Invisible plasmonic meta-materials through impedance matching to vacuum

J. W. Lee, M. A. Seo, J. Y. Sohn, Y. H. Ahn and D. S. Kim

School of Physics, Seoul National University, Seoul 151-747, Korea
denny@snu.ac.kr

S. C. Jeoung

Optical Nano Metrology Group, Korea Research Institute of Standard and Science, Daejeon 305-304, Korea

Ch. Lienau

Max-Born-Institut für Nichtlineare Optik und Kurzzeitspektroskopie, D-12489 Berlin, Germany

Q-Han Park

School of Physics, Korea University, Anam-Dong, Sungbuk-Gu, Seoul 136-701, Korea

Abstract: We report on perfect transmission in two-dimensional plasmonic matamaterials in the terahertz frequency range, in which zeroth order transmittance becomes essentially unity near specific resonance frequencies. Perfect transmission may occur when the plasmonic metamaterials are perfectly impedance matched to vacuum, which is equivalent to designing an effective dielectric constant around $\varepsilon_r = -2$. When the effective dielectric constant of the metamaterial is tuned towards ε_r *and* the hole coverage is larger than 0.2, strong evanescent field builds up in the near field, making perfect transmission possible.

OCIS codes: (240.6690) Surface waves; (050.1220) Apertures

References and links

1. J. D. Jackson, *Classical Electrodynamics* (Wiley, New York, 1999), p. 356.
2. R. W. Wood, “On a remarkable case of uneven distribution of light in a diffraction grating spectrum,” Phil. Mag. **4**, 396 (1902).
3. R. W. Wood, “Anomalous diffraction gratings,” Phys. Rev. **48**, 928 (1935).
4. Lord Rayleigh, “On the passage of electric waves through tubes, or the vibrations of dielectric cylinders,” Phil. Mag. **14**, 60 (1907).
5. Lord Rayleigh, “On the dynamical theory of gratings,” Proc. R. Soc. A **79**, 399 (1907).
6. R. Ulrich, “Interference filters for the far infrared,” Appl. Opt. **7**, 1987 (1968).
7. R. Ulrich, “Preparation of grids for far infrared filters,” Appl. Opt. **8**, 319 (1969).
8. C. C. Chen, “Transmission through a conducting screen perforated periodically with apertures.” IEEE trans. Microwave Theory Tech. **18**, 627 (1970).
9. P. J. Bliek, L. C. Botten, R. Deleuil, R. C. MC Phedran, and D. Maystre, “Inductive grids in the region of diffraction anomalies: theory, experiment, and applications,” IEEE trans. Microwave Theory Tech. **28**, 1119 (1980).
10. T. W. Ebbesen, H. L. Lezec, H. F. Ghaemi, T. Thio, and P. A. Wolff, “Extraordinary optical transmission through sub-wavelength hole arrays,” Nature (London) **391**, 667- 669 (1998).
11. H. Cao and A. Nahata, "Influence of aperture shape on the transmission properties of a periodic array of subwavelength apertures," Opt. Express **12,** 3664-3672 (2004), http://www.opticsexpress.org/abstract.cfm?URI=OPEX-12-16-3664
12. D. Qu, D. Grischkowsky, and W. Zhang, “Terahertz transmission properties of thin, subwavelength metallic hole arrays,” Opt. Lett. **29**, 896 (2004).
13. J. A. Porto, F. J. Garcia-Vidal, and J. B. Pendry, “Transmission resonances on metallic gratings with very narrow slits,” Phys. Rev. Lett. **83**, 2845-2848 (1999).

#9412 - $15.00 USD Received 11 November 2005; revised 1 December 2005; accepted 15 December 2005

