Impact on frequency combs of nonlinearity including bleaching in p-i-n photodetectors

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***Abstract*—We calculate the impact of nonlinearity in a p-i-n photodetector on an RF-modulated frequency comb taking into account bleaching due to the large peak-to-average power ratio in frequency combs. We characterized RF-modulated frequency combs by IMD2$_n$, IMD3$_n$, OIP2$_n$, and OIP3$_n$ for each comb line n.**

Bleaching or absorption saturation in a high-current photodetector can occur when intense optical fields deplete the number of available final energy states or depopulate the initial states [1]. Additionally, the high density of electrons that is created can increase the possibility that they are recaptured. Regardless of its origin, bleaching leads to a reduction in the photodetector's responsivity as the peak intensity and hence the average power increases. This reduction in responsivity can lead to nonlinear distortion of an incoming RF-photonic signal. Juodawlkis $et\ al.$ [2] have reported that this effect can limit the performance of photonic analog-to-digital converters.

Bleaching is an important issue in RF-photonic systems that use frequency combs. Examples include systems that use frequency combs to generate low-noise microwave signals [3] and systems that use frequency combs to disambiguate radar signals [4]. Frequency combs in the RF domain are generated by using a train of short, high-peak-power optical pulses that are converted into a comb in the RF domain by a photodetector. The pulses in a typical optical pulse train have durations less than 500 fs, and are separated by 10–50 ns, corresponding to a repetition rate of 20 MHz to 100 MHz. Hence, the peak power is larger than the average power by a factor of 10^4–10^5. In this work we use our empirical model of the bleaching [5] to calculate the impact of nonlinearity on an RF-modulated frequency comb in a p-i-n photodetector.

The p-i-n photodetector structure that we study [6] is a single heterojunction device made from InP and InGaAs. We modified the length of the intrinsic region from 0.95 μm in the original structure [6] to 0.75 μm in this study to match the responsivity of the structure in our simulations with experimental data that was collected at the Naval Research Laboratory. Figure 1 shows the responsivity as a function of average input optical power for the p-i-n photodetector for a pulsed input and compares the experimental results with our simulation results.

With a modulated continuous wave (CW) input, the device nonlinearity can be characterized using the second- and third-order intermodulation distortion powers (IMD2 and IMD3) and by the second- and third-order output intercept points (OIP2 and OIP3). When considering nonlinearity in photodetectors, IMD3 is particularly significant, since the frequencies that it generates can be close to the fundamental frequency. This simple characterization is no longer possible when working with frequency combs, since every electrical comb line is

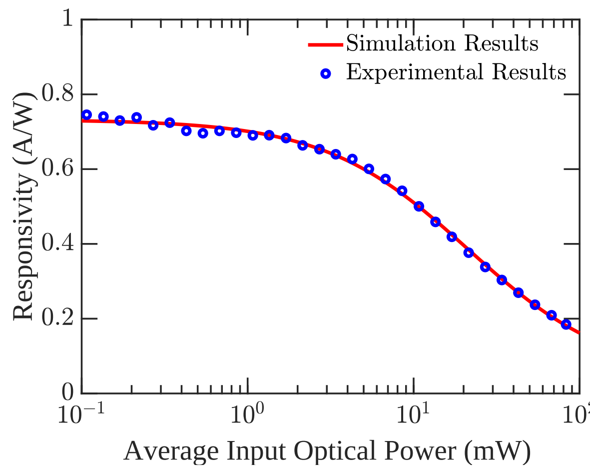

Fig. 1. Responsivity as a function of average input optical power for the p-i-n photodetector for a pulsed input.

impacted by the nonlinearity in a different way [5]. Instead, we define IMD2$_n$, IMD3$_n$, OIP2$_n$, and OIP3$_n$ for *each* comb line n. We calculate the impact of bleaching on the device nonlinearity as a function of the average input optical power for a frequency comb with an input frequency of $f_r = 50$ MHz and a FWHM pulse duration of 100 fs. We used the three-tone modulation technique [7] with modulation frequencies $f_1 = 10$ MHz, $f_2 = 10.5$ MHz, and $f_3 = 9$ MHz to calculate the IMD2$_n$, IMD3$_n$ powers in the pulsed mode for modulation depth m = 4%.

Figures 2(a) and 2(b) show the fundamental power S_{in}, as well as the corresponding IMD2$_n$ power at the modulated frequency $nf_r + f_1 + f_2$ and the corresponding IMD3$_n$ power at the modulated frequency $nf_r + f_1 + f_2 - f_3$. These figures show $n = 10$ ($nf_r = 0.5$ GHz) and $n = 500$ ($nf_r = 25$ GHz). In Fig. 2, the dotted curves show the harmonic powers when bleaching is not included and solid curves show the harmonic powers when bleaching 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. The reason is that bleaching reduces responsivity as the average input optical power increases [5]. For lower comb line numbers ($n \lesssim 100$) 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. The fluctuations in IMD3$_n$ when bleaching is not included are due to the Franz–Keldysh effect [8].

