Highly Linear, High Power Handling Photodiode for RF Photonic Links

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Abstract *We report a highly linear, high power handling InGaAs photodiode having a third order harmonic output intercept point of +53.7 dBm and an estimated OIP3 of +48.9 dBm up to 40 mA DC photocurrent.*

Introduction

Typical RF photonic links operating at optical power levels of ~10 dBm utilize low-noise microwave amplifiers to combat the insertion loss of the intrinsic photonic link (no pre-amplifier for modulator or post-amplifier for photodiode). These amplifiers introduce non-linear distortions in the RF signal, thereby limiting the spurious free dynamic range (SFDR) of the link[1]. Such amplifiers can be circumvented by utilizing photodiodes that demonstrate highly linear operation at optical power levels significantly exceeding 10 dBm. Operating the photodiodes at a high optical power level, and therefore large DC photocurrent, has an added benefit of reducing the noise figure (NF) of the link[1]. Recently, we established the utility of high power photodiodes for pulsed operation through experimental comparison with a similar photodiode coupled to a transimpedance RF amplifier[2]. In this work, we focus on photodiode's linearity in continuous wave (CW) operation, characterized by its third order output intercept point (OIP3).

We have recently demonstrated a top-illuminated InGaAs p-i-n photodiode having an OIP3 of 49.2 dBm up to 16 mA DC photocurrent[3]. We demonstrated an 8 dB improvement in OIP3 by achieving a nearly uniform optical intensity profile incident on the photodiode[3]. In this work, we apply the optical beam shaping technique to the partially depleted absorber[4] (PDA) top-illuminated photodiode structure and extend the highly linear operation (OIP3 = 48.9 dBm) up to 40 mA DC photocurrent. This photodiode has a 3 dB bandwidth of 3.2 GHz, and is suitable for ultra-high frequency (UHF) band applications such as cable TV distribution networks, RF-over-fiber links for cellular phones, and early warning phased array radars.

Device Description

The cross-section of the InGaAs PDA photodiode used for this work is shown in Fig. 1. The epitaxial growth was carried out in a metal-organic chemical vapour deposition (MOCVD) reactor on an n^+ doped InP substrate. Standard planar process was used to define the photodiode's 100 μm diameter active area. The photodiode structure contains a 1.5 μm thick $In_{0.53}Ga_{0.47}As$ absorption layer, of which the top 0.5 μm was p-doped to an acceptor concentration of ~$1x10^{18}$ through Zn diffusion. Similar PDA photodiode structures have previously demonstrated highly linear operation[4]. The photodiode was top-illuminated with

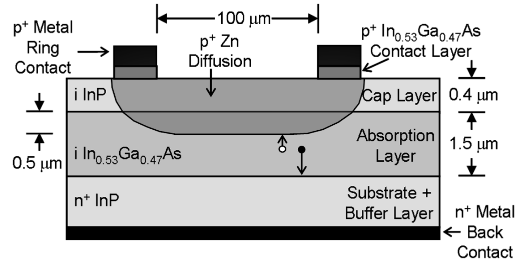

Fig. 1: Cross-section of the top-illuminated InP / $In_{0.53}Ga_{0.47}As$ photodiode's epitaxial structure.

an optical intensity profile having a peak-to-average intensity ratio of 1.4 in the active area. The photodiode was terminated to a 50 Ω load and hermetically sealed in a microwave package. This photodiode demonstrated a DC responsivity of 0.5 A/W and a 3 dB bandwidth of 3.2 GHz at 1550 nm wavelength.

Measurement Setup

The third order non-linearity of a photodiode can be characterized by stimulating the device with a two-tone RF modulated optical signal. The output RF power level at which the desired fundamental signal is equal to the extrapolated IMD is denoted as the OIP3. An alternative figure of merit is the output power level at which a single-tone fundamental signal power is equal to the extrapolated third order harmonic power, denoted as the third harmonic output intercept point (HOIP3). As has been previously explained, photodiode's HOIP3 exceeds OIP3 by 4.77 dB for memoryless device non-linearity[3].

The test setups for explicitly measuring the two-tone IMD are more complicated than single tone third harmonic test setup due to measurement system limitations. For example, the Agilent E4440A RF spectrum analyzer used in our measurement setup

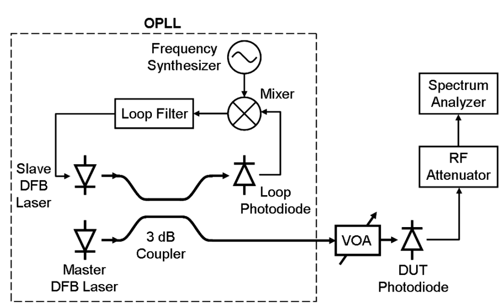

Fig. 2: Schematic of the optical phase locked loop based photodiode linearity measurement setup.

