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Terahertz near-field imaging using a Y splitter and Sommerfeld wire waves on bare metal rods

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***Abstract*— We describe a near-field experiment using a Y splitter supporting cw THz Sommerfeld wire modes coupled and decoupled with differential phase plates. Owing to a taper up to ~50 µm of one of the Y ends, a near-field imaging resolution of ~90 µm is demonstrated in agreement with calculations.**

I. Introduction and Background

Near-field imaging is a key technique for high resolution imaging. This is especially valuable in the terahertz (THz) range where the very long wavelength has a disastrous influence of the far-field imaging resolution limit. Besides the revamping of scanning near-field optical microscopy in the THz range, original systems taking benefit from Sommerfeld wire waves on bare metal rods[1] have been recently developed[2,3] since such waves have been demonstrated to be very efficient and easy to manage at THz frequencies[4-6].

Aiming at developing cw near-field imaging with versatile THz sources we already showed the combination of Sommerfeld wire modes excitation with a differential phase element and the longitudinal field selectivity of a tapered needle as near-field probe[3]. Awad *et al.*[2] showed separately that such a needle may provide large sub-wavelength resolution up to the µm scale. In this work, we carefully analyze the propagation of Sommerfeld waves on stainless steel rods. By combining them in a Y splitter[4,6] with a needle at one end and two differential phase plate elements, we obtain a cw near-field excitation near-field detection setup in the THz range. A great advantage of this setup is the coupling with external sources and detectors that involves only linearly polarized plane waves.

II. Method and Results

The proposed THz microscope system is shown in Fig. 1. It involves the coupling and propagation of Sommerfled waves along metallic wires. We already showed such coupling and propagation using a set of two parabolic mirrors and a Teflon differential phase element (DPE)[3]. The DPE induces a π-phase difference on half the input beam cross-section so that it efficiently overlaps with the radially polarized wire mode.

Sommerfled wave excitation is obtained with a microwave synthesizer followed by a 75-110 GHz sextupler electronic source from Spacek Labs Inc delivering ~0 dBm to a rectangular horn antenna. The linearly-polarized beam is focused and transformed into Sommerfled waves using two off-axis parabolic mirrors and a DPE. The detection is ensured by a similar quasi-optical system in front of the rectangular horn antenna coupled to a Schottky diode and a microwave spectrum analyzer. With acceptable settings of the spectrum analyzer, the noise detection level of the overall detection is estimated to -80 dBm. Stainless steel wires of 0.8 mm diameter and of known bulk resistivity $1.32\ 10^6\ \Omega^{-1}m^{-1}$ are placed in-between the two DPE couplers of diameter 6 cm. DPEs also serve as wire holders eventually supplemented by a Teflon disk of same diameter if long wires are considered. Emission and detection systems, including DPE and horn antennas, are cross-polarized to reduce any direct coupling. Additionally, an absorbing diaphragm with a clear aperture of 3 cm is used to cancel any direct transmission between horns while keeping a theoretical transmission in excess of 90% for the Sommerfeld wave. This was verified by measurements without the wire.

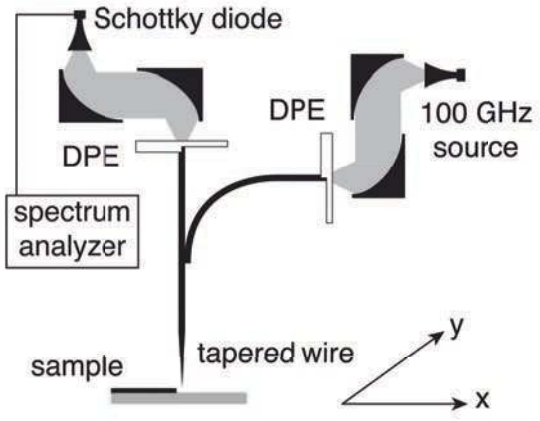


Fig. 1: Near-field experimental setup.

To optimize the system design, we conducted preliminary experiments to evaluate the various source of losses. Using successive cutback experiments, propagation losses of 0.2 dB/cm are measured, a value 5 times greater than the 0.04 dB/cm calculated[1], perhaps because of wire surface oxidation or contamination with organic materials that might have induced excess losses in combination with the low ~1 µm skin depth. Another result of this experiment was the estimation of a 32% DPE coupling efficiency deduced from the extrapolated transmission at null wire length as compared to the direct coupling between horns. This coupling efficiency is very close to the ~35% calculated value that we obtained from the known theoretical field profiles[1] and for an input Gaussian beam of waist ~11 mm.

