Terahertz transmission properties of thin, subwavelength metallic hole arrays

Dongxia Qu, D. Grischkowsky, and Weili Zhang

School of Electrical and Computer Engineering, Oklahoma State University, Stillwater, Oklahoma 74078

Received November 11, 2003

We present experimental results of the transmission magnitude and phase change of terahertz pulses through thin metallic films patterned with subwavelength hole arrays on silicon wafers. Terahertz time-domain spectroscopy measurements reveal a sharp phase peak centered on the surface plasmon resonance. Correspondingly, and consistent with the Kramers–Kronig relations, the measured transmission magnitude has the shape of the derivative of this peak. In addition, we determine that the aperture shape has a notable effect on the transmission properties of two-dimensional hole arrays. © 2004 Optical Society of America

OCIS codes: 320.7120, 240.6680.

Recently, there has been increasing interest in terahertz microstructured devices, such as dichroic filters,[1,2] terahertz photonic crystals,[3,4] terahertz wave plates,[5] and terahertz plasmonic high-pass filters.[6] Widespread applications are expected from these frequency-selective components in the development of terahertz optoelectronics. High transmission or reflection at selective terahertz frequencies can also be realized with a very thin metallic film perforated by a subwavelength hole array, for which $h/L < 0.004$, where h is the thickness of the film and L is the period of the array.[1] In the visible and near-infrared regions these thin periodic structures whose behavior is dominated by the surface plasmon (SP) response have attracted a lot of attention. Extensive experimental and theoretical works have been carried out to explain the physical details of the transmission process,[7,8] which suggested a totally different transmission mechanism from the dichroic filters referred to as the thick perforated metal plates. SP resonances do not play a role in the dichroic filters' transmission mechanism, and their frequency-selective characteristic can be explained well by waveguide theory and grating theory. Their transmission spectra can be simulated by use of mode-matching theory.[9]

In this Letter we report an experimental study in the frequency range 0.1–4.0 THz of the transmission properties of terahertz pulses through thin metallic films perforated by a subwavelength hole array. The transmission phase change of similar grooved structures has been predicted theoretically.[10,11] For example, it has been theoretically stated that the phase change plays an important role in governing the transmission properties of a one-dimensional array of slits.[11] Terahertz time-domain spectroscopy[12] (THz-TDS) transmission measurements have been demonstrated as an effective technique for characterizing various materials, including semiconductor materials, chemical vapors, nanostructures, and conducting polymers. The phase change of the transmission spectra can be obtained by a THz-TDS coherent system, allowing new information about the SP response to be obtained. Our THz-TDS study of the subwavelength microstructures described here revealed a sharp phase peak centered on the SP resonance. Correspondingly, the measured transmission magnitude has the shape of the derivative of this peak, which is consistent with the Kramers–Kronig relations. In addition, the hole shape of the thin metallic films has a significant effect on the transmission magnitude and the corresponding phase change of terahertz waves. In contrast, in the optical region, hole shape is not a decisive parameter for the transmission coefficient.[8]

The samples used in this study were fabricated by conventional photolithography and metallization processing. A 520-nm-thick aluminum layer was deposited on the polished side of a 0.64-mm-thick silicon wafer with a resistivity of $\rho = 20\ \Omega$ cm. For sample A the pattern is an 80 μm (x axis) $\times$ 100 μm (y axis) rectangular hole array; for sample B the pattern is a 100-μm circular hole array. The period of these different patterned microstructures is $L = 160\ \mu$m in both two-dimensional directions.

The terahertz system used in this measurement is a photoconductive-switch-based THz-TDS spectrometer as described in Ref. 13. The sample is attached to a mechanical holder and centered over a 30-mm-diameter hole in the holder, which defines the optical aperture. A similar blank silicon wafer attached to another identical clear hole is used to obtain the reference terahertz pulse. The transmission measurements were performed with linearly polarized terahertz ($E \parallel x$) waves impinging on the sample at normal incidence.

The transmitted terahertz pulses and the corresponding amplitude spectra of the reference and samples are illustrated in Fig. 1. The time extent of the terahertz pulse scans was limited by the strong reflection from the backside of the wafer. This situation in turn limits the frequency resolution of the numerical Fourier transforms. To perform a numerical interpolation between the measured frequency points, the measured pulses in the time domain were extended with zeros (zero padding) to a total time duration of 51 ps, three times the measured scan duration. The transmission magnitude and the corresponding phase change are shown in Fig. 2.

