Nonperiodic metallic gratings transparent for broadband terahertz waves

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In this work, we demonstrate both theoretically and experimentally that nonperiodic metallic gratings can become transparent for broadband terahertz waves. It is shown that broadband high transmission appears in aperiodic metallic gratings (including quasiperiodic and disordered ones), which originates from the nonresonant excitations in the grating system. Quasiperiodic and disordered metallic gratings effectively weaken and even eliminate Wood's anomalies, which are the diffraction-related characters of periodic gratings. Consequently, both the transparence bandwidth and transmission efficiency are significantly increased due to the structural aperiodicity. An optimal condition is also achieved for broadband high transparency in aperiodic metallic gratings. Experimental measurements at the terahertz regime reasonably agree with both analytical analysis and numerical simulations. Furthermore, we show that for a specific light source, for example, a line source, a corresponding nonperiodic transparent grating can be also designed. We expect that our findings can be applied for transparent conducting panels, perfect white-beam polarizers, antireflective conducting solar cells, and beyond.

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I. INTRODUCTION

The interaction between light and matter, which leads to various interesting phenomena, is usually strongly dependent on the structural symmetry and the ordering degree in the natural or artificial materials. Based on the existence or lack of long-range and short-range order, materials (or structures) may possess periodic, quasiperiodic, and random ordering, respectively. Specifically, periodic structures have both long-range and short-range order; quasiperiodic structures bear long-range order but short-range disorder; and random structures own neither long-range nor short-range order. It is well known that periodicity in structures brings about various important effects, such as what the Bloch theorem illustrates, in solid state physics [1]. However, lack of periodicity may also create fascinating features on some occasions. For example, the extraordinary optical transmission (EOT) was initially discovered by Ebbesen and coauthors [2] in a periodic subwavelength hole array perforated on silver film, but later on, Matsui *et al.* [3] significantly presented enhanced transmission resonances of light through quasiperiodic arrays of subwavelength apertures and opened new avenues for optoelectronic devices [4–10]. Actually, in the past decades, quite a few quasiperiodic structures [11–13], such as structures with Cantor [13], Fibonacci [14–16], Thue-Morse, [17–19], and double-period sequences [20,21], have received considerable attention.

It is known that broadband EOT is usually difficult to achieve in the metal/dielectric nanostructures. Fortunately, by introducing self-similarity in the structures, people have successfully realized broadband EOT in quasiperiodic (such as Penrose-tiling) subwavelength metal/dielectric systems [3] and also in plasmonic fractals [22]. Physically, broadband EOT in these systems originates from resonant excitations of surface plasmons (SPs) [23] at multiple but discrete frequencies, which restrict the transparency bandwidth and transmission efficiency to some extent. Very recently, we utilized a periodic design to successfully make structured metals transparent for broadband infrared and terahertz waves by relying on nonresonant excitation of spoof surface plasmons (SSPs) or SPs [24–26]. Similar phenomenon are further found in optical frequencies, which is explained by the anomalous impedance-matching mechanism [27–30]. However, the broadband transparence in periodic systems occurs for wavelengths larger than the first-order Wood's anomaly [24,25]. Around the Wood's anomalies [31,32], the transmission of electromagnetic waves drops to zero because of the interference between the wavelets scattered by the periodic structures, which is essentially a diffraction effect of the periodic structures. To further broaden the transparency bandwidth and improve the transmission efficiency of structured metals, we now try to exploit aperiodic structures to break the transitional symmetry and decrease the degree of ordering in the system, and then weaken or even eliminate Wood's anomalies, thus achieving broadband high transparency based on nonresonant excitations in aperiodic metallic gratings.

In this paper, we have theoretically and experimentally demonstrated that broadband high transmission appears in aperiodic metallic gratings (including quasiperiodic and disordered ones), which originates from the nonresonant excitations in the grating system. Quasiperiodic and disordered metallic gratings are capable of weakening and even eliminating Wood's anomalies, which consequently increase the transparence bandwidth and improve transmission efficiency in the terahertz region. Furthermore, with a specially designed nonperiodic metallic structure (a metallic grating with a gradually varying air void filling ratio, for example), the system can become transparent for transverse-magnetic (TM) polarized line sources. The broadband transparence for structured metals may have numerous important applications, such as

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for conducting panels [7,33–35], white-beam polarizers [36], antireflective solar cells [27,37], etc.

The paper is organized as follows. After the Introduction, in Sec. II we theoretically investigate the broadband transparence in nonperiodic metallic gratings based on detailed analytical solutions of Maxwell's equations. The optimal incident angle for broadband transparency of metallic gratings is achieved. In Sec. III, by using the finite-difference time-domain (FDTD) method, we present the numerical calculations on the optical transmission through periodic, Fibonacci, and disordered metallic gratings, respectively. And electrical field distributions prove that broadband transparency in the metallic gratings originate from the nonresonant effect. In Sec. IV we show experimental results for the broadband transparency of nonperiodic metallic gratings. Furthermore, in Sec. V, a metallic grating with a gradually varying air void filling ratio is demonstrated to be transparent for line sources. Finally, we summarize our results in Sec. VI.

II. ANALYTICAL ANALYSIS ON BROADBAND TRANSPARENCE IN NONPERIODIC METALLIC GRATINGS

We consider electromagnetic waves traveling through a nonperiodic metallic grating based on Maxwell's equations. Without loss of generality, we suppose that the nonperiodic metallic grating is constructed by arranging units A and B according to a nonperiodic sequence, such as the Fibonacci sequence or a disordered sequence, etc. As shown in Fig. 1(a), unit A has the overall unit size p_A, metal strip width b_A, and thickness h; the corresponding parameters for unit B are p_B, b_B, and thickness h, respectively. When TM-polarized waves are incident on the sample, we can divide the space adjacent to the sample into three regions: the incident region (I) above the sample, the sample region (II), and the emitting region (III) below the sample. To simplify the analysis, we defined the vertical positions of the top and bottom grating surfaces as $z = 0$ and $z = h$, respectively. We consider the regions $I(z < 0)$ and $III(z > h)$ as the free space of air, and the metal is treated as an ideal metal. It follows that the y component of the magnetic field in regions I and III can be expressed as

$$H_y^I = \exp(ik_{x0}x + ik_{z0}z) + \sum_m r_m \exp(ik_{xm}x - ik_{zm}z)$$
$$H_y^{III} = \sum_m t_m \exp(ik_{xm}x + ik_{zm}z), \quad (1)$$

where $k_{xm} = k_{x0} - \Delta k_{xm}$, Δk_{xm} is provided via high-order diffractive modes, $k_{zm} = (k_0{}^2 - k_{xm}{}^2)^{1/2}$, $k_{x0} = k_0 \sin\theta$, and

