Performance of a 1030 nm driven ErAs:InGaAs photoconductive receiver at high THz average power

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We demonstrate a 1030 nm 520fs-pulse-driven ErAs:InGaAs photoconductive receiver suitable for detecting 14 mW average THz power (~ 950 nJ pulse energy). To the knowledge of the authors, this is the highest detected pulsed THz power using photoconductive receivers reported so far. The current (field) responsivity of this receiver is in the range of $110 \pm 25\ \mu A/\sqrt{W}$ yet with slight saturation.

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https://ieeexplore.ieee.org/abstract/document/9370607

I. INTRODUCTION

In the past decade, important advances in the performance of Terahertz (THz, 100 GHz-10 THz) devices has resulted in many scientific breakthroughs as well as paved the way to industrial THz applications. For example, THz time domain spectroscopy (TDS) systems are nowadays under test for thickness measurement of paints and quality control in production lines [1]. Most of these applications require high measurement speeds, ideally with several hundreds of traces per second. Such high measurement speeds imply the need for high dynamic range, which is frequently limited by the power of THz emitters for TDS systems (typically in the tens to few hundreds of μW range) while detectors already show excellent noise floor levels at room temperature. In ref. [2], e.g. we have demonstrated fW/Hz noise floors under continuous-wave operation with highly sensitive ErAs:InGaAs photoconductive receivers. In this paper, we present first results on the combination of such low-noise receivers under pulsed operation with a record-high average power few-cycle THz source capable of reaching >10 mW of average power [3]. We show first results of the responsivity of these receivers at this unprecedented high power, indicating that systems with record-high dynamic range are within reach.

Key criteria of a low-noise photoconductive receiver are (i) a high absorption coefficient for the operating wavelength ($\alpha > 5000$/cm), (ii) high dark resistivity to reduce dark current and thus current noise, (iii) high mobility for high current yield, (iv) and a low carrier lifetime for optimized high frequency response, also under pulsed operation. Material engineering to achieve all these properties is challenging. For example, high trap concentration creates defects which decrease the carrier lifetime of the material at the cost of decreasing the dark resistivity due to additional, unwanted states close to one of the bande edges and a decrease of the mobility due to excessive scattering. Our receiver material consists of a superlattice structure- [100 × (10 nm InGaAs/δC 0.8ML ErAs)] grown using Molecular Beam Epitaxy (MBE) at 490°C. The bandgap of the receiver is 0.74eV which is suitable for both 1550 nm and 1030 nm laser operation. The ErAs precipitates are incorporated periodically between the InGaAs layers, forming quasi-metallic nano-island structures that acts as trap centers for carriers. We have yet demonstrated a carrier lifetime as low as 0.39 ps which is already shorter than that required for a 520 fs pulse. Further, the material offers a high mobility of ~775 cm^2/Vs [4-5]. For better heat dissipation the active region (~1.3μm thick) is placed over 500μm Fe:InP substrate with a high thermal conductance. The details of the material properties of these photoconductor material can be found in our pervious publication [2,4,5].

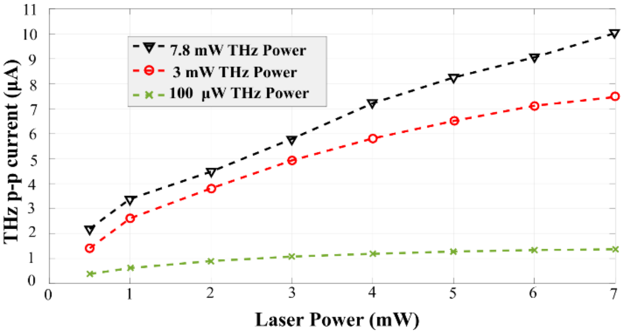

Fig. 1. Peak–Peak THz current received by the detector as a function of the probe laser power for varying incoming THz power.