14. S. Astilean, Ph. Lalanne, and M. Palamaru, "Light transmission through metallic channels much smaller than the wavelength," Opt. Commun. **175**, 265 (2000).
15. M.M.J. Treacy, "Dynamical diffraction explanation of the anomalous transmission of light through metallic gratings," Phys. Rev. B **66**, 195105 (2002).
16. F. J. Garcia-Vidal and L. Martin-Moreno, "Transmission and focusing of light in one-dimensional periodically nanostructured metals," Phys. Rev. B **66**, 155412 (2002).
17. J. T. Shen, Peter B. Catrysse, and Shanhui Fan, "Mechanism for designing metallic metamaterials with a high index of refraction," Phys. Rev. Lett. **94**, 197401 (2005).
18. F. J. Garcia de Abajo, G. Gomez-Santos, L. A. Blanco, A. G. Borisov, and S. V. Shabanov, "Tunneling mechanism of light transmission through metallic films," Phys. Rev. Lett. **95**, 067403 (2005).
19. L. M. Moreno and F. J. García-Vidal, "Optical transmission through circular hole arrays in optically thick metal films," Opt. Express **12**, 3619-3628 (2004),
20. F. J. Garcia de Abajo, R. Gomez-Medina, and J. J. Saenz, "Full transmission through perfect-conductor subwavelength hole arrays," Phys. Rev. E **72**, 016608 (2005).
21. L. Martin-Moreno, F. J. Garcia-Vidal, H. J. Lezec, K. M. Pellerin, T. Thio, J. B. Pendry, and T. W. Ebbesen, "Theory of extraordinary optical transmission through subwavelength hole arrays," Phys. Rev. Lett. **86**, 1114 (2001).
22. M. Tanaka, F. Miyamaru, M. Hangyo, T. Tanaka, M. Akazawa, E. Sano, "Effect of a thin dielectric layer on terahertz transmission characteristics for metal hole arrays," Opt. Lett. **30**, 1210 (2005).
23. V. Schmidt, W. Husinsky, and G. Betz, "Dynamics of laser desorption and ablation of metals at the threshold on the femtosecond time scale," Phys. Rev. Lett. **85,** 3516 (2000).
24. G. Zhao, R. N. Schouten, N. van der Valk, W. Th. Wenckebach, and P. C. M. Planken, "Design and performance of a THz emission and detection setup based on a semi-insulation GaAs emitter," Rev. Sci. Instrum. **73**, 1715 (2002).
25. G. Zhao, R. N. Schouten, N van der Valk, W. Th. Wenckebach and P. C. M. Planken, "A terahertz system using semi-large emitters: noise and performance characteristics," Phys. Med. Biol. **47**, 3699 (2002).
26. J. Y. Sohn, Y. H. Ahn, D. J. Park, E. Oh, and D. S. Kim, "Tunable terahertz generation using femtosecond pulse shaping," Appl. Phys. Lett. **81**, 13 (2002).
27. E. D. Palik (Ed.), "Handbook of Optical Constants of Solids" (Academic Press, San Diego, 1985).
28. J. B. Pendry, L. Martin-Moreno, and F. J. Garcia-Vidal, "Mimicking surface plasmons with suructured surfaces," Science **305**, 847 (2004).
29. F. J. Garcia-Vidal, L. Martin-Moreno, and J. B. Pendry, " Surfaces with holes in them: new plasmonic metamaterials," J. Opt. A: Pure Appl. Opt. **7**, S97 (2005).
30. K. G. Lee, and Q-Han Park, "Coupling of surface plasmon polaritions and light in metallic nanoslits," Phys. Rev. Lett. **95**, 103902 (2005).
31. H. Lochbihler and R. Depine, "Highly conducting wire gratings in the resonance region," Appl. Opt. **32**, 3459 (1993).

1. Introduction

One way to view vacuum is to interpret it as a medium with an impedance of $\frac{E_x}{H_y} = Z_0 = 1$ (or $\frac{E_x}{H_y} = Z_0 = \sqrt{\frac{\mu_0}{\varepsilon_0}} = 377\Omega$ in MKS units) through which an electromagnetic wave with its oscillating electric field E_x and magnetic field H_y along the x and y directions respectively, propagates along the z direction [1]. The electromagnetic wave does not reflect or scatter, because it is perfectly impedance matched to vacuum and the transmission is 100%. Needless to say, when a layer of dielectric or metal interrupts vacuum, the impedance deviates from Z_0. Traditionally, in planar structures, impedance matching to Z_0 is achieved by having stacks of dielectric layers (anti-reflection coating) or by varying the thickness of a dielectric thickness embedded between partially reflecting mirros (Fabry-Perot interferometer).

