Out-of-plane THz electric field enhancement in vertical nano-slit arrays

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***Abstract* — We report an out-of-plane electric field enhancement in the terahertz range, using a non-conventional planar nano-slit array. Both simulations and experiments demonstrate that the field enhancement and the transmission coefficient are comparable with those observed in a planar slit array. This novel geometry is realized using standard thin film technology and thus will open the way for many new experiments where strong out of plane THz fields are needed. The planar process allows fabrication of slits with sub-nanometer gap size.**

I. INTRODUCTION

Over the past decades our ability to fabricate and manipulate structures on the nanoscale has continuously grown and has resulted in numerous advances in nano-science and nano-optics. For example, in 1998 Ebbesen et al. [1] demonstrated that nanoscale metallic antennas can couple incident optical beams to length scales much smaller than the diffraction limit. This scheme has recently been extended to the THz regime. Using suitable structures that act as nano-antennas, the electric field generated by THz light can be enhanced and localized to length scales well beyond the diffraction limit.

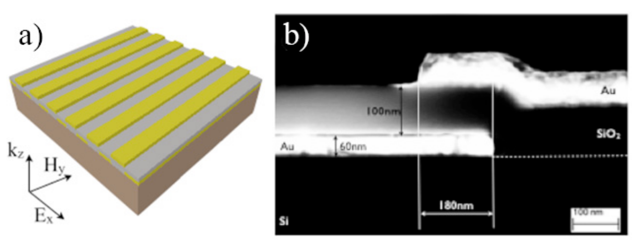

Fig. 1. a) Schematic illustration of the vertical nano-slit array. The slits are patterned with a periodicity of 40 µm over an area of 2x2 mm^2. b) Cross-section image of the vertical nano-slit array with a 100 nm high gap, obtained by scanning electron microscopy (SEM).

Due to the geometry of almost all structures, the electric field component, which is enhanced, is the in-plane component; see for example reference [2]. Here, we demonstrate the first out-of-plane field enhancement by using multilayer vertical nano-slit arrays. Through simulations and experiments we demonstrate that the field enhancement and the transmission coefficient are comparable to those observed in planar slit arrays. The corresponding structures are fabricated using standard thin film technology and will pave the way for experiments where strong out-of-plane THz electric fields are required. Our planar multilayer fabrication process is easy to implement, and allows fabrication of slits with sub-nanometer gap size.

II. RESULTS

In a planar slit array, for a fixed slit length and gap width, the field enhancement volume can be increased only by increasing the gold layer thickness. Conversely, when using a vertical slit array (Fig. 1a), the active volume can be increased by overlapping the two Au layers along the x-direction. In our structure the overlap is 180nm, approximately 3 times the Au layer thickness, as shown in Fig. 1b).

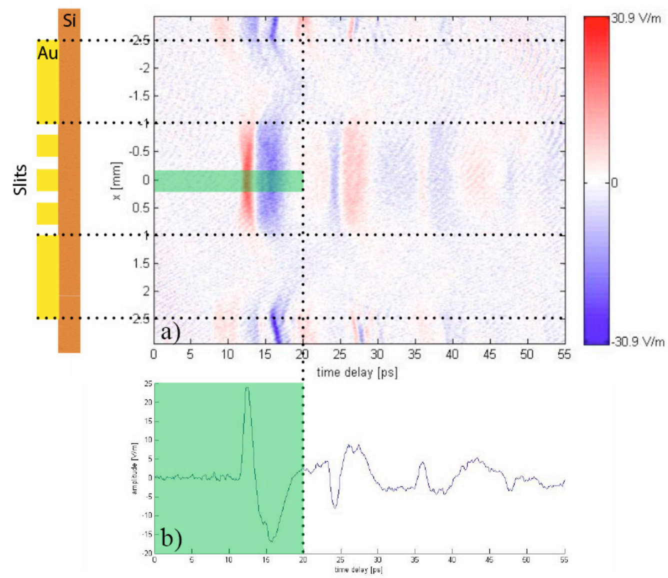

Fig. 2. a) THz pulse transmitted through a 2mm wide vertical nano-slit array with a gap of g=11nm and a periodicity of p=40µm. The vertical slits are surrounded by a solid gold frame (5x5mm^2) to guarantee the transmission of the pulse through the slits. Additionally, the pulses travelling around this gold frame are also plotted. The green box in a) shows the part of the measurement used for further calculations. Averaging the signal over x leads to the TD pulse pictured in b). Since there are several reflections present, the pulse is also cut after 20ps.

Figure 2a) shows an actual measurement of a vertical slit sample with g=11nm, p=40µm. A solid gold frame surrounds the 2x2mm^2-area of vertical slits, leading to a clearly recognizable signal and thus confirming a transmission through the slits. Additionally, the incoming pulse travelling around the gold frame is also visible at the edges. For further calculations, the middle part of the signal is averaged, leading to the time-domain signal shown in Figure 2b). Further, the pulses are cut after 20ps to suppress any reflections.