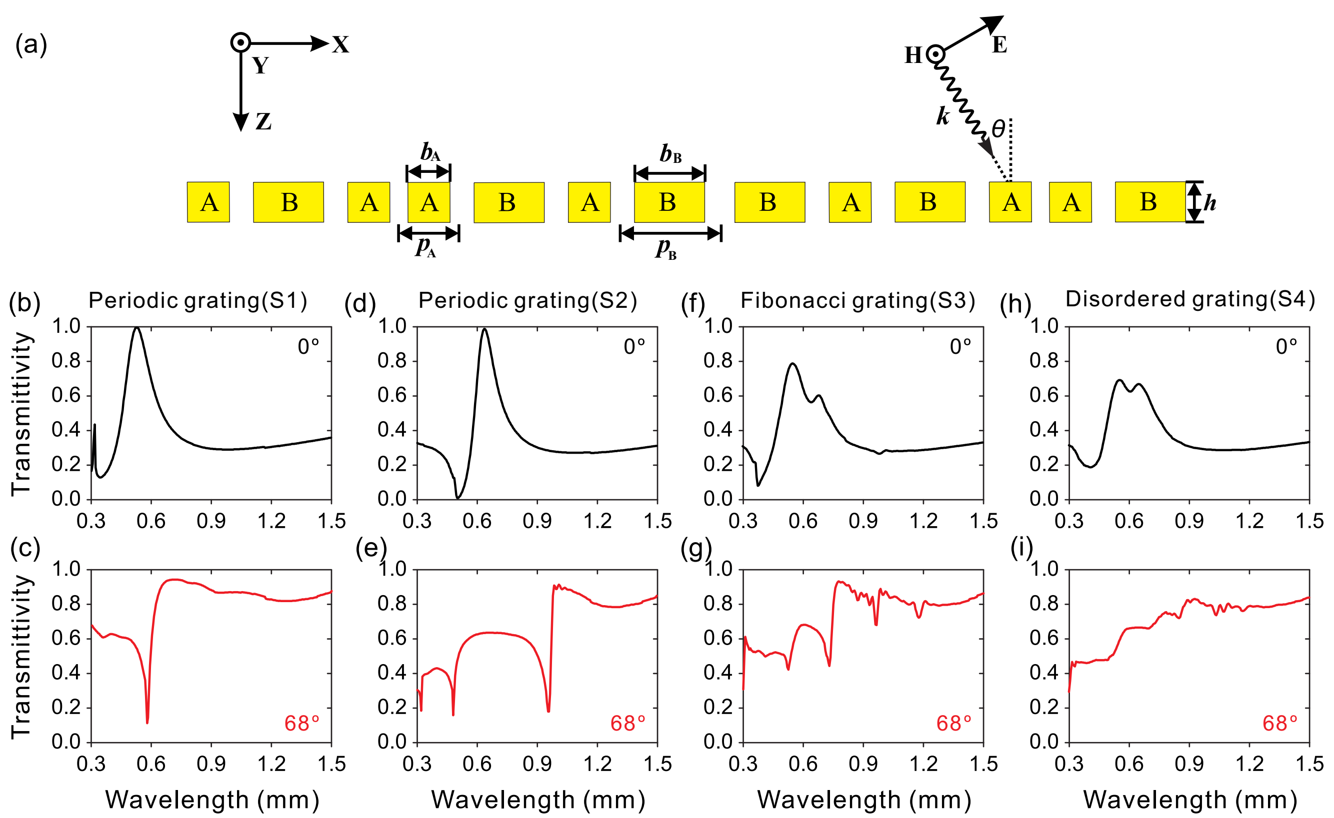

FIG. 1. (Color online) (a) Schematic of metallic grating with nonperiodic sequence (Fibonacci sequence, disordered sequence, etc.) constructed by units A and B. Calculated transmission spectra for TM polarization of structures: a periodic metallic grating (S1) constructed by unit A when incident angle (b) $\theta = 0^\circ$ and (c) $\theta = 68^\circ$; a periodic metallic grating (S2) constructed by unit B when incident angle (d) $\theta = 0^\circ$ and (e) $\theta = 68^\circ$; a metallic grating with the tenth-generation Fibonacci sequence (S3) constructed by units A and B when incident angle (f) $\theta = 0^\circ$ and (g) $\theta = 68^\circ$; a metallic grating with disordered sequence (S4) constructed by units A and B when incident angle (h) $\theta = 0^\circ$ and (i) $\theta = 68^\circ$. Unit sizes of units A and B are $p_A = 300\,\mu$m and $p_B = 500\,\mu$m, strip widths of units A and B are $b_A = 210\,\mu$m and $b_B = 350\,\mu$m, and the thickness of all gratings is $h = 200\,\mu$m.

$k_0 = 2\pi/\lambda$, r_m and t_m are the mth reflection coefficient and transmission coefficient, respectively. When the wavelength is much larger than the sizes of the constituent units, high-order diffractive modes are evanescent and are neglected for simplicity. Thus Eq. (1) is simplified as

$$H_y^I = \exp(ik_{x0}x + ik_{z0}z) + r_0 \exp(ik_{x0}x - ik_{z0}z)$$
$$H_y^{III} = t_0 \exp(ik_{x0}x + ik_{z0}z), \tag{2}$$

with $k_{z0} = ({k_0}^2 - {k_{x0}}^2)^{1/2} = k_0 \cos\theta$, $k_{x0} = k_0 \sin\theta$, and $k_0 = 2\pi/\lambda$.

