Deep subwavelength electromagnetic transparency through dual metallic gratings with ultranarrow slits

Chunyin Qiu,[1,*] Sucheng Li,[2] Ruirui Chen,[2] Bo Hou,[2,†] Feng Li,[3] and Zhengyou Liu[1]

[1]*Key Laboratory of Artificial Micro- and Nano-structures of Ministry of Education and School of Physics and Technology, Wuhan University, Wuhan 430072, China*

[2]*School of Physical Science and Technology, Soochow University, Suzhou 215006, China*

[3]*Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Sciences, Changchun 130033, China*

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We study the transmission response of microwaves through two identical metallic plates machined with ultranarrow slit arrays. The measured and calculated spectra consistently display a striking transmission peak at wavelength much larger than *any characteristic length* of the structure (e.g., about 20-fold of the lattice period), which cannot be directly explained by the existing mechanisms. Both the LC-circuit-based microscopic picture and the effective-medium-based macroscopic model are established to capture the essential physics behind such unexpected resonance at the deep subwavelength scale. Prospective applications of this transmission property can be anticipated, considering the merits of compact and excellent immunity to structural imperfections.

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I. INTRODUCTION

In recent years, the extraordinary optical transmission (EOT)[1–8] through an opaque metallic plate perforated with subwavelength apertures has drawn tremendous attention because of many fascinating applications. The studies involve various grating geometries and span a broad range of frequency regimes (from microwaves to optic waves).[9] Now it is widely accepted that the EOT can be attributed to the resonances induced by the coupling of the external electromagnetic (EM) waves with apertures, either individually or collectively: The former stems from the Fabry-Perot (FP) resonance of the fundamental waveguide mode inside the slit, in which the longest resonant wavelength is about twofold of the sample thickness;[4–8] the latter is induced by lattice resonance and always accompanied with exciting bound states (either the intrinsic surface plasmons or the structure-induced spoof surface waves) on the metal surface.[1–3,8] In that case, the resonant wavelength is comparable with the structure period unless the plasma frequency is approached. However, for ordinary metals, the plasma frequency lies in the ultraviolet regime, far beyond the scope of the most studies on EOT.

Here we propose a different physics mechanism responsible for the EOT effect. The system under consideration consists of two identical metallic plates perforated with ultranarrow slit arrays. The transmission spectra of such dual metallic gratings (DMGs) show a remarkable peak at a wavelength much larger than *any characteristic length* of the microstructure, which is absent in single metallic grating (SMG) systems. The resonance can be captured well by an equivalent LC-circuit model. Considering the characteristics of deep subwavelength, we have further developed an analytic model, in which each SMG is macroscopically treated as a homogeneous metamaterial slab with exotic dielectric properties, to reveal the essential physics behind the resonances. Throughout this paper, the finite-element-based software package (Comsol Mutiphysics 4.2) is adopted for full-wave calculations, and the dedicated microwave experiment is performed to measure the transmission spectra. The experimental results agree excellently with the numerical ones.

II. DEEP SUBWAVELENGTH EM TRANSPARENCY THROUGH DUAL METALLIC GRATINGS

As schematically illustrated in Fig. 1, each SMG consists of an aluminum plate (of thickness $h = 5.8$ mm) machined with a one-dimensional (1D) periodical (period $p = 5.0$ mm) array of cut-through slits (of width $w = 0.4$ mm). The ultranarrow slits are prepared by using the commercial wire-cut electrical discharge machining. The DMG forms when the two identical SMGs are separated by air spacer with precisely controllable distance d. The slits of the two gratings can be aligned perfectly or not. In the experiment, the SMG or DMG sample is placed between a couple of collinearly aligned rectangular microwave horns, one acting as the signal generator and the other as a receiver. The structure is illuminated by a microwave of transverse-magnetic (TM) polarization at incident angle θ, where the magnetic field acts along the z axis, and the electric field lies in the x-y plane. The transmission spectrum is determined by the ratio between the transmitted signals with and without the sample in presence.

