Sources of Nonlinearity in Phase Noise of MUTC Photodetectors at Comb-Line Frequencies

Ishraq Md Anjum, Ergun Simsek, Seyed Ehsan Jamali Mahabadi, Thomas F. Carruthers, and Curtis R. Menyuk
Computer Science and Electrical Engineering
University of Maryland Baltimore County
Maryland, USA
ianjum1@umbc.edu

***Abstract*—We calculate the phase noise of two high current modified uni-traveling carrier (MUTC) photodetectors at the first 100 comb-line frequencies. We observe a non-monotonic increase of phase noise. We investigate the underlying physics. Insights gained inform MUTC photodetector design and optimization for frequency-comb applications.**

Keywords*—*photodetectors, frequency combs, phase noise

I. Introduction

Modified uni-traveling carrier (MUTC) photodetectors have extensive applications in RF-photonics, time and frequency metrology, and frequency comb generation [1]. In most applications, minimizing the phase noise is a system requirement. Jamali Mahabadi $et\ al.$ [1] developed a procedure to calculate the phase noise of photodetectors by calculating the impulse response using the drift-diffusion equations. This procedure greatly simplifies the calculation and physical interpretation of the results compared to traditional calculations based on Monte Carlo simulations, which are also computationally time-consuming [2]. Using this approach and the computational model developed by Simsek $et\ al.$ [3], we previously calculated the phase noise at the first 100 comb-line frequencies of two MUTC photodetectors [4], [5] designed by Li $et\ al.$ [6] (MUTC-4) and Zang $et\ al.$ [7] (MUTC-9) In the calculated phase noise of the two photodetectors, we observe a non-monotonic increase of phase noise. In this work, we investigate the origins of the non-monotonic increase.

II. Results and Analysis

In this study, the output current for both devices is 10 mA; the bias voltage is 15 V; the device diameter is 30 µm; the pulse-width is 1 ps; the repetition frequency is 2 GHz. We use the equation [1]

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

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.

We plot the phase noise and impulse response power spectrum of the two photodetectors in Figs. 1(a) and 1(b) respectively. We observe that there is a correlation between the phase noise and power spectrum. This correlation can be explained using Eq. (1). The numerator of Eq. (1) in the limit $n \to \infty$ becomes

$$\lim_{n\to\infty} \int_0^L h_e(t)\, \sin^2\left[\frac{2\pi n}{L}(t-t_c)\right] dt = \frac{1}{2} \tag{2}$$

where we note that $\int_0^L h_e(t)\, dt = 1$. We can then simplify Eq. (1) for frequencies above 20 GHz to obtain

$$\left\langle \Phi_n^2 \right\rangle \approx \frac{1}{2N_{\text{tot}}|H(f)|^2}. \tag{3}$$

Above 20 GHz, the phase noise depends solely on the denominator. Hence, we observe an inverse correllation between phase noise and power spectrum. The non-monotonic increase and decrease of phase noise and power spectrum respectively is due to the irregular shape of the impulse response as can be seen in Figs. 2(a) and 2(b), and this

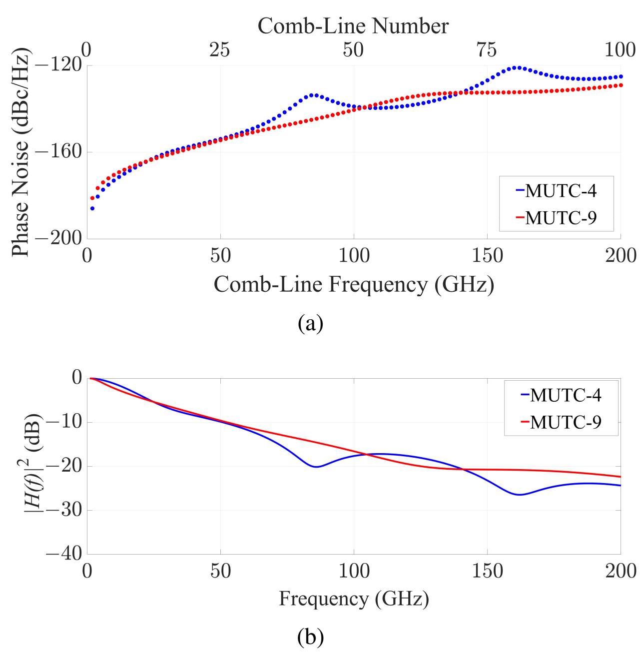
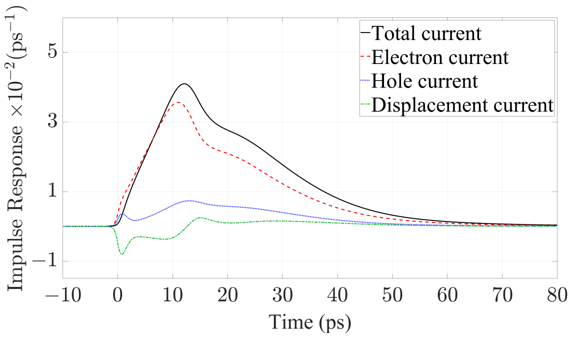
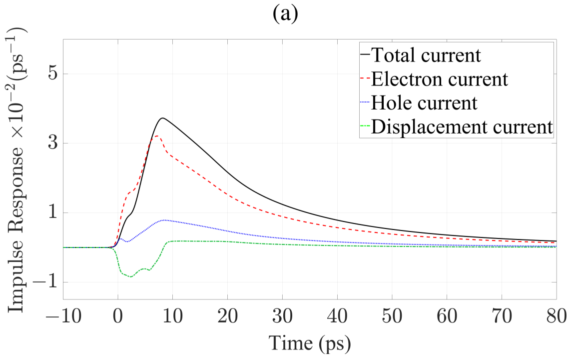


