of photodetectors by comparing the performance of the methods. The findings of this study can aid in selecting the right numerical optimization technique for designing photodetector-like opto-electronic devices with optimal performance for specific applications.

1. INTRODUCTION

Numerical optimization is the process of finding the best solution to a mathematical problem by iteratively adjusting input variables to minimize or maximize an objective function and is frequently used in many fields of engineering. There are many different numerical optimization methods and there is no straightforward recipe for choosing the most suitable one for a given problem. In this work, we investigate the suitability of four numerical optimization methods — Genetic Algorithm (GA), Particle Swarm Optimization (PSO), Surrogate Algorithm (SA), and the Nelder Mead Simplex Algorithm (NMSA) — for the design of photodetectors by comparing the performance of the methods.

Photodetectors convert incident optical excitations into electrical signals [1]. A semiconductor device as simple as a *p*-*n* junction can achieve this conversion for basic applications. However, for applications requiring high quantum efficiency, low phase noise, and broad bandwidth, one must carefully choose the material types, doping concentrations, and layer thicknesses of each layer of a complex photodetector. Since these devices are highly nonlinear, even a small change in one of these parameters can cause a large change in device performance.

With our drift-diffusion equations solver [2], we can calculate the quantum efficiency, phase noise, and bandwidth of photodetectors. Recent improvements we make in our solver, i.e., nonuniform time-stepping [3] and use of windowing functions, such as Blackman-Harris, as broadband excitations [4] make it possible to calculate the RF output power over a wide range of frequencies in one run and lead to a two-orders-of-magnitude reduction in compute time [5], which is essential for an efficient numerical optimization study.

We start our study with Si-Ge and III-V photodetectors that consist of three layers: a *p*-doped absorber layer, *n*-doped collection layer, and heavily doped $n+$ layer. Then, we gradually increase the number of layers in each region. We fix the material and doping types and allow the layer thicknesses and doping levels to vary. For a photodetector with N layers, we have $2N$ parameters to be optimized if we assume that the doping concentrations are constant in each layer. If we allow gradient doping, we have $3N$ variables to be optimized. For the sake of brevity, next, we go over one of the numerical optimization studies conducted as a part of this research and discuss the performance of four methods based on their performance when N is constant. Then, we share our observations on how the performance of the four methods changes with N and we conclude.

2. A CASE STUDY

Inspired by the experimental work presented in [6], we assume a 9-layer photodetector where the *p*-region consists of 5 gradient-doped Ge layers and the other two Si-regions both consist of two layers as shown in. Fig. 1(a). We first set the layer thicknesses and doping levels to the values provided in [6] and we calculate the output power of the photodetector for the conditions explained in [6]. Fig. 1(b) shows a very good agreement between our numerical results and the experimental results provided in [6]. After confirming the accuracy of our numerical solver, we utilize it along with the four aforementioned numerical optimization techniques to design photodetectors with a higher quantum efficiency, wider bandwidth, and lower phase noise.

We found out that at the end of hundreds of iterations, all four numerical optimization techniques were able to design photodetectors with a much higher quantum efficiency (~ 0.18 vs. 0.12) and a lower phase noise ($-180\,\mathrm{dBc/Hz}$ vs. $-168\,\mathrm{dBc/Hz}$). The exact numbers of iterations used by NMSA, genetic, PSO, and surrogate algorithm implementations are 2412, 2043, 1883, and 789, respectively. In Fig. 2, we provide histogram plots of the numbers of devices generated during the first 789 iterations of surrogate, PSO, and genetic algorithm implementations for (a) bandwidth, (b) phase noise, (c) quantum efficiency, and (d) decay time. Even though the same cost function was utilized in each optimization, we observe different trends. For example, most of the photodetectors created by the surrogate optimization have very high quantum efficiencies (> 0.15), but the genetic algorithm is the most successful one in terms of designing photodetectors with wide bandwidths and low phase noise levels. Decay time was not included in the cost function but both PSO and genetic algorithm were able to create very fast designs.

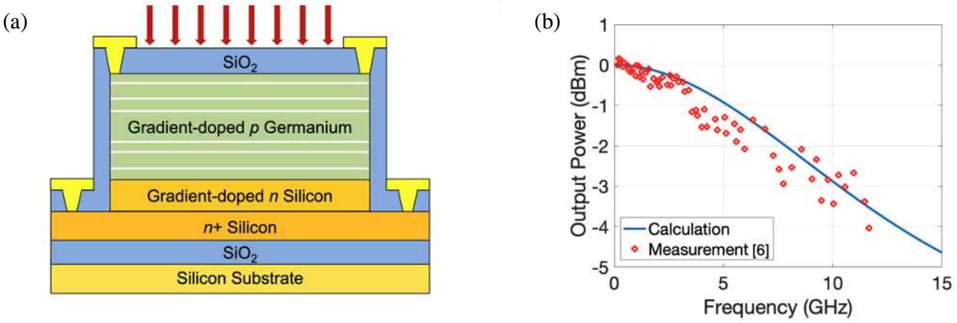

Figure 1: (a) Schematic view of the silicon-germanium (Si-Ge) photodetector cross-section with p Ge, n Si, and $n+$ Si layers. (b) Numerical and experimental [6] results for the RF output power vs. frequency.