The transmission of microwaves through a simple SMG structure with narrow slits has been well explored.[4–8] It is expected to be considerably low over a wide range of the low frequency, where both the localized FP resonance and the collective lattice resonance cannot occur. The conclusion also holds for the perfectly aligned DMG with zero separation (which is essentially a SMG of thickness $2h$). These are indeed manifested in Fig. 2(a) consistently by the experimental and numerical transmission spectra at normal incidence. However, when the separation d of the DMG is tuned to 5.0 mm, as shown in Fig. 2(b), a striking peak appears around 3.2 GHz in the experimental transmission spectrum, in excellent agreement with the numerical prediction. The corresponding resonant wavelength, $\lambda_R = 93.2$ mm, is much larger than any characteristic length in the DMG structure ($\lambda_R/w \simeq 230$, $\lambda_R/h \simeq 16$, and $\lambda_R/p \simeq 19$), precluding the possibilities of the collective lattice resonance and the FP resonance in individual slits. In Fig. 2(c) we also present frequency dependence of the phase accumulation across the DMG sample. It is surprising that although the whole sample

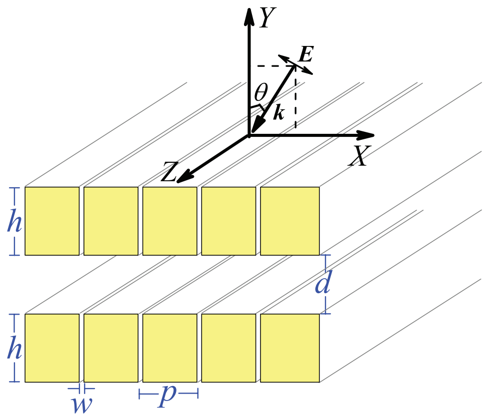

FIG. 1. (Color online) Schematic view of the sample illuminated by a microwave of TM polarization. Besides the adjustable separation d, the other geometric lengths are $p = 5.0$ mm,$h = 5.8$ mm, and $w = 0.4$ mm, respectively.

is considerably thin (with respect to λ_R), the phase difference grows rapidly to π near the resonance.

III. PHYSICS PICTURES BEHIND THE EM TRANSPARENCY

In order to gain physics insight into the aforementioned EM transparency emerging at deep subwavelength, in Figs. 3(a) and 3(b) we present the instantaneous field distributions for the electric component E_x and the magnetic component H_z, obtained by the full-wave calculation at the resonant frequency. It is observed that E_x is strongly squeezed inside the narrow slits (associated with enhancement over tenfold),

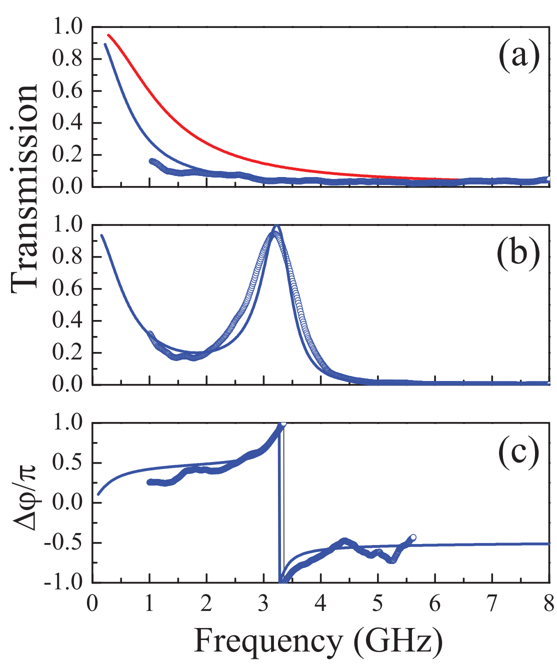

FIG. 2. (Color online) The measured (circle) and calculated (line) normal transmission spectra for the cases of (a) SMG (red) and perfectly aligned DMG with separation $d = 0$ (blue) and (b) DMG with $d = 5.0$ mm. (c) The measured (circle) and calculated (line) phase accumulation $\Delta\varphi$ across the DMG with $d = 5.0$ mm.

