Milliwatt THz Average Output Power from a Photoconductive Switch

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Abstract—We report the design and measurement details of a new GaAs-based THz photoconductive switch with an average power level in excess of 1 mW and peak power up to 33 W when pumped by a 780-nm, subpicosecond pulse train from a frequency-doubled 1.55-nm fiber mode-locked laser. The power was measured with a thermopile detector calibrated for THz operation and having very high saturation level. The median power frequency of the present photoconductive switch is estimated to be 400 GHz.

I. INTRODUCTION

Ultrafast photoconductive devices have been one of the most successful developments in the history of the THz field. The photoconductive (PC) switch is now a workhorse in time-domain systems used around the world, particularly spectrometers and imaging systems. The cw photomixer has been widely applied for applications requiring continuous, wideband tuning, such as high-resolution spectrometers and tunable local oscillators. The primary shortcoming of the photoconductive devices has always been average output power, limited to microwatt levels by low photoelectric conversion efficiency. This paper reports the design and measurement details of a recent switch design that produces milliwatt average power level into free space when pumped by a fiber mode-locked laser at ~780 nm [1].

II. PHOTOCONDUCTIVE MATERIAL AND DEVICE

The PC switch design is based on ultrafast epitaxial GaAs with embedded ErAs nanoparticles grown by molecular beam epitaxy at standard temperatures (>500°C). The ErAs nanoparticles play a similar role to the As precipitates in low-temperature-grown GaAs, but with a lower concentration of defects and superior GaAs photocarrier transport. The electron-hole recombination time is known to be well under 1 ps at zero bias, and stable photoconductivity is displayed up to bias fields of approximately 10^5 V/cm., above which soft impact ionization occurs. Like low-temperature-grown GaAs, the resistivity of the ErAs:GaAs is very high over the stable range, which is important for generation efficiency and reliability in all THz photoconductive devices.

As shown in Fig. 1, the PC switch is defined lithographically in a three-turn, self-complementary, square spiral antenna designed to couple short THz pulses to free space with minimal dispersion and loss. The active area is the 9x9 micron driving gap at the center of the antenna. This square spiral has been shown previously to provide desirable radiating characteristics over the entire sub-THz region, combining high driving-point resistance with a quasi-TEM_{00} Gaussian beam pattern [2].

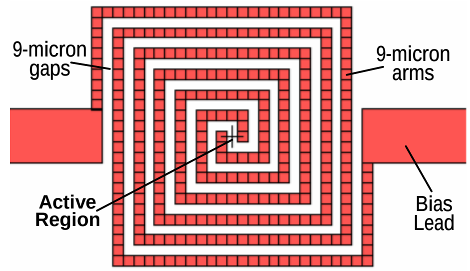

Fig. 1. Three-turn square spiral antenna used to couple the photoconductive-switch THz currents to free space.

III. RESULTS

Shown in Fig. 2 is the measurement set-up used to characterize the photoconductive switches. Thanks to 1.55-micron erbium-doped fiber technology, ultrafast mode-locked lasers are now available having pulse widths down ~200 fs and average power levels above 100 mW. This is enough peak power to drive a second-harmonic generator (SHG), producing subpicosecond pulses centered around 793 nm and having an average power of ~22 mW [3]. The pulsewidth can be estimated from the spectral bandwidth, $\Delta\lambda$ = 5.36 nm, measured with a grating spectrometer and shown in the spectrum of Fig. 3. This corresponds to a 3-dB bandwidth of $\Delta\nu$ = 2.56 THz at the peak wavelength of 793 nm. The corresponding pulsewidth is then approximated by $\Delta t \cong 1/\Delta\nu$ = 390 fs [4], which includes all dispersive and distortive effects from optical fibers and the SHG itself. The 793-nm pulses are focused on the PC switch while it is biased with a low-noise constant-voltage power supply.

The THz output beam is coupled to free space through a silicon hyperhemisphere, and the average power is measured with a commercial thermopile power meter. The thermopile was spot-calibrated at 104 using a commercial fundamental-mode Gunn oscillator whose output power in excess of 1 mW was cross-calibrated against a thermal waveguide power meter. The thermopile was also spot calibrated at 530 GHz using a commercial frequency multiplier chain having an output power < 1 mW that was carefully measured by the

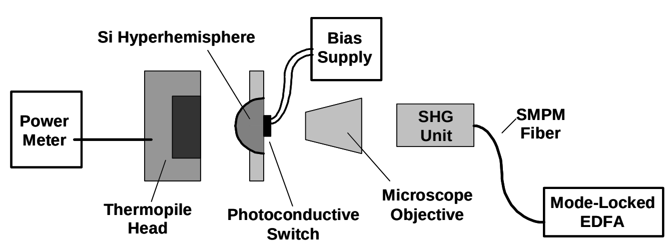

Fig. 2. Experimental set-up used in the present experiments.

manufacturer [5]. These two points were combined with the manufacturer-provided mid-infrared power calibration to calculate an average calibration factor between 100 GHz and 1.0 THz. Somewhat surprising was the fact that the calibration factor at 530 GHz was much closer to the infrared value than to the 104-GHz value, suggesting that thermopiles are be more useful in the sub-THz region than people may have thought. When using the thermopile for THz measurements, we also found it important to filter out the visible and near-infrared radiation using one sheet of black polyethylene.

