Terahertz transparency at Fabry-Perot resonances of periodic slit arrays in a metal plate: experiment and theory

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Abstract: We report on a perfect transmission in one-dimensional metallic structure using time-domain terahertz spectroscopy. Fabry-Perot resonance appearing in spectral region below first Rayleigh minimum strongly enhances transmission up to over ninety-nine percent. Theoretical calculations reveal that under the perfect transmission condition, a symmetric eigenmode inside the slits is excited and a funneling of all incident energy onto the slits occurs, resulting in large energy concentration equivalent to the inverse sample coverage and high near-field enhancement of electric and magnetic field intensities. Our work opens way toward near-field terahertz amplification, applicable to high-field terahertz spectroscopy.

OCIS codes: (050.1220) Apertures; (240.6690) Surface Waves; (310.2790) Guided Waves; (260.3910) Optics of metals; (300.6270) Far infrared spectroscopy

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1. Introduction

Wood’s anomaly originates from excitation of surface bound waves on one-dimensional metal reflection gratings [1, 2]. Transmission metal gratings, both one- and two-dimensional, have also been the subject of the pioneering works of Ulrich [3, 4], Lochbihler and Depine [5]. This classical research field has been re-invigorated after the so called enhanced transmission was discovered [6]. One major difference between transmission properties in optical and in microwave or terahertz regions is that perfect transmission is possible in microwave or terahertz regions since most metals in these regions act as perfect conductors with negligible loss. Perfect transmission in two-dimensional gratings and in even more complex structures was predicted theoretically by a few groups [7-9] and subsequently observed experimentally [9-11]. On the contrary, perfect transmission in the one-dimensional gratings has not been experimentally observed yet, despite its routine appearance in theoretical calculations [12-15]. Perfect transmission in the one-dimensional slit array for a specific frequency immediately implies the near-field enhancement of that frequency by a factor of the inverse coverage. In principle therefore, we can expect a huge enhancement factors for small-coverage samples, as long as the perfect transmission condition is maintained. One key component in one-dimensional gratings is the Fabry-Perot resonance in periodic arrays of slits [16, 17] and more fundamentally in a single slit, studied theoretically by Takakura [18] and subsequently observed experimentally [19, 20], which, in combination with the periodicity, has theoretically been shown to generate the perfect transmission.

2. Experiments and Theory

In this Letter, we present over ninety-nine percent transmissions in one-dimensional arrays of slits. Such *transparency* is experimentally seen only when the sample is thicker than a certain critical value, clearly indicating the crucial role played by the Fabry-Perot effect. For thinner samples, the transmission is smaller but as the sample becomes thicker, the first Fabry-Perot resonance mode approaches the position of Rayleigh minimum by periodicity and the transmission peak increases concomitantly, until the peak transmission reaches over ninety-nine percent at a specific frequency below the first Rayleigh frequency $f_R=c/\lambda_R=c/d$, where c is speed of the light in vacuum. Our results demonstrate that in one-dimensional metallic structure, experimentally near-unity transmission is realized only through the Fabry-Perot resonance.

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Our experimental setup uses coherent THz waves in the range of 0.1 to 2.5 THz and a standard THz time-domain spectroscopy [21-23]. When necessary, pulse-shaping methods are used to generate quasi-monochromatic terahertz sources [24]. 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 [Fig. 1(a)]. A femtosecond laser machining and a micro-drilling system are used to fabricate the arrays of sub-wavelength slits on aluminum plates. The samples have the line edge roughness (LER) 3σ of less than 3 μm, two orders of magnitudes less than the terahertz wavelengths of interest. We measure the angle dependence of transmission spectra by tilting the sample stage between -10° to +50° [Fig. 1(b)]. Fast Fourier transforming time traces [Fig. 1(c)] result in the corresponding spectral amplitudes [Fig. 1(d)], for both the reference and the signal beam.

