10 mW of THz Power Using Photoconductive Connected Array Source Excited by a 515 nm Laser at 91 MHz Repetition Rate.

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***Abstract*— We report the highest THz power ever achieved from photoconductive antennas. This result is obtained by employing a photoconductive connected array. Such arrays have previously shown to radiate efficiently when excited by a 780 nm laser source, but their scalability is constrained by the limited optical power available at this wavelength. In this work, we design a 361-element photoconductive connected array specifically optimized for 20 W of 515 nm green laser excitation, and demonstrate a record-high THz power of ~10 mW using this new device.**

I. Introduction

PHOTOCONDUCTIVE antenna (PCA) based sources driven by ultrafast lasers are the most commonly used emitters in TDS systems. Advances in material engineering have enabled great progress in their performance in the last decades, mostly focusing on conversion efficiency, bandwidth and overall dynamic range [1]. Most PCAs reported in the literature employ either LT-GaAs photoconductors driven by 780 nm Ti:Sa lasers or InGaAs combined with 1550 nm Erbium fiber lasers—both laser technologies being inherently limited in average power. This constraint restricts the potential to scale the average THz power by simply increasing optical power at these wavelengths.

An attractive solution to this shortcoming is to use higher average power driving ultrafast sources at different wavelengths and correspondingly large emitters to efficiently apply the large average powers currently available, for example using Yb lasers. So far, only large-area emitters (LAEs) have been explored in this regard. Recently 6.7 mW of THz average power could be obtained at 400 kHz repetition rate [2]. At higher repetition rates as desired for most linear spectroscopy applications significantly degraded conversion efficiencies, achieving only 65 μW at 9 W excitation power and 91 MHz repetition rate [3].

Photoconductive connected array sources (PCCA) utilizing LT-GaAs are promising candidates for achieving higher efficiencies. They are efficient radiators with 780 nm laser excitation, showing mW power level at 500 mW of optical power and 80 MHz repetition rate [4]. In this contribution, a PCCA design with 361 elements is presented which is specifically tailored to radiate efficiently when excited by a frequency-doubled high-power Yb laser operating with 20 W of average power at 515 nm, with a high repetition rate of 91 MHz. The design is fabricated and measurements are reported showing record-high radiated THz power of 10.1 mW using PCAs at this high repetition rate.

II. PCCA Design for 20 W optical power excitation

To maximize the radiated THz power, the active photoconductive area of the PCCA is designed to ensure impedance matching between the photoconductive gaps and the array element impedance when the full array is excited with 20 W of pump power. The design procedure for impedance matching is described in [5]. The optimal configuration of the array is found to be 19×19 elements where each gap element has a photoconductive gap size of 7.5 μm × 7.5 μm.

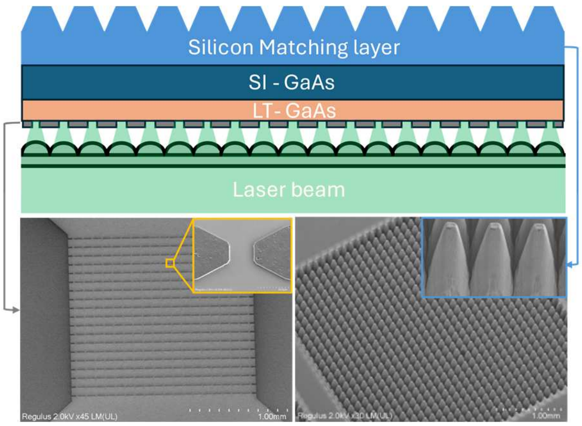

Fig. 1. Schematic overview of the designed 19×19 PCCA design, including SEM pictures of the array and frusta matching layer.

An overview of the PCCA design is shown in Fig. 1. The design is similar to the that of the 5×5 PCCA presented in [4]. The new device consists of a microlens array which focusses the pulsed laser beam onto the different photoconductive gaps of a 19×19 elements connected array structure. There are two considerable differences with the design in [4], first of all the area of this newly designed array is significantly larger to handle the 20 W of average optical power. Due to the large area of this 19×19 element array (1.9 mm × 1.9 mm), a broad-band silicon matching layer [6] designed for a bandwidth between 100 GHz and 800 GHz is used instead of a hyper-hemispherical silicon lens. The designed bandwidth of this matching layer matches the bandwidth of the array.

III. Experimental Setup and Results

For the optical excitation of the PCCA, the laser system from [3] is used, which is a Kerr-lens mode locked thin-disk laser with a separated gain medium (Yb:garnet disk) and Kerr medium (3 mm YAG) emitting 30 W and transform limited pulses of 157 fs at 91 MHz. The frequency-doubled laser beam can then provide up to $P_L^{pump} = 20.8\,\mathrm{W}$ of excitation power with pulses with a duration of 96 fs at a central wavelength of 515nm. The laser beam incident on the microlens array of the PCCA is collimated by a set of lenses, and the FWHM matches the array size of $D_{array} = 1.9\,\mathrm{mm}$ so that all elements in the array receive a similar amount of optical power. The PCCA is mounted in a holder, which can be moved through a 5-axis stage, so the alignment between the optical beam and microlens array can be accurately controlled. The array is biased by a DC voltage source (Spellman SL40*600).

