THz nanofocusing with cantilevered THz-resonant antenna tips

- Supplementary Information -

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S1. Fabrication process of THz antenna probes

The fabrication process of the THz antenna probes is illustrated in Figure S1, showing scattering electron microscopy (SEM) images of different fabrication steps. To manufacture the tips we used a Helios450s electron microscope (FEI, Netherlands). We use standard Si atomic force microscopy (AFM) cantilevers, where we first cylindrically remove the tip as shown in Figure S1 a) and b) (cantilever colored in green). Then, a high aspect ratio conical tip is milled out of a solid Pt80/Ir20 wire (Advent Research Materials, England) (Fig. S1 c)), colored in yellow), cut at the desired length and fitted into the cylindrical grove in the Si cantilever (Fig. S1 d)). The cone was attached by focused ion beam induced deposition of platinum (purple, Fig. 1 a)). Finally, the tip apex was sharpened by circular ion milling along the tip axis. While monitoring the apex diameter and adjusting the milling parameters such as the ion beam current, the apex diameter was reduced to about 50 nm for all tips. This value was chosen due to its high reproducibility and better comparability with standard Pt/Ir coated AFM tips, which have a similar apex diameter. In principle a further reduction of the tip apex diameter down to about 10 nm is possible. In total we fabricated six different tips with lengths 17 μm, 33 μm, 43 μm, 54 μm, 65 μm, and 78 μm, as shown in Fig. S2.

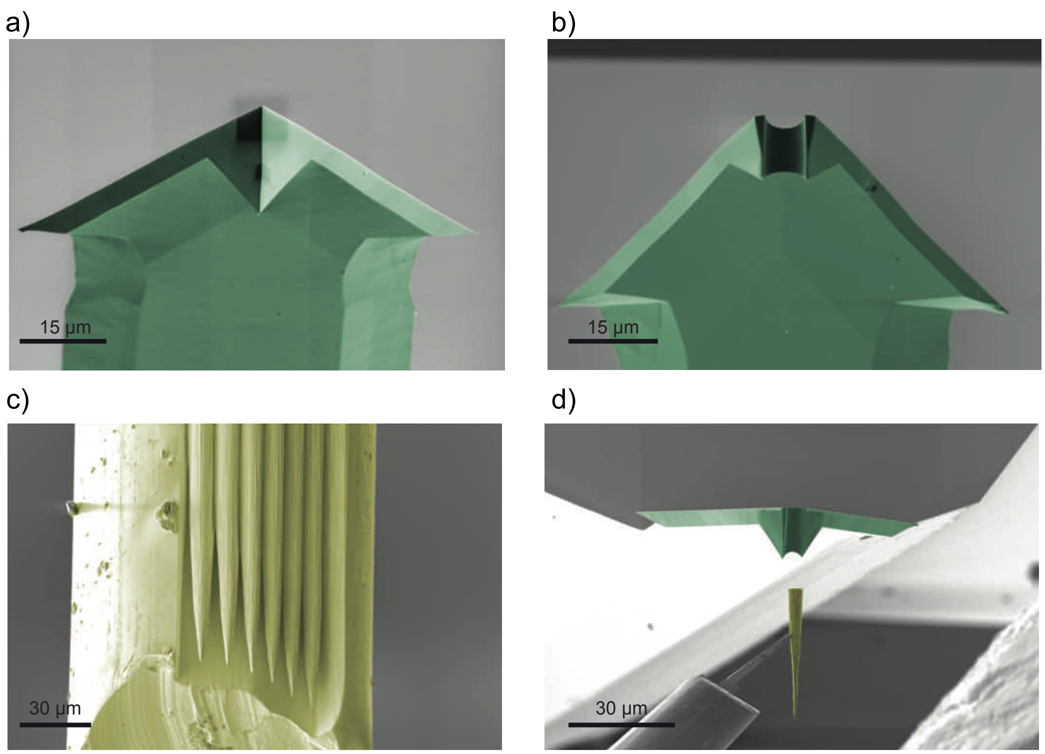

Figure S1: Illustration of the FIB fabrication process of resonant THz antenna probes. a) Commercial Si AFM cantilever with tip (green) (NanoWorld, Arrow NCR). b) Si AFM cantilever (green) with tip removed. c) Several cones cut from a 125 μm thick Pt/Ir wire (yellow). d) Pre-milled Pt/Ir cone (yellow) is fitted into the prepared cantilever (green) and attached using focused ion beam deposition of Pt.