In region II, since the metal can be taken as ideal metal in the present terahertz regime, the magnetic field is zero except in the slits ($p_n < x < p_n + a_n$), where p_n represents the corresponding starting coordinate of the nth slit, and a_n represents its width. The magnetic field in the nth slit ($p_n < x < p_n + a_n$) can be simply expressed as the zeroth-order rectangular waveguide mode:

$$H_{ny}^{II} = \cos[q(x - p_n)][M_n \exp(i\beta_s z) + N_n \exp(-i\beta_s z)], \tag{3}$$

where β_s is the wave number in the slits, q is the eigen wave vector of the waveguide, and M_n and N_n are component coefficients, respectively. The relation between the x component of the electric vector and the y component of the magnetic vector is given as

$$E_x = -\frac{i}{\omega\varepsilon}\frac{\partial H_y}{\partial z}. \tag{4}$$

The boundary conditions of the electric fields at the two grating surfaces should be satisfied, i.e.,

$$\int_{-\frac{D}{2}}^{\frac{D}{2}} E_x^I\big|_{z=0}\, dx = \sum \int_{p_j}^{p_j+a_j} E_{jx}^{II}\big|_{z=0}\, dx$$
$$\sum \int_{p_j}^{p_j+a_j} E_{jx}^{II}\big|_{z=h}\, dx = \int_{-\frac{D}{2}}^{\frac{D}{2}} E_x^{III}\big|_{z=h}\, dx. \tag{5}$$

Meanwhile, the boundary conditions of the magnetic fields follow the relation

$$\frac{1}{D}\int_{-\frac{D}{2}}^{\frac{D}{2}} H_y^I\big|_{z=0}\, dx = \frac{1}{W}\sum \int_{p_j}^{p_j+a_j} H_{jy}^{II}\big|_{z=0}\, dx$$
$$\frac{1}{W}\sum \int_{p_j}^{p_j+a_j} H_{jy}^{II}\big|_{z=h}\, dx = \frac{1}{D}\int_{-\frac{D}{2}}^{\frac{D}{2}} H_y^{III}\big|_{z=h}\, dx, \tag{6}$$

where $W = \sum a_j$ represents the sum of the width of all slits, and D is the total width of the sample, respectively.

By solving Eqs. (5) and (6), we can derive the reflection coefficient as

$$r_0 = \frac{\left(k_{z0}^2 D^2/W^2 - \beta_s^2\right)\tan(\beta_s h)}{\left(k_{z0}^2 D^2/W^2 + \beta_s^2\right)\tan(\beta_s h) + 2i\beta_s k_{z0} D/W}. \tag{7}$$

Equation (7) indicates that if

$$k_{z0}^2 D^2/W^2 - \beta_s^2 = 0, \tag{8}$$

the reflection coefficient reaches its minimum value $r_0 = 0$. When the slit is vacuum, we have $\beta_s = k_0$. Therefore once Eq. (8) is satisfied, zero reflection and high transmission are achieved. Furthermore, the optimal incident angle for high transmission follows:

$$\theta_f = \text{arcos}\,(W/D). \tag{9}$$

Note that Eq. (9) for nonperiodic gratings looks like the expression for periodic gratings [24,25], but here in Eq. (9), the air void filling ratio W/D is an average quantity representing the proportion of the empty space with respect to the volume of the entire nonperiodic grating.

The above analysis indicates that broadband extraordinary transmission is a universal property of one-dimensional (1D) metallic gratings under oblique incidence. The broadband transparence in aperiodic metal gratings is not sensitive to the structural details of the grating when the incident wavelength is much larger than the sizes of the constituent units. Instead, it is primarily dominated by the averaged structural geometry, such as air void filling ratio.

III. NUMERICAL SIMULATIONS ON BROADBAND TRANSPARENCE IN METALLIC GRATINGS

Based on the FDTD method [38], we have carried out the numerical calculations on the optical transmission through several metallic gratings with periodic, Fibonacci, and disordered sequence, respectively. All these metallic gratings are constructed by units A and B. In the calculations, unit A has unit size $p_A = 300\,\mu$m, metal strip width $b_A = 210\,\mu$m, and thickness $h = 200\,\mu$m, while the corresponding parameters for unit B are $p_B = 500\,\mu$m, $b_B = 350\,\mu$m, and $h = 200\,\mu$m, respectively. The numerical calculations are implemented based on the FDTD method with commercial software package LUMERICAL FDTD SOLUTION 8.0.1. Metals in the terahertz region can be considered to be perfect electric conductors (PECs), and we set the relative permittivity of the metal to -1 and the conductivity to $1.6\times10^7(\Omega\ \mathrm{m})^{-1}$ in the subsequent calculations, where $\sigma/(\varepsilon_0\varepsilon\,\omega) \gg 1$ is satisfied for a good electric conductor. (Here σ and ε stand for the conductivity and the relative dielectric permittivity of the metal, respectively.)

For the periodic metallic grating (S1) constructed by repeating unit A, when the incident angle is $\theta = 0^\circ$, the high-transmission peak [Fig. 1(b)] is caused by Fabry-Perot (FP) resonance occurring at $\lambda = 2h/N + \Delta_N$, where $N > 0$ is an integer and Δ_N is the redshift of the peak [39–41]. Additionally, broadband high transmission caused by the nonresonance effect occurs around the optimal incident angle of $\theta_f = 68^\circ$ when the wavelength λ is larger than the first-order Wood's anomaly of $\lambda_{\mathrm{WD1}} = p_A(1 + \sin\theta)$, as shown in Fig. 1(c). For the periodic grating (S2) constructed by repeating unit B, a similar FP resonance can be found at normal incidence [Fig. 1(d)], but the FP resonance peak is partially truncated by the Wood's anomalies. At oblique incidence, as shown in Figs. 1(c) and 1(e), both periodic gratings (S1 and S2) have the same optimal incident angle of $\theta_f = 68^\circ$ because they have the same ratio $(p_i - b_i)/p_i = 30\%\ (i = A,B)$ [24,28]. Note that in the short-wavelength range, Wood's anomalies appear due to the diffraction effects, which sharply interrupt the continuous high-transmission spectra. Therefore broadband transparency in the periodic metallic grating occurs only for wavelengths larger than the first-order Wood's anomaly. However, this situation will be significantly changed for nonperiodic metallic gratings as follows.

