RAPID COMMUNICATION

Electrically tunable resonant terahertz transmission in subwavelength hole arrays*

Zhang Ying(张 莹)[a)b)], Liu Ying-Kai(刘应开)[a)†], and Han Jia-Guang(韩家广)[b)‡]

[a)] School of Physics and Electronic Information, Yunnan Normal University, Kunming 650500, China

[b)] Center for Terahertz Wave, Key Laboratory of Opto-electronic Information Technology, Ministry of Education, College of Precision Instrument and Optoelectronics Engineering, Tianjin University, Tianjin 300072, China

(Received 20 November 2013; revised manuscript received 25 January 2014; published online 10 April 2014)

An actively enhanced resonant transmission in a plasmonic array of subwavelength holes is demonstrated by use of terahertz time-domain spectroscopy. By connecting this two-dimensional element into an electrical circuit, tunable resonance enhancement is observed in arrays made from good and relatively poor metals. The tunable feature is attributed to the nonlinear electric response of the periodic hole array film, which is confirmed by its voltage–current behavior. This finding could lead to a unique route to active plasmonic devices, such as tunable filters, spatial modulators, and integrated terahertz optoelectronic components.

Keywords: surface plasmons, enhanced terahertz transmission, electrically tunable

PACS: 73.20.Mf, 42.25.Bs, 78.66.–w **DOI:** 10.1088/1674-1056/23/6/067301

1. Introduction

The extraordinary transmission due to resonant excitation of surface plasmons (SPs) in subwavelength metallic structures enables manipulation of electromagnetic waves below the wavelength scale.[1–4] It leads to the development of a new field, plasmonics, and shows significant impact on a broad range of disciplines, particularly on nanofabrication, biochemical sensing, and integrated plasmonic devices.[5,6] But the tunable properties of surface plasmons are challenging in developing new types of plasmonic devices. As is well known, dielectric functions of the constituent metallic and surrounding dielectric media play a substantial role in establishing SP-enhanced transmission at metal–dielectric interfaces.[7–10] By changing the dielectric function of either the metallic or the surrounding media instantaneously, the properties of terahertz SPs can be tuned in a dynamic range.[11,12] The resonant frequencies of SPs in subwavelength holes were tuned simultaneously when the dielectric function of the surrounding medium, the nematic liquid crystal, was adjusted through an external magnetic field.[11] Recently, the dielectric function of a hole array made from silicon was essentially changed by photo-doping, leading to tunable SPs and an instantaneous transition between an out-of-plane photonic crystal effect and an SP resonance.[12] However, modifying the dielectric function of metal in a noticeable dynamic range is still challenging.[11,13–22]

In this paper, we demonstrate that external direct current (DC) voltage may result in the tunable dielectric function in hole array film, so that the enhanced resonant transmission can be observed. We characterize these properties by utilizing terahertz time-domain spectroscopy. The resonant terahertz transmission in metal arrays of subwavelength holes can become tunable through a simple but unique approach. When a moderate DC voltage is applied across the metal film, a remarkable transmission enhancement occurs and shows a dependence on the external voltage. The nonlinear voltage–current characteristics in the two-dimensional (2D) metal arrays are observed, which are responsible for the enhanced properties of the transmission dependent on the external voltages.[23–25]

2. Experiment

A schematic diagram of the experimental approach is illustrated in Fig. 1. The subwavelength hole array shown is prepared by conventional photolithography. The 25 mm $\times$25 mm-sized sample is a metal film thermally evaporated on a 0.64-mm-thick silicon wafer (p-type resistivity ρ = 20 Ω·cm). A square array of 100 μm$\times$80 μm rectangular holes is perforated in the metal film with a lattice constant 160 μm. The array is electrically connected by conducting wires into a circuit that contains a DC power supply, an adjustable resistor, a voltammeter, and an amperemeter. The transmission measurement is carried out in a broadband photoconductive switch-based terahertz time-domain spectroscopy system, where the array is placed midway between the transmitter and the receiver modules in the far field.[12,23] A blank silicon slab

*Project supported by the National Natural Science Foundation of China (Grant No. 61007034).

