Far-field subwavelength resolution imaging by encoding spatial harmonics into spoof surface plasmon polaritons

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Imaging below the diffraction limit is always a public interest because of the restricted resolution of conventional imaging systems. To beat the limit, evanescent harmonics decaying in space must participate in the imaging process. Here, we propose and experimentally demonstrate a novel far-field superresolution imaging method for microwave and terahertz regime. It is shown that, the spatial harmonics of the targets including both propagating and evanescent components can be encoded into spoof surface plasmon polaritons (SSP) and sent into the far field. This enable us to retrieve the broadband spatial spectrum by tuning and recording the SSP. Then, the subwavelength resolution is constructed by the inversed Fourier transform of the spatial spectrum. Using the modified subwavelength metallic grating as the spoof plasmonic structure, a far-field resolution of 0.17 λ is numerically and experimentally verified, and two-dimensional imaging ability is also fully discussed. The imaging ability can be further enhanced by scaling down the size of SSP structure. We are confident that our working mechanism will have great potentials in the superresolution imaging applications in the microwave and terahertz frequency range.

Achieving spatial resolution without limited by the working wavelength always attracts tremendous attention, due to the pervasive applications of imaging. However, the diffraction limit indicates the fine features smaller than half a wavelength are carried
by the evanescent harmonics [1], whose amplitude exponentially decays with distance. The contribution of these harmonics is negligible when the imaging distance larger than a wavelength. To circumvent the inherent limitation, the optical elements should own ability of capturing the evanescent part of spatial information. By mechanically canning a sensitive probe, the near-field microscope (NFSM) [2-4] can well surpass the diffraction limit for thousand times, but the imaging operation is very time-wasting. To obtain superresolution images in a single shot, the concept of perfect lens is theoretically exploited by Pendry [1], utilizing the plasmonic effect in materials to enhance the evanescent waves [5, 6]. Soon after this imaging method is experimentally verified at optical wavelength by plasmonic slab, such as the noble metal [7, 8] and dielectrics [9, 10]. Although the imaging ability of such lenses can be further enhanced by other methods [11], the working distance is still subject to the near field [12, 13]. A remarkable device, termed hyperlens, is capable of converting the evanescent harmonics into propagating waves through curved geometry [14-17] or gratings [18, 19]. In this way, superresolution pictures are formed in the far field. The hyperlens can be constructed by periodic arrangement of plasmonics materials and common dielectrics [14-21].

When it comes to the longer wavelength, for example, the terahertz domain, which has great potential in non-destructive testing and manufacturing quality control, the metal behaves as perfect electric conductor [22]. Fortunately, the graphene [23, 24] and some semiconductors [25] can be treated as unique plasmonic materials in this frequency regime. Based on this, several superlenses and hyperlens are proposed and demonstrated [25-29]. However, the loss issues still pose considerable challenges in developing the applications. Due to the lack of natural low-loss plasmonic materials at longer wavelength, the practical superresolution imaging methods is still highly desirable. In 2004, by texturing the geometrical features of high-conductivity metal, Pendry developed the concept of spoof surface plasmons (SSP) [30], with the ability of mimicking the intriguing properties of natural plasmonic effect. Based on this, new possibilities are offered to engineer surface waves [31-46] in the microwave and terahertz frequency ranges. Tremendous potentials have been corroborated based on the
SSP, including wavelength waveguides [31, 32], integrated photonics circuits [33-36], superfocusing waves [37, 38], trapping rainbow [39], controlling waveguide modes [40], on-chip terahertz sources [43], ultra-sensitive sensors [44-46] and so on. It is noted that, although the SSP structures have intriguing response to the evanescent waves, the corresponding researches of far-field superresolution imaging based on them are rarely reported.

