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High-Linearity Modified Uni-Traveling Carrier Photodiodes

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Abstract: We report novel InGaAs/InP modified uni-traveling carrier photodiodes with record linearity. At low frequencies the third-order output intercept point (OIP3) is 55 dBm and remains as high as 47.5 dBm at 20 GHz.

OCIS codes: (040.5160) Photodetectors; (230.5170) Photodiodes

1. Introduction

Analog photonic links which employ optical fibers to transmit microwave signals have gained wide application in various fields such as phased array radar [1], radio-over-fiber [2], optical signal processing, frequency metrology, optical stability, ultrafast noninvasive measurements, and radio astronomy. High-performance analog photonic links with low loss and large spurious-free dynamic range over a wide frequency range are essential for those applications, and high-power high-linearity photodiodes are key enabling [3]. When two optical signals modulated at fundamental frequencies of f_1 and f_2 are injected into the photodiode, the output photocurrent will contain not only the fundamental frequencies of f_1 and f_2, but also their harmonics and intermodulations due to the nonlinear behavior of the photodiode. Reducing the harmonics and intermodulation distortions is essential to ensure large spurious-free dynamic range of the analog photonic links. Among all the harmonics and intermodulation products the third-order intermodulations (IMD3) at frequencies of $2f_1$-f_2 and $2f_2$-f_1 are of particular interest because they may be close to the fundamental frequencies and, thus, difficult to filter. The third-order output intercept point (OIP3) is the accepted figure of merit to evaluate the linearity of photodiodes. It is defined as $\mathrm{OIP3} = P_f + (P_f - P_{IMD3})/2$ dBm [3] where P_f is the signal power at the fundamental frequencies and P_{IMD3} is the third-order intermodulation power measured in dBm.

At low frequencies, photodiodes with high OIP3 have been reported. Beling et al. reported a charge-compensated modified uni-traveling carrier (CC-MUTC) photodiode with an OIP3 of 52 dBm at 320 MHz [4]. However, wide-band operation is a requirement for essentially all analog photonic and, unfortunately, the OIP3 of photodiodes usually deteriorates significantly with increasing frequency [5]. The OIP3 of the CC-MUTC photodiode reported by Beling et al. decreased to only 36 dBm at 20 GHz [4]. Recently, an InGaAs/InP partially depleted absorber photodiode with a highly-doped absorber (HD-PDA) was demonstrated to have an OIP3 of 39 dBm at 20 GHz [6]. In this paper, we report an InGaAs/InP MUTC photodiode with a highly doped p-type absorber, which will be referred to in the following as an HD-MUTC photodiode. The OIP3 of this device exhibits significantly reduced frequency dependence. At low frequencies (< 1 GHz) the OIP3 is 55 dBm and it remains as high as 47.5 dBm up to 20 GHz. In comparison the highest OIP3 previously reported is 39 dBm in this frequency range. [6]. The high OIP3 at 20 GHz is due to the highly doped absorber of the HD-MUTC photodiode, which reduces the voltage and photocurrent dependences of the junction capacitance.

2. Device Design and Three-Tone Measurements

The vertical layer structure of the HD-MUTC photodiode is shown in Fig. 1. The epitaxial layers were grown on a semi-insulating InP substrate by molecular bean epitaxy. The InGaAs absorbing region with a thickness of 950 nm is comprised of a 650 nm p^+ absorbing region and a 300 nm unintentionally-doped absorber layer. In order to form an abrupt junction doping profile, which has been proved to improve the OIP3 of photodiodes especially at high frequencies [6], C was used instead of Zn as the dopant in the 650 nm p^+ absorbing layer. The p-type doping level was graded in 10 steps from $8\cdot10^{19}$ to $5\cdot10^{18}$ cm^{-3} so as to assist electron transport in the doped absorber. A 24 nm-thick InGaAs/InAlAs chirped superlattice and a 5 nm moderately n-type doped InP cliff layer were incorporated between the InGaAs and InP to reduce carrier pile up at the heterojunction interface. The background doping level in the unintentionally-doped absorbing layer was below $5\cdot10^{15}$ cm^{-3}. Back-illuminated mesa structures were fabricated by inductive coupled plasma reactive ion etching. Microwave contact pads and an air-bridge connection to the top p-contact layer were fabricated for high-speed measurements. Finally a 220 nm SiO_2 anti-reflection layer was deposited on the back of the wafer. The devices were mounted on an Al heat sink for testing. In this paper HD-MUTC photodiodes with an active diameter of 40 μm are studied, which exhibited a 3 dB bandwidth of 13 GHz at -6 V and responsivity of 0.49 A/W at 1550 nm.

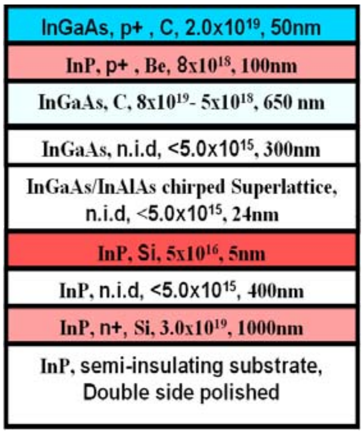

Figure 1. Schematic cross section of InGaAs/InP HD-MUTC photodiode.