†Corresponding author. E-mail: liuyingkai99@163.com

‡Corresponding author. E-mail: jiaghan@tju.edu.cn

© 2014 Chinese Physical Society and IOP Publishing Ltd

taken from the same wafer of the array substrate is used as a reference. The terahertz pulses propagate through the array at normal incidence with the direction of the electric field perpendicular to the longer axis of the holes. The amplitude transmission $t(\omega)$ is defined as $t(\omega) = |E_{\rm out}(\omega)|/|E_{\rm in}(\omega)|$, where $E_{\rm out}(\omega)$ and $E_{\rm in}(\omega)$ are the amplitudes of terahertz fields through the array and reference, respectively. To avoid thermal generation when current passes through the metal mesh, the sample is cooled using an external water-cooling system and keep the temperature changed within ± 5 °C. Figure 2 shows the measured frequency-dependent amplitude transmission in the array composed of a 180-nm-thick Al film with an external DC voltage switched on (solid curve) and off (dotted curve). The well-defined resonance at 0.5 THz is primarily attributed to the resonant excitation of the Al–Si $[\pm 1, 0]$ SP mode at the metal–dielectric interface.[7]

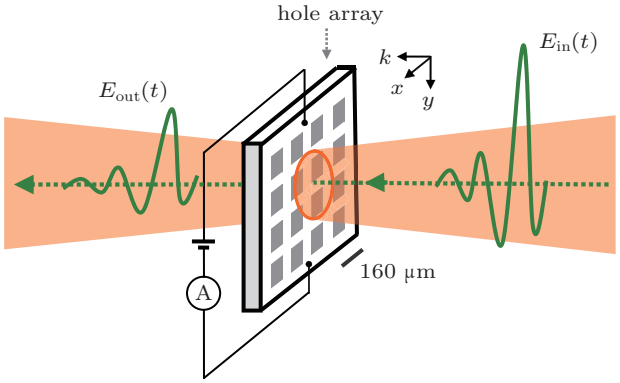


Fig. 1. (color online) Experimental diagram of electrically enhanced resonant terahertz transmission. The terahertz pulses transmit through the subwavelength hole array actively controlled by external DC voltages.

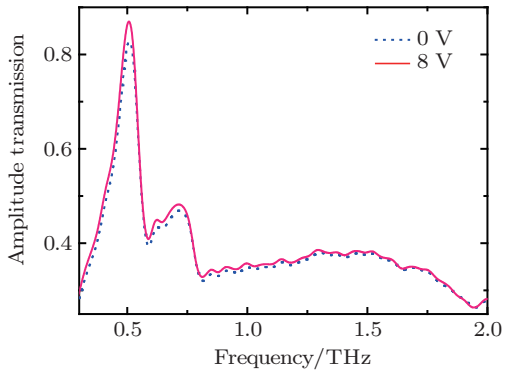


Fig. 2. (color online) Frequency-dependent amplitude transmission of the Al array. The resonance at the Al–Si $[\pm 1, 0]$ SP mode is enhanced when the DC voltage is switched on.

At normal incidence, electromagnetic waves can excite SPs only when the wave vector of the incident radiation matches with the in-plane grating momentum. The resonant wavelength of SPs in a rectangular lattice structure is generally given by $\lambda^{\rm SP}(m,n) = L\varepsilon_{\rm d}^{1/2}(m^2+n^2)^{-1/2}$,[23,26] where L is the lattice constant, m and n are the integer mode indices, $\varepsilon_{\rm d}$ is the dielectric constant of the adjacent dielectric medium to the array, here $\varepsilon_{\rm d} = 11.68$ for the silicon substrate; its imaginary permittivity can be ignored and thus it does not make a contribution to the calculated resonant wavelength. Based on this relation, the calculated Al–Si $[\pm 1, 0]$ SP mode at the metal–Si interface is located around 0.548 THz, which is higher than the measured resonance peak around 0.5 THz, since the latter also contains the contributions from non-resonant transmission and Wood's anomaly.[15,27,28]

