Microlens coupled large area photoconductive switch for powerful THz emission

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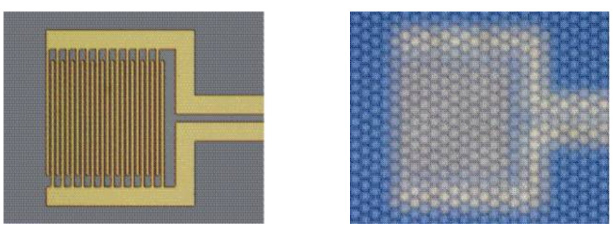
Abstract—**Powerful THz emission based on a finger electrode photoconductive switch attached to a micro lens array is presented. A hexagonal packed lens array directs the incident pump light into specified electrode gaps, yielding only constructive interference in the THz far-field. Using a Ti:Sapphire system operating at 80 MHz with 150 fs pulses and 3 W maximum optical excitation, 0.28 mW THz average power is obtained. The maximum IR–to-THz conversion efficiency is ≈ 1.3×10^{-4}.**

I. Introduction And Background

TODAY, ultrashort THz pulses have become a convenient source for time-resolved spectroscopy, nondestructive materials testing, medical imaging and homeland security applications. However, the scan time for imaging and sensing can be prohibitively long for many applications, thus motivating the development of sources with significantly higher average power. The first THz time-domain spectroscopy systems were completely based on photoconductive switches (PC) [1]. Still today, PC emitters and antennas provide the highest dynamic range for measurements around 1 THz [2]. In addition, the progress on available laser power [3] encourages newer concepts to utilize high power laser systems under avoidance of optical breakdown or screening.



(a) (b)

Fig. 1 Example for a 300 µm finger electrode structure (a), hexagonal lens array with a 30 µm pitch attached to the chip (b)

Dreyhaupt et al. have presented an innovative THz emitter with an interdigital electrode metal-semiconductor-metal (MSM) structure on semi-insulating GaAs [4]. They masked every second gap by an additional metallization layer to avoid destructive interference in the THz far-field. This technique renews an approach by Yoneda et al. presented in 2001 where a spatially modulated Kr*F laser was applied to a diamond based interdigital electrode structure [5]. However, due to a metal coverage of approximately 75 % and the reflectivity of the semiconductor material, only ≈ 20 % of the incident pump power can contribute to THz generation [4]. Recently, Awad et al. demonstrated an alternative fabrication concept for an interdigital finger electrode emitter based on substrate transferred thin films of low-temperature grown GaAs (LT GaAs) [6]. Though this epitaxial lift-off technique allows versatility in the choice of substrate materials, an epitaxial lift-off considerably complicates the fabrication process yielding increased manufacturing times and costs. Moreover, the utilized pump power still remains only a small fraction of the incident IR light.

Here, we present a novel approach for a large area emitter based on an interdigital finger electrode structure attached to a micro lens array (Fig 1). The hexagonal packed lenses direct the incident pump light into every second electrode gap to provide only constructive interference in the THz far-field and due to a lens packaging density of 73.4 % nearly three-fourths of the incident pump light can contribute to the generation of THz radiation.

During the fabrication of the THz emitter we processed two interdigital Ti/Pt/Au finger electrodes by optical lithography on the surface of a 3 µm LT GaAs layer grown on a 650 µm thick semi-insulating GaAs substrate. LT GaAs has subpicosecond carrier lifetime and can therefore be used interchangeable as THz emitter or detector. The electrode widths were conceived as 8 µm, whereas the electrode spacing was around 5 µm. The whole dimension of the emitter structure was 1×1 mm^2. In addition a dielectric antireflection coating based on a 63.9 nm thick Ta_2O_5 layer upon a 27.3 nm SiO_2 layer was added.

II. Experiment And Results

In our experiments we used a conventional Ti:Sapphire laser driven THz time-domain system (TDS). The laser oscillator delivered 150 fs pulses at 800 nm at a repetition rate of 80 MHz with a maximum average power of 3 W. The incident IR beam diameter on the whole emitter structure was 850 µm (1/e^2). For the acceleration of the photogenerated charge carriers a 30 kHz, 25 mV square wave voltage was applied. For coherent detection two off-axis parabolic mirrors collimated and refocused the emitted THz-trains onto a standard 6 µm LT GaAs antenna. The induced signal was amplified and recorded using a lock-in amplifier. In addition, the THz average power was measured using a pyroelectric detector based on a $LiTaO_3$ crystal with an active element size of 6 mm^2. The measurements are given in Fig. 2 and Fig. 3, respectively.