The anomalous optical properties of diffraction gratings have attracted much interest since the classical studies of Wood [2-5] and are intimitaly connected with the excitation of surface bound waves on the metal-dielectric interface. Thereafter transmission properties of grids have been studied in the microwave range [6-9]. Recently, this field has experienced a new boost since Ebbesen et al. discovered the extraordinary transmission through two dimensional arrays of nano-holes in thin metal films [10]. This also becomes an interesting research topic in the terahertz and microwave ranges [11, 12]. Since the upper limit for this linear transmission is 100%, the natural question arises as to whether tailoring such plasmonic

#9412 - $15.00 USD Received 11 November 2005; revised 1 December 2005; accepted 15 December 2005

metamaterials towards perfect transmission is possible. Until now, a few groups have theoretically predicted perfect transmission in plasmonic materials with no loss [13-21]. Recently nearly perfect transmission has been observed, but presumably above the cutoff frequency where strong surface field may not exist [22]. To a large extent, this quest for perfect transmission in metamaterials is triggered by the desire to design novel optical filters, possibly with ultrafast switching characteristics.

2. Experiments and theory

In this paper, we investigate surface plasmonic metamaterials in two dimensions: thin metal layers, perforated with periodic arrays of square and circular holes [Fig. 1(a)], in a effective medium [Fig. 2(b)] converted by an effective surface impedance in the structures where their effective impedance is matched to vacuum so that the transmission becomes close to 100% [Fig. 1(c)]. We demonstrate that for arrays of square holes, the effective impedance can become close to 1 when the coverage of the holes is larger than about 19% at a frequency slightly smaller than the first Rayleigh minima $f_R = c/d$, where d is the period and c the speed of light in vacuum. Under this condition, there is a large build-up of the evanescent field intensity at the surface, which makes the effective impedance essentially unity.

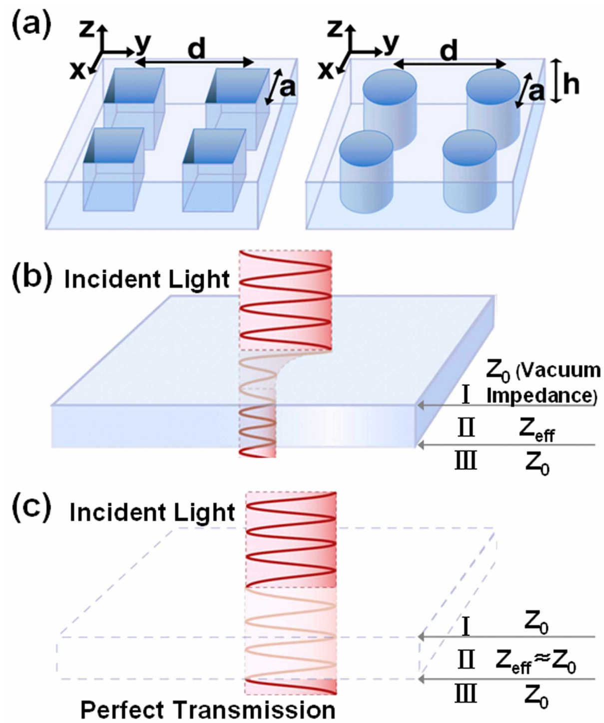

Fig. 1. (a) Schematic view of plasmonic meta-materials with periodic arrays of square holes and a SEM image. (b) An effective medium converted by an effective surface impedance in the structure displayed in (a). (c) At a specific frequency, the effective surface impedance becomes equal to the vacuum impedance and this medium has a perfect transmission.

A femtosecond laser machining system was used to fabricate arrays of sub-wavelength holes on aluminum plates [Fig. 2(a)] [23] Our experimental setup starts with coherent terahertz (THz) waves in the range of frequency f=0.1 to 2.5 THz, generated by a semi-insulating GaAs emitter biased with a 50 kHz and 300 V square voltage and a standard THz time-domain spectroscopy system [Fig. 2(b)] with a ZnTe crystal as a detector [24, 25]. When necessary, pulse-shaping methods in addition to insertion of secondary mechanical phase

#9412 - $15.00 USD Received 11 November 2005; revised 1 December 2005; accepted 15 December 2005

masks in the THz beam pathway are used to generate quasi-monochromatic THz sources [26]. Shown in Fig. 2(c) are time traces of the incident THz beam (solid line) and transmitted beam (red line). Fourier transformation of these time traces results in the amplitude spectra shown in Fig. 2(d).

