Terahertz Vector Beams

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Abstract—**We present a concept for the design of photoconductive antennas which allows the generation and detection of terahertz radiation pulses of freely selectable modes. We demonstrate the principle by showing electric field distributions for vector beams, namely the lowest order Gaussian-Bessel beams. They have a donut-like intensity distribution and either radial or azimuthal polarization. For comparison, Gaussian beams are investigated.**

I. Introduction And Background

FREELY propagating terahertz beams are usually described as Laguerre-Gauss modes, with the azimuthally symmetric Gauss beam being the lowest order type. Apart from these solutions of the scalar Helmholtz equation in paraxial approximation, Bessel-Gauss modes are an interesting family of solutions of Maxwell's vector wave equation [1]. Their lowest order modes have donut-like intensity distributions and radial or azimuthal polarization. The radially polarized vector beams are interesting because of longitudinal non-propagating electric fields in the focus of the beam and the possibility to obtain a sharper focus as compared to Gaussian beams [2]. This has been demonstrated for electromagnetic radiation in the visible range [2]. THz pulses of radial polarization couple to Sommerfeld modes propagating on wires with a much higher efficiency as compared to linearly polarized Gaussian beams [3]. While there are many investigations on these guided THz modes, only little work has been reported on freely propagating modes of radial polarization [4] and no publications exist for azimuthally polarized beams.

Here we use scalable photoconducting emitters and detectors to investigate THz vector beams and present beam patters for unfocused and focused radiation.

II. Experimental

The electrode geometry of the photoconductive antennas is inverse to the desired polarization pattern, i.e. emitters for radially polarized modes consist of equidistant concentric ring electrodes, while emitters for azimuthally polarized modes are a circular structure of metallized sectors. The principle layout of the electrode geometry for an emitter for radially and azimuthally polarized THz radiation is shown in Figs. 1a) and b), respectively. The diameter of both antenna patterns is 2 mm. The antenna for radially polarized THz beams consists of 100 gaps between the electrodes, the one for azimuthally polarized beams contains 92 gaps. This fine patterning makes the slight breaking of radial symmetry by the metallization

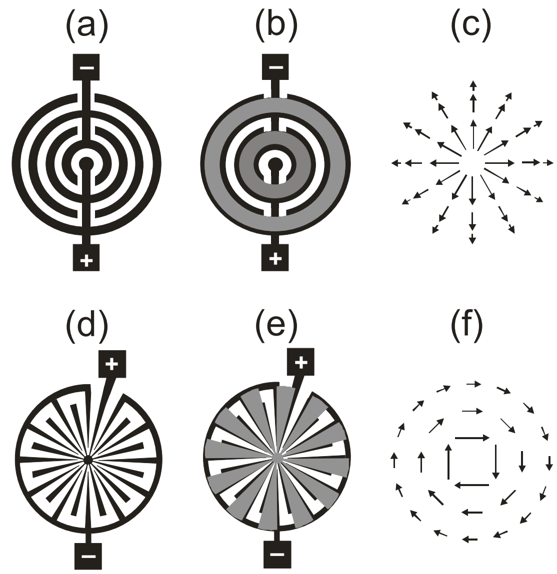

Fig. 1: Sketch of the electrode pattern (a, d), second metallization pattern (b, e) and mode pattern of the THz radiation (c, f) for radially (a-c) and azimuthally (d-f) polarized radiation.

lines, which connect all parts of the electrodes of similar polarity, negligible. To avoid electric fields pointing in the opposite direction, a second metallization layer, which is electrically insolated from the electrodes, is used to cover every second gap between the electrodes as indicated in Fig. 1 b) and 1 e). This principle has been used previously for emitters of linearly polarized radiation, where the electrodes are parallel stripes [5]. The resulting patterns of the THz field are sketched schematically in Fig. 1 c) and 1 f). Emitters for radially, azimuthally and linearly polarized THz radiation are fabricated on semi-insulating GaAs. Detectors of similar geometry are prepared on semi-insulating GaAs substrates implanted with N^+. Detectors with electrodes in the form of parallel stripes [6] detect the component of the terahertz field perpendicular to the stripes. For one set of measurements the detector is placed in the divergent THz beam 25 mm behind the emitter, in another set the THz beam is refocused by two parabolic mirrors. In the latter case the path of the THz beam is about 0.5 m. A titanium-sapphire laser (wavelength 805 nm, repetition rate 832 MHz, pulse duration 40 fs) is used for both excitation of the emitter and gating of the detector antenna. The power and spot size of the near-infrared beams are 470 mW and 400 μm for the excitation beam and 80 mW and 350 μm for the gating beam, respectively. The emitter is biased with a rectangular voltage of 15 V with a frequency of 5 kHz and a duty cycle of 50 %. The photocurrent induced in

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the detector is amplified by a transimpedance amplifier and detected with lock-in technique, where the modulation of the bias voltage of the emitter serves as a reference. Temporal resolution is achieved by a mechanical delay line. For the antennas for the Bessel-Gauss modes precise alignment with respect to the excitation and gating beam is crucial. Illumination of outer parts of the antenna would result in radial symmetric modes mixed with linearly polarized modes. Observing the diffraction pattern of the near infrared laser is useful for centering the antenna on the axis of the beam.

