Calculation of the Phase Noise at Comb-Line Frequencies in a Frequency Comb

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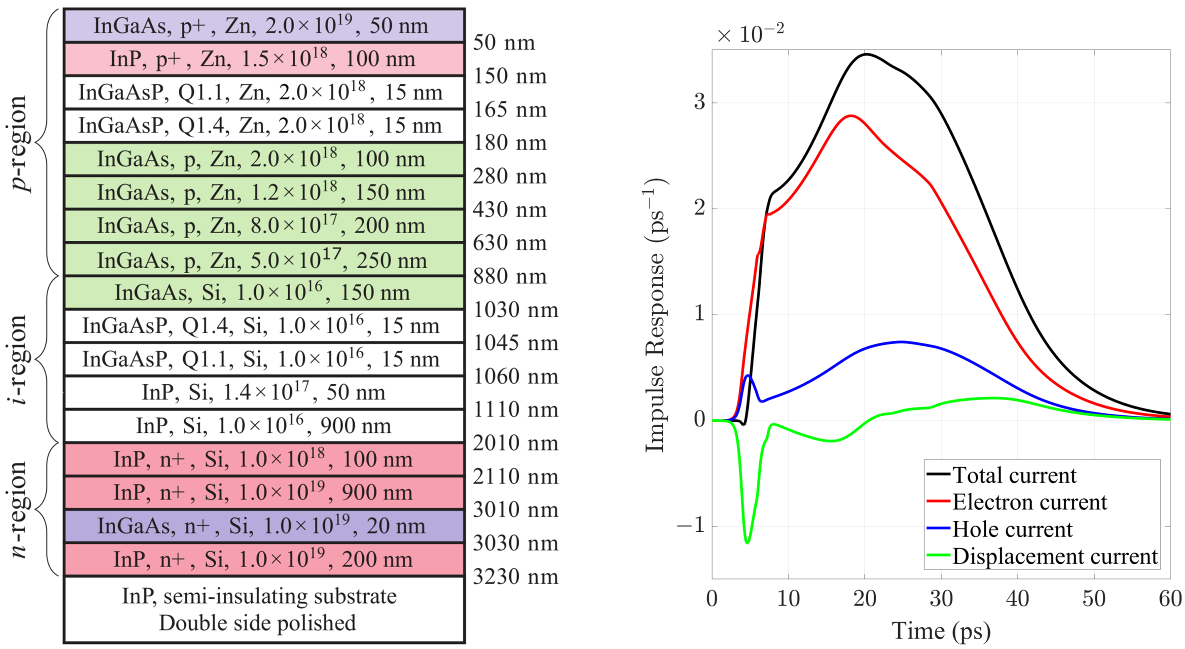
Abstract: We calculate the phase noise in a modified uni-traveling carrier photodetector for frequency comb applications. In contrast to a continuous wave, a frequency comb is characterized by a distinct phase noise for each comb line.

1. Introduction

Phase noise in photodetectors limits applications to RF-photonics, time and frequency metrology and photonic low-phase-noise microwave generation [1–3]. It is possible to calculate the phase noise using Monte Carlo simulations, but this approach is computationally time-consuming [4, 5]. Jamali et. al. [5] calculated the phase noise of high current photodetectors by calculating the impulse response using the drift-diffusion equations, and taking advantage of the fact that the distribution of electrons in any time slot is Poisonnian. This approach simplifies the calculation and the physical interpretation of the results, while also greatly reducing the computation time. In this work we extend the work of [5] to calculate the phase noise at the first 100 comb-line frequencies in the same modified uni-traveling carrier (MUTC) photodetector that was studied by Jamali et al. [5] and was first designed and studied by Li et al. [6]. We use the one-dimensional (1-D) computational model that was developed by Hu et. al. [7] and is based on the drift-diffusion equations to calculate the impulse response. We then used the approach described in [5] to calculate the phase noise. The model includes thermionic emission, the Franz-Keldysh effect, impact ionization, and recombination. We included thermionic emission of both electrons and holes [8] in this model, whereas the previous model [5] only included thermionic emission of electrons.



(a) (b)

Fig. 1. (a) Structure of the MUTC photodetector. (b) Normalized impulse response of the photodetector.

