500 GHz Operational Bandwidth MUTC-Photodiodes with Milliwatt Terahertz Output Power Levels

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Abstract *We present waveguide-integrated 1.55 µm InP-based modified uni-travelling-carrier photodiodes (MUTC-PDs) featuring coplanar waveguide outputs. The fabricated photodiodes yield an operational bandwidth of 500 GHz and milliwatt output power levels in the lower THz domain.*

Introduction

The ever increasing demand in high efficiency telecommunication systems has brought new requirements to the development of devices for such systems. High speed photodiodes (PDs) are key components to achieve ultrafast and high capacity data transmission. Today, high-speed PDs are widely used in fiber-optic front-ends but also in analog optical millimeter-wave and terahertz (30 GHz - 10 THz) transmitters. To be employed in such practical applications, wide operational bandwidths, high saturation output power, and quantum efficiency of the PDs are critical figures of merit [1,2]. Especially the broadband and high output power capabilities of the PDs enable their use in THz communications for wireless transmission of high data rates of 100 Gbit/s and beyond [3].

Among various PD configurations, especially the uni-travelling carrier photodiodes (UTC-PD) are attractive, e.g. for future communications requiring high speed and high output power PD [4]. Its operation principle relies on high mobility electrons as active carriers while suppressing the hole transport, which in turn reduces the junction transit time and improves high frequency response [5]. By adding non-intentionally doped absorber layers in modified UTC-PD (MUTC-PD), further performance enhancement can be obtained, such as reduced carrier transition time and improved power saturation [6].

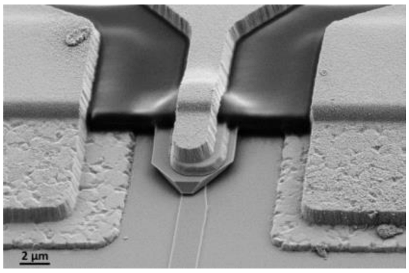

Fig. 1: SEM image of a fabricated waveguide MUTC-PD.

As waveguide PDs (WG-PDs) allow for the optimization of the absorber layer thickness regardless of the optical waveguide coupling, they typically exhibit higher responsivities than vertically illuminated PDs. In WG-PDs the optical field is evanescently coupled from the passive optical waveguide (POW) into the active region of the PD in order to obtain efficient photocurrent generation [7].

Tab. 1: State-of-the-art of THz power generation using single-device UTC-photodiodes.

Reference	Device Type	Coupling Type	Frequency (GHz)	Photocurrent (mA)	Output RF-Power (dBm)
[9]	UTC-PD	GSG probe	110	36	10
[6]	MUTC-PD	GSG probe	120	30	5.1
[8]	UTC-PD	GSG probe	120	25	12.3
[10]	TW-UTC-PD	GSG probe	200	23	0
[11]	RCE-UTC-PD	GSG probe	300	9.8	- 1.25
[12]	TW-UTC-PD	Antenna	457	10	- 8.3
[13]	UTC-PD	Antenna	500	10	- 17.7
This work	MUTC-PD	GSG probe	150	31	6.1
			320	30	- 4.6
			500	10	- 24.5

Table 1 shows the state-of-the-art of output RF-power generation at THz frequencies using single UTC-PDs. These previous studies reveal that at lower THz frequencies, high output powers have been extracted from UTC-PDs coupled with ground-signal-ground (GSG) probes [6,8-11]. Moving up to frequencies around 500 GHz, the devices have been integrated with planar antenna structures to achieve high output powers by avoiding limitations due to the impedance mismatch to coplanar waveguide (CPW) output at higher THz frequencies [12,13].

This work presents CPW-integrated MUTC-PDs achieving mW output power levels at lower terahertz frequencies. The fabricated MUTC-PDs furthermore exhibit a wide operational bandwidth of 500 GHz. To the best of our knowledge, this is the first report demonstrating on-chip output power measurements of a MUTC-PD up to 500 GHz.