In this work, an alternative far-field superresolution imaging method is proposed and experimentally demonstrated for the terahertz and microwave domain. Owing to the momentum conservation, the spatial harmonics of targets can be encoded into adjacent SSP mode when they have the same parallel wavevector. With the assist of a broadband coupler, the broadband spatial spectrum can be reached in the far field by tuning the wavevector of the SSP, which is realized by changing working frequency. Then, the subwavelength image is constructed by the Inverse Fourier Transform (IFT) of the spatial spectrum. The resolution of 0.17 \( \lambda \) is numerically and experimentally verified. The resolution potentially can be further enhanced via optimizing SSP structure. The extension of two-dimension imaging is also numerical verified by simply rotating the imaging device. As there are no moving parts in our techniques, almost real-time imaging process can be yielded for the further imaging applications.

**Results and Discussion**

**The principle of the imaging method**

The basic principle of our imaging method is illustrated in Fig. 1. In the conventional raster-scanning imaging, the sampling process is realized by mechanically moving a probe point-by-point, as shown in Fig. 1(a). The superresolution images can be obtained by combining the locations with their sampled field values. In contrast to that, our ambition is to perform imaging operations in the domain of spatial spectrum \( F(k_x) \) which is the Fourier transform (FT) of targets field \( E(x) \).

\[
F(k_x) = \int_{-\infty}^{\infty} E(x) e^{-ik_x x} dx, \tag{1}
\]
where $k_x$ is the transverse wavevector. Interestingly, for a certain field of the targets, its spatial spectrum is independent on the working frequency $f$. However, higher working frequency corresponds to larger wavevector $k_0$, ($k_0 = 2\pi f/c$, $c$ is the speed of light.), leading to a broadband propagating spectrum windows $|k_x|<k_0$. Therefore, a better resolution can be expected at higher frequency.

If our method is capable of capturing the evanescent information, the resolution of the recovered images can surpass the diffraction limit. Thanks to the strong responses between SSP modes and evanescent waves, we are able to encode spatial harmonics into SSP modes and recover the spatial spectrum by recording the SSP at far field. This operation enables the extraction of evanescent component. Note that, for a SSP mode at certain working frequency, it only has one parallel wavevector value. Because of the momentum conservation, it is hard to capture all the spatial information by one shot at specified frequency, especially when targets contains abundant evanescent waves. We try to alleviate this dilemma through tuning the working parallel wavevector of the SSP mode, which can be accomplished by changing the working frequency (details of this will be discussed in the next section). In this case, the imaging method can be treated as a sampling process to the spatial spectrum, as presented in Fig. 1(b). By tuning parallel wavevector of the SSP mode, the spatial profile of the targets is gradually sampled. Compared with Fig. 1(a), the imaging speed is significantly improved, as the time-assuming mechanical movement is avoided. With the assist of IFT, the sampled spatial spectrum (shown in Fig. 1(c)) is translated to the real image. We can beat the diffraction limit because the captured evanescent waves also participate into the imaging process. As plotted in Fig. 1(d), two spikes with a center to center distance $\lambda/4$ ($\lambda$ is wavelength of the working frequency) is successfully distinguished by this method.

**Encode spatial spectrum into SSP**

For the purpose of sampling the spatial harmonics, firstly, a unique structure with responses to broadband evanescent field should be chosen. The present method is based on the subwavelength metallic grating, due to its capability of manipulating waves in subwavelength scale. The schematic of this grating is rendered in Fig. 2(a). The period
\( \frac{\pi}{p}, \) width \( d \) and height of the grooves \( h \) are utilized to describe the geometrical characters. The modal expansion method (MEM) \([47, 48]\) is used to theoretically derivate the dispersion relationship under the condition of perfect electric conductor approximation. For simplification, the thickness of the grating in the \( y \) direction is suppose to be infinite. After matching the tangential components of electric and magnetic field at the air-grating interface and the bottom of grating, the dispersive equation describing the parallel wavevector \( k_s \) of SSP can be obtained

\[
\sum_{n} \frac{\sin^2 \left( \frac{k_{mn}}{2} d \right)}{\sqrt{k_{mn}^2 - k_0^2}} = \frac{p \cot(k_0 h)}{d k_0}, \tag{2}
\]

