Time-domain high-speed read-out of Terahertz resonator arrays with sub-single-resonator resolution

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***Abstract*—Planar resonator arrays are becoming increasingly important for THz sensing applications. Minute amounts of sample substances placed at the array surface can be detected with orders of magnitude enhanced sensitivity compared to pure transmission because of resonator-induced local field enhancement. However, for further optimization of sensitivity and read-out speeds as well as advanced scientific investigations of sub-wavelength-scale EM properties, a non-invasive method for high-resolution field sampling is required. In this work, we demonstrate photoconductive microprobes for the high-resolution and high-speed near-field read-out of resonator arrays at acquisition speeds of up to 3 ms/resonator.**

I. INTRODUCTION

PLANAR resonator arrays are often used as spectral filters (also known as frequency-selective surfaces) or as optical elements (e.g. for light polarization state manipulation). Another especially at THz frequencies increasingly important application is the sensing of minute amounts of substances placed at the surface of planar resonator arrays [1]. In contrast to classic spectroscopic investigation, using conventional layer transmission the application of planar resonators effectively increases (da 2mal enhance) the field-interaction with the sample material by generating spatially and spectrally localized field enhancement [2]. As a result, small amounts of material can be detected with several orders of magnitude improved sensitivity compared to pure layer transmission [3]. So far, the read-out of the loading-state of the resonators has been commonly done using far-field emitter and detector components. Since the read-out area cannot be smaller than governed by the diffraction-limit – while resonator structure sizes are usually in the sub-wavelength range – it has been virtually impossible to read-out single resonators. Instead, ensembles of 5x5 resonators can be regarded as a typical lower limit of read-out resolution using free-space optics [4].

In this work, the read-out of 2304 individual resonators in a densely packed array configuration is demonstrated using non-invasive photoconductive (PC) THz microprobes [5] for field detection in only a few µm-distance to the array chip surface. The approach enables considerably higher sensitivities and increased chip read-out speeds as well as a direct monitoring of near-field electromagnetic dynamics, which are important advantages for future industrial and scientific applications**.**

II. RESULTS

The investigated resonator array structure is shown in Fig. 1. It is based on inverted asymmetrically split ring resonators fabricated on a 500-µm-thick fused silica substrate. The resonator array constant is 263 µm and the slit width of the rings is 20 µm. Individual resonators from the array are covered with a 1-µm-thin layer of photo-resist (AZ5214E, MicroChemicals) in order to investigate read-out of an arbitrary loaded array by the near-field microprobe sensor. The chip surface has been divided into four equally large sectors featuring different ratios of dielectrically loaded to unloaded resonators ranging from 3.6% to 50%. For the read-out the chip is excited from the bottom side with a y-polarized pulsed THz plane-wave propagating in z-direction. The beam diameter is approx. 3 mm. The PC microprobe is held in a fixed position with a chip-to-tip distance of ca. 10 µm while the chip is *xy*-scanned for spatial- and time-domain sampling of the *y*-component of the THz near-field.

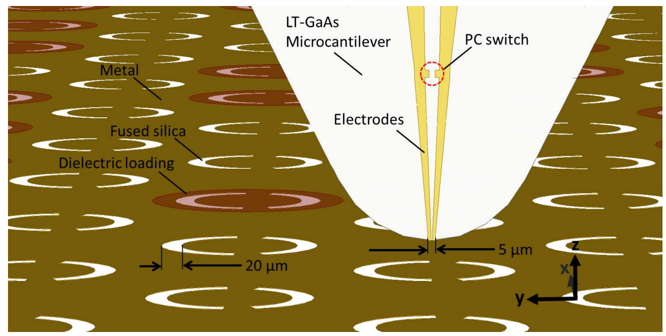

Fig. 1. 3D drawing of the applied PC micro-probe structure to scale with the investigated resonator array.

Fig. 2 shows the field mapping over almost the full chip area (13.5 mm x 13.5 mm scanning area) at the initial excitation state where the incident THz pulse is on its peak position (t = 0 ps). Each resonator is clearly recognizable by a local field enhancement. However, at this sampling time with a delay of 0ps between THz pulse and probe pulse, there is no distinct sign of an individual dielectric loading.

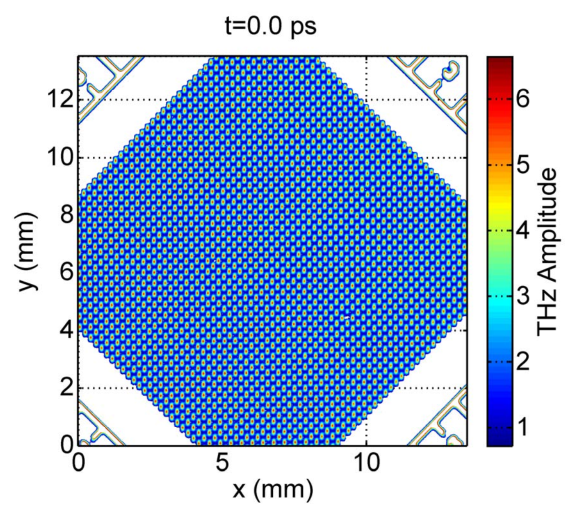

Fig. 2. Time-domain measurement data showing the E_x -field distribution at t = 0 ps (on THz pulse peak position). Raster scan resolution is 20 µm.