The voltage-dependent capacitance C(V) and the photocurrent-dependent capacitance C(I) have been shown previously to be the limiting nonlinear mechanisms for the OIP3 at high frequencies [5]. The C(V) and C(I) curves of the HD-MUTC were measured and compared to those of the previously reported CC-MUTC photodiodes [5] as shown in Fig. 2. The measured capacitance is normalized into capacitance density, which is independent of the size of the photodiodes. Comparing with the CC-MUTC, whose p-type InGaAs absorber is doped with Zn, the capacitance of the HD-MUTC shows very weak dependence on reverse bias, and almost no dependence on photocurrent as the photocurrent increases up to 40 mA. This is due to the fact that the p-type InGaAs absorber of the HD-MUTC is heavily doped with C, which enables not only a very high doping level but also a very abrupt doping profile. Thus the voltage and photocurrent dependence of the capacitance of the HD-MUTC photodiodes are significantly reduced.

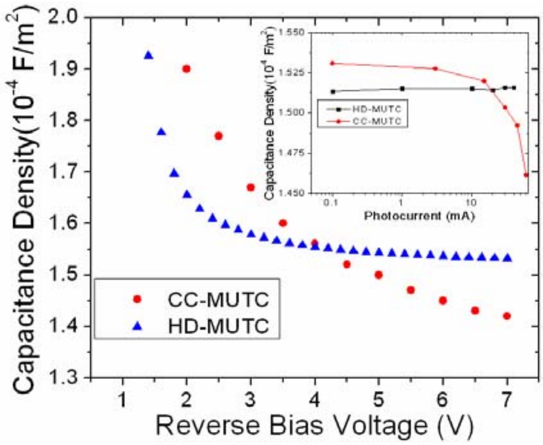

Figure 2 Capacitance density versus reverse bias for HD-MUTC and CC-MUTC. Inset: capacitance density versus photocurrent for HD-MUTC and CC-MUTC

Conventionally two-tone techniques are used to measure the OIP3 of photodiodes [4-6]. However, it has recently been suggested that the harmonics from the optical modulators may result in inaccuracies in the two-tone measurement results [7]. Hence, a three-tone setup, which is less sensitive to nonlinearities in the modulator response [8], was also utilized to provide more accurate measurements. For the three-tone measurement, the output power P_f at the fundamental frequencies f_1, f_2, f_3 and the power P_{IMD3} at the third-order intermodulations of $(f_1+f_2-f_3)$, $(f_2+f_3-f_1)$, $(f_3+f_1-f_2)$ were measured. If the three-tone OIP3 is defined analogously to the two-tone OIP3, then, following the approach in Ref. [9], a factor of 3dB should be added to the measured three-tone OIP3 in order to compare with the two-tone measurements.

The OIP3 of the HD-MUTC photodiode was measured versus photocurrent, and we observed that the OIP3 shows a peak at different photocurrent levels for different reverse bias conditions. The frequency dependences of the

OIP3 at different reverse bias were measured at their corresponding optimized photocurrent levels (30.5 mA for 7 V, 32.5 mA for 9 V and 33 mA for 10 V), and the results are shown in Fig. 3. At 10 V reverse bias, the OIP3 reaches 55 dBm at low frequencies and remains as high as 47.5 dBm at 20 GHz. The C(V) curve of the HD-MUTC photodiode was measured with a LRC meter and the C(V)-limited OIP3 curves were calculated using the equivalent circuit model reported in [5] at different reverse biases. The C(V)-limited OIP3 at 10 V and 7 V reverse bias are shown as the dashed and solid lines in Fig. 3, respectively. Since the derivative of capacitance on bias, i.e. dC(V)/dV, decreases with reverse bias, the C(V)-limited OIP3 calculated from the equivalent circuit model increases with reverse bias, which explains the fact that at 20 GHz the OIP3 increases monotonically with reverse bias. Thus increasing reverse bias is beneficial in improving the OIP3 of the photodiode especially at high frequencies.

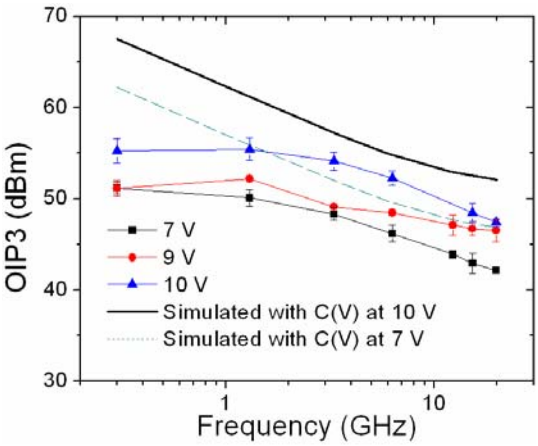

Figure 3. Frequency dependence of OIP3 at various reverse biases and their corresponding optimized photocurrents. Solid line: C(V)-limited OIP3 at 10 V; Dashed line: C(V)-limited OIP3 at 7 V.

3. Conclusions

In conclusion, a novel modified uni-traveling-carrier photodiode with highly doped absorbers is reported. The third-order intermodulation distortions of HD-MUTC photodiodes have been characterized using a three-tone setup. The OIP3 of the HD-MUTC photodiode reaches 55 dBm at low frequencies with only slight roll off with frequency; at 20 GHz the OIP3 remains as high as 47.5 dBm. In comparison the highest OIP3 previously reported at this frequency range was 39 dBm. The high OIP3 at 20 GHz was achieved by employing highly C-doped InGaAs absorption layers, which reduces the voltage and photocurrent dependence of the junction capacitance. Increasing reverse bias was shown to increase the OIP3 of the HD-MUTC photodiodes.

4. References

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