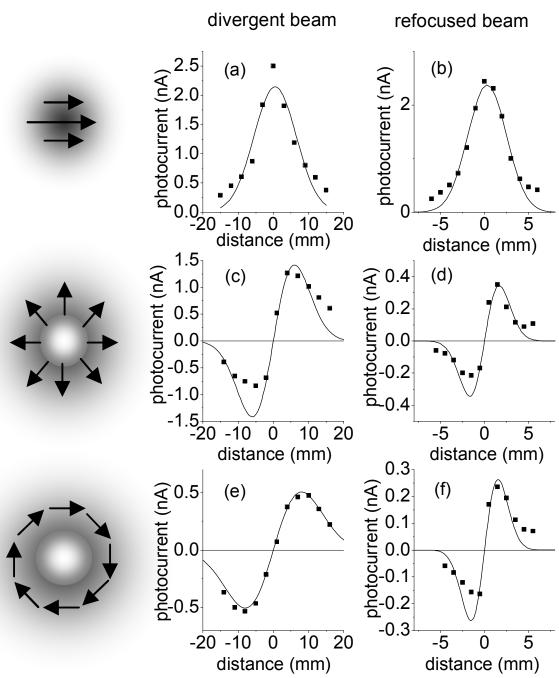

Fig. 2: Measured (dots) and fitted (lines) beam profiles in the horizontal direction for different modes. The calculation is based on the lowest order fundamental modes described in [1].

III. RESULTS AND DISCUSSION

In Fig. 1 the patters detected with an antenna for linearly polarized light (horizontal polarization for a-d, and vertical polarization for e, f) are shown for three different emitters, which generate linearly polarized Gauss beams (a, b), radially polarized (c, d), and azimuthally polarized Bessel-Gauss beams (e, f). One set of data is for the divergent beam and the other for the refocused beam. In all measurements the profile is scanned in the horizontal direction. For detection of the linearly and radially polarized beams (Fig. 2 a-d) the detector is oriented with the stripes in vertical direction, hence it is sensitive to the horizontal component of the THz field. For detection of the azimuthal mode the detector is rotated by 90° to be sensitive to the vertical component. The measured profiles can be well described by a Gaussian in the case of linear polarized light and a product of a Gaussian and the first order Bessel function in the case of the radially and azimuthally polarized beams. In Fig. 3 THz transients from an emitter for radially polarized modes are shown. Detection with an antenna matched for this mode results in seven times higher signals as compared to detection with an antenna for azimuthally polarized beams. This is a proof-of-principle that the antennas are useful for detection schemes that are sensitive for changes of the mode pattern. We note that the excitation beam and gating beam of our experiment have a slightly elliptical profile with Gaussian distribution along the horizontal and vertical axes. Optimized near-infrared beams for emission and detection of the THz-Bessel-Gauss modes would require a donut-like intensity distribution.

In summary interesting basic properties of THz vector beams can be studied with the flexible emitter designs. As a promising application, these structures are optimized for efficient coupling into THz waveguides.

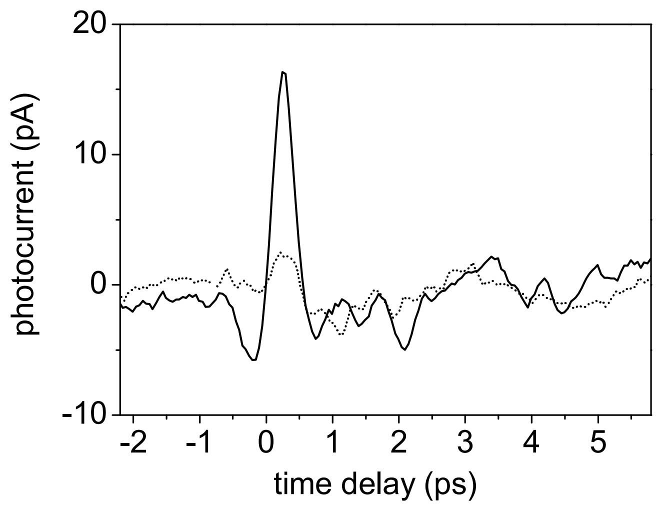

Fig. 3: THz trace from an emitter for radially polarized radiation detected with an antenna matched for this mode (solid line), and with an antenna matched for azimuthally polarized beams (dotted line).

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