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Fabry–Perot effects in THz time-domain spectroscopy of plasmonic band-gap structures

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Using terahertz time-domain spectroscopy, we study transmission in one-dimensional arrays of slits fabricated on metal plates by laser machining. The enhanced peaks of zero-order transmission spectra are attributed to the combined effects of Fabry–Perot and surface plasmon resonances. Angle dependence of transmission spectra shows that the strongly surface plasmon-enhanced peaks appear when the Fabry–Perot-type resonance is located nearby in energy. This means that surface waves traveling in the horizontal direction couple with nearest Fabry–Perot resonance to generate enhanced peaks. These results are in excellent agreement with theoretical calculations. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2174104]

Optical property of plamonic band-gap structures with metallic arrays of subwavelength slits is a research topic with rich history. After Wood's famous investigation[1] of spectral anomalies in reflection gratings, many researchers studied mechanisms of optical anomalies in metallic gratings.[2–4] In particular, the work of Lochbihler and Depine,[5] published more than ten years ago, dealt with a transmission metallic grating. The one- and two-dimensional transmission gratings have become an intense subject of research ever since Ebbesen *et al.*[6] reported the enhanced transmission in two-dimensional arrays of sub-wavelength holes.

One major difference between one- and two-dimensional structures is the existence of Fabry–Perot resonance in one-dimensional gratings as mentioned theoretically in the infrared region[7] and experimentally in the microwave region.[8] Porto *et al.*[9] reported two types of mechanisms of the enhanced transmission in the transmission metallic gratings, coupled surface plasmon polaritons, and cavity modes located inside the slits which was also studied by other groups.[10–12] In addition, transmission resonances on the surface of metals or semiconductors were reported in the terahertz (THz) region.[13–16] We however note that Fabry–Perot resonance has never been observed in the optical or near-infrared region, and it is not clear how Fabry–Perot affects coupled surface plasmons in the optical and THz regions.

In this letter, we explicitly show that transmission resonances in periodic arrays of slits are due to the Fabry–Perot-type modes, related to the sample thickness, combined with the surface plasmon resonances. We used a standard THz time-domain spectroscopy system with a spectral range from 0.1 to 2.5 THz generated by a semi-insulating GaAs emitter biased with a 50 kHz and 300 V square voltages.[17] A laser machining system has been used to fabricate periodic structures on aluminum plates of different thicknesses. A scanning electron microscopy (SEM) image of the periodic arrays of slits is shown in Fig. 1(a). We measure the angle dependence of transmission spectra by tilting the sample stage as shown in Fig. 1(b). The input THz pulses are incident on the metal surface with a polarization along the x axis, which is perpendicular to the metallic slits running along the y direction. As shown in Fig. 1(b), the incident angle is changed from $-10°$ to $+50°$ by a rotating sample stage.

To calculate transmittance, metallic structures are considered a perfect conductor so that finite conductivity effects are neglected. This is a good approximation in the THz range, because the real and imaginary parts of dielectric constant of most metals are of the order of −30 000 and 100 000, respectively. Therefore, most metals in this range act as perfect conductors and there are no surface plasmon modes on the flat metal surface. Having periodic arrays of holes generate "designer" (or "spoof") surface plasmons,[18] whereby the perfect metals interrupted with a periodic array of slits behave as if it is a poor metal with finite conductivity, this time without interruption.

We consider a simple model system with rectangular-shaped slits as shown in Fig. 2. Matching the cavity modes expansion inside the slits with the Rayleigh expansion out-

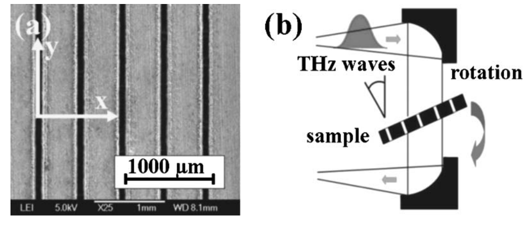

FIG. 1. (a) A SEM image for a typical sample laser machined on an aluminum plate. (b) Experimental setup. The angle dependent transmission spectra are measured by tilting the sample stage.

