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Dual-Objective Numerical Optimization of MUTC Photodetectors for Frequency Comb Applications

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Abstract—We calculate phase noise as a function of comb-line frequencies for two modified uni-traveling carrier photodetectors and then optimize the two devices for lower phase noise and higher quantum efficiency using the particle swarm optimization algorithm.

Keywords—photodetectors, frequency combs, phase noise, particle swarm optimization

I. INTRODUCTION

Modified uni-traveling carrier photodetectors (MUTC PDs) have been widely used in RF-photonics, time and frequency metrology, and photonic low-phase-noise generation. Phase noise in MUTC PDs is a critical limiting factor [1] for frequency comb applications. Li *et al.* [2] designed and studied an MUTC PD (MUTC-4) that was later analyzed by Mahabadi *et al.* [3]. We had extended the work of [3] by calculating the phase noise at the first 100 comb-line frequencies in this detector [4]. We used a one-dimensional (1-D) computational model [5-6] based on the drift-diffusion equations to calculate the impulse response and followed the procedure described by Mahabadi *et al.* [3] to calculate the phase noise. We use the same procedure to calculate the phase noise at the first 100 comb-line frequencies in a newly designed MUTC PD (MUTC-19) [7]. We optimize both devices using the particle swarm optimization (PSO) algorithm [8]. We previously optimized the MUTC-4 PD for phase noise at one comb-line frequency [9] and for low-bias applications [10]. In the current study, we chose the PSO algorithm because of its parallelizability and ability to handle tens of parameters. We ran the optimization algorithm on a high-performance computing cluster for 24 hours. We found an improvement in phase noise for both optimized designs for a range of frequencies as well as a substantially increased quantum efficiency.

II. MUTC OPTIMIZATION

We used a dual-objective cost function $(2/(1/P + 1/Q) - 1)$, where P and Q are normalized phase noise and quantum efficiency respectively. The cost function was defined so as to minimize phase noise and maximize quantum efficiency. We optimized the layer thicknesses and doping densities of the PDs and enforced the thicknesses to be integers. The swarm size of the PSO algorithm was 400. In Fig. 1(a) and (b), we show the structure of the optimized MUTC-4 and MUTC-19 PD respectively. In this study, for both devices the output current

InGaAs, p+, Zn, 1.0×10^{19} , 62 nm
InP, p+, Zn, 2.51×10^{17} , 30 nm
InGaAsP, Q1.1, p+, Zn, 3.43×10^{19} , 47 nm
InGaAsP, Q1.4, p+, Zn, 7.08×10^{19} , 20 nm
InGaAs, p+, Zn, 2.40×10^{17} , 48 nm
InGaAs, p+, Zn, 4.73×10^{19} , 206 nm
InGaAs, p+, Zn, 4.40×10^{17} , 361 nm
InGaAs, p+, Zn, 1.38×10^{17} , 465 nm
InGaAs, n, Si, 1.00×10^{16} , 347 nm
InGaAsP, Q1.4, p+, Si, 2.38×10^{17} , 35 nm
InGaAsP, Q1.1, p+, Si, 5.13×10^{16} , 35 nm
InP, n, Si, 1.87×10^{16} , 51 nm
InP, n, Si, 4.21×10^{16} , 595 nm
InP, n+, Si, 5.0×10^{18} , 99 nm
InP, n+, Si, 3.29×10^{18} , 752 nm
InGaAs, n+, Si, 8.25×10^{19} , 43 nm
InP, n+, Si, 2.25×10^{19} , 203 nm
InP, semi-insulating substrate

(a)

InGaAs, p+, Zn, 4.34×10^{19} , 68 nm
InP, p+, Zn, 8.7×10^{18} , 132 nm
InGaAsP, Q1.1, p+, Zn, 2.6×10^{18} , 18 nm
InGaAsP, Q1.4, p+, Zn, 1.92×10^{18} , 19 nm
InGaAs, p+, Zn, 4.51×10^{18} , 71 nm
InGaAs, p+, Zn, 1.91×10^{18} , 204 nm
InGaAs, n, Si, 2.33×10^{17} , 240 nm
InGaAs, n, Si, 1.26×10^{16} , 150 nm
InGaAsP, Q1.62, n, Si, 2.78×10^{16} , 237 nm
InGaAsP, Q1.58, n, Si, 1.23×10^{16} , 271 nm
InGaAsP, Q1.4, n, Si, 9.26×10^{16} , 19 nm
InGaAsP, Q1.1, n, Si, 5.74×10^{16} , 15 nm
InP, n, Si, 1.01×10^{16} , 147 nm
InP, n, Si, 3.71×10^{16} , 436 nm
InP, n+, Si, 5.59×10^{18} , 258 nm
InP, n+, Si, 1.83×10^{19} , 1067 nm
InP, semi-insulating substrate

