THz Time-Domain Spectroscopy of Surface Plasmon Polaritons on Periodic Metal Arrays

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The coupling of electromagnetic radiation to surface plasmon polaritons (SPPs) by the use of periodic metal arrays is studied. Periodic metal arrays with different structures and distinct dimensions are investigated using a terahertz (THz) time-domain spectroscopy system. Transmission and reflection measurements on such metal arrays were performed. Good correlation between theory and experiment has been observed.

Introduction

The study of electromagnetic radiation interacting with periodic metallic arrays has experienced great interest in recent years [1]. In the case where radiation and pattern parameters are of the same scale the coupling to surface plasmon polaritons (SPP) offers a broad spectrum of research. For example, effects as extraordinary optical transmission [2] and photonic gaps are investigated [3]. Future applications such as optical sources and detectors or optical elements can be improved by these advances.

Coupling to two-dimensional photonic crystals in the terahertz (THz) region has been presented by several groups, showing the existence of SPPs on metals [4] as well as on semiconductors [5]. Mainly transmission measurements were presented while there are only few reflection measurements [6].

There has been work done on propagating SPPs through periodic structures in the visible [7] and more recently in the THz region [8]. To our knowledge, for two-dimensional photonic crystals there has been only research in the visible [9]. In this manuscript we present the study of surface plasmon polaritons on two-dimensional photonic crystals in transmission and reflection measurements by use of terahertz time-domain spectroscopy (THz-TDS).

Surface Plasmons and Their Coupling Techniques

The SPPs are electromagnetic waves coupled to the interface of two media, for example an air/gold interface or an air/semiconductor interface in the THz frequency region. The challenge when coupling to them is to overcome the k-vector mismatch between free propagating radiation and SPP.

Grating coupling uses the effect of scattering at the periodic array. Then, coupled SPP modes are given by

$$k_{SP} = k_0 \pm lk_x \pm mk_y$$

with k_0 the in-plane component of incident wave vector, k_x and k_y the reciprocal lattice vectors and l and m the mode defining integers. By varying the in-plane component k_0 the resonances get shifted, observable in a splitting of resonance frequency. Therefore grating coupling only allows to couple to certain given frequencies.

There are further coupling methods as it is attenuated total reflection (ATR). ATR in the THz region has been reported in [10]. Later, instead of finding ATR-coupling, the coupling by scattering on a prism has been observed [11]. Coupling by use of scattering is also applied at a technique referred as aperture coupling [12]. Further, waveguide coupling has been presented [13].

Results

Sample Fabrication and Measurement Setup

For measurements samples were prepared using standard microfabrication techniques. The metallic grid array has been deposited on highly resistive gallium arsenide plates. This material provides convenient mechanical support for the metal film and almost does not contribute to absorption and to dispersion of terahertz waves. The material used for the metallic grid array has been a 260 nm thick gold film. The SPPs were generated on the gallium-arsenide/gold and on air/gold interface. Different structures such as square, triangular and hexagonal have been prepared. Both, gold patches on GaAs and inverted structures with holes in gold on GaAs were used for measurements.

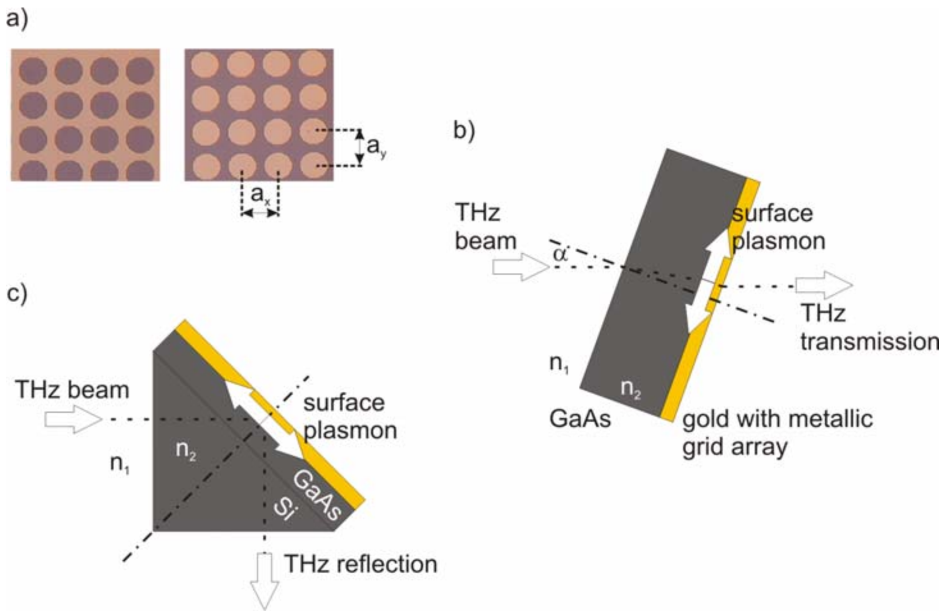

Fig. 1: Measurement Setup: (a) photograph of square samples with gold patches on GaAs and inverted structures with holes in the gold film; (b) transmission measurement configuration for varying angles of incidence; (c) reflection measurement configuration by use of a silicon prism attached to the perforated GaAs slab.

