Perspective

Reflective moiré metasurface: Challenges and opportunities

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Dynamic beamforming is a critical technique in applications like radar detection, holographic imaging, and reconfigurable intelligent surfaces (RIS). Current approaches to dynamic beamforming rely heavily on active components (e.g., PIN diodes, varactor diodes), leading to substantial cost challenges in large-scale deployments, particularly at millimeter-wave and subterahertz frequencies, where these components are prohibitively expensive or unavailable. In 2022, we proposed a mechanism to achieve dynamic beamforming based on two closely stacked reflective moiré metasurfaces. By making mutual in-plane rotation of the two metasurfaces, we can continuously direct the beam in reflective space and achieve almost any beam shape and trajectory with judicious pattern selection. Our design offers a cost-effective solution for dynamic beamforming in RIS applications and unveils an alternative approach to explore the physics of programmable metasurfaces. Here, we provide an overview of the reflective moiré metasurface, explaining its principles and design, addressing current challenges with potential solutions, and envisioning its applications and future directions.

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I. INTRODUCTION

A. Background and motivation

Programmable metasurfaces, a type of two-dimensional (2D) material consisting of digitally controlled unit cells, enable dynamic control of incident wave fronts via independent modulation of phase, amplitude, and polarization at the individual cell level [1–4]. This has led to various practical applications in wireless communication [5,6], holographic imaging [7], and microwave imaging [8], along with discoveries in programmable space-time modulation [9], nonreciprocity [10], and harmonic manipulation [11]. However, the widespread use of active components, such as PIN diodes, varactor diodes, and external control circuits, makes programmable metasurfaces costly, especially at millimeter-wave frequencies, where rf diodes are either prohibitively expensive or not commercially available. This cost issue significantly impedes their large-scale application in wireless communication.

Recently, the intricate physics inherent to moiré patterns formed by overlapping 2D materials has gained renewed interest [12,13] and has led to many groundbreaking discoveries, including "magic angle" superconductivity [14,15], Hofstadter's butterfly [16], topological insulators [17], and band-gap engineering [18]. Inspired by the constantly evolving moiré patterns resulting from mutual twisting, we recently introduced an approach for dynamic beamforming using two closely aligned metasurfaces with mutual twisting [19]. This method allows for continuous beam-direction control on the reflective side through a simple in-plane twist of the metasurfaces. Different pattern designs for each metasurface enable manipulation of the beam's shape (e.g., quantity, orientation) and path, offering high flexibility and customization, as shown in Fig. 1(a).

B. Differences and advantages

It is important to note that our moiré metasurface significantly differs from previously developed multiple stacked metasurfaces [20,21] and varifocal metalens doublet designs [22–24]. In these designs, the phase profiles or functions of each layer were independently engineered to enable their collective operation as a simple combination of each layer's function. Additionally, these designs demand sufficiently large interlayer spacing to minimize interlayer coupling and precise alignment to ensure the accuracy of the combined phase profiles. In contrast, the wave reflected from our moiré metasurface is not merely a linear superposition of its two constituent metasurfaces. However, it originates from a relatively complex electromagnetic (EM) interference process, the mechanism of which remains elusive. The two metallic patterns are tightly combined with zero distance to form an ultrathin moiré pattern, thus eliminating the requirement for precise interlayer spacing and exact alignment. This simplifies the design process and results in a more compact and robust structure, which is particularly advantageous in practical