In a second experiment, the radial extension of the wire mode was estimated using an iris around the rod that reduces progressively the allowed clear space for the wire mode transmission. We measured the power transmission by the Sommerfeld waves while the clear aperture of the iris is var-

ied. As shown in Fig. 2, the propagating mode is confined in a cylinder volume of radius about 5 times the wire radius (0.8 mm in our case). Notice that results at 220 GHz are very noisy because our detection system is very inefficient in that case. We calculated the corresponding transmission using the theoretical field profiles[1] and obtained a nearly perfect comparison with experiments, the mode being more confined at higher frequency. Nonetheless calculations show that the mode concentration in a cylinder volume of ~5 times the wire radius scales down up to the µm size, thus allowing a high field concentration at the near-field probe.[7]

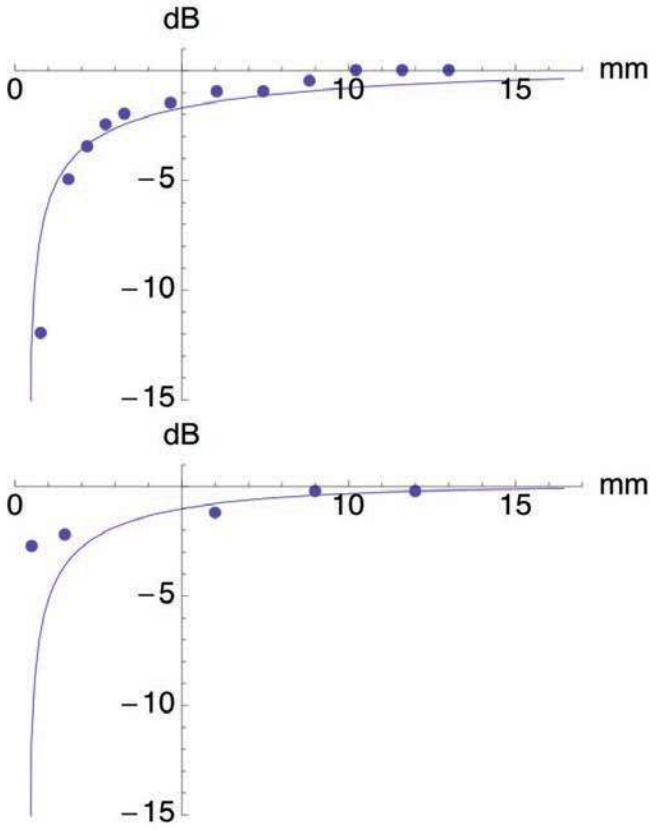


Fig. 2: Power transmissions of a Sommerfeld wire mode through an iris of variable clear aperture (abcissa is radius in mm). Upper curve: 100 GHz, lower curve: 220 GHz. Dots: measurement. Solid line: calculations.

Bending losses were evaluated with the same setup. We used the natural flexibility of metals by increasing the angle between emission and detection to progressively bend the wires. Figure 3 reports the measured losses per unit length of two wires with different metal nature and diameters. This procedure is different from that used in previous reports of the same measurement[6,8], but it produces very similar results as seen in Fig. 3. Note that bending radius below 15 cm are unattainable without inducing permanent distortion of the wire and large radius ≥60 cm are also impossible because they cannot be distinguished from the natural bending of the wire induced by its own weight. Also worth to be pointed out are the losses that appear nearly metal independent. This was previously suggested[6] and also validated by our own calculations. As a result, the differences between the two experimental curves are most likely due to the different wire radius than to the metal nature.

In the microscope of Fig. 1, we found necessary to introduce a right angle between source and detector to cancel the direct coupling due to sample specular reflection. It results in a 90° bend of 20 cm radius on one wire that induces a ~30 dB attenuation. Therefore, even with a perfect Y-splitter and an adiabatic focusing needle, large attenuations take action during image acquisition and reduce the signal to noise ratio.