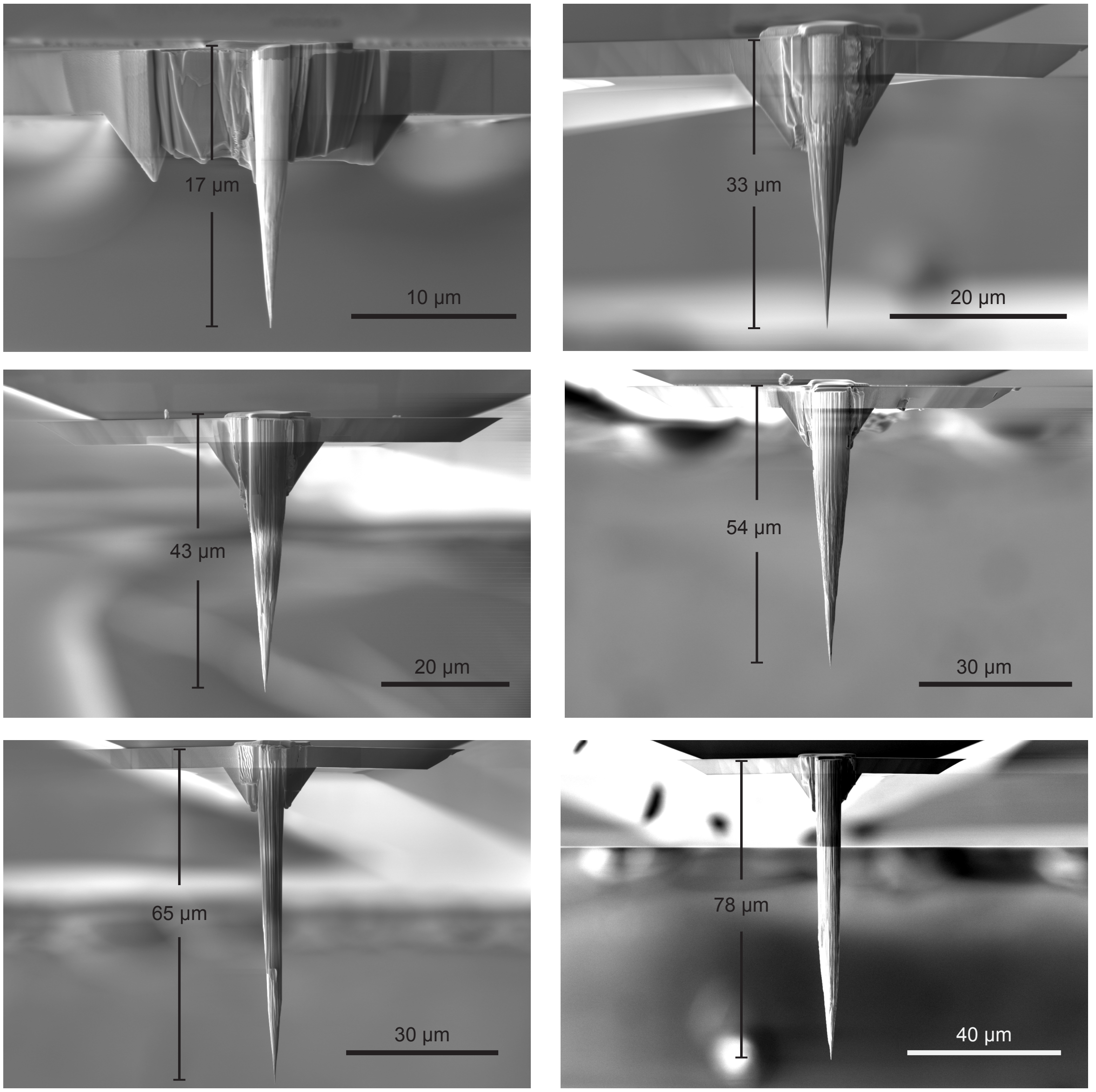

Figure S2: SEM images of the six fabricated THz antenna probes.

S2. Linearity of the graphene based THz detector

Figure S3 shows the linear dependence of the background-corrected DC photocurrent $\Delta I_{PC,DC}$ on the laser illumination power. It was measured with the 33 μm long tip, which supports the first dipolar antenna resonance, as shown in the Figure 3. For this measurements, all parameters were the same as in the main part of this article, except the laser power was varied to record a laser power – photocurrent $\Delta I_{PC,DC}$ dependence. The dependence shows a linear response of $\Delta I_{PC,DC}$ to the illuminating laser power (black dots, Fig. S3), which is supported by a least-squares fit on the data (red dashed line).