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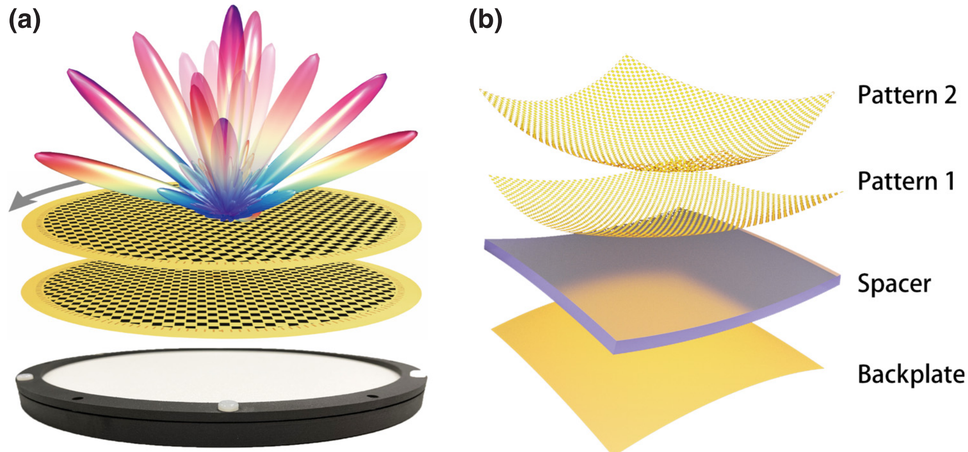

FIG. 1. (a) Illustration of the reflective moiré metasurface. Shape (e.g., quantity, orientation) and path of the beam can be controlled through the mutual rotation of two metasurfaces in a highly flexible and customizable manner. Inset at the bottom displays a photograph of the prototype, with all four layers securely assembled within a nylon holder. (b) Moiré metasurface comprises, from bottom to top, a metallic backplate, a spacer, and two closely aligned metasurface layers with a mutual twist.

applications where space constraints and environmental robustness are key considerations.

There have been some recent studies on applying the moiré concept to photonics, targeting innovative control over wave fronts, dispersion, and the localization of EM waves. For instance, the moiré principle was applied to leaky-wave antennas to achieve beam steering by altering the direction of guided wave feed [25,26], whereas the realized sample allows only single-beam scanning. Recent studies have shown that flat bands induced in twisted photonic graphene lattices can be exploited to realize nanocavities with strong field confinement and a high-quality factor [27,28]. Another recent study proposed an alternative mechanism for generating orbital angular momentum waves through twist-enabled coupling between the bound states in continuum mode and other nonlocal modes in a twisted bilayer photonic crystal [29]. While all such designs have focused on the adjustable focal length of transmission [22–24], the chirality and nonreciprocity properties of transmission [28,29], the reconfigurable field localization on the metasurface [29–31], and the dispersion and band-structure properties at the magic angle [32–37], they tended to neglect the aspect of reflection, thereby offering limited direct insights for wireless communications. This perspective reviews the theory, design, and fabrication of the reflective moiré metasurface; highlights key challenges; discusses possible solutions; and finally envisions its application and future research directions.

II. DESIGN AND FABRICATION

A. Structure

Figure 1(b) depicts the structure of a typical moiré metasurface, which comprises, from bottom to top, a metallic backplate, an interlayer spacer, and two metasurfaces attached with zero distance and with a specific mutual twist angle. Notably, in addition to the pattern design of each metasurface, the thickness and dielectric properties of the interlayer spacer also play a crucial role in radiation performance.

B. *k*-Space analysis

Since each pattern can be represented as a binary image due to the sharp contrast in dielectric properties between the metal and dielectric substrate, the moiré pattern emerges as a result of a logical OR operation on these two binary images, which involves their multiplication. Consequently, characterizing the moiré pattern and its changes during mutual twisting can be achieved by examining the convolution of the frequency spectra of these two patterns in the k space. Importantly, this convolution of frequency spectra is simply equivalent to their vectorial summation because the frequency spectrum of each pattern is simply an array of delta functions positioned on the grids of the reciprocal lattice. Practically, it is sufficient to consider only the first- or second-order diffraction components of each pattern in the convolution. Once we have chosen certain patterns for the two metasurfaces, we can calculate the trajectory of the moiré components in the k space as a function of twist angle. Only those moiré components that reside in the light cone will contribute to free-space radiation at the direction determined by $(k_x, k_y) = (\sin\theta\cos\varphi, \sin\theta\sin\varphi)$, in which θ and φ are the elevation and azimuthal angles; k_x and k_y are the normalized wave vectors along the x and y axes, respectively. The manipulation of moiré components enables us to effectively determine the beam's number, direction, and polarization. It should be noted that while k-space analysis can determine beam directions, it does not provide any information regarding their intensity.