Photodiode Fabrication

The epitaxial layers of the MUTC-photodiodes were grown by metal organic chemical vapor deposition (MOCVD). Details about the layer structure and fabrication process can be found in [14]. All MUTC-PDs are integrated with 50 Ω GSG CPWs output. Fig. 1 shows a scanning electron microscope (SEM) image of a fabricated device. For this work, MUTC-PDs with an absorber length of 30 µm and widths ranging from 4 to 6 µm were fabricated.

Broadband RF Power Measurements

The RF-response of the MUTC-PDs were characterized using an optical heterodyne set-up, dedicated GSG RF-probes and power detectors for the different frequency bands. As for the probes, a 100 µm pitch RF probe with 1 mm-connector for DC - 110 GHz was used. For 135 - 220 GHz, an infinity probe with a 100 µm pitch, internal bias-T, and WR-5.1 rectangular waveguide (WR) output was employed. For 220 - 330 GHz, a T-Wave type probe with 50 µm pitch and WR-3.4 output, and for 340 - 500 GHz, a infinity-type WR-2.2 probe with 50 µm pitch were used.

The optically generated RF power levels were measured using an RF-power meter (Rohde & Schwarz NRP-Z58) up to 110 GHz and a calorimeter (PM5B from Virginia Diodes) for the THz frequencies. A waveguide taper was used in front of the PM5B power-meter for the different WR-type probes, i.e., for the different frequency bands. Losses of these waveguide tapers were taken into account, as well as losses of the various probes.

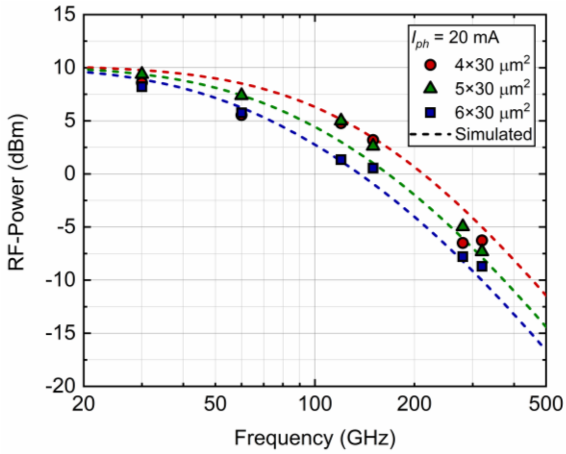

Fig. 2: Simulated and measured frequency response of photodiodes with different widths up to 320 GHz.

Broadband RF Characterization

Previously, we reported output power level for similar 30 µm long waveguide-integrated MUTC-PDs reaching -3.0 dBm at 280 GHz at a photocurrent level of 25 mA [15]. Here, in Fig. 2, we compare the frequency response of MUTC-PDs with different widths from 4 - 6 µm. To allow for comparison, the measured power level were adjusted for a photocurrent of 20 mA. As can be seen, there are deviations between the measured and simulated results, which are attributed to standing waves and under-etching effects of the active PD layers during the wet chemical etching process. We also found an effect of the probes as well as contact issues that have an increasing impact at frequencies beyond 120 GHz. According to measurements, the 5×30 µm² MUTC-PD exhibits the highest output power levels at lower frequencies up to 150 GHz whereas the 4×30 µm devices become superior at higher frequencies.

Fig. 3 demonstrates the saturation characteristics of the 5×30 µm² PD measured for

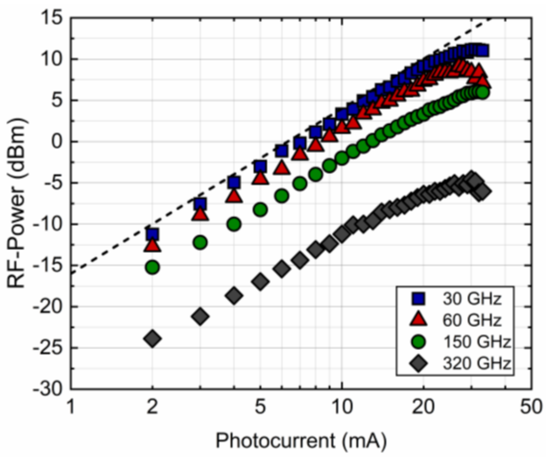

Fig. 3: Measured saturation characteristics of the 5×30 µm² MUTC-PD for varying frequencies at - 2.5 V for 30 GHz and 60 GHz, at - 2.3 V for 150 GHz, and at - 1.7 V for 320 GHz.

varying frequencies. The PD exhibited high saturation currents due to the optimized E-field management through the epilayers and the suppression of charge carrier screening for enhanced electron transition into the collector layer. The measured saturated output powers are 11.2 dBm, 9.1 dBm, 6.1 dBm, and - 4.6 dBm at 30 GHz, 60 GHz, 150 GHz, and 320 GHz, respectively.

