Pump Beam Diameter Dependent Terahertz Generation from Surface Emitters – Experiment and Simulation

M. Theuer[a,c], C. Imhof[b], G. Torosyan[a], F. Ellrich[a], R. Zengerle[b], R. Beigang[a,c]
[a] Fraunhofer Institute for Physical Measurement Techniques IPM, Kaiserslautern, Germany
[b] University of Kaiserslautern, Dept. of Electrical and Computer Engineering, Kaiserslautern, Germany
[c] University of Kaiserslautern, Dept. of Physics, Kaiserslautern, Germany

***Abstract*—We report on terahertz wave generation using transient photoconductivity induced by femtosecond laser pulses in semiconductor surfaces. In particular the dependence of terahertz emission characteristics on pump pulse parameters like diameter and input angle is investigated in detail both experimentally and theoretically. It is shown that the emission in forward (quasi-optical reflection) as well as in backward direction (back to the laser) is strongly depending on the diameter of the pump beam on the semiconductor. This is explained in terms of Huygens' principle of fundamental waves together with a Hertzian dipole model. The emission properties are simulated using CST MICROWAVE STUDIO® and compared with experimental results.**

I. Introduction And Background

Surface emitters are widely used terahertz (THz) sources for femtosecond Ti:Sapphire oscillator pumped systems. The mechanism of THz generation is based on the acceleration of electrons by the surface depletion field in the vicinity of the semiconductor surface [1,2]. All excited oscillating dipoles contribute to the emitted THz signal. The direction of propagation of the signal is given by the envelope of the phase fronts in the far field. Since the refractive index of air is nearly the same for the near infrared and THz range the main direction of the THz emission coincides with the optical reflection of the pump beam [3,4]. The typical explanation describes the emitter as a diffraction limited source with respect to the pump spot size. Concerning the pump beam diameter, the only noticeable effect in the emission characteristics is a change of the angular width of the main lobe. This is exemplarily shown in Fig. 1 for two diffraction limited sources (grey curves) with different pump spot sizes radiating at a wavelength of 600 µm. However, the radiation characteristic of the single dipoles (black curve) emitting the THz signals has to be taken into account, too. This fact is of special importance for small pump spots, because in this case the dipole characteristic will be the dominating effect. This interplay leads to sensible changes in the position of the angular position of the maximum radiated power. A clear understanding of the radiation characteristic is important since this input parameter is needed for the design of complex THz systems. In particular, the THz focal diameter in imaging systems strongly depends on the total emission characteristics of the THz source.

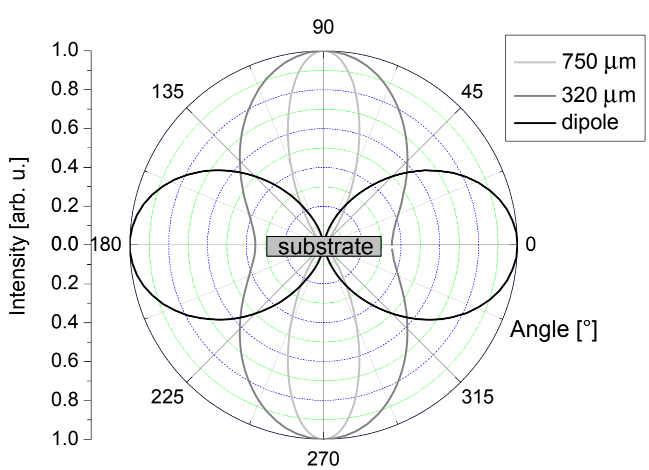

Fig. 1: Diffraction limited source (wavelength 600 µm) for different pump spot sizes, dipole emitter characteristic.

II. Experiment

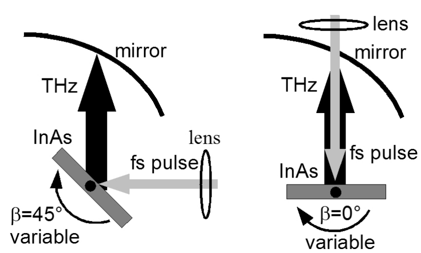

Fig. 2: Experimental setup for quasi reflection (left) and “back to the source" geometry (right).

In our experiments we have used a standard THz TDS system with two off-axis parabolic mirrors to collimate and refocus the THz radiation. The surface emitter is located in the focus of the first parabolic mirror. The emitter geometries used in our experiments are schematically shown in Fig. 2. The angle between laser excitation and direction of detection can be set to a fixed value of either 90° or 0°. The left arrangement shows the standard reflection geometry with a fixed angle of 90° between the laser beam and the direction of THz detection. The angle β between the surface normal of the emitter and pump beam direction is varied by rotating the emitter around the incidence point of the pump beam onto the substrate. The rotation axis is perpendicular to the plane of incidence. This keeps the alignment of the THz-optical system nearly constant. On the right side the setup for THz detection in the 0° direction "back to the laser source" is illustrated. This case corresponds to the detection in backward direction. The pump beam is brought to the emitter through a hole drilled into the parabolic mirror. The extended collection angle of the mirrors (approx. 15°) reduces the resolution in the experiment

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and has to be taken into account for the modeling of the system.

