Ultra-Fast Photodiodes for Terahertz Generation

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Abstract: Recent progress in the development of Continuous Wave Terahertz sources based on Ultra-Fast Photodetectors operating at 1.55 μm is reported. The Uni-Travelling Carrier Photodiode is realised as a broadband and high-efficiency photomixer while the frequency response advantage of employing a travelling wave design is demonstrated. State-of-the-art bandwidth-efficiency product from Coplanar Waveguide integrated devices was measured. Antenna-integrated devices achieved record levels of Continuous Wave generated power together with record Terahertz figure of merit (P_{THz}/P_{opt}^2 in W^{-1}).

1 Introduction.

The Terahertz part of the electromagnetic spectrum, located between microwaves and far-infrared, is of great significance for spectroscopic characterisation of numerous materials [1,2]. A plethora of applications has emerged recently that exploit the properties of Terahertz radiation [3]. Additionally, numerous applications can be found in communications technology [4,5], security [6], imaging [7], biology and medicine [8]. However, development of technology for this part of the electromagnetic spectrum has been limited due to the absence of compact sources that can operate efficiently at these frequencies. So far, most Terahertz systems are based on ultra-fast LT-GaAs photoconductive switches excited by femtosecond lasers operating at 0.8 μm. By optimising the device in conjunction with the fast response of the material, short pulses can be generated. However, existing Terahertz systems are usually bulky and expensive while the scanning speed is low. Compact frequency domain systems can be built with a low cost and a very high resolution [9]. InP-based continuous wave photomixing can provide broadband emission with the use of standard semiconductor tuneable lasers. For this purpose, the development of broadband, high-power photomixers is essential.

2. Travelling-Wave Uni-Travelling Carrier Photodiode (TW-UTC-PD).

Bandwidth limitations in standard p-i-n photodiodes are imposed by the carrier transit time as well as the load resistance and the intrinsic and parasitic capacitances. The Travelling-Wave Photodiode (TW-PD) [10] and the Uni-Travelling Carrier Photodiode (UTC-PD) [11] are two separate photodetection structures that have already been independently demonstrated, with improved performance compared to conventional p-i-n devices. In UTC-PDs (Figure 1a) absorption and carrier collection are separated allowing for a higher -3dB bandwidth. However, a vertically-illuminated UTC-PD is still RC-limited and a 40 dB/decade roll-off results in reduced levels of power at high frequencies.

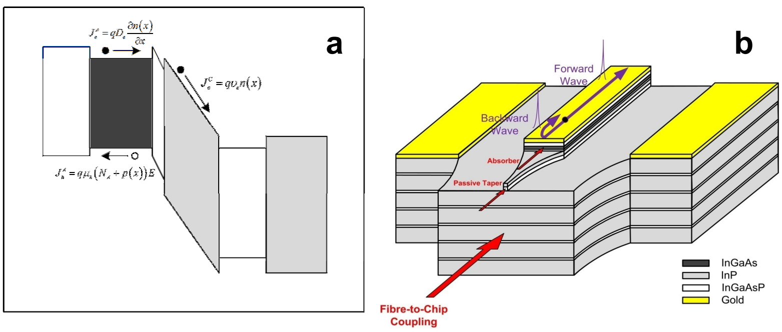

Figure 1: a) Band Structure of a Uni-Travelling Carrier Photodiode b) Travelling Wave Photodiode integrated with a taper waveguide for efficient fibre-to-chip coupling.

In addition, since the transit-time limited -3dB bandwidth depends on the absorber thickness, high speed operation requires a reduced thickness of the absorption layer, resulting in a low coupling efficiency. The Travelling-Wave configuration (Figure 1b) can allow for an improved roll-off together with a high coupling efficiency from an optical fibre. In this case, the mismatch between the optical and the electrical co-propagating waves is the critical parameter for improved performance. High frequency operation with a roll-off of 23 dB/decade has been demonstrated in GaAs-based photodiodes [10]. However, the coupling of the optical signal to a waveguide photodiode is challenging. In order to improve the fibre-to-chip coupling efficiency, the use of a secondary, non-absorbing, InGaAsP waveguide adjacent to the carrier collection layer is proposed. In order to depict the advantage arising from employing a travelling wave configuration, a vertically illuminated UTC-PD, a p-i-n TW-PD and a TW-UTC-PD with the same capacitance, series resistance and inductance were modelled (Figure 2).

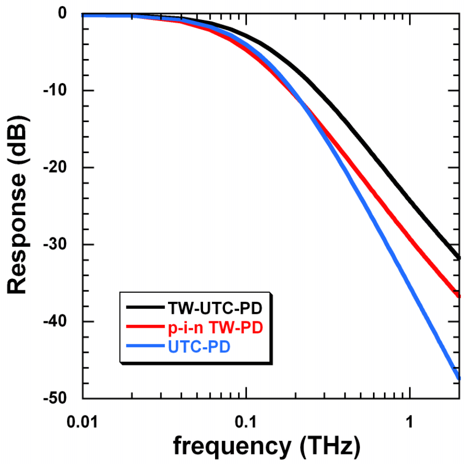

Figure 2: Modeled frequency response up to 2 THz on a 50 Ω load for a TW-UTC-PD (black) compared with p-i-n TW-PD (red) and a UTC-PD (blue).