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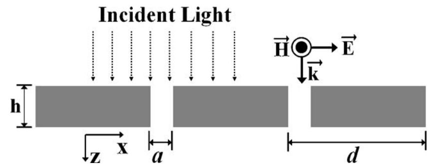

FIG. 2. Geometry of a simple model system with rectangular-shaped slits. a, d, and h are slit width, period, and sample thickness, respectively. The input THz wave is incident with a polarization along the x axis.

side the slits gives good description of our experiments. This method was presented in Ref. 5 which is based on surface impedance boundary condition. However in the THz region, boundaries at both interfaces between air and metal are matched by the perfect conductor condition. This boundary matching condition finally provides the reflection and the transmission coefficients. Inside the slits, we applied a single-mode approximation since the slit width is much smaller than the wavelength. For normal incidence, zero-order transmittance for the periodic arrays of slits is expressed as follows:

$$T_0 = \frac{2ia}{d\sin(kh)[1 + k^2W^2 + 2ikW\cot(kh)]}, \tag{1}$$

where W is defined as:

$$W = \sum_n \frac{\frac{1}{a}\int_0^a e^{i\alpha_n x}dx \frac{1}{d}\int_0^a e^{-i\alpha_n x}dx}{\sqrt{k^2 - (\alpha_n)^2}}. \tag{2}$$

Here, α_n is given by the Bragg condition, $\alpha_n = (2\pi n/d)$, and k is the wave vector of the incident light. The transmittance according to Eq. (1) may exhibit maxima around wavelengths satisfying $\sin(kh)=0$ which is the typical Fabry–Perot resonance, when the contribution due to the coupled evanescent surface modes in Eq. (2) becomes weak. Peak positions of the transmittance by Fabry–Perot resonance are shifted to longer wavelengths than given by the classical Fabry–Perot resonance, because of the contribution from the evanescent surface waves on these structures.

Time traces of transmitted signals and spectral amplitudes for samples with various thicknesses show resonance oscillations at wavelengths of 540 and 262 μm, respectively, which correspond to the optical frequencies of 0.556 and 1.145 THz, respectively. Normalized field amplitude of the

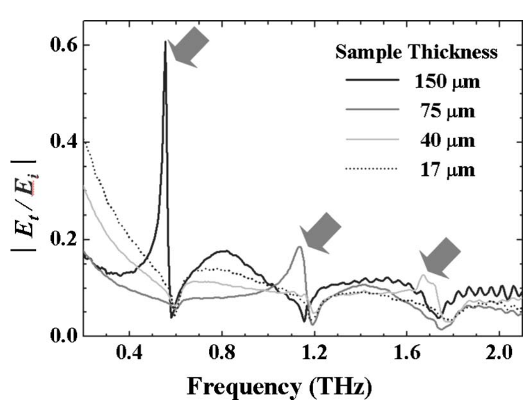

FIG. 3. Normalized transmission spectra at normal incidence for four samples with the slit width and period of 60 and 510 μm respectively, but varying the sample thickness of 17, 40, 75, and 150 μm, respectively.

