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Proceedings of Symposium on Ultrasonic Electronics, Vol. 32 (2011) pp. 9-10
8-10 November, 2011

Extraordinary optical transmission modulated by the vibrational modes of a periodic structure of square holes

2D プラズモニック結晶における GHz 振動モードによる透過率変調

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1. Introduction

Coherent acoustic phonons in nanostructures can be generated and detected in solids with femtosecond optical pulses [1-3]. The use of such phonons has been suggested for the active control of surface plasmon polaritons (SPP). Guyader *et al.* [4] demonstrated the coherent control of SPP-mediated extraordinary optical transmission (EOT) through arrays of circular nano-holes in a gold film on a garnet substrate by surface acoustic waves induced by a sequence of ultrashort laser pulses. Gerard *et al.* [5] made a numerical study of the optoacoustic effect in a one-dimensional slit EOT piezoelectric structure. However, these studies lacked sufficient quantitative analysis of the vibrational modes excited.

In this work we report on the modulation of EOT by gigahertz vibrational modes using a combination of both experiment and numerical simulations. The samples consist of square lattices of microscopic square holes in a gold film on glass. We use an ultrafast optical pump-probe technique for the experiments and a time-domain finite-element technique for simulations.

2. Samples

EOT structure arrays were fabricated on the borosilicate glass substrate using high resolution electron beam patterning of 2 nm Ti and 37 nm Au bilayers deposited by sputtering. A typical sample is shown in the scanning electron micrograph (SEM) of Fig. 1(a), showing hole width 240 nm and pitch 780 nm, as estimated by SEM.

3. Experimental setup

Figure 2 shows a schematic diagram of the experimental setup. We use a dual mode-locked pulsed laser system that allows independent control of the probe photon energy. Infrared optical probe pulses of photon energy tunable in the range 1.44 eV to 1.68 eV (wavelength 860 nm to 740 nm) and repetition rate 81.8 MHz from a mode-locked picosecond Ti:Sapphire laser are used to probe the vibrational modes. The second harmonic at 415 nm is used for the pump beam, and this beam is modulated at a frequency of 1 MHz by an acousto-optic modulator for purposes of lock-in detection. Vibrations of the EOT structures are generated through a thermoelastic mechanism. The pump and probe spot diameters are ~2 µm. With these spot sizes, ~10 holes are simultaneously probed. Both pump and probe are horizontally linearly polarized. All experiments were performed at room temperature.

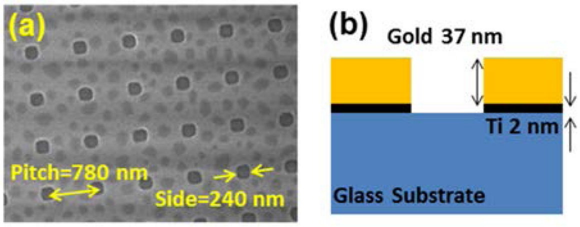

Fig. 1: (a) Scanning electron micrograph of the EOT sample. (b) EOT sample section.

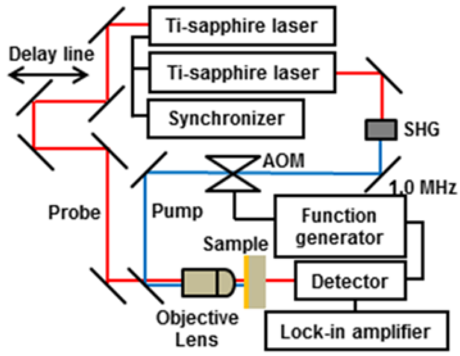

Fig. 2: Experimental setup. AOM = acousto - optic modulator, SHG = second - harmonic generation crystal.

