Terahertz transparency of optically opaque metallic films

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Abstract – Here we present an alternative approach to design a freestanding transparent conducting device for wide-angle and polarization-insensitive incidence of electromagnetic waves at terahertz frequencies. It is realized by depositing periodic metallic patches on top and bottom of the subwavelength metallic mesh. Based on the numerical computations, the deposited metallic patches can suppress the reflection and enhance the transmission. The high transmission of the designed system is attributed to the impedance matching to the vacuum. This design of a transparent conducting device can be useful in applications, such as optoelectronic electrodes and micro-electronic displays, where both high electrical conductivity and high optical transmittance are desirable.

Introduction. – Metamaterials (MTMs) are made of densely arranged subwavelength cells, each scalable over orders of frequencies throughout microwave and optical regimes. The associated permittivity and permeability, either positive or negative, can be freely tuned in principle over the entire range. In the past decade, MTMs have enabled the realization of many unprecedented phenomena and functionalities in a controllable manner through the use of naturally available materials, including negative index of refraction [1,2], optical magnetism [3], invisibility cloaks [4,5], superlenses [6,7], and perfect absorbers [8,9]. Meanwhile, electromagnetic radiation in the terahertz (THz) range bridges a gap between the optical and the microwave regimes, and has great potential in a broad range of scientific and technological areas such as medical diagnostics, material characterization, biological spectroscopy, security imaging, and wireless communications [10–12]. As compared to the microwave electronic and optical photonic technologies, the development of THz technology is lagging far behind. Due to the lack of suitable natural materials for THz device applications, MTM-based devices are particularly attractive in the THz frequency range.

Transparent conducting metals (TCMs) have drawn lots of attention recently [13–20], because of their potential applications in optoelectronic devices varying from solar cells to electronic papers, touch screens, and optical displays. TCMs possess the unique property of allowing a certain portion of the electromagnetic spectrum of interest to pass through a continuous metal film while its electrical connection is kept intact. However, it is well known that a high-conducting metal with a high electron density is generally opaque for light, since the metal's permittivity is generally very negative at optical frequencies.

In the THz regions, metals behave as perfect electric conductors and do not exhibit finite negative permittivity. However, metallic meshes with subwavelength openings are shown to exhibit negative Drude-like permittivity in the THz regime [20,21], and are generally optically opaque. Therefore, we can design the subwavelength metallic mesh-based MTMs to mimic the plasmonic metals at optical frequencies. In this paper, we propose a new type of freestanding TCM based on multilayer MTMs at THz frequencies. It is capable of operating over a wide range of incident angles, and it is insensitive to incidence polarizations. The whole thickness of this TCM is ~41 μm, which is ~10 times shorter than the working wavelength. In terms of fabrication, we emphasize that this freestanding design is practically realizable with the current technology, particularly noting the recent remarkable achievements in multilayer fabrications [22,23].

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paper is organized as follows. We first numerically calculated the transmission behavior of the proposed system in the following section. The interesting transparency at THz frequencies is verified based on full-wave simulations. In the third section we discussed the underlying physics behind this phenomenon. After presenting the properties of wide angle and polarization insensitivity of the proposed system in the fourth section, we concluded our paper in the last section.

**Numerical calculations on the designed system.**

As shown in fig. 1, the proposed TCM consists of three thin MTM layers. The top and bottom layers are an array of square metal patches which are arranged periodically in square lattices; the middle layer is an isotropic subwavelength metallic mesh. These three MTM layers are separated by two polyimide dielectric layers (called the spacer layers). The metallic structures, including the square metallic patches and the metallic mesh, are made of 200 nm thick gold films. The thickness of the spacer layer is \( t = 20 \mu m \). For the subwavelength metallic mesh, the unit cell is a 50 \( \mu m \) \( \times \) 50 \( \mu m \) square with metallic line width \( w = 5 \mu m \). The whole structure is assumed to be freestanding. Here our aim is to transmit electromagnetic waves efficiently through this system.