For the generation of THz radiation due to the temporal formation of electric dipoles, the emitted THz field E_{THz} is direct proportional to the photo-induced charge carrier density ρ_{opt} which is accelerated by the local electric field E:

$$E_{THz} \propto \rho_{opt} \cdot E \propto \frac{P_{opt}}{A} \cdot E \tag{1}$$

P_{opt} is the IR average power incident on the area A. Using (1), the THz power P_{THz} obeys:

$$P_{THz} \propto \left(\frac{P_{opt}}{A} \cdot E \right)^2 \tag{2}$$

As one can see, the THz power increases quadratic with the electric field strength and the absorbed optical power. However, this

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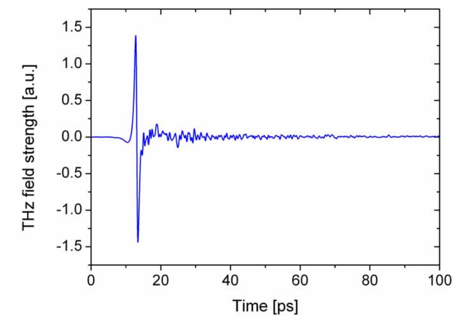
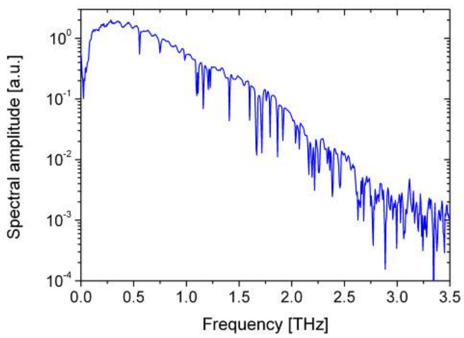
parabolic dependency can only be valid for the absence of any saturation effects. In general, for strong optical excitation and high electric field strengths saturation effects have two origins. Firstly, for high optical fluencies the space charge region generated by the free charge carriers becomes comparable to the external applied bias field and thus decelerates the electrons [7].



(a)



(b)

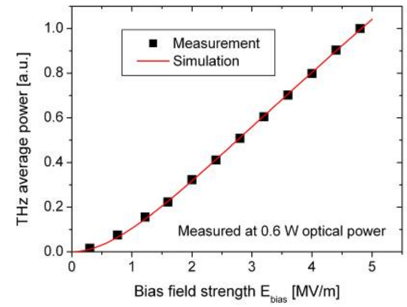
Fig.2 Time-domain THz field scan (a) for an acceleration field strength of 5 MV/m, (b) corresponding spectrum

Secondly, the charge carrier acceleration is limited by the saturation velocities of the electrons due to the increasing probability of intervalley scattering [8]. As a consequence equation (2) has to be extended to:

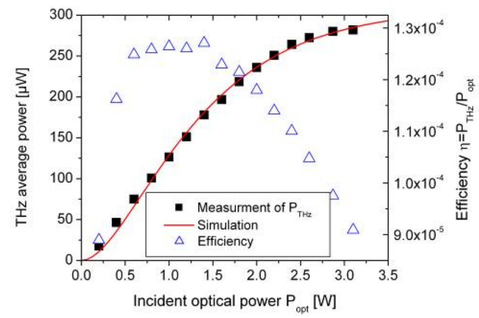
$$P_{THz} = \frac{CE_{bias}}{A^2} \cdot E_{sat}\left(1 - e^{-\frac{E_{bias}}{E}}\right) \cdot P_{sat}^2 \left(1 - e^{-\frac{P_{opt}}{P_{sat}}}\right)^2 \qquad (3)$$

In order to take these saturation effects into account. E_{sat} and P_{sat} are the saturation electric field strength and the saturation optical power. C is a specific constant that represents the conversion efficiency given by the material itself. It includes, among other properties, the recombination and relaxation time of the electrons, the absorption coefficient of the semiconductor as well as an estimated outcoupling efficiency determined by the refractive index of the material. In addition, C includes also a factor 1/2 due to the emission of THz radiation in two directions.

One can easily obtain E_{sat} by measuring the THz power over the applied electric field strength E_{bias} for constant optical excitation. The result is plotted in Fig. 3 (a). P_{sat} and C can be estimated by investigating the THz power as a function of the optical excitation (Fig 3 (b)). For $E_{sat} \approx 1.5$ MV/m and $P_{sat} \approx 0.97$ W, the measurements can be well reproduced using equation (3). As one can see in Fig. 3 (b), the optimum conversion efficiency is obtained for an optical excitation of 0.5 to 1.5 W.



(a)



(b)

Fig.3 THz average power dependency for: (a) increasing bias field strength, (b) increasing incident optical power at E_{bias} = 4.8 MV/m. The maximum THz average power is $P_{THz} \approx 280$ µW.

Hence, the emitter area should be scaled with increasing pump levels. For instance, one could obtain more than 1 mW THz average power for a four times larger emitter area and an optical excitation of 4 W.

In conclusion, we demonstrated a novel THz emitter based on an interdigital electrode structure coupled to a micro lens array. The highest obtained IR-to-THz conversion efficiency was $\approx 1.3\times10^{-4}$. So far, the achieved THz average power was ≈ 280 µW but can be easily upscaled by a simple increase of the emitter dimensions.

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