In the THz region, the dielectric function of most metals, including aluminum, can be described phenomenologically to within experimental error with a Drude-model dielectric function for the electron gas and the real and imaginary parts of dielectric constant are roughly of the order of about -30000 and 100000, respectively [27]. Therefore, the ohmic loss fraction, which is of the order of δ/λ, with δ being the skin depth and λ the wavelength, is only 0.1% or less. This makes any metal in this frequency range essentially a perfect conductor with negligible loss. The array structures investigated here have square and circular holes with periods d of about 400 μm and a sample thickness of about 17 μm, but varying hole diameters. Figure 3(a) shows transmission spectra of field amplitude for square hole samples with different hole widths a of 125, 165, 183 and 200 μm respectively. The transmittance above the first Rayleigh minimum, $f_R = 0.75$ THz in the frequency range of approximately 0.8 to 1.5 THz is roughly equal to the sample coverage $\beta = a^2/d^2$, whereas the sharp peak around 0.6 THz increases drastically with sample coverage and therefore hole width. This sharp peak corresponds to what is frequently referred to as the air-metal (1, 0) surface plasmon mode in the visible and near-infrared range. As the sample coverage increases, this peak transmittance sharply increases, until it finally reaches unity (over 99.6% limited only by the laser stability) at the frequency of 0.66 THz for sample coverage above 0.2. Figs. 3(b) and (c) show time traces for samples with a hole coverage of 0.1 and 0.25 respectively, measured using a quasi-monochromatic THz source around 0.66 THz. The near-unity transmission for β=0.25 is therefore experimentally verified in time domain directly.

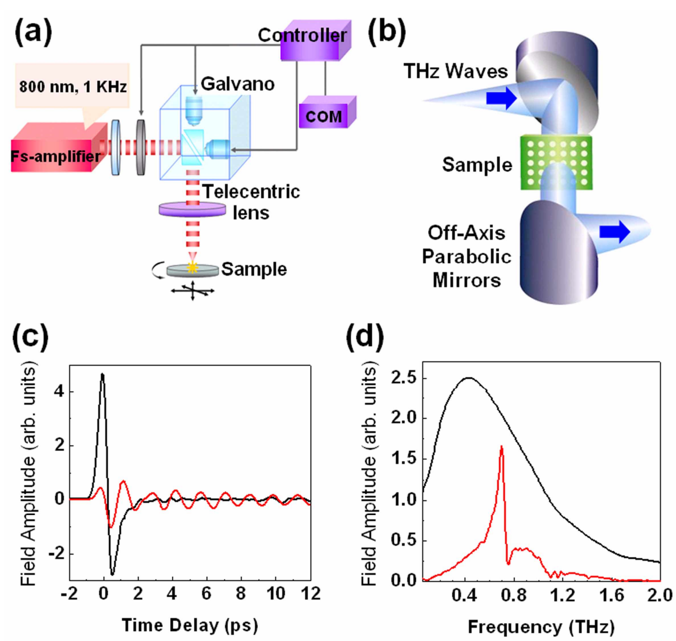

Fig. 2. (a) Schematics of the Femtosecond machining system used for manufacturing our samples. (b) Schematics of our terahertz transmission experiments. (c) Time trace of the incident terahertz beam (black line) and the transmitted beam (red line) for a typical sample. (d) Fourier transform of (c).

#9412 - $15.00 USD Received 11 November 2005; revised 1 December 2005; accepted 15 December 2005

In the following we compare our experimental results to a phenomenological model for impedance matching in plasmonic metamaterials. The idea is to have a simplified model that can give some insight into the underlying physics without the need for mathematically rigorous solutions of Maxwell's Eqs. What is essential is an easy framework to estimate the *average* in-plane electric field at the out-going surface, which is the zeroth order diffraction term. This is the only Fourier term that survives into the far field, and therefore directly determines the transmittance: the larger the zeroth order surface field is, the larger the transmittance is. Recent theoretical work by Pendry et al. [28] proposing designer or spoof surface plasmons gives such framework, because it gives an easy way to estimate a phenomenological effective dielectric constant, which in turn determines the surface electric field strength through an effective surface impedance. The square holes confine electric field along both x and y directions, which introduces a cut-off frequency for the wave-guiding modes inside the holes. In ref. [28, 29], this cut-off frequency acts as an effective plasmon frequency for the imaginary, flat and imperfect metal surface that mimics the perforated metal film. Its effective dielectric constant in then given as:

$$\varepsilon_{eff} = \frac{\pi^2}{8}\frac{1}{\beta}\left(1-\frac{f_c^2}{f^2}\right) \tag{1}$$

where $f_c = c/2a$.