II. SETUP

The TDS system is driven by a one-box mode-locked Yb-doped thin-disk oscillator capable of delivering up to 120 W of average power at 1030 nm [3,6], and emitting pulses with a duration of 520 fs, at a repetition rate 13.3 MHz. The high-power few-cycle THz source used to test the receiver is based on optical rectification using the tilted-pulse front method in a trapezoidal shaped Lithium Niobate ($LiNbO_3$) crystal. Using this system, we recently demonstrated a THz power of up to 66 mW, which is the highest reported so far for a laser driven THz source [3]. Note that for this first proof of principle experiment, we only used up to 14 mW, but much higher powers are available for future improvements. For guiding the THz wave from the source to the receiver two parabolic mirrors of focal length of 5 cm and 10 cm are used, respectively. The photoconductive receiver is attached to an H-dipole antenna with a length of 100 μm and a 10 μm gap. This antenna is tailored to operation around 1 THz, matched to the expected spectrum of the laser pulse. This offers a higher DNR at lower frequencies at the cost of slightly lower bandwidth [7]. A hyper-hemispheric high resistivity float zone silicon lens assists in coupling of the THz wave through the substrate-side of the photoconductor. The data acquisition was done with a high resolution 10 bits oscilloscope with a sampling rate of 125

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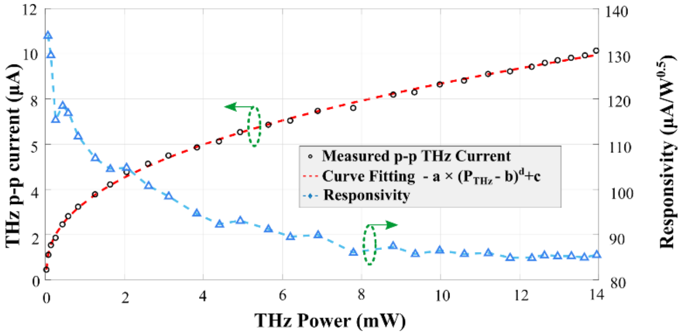

Fig. 2. Peak–Peak THz current as a function of the received THz power (left y-axis). Fit of the received current according to the text with d =0.42, *a* = 3.19µA/$W^{0.42}$, *b* =27µW and *c*= 0.28 µA. Responsivity of the receiver as a function of the received THz power (right y-axis).

kSamples/sec. The delay stage consists of a sinusoidal shaker featuring a 4 mm travel range with 15 Hz repetition rate. Fig. 1 shows the initial investigation of the detected THz peak-peak current by the receiver as a function of the probe laser power. At high THz power (> 3 mW) the detected current increases sublinearly with increased probe laser power, yet showing some minor saturation above 3-4 mW of laser power. The receiver was therefore operated with a laser probe power as low as 4 mW with a 7 mm focal length lens having approx. spot size of 10±3µm.

III. RESULTS

The emitted THz power from the $LiNbO_3$ crystal was measured as a function of the pump NIR power using a commercially available power detector (Ophir 3A-P-THz Thermopile. Fig. 2. shows the measured peak-peak current of the receiver as a function of the received THz power (left y-axis). The detected current was in the range of several µA which is close to 2 orders of magnitude higher than the receiver currents of conventional 1550 nm TDS systems using photoconductive sources driven by few 10 mW of laser power (THz power levels typically < 200µW) [4]. We note that the actual received power by the photoconductive antenna is 30% less due to the in-coupling losses through the silicon lens. In order to investigate linearity, the detected THz current vs. THz power was fitted by $I_{THz} = a \times (P_{THz} - b)^d + c$. An ideal, non-saturated receiver shows *d*=0.5 while *a* would be the current responsivity. Fig. 2 shows an almost perfectly matched fit with *d*=0.42, *a* = 3.19 µA/$W^{0.42}$, *b* =27 µW and *c*= 0.28 µA. As *d* is slightly smaller than 0.5, there is some slight saturation. This is remarkable considering the extreme THz power of 14 mW. In previous publications, we have shown that similar detectors offer dynamic ranges beyond 100 dB at THz power levels below 200 µW, pointing out an extreme linearity range of photoconductive receivers. We remark that the large values of *b* =27 µW *c*= 0.28 µA are only due to the offset of the power meter and the current noise level of the oscilloscope and post-detection electronics, respectively, and are not related to the noise floor of the photoconductor.

Fig. 2. also shows the current (field) responsivity of the receiver which is in the range of 85 – 135 µA/$\sqrt{W}$. The responsivity at the highest received THz power (~ 14 mW) is approx. 63% of the maximum responsivity and it remains relatively constant as we go to high THz power (> 6 mW THz power).