with \( k_{mn} = k_s + 2\pi n/p, \) \( n \) represents the diffraction order. In Fig. 2(b), we calculate and plot the dispersion curve, under the parameters of \( p = 100 \mu m, \) \( d = 50 \mu m, \) and \( h = 260 \mu m. \) The \( x \) coordinate is normalized by the free space wavevector \( k_c \) at 0.26 THz, near the cutoff frequency of the foundational SSP mode. It is clear that, the dispersive curve significantly departs from the light line. The parallel momentum range of SSP is only dependent on the period of grating following the relation \(-\pi/p \leq k_s \leq \pi/p. \) Under the present parameters, the maximum \( k_s \) remarkably reaches up to 5.8\( k_c, \) located at the deeply evanescent domain. The value of maximum \( k_s \) can be further improved by adjusting \( p. \) To visualize the SSP with various \( k_s, \) the finite element method (FEM) is utilized to calculate the evolution of electromagnetic (EM) waves. The material of the grating is set as copper, its conductivity being 5.959\( \times 10^7 \) S/m. We plot \( x \)-component electric field maps in the inset of Fig. 2(b), respectively corresponding to \( k_s = -0.8k_c (0.171 \text{ THz}), k_s = -2k_c (0.237 \text{ THz}), k_s = 5k_c (0.26 \text{ THz}). \) From these field distributions, we can see that SSP is evanescent in the vertical direction, and its transverse wavevector can be freely tuned by simply changing frequency due to the strong dispersion.

For a single working frequency point, the parallel momentum of SSP owns two certain opposite values which are related with the backward and forward waves with respect to the \( x \)-axis. If the scattering wave impinges on the grating, as shown in Fig. 2(a), by tuning the working frequency from zero to the cutoff frequency, the SSP modes with \( |k_s| < \pi/p \) can be sequentially launched without any separation. The amplitude of the SSP
mode is strongly related to the corresponding spectral component of the incident waves. At a specific working frequency, the coupling coefficient between spectral harmonics and the SSP mode is bound up with the difference of their parallel wavevector. To give a quantitative demonstration, we record the intensity of the excited SSP from 0.16 THz to 0.23 THz when the parallel wavevector of the incident waves are $-2k_c$, $3k_c$, $-5k_c$. The simulated results are plotted in Fig. 2(c). Obviously, in the intensity profile of SSP, there are several sharp peaks excellently coinciding with the input spectral components. The physical mechanisms behind this is easy to be explained by the momentum conservation. We also present a theoretical deduction for the coupling. A TM-polarized incident wave with particular parallel wavevector $k_x$ is expressed by

$$E' (\mathbf{r}) = \frac{1}{\sqrt{d}} e^{i k_x x} e^{i k_z z} \left( \mathbf{r} - \frac{k_x x + k_z z}{k_c} \right), \quad (3)$$

where $k_c = \sqrt{k_0^2 - k_x^2}$. The reflected waves from the grating associated with n-diffraction order can be written as

$$E_{\text{ref,n}} (\mathbf{r}) = \rho_n \frac{1}{\sqrt{d}} e^{i k_m x} e^{i k_m z} \left( \mathbf{r} - \frac{k_m x + k_m z}{k_m} \right), \quad (4)$$

where $k_m = k_x + 2\pi n / d$, $k_m = \sqrt{k_0^2 - k_m^2}$ and $\rho_n$ is the n-order reflection coefficient. After considering the boundary condition, the reflection coefficients can be easily extracted

$$\rho_n = -\delta_{0,n} - \frac{2i \tan (k_0 h) S_n S'_0 \left( 1 + \delta_{0,n} \right)}{1 - i \tan (k_0 h) \sum_i S_i^2 k_0 k_{ji}}, \quad (5)$$