The resonant transmission reveals a prominent enhancement when a DC voltage is applied to the array. At the Al–Si $[\pm 1, 0]$ SP mode 0.5 THz, the static array shows a maximum amplitude transmission of 82.5%, while it increases to 87.0% under a 8.157-V DC voltage, corresponding to a 5.5% electrically tunable enhancement. The measured dependence of peak transmission on external DC voltage is plotted in Fig. 3(a), where resonance efficiency is enhanced with increasing voltages from 0 V to 8.157 V. Furthermore, at 0.71 THz, the Al–Si $[\pm 1, 1]$ SP mode, the resonant transmission shows a similar behavior to that at the Al–Si $[\pm 1, 0]$ SP mode; it also increases with the increase of applied voltage.

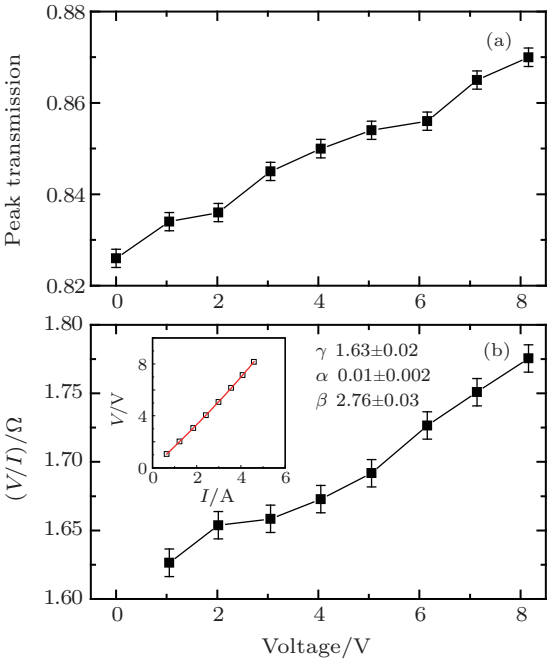


Fig. 3. (color online) (a) Measured voltage-dependent peak amplitude transmission of Al array, (b) corresponding resistance, V/I of the Al array as a function of the DC voltage. The inset shows the comparison between measured V–I data (squares) and theoretical fitting (solid line) by the NLRRN model at parameters: $\gamma = 1.63 \pm 0.02$, $\alpha = 0.01 \pm 0.002$, and $\beta = 2.76 \pm 0.03$.

3. Results and discussion

Since many factors may be associated with the tunable properties of enhanced transmission, their relationships are discussed first. As is well known, when the current through a metal sample is increased, the sample is heated. As a result, the THz transmission properties of the measured sample

would be changed due to the temperature change and thermal generation of carriers. About this case, we notice that some detailed investigations have been recently reported.[29,30] The most significant features due to the heat effect are found that the temperature change and thermal generation of carriers would modulate the dielectric function of the measured sample and thus give rise to a remarkable shift of the resonance frequency but no significant enhancement in the transmission. In our experiment, the sample is cooled using an external cooling system and the temperature change is kept in a narrow range (± 5 °C). Therefore, the enhanced transmission dependence of the external voltage is not associated with the heat effect, which is further confirmed by the fact that no obvious shift of resonance frequency is observed with increasing external voltage in our measurement. Another speculation may be the influence from the semiconductor Si substrate. To exclude this, we perform a similar measurement on the Al–quartz (quartz as substrate) sample. It is found when we just apply a 3-V external voltage, that the 2% increase in the peak transmission can be achieved. What we have discussed above indicates that neither the heat effect nor the substrate is responsible for the enhancement feature in transmission.