Figures 3(a) and 3(b) show the OIP3$_n$ and IMD3$_n/S_{in}$ ratio as a function of both frequency $f = nf_r$ and n at 25 mW average input optical power both with and without bleaching. In Fig. 3(a) intercept points occur at a lower power when bleaching is included than when it is not. The gap is larger for low comb line numbers. The intercept point decreases both with and without bleaching when n increases, but this decrease is noticeably slower when bleaching is included so that the intercepts converge when n is large. The trend and the rate of decrease is defined by the impulse response of the photodetector in frequency domain. Figure 3(b) shows the ratio of the IMD3$_n$ power to the fundamental power S_{in} as a function of frequency with and without bleaching. As can be seen from the figure the ratio and hence the fraction of each comb line power in IMD3$_n$ increases as comb line number increases, which is not favorable since the frequency that IMD3$_n$ generates can be close to the fundamental frequency S_{in}. The OIP2$_n$ and IMD2$_n/S_{in}$ exhibit similar trends.

We have studied the impact on frequency combs of nonlinearity including bleaching in a p-i-n photodetector. We found that the impact of bleaching is to reduce not only the the fundamental power S_{in} but also the nonlinear distortion products as the average input optical power increases. The effect is bigger at low frequencies. We show that as the frequency increases the ratio of nonlinear distortion products to fundamental power S_{in} increases, but the rate of increase is lower with bleaching. This result implies that bleaching in the p-i-n photodetector introduces more nonlinearity into the RF-photonic systems and the impact is more severe at low frequencies.

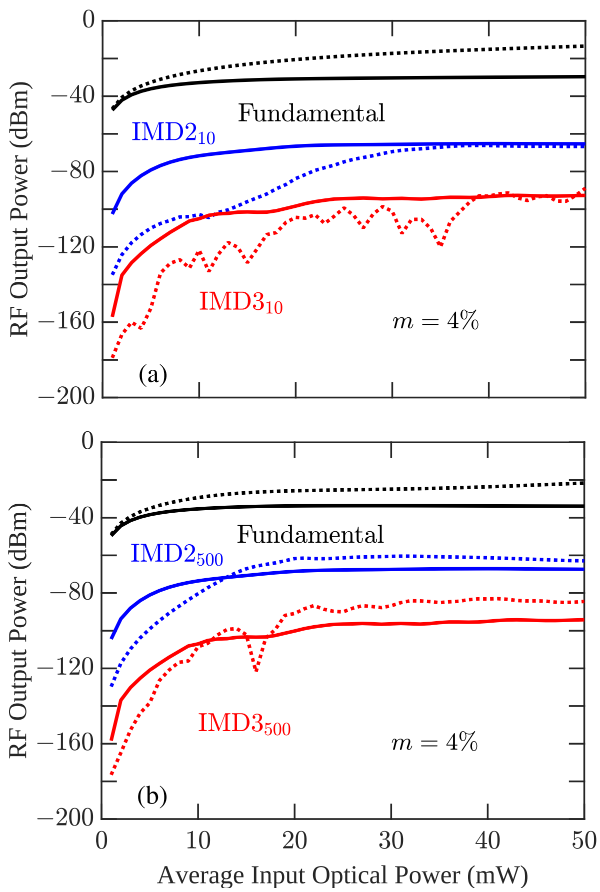

Fig. 2. Power at the fundamental frequency (nf_r), the IMD2$_n$ power at the modulated frequency $nf_r + f_1 + f_2$, and the IMD3$_n$ power at the modulated frequency $nf_r + f_1 + f_2 - f_3$. Solid lines show results with bleaching; dotted lines show results without bleaching with $m = 4\%$: (a) $n = 10$ ($nf_r = 0.5$ GHz), (b) $n = 500$ ($nf_r = 25$ GHz).

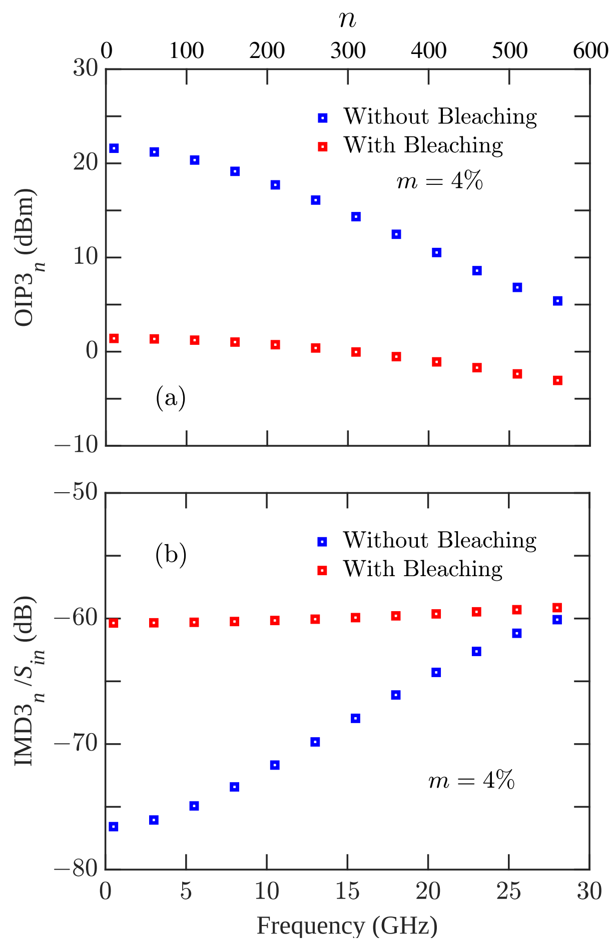

Fig. 3. OIP3$_n$ and IMD3$_n/S_{in}$ as a function of frequency and the comb line number n for the p-i-n photodetector at 25 mW average input optical power for a modulation depth $m = 4\%$. (a) OIP3$_n$. (b) IMD3$_n/S_{in}$.

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