The Fibonacci metallic grating (S3) constructed by units A and B is produced by repeating the substitution rules [11–13] $A \rightarrow AB$ and $B \rightarrow A$. We keep the air void filling ratio at $(p_{A(B)} - b_{A(B)})/p_{A(B)} = 30\%$ for each unit. Here our Fibonacci structure (S3) contains 89 units. When the TM-polarized waves go through the Fibonacci grating at normal incidence, as shown in Fig. 1(f), the wavelength of high transmission caused by FP resonance occurs around the similar one as the periodic gratings [Figs. 1(b) and 1(d)], because these gratings here have the same thickness, and the FP resonance peaks are mainly determined by the sample thickness. However, at oblique incidence, it is shown that the broadband high transmission caused by nonresonant excitations, which we will demonstrate later, still occurs around the optimal incident angle of $\theta_f = 68^\circ$, as shown in Fig. 1(g). We can see that the Wood's anomalies in Fig. 1(g) are significantly weakened by the structure changing from periodic to Fibonacci sequence. Note that the first-order Wood's anomalies move to the wavelength $\lambda_{\mathrm{Fib}} = p_F(1 + \sin\theta)$, where $p_F = (\tau\, p_A + p_B)/(1 + \tau)$ with the golden ratio $\tau = (\sqrt{5} + 1)/2$. Obviously, λ_{Fib} is between the first-order Wood's anomalies $\lambda_{\mathrm{WD1}} = p_A(1 + \sin\theta)$ and $\lambda_{\mathrm{WD2}} = p_B(1 + \sin\theta)$ of the periodic gratings in Fig. 1(g). For the incident waves with $\lambda > \lambda_{\mathrm{Fib}}$, we can achieve broadband high transmission at an optimal incident angle θ_f. Therefore quasiperiodicity in the Fibonacci structure has significantly suppressed the Wood's anomalies yet effectively kept the nonresonant excitations that we discuss later, which eventually led to broadband high transmission in the Fibonacci metallic grating.

Meanwhile, the disordered grating (S4) contains two basic units A and B just the same as Fibonacci grating but with a disordered sequence, where unit A and unit B are arranged randomly. Here our disordered structure (S4) contains a total of 100 units. Figures 1(h) and 1(i) are the calculated transmission spectra of TM waves in disordered metallic grating at incidence angles of $\theta = 0^\circ$ and $\theta = 68^\circ$, respectively. At normal incidence, the wavelength of high transmission caused by FP resonance occurs because the gratings have the same thickness as those we mentioned above; at an oblique incidence of $\theta_f = 68^\circ$, it is clearly shown that the broadband high transmission caused by the nonresonance effect exists as shown in Fig. 1(i). Different from the periodic and Fibonacci gratings, the Wood's anomalies disappear in this disordered metallic grating. This indicates that the randomness in the structure has completely broken both long-range and short-range ordering and manifested broadband high transmission of the TM-polarized waves in an extremely wide waveband.

It is interesting to discuss the dependence of the optimal incident angle on air void filling ratio W/D. As shown in Fig. 2, we illustrate the optimal incident angle as a function of air void filling ratio W/D in a series of disordered gratings, which are obtained by Eq. (9) and FDTD simulations, respectively. In each grating sample, we randomly generate the width of all the slits and strips but fix air void filling ratio, totally have for about 4-cm-long sample with 100 metal strips. These two sets of results match well, as shown in Fig. 2, particularly in the range with small W/D. As W/D becomes larger, the electromagnetic field in the slits cannot be simply expressed as the zeroth-order rectangular waveguide mode; instead, the high-order modes should be included in the analytical analysis. The high-order modes may reduce the wave number of the terahertz waves propagating through the slits, and then influence the overall the reflection coefficient, which leads to the larger θ_f predicted by Eq. (9) compared to FDTD simulations.

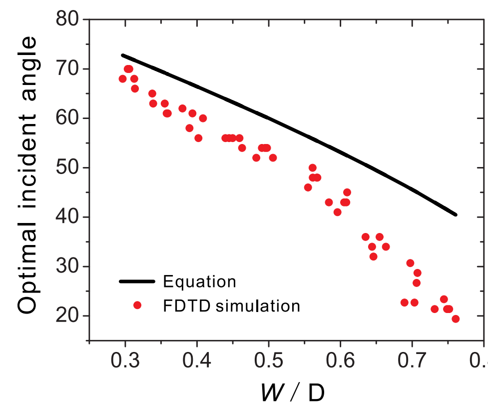

FIG. 2. (Color online) Dependence of the optimal incident angle on the average air void filling ratio W/D obtained by $\theta_f = \arccos(W/D)$ (black line) and FDTD simulation (red dot). In the simulation, the width of all slits and strips are generated randomly, but the average air void filling ratio W/D is fixed for each simulation sample. Each sample of our simulation is about 4 cm in width and contains about 100 metal strips.

For further understanding the physical mechanisms of the broadband high transmission, we have calculated the electric field distributions in periodic and nonperiodic gratings at the high-transmission wavelengths for both normal incidence and optimal angle incidence (as shown in Fig. 3). For normal incidence, all the electric field ($|\mathbf{E}|^2$) distributions are very similar in periodic gratings [Figs. 3(a) and 3(c)], Fibonacci grating [Fig. 3(e)], and disordered grating [Fig. 3(g)], and we can find high $|\mathbf{E}|^2$ distribution at every corner of the strip, which means high transmission comes from resonant excitations, so they belong to narrow band effects. However, for optimal incidence at $\theta_f = 68^\circ$, all the $|\mathbf{E}|^2$ distributions in periodic gratings [Figs. 3(b) and 3(d)], Fibonacci grating [Fig. 3(f)], and disordered grating [Fig. 3(h)] show no obvious enhancement of electric fields at two neighboring corners, and thus the resonances do not happen in these systems. These evidences indicate that the broadband high transmission is indeed caused by a nonresonance effect in the metallic grating systems.