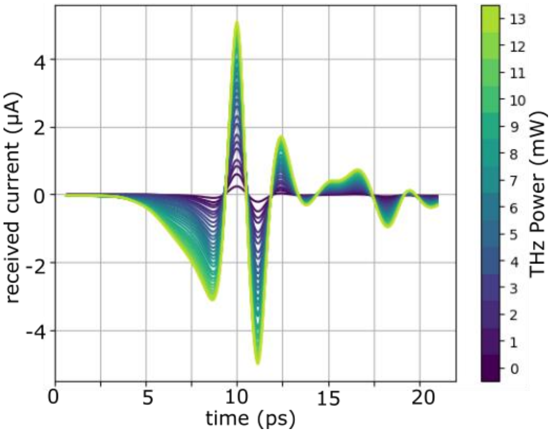

Fig. 3. Received THz pulse averaged over 75 traces (measurement time ~6 sec) and a 22.5 ps window for various recorded THz powers.

Fig. 3. shows the transient THz pulse in a time window of 22.5 ps. One can observe that the pulse shape remains unchanged with a maximum peak-peak THz current of 10.1 µA Industrial at 14 mW THz power. Earlier measurements using Be-doped InGaAs/InAlAs multilayer photoconductive structure, employing 1030nm laser, had demonstrated to have received less than 150µW THz power [8].

IV. SUMMARY

In conclusion, we have demonstrated a TDS system using a $LiNbO_3$ crystal as high THz power source and an ErAs:InGaAs photoconductive receiver operated at 1030nm. We show that these receivers are capable of operating at very high THz power of 14 mW with little saturation. The maximum responsivity of the receiver is 135 µA/$\sqrt{W}$ with no drastic change in responsivity even at very high THz power of 14 mW (~ 85 µA/$\sqrt{W}$). This proves that ErAs doped InGaAs receivers are capable of detecting very high THz power of several mW. Hence, record-breaking dynamic ranges should be possible with systems using powerful non-linear crystal-based THz sources combined with sensitive photoconductive receivers.

REFERENCES

[1]. S. Krimi, et al. "Highly accurate thickness measurement of multi-layered automotive paints using terahertz technology." Applied Physics Letters 109.2 (2016): 021105.

[2]. A. D. J. F. Olvera, et al. "International system of units (SI) traceable noise-equivalent power and responsivity characterization of continuous wave ErAs: InGaAs photoconductive terahertz detectors." Photonics. Vol. 6. No. 1. Multidisciplinary Digital Publishing Institute, 2019.

[3]. F. Meyer, et al. "Single-cycle, MHz repetition rate THz source with 66 mW of average power." Optics Letters 45.9 (2020): 2494-2497.

[4]. U. Nandi, et al. "1550-nm driven ErAs: In (Al) GaAs photoconductor-based terahertz time domain system with 6.5 THz bandwidth." Journal of Infrared, Millimeter, and Terahertz Waves 39.4 (2018): 340-348.

[5]. U. Nandi, et al. "ErAs: In (Al) GaAs photoconductor-based time domain system with 4.5 THz single shot bandwidth and emitted terahertz power of 164 µW." Optics Letters 45.10 (2020): 2812-2815.

[6]. C. J. Saraceno, "Mode-locked thin-disk lasers and their potential application for high-power terahertz generation." Journal of Optics 20.4 (2018): 044010.

[7]. U. Nandi, et al. "Antenna-coupled spintronic terahertz emitters driven by a 1550 nm femtosecond laser oscillator." Applied Physics Letters 115.2 (2019): 022405.

[8]. R. J. B. Dietz, et al. "Low temperature grown Be-doped InGaAs/InAlAs photoconductive antennas excited at 1030 nm." Journal of Infrared, Millimeter, and Terahertz Waves 34.3-4 (2013): 231-237.

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Published article: U. Nandi et al., "Performance of a 1030 nm driven ErAs: InGaAs photoconductive receiver at high THz average power," 2020 45th International Conference on Infrared, Millimeter, and Terahertz Waves (IRMMW-THz), Buffalo, NY, USA, 2020, pp. 1-2, doi: 10.1109/IRMMW-THz46771.2020.9370607.