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Exploiting extreme coupling to realize a metamaterial perfect absorber

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ABSTRACT

An optical metamaterial, operating in between the MID/IR and the visible domain, which uses the effect of extreme coupling between closely spaced nanostructured gold metal plates and a planar gold substrate was realized by means of electron beam lithography and lift-off technique. This regime is only accessible by using an ultrathin oxide layer between metal plates and substrate, where the oxide layerisrealized by atomic layer deposition here. The involved fabrication is discussed in detail. The metamaterial shows the predicted effect of perfect absorption with multiple resonances in the spectral range from 100 THz to 600 THz. The plasmonic based resonance frequencies are very sensitive to the plate size of the grating and the spacer thickness.

1. Introduction

Recent developments in the field of metamaterials suggest that perfect absorbers have a high potential for a number of applications and are therefore of high interest [1–8] To achieve perfect absorption, transmission is commonly eliminated by metal-coating of the substrate, where reflection is significantly suppressed by exploiting specifically tailored plasmonic resonances that dissipate the energy with no or only marginal radiation losses. In perfect absorbers, these plasmonic resonances are usually achieved by coupling metallic nanoparticles with the metallic substrate by bringing them in close proximity [2,4,9,10]. While such functionality may be rather easily achieved for a specific propagation direction and frequency, it is a challenge to retain perfect absorption for all angles of incidence at a desired frequency or even at several frequencies [10,11]. In the present contribution we show that the exploitation of the extreme coupling regime [12] between nanostructured gold metal plates and the planar gold-covered substrate (see Fig. 1) allows for an easy control even at multiple resonance frequencies, which are extremely sensitive to the thickness d_{Oxide} [13]. Extreme coupling requires the distance between the metal plates and the planar substrate to bein the order of a few nanometersonly, a size domain only accessible by atomic layer deposition [14]. The extreme coupling regime even provides a new quality compared to strong coupling or coupling in general. Where coupling suggest as hybridization of electric dipolar modes with a frequency splitting proportional to the strength of the coupling, extreme coupling allows for multiple resonances which can be explained just in the context of resonant metal-insulator-metal waveguide modes [13].

2. Grating design and simulations

A well-documented concept to achieve very high or even perfect absorption relies on the idea to block the transmission by a thick metal plate and to reduce the reflection (and therefore to increase the absorption significantly) by placing appropriate resonators on top of the metallic substrate [9,10,15]. However, it is very difficult to realize resonators that show almost no dependence on the angle of incidence of the incoming light. For example, small metallic plates separated by a dielectric spacer from the metallic substrate show strong absorption at certain discrete resonance frequencies at normal incidence. However, at oblique incidence the resonance frequencies are shifted, the excitation strength is weakened and the absorption is reduced [2,9]. On the other hand, within the extreme coupling regime a dielectric layer between the metallic plates will serve as a metal-insulator-metal (MIM) waveguide with a large effective propagation constant for a small spacer thickness [13] such that the resonance frequency is almost unchanged by a variation of the angle of incidence. Following this regime the first resonance appears at a quite large wavelength compared to the plate size due to the high index waveguide and even higher order modes are possible due to the resonance shift towards smaller frequencies.

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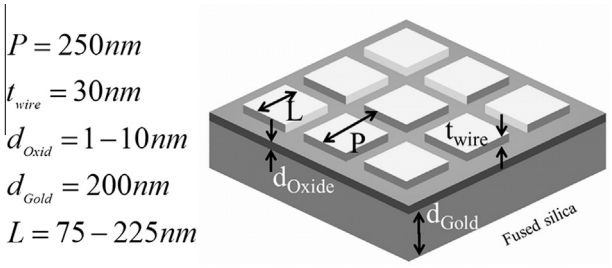

Fig. 1. Schematic illustration of the design and the parameters of the MPA-grating. The fused silica substrate is not shown.

The "metamaterial perfect absorber"-grating (MPA) we consider here consists of a 200 nm thick gold bottom layer (the mirror layer) followed by an ultrathin dielectric interlayer (SiO_2 or Al_2O_3) and a 2D-gold grating with a pitch of 250 nm (Fig. 1).

Due to the vanishing transmission T and absorption A = 1−R(eflection) we concentrate on the evaluation of spectra in reflection. To simulate these spectra a Fourier Modal Method (FMM) [16] was used. The reflection for a system with an ALD-layer thickness of 4 nm, a period of 250 nm and plate length (or plate size) L of 175 nm is exemplarily shown in Fig. 2. The fundamental resonance appears at 150 THz, i.e. a vacuum wavelength of 2 μm, exhibiting a reasonably large resonance-wavelength to cell size ratio of 8. At normal incidence just the even modes are excitable, whereas at oblique incidence additional oddresonances are excited around 275 THz (first) and 390 THz (third). The current distributions for the fundamental (zeroth) and second order resonances are shown in Fig. 3.

For the fundamental mode the reflection is very small, i.e. the absorption is very large. The excitation strength of the modes decreases with increasing order and, hence, increasing frequency, which is due to the reduced overlap of the incoming plane wave with the respective mode [9]. For higher order modes the number of nodes N of the field in tangential direction increases, as can be seen from Fig. 3, such that the overlap with a plane wave at normal incidence vanishes for N tending to infinity.