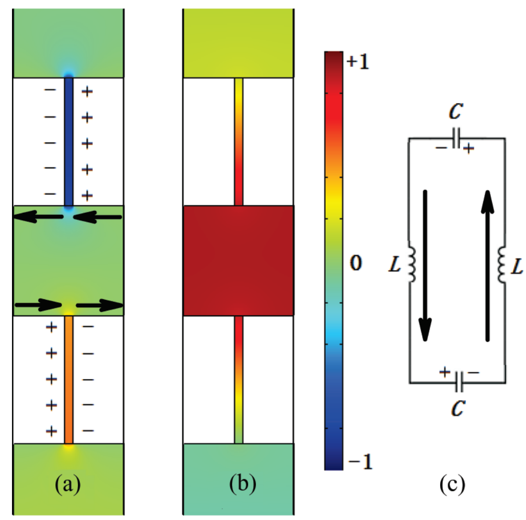

FIG. 3. (Color online) Instantaneous E_x (a) and H_z (b) field distributions at resonance, normalized by the corresponding maximum values and sharing the same color bar. (c) The equivalent LC circuit that accounts for the surface charges (signs) and surface currents (arrows) depicted in (a).

whereas H_z is mostly concentrated in the air space sandwiched between the two metallic gratings. The alternating EM field induces the oscillations of the free charges and currents on the highly conductive surfaces, as displayed schematically in Fig. 3(a). The oscillatory surface charge and current configurations can be accounted for by an equivalent LC circuit[10,11] manifested in Fig. 3(c). For simplicity, here the dissipative resistor elements (which are negligibly small in the microwave regime) are omitted. Since the dominant electric (or magnetic) field is distributed almost uniformly in the slits (or the sandwiched air cavity), each capacitance (or inductance) can be estimated by $C = \varepsilon_0 h\Lambda/w$ (or $L = 0.5\mu_0 dp/\Lambda$), where ε_0 and μ_0 are respectively the dielectric permittivity and magnetic permeability in vacuum and Λ is the length along the z axis (assumed to be infinity). The complex impedance of the whole LC circuit is $Z_c = 2[i\omega L + (i\omega C)^{-1}]$, with ω being the angular frequency. By requiring $Z_c = 0$ one can obtain a resonant frequency $F_R = \frac{c_0}{2\pi}\sqrt{\frac{2w}{phd}}$, at which the EM wave can be efficiently harvested and subsequently squeezed through the double slit arrays. Here $c_0 = 1/\sqrt{\mu_0\varepsilon_0}$ is the light speed in vacuum. When the slit is sufficiently narrow, the corresponding resonant wavelength (in vacuum) $\lambda_R = \pi\sqrt{2phd/w}$ can be much larger than the other geometric lengths, i.e., the structure period p, grating thickness h, and separation d. For the current DMG system with $d = 5.0$ mm, the resonant wavelength λ_R predicted by the simple LC-circuit model is 84.6 mm, deviating by less than 10% from the above full-wave calculation, i.e., 93.2 mm. It is worth pointing out that Lockyear *et al.*[12] have reported an abnormal transmission enhancement through a single-stepped subwavelength slit, where the resonant wavelength grows as the slit narrowed down, a tendency consistent with the above formula. In fact, the physics behind that phenomenon is essentially the same as the current one at normal incidence. Moreover, the resonant wavelength (in that system) could also be quantitatively described by our LC-circuit model, associated with replacements of p and d by the width and length of the stepped cavity, and h by the length of the narrow slit, respectively.

In fact, the above EOT effect can also be understood in a macroscopic way. At a wavelength much larger than the microstructures of the sample, each SMG (made of perfect conductor) can be viewed as a homogenous metamaterial plate of thickness h, characterized by extremely anisotropic electric permittivity and magnetic permeability tensors.[13] Both tensors are controlled only by the filling ratio of the slit $\eta = w/p$. The effective-medium-theory (EMT) model is particularly valid when the slit is long and narrow (i.e., $w \ll h$), where the evanescent nonzero order of waveguide mode inside the slit can be safely omitted. For clarity, we first focus on the normal incidence that involves only the x component of permittivity $\varepsilon_x = \varepsilon_0/\eta$ and the z component of permeability $\mu_z = \eta\mu_0$. It is of interest that such exotic material parameters keep the propagation constant k_0 invariant, but give a tiny impedance ratio $Z_r = \eta$ with respect to free space, which are essentially inaccessible in natural materials. For the artificial bilayer structure it is easy to analytically derive the reflection and transmission coefficients by using the conventional transfer-matrix method. The reflection coefficient exhibits two distinct zero-reflection conditions. The first one is determined by $k_0 h = m\pi$ (with m being positive integer) and corresponds to the usual FP resonance in each artificial dielectric plate. It is only dependent on the grating thickness and has been extensively studied in previous SMG systems.[4–8] The second one is determined by the formula