The experimental results for THz average power P_{ave} vs PC switch bias voltage are plotted in Fig. 3 along with the "dark" current-voltage (I-V) characteristic. As in typical PC switches and photomixers, P_{ave} rises monotonically with bias voltage and approaches a maximum value of 1.6 mW at 150-V bias. Higher bias voltage was not attempted because of the onset of impact ionization seen in dark I-V curve of Fig. 3. Although the impact ionization is "soft" by device physics standards, it is exacerbated by the presence of the powerful laser beam such that the device integrity is seriously jeopardized

To the best of our knowledge, this is the highest P_{ave} ever reported for a THz PC switch and exceeds by almost 40x times the initial report from a device having similar design [6]. The discrepancy is still being studied, but can be attributed in part to the difference in pump power: 22 mW average in the present experiment vs 8 mW in the previous demonstration. However, since THz output power is known to vary sub-quadratically with pump power, this fact alone cannot explain the discrepancy. We believe a comparably important factor is saturation of the free-space-coupled THz thermal detectors previously used to measure THz power (e.g., the Golay cell in Ref. [6] or LHe-cooled bolometers used by other researchers). Thermopiles are famous for their large dynamic range and the ability to accurately measure the average power of pulse trains having very high peak power P_{peak} , such as the output from Q-switched Nd:YAG lasers.

The transmitted power spectrum of the photoconductive switch was estimated using a pair of high-pass mesh filters. The first filter consisted of gold-plated nickel mesh having a 0.6-mm period and an associated turn-on frequency of 300 GHz. The second filter consisted of a similar mesh but having a 0.4-mm period and an associated turn-on frequency of 500 GHz The transmission spectrum of both filters was measured using a separate photomixing spectrometer between 100 GHz and 1.0 THz. From this measurement, we estimate a median power frequency of f_m ~400 GHz. This is the frequency above and below which there are equal average power levels.

The peak THz power P_{peak} from the photoconductive switch is more difficult to measure than the average power, but can be roughly estimated as follows. The THz pulse must be wider than the 793-nm mode-locked laser pulse, but not by so much that there is any significant THz power transmitted between successive pulses at the f_{rep} = 49-MHz repetition rate. Therefore, the peak power can be estimated from the average power using $P_{peak} \sim P_{ave}/(f_{rep} \cdot t_p)$ where t_p is the THz pulsewidth. From the present experiments, we do not know t_p accurately but can certainly place it between the 390-fs 793-nm laser pulsewidth and the inverse median frequency, t_m = 1/f_m = 2.5 ps. Taking the geometric mean of these two, we obtain t_p ~ 1.0 ps and a peak THz power of P_{peak} ~ 33 W at the 150-V bias point in Fig. 3. This is an impressive number for the THz region where powerful sources, are still lacking.

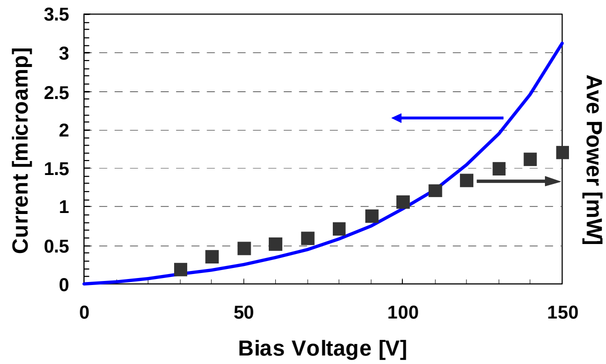

Fig. 3. Dark current at 300 K and average THz output power from photoconductive switch of Fig. 1.

III. CONCLUSION AND ACKNOWLEDGEMENTS

Ultrafast photonductive devices have come a long way since their advent in the late 1980s. The THz output power of photoconductive switches has remained rather mysterious because of the difficulty in measuring THz output power over such a large instantaneous bandwidth. The present experiments have confirmed the intuitive notion that photoconductive switches should produce much higher power levels than photomixers, in excess of 1 mW for the present device, antenna design, and laser pumping technique. By measuring the power with a calibrated thermopile detector, issues about detector nonlinearities or saturation from the high-peak power of the photoconductive switches have been mitigated. At the reported power levels, we anticipate that the utilization of photoconductive switches will advance beyond their use in time-domain spectrometers and related systems.

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