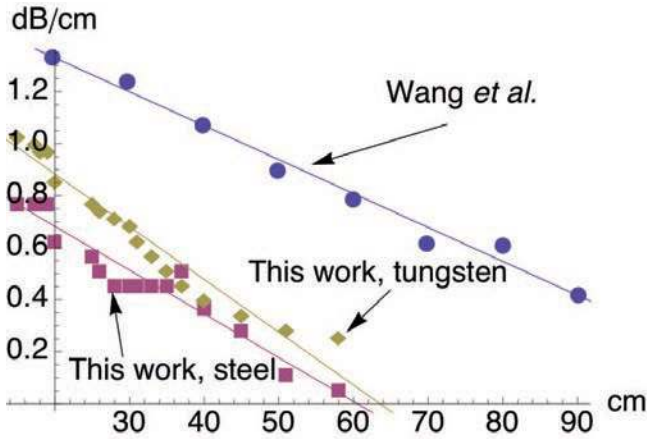


Fig. 3: Measured attenuations of Sommerfeld wire modes as a function of the radius of curvature. Two wires were tested at 100 GHz, a 0.8 mm diameter stainless steel and a 0.5 mm tungsten wire. Dots: measurement. Solid line: linear fits. Results are compared to Wang and Mittleman results of Ref. [6].

In a final integration, the Y splitter was built and we mechanically attached a 4 cm long metal needle to one of its end. Needle diameter was chosen to fit that of the wire and its end was tapered over a distance of 5 mm up to a spike with a 50 µm radius of curvature. This sharp end thus operates as a near-field probe sensitive to the longitudinal electric field[2,3]. The sample is raster-scanned right beneath the needle apex using two motorized translation stages and the probe height is adjusted before the scan with a manual translation stage of micrometer resolution. No active height control is applied during scans.

The imaging properties and the resolution ability of our setup were tested by scanning one metal (Au) right angle corner deposited on glass substrate. For an estimated ~10 µm flyover distance, a 1D scan obtained with a 5 µm linear step in given in Fig. 4. This scan exhibits a piecewise evolution with a linear transition from the upper level (probe over the metal) to the lower level (probe over the glass substrate). The transition between both occurs over a distance of 90 µm (10% to 90% edge criterion). This value corresponds to λ/33 and is close to the 50 µm characteristic size of the needle apex. The measured varying signal then comes from the near-field and corresponds to the detection of the longitudinal electric-field component[2,3]. This was confirmed by calculating from the theoretical field profiles[1], a 660 µm radial field extension at -3 dB for a 50 µm diameter stainless steel wire. As a consequence, any variation

in the detected signal that may originate from the radial field component would have extended over more than the spans used in experiments and just produced an increase of the background.

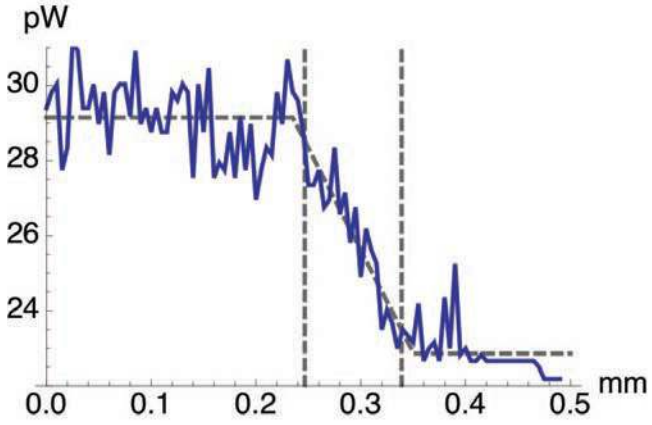


Fig. 4 : Measured transfer function during the probe flyover on the edge of an Au line on glass substrate. The dashed lines are the measurement piecewise approximations used for evaluating resolution.

III. Conclusion

We have built a versatile cw measurement setup for terahertz near-field reflectometry with a λ/33 resolution. Measurement examples have shown a detected power of only ~30 pW (i.e. -75 dBm) that is very close to the detection background level of our experimental setup. As characterized, most of the losses come from the wire bending. Changing the geometry in next evolutions of the setup can eventually reduce them efficiently. Improvements are also expected both in resolution and sensitivity by using sharper needles for which high electric field enhancements are expected in the near-field[7].

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