Figure 3a) shows the time-dependent THz signal after passing through the array of vertical nano-slits with a gap height of 110nm (red curve) and the substrate only (i.e. substrate with a gold frame) for reference (black curve). The

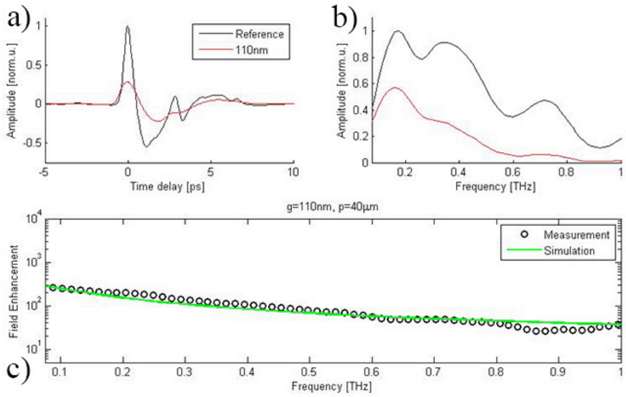

Fig. 3. THz fields transmitted through a 110nm vertical nano-slit array (red curves) and a reference sample (black curves) in time a) and in frequency domain b). c) Field enhancement derived from b) (green circles) and corresponding simulation (blue curve).

field enhancement is obtained from $FE(\omega) = (p/g)\, E_{sample}(\omega) \,/\, E_{reference}(\omega)$, where p is the periodicity of the array, and g is the gap height.

Figure 3c) shows the measured together with the simulated field enhancement. The simulations are performed in two dimensions with a commercial software (COMSOL) based on the finite element method (FEM).

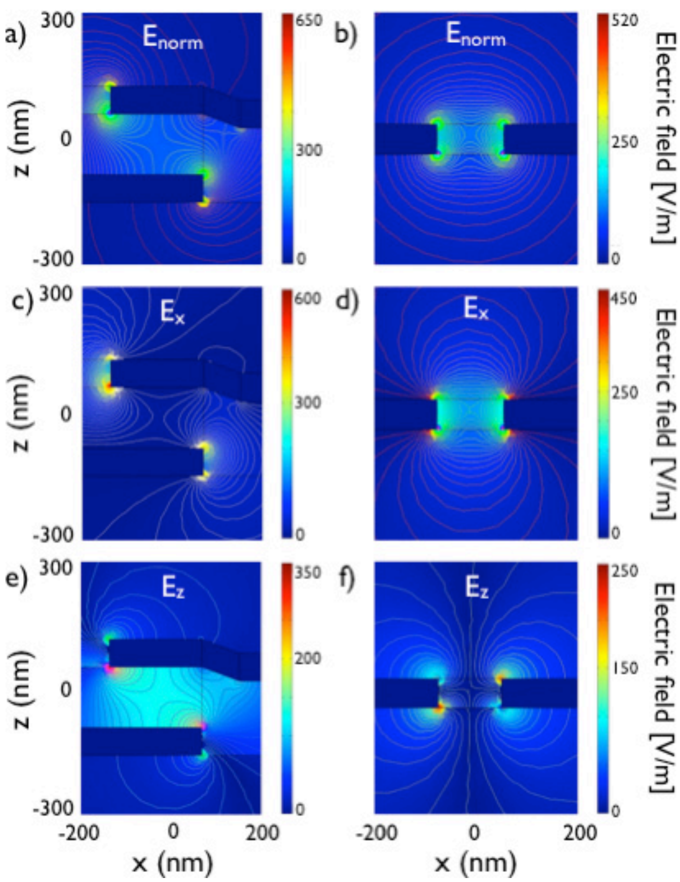

Fig. 4. Comparison between the vertical (left) and a planar nano-slit array (right); (a)-(b) Distribution of the normalized absolute electric field amplitude in an *xz*-slice cutting through the slit. (c)-(d) Electric field component along *x*-axis; (e)-(f) Electric field component along *z*-axis.

Finally, in Figure 4 we show the electric field distribution inside a vertical slit array (Fig. 4a, c, e) and a planar slit array (Fig. 4b, d, f). The FEM simulations confirm an in-plane field enhancement in the case of a standard nano-slit array and out-of-plane field enhancement in the case of the novel geometry. The simulated normalized absolute electric field amplitudes ($E_{norm} = (E_x^2 + E_y^2)^{1/2}$) are about 150 *V/m* (Fig. 4a, 4b) inside the gap in both cases; however, the *x* and *z* components of the electric field are very different. Whereas the incoming THz light is polarized along the *x*-axis in both structures, the planar slit array shows a field enhancement along the *x*-axis, whereas in the vertical slit array the field enhancement is mostly along the *z*-axis, and thus perpendicular to the incident THz field. This means that the modified slit array is able to rotate the electric field inside the gap without reducing its field enhancement, and thus creating an out-of-plane field enhancement.

III. Summary

We have demonstrated the possibility to rotate and to strongly enhance the incident THz field inside a vertically stacked nano-slit arrangement. Field enhancements as high as 300 were measured between 0.1 and 1 THz for 100 nm gaps.

References

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