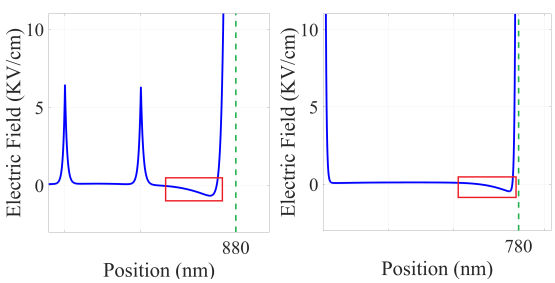
Fig. 1: (a) Phase noise and (b) impulse response power spectrum for the MUTC-4 and MUTC-9 photodetectors.



(a)



(b)



(c)

Fig. 2: Impulse response of the (a) MUTC-4 and (b) MUTC-9 photodetectors. (c) A negative electric field that appears in the MUTC-4 (left) and MUTC-9 (right) photodetectors highlighted with rectangles. The vertical grid lines indicate the layer interfaces and the green dashed line indicate the p-region and intrinsic region interface.

non-monotonic behavior is itself a result of complex carrier transport inside the photodetector.

The electron drift current significantly influences the impulse response characteristics of MUTC photodetectors (PDs); variations in the velocity profile of majority electrons affect the slope of the response. In the MUTC-9 PD, this slope change becomes visible at 1 ps when the electrons pass through the four InGaAsP layers in the intrinsic region. Conversely, in the MUTC-4 PD, the slope transition is more nuanced due to the thinner 30-nm InGaAsP layers within its intrinsic region, compared to the 270-nm thickness in the MUTC-9 PD.

We see a fluctuation in the impulse response tail of MUTC-4 PD at 20 ps that is absent in MUTC-9 PD. Due to the space charge effect, a negative electric field is created in the last layer of the p-region, as can be seen in Fig. 2(c). A negative electron and hole drift current is the result, and a portion of photogenerated electrons and holes is trapped. In the MUTC-4 PD, the last InGaAs layer in the p-region has a lower doping density compared to the MUTC-9 PD. Consequently, the negative electric field that is induced by the space charge is both more negative and lasts longer. Moreover, the MUTC-4 PD has a lower steady state electric field in the first intrinsic InGaAs layer that becomes even lower during the evolution and thus facilitates a higher electron drift velocity. Therefore, in MUTC-4 PD, the trapped electrons entering the intrinsic region subsequent to the dissipation of the electric field have a greater drift velocity than they do in the in MUTC-9 PD. As a result, the batch of trapped electrons transit through the intrinsic region in the form of a secondary pulse in the MUTC-4 PD. Conversely, in MUTC-9 PD, the arrival and passage of the second batch of electrons through the intrinsic region occurs gradually. This secondary electron pulse in MUTC-4 PD causes fluctuations in the tail of the impulse response. High electron drift velocity, though causing fluctuations, enables faster movement through the intrinsic region, leading to a shorter MUTC-4 PD impulse response and reduced low-frequency phase noise [1]. So we find that the primary origins of the fluctuations in high current MUTC PDs are the space charge effect and the nonlinear relationship between electric field and electron drift velocity of different layer materials.

These results suggest that the best approach for optimizing the MUTC device for low phase noise depends on the frequencies of interest. Below 20 Ghz, the photodetector electric field distribution should be engineered so that the electrons pass through the device as rapidly as possible. Above 20 GHz, the device design becomes more complex, and optimization algorithms should be used to produce the desired power spectral density.

References

[1] S. E. Jamali 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*, 27, 3717-3730, 2019.

[2] W. Sun, F. Quinlan, T. M. Fortier, J. D. Deschenes, Y. Fu, Scott A. Diddams, and J. C. Campbell, "Broadband noise limit in the photodetection of ultralow jitter optical pulses", *Phys. Rev. Lett.*, 113, 203901, 2014.

[3] E. Simsek, I. Md Anjum, T. F. Carruthers, C. R. Menyuk, J. C. Campbell, D. A. Tulchinsky, K. J. Williams, "Fast Evaluation of RF Power Spectrum of Photodetectors with Windowing Functions", *IEEE Trans. Electron Devices*, 70, 3643-3648, 2023.

[4] I. M. Anjum, S. E. Jamali Mahabadi, E. Simsek, and C. R. Menyuk, "Calculation of the Phase Noise at Comb-Line Frequencies in a Frequency Comb", *Frontiers in Optics + Laser Science 2021*, JTh5A.122, 2021.

[5] I. M. Anjum, E. Simsek, S. E. Jamali Mahabadi, T. F. Carruthers and C. R. Menyuk, "Dual-Objective Numerical Optimization of MUTC Photodetectors for Frequency Comb Applications", *2023 IEEE Research and Applications of Photonics in Defense Conference (RAPID)*, 1-2, 2023.

[6] 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*, 46, 626-632, 2010.

[7] J. Zang, X. Xie, Q. Yu, Z. Yang, A. Beling, and J. C. Campbell, "Reduction of Amplitude-to-Phase Conversion in Charge-Compensated Modified Unitraveling Carrier Photodiodes," *J. Lightw. Technol.* 36, 5218-5223, 2018.