Further study indicates that the mechanism could originate from the nonlinear electric response of the 2D periodic metal microstructure. Generally, the direction of current density j in a bulk metal coincides with the direction of external electric field E, and the bulk conductivity σ usually follows Ohm's law, $j = \sigma E$. It means that in an electrical circuit, the current I is directly proportional to the voltage V across the conductor, i.e., $I \propto V$.[31,32] However, for a metal thin film perforated with periodic holes, the electric field exhibits obvious fluctuation and results in a significant nonlinear electric response. In reality, the nonlinear behavior in such an inhomogeneous, discontinuous, and periodic system is more complicated. The previous investigations indicated that the nonlinear electric response in periodic structures is mainly attributed to the current lines concentrated in narrow links connecting regions occupied by highly conducting components.[33,34] The applicable method of depicting the nonlinear properties of such a system is mostly characterized by a voltage–current (V–I) curve. To accurately study these, the V–I curve of the Al–Si sample is measured as shown in Fig. 3(b). The nonlinear electric response is presented as the fact that the resistance (V/I) of the array increases with the increase of external DC voltage, deviating from a linear ohmic slope. When the DC voltage is ramped to 1.053 V, the measured resistance shows a value 1.626 Ω. However, a further increase in the DC voltage to 8.157 V has led to a rapid enhancement in resistance to 1.775 Ω. This indicates that the typical nonlinear electric response occurs in the periodic metal microstructure. According to the previous reports, the nonlinear V–I characteristics can be well described by the nonlinear-random-resistor-network (NLRRN) model of the form:[24,25] $V = \gamma I + \alpha I^{\beta}$, where α, β, and γ are scaling parameters with $\beta > 1$. The NLRRN model assumes that the conducting backbone consists of microscopic components, each of which contributes a small V–I nonlinear characteristic.[24,25] As shown in the inset of Fig. 3, the V–I characteristic data are well fitted by the NLRRN model with scaling parameters: $\gamma = 1.63 \pm 0.02$, $\alpha = 0.01 \pm 0.002$, and $\beta = 2.76 \pm 0.03$.

For an Al–Si sample, the nonlinear electric response is well indentified by the V–I plot and nonlinear model fitting. Since metal Al is a good conductor with low resistance, the V–I curve is smoothly varying in the measurement voltage range. This feature is also quite consistent with that in previous studies.[24,25] In order to gain more insight into this effect, the experiment is performed on another array made of a 120-nm-thick Pb film with identical patterns to those in the Al array. Pb is generally a poor electrical conductor compared with Al. When a DC voltage is not applied, the measured amplitude transmission at the Pb–Si $[\pm 1, 0]$ SP mode is 64.3% as shown by the dotted curve in Fig. 4(a). This is quite low compared with the value 82.6% achieved through the Al array because of two reasons. First, the thickness of the Pb film is only one-third of the skin depth at 0.5 THz. It thus shows a lower transmission than that observed in the Al array, which is optically

