Impact of Nonlinearity in an MUTC Photodetector on an RF-Modulated Frequency Comb

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***Abstract*—We calculate the impact of nonlinearity in an MUTC photodetector on an RF-modulated frequency comb, taking into account bleaching (gain saturation). An RF-modulated frequency comb is characterized by a distinct IMD2$_n$ and IMD3$_n$ and hence a distinct OIP2$_n$ and OIP3$_n$ for each comb line n.**

Frequency combs can play an important role in RF-photonic systems. They provide the lowest close-in RF phase noise of any systems to date [1]. Thay can be used to increase the Brillouin threshold for transmission through optical fibers [2] and to disambiguate radar signals [3]. These combs are generated in the optical domain by creating a stream of short pulses, using for example a short pulse laser [4] or a continuous wave laser followed by an electro-optic modulator [5]. These pulses may then be modulated by an RF signal. When the signal passes through a photodetector, an RF comb is produced in which the original RF modulation appears as sidebands around each comb line. The pulses in a typical optical pulse train have durations less than 500 fs and are spaced by 10–50 ns. Hence, the peak-to-average power ratio is 10^4–10^5.

A consequence of the large peak-to-average power ratio is that the detection can be impaired by bleaching (nonlinear saturation) in the photodetectors [1]. Bleaching leads to a reduction in the photodetector responsivity as the peak power increases and can lead to nonlinear distortion. Juodawlkis $et\ al.$ [6] have reported that this effect can limit the performance of photonic analog-to-digital converters (PADCs). In RF-photonic systems, nonlinearity induces second- and third-order intermodulation distortion (IMD2 and IMD3) [7]. The intermodulation distortion is characterized using the second- and third-order intercept points (OIP2 and OIP3). When the optical source is continuous wave (CW) and is modulated by an RF signal, one set of intermodulation products is induced. The impact of nonlinearity is more complex when working with frequency combs since every electrical comb line is impacted by the nonlinearity in a different way, so that there is an IMD2$_n$ and IMD3$_n$ for $each$ comb line n and hence a different OIP2$_n$ and OIP3$_n$ for each comb line n.

In this work, we use the drift-diffusion equations to study the impact of device nonlinearity in a modified uni-traveling carrier (MUTC) photodetector on an RF-modulated frequency comb. The comb is generated by optical pulses with a duration of 100 fs, a repetition rate of 50 MHz, and an average power that varies between 0.1 and 100 mW. The RF-modulated frequencies are all close to 10 MHz. We have modified a model that we previously used [8] to study an MUTC photodetector [9] to include an empirical model of the bleaching-induced reduction in the device responsivity at high peak powers. This model is based on data that was collected at the Naval Research Laboratory. The responsivity $\Re$ is the ratio of the output current I_{out} to the input optical power P_{opt}, $\Re = I_{\mathrm{out}}/P_{\mathrm{opt}}$ [10]. The optical generation rate in the drift-diffusion equations is given by

$$G_{\mathrm{opt}} = A\ G_c\ \exp\left[-\alpha(L-x)\right], \qquad (1)$$

where A is the bleaching coefficient as a function of average input optical power that we calculated, G_{opt} is the optical generation rate, G_c is the generation rate coefficient when bleaching is absent, α is the absorption coefficient, x is distance across the device, and L is the device length.

In the experiments, a Calmar Mendecino passively-modelocked erbium doped fiber laser was used. The output of the laser was a pulse train with 100 fs pulse-width and 50 MHz repetition rate. The average optical power and average photocurrent were measured as an optical attenuator was adjusted. Knowing the repetition rate, the optical power was then converted to pulse energy to calculate the responsivity. Figure 1 shows the responsivity and compares our empirical model to the experimental results. Agreement is well within the experimental uncertainty.

When considering nonlinearity in photodetectors, IMD3 is particularly significant, since the frequencies that it generates can be close to the fundamental modulation frequencies [11]. Figures 2 and 3 show the fundamental RF output power, IMD2 at $F_1{+}F_2$, and IMD3 at $F_1{+}F_2{-}F_3$, powers as functions of the average input optical power for the $n = 20$ comb line at 1 GHz and $n = 200$ comb line at 10 GHz, respectively.

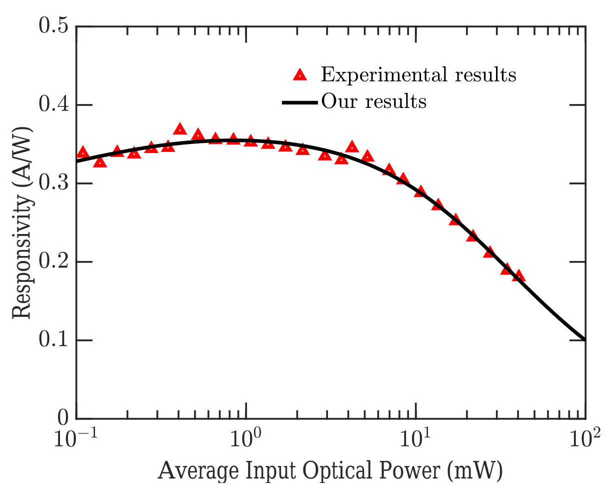

Fig. 1. Responsivity as a function of average input optical power for the MUTC photodetector.

