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Non-invasive method of field imaging in parallel plate waveguides

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Abstract—**We present a new non-invasive air-photonic-based method of terahertz (THz) field imaging inside a parallel plate waveguide. The method is based on THz field-enhanced second harmonic generation of the fundamental laser beam in an external electric field. We also demonstrate the direct measurements of the frequency-dependent reflection coefficient at the end of the waveguide.**

I. INTRODUCTION

PARALLEL plate waveguide (PPWG) due to its simplicity but also unique properties has been an object of intensive investigation for guiding THz waves. The TEM mode of the PPWG is characterized by dispersionless propagation without a cut-off frequency, which makes it extremely useful for THz time domain spectroscopy (TDS) applications [1-3]. Recently tapered parallel plate waveguide (TPPWG) has been proposed [4-6]. It has been showed that TPPWG allows for subwavelength THz field confinement inside the TPPWG in both transverse dimensions [7], what could enable THz near-field imaging with subwavelength resolution. Also strong field enhancement can be achieved using TPPWG, which gives TPPWG big potential for investigation of nonlinear THz phenomena. For full experimental characterization of TPPWG properties, THz field distribution inside the waveguide is required. So far only method based on wave scattering from needle tip was demonstrated [8]. In this paper we present a new non-invasive method for characterization of the subpicosecond-long propagating electric transients inside a PPWG. The method is based on air biased coherent detection (ABCD) technique and does not disturb propagation of THz waves inside the waveguide. As an example of the application of our method a direct measurement of THz wave reflection from the waveguide end is presented.

II. RESULTS

The air biased coherent detection of THz radiation proposed by N. Karpowicz *et al.* [9] is based on the measurement of the terahertz-field-induced optical second harmonic generation (SHG) through a third order nonlinear process in the presence of external oscillating electric field E_{bias}. The intensity of the generated second harmonic $I_{2\omega}$ measured using lock-in detection at the frequency of oscillating bias field is given by

$$I_{2\omega} \propto \left(\chi^{(3)} I_\omega\right)^2 E_{bias} E_{THz},$$

where $\chi^{(3)}$ is the third-order susceptibility of air, E_{THz} the electric field of the THz transient and I_ω is the intensity of the fundamental beam. In our case the fundamental beam of intensity I_ω propagates perpendicular to the waveguide and is focused in the volume between waveguide plates. The TPPWG consists of two electrically isolated, fine polished aluminum plates of a varying width (input 3 mm, output 49 µm) and a varying plate separation (input 1 mm, output 200 µm). The total length of the waveguide is 25.4 mm. The metal plates of the TPPWG are connected to a high voltage modulator and in this way an external bias field E_{bias} of ± 5 kV/cm at the point of the narrowest gap between metal plates is provided. Broadband THz pulses generated by tilted pulse front optical rectification in LiNbO3 [10] is coupled into the TPPWG at the wide end of the waveguide. The THz wave propagates between aluminum and then couples out into the free space at the narrow end of the waveguide. A near-infrared (NIR) beam from a 1 kHz, 90 fs, 800 nm regenerative Ti:sapphire femtosecond laser amplifier is used for probing the THz field between the plates of the waveguide. The NIR beam is focused in the center of the volume between the plates and recollimated after the waveguide. The 400-nm light generated in the ABCD process is measured by a photomultiplier tube (PMT) referenced to HVM modulation frequency. By moving the focus point of the fundamental beam along the waveguide and changing the time delay between the THz pulse and the probing pulse THz enhanced second harmonic can be mapped out at different position along the TPPWG.
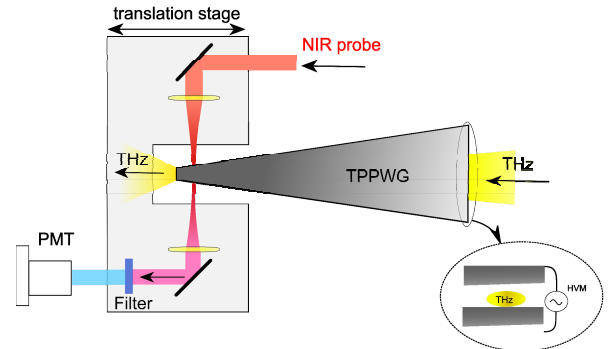

Fig. 1. Schematic of the air photonic setup for non-invasive field imaging inside a tapered parallel plate waveguide. THz radiation is coupled into the TPPWG, propagates along it and then interacts with NIR probe inducing second harmonic generation in the presence of oscillating local electric bias field delivered by high voltage modulator (HVM) and is measured by photomultiplying tube (PMT).