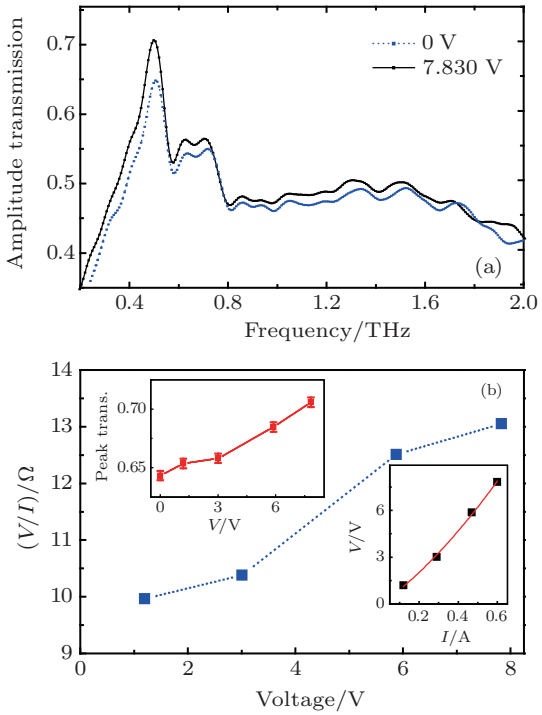


Fig. 4. (color online) (a) Frequency-dependent terahertz amplitude transmissions at the Pb–Si $[\pm 1, 0]$ SP mode when the DC voltage is switched on (solid curve) and off (dotted curve), and (b) conductance of the Pb array as a function of the DC voltage. The left inset shows the voltage-dependent peak amplitude transmission, and the right inset displays the comparison of measured V–I data (squares) with theoretical fit (solid line) by the NLRRN model with parameters: $\gamma = 7.57 \pm 0.34$, $\alpha = 8.05 \pm 0.31$, and $\beta = 1.72 \pm 0.26$.

thick due to its film thickness value being greater than the skin depth.[35–37] Second, Pb has a lower ratio $-\varepsilon_{\rm rm}/\varepsilon_{\rm im}$ than Al, and hence the transmission in the Pb array is lower than that in an identical Al array, even with the same skin depth.[23]

When the DC voltage is applied to the Pb array, the resonant transmission exhibits a similar behavior to that observed in the Al array; it is enhanced with increasing voltage. When the external DC voltage is turned on and ramps up to 7.830 V, the peak amplitude transmission at the Pb–Si $[\pm 1, 0]$ resonance mode is enhanced from 64.3% to 70.6%, as shown in Fig. 4(a). The inset of Fig. 4(b) illustrates a dependence of peak amplitude transmission on external DC voltage. The measured resistance of the Pb array is plotted in Fig. 4(b), where a nonlinear electric response is clearly revealed. The recorded data indicate that the Pb array shows a higher resistance than the Al array. When the DC voltage increases from 1.196 V to 7.830 V, the resistance is found to increase from 9.97 Ω to 13.05 Ω. The measured V–I data are well fitted by NLRRN model, as shown in the inset of Fig. 4. For Pb, it has a higher resistance than Al and the V–I curves remarkably deviate from linear characteristic. The measured results in the Pb array reveal a good consistency with what are observed in the Al array, thereby verifying that the tunable feature in resonant transmission is closely related to the nonlinear electric effect in the 2D metal periodic microstructure.

4. Conclusions

In this paper, we demonstrate that the resonant SP transmission is actively enhanced when the array of subwavelength holes is charged with a moderate external DC voltage. The tunable feature is attributed to the nonlinear electric response that occurs in the 2D metal periodic microstructure. This effect can be extended to a variety of subwavelength structures, providing a considerable flexibility in developing active plasmonic devices, such as optoelectronic circuits, spatial modulators, and tunable filters.[38,39] The presented new mechanism in tuning resonant transmission may pave the way for actively controlling the terahertz transmission in integrated plasmonic devices.

Acknowledgment

The authors are indebted to professor Zhang Wei-Li for our encouraging discussions and also to Dr. Lu X for their exceptional efforts.