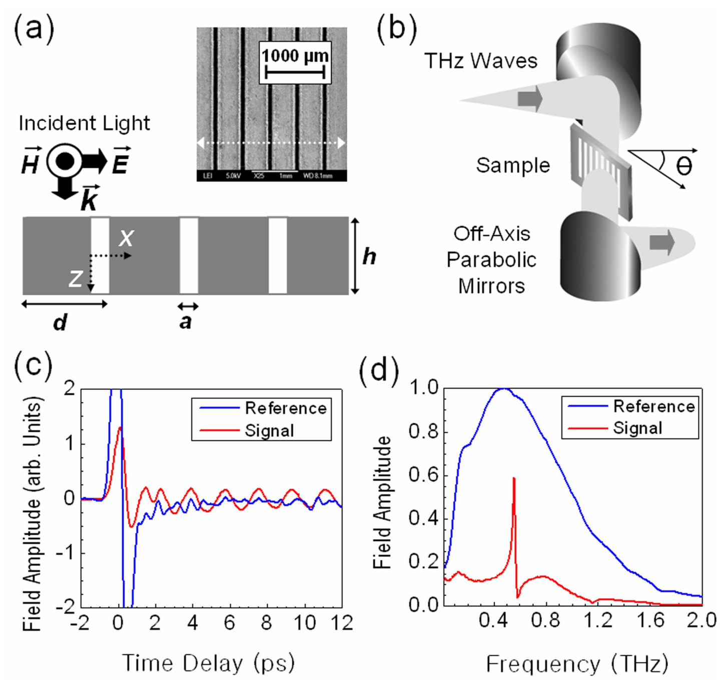

Fig. 1. (a) Schematic view of a one-dimensional metallic structure and an SEM image for a typical sample. (b) Experimental setup. (c) Terahertz time traces of a reference signal (blue line) and the signal after passing through a sample with thickness of 153 μm (red line) at normal incidence. (d) Fourier transform for time traces in (c).

Figure 2 shows transmission amplitudes at zero incident angles, experimentally in Fig. 2(a) and theoretically in Fig. 2(b). All samples show minima (called Rayleigh minima) around the first and second Rayleigh frequencies at 0.6 and 1.2 THz respectively. For the thinnest sample (h=17 μm), resonant peak does not appear, whereas for the samples with h=75, 153 and 195 μm, resonant peaks are manifested at 1.14, 0.556 and 0.465 THz, respectively. In particular, near-unity transmissions appear at 0.465 THz for the sample with h=195 μm and at 0.301 THz for the sample with h=400 μm respectively. At these frequencies, the incoming terahertz wave onto the sample area of 2 cm by 2cm is totally transmitted. We note that the resonant peaks shift to longer wavelength region with increasing sample thickness, which suggests that the Fabry-Perot resonance plays a crucial role.

Theoretical calculations based on perfect conductor model are in excellent agreement with experimental results. In THz region, the real and imaginary parts of dielectric constant for most of metals are roughly of the order of about -30000 and 100000, respectively.

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Therefore, the ohmic loss fraction which is of the order of δ/λ is only 0.1% or less, where δ is the skin depth and λ the wavelength. Under this condition, an extension of the modal expansion method [5] gives, for normal incidence:

$$T_n = \frac{2iQ_n kP_0}{\chi_n \sin(kh)[1+k^2W^2+2ikW\cot(kh)]}, \tag{1}$$

$$R_n = 1 - \frac{2iQ_n kP_0[\cot(kh) - ikW]}{\chi_n[1+k^2W^2+2ikW\cot(kh)]}, \tag{2}$$