In Fig. 2 we show a 2D map of THz induced second harmonic $I_{2\omega}(z,t)$ as a function of probe delay time τ for different positions z along the waveguide. Two THz transients are present in the plot: the first transient, centered at 5 ps time delay, is the incident pulse propagating inside the waveguide.

The second transient, propagating in the opposite direction, originates from the reflection at the waveguide end (position z = 0 mm) due to the impedance mismatch between the waveguide ($z < 0$) and free space ($z > 0$). We have to note that for $z > 0$ (outside the waveguide) the bias electric field quickly decays, which leads to vanishing $I_{2\omega}(t, z)$.
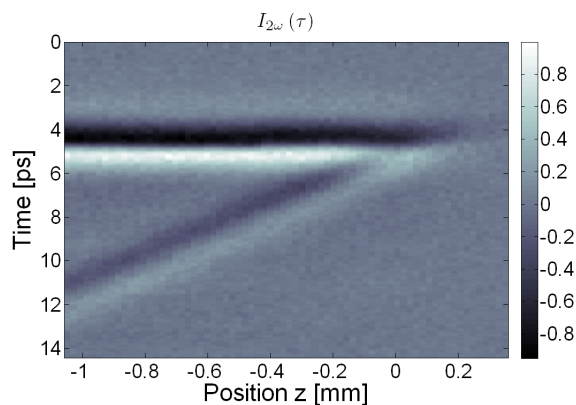

Fig. 2. 2D map of THz induced second harmonic $I_{2\omega}$ as a function of probe delay time τ for different positions z along the waveguide.

Fig. 3 presents measured frequency dependent amplitude refection coefficient of the waveguide defined as a ratio between Fourier components of reflected and incident electric fields. The reflection of the THz wave is caused by impedance mismatch between free space Z_0 and the waveguide Z_{PPWG}. We observe that the reflection coefficient $\Gamma = (Z_{PPWG} - Z_0) / (Z_{PPWG} + Z_0)$ decreases with increasing THz frequency, what is caused by frequency depended characteristics of Z_{PPWG}. The data for extraction of Γ(f) has been taken at a point $z = - 0.9$ mm from the waveguide tip to assure good temporal separation between the incident and reflected transients. That implies that the calculated reflection coefficient Γ includes not only reflection but also propagation effects, such as ohmic losses and wave scattering, which lead to additional reduction of the amplitude of the reflected wave.
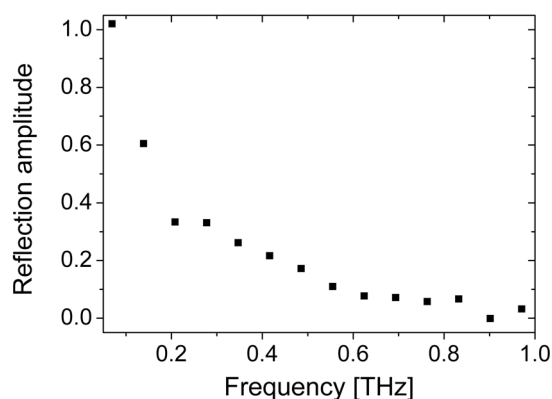

Fig. 3. Frequency dependent amplitude reflection coefficient Γ(f) of the waveguide end.

In conclusion we have presented a new non-invasive technique of imaging broadband THz transients inside parallel plate waveguides. The method does not disturb the propagating THz pulses, what has been shown on the direct measurement of THz reflection coefficient from the end of the waveguide.

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