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Nonlinearity and Phase Noise in High-Current Photodetectors

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Abstract: Great progress has been made in the past decade in developing high-current photodetectors, but the modeling of these devices has not kept pace. The status of the devices and the models is reviewed.

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1. Introduction

In traditional RF-photonic systems, the photodetector appears at the end of the optical link [1]. Example applications include the transfer of broadband radar data in a phased array radar system, phased-array antenna systems, and microwave filters. For these applications, the key requirement is for the photodetector's output current to linearly track the input optical power over a large dynamic range [2].

In the last fifteen years, oscillator systems have appeared in which the photodetector appears as an element in a feedback loop. These are the optoelectronic oscillator [3] and the carrier-envelope phase-locked (CEPL) laser [4]. In these systems, linearity is not as important. In the case of the optoelectronic oscillator, extra harmonics of the fundamental radio frequency (RF) tone are filtered out in an RF amplifier. In the case of the CEPL laser, optical pulses that are on the order of 100 fs are converted into RF current pulses that are around 50 ps long [5,6]. However, the phase noise that is produced by the photodetector is a critical limit to system performance. In the case of the optoelectronic oscillators, the principal noise sources that impact the performance are the traditional white noise sources — shot noise, dark current, and Johnson noise. Additionally, flicker noise ($1/f$ noise) that is upconverted from baseband also plays an important role [7]. In the case of CEPL lasers, amplitude noise is converted to phase noise [5,6]. Large amplitude noise in the optical domain translates into large phase noise in the RF domain.

2. Figures of merit and their relationship to the physical sources of impairment

The figures of merit change, depending upon the application.

For traditional point-to-point applications with the photodetector at the back end of the system, the slope of the 1-dB compression point, the threshold voltage, and the linear figure of merit are the key performance metrics [2]. Physical sources of the nonlinearity include space-charge effects, series impedance, thermal effects, and non-uniform illumination of the photodetector surface [2]. While these effects are understood qualitatively, quantitative design tools that can predict the figures of merit from a given design are lacking. As a consequence, minimizing these effects is a matter of trial and error.

The key figures of merit for photodetectors in optoelectronic oscillators and CEPL lasers are the power spectrum of the phase noise, including both the white noise and flicker noise contributions, and the power-to-phase conversion ratio. The former is more important in optoelectronic oscillators [7], while the latter is more important in CEPL lasers [5,6]. While the impact of these processes on device performance is understood and have impacted the design of the detection systems [6], quantitative design tools are lacking.

The situation can be contrasted with that of RF amplifiers, whose noise has long been a critical factor in limiting the performance of microwave oscillators. The development of quantitative models has played an important role in finding the sources of flicker noise in these amplifiers and reducing their impact [8]. In the transistors that are at the heart of the RF amplifiers, the Hooge parameter, which is often used to characterize the flicker noise, has dropped by three orders of magnitude in over the past two decades [9].

3. Status of computational modeling and model requirements

In the mid-1990s, Williams, et al. [10,11] developed a one-dimensional model of high-current photodetectors, based on the drift-diffusion equations, which served to greatly elucidate the space-charge effects in these devices. Since that time, this model has been improved in several ways. Improvements include taking into account the barrier heights at the material interfaces [12], taking into account the external circuit [12], and taking into account the change in the refractive index [13]. However, computational models that are capable of predicting the figures-of-merit for high-current photodetectors have yet to be demonstrated.

There are some features that a quantitatively accurate model that can predict the figures of merit would almost certainly have to include: (1) Two-dimensional modeling: Non-uniform illumination has a profound effect on the linearity and that can only be studied in two dimensions. (2) A realistic model of potential barriers and charged particle trapping — particularly at the current leads: Understanding these process was critical in reducing the flicker noise in RF amplifiers. (3) Noise sources, including the flicker noise sources. (4) Thermal modeling.

4. Conclusions

In conclusion, there has been great progress in developing high-current photodetectors for different applications. However, the computational models for designing these devices have not kept pace with these developments. Modern high-speed computers puts the development of quantitatively useful design models within reach, and the importance of high-current photodetectors makes the development of these models important.

4. References

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