where $\chi_n = \sqrt{k^2 - \alpha_n^2}$, $\alpha_n = 2\pi n/d$, $W = \sum_{m=-\infty}^{\infty} \frac{Q_m P_m}{\chi_m}$, $P_n = \frac{1}{a}\int_0^a e^{i\alpha_n x}dx$, $Q_n = \frac{1}{d}\int_0^a e^{-i\alpha_n x}dx$ and k is the wave vector of the incident light. Eqs. (1) and (2) are exact, and the denominator for T_n include Takakura's shifted Fabry-Perot resonance [18] for single slits as a limit for d approaching infinity. A very useful condition for the perfect transmission, consisting entirely of dimensionless real numbers, can be derived by setting the zeroth order reflection coefficient at zero, and is given by:

$$1 - (P_0Q_0)^2 - \gamma^2 - 2\gamma\cot(kh) = 0, \tag{3}$$

where γ is an imaginary part of W given by: $kW = P_0Q_0 + i\gamma$.

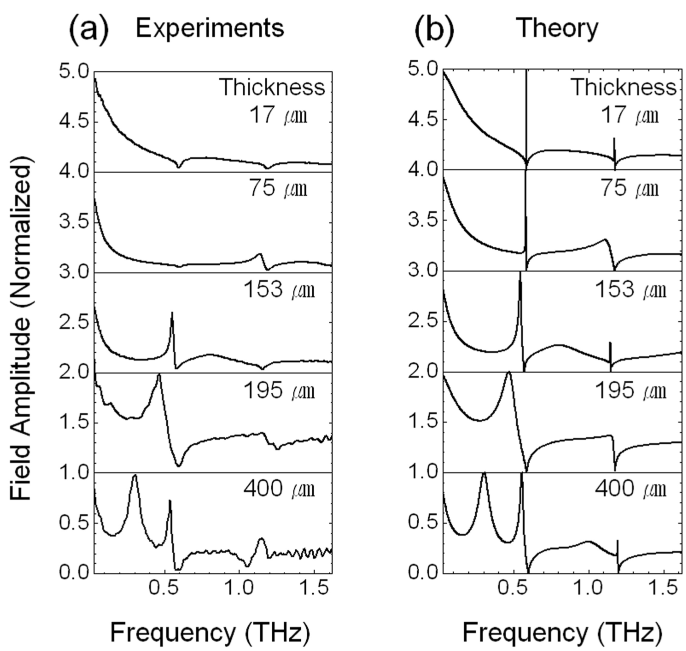

Fig. 2. (a) Normalized transmission amplitudes at normal incidence for samples with a fixed period of d=500μm and thicknesses of 17, 75, 153, 195 and 400 μm. The slit widths of the five samples are 78, 80, 83, 140, and 100 μm respectively, which are properly designed to realize the perfect transmission. (b) Theoretical calculations for the samples in (a).

Theoretical calculations show extremely sharp perfect transmission peaks immediately below the first Rayleigh frequency for the two thinnest samples [top two curves, Fig. 2(b)], whereas no such peaks exist experimentally [top two curves, Fig. 2(a)]. The theoretical linewidths of these peaks are almost infinitesimal: about 0.00002 THz and 0.002 THz for the two thinnest samples, too sharp to experimentally observe because of the finite temporal range of time-domain signals and finite sample size. The *sudden* appearance of a pronounced peak

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at 0.556 THz for h=153 μm in experiments [third curve from the top, Fig. 2(a)] is consistent with the rapid increase of the line width of the theoretical perfect transmission peak between h=17 and 153 μm in Fig. 2(b): the theoretical linewidth increases by a 1000-fold This rapid increase results from the approach of the Fabry-Perot resonance toward the spectral region of interest, which enables observation of the enhanced transmission of near-unity when the shifted Fabry-Perot resonance approaches the first Rayleigh frequency at which all the diffracted orders except the zeroth are converted to evanescent surface waves.