C. Symmetry

The fundamental symmetry of each constituent pattern plays a crucial role in determining the symmetry of the resultant moiré pattern, which consequently affects the radiation pattern in terms of two distinct yet interconnected aspects: the symmetry of the radiation pattern and the symmetry of the beam path. For instance, for a moiré metasurface designed with highly symmetrical patterns, the beam tends to appear in high-symmetry directions, and its intensity is protected by the inherent symmetry of the moiré patterns across a wide range of twist angles. Conversely, moiré metasurfaces designed with lower-symmetry patterns typically exhibit less-stable beam intensity during twisting. However, lower-symmetry patterns enrich the diversity of moiré patterns, leading to more varied radiation patterns as the twist angle changes. This versatility in radiation patterns affords greater flexibility for dynamic beamforming in reconfigurable intelligent surface (RIS) applications.

D. Sample fabrication and measurement

The first sample of a moiré metasurface was prepared through the tight stacking of two layers of 40-μm-thick metallic patterns (copper), fabricated with a flexible polyimide substrate ($\varepsilon_r = 3.1$, $\delta = 0.03$), on top of a rigid metal plate. The top two layers were separated from the backplate by a foam spacer ($\varepsilon_r = 1.07$) with a thickness of about 3 mm. Given the importance of this distance for radiation performance, all layers were securely assembled within a nylon holder to ensure precise and uniform separation between the moiré pattern and the metal backplate [Fig. 1(b)]. Note that for RIS applications where the operation frequency is limited to below millimeter waves, both layers of the metasurfaces can be manufactured using the standard printed-circuit-board technique at low cost. As a proof-of-concept demonstration, the mutual rotation of the prototype was achieved manually. We envisage that the final product will incorporate a servo-motor drive system for precise and rapid rotation, with all components compactly housed in a waterproof microwave-transparent shell. To boost functionality, sensors may be added to the sample's edges for detecting the direction of incident waves. Given that moiré metasurfaces produce beams in varied and irregular directions with changing polarization states, it is essential to develop a measurement system that can automatically assess radiation patterns for both orthogonal polarization states across the entire reflective side, unlike conventional metasurfaces that measure a single polarization in the E and H planes.

III. ISSUES AND CHALLENGES

A. Absence of unit cells

The design approach for reflective moiré metasurfaces fundamentally differs from that of traditional metasurfaces. Unit cells with locally periodic boundary conditions, typical in conventional metasurfaces, are infeasible for moiré metasurfaces. It should be noted that the moiré periodicity, as perceived by the human eye at most twist angles, does not equate to true two-dimensional crystallinity. However, the moiré periodicity corresponds to the rigorous two-dimensional period at certain discrete twist angles, at which the mutually rotated grid lattices of the two patterns are commensurate. Analytical calculations reveal that the lower limit of strict periodicity matches exactly with the observed dominant moiré periodicity [19].

B. High anisotropy

The unit-cell design of conventional metasurfaces is typically neat and straightforward. Often, these unit cells utilize simple geometric patterns in square or hexagonal lattices, with EM responses being isotropic or exhibiting diagonal anisotropy. However, the polarization state of reflections from moiré metasurfaces is more complex, for the following reasons. First, although individual patterns may have straightforward geometries, the superimposed moiré pattern becomes progressively more complex, particularly with nonzero mutual twists. Consequently, reflections include both copolarized and cross-polarized components of the incident wave, with varying amplitudes and phases, depending on the twist angle. Second, selecting patterns with various Bravais lattices causes the moiré periodicity to shift among these lattices (e.g., oblique, hexagonal, rectangular, rhombic, square) with the change of the twist angle, further complicating the radiation pattern.