IV. EXPERIMENTS OF THE BROADBAND HIGH TRANSMISSION IN METALLIC GRATINGS

The above broadband high transmission in metallic gratings can be further experimentally demonstrated. In the experiments, we fabricated four types of gratings containing two periodic gratings (S1 and S2) and two nonperiodic gratings (S3 and S4), just as discussed in Sec. III. During the fabrication process, the grating pattern was first designed via software (AutoCAD, 2007) and printed on both sides of a stainless-steel plate via photochemical reaction. In order to construct the gratings, the uncoated parts of the stainless-steel surfaces

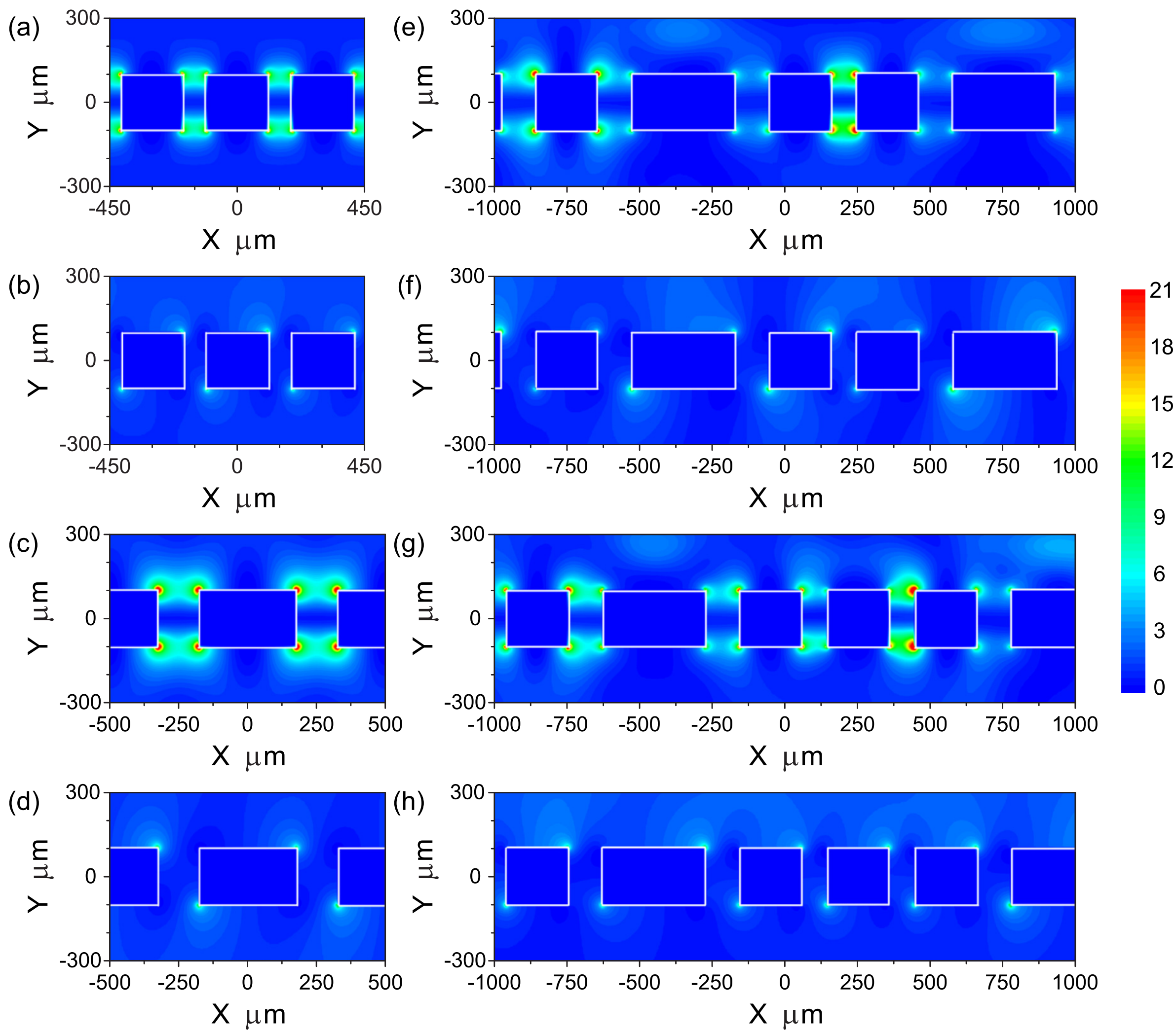

FIG. 3. (Color online) Calculated electric field ($|\mathbf{E}|^2$) distributions of a periodic metallic grating constructed by unit A: (a) $\theta = 0^\circ$ at $\lambda = 525\,\mu$m; (b) $\theta = 68^\circ$ at $\lambda = 1200\,\mu$m. Calculated $|\mathbf{E}|^2$ distributions of a periodic metallic grating constructed by unit B: (c) $\theta = 0^\circ$ at $\lambda = 635\,\mu$m; (d) $\theta = 68^\circ$ at $\lambda = 1200\,\mu$m. Calculated $|\mathbf{E}|^2$ distributions of a metallic grating with the tenth-generation Fibonacci sequence constructed by units A and B: (e) $\theta = 0^\circ$ at $\lambda = 550\,\mu$m; (f) $\theta = 68^\circ$ at $\lambda = 1200\,\mu$m. Calculated $|\mathbf{E}|^2$ distributions of a metallic grating with disordered sequence constructed by units A and B: (g) $\theta = 0^\circ$ at $\lambda = 550\,\mu$m; (h) $\theta = 68^\circ$ at $\lambda = 1200\,\mu$m. Unit sizes of units A and B are $p_A = 300\,\mu$m and $p_B = 500\,\mu$m, strip widths of units A and B are $b_A = 210\,\mu$m and $b_B = 350\,\mu$m, and the thickness of all gratings is $h = 200\,\mu$m.

were then etched by chemicals on both sides. To protect the stainless-steel grating and enhance the conductivity, all surfaces, including the slit walls, were coated with a nearly 3-μm-thick gold film by magnetron sputtering. The transmission spectra were measured by a terahertz real-time spectrometer (EKSPLA/THz, Lithuania). By scanning the delay line, we obtained the time-domain signal $E(t)$ of the polychromatic terahertz pulse transmitted through the samples. Thereafter, the transmission spectrum was obtained from the Fourier transform of $E(t)$ within the 0.2–1.5 THz frequency range and normalized with respect to the transmission spectrum of air.

Figures 4 and 5 show the sample photographs and measured transmission spectra of four different metallic gratings, respectively. In the transmission spectra of four gratings at normal incidence, we can find FP resonance peaks occur around the same wavelength because grating samples here have the same thickness. Specially, the FP resonance peak is partially truncated by the Wood's anomaly in periodic gratings [as shown in Figs. 5(a) and 5(c)]; but in nonperiodic gratings [to see Figs. 5(e) and 5(g)], they become much weaker, which means that the Wood's anomalies in nonperiodic gratings are not obvious.