To further confirm the perfect transmission, we tailored our terahertz source so that it is quasi-monochromatic at the frequency of the perfect transmission (0.465 THz) for the 195 μm thick sample. As shown in Fig. 3(a), the source and transmitted waves are nearly identical, demonstrating near-unity transmission at this frequency. The perfect transmission is unique in that only under this condition, the amplitude of the incoming and transmitted waves are the same, implying a spatially symmetric (relative to the sample plane) profile. Inside the slits, the magnetic field can be written as, under the single mode approximation [5] and assuming z=0 to be at the middle of the slits, $H_{slit} = A\sin(kz) + B\cos(kz)$, where A and B are determined by boundary-matching the slit-mode with the incoming, reflected, and outgoing waves: $A = \left[\sin\left(\frac{kh}{2}\right)\left\{1 + ikW\cot\left(\frac{kh}{2}\right)\right\}\right]^{-1}$ and $B = \left[\cos\left(\frac{kh}{2}\right)\left\{1 - ikW\tan\left(\frac{kh}{2}\right)\right\}\right]^{-1}$. It is easy to show that $H_{slit} \cong B\cos(kz)$ under the perfect transmission condition given by Eq. (3), which proves that indeed, the inside-slit mode is symmetric.

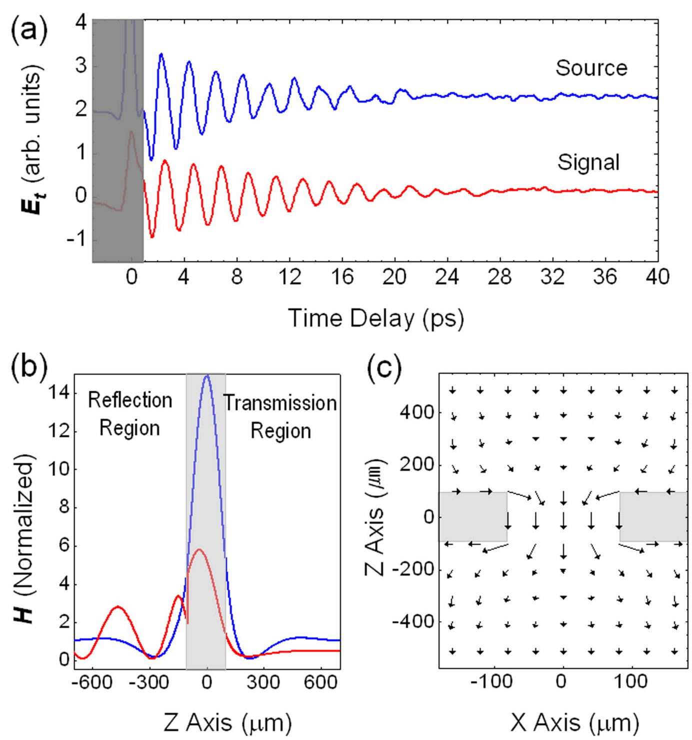

Fig. 3. (a) Terahertz time trace of a quasi-monochromatic source at 0.466 THz (top), together with its trace after transmission through the sample with h=195 μm (bottom). (b) The magnetic field profiles along the z direction passing through the slit. Shadow area indicates the sample. Under 100% transmission, field profile is symmetric relative to z=0 (blue line). At a neighboring frequency with 50% transmission, field profile becomes asymmetric (red line). (c) Poynting vector near the slit under 100% transmission.

A theoretical plot of magnetic field H_y along a z-axis passing through a slit shows a symmetric profile [Fig. 3 (b), blue line]. As the spectral position deviates from the perfect transmission, the symmetry is broken and the mode becomes heavily asymmetric, as shown for the case of fifty percent transmission (red line). It should be noted, however, that this symmetric magnetic field profile does not imply symmetric energy flow: energy flow should be from left to right. To examine this issue, we plot the Poynting vector, $\vec{S} = \mathrm{Re}(\vec{E} \times \overrightarrow{H^*})$ around the region of slit entrance and exit, under the perfect transmission in Fig. 3(c). It is clear that the incident energy flow is *funneled* to the slit, so that the inside-slit Poynting vector is exactly the inverse sample coverage, $\beta^{-1} = d/a$, resulting in the perfect transmission. The electric near-field intensity is expected to be amplified by a factor of square of the inverse sample coverage, which is 13 for the sample with *h*=195 μm and 25 for the sample with *h*=400 μm. The enhancement of the near-field intensity is ensured by the realization of the perfect transmission. In this condition and under this condition only, the continuing decrease of the sample coverage will inevitably lead the electric and magnetic near-field intensities to be enhanced practically up to over several hundred times, which opens a strong possibility of potential applications in biological sensing and terahertz spectroscopy requiring high power sources.