$$2Z_r/\left(1 + Z_r^2\right) = \tan(k_0 h)\tan(k_0 d), \tag{1}$$

which is unique in the bilayer system. In view of the characteristic of the trigonometric function, Eq. (1) has a series of solutions. Here we focus on the fundamental one, which is associated with the lowest resonant frequency. For the ultranarrow slit case (with $Z_r = \eta \ll 1$), Eq. (1) can be well approximated by $2Z_r \cong \tan(k_0 h)\tan(k_0 d)$. At the low frequency (i.e., $k_0 d \ll 1$ and $k_0 h \ll 1$), it is further simplified into $2\eta \cong k_0^2 hd$ considering that $\tan(k_0 d) \cong k_0 d$ and $\tan(k_0 h) \cong k_0 h$. This gives rise to the fundamental resonant frequency[14]

$$F_R \cong \frac{c_0}{2\pi}\sqrt{\frac{2\eta}{hd}}, \tag{2}$$

which is exactly the one deduced from the LC-circuit model.

The low resonant frequency derived based on the EMT is still somehow counterintuitive considering the fact that the "preconceived" phase accumulations across the double effective plates ($2k_0 h$) and the sandwiched air space ($k_0 d$) are very small. Remember that in a macroscopic sense, there are two well-established physics mechanisms behind the full transmission through a uniform plate: One is the perfect matching of the impedance with surroundings, and the other is the thickness-dependent FP resonance. The EOT involved here is closely connected to the latter one. Let us consider an infinite 1D array of the above artificial dielectric plates (with permittivity $\varepsilon_x = \varepsilon_0/\eta$ and permeability $\mu_z = \eta\mu_0$), arranged periodically (at a pitch $h + d$) along the y direction. At the low frequency the system can be further homogenized and corresponds to a uniform medium with effective permittivity $\frac{d\varepsilon_0 + h\varepsilon_x}{d+h}$ and permeability $\frac{d\mu_0 + h\mu_z}{d+h}$. Again, if the slit is extremely narrow ($\eta \ll 1$), the effective permittivity and permeability can be approximated by $\frac{h\varepsilon_0}{\eta(d+h)}$ and $\frac{d\mu_0}{d+h}$, respectively, resulting in a high relative refraction index $\sqrt{\frac{hd}{\eta(d+h)^2}}$. As a consequence, for such a high refraction index plate of thickness $2(h + d)$, the fundamental FP resonant frequency can be roughly estimated by $\frac{c_0}{4}\sqrt{\frac{\eta}{hd}}$, which is very close to the prediction in Eq. (2). This FP analogy also clearly elucidates the phase compression of π by such a thin DMG sample, as exhibited in Fig. 2(c).

IV. DISCUSSIONS

It is worth pointing out that there have been many studies on the transmission response of EM waves through DMG structures,[15–26] which span a wide range of frequency regimes (from microwaves to optic waves) for different geometries (formed from slit or hole arrays). For the slit-based DMG systems,[15–19] a pioneering work in the microwave regime states that the EOT can be realized by exciting the standing-wave mode inside the extremely narrow gap sandwiched between the bilayers,[15] in which the resonant wavelength mostly depends on the structural period. The following studies in the infrared regime[16–18] have also exhibited rich transmission features, where the enhanced transmission could be mediated by the FP-like guided-mode resonance inside the slits.[17,18] However, the deep subwavelength EOT considered here has not been observed due to the absence of the long wavelength spectra. For the hole-based DMG systems,[20–22] i.e., the so-called double fishnet structures, the physics is remarkably different. In those systems, there are no propagating waveguide modes inside the apertures at long wavelength. The EOT effect is always closely related with the resonant excitation of bound states (either the intrinsic or the structure-induced surface plasmons). Moreover, the scheme of homogenization is considerably different, which could reveal negative refraction around specific frequencies.[23–25] Of course, the deep subwavelength EOT focused here can also be extended to a 2D geometry made of dual arrays of metallic tiles, allowing the further design with better isotropy.

Recently, the exotic transmission of acoustic waves by similar dual grating structures has also attracted great interest.[27–30] Based on a simple mapping of physics quantities, the resonant mechanism proposed here for EM waves can be easily extended to acoustic systems (i.e., dual gratings made of acoustically rigid plates perforated with periodic slit arrays). Different from the optical case, such a transmission enhancement at a deep subwavelength remains in hole-based dual gratings, since there are no frequency cutoffs for the fundamental waveguide modes inside the holes (resembling the slit cases). It is of interest that in Ref. 30 Bell *et al.* has also reported a series of resonances for acoustic waves transmitted through a hole-based dual grating structure, where the first odd order of resonance might be homologous to the resonance considered here. However, it is explored in a different parameter region (i.e., with extremely narrow gap spacing compared to the lattice period) and explained by a semiquantitative analytical model (associated with an empirical parameter to fit the resonant position).