3. Fabrication

The fabrication of the MPA-gratings starts on wafer-level by using a 4" fused-silica wafer. The wafer layout consists of an

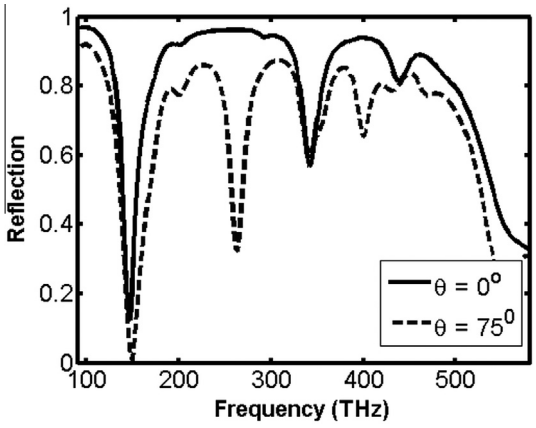

Fig. 2. Reflection at normal and oblique incidence for TM-polarization obtained from numerical simulations. The thickness of the spacer is d_{oxid} = 4 nm and the length of the plate L = 175 nm. Note that the fundamental and the second order resonance (even ones) can be excited at normal as well as oblique incidence; the odd ones just at oblique incidence. The resonance frequency is almost unaffected by the angle due to the large propagation constant of the resonant MIM-waveguide mode [13], leading to an angular independent resonance [12].

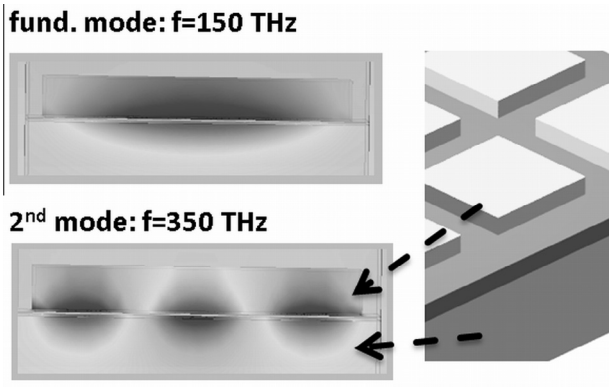

Fig. 3. Current distribution for the two lowest modes (fundamental and second order) which can be excited at normal incidence. For symmetry reasons, odd modes are excitable only at oblique incidence.

arrangement of several 15 × 15 mm^2 chips. Each chip contains six numbered gold mirror plates with a size of 2 × 2 mm^2 and alignment marks.

Both the gold mirror plates and the alignment marks were prepared by using electron beam lithography, thermal evaporation and lift-off-technique. The pre-cleaned fused silica wafer was coated with a two-layer lift-off resist (300 nm ZEP 520A on 200 nm ARP 617.06) and was additionally covered with a 10 nm thick gold conduction layer. The e-beam exposure of the large scale mirror plate pattern was performed using the shaped beam writer SB350 OS (50 keV, Vistec Electron Beam GmbH) at an electron dose of 90 μC/cm^2. After the development (40 s in ZED RD and 60 s in AR600-50, both stopped in IPA) the resist patterns were covered by means of thermal evaporation with a 3 nm thick titanium-adhesion-layer followed by a 200 nm thick gold layer. The lift-off process was performed in a 10:1-mixture of 2-methoxyethanol and acetone. After the lift-off the wafer with the gold mirror plates was tempered for 2 h at 230 °C on a hotplate. Both the post-curing process and the film growth at an evaporation rate of 0.1 nm/s result in a smooth but also wave-like surface of the 200 nm thick gold layer. The typical grain structure with a mean grain size of 80 nm is also shown in the SEM-micrographs (Fig. 4). Cross-sectional TEM measurements show that the surface roughness on an individual grain area is very small (Δz < 1 nm) but the roughness from grain to grain is in the range of Δz = 7–10 nm (peak-to-valley).

To enable investigations with different oxide thickness (d_{Oxid}), the wafer was sliced into chips. These chips were individually coated with ultrathin SiO_2 or Al_2O_3 films (between 1 and 10 nm) by using atomic layer deposition. The plasma-enhanced ALD process was performed with an OpAL-reactor from Oxford Instruments. The OpAL has been upgraded with an inductive-coupled plasma source. A detailed configuration of a similar reactor is described for example in [17]. In contrast to the equipment described in this reference, our OpAL is only equipped with a rotary vane pump. As precursors we used trimethylaluminum (TMAl) for aluminium oxide (Al_2O_3) and tris-(dimethylamino)-silane (TDMAS) for silicon oxide (SiO_2). Al_2O_3 was deposited with thermal ALD using water as second precursor. The deposition temperature was 80 °C. SiO_2 was deposited with remote oxygen plasma at a plasma pressure of 22.3 Pa. Argon as well as nitrogen were used as inert purge gases between both precursor dosing steps. The growth rate of SiO_2 was estimated to 1.19 ± 0.06 Å/cycle, the rate of thermal deposited Al_2O_3 was 1.05 ± 0.06 Å/cycle. For both materials, SiO_2 and Al_2O_3, the time for one cycle is about 20 s. Using ALD, the film thickness is the product of the number of reaction cycles and the growth rate (=growth per cycle). This