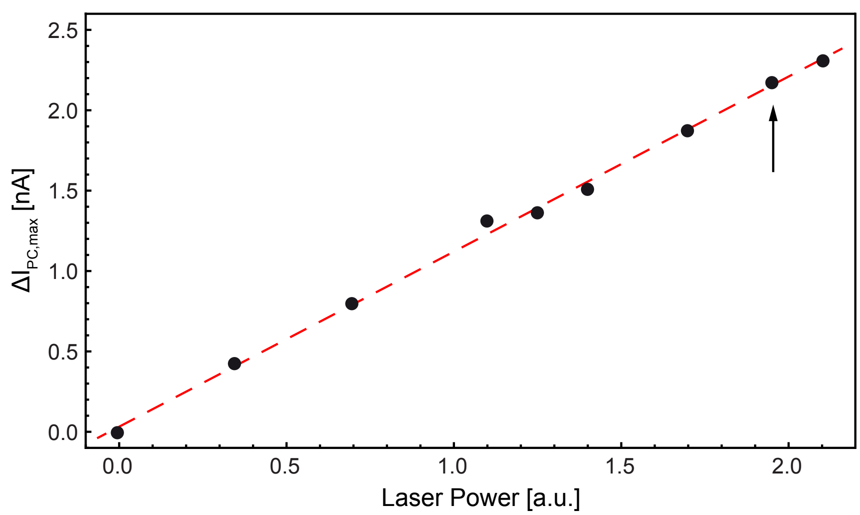

Figure S3: Linear dependence of the photocurrent I_{PC} on the THz laser illumination power. The black dots are measured data points and the red dashed line is a linear least-squares fit to the data. The arrow marks the power applied in the experiment.

S3. Fourier Filtering of DC photocurrent signals

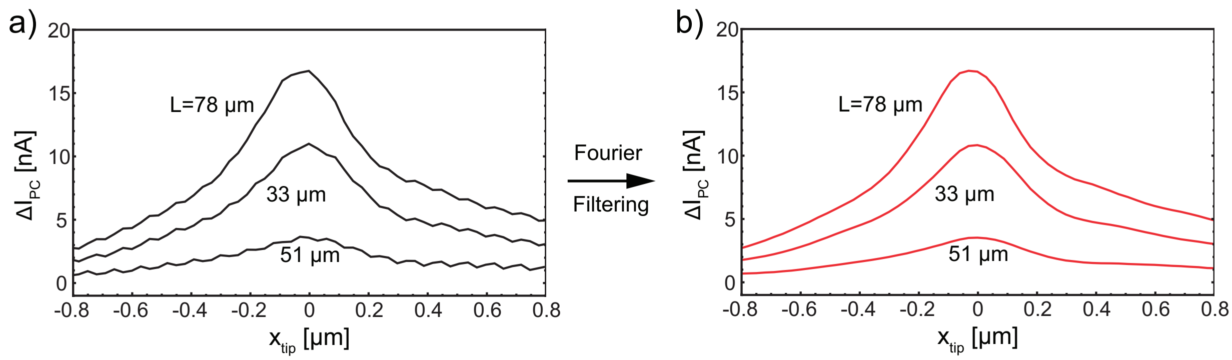

Figure S4: DC photocurrent line profiles presented in Fig. 3a. a) Line profiles as recorded and b) after Fourier filtering.

S4. Field confinement vs. field enhancement below tip apex

Figure S5 shows the calculated lateral field enhancement for tips with length L = 35 μm and 80 μm, which represent the lengths of the first and second antenna resonance as shown in the manuscript in Fig. 3b. For both tips, the field enhancement is strongest right below the tip apex, and decays for larger lateral distances, while the maximum field enhancement is different for the different tips (3600 for L = 35 μm and 4700 for L = 80 μm). However, the lateral field confinement is independent of the tips length for constant apex diameter of 50 nm. This shows that, by keeping the apex diameter constant, we avoid a change in photocurrent generation through a varying tip apex size, and can isolate the effect of excited antenna modes on the photocurrent generation.

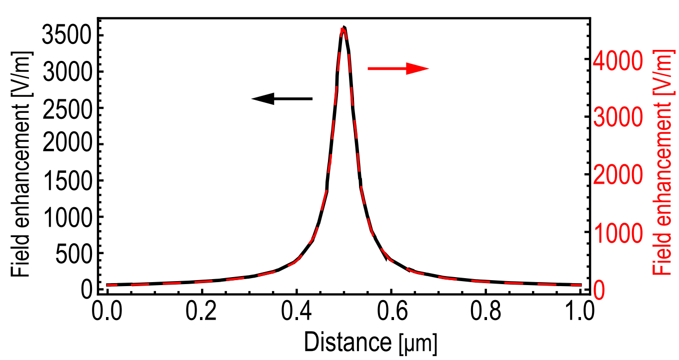

Figure S5: Calculated lateral field confinement below the tip apex (50 nm diameter) for length L = 35 μm and 80 μm