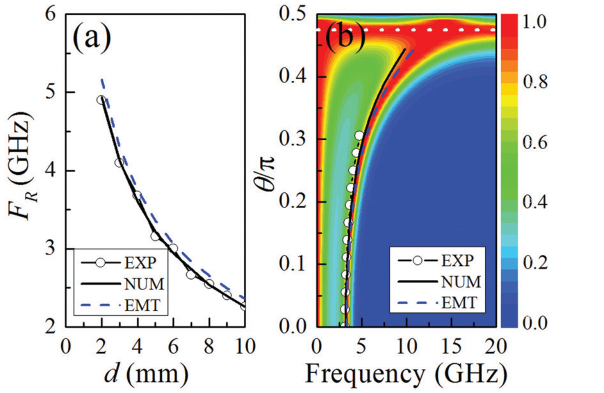

FIG. 4. (Color online) (a) The resonant frequency F_R plotted as a function of the separation d. (b) The EMT prediction of the angle-dependent transmission spectra for a given $d = 5.0$ mm, where the horizontal dot line corresponds to the angular sensitive transparency induced by perfect impedance matching. In (a) and (b) the open circles and solid lines denote, respectively, the peak positions extracted from the experimental and numerical transmission spectra, while the dashed lines come from the EMT result.

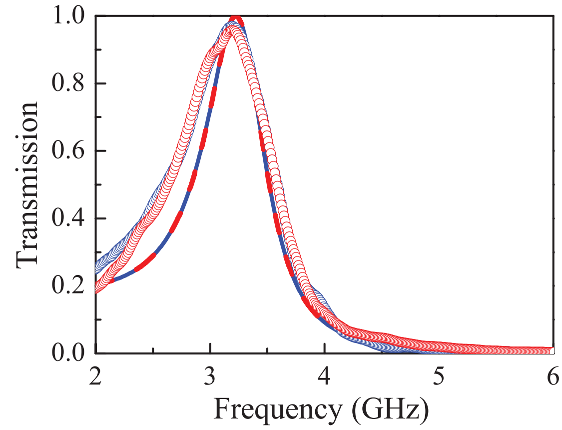

FIG. 5. (Color online) Numerical (line) and experimental (circle) transmission spectra at normal incidence for the perfectly aligned DMG (blue) mentioned in Fig. 2(b), compared with those for the DMG with relative lateral shift of half period (red).

V. GEOMETRIC AND ANGULAR DEPENDENCIES OF THE EOT EFFECTS

As revealed by both the LC-circuit-based microscopic picture and the EMT-based macroscopic model, the resonant frequency F_R is closely relevant to all of the characteristic lengths involved in the DMG system. Besides the decrease of the slit ratio $\eta = w/p$, both the increase of the SMG thickness h and the separation d enable a drastic reduction of F_R. As an example, here we validate the dependence of F_R on d, which is easily controlled for an already fabricated DMG system. As shown in Fig. 4(a), the experimental result (open circle) agrees pretty well with the full-wave calculation (solid line) and the EMT-based analytical model (dashed line). Without results presented here, the dependencies of the resonant frequencies on the other geometric parameters have also been verified numerically.[31]

Equation (1) can be straightforwardly extended to the oblique incidence with simply replacing the physics quantities Z_r with $Z_r/\cos\theta$ and $k_0 d$ with $k_0 d\cos\theta$, in which the extreme anisotropy ($\varepsilon_y/\varepsilon_x \to \infty$) of the artificial dielectric is taken into account. Within a broad range of incident angle θ, the resonant frequency can be estimated by $F_R \cong \frac{c_0}{2\pi\cos\theta}\sqrt{\frac{2\eta}{hd}}$, which is still in the deep subwavelength regime as long as the slit ratio η is small enough. (Note that this formula fails to describe the angular dependence of the resonant frequency for the single-stepped slit mentioned in Ref. 12). This angular robustness is clearly manifested in Fig. 4(b) by the angle-dependent transmission spectra evaluated for the EMT-based bilayer system. For comparison, in Fig. 4(b) we also provide the peak positions extracted from the experimental and numerical transmission spectra, which coincide well with the EMT prediction. It is worth pointing out that the angular spectra predicted by EMT exhibit clearly another two types of peaks: one emerging from the zero frequency (associated with near-zero phase change across the sample) is robust to the incident angle, whereas the other is sensitive to the incident angle (occurring near the grazing angle; see the horizontal dot line). For the latter case, the broadband EM transparency stems from the perfect impedance matching between the metamaterial and surroundings when $\cos\theta = \eta$, which has been reported recently in SMG systems[32–34] and interpreted by an analogy of Brewster effect.[33–35]