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4. Results and discussion

Results for the transient changes in relative transmission $\Delta T(t)/T$ of the EOT structure at 820 nm probe wavelength are shown in Fig. 3(a). Ultrafast carrier excitation produces a sharp spike at the moment of pump pulse arrival (t=0). Variations in transmission subsequently show oscillations superimposed on a slowly varying background arising from thermal diffusion. We plot in Fig. 3(b) the modulus of the temporal Fourier transform. The peak at 22 GHz is a Brillouin peak arising from the interference between the light reflected from the sample surface and from the longitudinal strain pulse propagating directly away from the surface. The oscillation frequency for normal optical probe incidence is given by $f = 2nv_l/\lambda$ where n is refractive index of glass, v_l is the longitudinal sound velocity of glass, and λ is wavelength of the probe light. The calculated frequency is in good agreement with the experimental value. The peaks at 5.5, 7.5, 12.5 GHz correspond to vibrational modes of the EOT structure. We verified that on changing the probe wavelength the Brillouin peak shifted as expected whereas the EOT structural resonances did not.

To better understanding the vibrational modes we implement a time-domain finite-element simulation (PZFlex, Weidlinger Associates Inc.). A substrate region of dimensions $3.5 \times 3.5 \times 3\ \mu\mathrm{m}^3$ was modeled. Symmetric boundary conditions were applied in vertical and lateral planes to effectively reduce the sample volume. Absorbing boundary conditions were used on the other surfaces, with the top surface remaining free. The element size was ~6 nm^3, the time step was 0.84 ps and the total time for the simulation was 1 ns. A downward vertical force field in the form of a half sine wave of duration 50 ps was applied uniformly over all the top surface of the EOT structure. The z axis is defined in Fig. 4 (c). In this simulation different acousto-optical effects contribute to probe beam modulation: (i) $\Delta T/T$ from photoelastic effects in the gold and substrate, (ii) $\Delta T/T$ from the z-directed deformation of the gold (change in hole depth), (iii) $\Delta T/T$ from x- and y-directed deformations of the gold (change in hole shape), (iv) $\Delta T/T$ from deformations of the substrate surface. These effects depend on the presence of SPP or spoof-SPP. Figure 4 (a), (b) show the simulated time domain z-displacement in the gold layer and its temporal Fourier transform modulus, respectively. Various dominant vibrational modes are evident in approximate agreement with experiment.

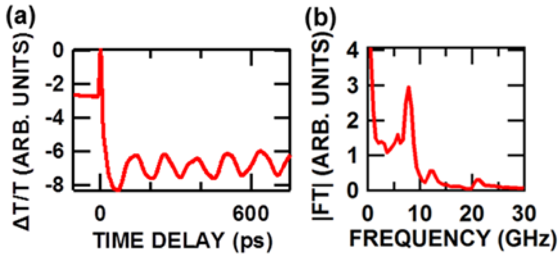

Fig. 3: (a) Relative transmission change vs. time delay between the pump and the probe pulses at 820 nm probe wavelength. (b) Modulus of the temporal Fourier transform of the transmittance variation.

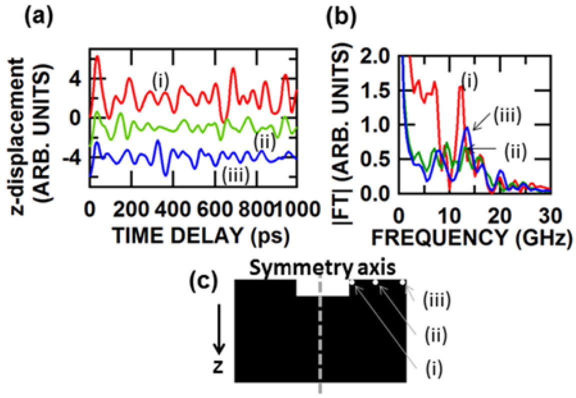

Fig. 4: (a), (b) simulated time domain z-displacement and its temporal Fourier transform modulus. (c) sample section showing sampling for (i), (ii), (iii) in (a), (b).

5. Conclusions

We show by experiment and simulation that several GHz vibrational modes of an EOT structure can be detected with transmitted ultrashort light pulses. This research may lead to the development of novel acousto-optic modulators based on SPP.

References

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