C. Far-field calculations

As mentioned earlier, analyzing the moiré pattern in k space only predicts the beam directions. Full-wave numerical simulations are necessary to accurately determine each beam's intensity in these directions, currently posing a major challenge. On one hand, we need to simulate the entire structure of a moiré metasurface, due to the lack of a unit cell in reflective moiré metasurfaces. The intricate details of the moiré pattern require an excessive amount of mesh in the numerical simulation to reach an acceptable convergence, resulting in an exceedingly high computational burden. On the other hand, once we modify the geometry of each pattern, we need to simulate the radiation performance across all twist angles, leading to a substantial increase in the optimization workload. To expedite the optimization process, there is a pressing need to develop a fast and accurate algorithm to calculate the radiation of reflective moiré metasurfaces. Simulating just a single moiré unit cell could be an efficient method to reduce computational time. However, it is important to be aware of the challenges in identifying the moiré unit cell, as well as the inaccuracies resulting from the nonperiodic nature of the moiré unit cell itself.

IV. CONCLUSION AND OUTLOOK

Reflective moiré metasurfaces present a revolutionary approach to metasurface design and offer a cost-effective solution for dynamic beamforming. Their flat design lends versatility to both indoor and outdoor applications, integrating smoothly into indoor decorations, such as walls, ceilings, and art pieces, and outdoor structures, including building exteriors, lampposts, and billboards, for expanded signal coverage. Besides cost-effectiveness, moiré metasurfaces boast additional features like zero-static power consumption, noise-free signal-relay transmission, and the ability to handle high-power signals. Looking ahead, integrating a direction-of-arrival module could extend the applications of reflective moiré metasurfaces to broader fields, such as satellite communications and radar systems.

While the reflective moiré metasurfaces may not match the programmable metasurfaces in responsiveness, they adapt to scenarios requiring medium-to-slow channel adjustment based on channel-condition data over seconds to minutes. It is notable that reflective moiré metasurfaces show superior beam efficiencies compared to their conventional counterparts designed with super unit cells [1,19]. The enhanced performance is attributable to the smoother phase gradient of moiré patterns.

Although the current moiré metasurface displays remarkable beamforming capabilities, a significant limitation is that beams appear as inversion-symmetry pairs relative to the surface normal. In RIS applications, directing the beam in any selected direction is preferred, and this can be achieved by allowing each pattern to be freely selected from the 17 groups of Euclidean symmetries. As a result, one can expect a total of C_{17}^{2} different combinations of the moiré pattern, each with its unique static and dynamic symmetries. Static symmetry determines the shape and polarization of the beam, whereas dynamic symmetry affects the beam's path and symmetry over the 2π-angle range of twisting. Exploring the connection between pattern combinations across different symmetry groups and radiation provides fundamental principles for the rapid design of reflective moiré metasurfaces with specific beam-shape and -path requirements.

We believe that the impact of reflective Moiré metasurfaces can be extended beyond the microwave and antenna-engineering communities, reaching into the fields of photonics and micro- or nanodevices [38]. Its passive approach to synthesize far-field scattering using tightly stacked ultrathin metallic patterns with varying plane symmetries establishes it as a powerful solution for developing programmable photonic devices across terahertz, infrared, or even visible-light spectra, for instance, spatial light modulators and reconfigurable polarizer plates. Furthermore, the high-Q-factor localized modes generated by the Moiré flat bands can be exploited for field enhancement and high-harmonic generation in optics.