Recently, a hot topic associated with DMG structures is the sensitivity of the peak position on the relative lateral shift between the double gratings.[15–18] This interesting phenomenon can be attributed to the strong interference of the evanescent waves emitting from the openings, especially in the situation of narrow gap spacing. For the present system, we have also studied the influence of the misalignment on transmission spectra. As an example, Fig. 5 shows the comparison of the numerical transmission spectra (lines) between the cases of perfectly aligned (blue) and misaligned (red) DMGs, from which one cannot find observable deviation. This is consistent with the prediction from the EMT model, in which the evanescent EM field is not taken into account. The weak dependence of transmission spectra on the misalignment has also been validated considerably well by the experimental results (circles).

To investigate the robustness of the EOT effect in different frequency ranges, the sample is scaled down from millimeter to micrometer. The plasmonic effect is taken into account by using the Drude model. In Fig. 6(a) we present the numerical transmission (solid) and absorption (dash) spectra for the DMGs made of silver.[17] It is observed that, although the peak amplitude reduces due to the absorption, the enhancement effect in transmission remains even for the sample with unit size of micrometers (e.g., for the case of period 0.5 μm, the resonant frequency is about 0.3 THz). From the viewpoint of the EMT, one can also predict the existence of such a compelling EOT effect if the air gap is replaced with a solid dielectric. This is validated in Fig. 6(b), where the silicon substrate (with relative dielectric permittivity of 11.9) is employed. Obviously, the introduction of the solid substrate may greatly facilitate the miniaturization of the sample. Note that the sandwiched structure is quite different from that

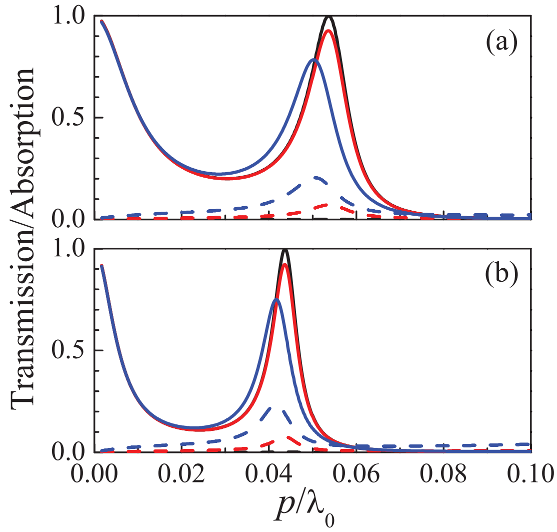

FIG. 6. (Color online) (a) Numerical transmission (solid lines) and absorption (dashed lines) spectra at normal incidence for the DMGs made of silver, plotted as a function of the normalized frequency p/λ_0, where λ_0 is the wavelength in vacuum. Here the black, red, and blue lines represent the samples of period 5 mm, 50 μm, and 0.5 μm, respectively, scaled down from the geometry mentioned in Fig. 2(b). (b) The same as in (a), except that the gap space between the bilayers is inserted with silicon instead of air.

proposed by Zhou *et al.*,[36,37] which involves metamaterial with *negative* permittivity.

VI. CONCLUSIONS

In summary, by using DMG structures we have introduced a new type of EOT effect that occurs at wavelength much larger than any characteristic length of the microstructure. This phenomenon is elucidated clearly in both microscopic and macroscopic ways. Such a deep subwavelength EOT effect also remains in the terahertz regime as the sample size scaled down to micrometers, where the damage of Ohmic loss in metals is not very severe. Considering the merits of the angular robustness and excellent immunity to structural imperfections, this simple and compact structure is promising for practical applications, such as in polarization filtering and energy harvesting.

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*cyqiu@whu.edu.cn
†houbo@suda.edu.cn

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