For optimal incident angles $\theta_f = 68^\circ$, the periodic gratings have high transmission for long wavelengths, larger than that for the Wood's anomalies, which is clear with a very deep valley. For the S1 grating [as shown in Fig. 5(b)], the Wood's anomaly is at $\lambda = 575\,\mu$m, where the transmittance is less than 30% and the width of valley band is more than 80 μm. For the S2 grating [as shown in Fig. 5(d)], the Wood's anomaly is at $\lambda = 950\,\mu$m, where the transmittance is 27% and the bandwidth of valley is more than 200 μm. So for further broadening the bandwidth of high transmission, we are restricted by the Wood's anomalies in periodic gratings.

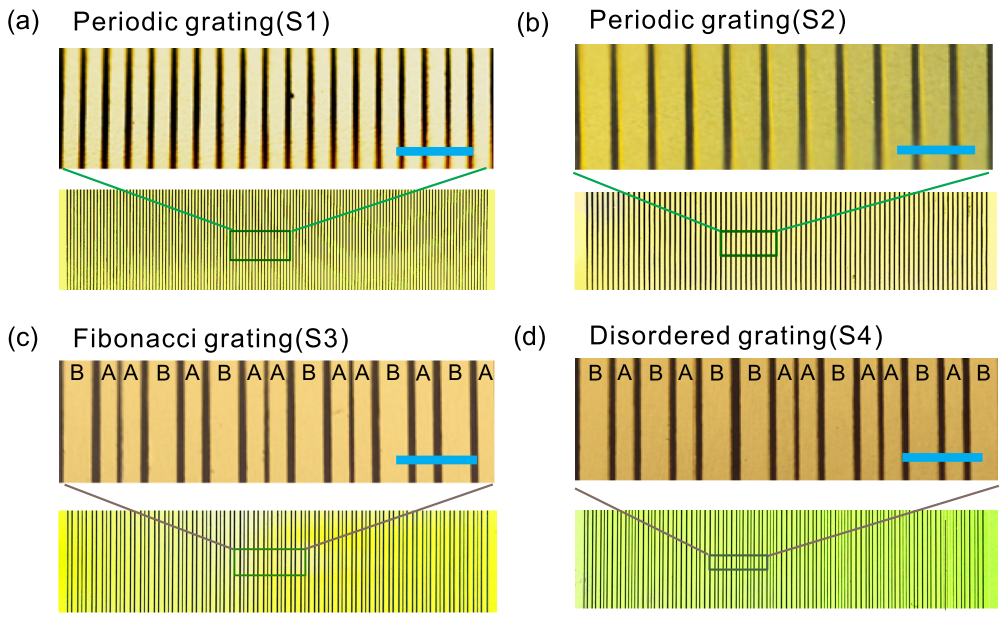

FIG. 4. (Color online) (a) Photograph of periodic metallic grating (S1) constructed by unit A. (b) Photograph of periodic metallic grating (S2) constructed by unit B. (c) Photograph of a metallic grating with the tenth-generation Fibonacci sequence (S3) constructed by units A and B. (d) Photograph of a metallic grating with disordered sequence (S4) constructed by units A and B. The scale bar is 1 mm for all the four photographs. Unit sizes of units A and B are $p_A = 300\,\mu$m and $p_B = 500\,\mu$m, strip widths of units A and B are $b_A = 210\,\mu$m and $b_B = 350\,\mu$m, and the thickness of all gratings is $h = 200\,\mu$m.

However, once we break the periodic order, different results are presented in Fig. 5(f) (Fibonacci grating) and Fig. 5(h) (disordered grating). There are two little valleys in the measured transmission spectra for Fibonacci grating (S3) at $\lambda = 530\,\mu$m and $\lambda = 735\,\mu$m and none for disordered grating (S4) when at the optimal incident angle of $\theta_f = 68^\circ$. The transmittance of the nonperiodic gratings remains very high for wavelengths from 875 to 945 μm in the Fibonacci case, for wavelengths from 965 to 1000 μm and wavelengths larger than 1430 μm in the disordered case, and their transmittance