(b)

Fig. 1: Structure of (a) the optimized MUTC-4 PD and (b) the optimized MUTC-19 PD. Blue indicates the p-region, red indicates the n-region, white indicates the i-region and grey indicates the substrate.

is 15 mA; the bias voltage is 21 V; the device diameter is 30 μm ; the pulse-width is 1 ps; the repetition frequency is 2 GHz.

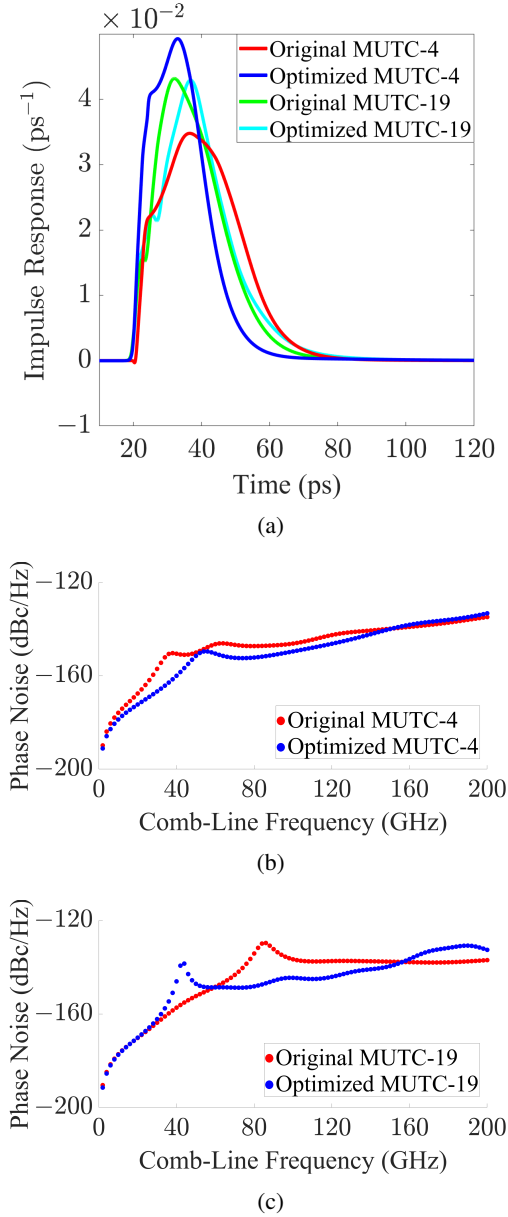


Fig. 2: (a) Normalized impulse responses of original and optimized MUTC PDs and phase noise vs. comb-line frequency of (b) the original and optimized MUTC-4 PDs and (c) the original and optimized MUTC-19 PDs.

III. PHASE NOISE CALCULATION

We show the normalized impulse responses of original and optimized MUTC PDs in Fig. 2(a). We use the equation [3]

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

to calculate the phase noise, where Φ_n^2 is the mean square phase fluctuation at comb-line number n , N_{tot} is the total number of electrons in the photocurrent, T_R is the repetition

period, $h_e(t)$ is the electronic impulse response, and t_c is the central time of the output current. In Fig. 2 we show the phase noise at the comb lines in the frequency range of 2 GHz to 200 GHz for both (b) the original and optimized MUTC-4 PDs and (c) the original and optimized MUTC-19 PDs. We find that the optimized MUTC-4 PD has lower phase noise in the frequency range of 2 GHz–150 GHz and has a 54.3% higher quantum efficiency. The optimized MUTC-19 has slightly lower phase noise up to 16 GHz and then lower phase noise between 60 GHz and 156 GHz and has a 16.3% improvement in quantum efficiency.

IV. CONCLUSION

We have demonstrated that dual-objective optimization of photodetectors is possible for a wide range of frequencies using particle swarm optimization, an evolutionary optimization algorithm. It will be possible to further improve the results using a broadband objective function for the optimization, which we will implement in the future.

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