III. Results And Discussion

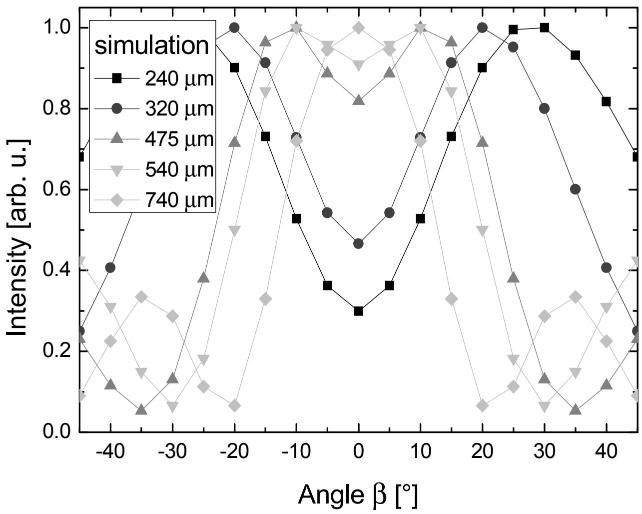

Fig. 3: Simulation of angle dependent THz emission at 500 GHz for different pump spot sizes.

Figure 3 shows the emission characteristics at 500 GHz in backward direction as obtained from a simulation using CST MICROWAVE STUDIO® for different pump spot sizes. The simulations are carried out using pulsed currents representing the oscillating dipoles. It turned out that already 20 infinitesimal currents are enough to get an appropriate model of the emitter. By monitoring the far field radiation pattern of the pulsed excitation we are able to obtain the spectral emission characteristics.

The emission characteristics can be explained in terms of a superposition of the emission characteristics of a single dipole and the constructive interference of wave fronts according to Huygens' principle. As expected, a clear transition between the behavior of a single dipole with a minimum of emitted radiation in the direction of the oscillation (here at $\beta = 0°$) and the envelope of the phase fronts of multiple dipoles can be seen. For pump beam diameters smaller than the emitted THz wavelength the dipole characteristics dominate with a minimum of emission in the backward direction. The maxima of the barbell shaped emission curves move to larger angles for smaller pump beam diameters (black curves) with a pronounced minimum in the center. For pump beam diameters larger than the emitted wavelength an emission in the backward direction of the pump incidence is observed (grey curves). The diameter of the pump beam also influences the angular width of the emission cone. The limited angle of view of the detector is considered in the simulations as an averaging in the far field.

The results of the simulations are in good agreement with measurements using a broadband THz TDS system. The experimental results obtained under comparable conditions are shown in Fig. 4. It is obvious that the maxima of the THz emission move to larger angles for smaller spot sizes, too. The asymmetric shape for negative angles and the deviation from the 0°-symmetry center is caused by the off-axis optics and offset between the pump spot and the rotation axis.

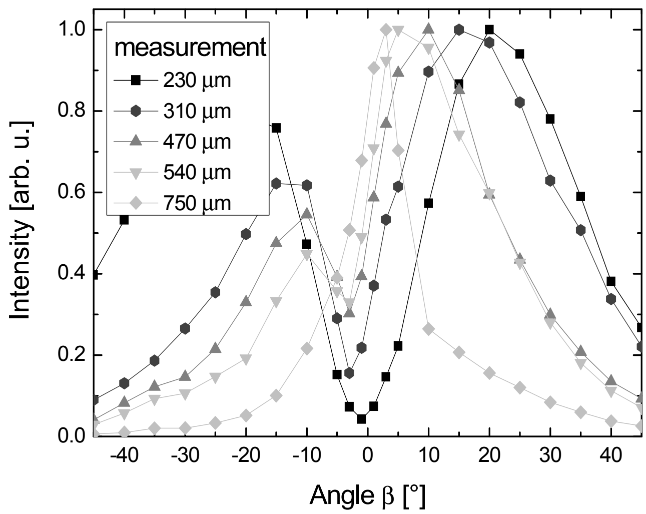

Fig. 4: Measurement of angle dependent THz emission for different pump spot sizes.

A detailed discussion is presented for different frequency ranges within the broadband THz pulse spectrum. This is essential because the diffraction condition (ratio between pump spot diameter and wavelength) changes drastically within one THz pulse typically extending by one decade. The above mentioned discussions are also presented for the well-known geometry of 90° between the incident pump beam and the detection direction.

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