in which $S_n = \frac{a}{\sqrt{d}} \sin \left( \frac{k_0 a}{2} \right)$. Here, we only calculate the zero-order reflection coefficient, and combine the equation (2) to substitute $k_0$ for $k_s$. The amplitude of theoretical results is plotted in Fig. 2(d). Clearly, the trend of theoretical prediction and numerical calculation matches well. The amplitude of excited SPP appears strongly sensitive to the condition of momentum match, i.e., $k_x = k_s$, which indicates the SSP structure is capable of sampling the spatial spectrum of the near-field scattering waves.
The intensity of excited SSP waves is highly dependent on the corresponding spectral component of the incident waves. It should be kept in mind that, the spatial spectrum of the targets is independent of working frequency, as discussed previously. Therefore, the whole spatial spectrum of the targets can be sampled and reconstructed by adjusting the working frequency, without any mechanically moving parts.

Considering the practical usage, we always want to perform the imaging operations in the far field. Due to the momentum mismatch between free space waves and SSP mode [49, 50], the extracted information carried by SSP is still stuck in the grating surface. Fortunately, in our previous investigations [51], an ultra-broadband SSP coupler has been proposed and demonstrated to alleviate the momentum mismatch. This coupler can be utilized to efficiently radiate the sampled spatial spectrum into the far field. The structure of this coupler is rendered in Fig. 3(a), where all the parameters are clearly defined. The coupler is composed of three parts: a tapered cover plate used for gradually compressing the energy of incoming SSP; a grade grating used for mitigating the momentum mismatch between SSP and TEM mode inside the parallel-plate waveguide (PPWG); a tapered PPWG used for sending the EM energy into the far-field, similar with an antenna. The working performance of this coupler is studied and presented in Fig. 3(b), which is also calculated by the FEM method. The parameters are set as: \( L_1 = 2.25 \text{ mm}, L_2 = 2.75 \text{ mm}, L_3 = 2.5 \text{ mm}, L_4 = 1.25 \text{ mm}, L_5 = 0.41 \text{ mm}, N = 9, \theta_1 = 14.6^\circ, \theta_2 = 14.9^\circ \). Within the frequency band from 0.14 to 0.26 THz, the coupler holds extremely low reflection coefficient, indicating the high-efficiency conversion between SSP and far-field radiation, as shown by the S11. Here, the uniform grating side is defined as the port 1. The field evolution of transmission between SSP and free space waves is depicted in the inset of Fig. 3(b), with the frequency being 0.237 THz. From this field map, we can recognize that the SPP gradually converts to the TEM modes, and radiates into the space through the coupler.

**Construct superresolution image**

By combing all the SSP parts, the imaging device is presented in Fig. 3(c). The uniform metallic grating at center is utilized for sampling the spatial spectral information of
scattering waves from the targets. The SSP waves carrying spatial harmonics \( k_s > 0 \) \((k_s < 0)\) will propagating toward the +x (-x) direction. Two couplers at both ends can send the sampled information into the far field. By collecting the radiations in the far field over a certain bandwidth, the whole spatial spectrum is able to be retrieved. Before these operations, the system equation \( G(k_s) \) of the imaging device should be investigated. The received spatial spectrum \( H(k_s) \) can be thought as the convolution of the input \( F(k_s) \) (the spatial spectrum of the targets) and the system equation \( G(k_s) \)

\[
H(k_s) = F(k_s) * G(k_s),
\]

where * denoted the convolution calculation. To simplify the theoretical deduction, the \( G(k_s) \) is treated as the delta function \( \delta(k_s) \) with specified amplitude and phase responses \( \Delta A \) and \( \Delta \theta \). We rewrite the equation (6) as

\[
H(k_s) = F(k_s) \cdot \Delta A(k_s) \exp(i\Delta \theta(k_s)),
\]

in which \( \Delta \theta(k_s) \) is expressed by

\[
\Delta \theta(k_s) = \int k_s(k_s)dx + \int k_{TEM}(k_s)dx + k_sL,
\]