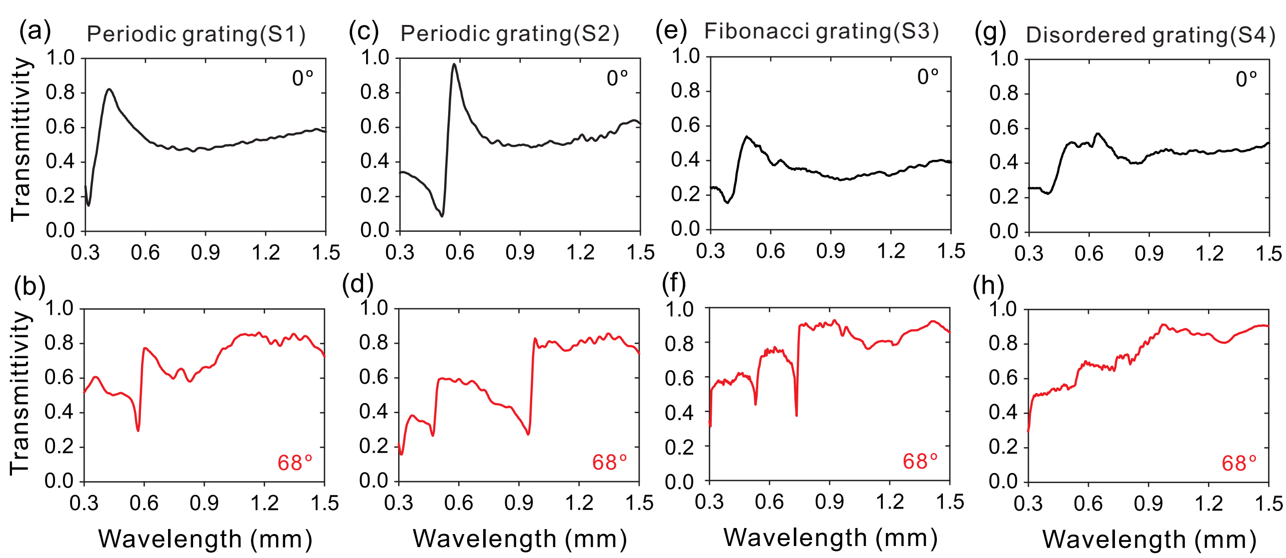

FIG. 5. (Color online) Experimentally measured transmission spectra of a periodic metallic grating (S1) constructed by unit A when incident angle (a) $\theta = 0^\circ$ and (b) $\theta = 68^\circ$. Experimentally measured transmission spectra of a periodic metallic grating (S2) constructed by unit B when incident angle (c) $\theta = 0^\circ$ and (d) $\theta = 68^\circ$. Experimentally measured transmission spectra of a metallic grating with the tenth-generation Fibonacci sequence (S3) constructed by units A and B when incident angle (e) $\theta = 0^\circ$ and (f) $\theta = 68^\circ$. Experimentally measured transmission spectra of a metallic grating with disordered sequence (S4) constructed by units A and B when incident angle (g) $\theta = 0^\circ$ and (h) $\theta = 68^\circ$. Experimentally measured transmission spectra are carried out at incident angle $\theta = 0^\circ$ and $\theta = 68^\circ$ for TM polarization. Unit sizes of units A and B are $p_A = 300\,\mu$m and $p_B = 500\,\mu$m, strip widths of units A and B are $b_A = 210\,\mu$m and $b_B = 350\,\mu$m, and the thickness of all gratings is $h = 200\,\mu$m.

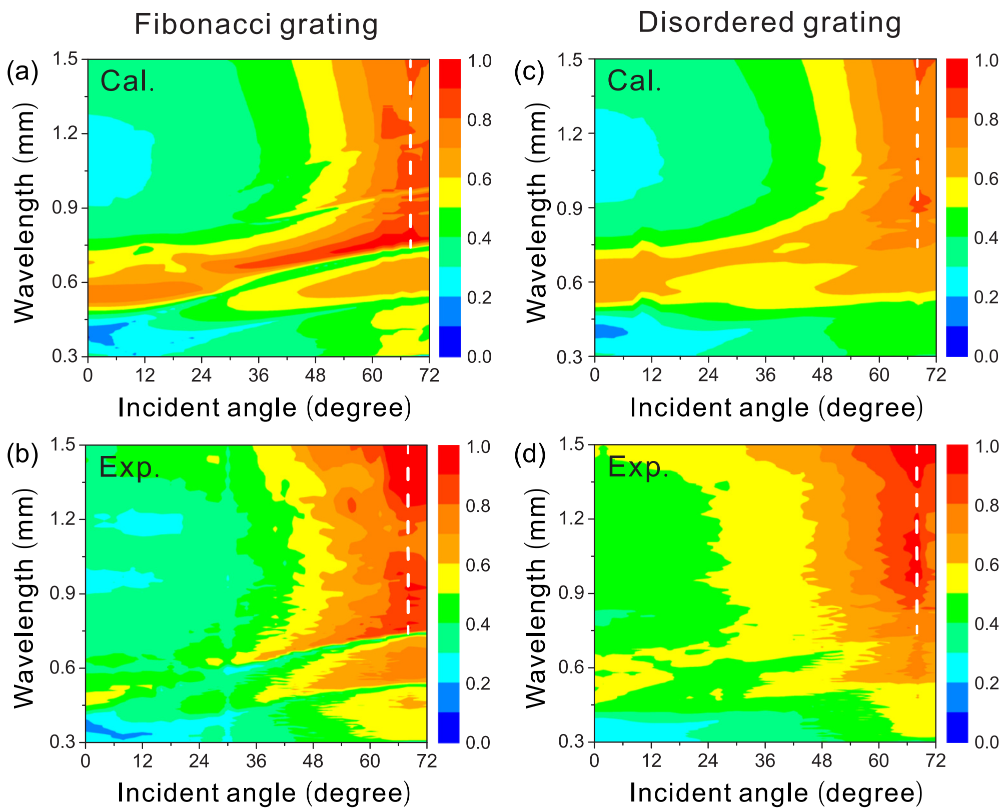

FIG. 6. (Color online) (a) Calculated and (b) experimentally measured angular transmission spectra for a metallic grating with the tenth-generation Fibonacci sequence constructed by units A and B for TM polarization. (c) Calculated and (d) experimentally measured angular transmission spectra for a metallic grating with disordered sequence constructed by units A and B for TM polarization. The color bars show the transmission intensity. The white dashed lines represent the incident angle with maximum transmission. Unit sizes of units A and B are $p_A = 300\,\mu$m and $p_B = 500\,\mu$m, strip widths of units A and B are $b_A = 210\,\mu$m and $b_B = 350\,\mu$m, and the thickness of all gratings is $h = 200\,\mu$m.

is more than 90%, which is higher than that for periodic gratings.

From the above experimental measurements, we have demonstrated that metallic gratings can become transparent for extremely broadband terahertz waves under optical oblique incidence, which is found in periodic, quasiperiodic, and disordered gratings. The transparent bandwidth is broadened and transmission efficiency is improved in quasiperiodic and disordered systems due to the fact that Wood's anomalies are weakened or eliminated by nonperiodicity. In order to evaluate the feature of high-transmission bands in the grating, we define a broadband high-transmission factor as $\Delta = (1/\sigma)(1/\delta)$, where $\sigma = \sqrt{\int_{\lambda_{\min}}^{\lambda_{\max}} (T - \bar{T})^2/(\lambda_{\max} - \lambda_{\min}) d\lambda}$ is the standard deviation which reflects the discrete degree of transmission compared with the mean value $\bar{T}$, and the quantity $\delta = \int_{\lambda_{\min}}^{\lambda_{\max}} [(1-T)/T]^2/(\lambda_{\max} - \lambda_{\min}) d\lambda$ describes the transmission deviation compared with perfect transmission. Obviously, higher factor Δ indicates a band-broader and higher transmission. Based on the experimental data shown in Fig. 5, we find that at the optimal incident angle $\theta_f = 68^\circ$, $\Delta_{\mathrm{Fib}} \cong 34.7$ in Fibonacci grating S3, and $\Delta_{\mathrm{dis}} \cong 25.5$ in disordered grating S4, which are much larger than those in periodic gratings as $\Delta_A \cong 18.6$ in S1 and $\Delta_B \cong 2.9$ in S2. All these experimental factors reasonably agree with the calculated ones. (Note: $\Delta_A \cong 10.6$, $\Delta_B \cong 4.8$, $\Delta_{\mathrm{Fib}} \cong 22.9$, and $\Delta_{\mathrm{dis}} \cong 21.0$ from the data in Fig. 1.) Therefore, compared with periodic cases, both Fibonacci and disordered gratings achieve much better features on broadband high transmission.