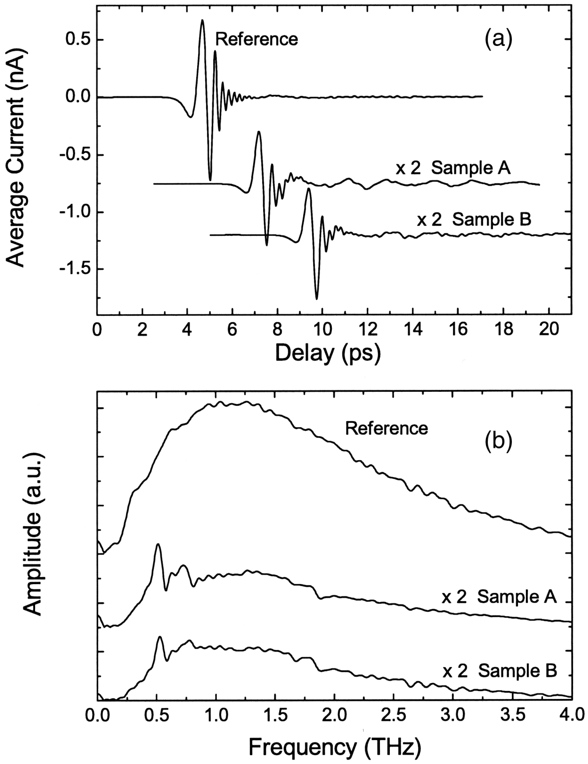

Fig. 1. (a) Measured transmitted terahertz pulses and (b) the corresponding spectra through reference and samples (multiplied by two). The curves in (a) and (b) are displaced vertically for clarity.

The transmission is obtained from the ratio between the Fourier-transformed sample and the reference amplitudes, whereas the phase change is the phase difference between the sample and the reference spectra. We observed sharp phase peaks centered on the SP resonance modes to within the accuracy of our measurements at the frequencies indicated by the vertical dashed lines. The transmission features appear similar to the derivatives of the measured sharp phase peaks.

We now present the calculation for obtaining the SP resonant frequencies. For a smooth metallic film the propagation vector of the SP for any direction in the plane of the surface is given by[14]

$$k_{\mathrm{sp}} = k_0\left[\frac{\epsilon_1}{(\epsilon_{r2} + \epsilon_1)^2 + \epsilon_{i2}^2}\right]^{1/2}\left[\frac{\epsilon_e^2 + (\epsilon_e^4 + \epsilon_1^2\epsilon_{i2}^2)^{1/2}}{2}\right]^{1/2}, \quad (1)$$

where k_{sp} is the SP wave vector; $k_0 = \omega/c = 2\pi/\lambda_{\mathrm{resonance}}$ is the free-space wave vector; ϵ_1 is the dielectric constant of the medium; $\epsilon_2 = \epsilon_{r2} + i\epsilon_{i2}$ is the dielectric constant of the metal, for which ϵ_{r2} is the real part and ϵ_{i2} is the imaginary part; and $\epsilon_e^2 = \epsilon_{r2}^2 + \epsilon_{i2}^2 + \epsilon_1\epsilon_{r2}$. For our case, $\epsilon_1 = 11.70$ (Ref. 12) for silicon or $\epsilon_1 = 1$ for air; for aluminum at 1 THz, $\epsilon_{r2} = -3.3 \times 10^4$ and $\epsilon_{i2} = 6.4 \times 10^5$ (Refs. 15 and 16). Because of these very large values for ϵ_{r2} and ϵ_{i2}, in the terahertz domain the SP wave vector of Eq. (1) can be approximated by the simple relationship

$$k_{\mathrm{sp}} \approx k_0\sqrt{\epsilon_1}\,. \quad (2)$$

The condition for electromagnetic wave coupling into the SP modes by the array is given by $\mathbf{k}_{\mathrm{sp}} = \mathbf{k}_0 \pm m\mathbf{k}_x \pm n\mathbf{k}_y$, where $\mathbf{k}_0$ is the component of the incident wave vector in the metallic film plane, $\mathbf{k}_x$ and $\mathbf{k}_y$ are the array (grating) momentum wave vectors with $|\mathbf{k}_x| = |\mathbf{k}_y| = 2\pi/L$, and m and n are integers. At normal incidence, $\mathbf{k}_0 = 0$, and the free-space wavelengths of the SP modes excited by the array are given by a very good approximation as[17]

$$\lambda_{\mathrm{resonance}} = \frac{L}{\sqrt{m^2 + n^2}}\sqrt{\epsilon_1}\,. \quad (3)$$