where the first integral represents the phase accumulation by the SSP propagation along the uniform and graded parts, the second integral represents the phase change induced by the PPWG including both the uniform and tapered parts, and the third issue is caused by the transmission of radiated waves in the free space, where \( L \) is the distance between the coupler and the receiving antenna. The amplitude response \( \Delta A \) is induced by the imperfect coupling, propagating loss, reflection of couplers, and transmission loss between coupler and receiving antennas. Presenting a rigorous theoretical deduction of \( \Delta A \) can be very difficult and time-wasting. Here, for the purpose of giving a principal verification of this imaging method, \( \Delta A \) is thought as a constant for any value of \( k_s \). Actually, \( \Delta A \) and \( \Delta \theta \) can be obtained by the pre-measurement, i.e., measuring the receiving signal \( H(k_s) \), then \( \Delta A(k_s) \cdot \exp(i\Delta \theta(k_s)) = H(k_s)/F(k_s) \).

To complete the imaging process, the imaging device is utilized to calculation. The length of uniform grating is 7.6 mm, and the distance between the coupler and the recording antenna is 1.5 mm. Other parameters are the same with above. The targets are localized at the center of this structure, 100 \( \mu \)m above the grating, avoiding the
severe decay of evanescent waves before sampled by SSP structure. The phase retardation $\Delta \theta$ from $k_c$ to $4k_c$ is calculated through equation (8) and presented in Fig. 4(a). The dashed line in Fig. 4(a) is the simulated results by FEM, matching well with the theory. Obviously, $\Delta \theta$ varies quasi-periodically with the change of parallel wavevector, which consists with the theoretical prediction.

Then, we move step to extract the spatial spectrum of two slits, with 100 $\mu$m width and 200 $\mu$m (about 0.17$\lambda$ for 0.26 THz) center-to-center distance. The calculation frequency range is from 0.16 to 0.26 THz. The amplitude profile of the retrieved spatial spectrum by our imaging device is rendered in Fig. 4(b). Compared with the theoretical result calculated by equation 1, we find this sampling device remarkably covering the spectral band $0.6k_c < |k_s| < 4.8k_c$, even within the deep evanescent domain. This provides a direct evidence of the superresolution imaging capability. Note that, the working spectrum can be further significantly enhanced by optimizing the parameters of the SSP device, since the maximum $k_s = \pi/p$. To visualize the field evolution in the sampling process, we illustrated the electric field distribution related to $k_s = 1.5k_c$ and $k_s = 2.9k_c$ in Fig. 4(c) and (d). Clearly, in the case of $k_s = 1.5k_c$, the evanescent component is efficiently converted into the propagating SSP, and then radiated into far-field with the assist of two couplers. While under the circumstance that $k_s = 2.9k_c$, the launched SSP from two slits will interference destructively with each other, resulting in no excited SSP, which is consistent with the theoretical prediction.

The amplitude of the information of $|k_s| > 4.8k_c$ dramatically decreases, which is attributed to severe decay of deep evanescent component before reaching our device. This attenuation is able to be compensated by the pre-measurement. For the purpose of simply manifesting our imaging mechanism, the compensation is not taken into consideration in this work. Due to the limited working frequency band and deteriorating coupling efficiency, the spatial information of $|k_s| < 0.6k_c$ is lost. We can cover this part by a single shoot at far field, as they are all propagating waves. The spectrum of this part is depicted in Fig. 4(f), which is obtained by the spatial FT of the scattering far field at 0.26 THz. The retrieved phase is presented in Fig. 4(d), which match with the theoretical results. Compared with phase profile with Fig. 4(a), there are many
fluctuations in Fig. 4(d). This is because the imperfect of two couplers. Part of SSP propagating back and forth along the grating induces reflections at both terminations, lending to Fabry-Perot-like resonance. This fluctuation can be alleviated by optimizing the coupler. Finally, the image is reconstructed by combing all the simulated results and performing IFT operations, as illustrated in Fig. 4(g). Notably, the objects are well distinguished, verifying the validity of the proposed far-field superresolution imaging method.