This can be explained by the dielectric properties of the applied photo-resist cladding material, which is introducing only negligible absorption of the THz field. An absorptive influence would have been visible in terms of a field amplitude reduction.

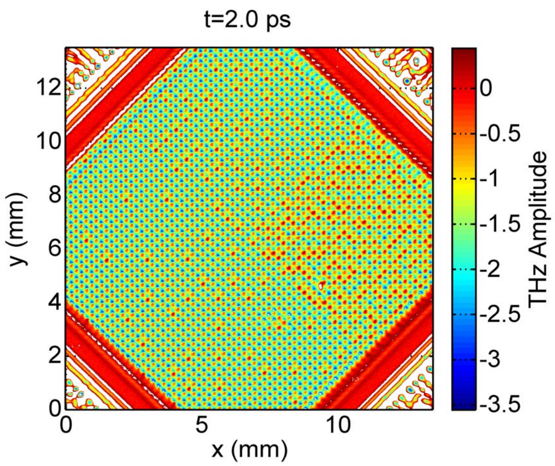

Fig. 3. Time-domain measurement data showing the E_x -field distribution at $t = 2$ ps. Raster scan resolution is 20 µm.

The main influence of the dielectric layer on the cladded ring resonator is a downshift of its resonance frequency [6], which cannot be seen at the initial excitation state, however, becomes visible afterwards due to an increasing phase delay causing a field amplitude contrast. The comparative near-field mapping plotted in Fig. 3 recorded at $t = 2$ ps is showing this very clearly. The near-field amplitude at the loaded ring resonators is considerably different from the unloaded ring resonators and appears as dark red spots.

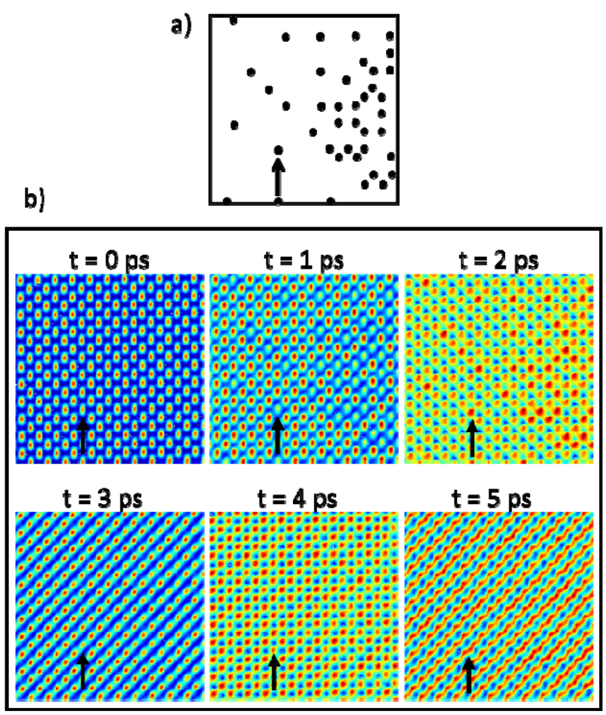

Fig. 4. (a) Pattern showing the positions of the dielectrically loaded resonators within the scanning range cutout as shown in the near-field amplitude plots under (b) for $t = 0$–5 ps.

In order to demonstrate the benefits of using a highly sensitive near-field microprobe over diffraction-limited far-field transmission for the read-out of densely packed sensor arrays further measurements at different time delays t are shown in Fig. 4 (b). The positions of the dielectrically loaded resonators within the considered scanning range are shown in Fig. 4 (a). For better orientation, a particular loaded resonator is marked with an arrow within the measurement data. The field mappings taken from $t = 0$–5 ps in 1 ps steps exhibit the transition from the initial excitation state until the occurrence of coupling between loaded and unloaded resonators which is impeding the clear assignment of loading states. For $t = 1$ ps – corresponding to a half oscillation of the 0.5 THz main resonance – the discrimination between the differently loaded resonators is maximally clear. At $t = 2$ ps the onset of inter-resonator coupling can be seen in terms of a slight yellowish shadow. The following field mappings taken at $t = 3$, 4 and 5 ps are all showing a strong presence of inter-resonator coupling making it practically impossible to identify the resonator loading state. At $t = 3$ ps a strong linear polarized coupling state is observed.

In order to optimize the read-out process in terms of required measurement time it is important to identify the optimum time delay where a strong material induced field contrast can be found *and* a clear discrimination between loaded and unloaded resonators is also possible. Both requirements are valid at $t = 1$ ps in this case. In addition, read-out times can be further reduced by limiting the chip sampling points to the field enhancement positions of the resonators. Here, with a min. sampling time of 3 ms/point a theoretical chip read-out time of <7 s could be achieved. In order to profit from an increased sample layer/resonator interaction at later sampling times without suffering from blurring through coupling effects larger resonator distances could be applied. This will however increase the effort for the efficient local capturing or placement of sample material at the sensitive hot-spots on the sensor array surface. In the talk, further data will be presented and optimized read-out scenarios will be introduced.

III. Summary

In summary, a non-invasive, highly sensitive and fast approach for the near-field read-out of individual sub-wavelength scale resonators has been presented.

References

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