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[1] T. J. Cui, M. Q. Qi, X. Wang, J. Zhao, and Q. Cheng, Coding metamaterials, digital metamaterials and programmable metamaterials, Light: Sci. Appl. **3**, e218 (2014).
[2] T. J. Cui, S. Liu, and L. Zhang, Information metamaterials and metasurfaces, J. Mater. Chem. C **5**, 3644 (2017).
[3] S. Liu and T. J. Cui, Concepts, working principles, and applications of coding and programmable metamaterials, Adv. Opt. Mater. **5**, 1700624 (2017).
[4] T. J. Cui, L. Li, S. Liu, Q. Ma, L. Zhang, X. Wan, W. X. Jiang, and Q. Cheng, Information metamaterial systems, iScience **23**, 101403 (2020).
[5] T. J. Cui, S. Liu, G. D. Bai, and Q. Ma, Direct transmission of digital message via programmable coding metasurface, Research **2019**, 2584509 (2019).
[6] W. Tang, M. Z. Chen, X. Chen, J. Y. Dai, Y. Han, M. D. Renzo, Y. Zeng, S. Jin, Q. Cheng, and T. J. Cui, Wireless communications with reconfigurable intelligent surface: Path loss modeling and experimental measurement, IEEE Trans. Wirel. Commun. **20**, 421 (2021).
[7] L. L. Li, T. J. Cui, W. Ji, S. Liu, J. Ding, X. Wan, Y. B. Li, M. Jiang, C.-W. Qiu, and S. Zhang, Electromagnetic reprogrammable coding metasurface holograms, Nat. Commun. **8**, 197 (2017).
[8] L. L. Li, H. Ruan, C. Liu, Y. Li, Y. Shuang, A. Alu, C.-W. Qiu, and T. J. Cui, Machine learning reprogrammable metasurface imager, Nat. Commun. **10**, 1082 (2019).
[9] L. Zhang, X. Q. Chen, S. Liu, Q. Zhang, J. Zhao, J. Y. Dai, G. D. Bai, X. Wan, Q. Cheng, G. Castaldi, V. Galdi, and T. J. Cui, Space-time-coding digital metasurfaces, Nat. Commun. **9**, 4334 (2018).
[10] L. Zhang, X. Q. Chen, R. W. Shao, J. Y. Dai, Q. Cheng, G. Castaldi, V. Galdi, and T. J. Cui, Breaking reciprocity

with space-time-coding digital metasurfaces, Adv. Mater. **31**, 1904069 (2019).

[11] J. Y. Dai, J. Zhao, Q. Cheng, and T. J. Cui, Independent control of harmonic amplitudes and phases via a time-domain digital coding metasurface, Light: Sci. Appl. **7**, 90 (2018).

[12] M. Yankowitz, S. Chen, H. Polshyn, Y. Zhang, K. Watanabe, T. Taniguchi, D. Graf, A. Young, and C. R. Dean, Tuning superconductivity in twisted bilayer graphene, Science **363**, 1059 (2019).

[13] S. S. Sunku, G. X. Ni, H. Yoo, A. Sternbach, A. S. Mcleod, L. Xiong, T. Taniguchi, K. Watanabe, P. Kim, M. M. Fogler, and D. N. Basov, Photonic crystals for nano-light in moiré graphene superlattices, Science **362**, 1153 (2018).

[14] Y. Cao, V. Fatemi, S. Fang, K. Watanabe, T. Taniguchi, E. Kaxiras, and P. Jarillo-Herrero, Unconventional superconductivity in magic-angle graphene superlattices, Nature **556**, 43 (2018).

[15] Y. Cao, V. Fatemi, A. Demir, S. Fang, S. L. Tomarken, J. Y. Luo, J. D. Sanchez-Yamagishi, K. Watanabe, T. Taniguchi, E. Kaxiras, R. C. Ashoori, and P. Jarillo-Herrero, Correlated insulator behaviour at half-filling in magic-angle graphene superlattices, Nature **556**, 80 (2018).

[16] C. R. Dean, L. Wang, P. Maher, C. Forsythe, F. Ghahari, Y. Gao, J. Katoch, M. Ishigami, P. Moon, M. Koshino, T. Taniguchi, K. Watanabe, K. L. Shepard, J. Hone, and P. Kim, Hofstadter's butterfly and the fractal quantum Hall effect in moiré superlattices, Nature **497**, 598 (2013).

[17] Y. Huang, K. Kim, D. K. Efimkin, T. Lovorn, T. Taniguchi, K. Watanabe, A. H. MacDonald, E. Tutuc, and B. J. LeRoy, Topologically protected helical edge states in minimally twisted bilayer graphene, Phy. Rev. Lett. **121**, 037702 (2018).

[18] K. L. Seyler, P. Rivera, H. Yu, N. P. Wilson, E. L. Ray, D. G. Mandrus, J. Yan, W. Yao, and X. Xu, Signatures of moiré-trapped valley excitons in MoSe2/WSe2 heterobilayers, Nature **567**, 66 (2019).