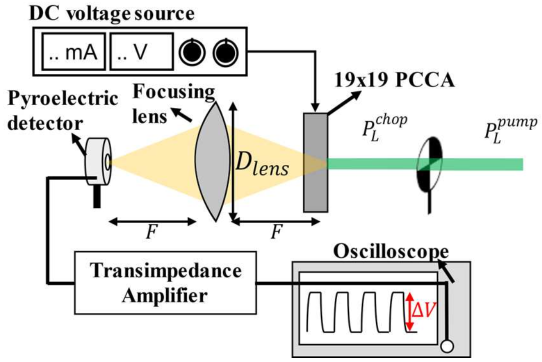

Fig. 2. Experimental power measurement setup. The focusing lens has a diameter of $D_{lens} = 35.5$ mm, and on both sides has a focal length of $F = 50$ mm.

Power Measurements: The THz power radiated by the PCCA device is focused using an HDPE lens onto a pyroelectric thin-film detector (THz 30, SLT GmbH) calibrated by the German metrology institute (PTB), as shown in Fig. 2. The readout of this pyroelectric detector requires chopping of the optical beam at 18 Hz with a duty cycle of 50%. We here denote the total average optical pump power as P_L^{pump}, and the average chopped power as P_L^{chop}.

Initially, a strong heating of the device was observed already at $P_L^{pump} = \sim 3$ W, rendering the device unsuitable for higher average optical power. After introducing an N_2 airflow directed onto the frusta via a 4 mm diameter tube at 3.5 bar, the full optical power of $P_L^{pump} = 20$ W could be applied without observing significant heating effects. Note that during the measurements with the pyroelectric detector, a cap provided by SLT GmbH which is transparent to THz radiation is used to make sure the air from the air-tube does not disturb the measurement.

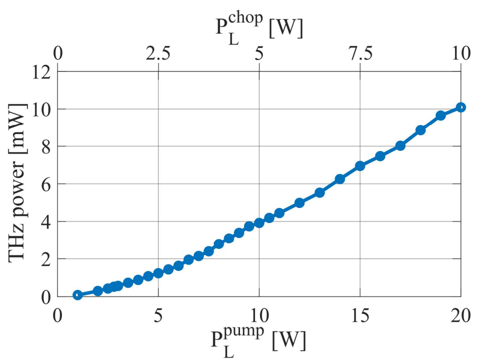

Fig. 3. Detected THz power for a 19×19 PCCA as a function of the average pump power when the array is biased by $V_b = 900\ V$, measured using the setup in Fig. 2.

The THz power as a function of the pump power is shown in Fig. 3. Here a bias voltage of 900 V is used, as above this value the device behavior is unstable. We demonstrate 10.1 mW of THz power during the on-cycle of the chopper when the pump power is set to $P_L^{pump} = 20$ W. To the knowledge of the authors, this THz power is the highest reported thus far for PCAs. In particular, this was achieved at very high repetition rate of 91 MHz, which is key for future applications in spectroscopy and THz imaging.

When removing the chopper, one would expect that the device radiates 10.1 mW continuously when excited by 20 W of pump power. Without chopper, the THz power cannot be measured using the pyroelectric detector. However, after removing the chopper, we could see from the steadily increasing DC supply current that the device suffered from heating effects as was previously observed with LAEs. We expect to solve this with proper active cooling of the device.

Electro-Optic Sampling Measurements: Additionally, the spectrum of the PCCA has been measured for different optical pump powers P_L^{pump} using conventional Electro-Optic Sampling (EOS) in combination with a balanced detection scheme. A 3 mm gallium phosphide detection crystal is used, and the PCCA radiation is coupled to the crystal via two OAPs, as done in [3]. The optical beam is chopped with 50% duty cycle and a chopping frequency of 2847 Hz. The signal is detected using a lock-in amplifier.

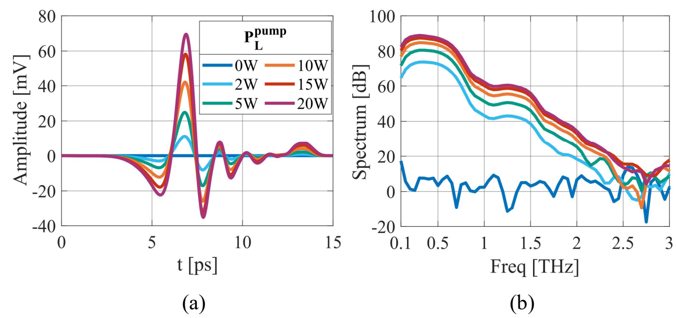

Fig. 4. EOS trace in (a) time-domain and (b) frequency domain.

The time-domain THz pulse and corresponding frequency spectrum are shown for different pump powers in Fig. 4(a) and (b) respectively. The spectrum is as expected from a PCCA source, showing an excellent frequency response between 100 GHz and 800 GHz. The upper frequency limit of 800 GHz is present because of the occurrence of grating lobes [4].

I. Conclusions

The presented 19×19 PCCA structure designed to work with 20 W of optical power achieves a record-high radiated THz power at 91 MHz of repetition rate. Measurements using EOS show excellent spectral response within the design bandwidth between 100 GHz and 800 GHz.

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