2. MUTC Photodetector

In Fig.1, we show the structure of the MUTC photodetector that we are modeling [4, 6, 7] and the normalized impulse response of the photodetector. The output current is 15 mA; the bias voltage is 21 V; the device length is 3230 nm; the device diameter is 50 μm; the pulse-width is 1 ps; the repetition frequency is 2 GHz.

3. Phase Noise

We use the equation [5]

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

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 centroid time. In Fig. 2(a) we show the phase noise at the comb lines in the frequency range of 2 GHz to 200 GHz. The calculated phase noise at 10 GHz is in good agreement with the experimental result [9]. We see that the phase noise increases up-to the comb-line frequency of 36 GHz, after which the phase noise decreases before increasing again. The initial increase in the phase noise is due to the decrease in the magnitude of the frequency components as the comb-line frequency and number increases and the decrease in the phase noise beyond 38 GHz is due to an increase in the magnitude of the frequency components that begin at 38 GHz before decreasing again, as can be seen from the power spectrum in Fig. 2(b). The non-monotonic variation of the phase noise is a consequence of the complex carrier transport through the photodetector, which we will examine in detail.

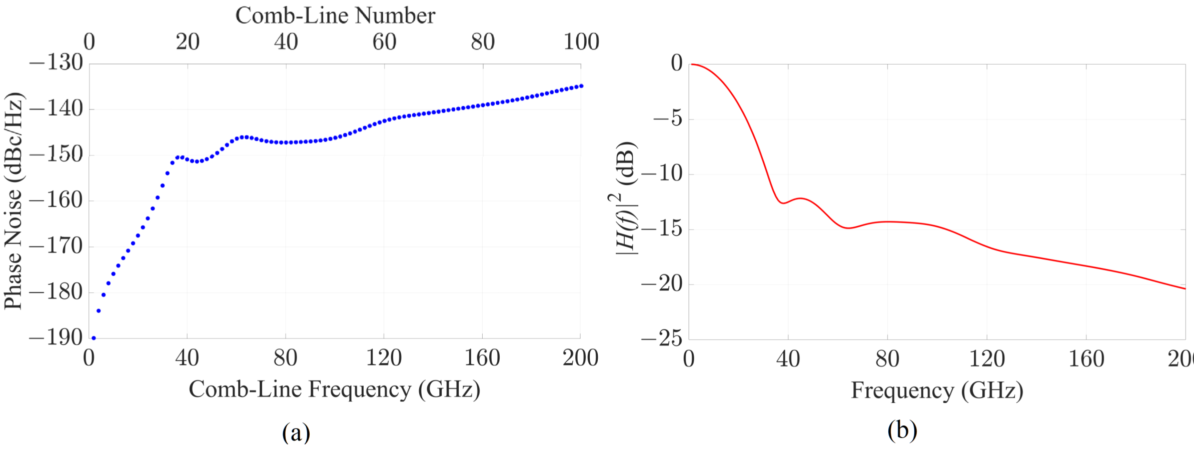


Fig. 2. (a) Phase noise vs. comb line frequency. (b) Power spectrum of the impulse response.

References

1. B. E. A. Saleh and M. C. Teich, *Fundamentals of Photonics* (Wiley, 1991).
2. V. J. Urick, K. J. Williams, and J. D. McKinney, *Fundamentals of Microwave Photonics* (Wiley, 2015).
3. F. Quinlan, T. M. Fortier, H. Jiang, and S. A. Diddams, "Analysis of shot noise in the detection of ultrashort optical pulses," J. Opt. Soc. Am. B **30**, 1775–1785 (2013).
4. 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).
5. S. E. J. 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).
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. Y. Hu, T. F. Carruthers, C. R. Menyuk, M. Hutchinson, V. J. Urick, and K. J. Williams, "Modeling nonlinearity in a modified uni-traveling-carrier (MUTC) photodetector," *IEEE Photonics Conference (IPC)* (IEEE, 2015), pp.122–123.
8. Nicolas Sommer, Jürgen Hüpkes, and Uwe Rau, "Field Emission at Grain Boundaries: Modeling the Conductivity in Highly Doped Polycrystalline Semiconductors," Phys. Rev. Applied **5**, 024009 (2016).
9. F. Quinlan, T. M. Fortier, H. Jiang, A. Hati, C. Nelson, Y. Fu, J. C. Campbell, and S. A. Diddams, "Exploiting shot noise correlations in the photodetection of ultrashort optical pulse trains," Nat. Photonics **7**, 290–293 (2013).