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The input modulation frequencies are $F_1 = 10.0$ MHz, $F_2 = 10.5$ MHz, and $F_3 = 9.0$ MHz. In Figs. 2 and 3 the dotted curves show the RF output powers when the bleaching effect is not included and solid curves show the RF output powers when the bleaching effect is included. As expected for higher average input optical powers, the fundamental RF output power is lower when bleaching is included than when it is not. For lower comb line numbers ($n \lesssim 50$) IMD2$_n$ and IMD3$_n$ are larger when bleaching is included, but for higher comb line numbers IMD2$_n$ and IMD3$_n$ are larger when bleaching is not included. Figure 4 shows the OIP3 as a function of frequency at 25 mW average input optical power with and without bleaching. We find that OIP3$_n$ decreases both with and without bleaching, but the decrease is less dramatic when bleaching is taken into account because lower frequency comb lines are impacted more strongly.

In conclusion, we used the drift-diffusion equations to study the impact of nonlinearity in an MUTC photodetector on an RF-modulated frequency comb, taking into account the effect of bleaching. To account for bleaching, we included an empirical model of the bleaching-induced reduction of the optical generation rate, which we incorporated in the drift-diffusion equations. We then calculated IMD2$_n$, IMD3$_n$, OIP2$_n$, and OIP3$_n$ for each comb line n. Bleaching leads to a significant decrease in the output powers. However, the increase in the nonlinear distortion is less dramatic since the nonlinearly induced powers are also significantly reduced.

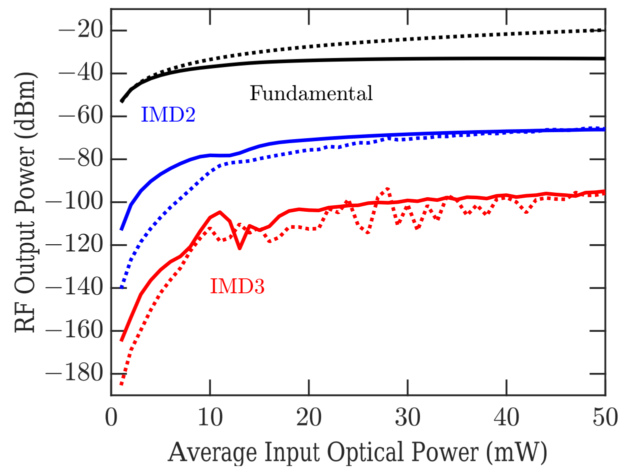

Fig. 2. Fundamental, IMD2$_n$, and IMD3$_n$ powers as a function of average input optical power for the $n = 20$ comb line at 1 GHz. The dotted curves show the RF output powers when the bleaching effect is not included and solid curves show the RF output powers when the bleaching effect is included.

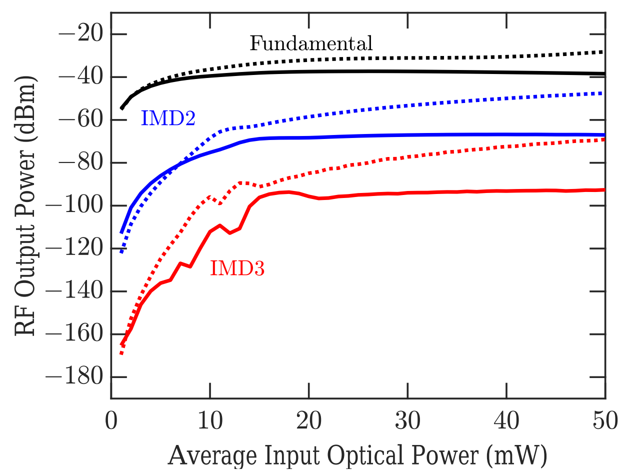

Fig. 3. Fundamental, IMD2$_n$, and IMD3$_n$ powers as a function of average input optical power for the $n = 200$ comb line at 10 GHz. The dotted curves show the RF output powers when the bleaching effect is not included and solid curves show the RF output powers when the bleaching effect is included.

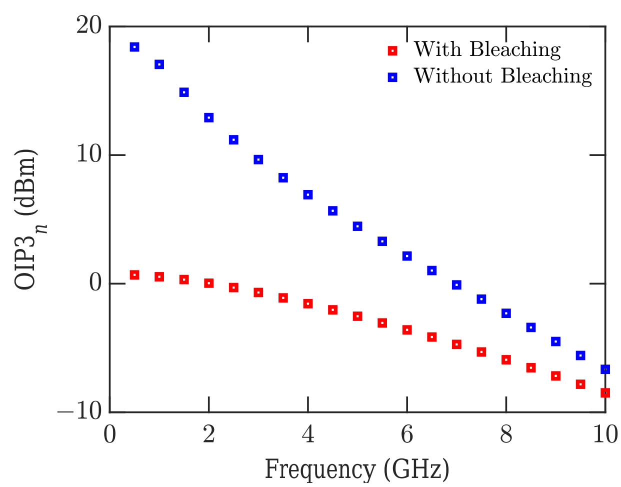

Fig. 4. OIP3$_n$ as a function of frequency for the MUTC photodetector at 25 mW average input optical power.

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