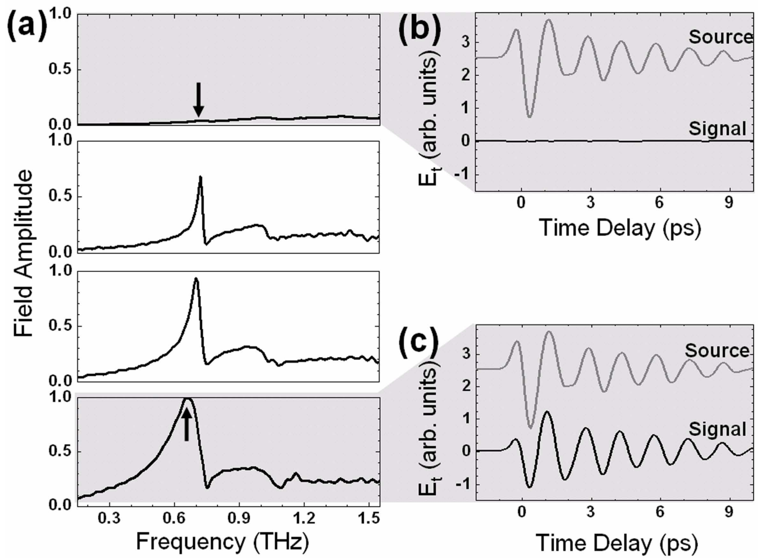

Fig. 3. (a) Transmission spectra of the transmitted field amplitude for four samples with different sample coverages of 0.1, 0.17, 0.2 and 0.25, respectively, from top to bottom. At the bottom the sample with the coverage 0.25 is shown. (b) and (c) THz time traces for samples with sample coverage of 0.1 and 0.25 respectively. The source signals (top) are quasi-monochromatic THz waves at 0.66 THz tailored by the pulse shaping.

Applying Eq. (1) to our square-hole samples, we obtain the effective dielectric constants as a function of frequency, as shown in Fig. 4(a). It is clear that at any given frequency, $-\varepsilon_{eff}$ decreases rapidly with increasing coverage. This has an important implication on the in-plane surface electric field, which is related to the incident magnetic field through the surface impedance. In general, the surface impedance is given by Eq. (2) in Ref. [30] and Eq. (9) in Ref. [31]:

$$|Z| = Z_0 \sqrt{\frac{1}{1+\varepsilon_m}} \qquad (2)$$

where ε_m is the real part of the dielectric constant of the metal, which is negative . The surface impedance of the fictitious, flat poor metal surface is then given by:

$$|Z_{eff}| = Z_0 \sqrt{\frac{1}{1+\varepsilon_{eff}}} \qquad (3)$$

where ε_{eff} follows from by Eq. (1). It is important to note that:

$$|Z_{eff}| = Z_0 \text{ for } \varepsilon_{eff} = -2 \qquad (4)$$

in which case we may claim that our structure has been impedance matched to vacuum and we may anticipate perfect transmission. From Eqs. (1) and (4), one sees that the hole-perforated metal film may become transparent at a frequency f_t given by:

$$f_t = \frac{f_c}{\sqrt{1+\frac{16\beta}{\pi^2}}} \qquad (5)$$

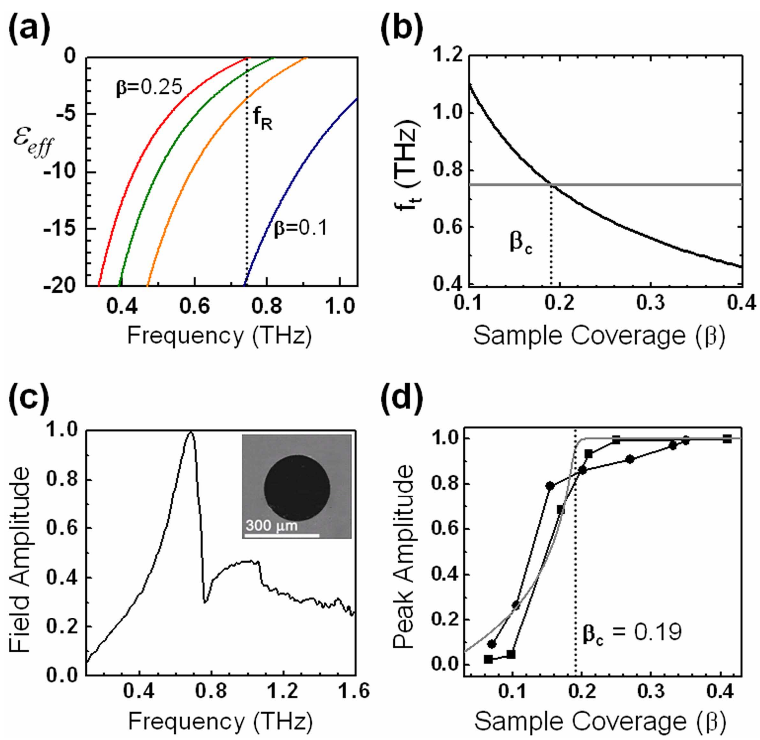

Fig. 4. (a). The effective dielectric constant plotted versus the frequency for coverages of 0.25 (red line), 0.2 (green line), 0.17 (orange line), and 0.1 (blue line). (b) Peak transmission frequency f_t at which the transmittance becomes unity, plotted against the sample coverage (from Eq. 5). Only for a coverage larger than 0.19 is f_t smaller than Rayleigh minimum as indicated by the gray line. (c) Transmittance for the hole sample with coverage 0.3, along with the sample image (inset). (d) Peak field amplitude plotted against the coverage for the square hole (filled squares) and the circular hole (filled circles) samples. The gray line represents Eq. (3), truncated at the amplitude of unity, calculated for f=0.66 THz.

#9412 - $15.00 USD Received 11 November 2005; revised 1 December 2005; accepted 15 December 2005

Eq. (5), however is only a necessary but not a sufficient condition for the perfect transmission, because for the concept of designer surface plasmon to be valid, and to be able to have a large build-up of surface field, f_t should be less than $f_R = c/d$. Applying this condition of evanescence, the model predicts that in order to have a 100% peak transmission efficiency, the coverage needs to be larger than 0.19, as seen in Fig. 4(b). We note that while the model assumes square hole samples, it should be also applicable without major modifications to circular hole samples, which also show perfect transmission at a coverage of about 0.3 (Fig. 4(c)),. We now discuss how the transmittance changes as a function of β.

Shown in Fig. 4(d) is the peak transmittance near the surface plasmon peak around 0.66 THz versus the coverage for the square hole samples (filled squares) and also for the circular hole samples (filled circles). The peak transmittance indeed becomes close to unity for a sample coverage $\beta \approx 0.2$. In both cases, the peak transmittance sharply increases with coverage, and begins to saturate near $\beta \approx 0.2$. The gray line represents theoretical effective impedance at 0.66 THz, calculated by Eqs. (1) and (3) at 0.66 THz and is in good agreement with experiments. Since the transmittance cannot exceed unity, we truncate our calculation at 1 . It is also important to note that the effective dielectric constant ε_{eff} indeed ranges from –1.5 and –2 at the peak frequencies where the experimentally measured transmittance is near unity, further supporting the validity of our model.

Finally, we comment on the limits of our simplified theory. Our theory is designed to address the experimental aspect of perfect transmission in two-dimensional arrays of square and circular holes, especially the intriguing dependence on coverage. It gives an easy and insightful way to estimate, in the fashion of ref. [27], the surface electric field that determines the ultimate transmission. It cannot, for instance, allow for the extremely sharp peaks of 100% transmittance theoretically predicted by many authors [19-21] both for two-dimensional holes and for one-dimensional slits of arbitrarily small coverages. These extremely sharp peaks are difficult to observe in real samples mainly because the finite sample size, finite range of time-trace, and sample inhomogeneity effectively limit the spectral resolution.

3. Conclusion

In conclusion, we have experimentally demonstrated *invisibility* of plasmonic metamaterials at specific wavelengths for the arrays of square and circular holes punctured in metal films in the THz frequency range. The sample coverage is the critical parameter in the observability of perfect transmission. We have introduced the concept of impedance matching surface plasmonic materials to vacuum thereby ensuring nearly perfect transmission. The invisibility of these metamaterials could have important applications: for example, they can be used as a perfect transmission filter with no loss and also to realize perfect transmissive waveguide with sub-wavelength geometries.

Acknowledgments

This research was supported by MOST, MOCIE and KOSEF. The authors wish to acknowledge valuable discussions with F. J. Garcia-Vidal, L. Martin-Moreno, P. C. M. Planken and D. J. Park.

#9412 - $15.00 USD Received 11 November 2005; revised 1 December 2005; accepted 15 December 2005