The samples were measured in transmission and reflection measurements using a THz time-domain spectroscopy (THz-TDS) system. An image of a square sample and the principle of transmission and reflection measurement are shown in Fig. 1.

Transmission Measurements

By use of transmission measurements on periodic metal arrays a study of coupling to SPPs has been performed. In transmission measurements a coupling to SPP is observed as an absorption in frequency. As can be seen in Fig. 2(a), the observed resonance frequencies for golden patches correspond to the frequencies calculated by the k-vector-matching condition given above. By tilting the axis a shift of resonance frequencies can be observed due to the increasing in-plane wave vector. Equivalent results could be observed from the inverted structures, i.e. holes in gold.

Reflection Measurements

Reflection measurements at an angle of incidence α=45° on the same samples were supposed to complete the picture of coupling to SPP. Additionally to the expected distinct resonance frequencies a coupling of SPPs to difference frequencies of calculated resonance frequencies for both interfaces, i.e. air/gold and GaAs/gold were observed. This can be seen in Fig. 2(b).

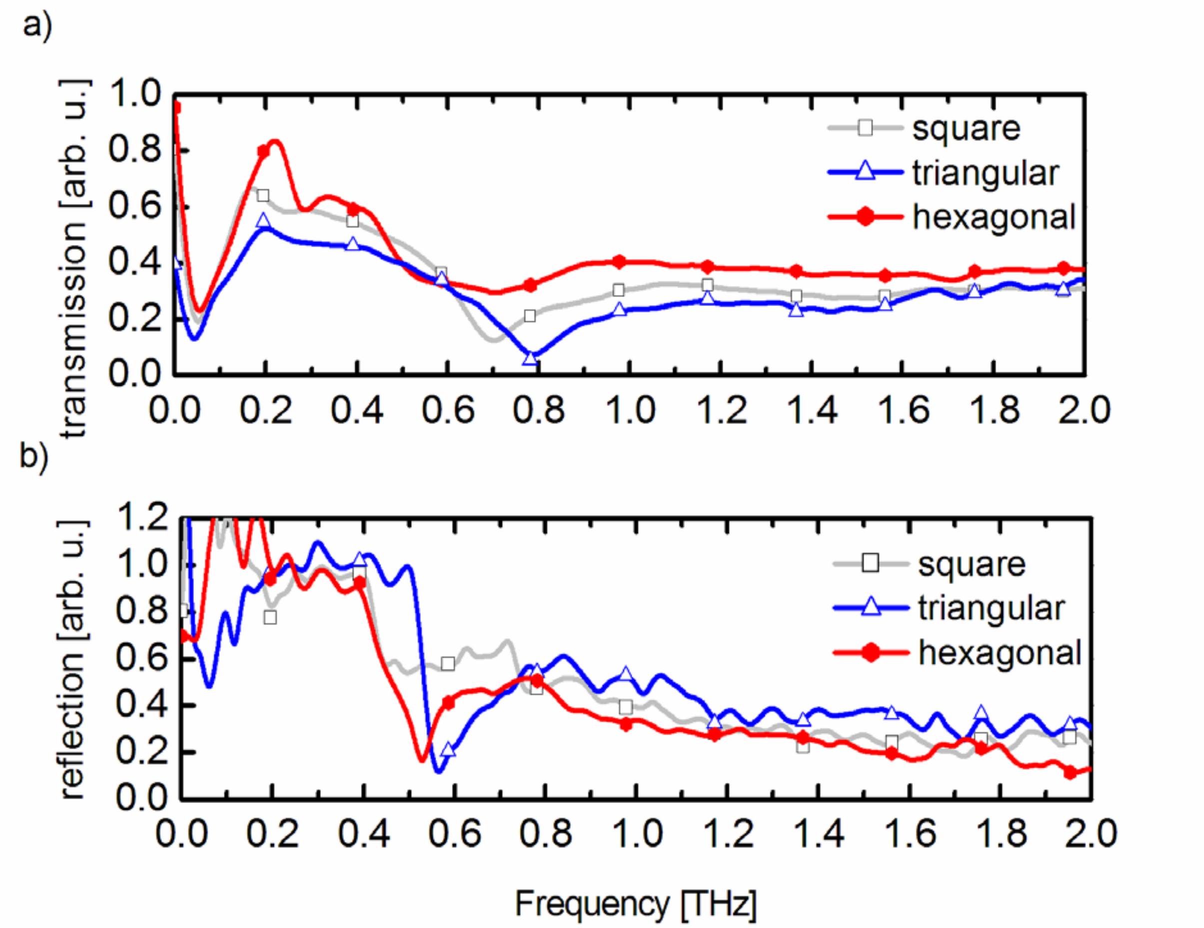

Fig. 2: Transmission at normal incidence (a) and reflection at 45° (b) for samples with golden patches on highly resistive GaAs, ordered in square, triangular and hexagonal structures.

Conclusion

In conclusion we were investigating SPPs using a THz-TDS system. We found good correlation between transmission and reflection measurements mapping the spectral response of SPPs.

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