References

[1] Ebbesen T W, Lezec H J, Ghaemi H F, Thio T and Wolff P A 1998 *Nature* **391** 667
[2] Gordon R, Hughes M, Leathem B, Kavanagh K L and Brolo A G 2005 *Nano Lett.* **5** 1243
[3] Molen K, Koerkamp K, Enoch S, Segerink F, Hulst N and Kuipers L 2005 *Phys. Rev. B* **72** 045421
[4] Martín-Moreno L, García-Vidal F J, Lezec H J, Degiron A and Ebbesen T W 2003 *Phys. Rev. Lett.* **90** 167401
[5] Barnes W L, Dereux A and Ebbesen T W 2003 *Nature* **424** 824
[6] Ozbay E 2006 *Science* **311** 189
[7] Raether H 1988 *Surface Plasmons on Smooth and Rough Surfaces and on Gratings* (Berlin: Springer-Verlag) p. 40
[8] Chen H, Sun Y and Wang L 2009 *Chin. Phys. B* **18** 4287
[9] Sun M, Liu R, Li Z, Cheng B, Zhang D, Yang H and Jin A 2006 *Chin. Phys.* **15** 1591
[10] Yang P, Gu Y and Gong Q 2008 *Chin. Phys. B* **17** 3880
[11] Pan C L, Hsieh C F, Pan R P, Tanaka M, Miyamaru F, Tani M and Hangyo M 2005 *Opt. Express* **13** 3921
[12] Zhang W, Azad A K, Han J, Xu J, Chen J and Zhang X C 2007 *Phys. Rev. Lett.* **98** 183901
[13] Qu D, Grischkowsky D and Zhang W 2004 *Opt. Lett.* **29** 896
[14] Qu D and Grischkowsky D 2004 *Phys. Rev. Lett.* **93** 196804
[15] Torosyan G, Rau C, Pradarutti B and Beigang R 2004 *Appl. Phys. Lett.* **85** 3372
[16] O'Hara J, Averitt R D and Taylor A J 2004 *Opt. Express* **12** 6397
[17] Saxler J, Rivas J G, Janke C, Pellemans H P M, Bolver P H and Kurz H 2004 *Phys. Rev. B* **69** 155427
[18] Cao H and Nahata A 2004 *Opt. Express* **12** 1004
[19] Lee J W, Seo M A, Park D J, Kim D S, Jeoung S C, Lienau C, Park Q H and Planken P C M 2006 *Opt. Express* **14** 1253
[20] Masson J B and Gallot G 2006 *Phys. Rev. B* **73** 121401
[21] Grischkowsky D, Keiding S, Van Exter M and Fattinger Ch 1990 *J. Opt. Soc. Am. B* **7** 2006
[22] Hamon B V 1952 *Proc. IEE* **99** 151
[23] Azad A K, Zhao Y, Zhang W and He M 2006 *Opt. Lett.* **31** 2637
[24] Gefen Y, Shih W H, Laibowitz R B and Viggiano J M 1986 *Phys. Rev. Lett.* **57** 3097
[25] Chakrabarty R K, Bardhan K K and Basu A 1991 *Phys. Rev. B* **44** 6773
[26] Ghaemi H F, Thio T, Grupp D E, Ebbesen T W and Lezec H J 1998 *Phys. Rev. B* **58** 6779
[27] Ruan Z and Qiu M 2006 *Phys. Rev. Lett.* **96** 233901
[28] Han J G, Azad A K, Gong M F, Lu X C and Zhang W 2007 *Appl. Phys. Lett.* **91** 071122
[29] Shaner E A, Cederberg J G and Wasserman D 2007 *Appl. Phys. Lett.* **91** 181110
[30] Rivas J G, Janke C, Bolivar P H and Kurz H 2005 *Opt. Express* **13** 847
[31] Zhigalskii G P and Jones B K 2003 *The Physical Properties of Thin Metal Films* (New York: Taylor & Francis Inc.)
[32] Birey H 1978 *J. Appl. Phys.* **49** 2898
[33] Khor'kov S V 2005 *Tech. Phys. Lett.* **31** 555
[34] Satanin A M, Skuzovatkin V V and Khor'kov S V 1997 *JETP* **85** 351
[35] Thio T, Ghaemi H F, Lezec H J, Wolff P A and Ebbesen T W 1999 *J. Opt. Soc. Am. B* **16** 1743
[36] Grupp D E, Lezec H J, Ebbesen T W, Pellerin K M and Thio T 2000 *Appl. Phys. Lett.* **77** 1569
[37] Azad A K and Zhang W 2005 *Opt. Lett.* **30** 2945
[38] Chen H T, Padilla W J, Zide J M, Gossard A C, Taylor A J and Averitt R D 2006 *Nature* **444** 597
[39] Wang Y, Russell S D and Shimabukuro R L 2005 *J. Appl. Phys.* **97** 023708