The three calculated SP $[m, n]$ resonance frequencies are shown in Fig. 2, where, for the metal–silicon modes at 0.548 $[\pm1, 0]$ and 0.775 $[\pm1, \pm1]$ THz, $\epsilon_1 = 11.70$ and, for the metal–air mode $[\pm1, 0]$ at 1.875 THz, $\epsilon_1 = 1$. The measured SP frequencies for the metal–silicon $[\pm1, 0]$ modes are 0.55 and 0.57 THz for the phase peak associated with the arrays of rectangles and circles, respectively.

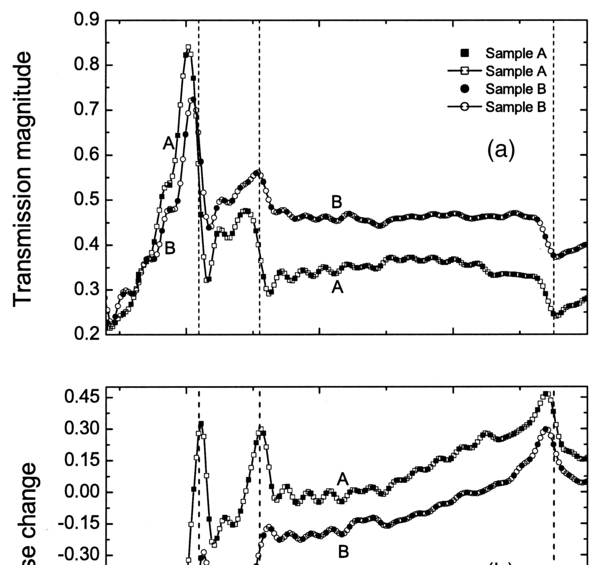

Fig. 2. (a) Spectra of the measured transmission magnitude of the signal pulse compared with the reference pulse and (b) the corresponding comparative phase change in radians for 80 μm × 100 μm rectangular hole arrays (sample A, without zero pad, filled squares; three times zero pad, open squares) and 100-μm-diameter circular hole arrays (sample B without zero pad, filled circles; three times zero pad, open circles). In (a) the spectrum of sample B is moved up by 0.1, and in (b) the phase change of sample B is moved down by 0.1 for clarity. The dashed lines indicate the SP frequencies.

The amplitude of the SP is attenuated with propagation as

$$S(x) = S_0 \exp(-k_i x)\,, \tag{4}$$

where k_i is the imaginary part of the propagation constant for the SP mode as given by[14]

$$k_i = k_0 \left[\frac{\epsilon_1}{(\epsilon_{r2} + \epsilon_1)^2 + \epsilon_{i2}^2} \right]^{1/2} \times \frac{\epsilon_1 \epsilon_{i2}}{\{2[\epsilon_e^2 + (\epsilon_e^4 + \epsilon_1^2 \epsilon_{i2}^2)^{1/2}]\}^{1/2}}\,. \tag{5}$$

For our conditions, k_i is given by a very good approximation as

$$k_i = k_0 \frac{\epsilon_1^{3/2}}{2\epsilon_{i2}}\,. \tag{6}$$

At the $[\pm 1, 0]$ metal–silicon SP resonance frequency of 0.548 THz, with $\epsilon_i = 11.70$ and $\epsilon_{i2} = 1.17 \times 10^6$, we obtain $k_i = 0.002\ \mathrm{cm}^{-1}$, indicating extremely low propagation loss for the SPs.

To gain an understanding of the relationship between phase change peaks and the transmission magnitude shape, we measured a set of samples with rectangular, square, and circular holes. We observed that with the same fundamental period the hole shape and dimensions can appreciably modify the strengths and shapes of the transmission and phase change peaks. Here, we show only the result of the rectangular (sample A) and circular (sample B) holes. One observation shown in Fig. 2 is that the 100-μm-diameter circular-hole array (sample B) incited a much lower phase change peak at the $[\pm 1, 0]$ metal–silicon SP resonance frequency than the sharp peak of sample A. This difference results from the fact that the rectangular shape preserves the input linear polarization for the $[\pm 1, 0]$ SP, whereas the circular shape does not.