An equivalent Transmission Line model was developed for both TW devices and a lumped circuit model for the vertically-illuminated device. According to the modelling results, the advantage was calculated to be >10 dB at 1 THz and >14 dB at 2 THz for the TW-UTC-PD. A comparison with a p-i-n TW-PD shows an advantage of >5 dB at the same frequencies. The combination of the UTC and the TW photodetection structures in a single device with a diluted taper waveguide is therefore expected to give significantly improved performance in terms of output power for a given optical input power compared with other types of photodiodes.

3. Experimental Results.

TW-UTC-PDs were fabricated with two different output configurations [12]. The first employed a Coplanar Waveguide output (Figure 3a) for assessment up to 110 GHz. The second type of devices employed different broadband (Figure 3b, 3c) and narrowband (Figure 3d) antennas for Terahertz generation.

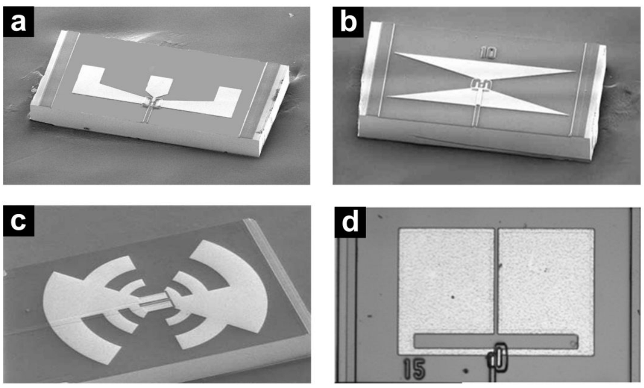

Figure 3: SEM pictures of the different TW-UTC-PDs fabricated with: a) coplanar probe contacts , b) Bow-Tie antennas, c) Log-Periodic antennas, d) resonant antennas.

With the first type of devices, measurements up to 110 GHz were performed. A -3dB electrical bandwidth of about 110 GHz was achieved together with a DC responsivity of up to 0.53 A/W (43% external quantum efficiency) resulting in a 47.3 GHz bandwidth efficiency product. For measurements above 110 GHz, photodiodes with integrated antennas were used and the Terahertz power was measured using a Thomas Keating Power Meter with accuracy of 5 μW which was operated within an homodyne chopping system at a frequency of 25 Hz in order to increase the Signal-to-Noise Ratio (SNR). A Bow-Tie antenna (Figure 3b) and a Log-Periodic (Figure 3c) antenna were designed for optimum operation from 250 GHz and 150 GHz respectively up to 1.5 THz limited by the feed. The resonant antenna was designed for operation

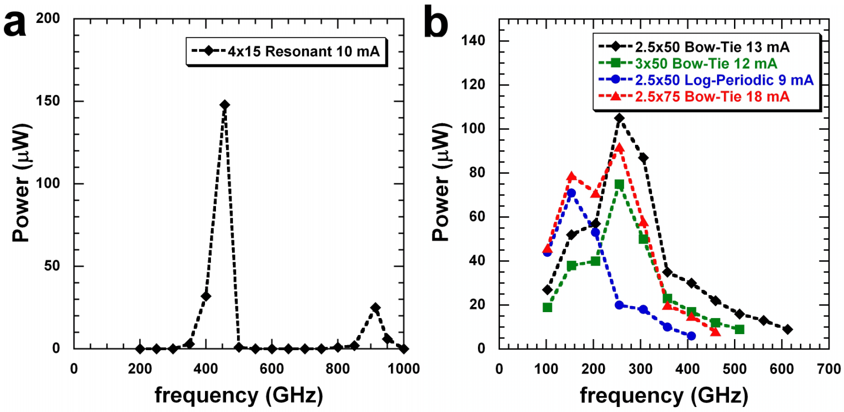

Figure 4: Emitted THz power as a function of frequency. (a) Narrowband emission from 4x15 μm^2 devices integrated with resonant antennas, (b) Broadband emission up to 612 GHz from type 2 devices (device dimensions in μm^2, antenna type and photocurrent levels given in the inset)

around 450 GHz and 900 GHz (Fig. 3d). The experimental arrangement used a hemispherical silicon lens for efficient coupling of the Terahertz signal into the power meter. Two SG-DBR lasers Optically Injection-Locked by a reference comb were used and the generated signal had a Full Width at Half Maximum (FWHM) of <10 Hz. Figure 4 shows the measured extracted power at frequencies ranging from 100 GHz to 1 THz. Figure 4a shows that the response resonant antenna integrated devices resulted in two narrowband emission peaks around 450 GHz and 900 GHz. The maximum extracted power was 148 μW at a frequency of 457 GHz and 24 μW at 914 GHz with an input optical power of 100 mW. Broadband emission (Figure 4b) was obtained for frequencies up to 612 GHz with 105 μW at 255 GHz, 30 μW at 408 GHz, 16 μW at 510 GHz and 10 μW at 612 GHz, the last result being at a DC photocurrent of 13 mA, a bias level of -3.5V and an input optical power of only 40 mW. The ratio of the Terahertz emitted power divided by the square of the optical input power (in W^{-1}) at a certain frequency, which can be defined as a figure of merit, ranged from 1 W^{-1} at 110 GHz [17] to 0.053 W^{-1} at 306 GHz and 0.0024 W^{-1} at 914 GHz.

4. Conclusions.

The TW-UTC-PD is proposed as a highly efficient photomixer for Continuous Wave Terahertz generation. A state-of-the-art bandwidth-efficiency product was achieved. Record levels of continuous wave Terahertz power at 457 GHz and 914 GHz with resonant antennas and a record Terahertz figure of merit up to 612 GHz from broadband antennas were obtained.

Acknowledgments.

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