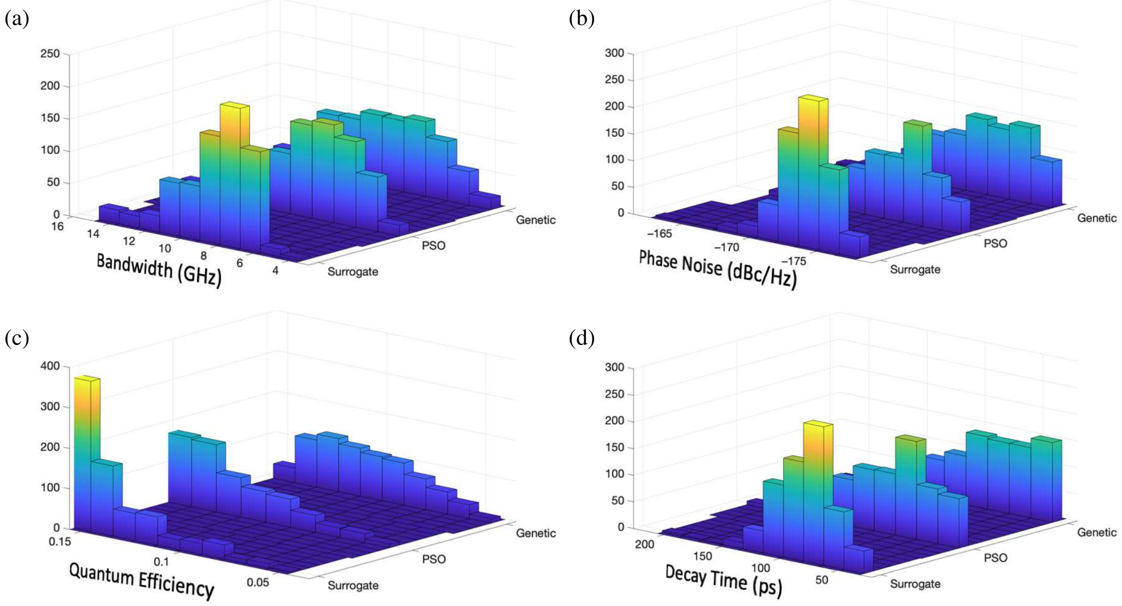

Figure 2: Histogram plots for (a) bandwidth, (b) phase noise, (c) quantum efficiency, and (d) decay time of the 2367 unique designs generated by the surrogate, PSO, and genetic algorithms.

In Fig. 3, the x-axis is the phase noise of each unique design generated during this numerical optimization study and the y-axis is $Q_{eff} \times BW$, the multiplication of the quantum efficiency and bandwidth of the corresponding photodetector. Here, we can clearly observe that the photodetectors with lower phase noise are likely to have higher $Q_{eff} \times BW$ values but for a fixed number of layers and material selection, there is an upper limit for the $Q_{eff} \times BW$, that can be determined numerically.

When we change the number of layers of the photodetectors, we first observe that in each case the NMSA is always reliable but requires many iterations to converge. For small N, the genetic algorithm is the fastest when the search domain is relatively small, and for larger search domains, the PSO performs better. However, when N is large, the surrogate algorithm performs best in terms of meeting the stopping criterion using the least number of iterations.

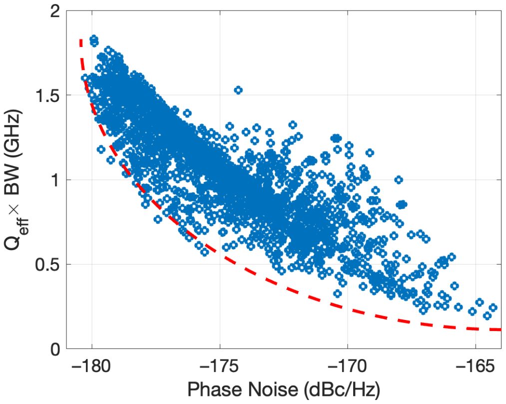

Figure 3: Phase noise vs. $Q_{eff} \times BW$ of 2367 unique photodetector. The red dashed line is added to highlight the following fact: for a desired $Q_{eff} \times BW$ value, there is a certain minimum for the phase of the corresponding device.

3. CONCLUSION

We investigate the suitability of four numerical optimization methods in the design of photodetectors by comparing their performance. We utilize a drift-diffusion equation solver to calculate the quantum efficiency, phase noise, and bandwidth of the photodetectors. The study begins with 3-layer photodetectors and gradually increases the number of layers in each region. The numerical results indicate that all of the implemented optimization methods were able to design photodetectors with higher quantum efficiency, wider bandwidth, and lower phase noise. However, different methods display distinct trends concerning the number of devices with the desired specifications. The study provides insights into the performance of various optimization methods in designing photodetectors and could be valuable for future research in this field.

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