Contrary to previous expectations,[10,18] for our measurements of both samples, as shown in Fig. 2, the transmission has the derivative shape of the sharp phase changes observed at the SP resonance frequencies. These complementary results for phase and transmission are consistent with the natural properties of a causal system. For any linear system (our metallic hole array) the real and imaginary parts of the transfer function are related by the Kramers–Kronig relations.[19] It then follows that the expected transmission should be determined by the observed phase change through the Hilbert transform, in qualitative agreement with experiment. This statement is not an explanation of why a transmission peak is not observed (at SP resonance frequencies). It only shows the consistency of both the measured phase and the amplitude transmission. This consistency adds to our confidence in the accuracy of our THz-TDS characterization. Compared with previous measurements in the optical regime, the conductivity of our metal film is more than 100 times higher, thereby leading to a much more simplified calculation of the plasmon frequency and to an extremely low propagation loss for the excited SPs. It is our intuitive opinion that the high conductivity is in part responsible for the change in the shape of the observed transmission compared with previous measurements.

To summarize, we have presented a study of SP-enhanced terahertz transmission through subwavelength metallic structures. The THz-TDS study measured a sharp phase peak centered on the SP resonance. The corresponding transmission magnitude has the shape of the derivative of this peak consistent with the Kramers–Kronig relations. Furthermore, the strengths and shapes of the transmission and phase change peaks appear to be strongly dependent on the hole shape.

This work was partially funded by the Oklahoma Experimental Program to Stimulate Competitive Research for the National Science Foundation (grant EPS-0132534), the National Science Foundation, and the Army Research Office. Weili Zhang's e-mail address is wwzhang@okstate.edu.

References

1. C. Winnewisser, F. Lewen, J. Weinzierl, and H. Helm, Appl. Opt. **38,** 3961 (1999).
2. F. Baumann, W. A. Bailey, Jr., A. Naweed, W. D. Goodhue, and A. J. Gatesman, Opt. Lett. **28,** 938 (2003).
3. N. Jukam and M. S. Sherwin, Appl. Phys. Lett. **83,** 21 (2003).
4. C. Jin, B. Cheng, Z. Li, D. Zhang, L. Li, and Z. Zhang, Opt. Commun. **166,** 9 (1999).
5. F. Miyamary, T. Kondo, T. Nagashima, and M. Hangyo, Appl. Phys. Lett. **82,** 2568 (2003).
6. D. Wu, N. Fang, C. Sun, and X. Zhang, Appl. Phys. Lett. **83,** 201 (2003).
7. T. W. Ebbesen, H. J. Lezec, H. F. Ghaemi, T. Thio, and P. Q. Wolff, Nature **391,** 667 (1998).
8. L. Martín-Moreno, F. J. García-Vidall, H. J. Lezec, K. M. Pellerin, T. Thio, J. B. Pendry, and T. W. Ebbesen, Phys. Rev. Lett. **86,** 1114 (2001).
9. C.-C. Chen, IEEE Trans. Microwave Theory Tech. **21,** 1 (1973).
10. W. Liu and D. Tsai, Phys. Rev. B **65,** 155423 (2002).
11. F. J. García-Vidall and L. Martín-Moreno, Phys. Rev. B **66,** 155412 (2002).
12. D. Grischkowsky, S. Keiding, M. van Exter, and Ch. Fattinger, J. Opt. Soc. Am. B **7,** 2006 (1990).
13. W. Zhang, A. Azad, and D. Grischkowsky, Appl. Phys. Lett. **82,** 2841 (2003).
14. F. Yang, J. R. Sambles, and G. W. Bradberry, Phys. Rev. B **44,** 5855 (1991).
15. W. Ehrenberg, *Electric Conduction in Semiconductors and Metals* (Clarendon, Oxford, 1958).
16. M. A. Ordal, L. L. Long, R. J. Bell, S. E. Bell, R. R. Bell, R. W. Alexander, Jr., and C. A. Ward, Appl. Opt. **22,** 1099 (1983).
17. H. F. Ghaemi, T. Thio, D. E. Grupp, T. W. Ebbesen, and H. J. Lezec, Phys. Rev. B **58,** 6779 (1998).
18. A. Dogariu, T. Thio, L. J. Wang, T. W. Ebbesen, and H. J. Lezec, Opt. Lett. **26,** 450 (2001).
19. E. A. Saleh and M. C. Teich, *Fundamentals of Photonics* (Wiley, New York, 1991).