Actually, we can prove the phenomena on broadband high transmission more clearly in the angular transmission spectra for a metallic grating with the tenth-generation Fibonacci and disordered sequence given in Fig. 6. It is obvious that the Wood's anomalies are weakened but still exist for Fibonacci grating [Figs. 6(a) and 6(b)], but they nearly disappear for the disordered metallic grating [Figs. 6(c) and 6(d)] because of long-range disorder. Here, we have successfully broadened the high-transmission band by making the units of the gratings disordered, so as to achieve maximum breaking of the Wood's anomalies which affect the bandwidth. Further studies can be carried on to find a unique aperiodic metallic structure with a maximum feature of high-transmission band by optimizing both the geometry of units and the ordering degree of the structure.

V. DESIGN A SPECIFIC STRUCTURED METALLIC GRATING TRANSPARENT FOR A LINE SOURCE

It is known that the terahertz waves, which cover the frequencies from 10^{11} to 10^{13}Hz, can bridge the gap between

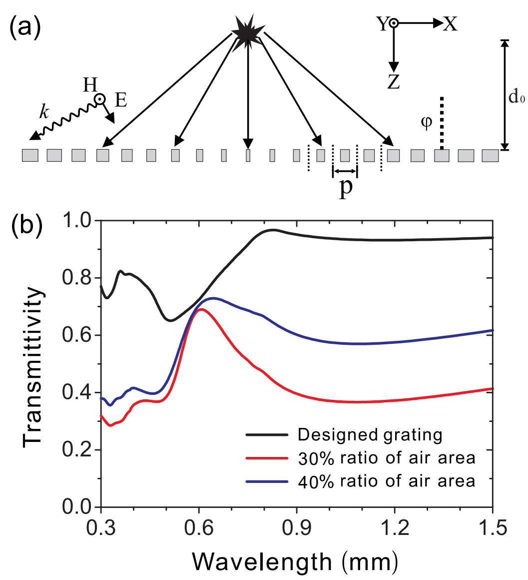

FIG. 7. (Color online) (a) Schematic of the specially designed grating for the TM-polarized line source. The structure consists of units along the X axis, which has a length of $p = 0.4$ mm and a thickness of $h = 200\,\mu$m. The distance between the line source and sample is $d_0 = 2$ mm. The air void filling ratio of each unit is decided according to the incident angle φ. (b) Calculated transmission spectra for different metallic gratings for the TM-polarized line source. The black line is the transmission spectra of the specially designed grating for the TM-polarized line source. The red line and blue lines show the periodic grating with 30% and 40% air void filling ratio, respectively.

the infrared and the microwaves in the electromagnetic spectrum. The terahertz technology [42–44] has been applied in information and communications, imaging and sensing, biology and medical sciences, homeland security, and so on. In order to contribute to these applications, one of the key points is to manipulate the transmission of terahertz waves efficiently and actively. In recent years, many novel electromagnetic phenomena have been found in the terahertz region [45–47], such as EOT through structured metallic films and electromagnetically induced transparency (EIT) using metamaterial. Most of those studies have focused on the plane waves; however, in practical applications we may have different kinds of light sources, such as point sources and line sources. Our following simulations show that an extraordinary transmission of light from a line source is also insensitive to the grating periodicity, which makes it possible to design specific structured metallic gratings to achieve broadband transparency for specific light sources.

As an example, we designed a metallic grating with a gradual variation of air void filling ratio to achieve transparency of TM-polarized light from a line source along the Y axis. As illustrated in Fig. 7(a), the structure consists of a large number of units, which have the identical width p along the X axis. If we define the unit exactly below the line source as the zeroth order, the air void filling ratio of the nth unit is determined by the local incident angle φ according to $t_n = \cos\varphi_n = d_0/({d_0}^2 + n^2p^2)^{1/2}$, where d_0 is the distance between the line source and the grating. When the incident angle φ increases, the ratio t_n decreases. Therefore this structure, which is specifically designed for a line source, has a gradually varying air void filling ratio. Figure 7(b) shows the simulated transmission spectra for several kinds of metallic gratings using TM-polarized line sources. In our simulation, the grating has the following parameters: $p = 0.4$ mm, $d_0 = 2$ mm, width of 3.2 cm, and thickness of 0.2 mm. The transmission here is normalized to the intensity collected by the monitor in air. Obviously, our designed metallic grating [black line in Fig. 7(b)] can achieve more than 90% transmission for a line source. Interestingly, this high transmission is comparable to the results of the periodic grating for plane waves. In comparison, periodic gratings have much lower transmission for line sources. For example, the periodic grating with a constant ratio of air area of 30% has a transmission value of about 40% [red curve in Fig. 7(b)] under the incidence of a line source with $d_0 = 2$ mm, and the periodic grating with a 40% air void filling ratio has around 60% maximum transmission [blue curve in Fig. 7(b)], even for long wavelengths. These results suggest that it is possible to make structured metallic gratings transparent for various kinds of light sources following the mechanism discussed in Sec. II.

VI. SUMMARY

We have theoretically and experimentally demonstrated broadband high transmission of terahertz waves in quasiperiodic and disordered metallic gratings, which originates from the nonresonant excitations in the grating system. Quasiperiodic and disordered metallic gratings effectively weaken and even eliminate Wood's anomalies. Consequently, both the transparence bandwidth and transmission efficiency are significantly increased due to the structural aperiodicity. We also derive an optimal condition for broadband high transparency in aperiodic metallic gratings. Experimental measurements at the terahertz regime reasonably agree with both analytical analysis and numerical simulations. Furthermore, we show that for a specific light source, for example, a line source, a corresponding nonperiodic transparent grating can be also designed. We expect that these results would have potential applications in many fields such as transparent conducting panels and stealth objects. In addition, the observed phenomena may also shed new light on the development of broadband metamaterials, including sonic artificial materials.

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