To illustrate how the idea works, numerical simulations for high transmission were performed based on the finite element method. In our simulations, the relative electric permittivity of the polyimide is \( \varepsilon_{\text{polyimide}} = 3 + i0.15 \) [23], and that for gold is described by a Drude metal \( \varepsilon_{\text{Au}} = 1 - \omega_p^2/\omega(\omega+i\Gamma) \) with plasma frequency \( \omega_p = 1.37 \times 10^{16} \text{Hz} \) and collision frequency \( \Gamma = 4.07 \times 10^{13} \text{Hz} \) [24]. All materials are assumed to be non-magnetic (\( \mu = \mu_0 \)). The system is illuminated with a linearly polarized plane wave propagating along the negative z-direction. The dimensions of this TCM with central operating frequency of 0.715 THz are optimized to be \( a = 70 \mu m \) and \( P = 100 \mu m \), where \( a \) and \( P \) are the width and the period of the square metallic patches, respectively. The solid line of fig. 2 shows the simulated transmittance spectrum of our designed TCM with the parameters mentioned above. At the frequency of 0.715 THz, \( \sim 74\% \) of energy of light can pass through the subwavelength metallic mesh and enter into another side. Losses in the polyimide dielectric layer mainly limit the transmittance performance. As a comparison, one can see that the transmittance curve of the bare metallic mesh in the 40 \( \mu m \) polyimide is less than \( \sim 20\% \). Therefore, it is worth noting that by putting square metallic patches on top and bottom of the subwavelength metallic mesh, one can make an optically opaque medium transparent. Therefore, such a device not only has high optical transmittance, but is also a good in-plane electrical conductor, which is highly desirable in many optoelectronic applications.

**Discussion on physics behind this phenomenon.**

Due to the very negative permittivity of gold at terahertz frequency, neither the gold patch layer nor the gold mesh layer is transparent within this frequency range, yet the combination of these opaque layers can lead to good transparency. In order to quantitatively and straightforwardly reveal the underlying mechanism of high transmission through such a deeply subwavelength metallic mesh, the effective relative constitutive parameters (permittivity \( \varepsilon \), permeability \( \mu \), refractive index \( n \), impedance \( z \) ) of this freestanding structure from reflection and transmission coefficients are extracted. At the peak frequency \( \sim 0.715 \text{THz} \), the corresponding wavelength is \( \sim 419 \mu m \), and \( \lambda/P \approx 4.19 \). So it is reasonable to consider this system as a homogeneous MTM medium under the condition of effective medium limit. The scattering parameter method is employed to retrieve the constitutive parameters [25,26]. Based on scattering parameters, the constitutive parameters of this system are shown in figs. 3(a)–(d). At the resonant frequency \( \sim 0.715 \text{THz} \), impedance is \( z = 0.97 - i0.05 \), whose real part approaches to unity and the imaginary part.
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Fig. 3: (Color online) Real (blue solid line) and imaginary (red dotted line) parts of the effective relative permittivity (a), permeability (b), refractive index (c), and impedance (d).

Fig. 4: (Color online) Simulated transmittance as a function of frequency and incidence angle for (a) TE- and (b) TM-polarized incident waves, where $a = 70\ \mu m$, $P = 100\ \mu m$, $t = 20\ \mu m$, $l = 50\ \mu m$, and $w = 5\ \mu m$.

approaches to zero. The retrieving results show that the impedance of the designed system is well matched to that of free space, leading to very small reflection. Meanwhile, the rather small imaginary part of the refractive index ($n = 2.39 + i0.25$) shown in fig. 3(c) generates little losses in the structure and consequently it leads to high transmission. This explanation gives a straightforward understanding of the phenomenon of this high transmission. Alternatively, the physical mechanism of this transmission enhancement could also be explained by the scattering cancellation mechanism [15–18,20]. For the deeply subwavelength metallic mesh, it is always highly reflective [21]. Yet, by appropriately adjusting the geometric parameters of the square metallic patch and the subwavelength metallic mesh, one can make the reflections from the square metallic patch layers strong enough to cancel the reflection from the subwavelength metallic mesh alone. Then the whole structure can become transparent in a certain frequency window.

Polarization-insensitive and large tolerance of oblique incidence. – In addition, for this newly designed device, the high transmission is robust against polarization and oblique incidence. Simulations were performed to verify these features with the same dimensions in fig. 2. The simulated transmittances as a function of frequencies ($f$) and incidence angles ($\theta$) are shown in fig. 4(a) for transverse-electric (TE) polarization and fig. 4(b) for transverse-magnetic (TM) polarization. Numerical results reveal that the transmittance is rather stable even for the incidence angles up to 35° for TE waves and 50° for TM waves.

Conclusions. – To summarize, our work theoretically demonstrates a freestanding transparent metal based on freestanding multilayer MTMs. It opens a high-transmission window within the technologically relevant THz frequency range. Theoretical results show that high transmission is polarization-insensitive and wide-angle. Our demonstration can be extended to other relevant frequencies. However, fabrication challenges and metal losses that may substantially degrade the device performance can become issues when using freestanding multilayers plasmonic metal films at optical frequencies. This device may find plenty of applications in the miniaturization and integration of THz components.

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