The broadband capabilities of the CPW-integrated waveguide MUTC-PDs were characterized between 20 - 500 GHz. The measurements were carried out using a 6×30 µm² MUTC-PD with a responsivity of 0.2 A/W at a photocurrent level of 10 mA to prevent saturation effects and stay in the small signal regime for the PD. The measured broadband spectrum of the PD is demonstrated in Fig. 4.

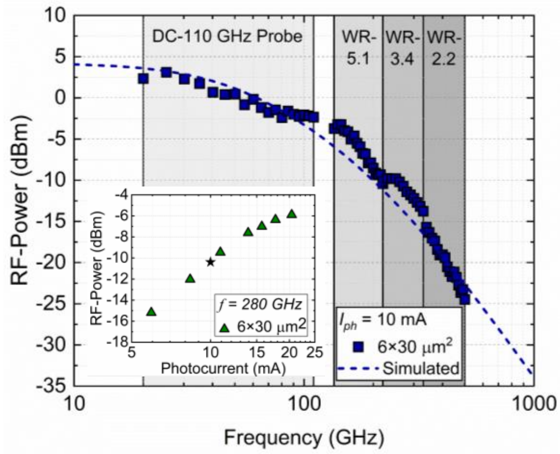

Fig. 4: Measured frequency response of the 6×30 µm² MUTC-PD at 10 mA and - 1.7 V up to 0.5 THz.
Inset: Measured saturation characteristics of the same PD at 280 GHz and - 1.7 V. The imaginary star marks the photocurrent level of the broadband measurements.

As can be seen, the measured data reveals a good agreement with the simulated broadband response with less than 3.5 dB deviation throughout the measured spectrum. The simulation includes the transit-time and RC-time constant limitations obtained from the previous work [14]. It should be highlighted that at high THz frequencies, the loading and contact effects from the probe become more significant. This results in deviations from model predictions, which assume a constant load of the PD over the frequency range. Despite these uncertainties and the impedance limitations of the CPW at THz frequencies, the PD exhibits ultra-broadband capabilities in a wide frequency range up to 500 GHz. Measurements beyond 500 GHz were not possible as the probe pitch goes down to 25 µm, which was not compatible with the device CPW. The power measurement at 500 GHz revealed an output power of - 24.5 dBm. Given that this output power was measured at 10 mA, i.e., well below the saturation current of the MUTC-PD, even higher output power could be achieved from this device.

Conclusions

We reported on high output power broadband 1.55 µm THz MUTC-PDs. Experimentally, the fabricated 30 µm long MUTC-PDs with widths between 4 - 6 µm were systematically characterized using an optical heterodyne set-up up to 500 GHz. Numerical and experimental data reveal that the narrower MUTC-PDs yield the highest output power levels. Typically, the saturation output power of the fabricated MUTC-PDs with an average responsivity of 0.2 A/W is reached at a photocurrent level of ~30 mA. The highest measured output power levels at 30 GHz, 60 GHz, 150 GHz, and 320 GHz are 11.2 dBm, 9.1 dBm, 6.1 dBm, and - 4.6 dBm, respectively. The output power level at 500 GHz is found to be - 24.5 dBm at 10 mA photocurrent, which is way below saturation, in order to ensure the small signal regime. The experimentally confirmed excellent linearity allows to estimate about 8 dB higher output power at 30 mA.

Thanks to their high output power, excellent linearity and broad operational band of 500 GHz, we expect these MUTC-PDs to be beneficial, especially for future THz wireless communications as well as spectroscopy and imaging systems.

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