Obviously, to complete the imaging process, the parallel wavevector of the SSP mode should be tuned, which is based on the change of working frequency. This brings two inevitably issues. Firstly, a terahertz with the ability of tuning working frequency or providing broadband signal is needed. The time-domain terahertz spectroscopy or terahertz vector network analyzer can well fulfill this condition. Considering the cost, some diode oscillators is also available, for example, the products of Lytid. Secondly, the scattering field of the targets may changes through the imaging process, because the variable responses of the dielectrics at different frequency. We can mitigate this situation by decreasing the frequency bandwidth. This is realized by optimizing the dispersion of the SSP structure, for example decreasing the duty ratio of the air in the subwavelength grating [38], or using some TE-polarized SSP structure [32, 52]. The SSP mode in such structure is highly sensitive to the working frequency, and the k_s of the SSP can be tuned through much narrowband frequency range.

Constrained by the fabrication capabilities and test conditions, we experimentally demonstrate the imaging mechanism only in the microwave regime. This is totally acceptable as the proposed method is applicable at the longer wavelength, i.e., from to microwave to terahertz. And the analytical deduction is feasibility independent the working frequency. The chosen parameters are p = 2 mm, d = 1 mm, L_1 = 45 mm, L_2 = 55 mm, L_3 = 50 mm, L_4 = 25 mm, L_5 = 8.2 mm, N = 9, \theta_1 = 14.6^\circ, \theta_2 = 14.9^\circ, which is 20 times scaled from original simulation. The corresponding working frequency range is from 8 to 13 GHz. The image of the fabricated prototype is present in Fig. 5(a), along with two close shots of the uniform and gradient gratings. Two monopole antennas with 4 mm separation (0.17 \lambda with respect to 13 GHz), are used as the emitting source. A
horn antenna is employed to receive the radiated energy from the coupler. All the antennas are connected to a four-port vector network analyzer (Agilent N5245A PNA-X), as shown in the inset of Fig. 5(b). We only record the information of \(-5k_c < k_x < -0.6k_c\) due to the total symmetrical structure. For the propagating part of \(|k_x| < 0.6k_c\), it is obtained by recording the electric field in the far field at 13 GHz. By combing all the results, the retrieved phase and amplitude of the spatial spectrum are plotted in Fig. 5(b) and (c). The trend of experimental data satisfactorily consistent with the theory. Note that, compared with the theory, the measured data is slightly ‘stretched’. The zero of the spatial spectrum appears in \(k_x = 3.3k_c\) rather than \(k_x = 2.9k_c\). The spectrum still owns considerable strength near \(|k_x| = 5k_c\), while in the simulation only \(|k_x| < 4.8k_c\) can be captured. The deviation results from the manufacturing tolerance, i.e., the depth of the groove is slightly less than 5.2 mm. This machining error leads to a blue shift of working frequency. From the reconstructed image in Fig 5(d), we can conclude that the two targets are clearly distinguished. The distance between two spikes in Fig. 5(d) is about 0.16\(\lambda\), slightly smaller than the original 0.17\(\lambda\), which is also attributed to the blue shift. By combing all the results, the capability of our imaging method can be fairly verified.