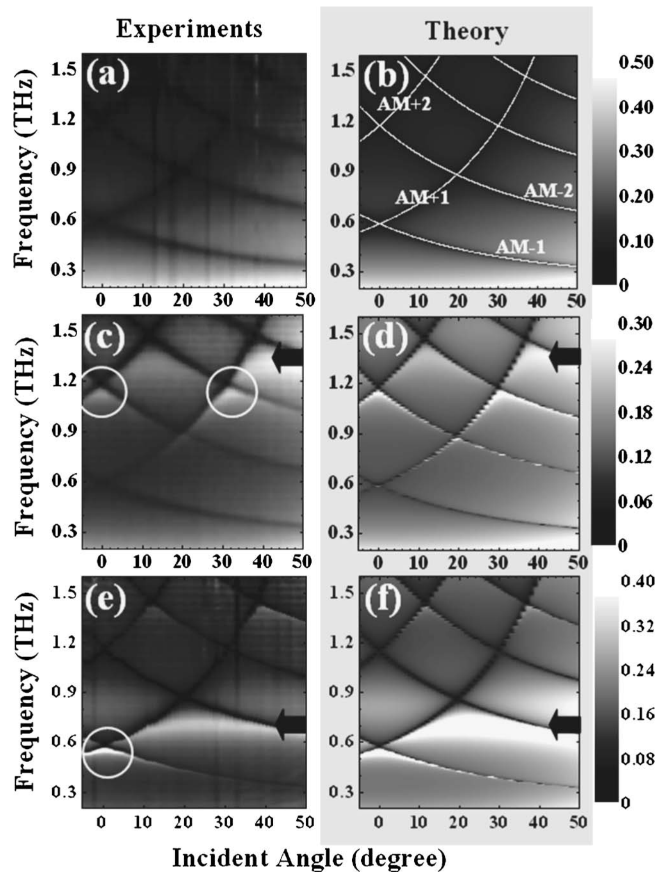

FIG. 4. Angle dependent transmission spectra for three samples with different thickness of 17 [(a) and (b)], 75 [(c) and (d)], and 150 μm [(e) and (f)], respectively. (a), (c), and (e) show the experimental results; and (b), (d), and (f) theoretical calculations. White lines in (b) represent the surface plasmon polariton modes due to various diffraction orders, and white circles in (c) represent the crossing of the surface plasmon modes with the enhanced transmission.

transmission spectra are shown in Fig. 3. The spectra are obtained by a fast Fourier transform method, and normalized by dividing them with the reference signal from an empty square aperture of 20×20 mm^2. Note that there is no transmission resonance for the thinnest sample with thickness of 17 μm. Transmission resonances however appear at three thicker samples with thicknesses of 40, 75, and 150 μm. Peaks positions shift toward longer wavelengths, and field amplitudes increase as the sample thickness increases. These observations are consistent with the downward shift of the Fabry–Perot position with increasing thickness, which in turn build up nearby surface plasmon resonances.

Figure 4 shows experimental and theoretical results for the angle dependence of transmission spectra in three samples with thicknesses of 17, 75, and 150 μm. Experimental results in Figs. 4(a), 4(c), and 4(e) are in excellent agreement with the theoretical calculations shown in Figs. 4(b), 4(d), and 4(f), obtained from the modal expansion method.[5] For the thickness of 17 μm, Fabry–Perot resonance is placed at higher frequency than the measurable spectral range since the sample thickness is small. Therefore, the enhanced peak of coupled surface plasmon polaritons does not appear in the measurable spectral range. Figures 3(c) and 3(d), showing experimental and theoretical results for the sample thickness of 75 μm, however exhibit combined Fabry–Perot-surface plasmon resonance at around 1.3 THz as indicated by black arrows. In this case, resonant peaks appear at the frequency region slightly below the crossings of the surface plasmon polaritons corresponding to AM+1/−3 and AM+2/−2 modes at air-metal (AM) interfaces [white circles in Fig. 4(c)]. A Fabry–Perot resonance band also appears around 0.7 THz for the sample with the thickness of 150 μm as shown in Figs. 4(e) and 4(f). Fabry–Perot-type peak is located at around 0.7 THz [black arrows in Figs. 4(e) and 4(f)], and the nearby surface plasmon AM+1/−1 crossing [white circle in Fig. 4(e)] is concomitantly enhanced.

From these experimental and theoretical results, we note that strong resonance peaks are not experimentally possible without Fabry–Perot-type resonance existing nearby. On the other hand, Fabry–Perot does not alter the position of the resonance peaks significantly, which are mostly determined by the periodicity. In other words, the enhanced transmission only appears below the crossings of surface plasmon polariton modes in which condition the standing waves are strongly built up, by the combined effects of Fabry–Perot and surface plasmon resonances.

In conclusion, the transmission properties for metallic arrays with subwavelength slits have been studied in the THz region theoretically and experimentally. We confirmed that the zero-order enhanced transmission appears at the crossing of two surface plasmon modes roughly coinciding with Fabry–Perot-type resonances. These understandings for enhanced transmission in periodic gratings can contribute to the development of sensitive imaging systems, waveguides, and microwave filters.

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