978-3-8007-3173-2

has an HOIP3 of >60 dBm from 500 MHz to 3 GHz, and -145 dBm noise floor at 1 Hz resolution bandwidth. In contrast, the same spectrum analyzer has an OIP3 of only 19dBm. Such practical concerns led us to estimate the photodiode's two-tone OIP3 from its measured single tone HOIP3.

The schematic of the photodiode linearity measurement setup is shown in Fig. 2. An optical signal with single-tone RF modulation with 63% modulation depth was generated by using two optically phase locked CW distributed feedback (DFB) lasers operating at 1550 nm wavelength. The outputs of the two lasers were combined in a polarization maintaining 3 dB optical coupler. The optical power from one of the coupler outputs was fed into a photodiode that drives the OPLL. The loop photodiode's output was down-converted to baseband by using a mixer and fed to a second order loop filter. The loop filter output tuned the frequency of the slave laser, thereby closing the feedback loop. The frequency offset between the two lasers was determined by a low-noise frequency synthesizer driving the mixer. This frequency offset was the single-tone modulation test frequency which was chosen to be 829 MHz.

The second output of the 3 dB coupler was fed to the device under test (DUT) through a variable optical attenuator (VOA). The fundamental and third harmonic RF signals generated by the DUT were measured using a RF spectrum analyzer (Agilent E4440A). The DUT was characterized at ambient room temperature without any active cooling. These measurements were taken using different RF attenuators (10 dB and 20 dB) to ensure that the third harmonic signal was not generated by the spectrum analyzer. The single-tone RF modulation generated by the OPLL had a resolution limited bandwidth of 1 Hz. The SNR at the fundamental frequency was 62 dB at 1 Hz resolution bandwidth[3].

Results and Discussion

The fundamental and third harmonic RF powers of the photodiode at 16 V bias are shown in Fig. 3. The extrapolated RF powers (solid lines in Fig. 3) intersect at an HOIP3 of +53.7 dBm, which corresponds to an OIP3 of +48.9 dBm. Such highly linear behavior is demonstrated at DC photocurrent as high as 40 mA, where the photodiode outputs +2.6 dBm fundamental RF power. Please note that at this operating condition, the device dissipates 640 mW (= 16 V x 40 mA) power without any active cooling. Such a high linearity and high power handling was achieved through a combination of the PDA photodiode structure[4], nearly uniform illumination profile through optical beam shaping[3], and use of n^+ doped InP conducting substrate for better heat management.

The implications of DC photocurrent on the performance metrics of RF link, namely link gain, NF,

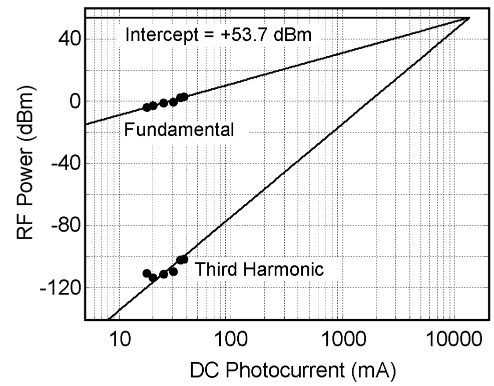

Fig. 3: The RF output power at the fundamental (829 MHz) and the third harmonic frequency (2487 MHz) as a function of DC photocurrent at 16 V bias.

and SFDR, have been explained previously[1]. Table 1 compares these performance metrics for an intrinsic externally modulated direct-detection link operating at DC photocurrents of 16 mA (representative of our previous effort[3]) and 40 mA. The external modulator is assumed to have a $V\pi$ = 3 V for these calculations, which is a reasonable number over 3.2 GHz bandwidth. Also, the laser relative intensity noise (RIN) is ignored in these calculations. Increasing the DC photocurrent leads to improvements in all the three performance metrics simultaneously. Please note that the 40 mA DC photocurrent leads to a link gain greater than unity, thereby obviating the need for a microwave amplifier.

Tab. 1: Performance of an intrinsic direct-detection link for a modulator $V\pi$ = 3 V

DC Photocurrent (mA)	Link Gain (dB)	NF (dB)	SFDR ($dB \cdot Hz^{2/3}$)
16	-7.5	19.7	115.3
40	0.4	15.7	117.1
Improvement	**7.9**	**4**	**2.9**

Conclusions

We have demonstrated an InGaAs photodiode having a third order harmonic output intercept point of +53.7 dBm and an estimated OIP3 of +48.9 dBm up to 40 mA DC photocurrent. This was achieved by applying an optimized optical illumination profile to the partially depleted absorber photodiode structure. A photonic link employing such a photodiode should demonstrate a link gain greater than unity, therefore not needing any microwave amplifiers.

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