Two-dimension superresolution imaging

In the practical usage, two-dimensional (2D) subwavelength imaging ability is also desirable. All the discussion performed above only covers one-dimensional resolution, i.e., the thickness of SSP structure in the y direction is infinite and it has no response to the parallel wavevector \(k_y\). To obtain 2D sub-diffraction-limited images, the information in all direction is needed. Therefore, the method of rotating imaging device in reference is employed, i.e., the imaging devices will be rotated 30 degree after each measurement, and then the spectral information of all directions can be retrieved. Firstly, we want to enhance the working performance of the imaging device. The parameters of the grating are optimized as \(p = 120 \, \mu m, d = 60 \, \mu m, h = 255 \, \mu m\), the thickness of the grating in the y direction is truncated to 500 \(\mu m\), other parameters keeps unchanged. The working frequency band is changed into 0.16 THz-0.274 THz. Under these parameters, the spatial spectrum of the grating can be extended to 8\(k_c\) (with respect to 0.274 THz). For
a particular case, one 2D pattern is used to verified the 2D subwavelength imaging ability of our device. The electric field of 2D object is shown in Fig. 6(a), two 0.12\(\lambda\)-sized squares with center-to-center distance of 0.25\(\lambda\). Its spatial spectrum is calculated and presented in Fig. 6(b). To reconstruct the spectrum, forgoing process of six measurements is employed. The propagating component of the spectrum is obtained by a single shoot at far field. The retrieved spectrum shown in Fig. 6(c) clearly reproduces the features of original data. Then, using IFT process, the 2D sub-diffraction resolution image is clearly distinguished, as illustrated in Fig. 6(d). Obviously, some details are lost when comparing the reconstructed image with Fig. 6(a). To further improve the quality of the imaging, one can increase the times of rotating measurement, with the price of time wasting. It is also feasible to replace the metallic grating with some 2D SSP structure [53], then the spectrum with all direction can be captured simultaneously.

**Conclusion**

In conclusion, we demonstrate the SSP is capable of realizing far-field superresolution imaging by recording the broadband spatial spectrum in the microwave and terahertz frequency range. Both the theory and simulations indicate that, the features of spatial harmonics can be well encoded into near-field SSP mode and send into the far field, when they own the same parallel wavevectors. By changing the working frequency of the SSP mode, the corresponding wavevectors of SSP mode can be tuned. Therefore, the broadband spatial spectrum of the targets is obtained through the tuning process. The image with resolution of 0.17 \(\lambda\) is numerically and experimentally retrieved in almost real time. Most importantly, the imaging ability can be significantly enhanced by optimizing the parameters of the SSP structure. Our imaging mechanism also has ability on realizing 2D subwavelength imaging. Our work could find applications on non-destructive testing and manufacturing quality control.
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Fig.1 (a) and (b) present the imaging methods of conventionally mechanical scanning and our spatial spectrum sampling, respectively. (c) The extracted spatial spectrum after sampling. (d) The reconstructed image by doing IFT process to the data in (c).
Fig. 2. (a) the schematic of the subwavelength metallic grating; (b) The dispersive curve of the SSP supported by the gratings; the pictures in the inset are the electric field maps corresponding to $k_s = -0.8k_c$ (0.171 THz), $k_s = -2k_c$ (0.237 THz), $k_s = 5k_c$ (0.26 THz); (c) and (d) are the simulated and theoretical intensity of the excited SSP when the incident waves with parallel wavevector of $k_x = -5k_c$, $k_x = -2k_c$ and $k_x = 3k_c$. 
Fig. 3. (a) the picture of SSP coupler, which consists of a gradient grating part and a tapered PPWG; (b) the conversion coefficient between SSP and free space waves of this coupler. The inserted picture is the field evolution of the coupler when radiating SSP into space; (c) the working principle of our imaging device, including a uniform grating and two couplers.
Fig. 4 (a) the theoretical and numerical results of the phase retardation $\Delta \theta$ of this imaging device; (b) and (e) are the amplitude and phase profile of the spatial spectrum of the targets, respectively, where blue solid line and red dashed line represent the theoretical result and retrieved result by our imaging device; (c) and (e) are the electric field distributions when the device sampling spatial harmonics with $k_x = 2k_c$ and $k_x = 3.5k_0$; (f) the retrieved spatial spectrum of propagating component by spatial FT process; (g) The reconstructed image by the IFT procedure, where two targets are clearly distinguished.
Fig. 5. (a) the picture of the imaging device, companying with two close shot of uniform and gradient gratings; (b) and (c) the measured results of the phase and amplitude profile of the targets. The inset of (b) is the picture of test scene; (d) shows the image constructed by the measured data.

Fig. 6. (a) and (b) are the electric field pattern of sub-diffraction object and its spatial spectrum. (c) the retrieved 2D spatial spectrum by rotating the SSP sampling device. (d) the reconstructed image using the spectrum present in (c).

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