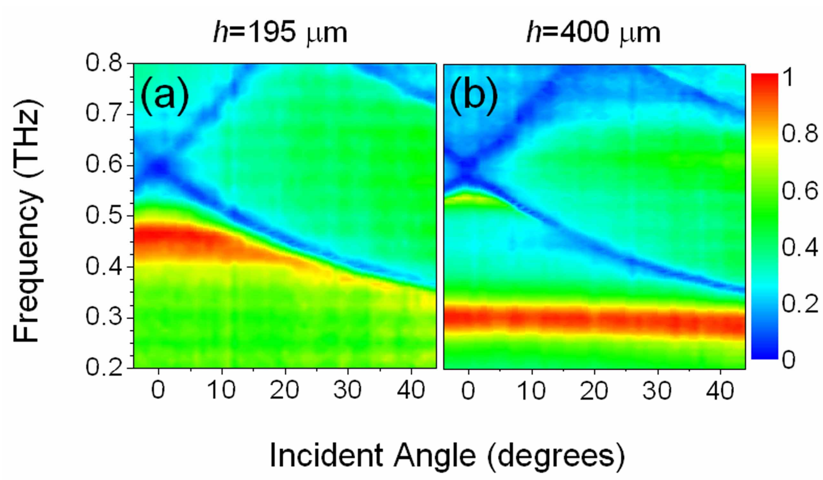

Fig. 4. Normalized angle dependent transmission amplitudes for thickness of 195 (a) and 400 μm (b).

Thus far, we saw how Fabry-Perot resonance enhances transmission around Rayleigh minima by periodicity. We have not, however, seen any direct signature of the single-slit Fabry-Perot resonance. Shown in Fig. 4 are the angle dependent transmission amplitudes for samples with *h*=195 and 400 μm, exhibiting near-unity peak transmissions. For both samples, two transmission minima lines that cross at about 0.6 THz at zero angle represent Rayleigh frequencies for the ± 1 diffraction orders, $f_R(\theta) = \frac{c}{d}\frac{1}{1 \mp \sin\theta}$. For *h*=195 μm, the Fabry-Perot resonance is situated near the first Rayleigh minimum, so that two resonances merge together to generate a broad guided plasmon-like peak that reaches transmission of near-unity [Fig. 4(a)]. Further increasing sample thickness to 400 μm makes the Fabry-Perot resonance appear as a completely isolated, angle-independent peak centered at 0.30 THz. This isolation is possible because at this sample thickness, the Fabry-Perot resonance is away from any Rayleigh-line crossings.

3. Conclusion

In conclusion, we have presented the perfect transmission in one-dimensional metallic structures. While there always exists an extremely sharp perfect transmission peak near the Rayleigh frequency theoretically even for thin samples, we have shown that experimental observation of the perfect transmission is possible only by taking advantage of the Fabry-Perot resonance. Theoretical study reveals that the perfect transmission is accompanied by the excitation of a symmetric eigenmode inside the slits, and under this condition, the field amplitudes are symmetric with respect to the sample plane, while energy *funneling* onto the slit occurs. Our experiments show that huge enhancement of field strength is possible taking advantage of the Fabry-Perot effect, which would enable terahertz nonlinear experiments by combining high power terahertz generation mechanisms such as free electron lasers.

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