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Optimized MUTC Photodetector for Lower Phase Noise at Comb-Line Frequencies Below 40 GHz

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Abstract: We present an optimized structure of a modified uni-traveling carrier photodetector that has a faster impulse response and a lower phase noise at comb-line frequencies below 40 GHz. The highest improvement of phase noise is 9.5 dBc/Hz at 36 GHz comb-line frequency. © 2023 The Author(s)

1. Introduction

Modified uni-traveling carrier (MUTC) photodetectors have been widely used in RF-photonics, time and frequency metrology, and photonic low-phase-noise generation. Phase noise in MUTC photodetectors is a critical limiting factor [1]. Li et al. [2] designed and studied an MUTC photodetector that was later analyzed by Mahabadi et al. [3]. Recently we have extended the work of [3] by calculating the phase noise at the first 100 comb-line frequencies in this detector [4]. We found that the phase noise increases non-monotonically as a function of comb-line frequencies. We investigated the reason for the non-monotonic increase of the phase noise and found that the electric field at the boundary of the two InP layers in the intrinsic region becomes negative due to the electric field created by the photogenerated electrons and holes as the pulse propagates through the photodetector. As a result, the electron drift current becomes negative and gives rise to peaks in the impulse response. Due to the negative drift current, it also takes longer for the electrons to be swept across the photodetector and hence causes a long tail in the impulse response. It is possible to decrease the reversal of the electric field at the layer boundary by "pre-emphasizing" the electric field at the layer boundaries, which may be done by controlling the doping concentration of the layers. As a result, the electron drift current does not become negative, the tail of the impulse response shortens, and the phase noise decreases. Based on this insight, we designed an MUTC photodetector structure that has a shorter tail in the impulse response and lower phase noise below 40 GHz. In this work, we present the modified structure of the MUTC photodetector and the calculated phase noise as a function of the comb-line frequency. We used the 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.

Table 1. Material and doping types, doping densities, and layer thicknesses for the proposed design

Layer No	Material and Doping Type	Doping Density (cm^{-3})	Thickness (nm)	Layer No	Material and Doping Type	Doping Density (cm^{-3})	Thickness (nm)
1	InGaAs, p^+, Zn	2.0×10^{19}	50	10	InGaAsP, Q1.4, n, Si	1.0×10^{16}	15
2	InP, p , Zn	1.5×10^{18}	100	11	InGaAsP, Q1.1, n, Si	$\mathbf{2.0}\times10^{16}$	15
3	InGaAsP, Q1.1, p, Zn	2.0×10^{18}	15	12	InP, n, Si	$\mathbf{3.0}\times10^{16}$	50
4	InGaAsP, Q1.4, p, Zn	2.0×10^{18}	15	13	InP, n, Si	$\mathbf{4.0}\times10^{16}$	900
5	InGaAs, p, Zn	2.0×10^{18}	100	14	InP, n^+, Si	1.0×10^{18}	100
6	InGaAs, p, Zn	1.2×10^{18}	150	15	InP, n^+, Si	1.0×10^{19}	900
7	InGaAs, p, Zn	8.0×10^{17}	200	16	InGaAs, n^+, Si	1.0×10^{19}	20
8	InGaAs, p, Zn	5.0×10^{17}	250	17	InP, n^+, Si	1.0×10^{19}	200
9	InGaAs, n, Si	1.0×10^{16}	150		InP (Substrate)		

2. Modified MUTC Structure

In Table 1, we list the doping densities and the thicknesses of the modified MUTC photodetector. The doping densities in three of five layers in the intrinsic region have been modified. In Table 1, we have boldened the doping densities of the modified layers. In Figs. 1(a) and 1(b) we show the calculated normalized impulse responses of the photocurrent components, as well as the total normalized impulse response of the original and modified structure, respectively. In this study, 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.

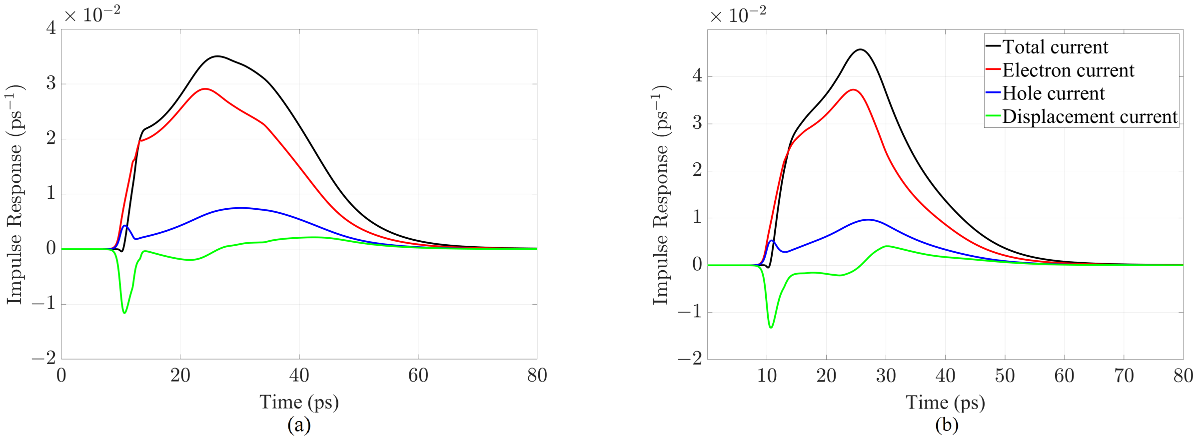

Fig. 1. (a) Normalized impulse response of the original MUTC photodetector and (b) of the modified MUTC photodetector.

3. Phase Noise

We use the equation [3]

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

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 central time of the output current. In Fig. 2(a) we show the phase noise at the comb lines in the frequency range of 2 GHz to 40 GHz and in Fig. 2(b) we show the phase noise difference between the modified and original MUTC photodetectors. In addition to the decrease of phase noise, the time response of the total photocurrent of the modified MUTC photodetector is approximately 28% narrower than that of the original MUTC photodetector.

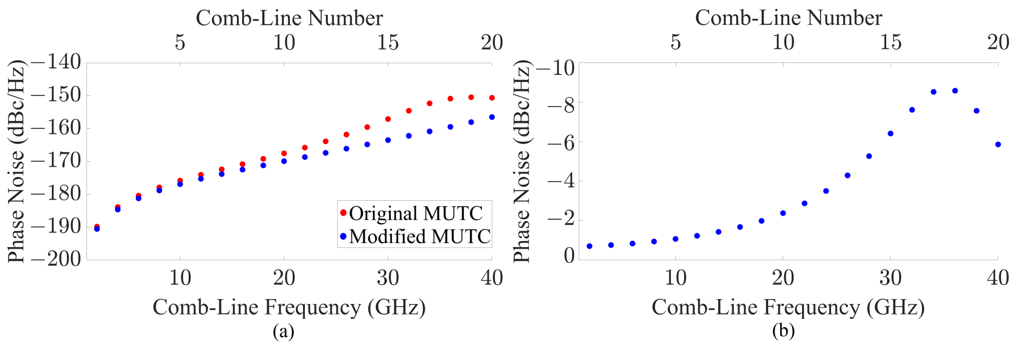

Fig. 2. (a) Phase noise vs. comb line frequency of the original and modified MUTC photodetectors. (b) Phase noise reduction between the modified and the original MUTC photodetectors.

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