[19] S. Liu, S. Ma, R. Shao, L. Zhang, T. Yan, Q. Ma, S. Zhang, and T. J. Cui, Moiré metasurfaces for dynamic beamforming, Sci. Adv. **8**, abo1511 (2022).

[20] O. Avayu, E. Almeida, Y. Prior, and T. Ellenbogen, Composite functional metasurfaces for multispectral achromatic optics, Nat. Commun. **8**, 14992 (2017).

[21] E. Arbabi, A. Arbabi, S. M. Kamali, Y. Horie, M. Faraji-Dana, and A. Faraon, MEMS-tunable dielectric metasurface lens, Nat. Commun. **9**, 812 (2018).

[22] Y. Wei, Y. Wang, X. Feng, S. Xiao, Z. Wang, T. Hu, M. Hu, J. Song, M. Wegener, M. Zhao, J. Xia, and Z. Yang, Compact optical polarization-insensitive zoom metalens doublet, Adv. Opt. Mater. **8**, 2000142 (2020).

[23] K. Iwami, C. Ogawa, T. Nagase, and S. Ikezawa, Demonstration of focal length tuning by rotational varifocal moiré metalens in an IR-A wavelength, Opt. Express **28**, 35602 (2020).

[24] S. Colburn, A. Zhan, and A. Majumdar, Varifocal zoom imaging with large area focal length adjustable metalenses, Optica **5**, 825 (2018).

[25] B. H. McGuyer and Qi Tang, Connection between antennas, beam steering, and the moiré effect, Phys. Rev. Appl. **17**, 034008 (2022).

[26] Qi Tang, B. H. Mcguyer, E. Booen, S. Saraswat, F. Tabatabai, H. Bolandhemmat, C. V. Badinski, and W. H. Theunissen, Flat-panel mechanical beam steerable array antennas with in-plane rotations: Theory, design and low-cost implementation, IEEE Open J. Antennas Propag. **2**, 679 (2021).

[27] X. Mao, Z. Shao, H. Luan, S. Wang, and R. Ma, Magic-angle lasers in nanostructured moiré superlattice, Nat. Nanotechnol. **16**, 1099 (2021).

[28] H. Luan, Y. Ouyang, Z. Zhao, W. Mao, and R. Ma, Reconfigurable moiré nanolaser arrays with phase synchronization, Nature **624**, 282 (2023).

[29] Z. Tan, F. Fan, S. Guan, H. Wang, D. Zhao, Y. Ji, and S. Chang, Terahertz spin-conjugate symmetry breaking for nonreciprocal chirality and one-way transmission based on magneto-optical moiré metasurface, Adv. Sci. **10**, 2204916 (2023).

[30] B. Lyu, Q. Jia, H. Li, G. Yang, F. Cao, S. Kou, D. Liu, T. Cao, G. Li, and J. Shi, Manipulating the chirality of moiré metasurface by symmetry breaking, Laser Photonics Rev. **17**, 2201004 (2023).

[31] T. Zhang, K. Dong, J. Li, F. Meng, J. Li, S. Munagavalasa, C. P. Grigoropoulos, J. Wu, and J. Yao, Twisted moiré photonic crystal enabled optical vortex generation through bound states in the continuum, Nat. Commun. **14**, 6014 (2023).

[32] Z. Wu and Y. Zheng, Moiré metamaterials and metasurfaces, Adv. Opt. Mater. **6**, 1701057 (2018).

[33] P. Wang, Y. Zheng, X. Chen, C. Huang, Y. V. Kartashov, L. Torner, V. V. Konotop, and F. Ye, Localization and delocalization of light in photonic moiré lattices, Nature **577**, 42 (2020).

[34] B. Lou, N. Zhao, M. Minkov, C. Guo, M. Orenstein, and S. Fan, Theory for twisted bilayer photonic crystal slabs, Phys. Rev. Lett. **126**, 136101 (2021).

[35] K. Dong, T. Zhang, J. Li, Q. Wang, F. Yang, Y. Rho, D. Wang, C. P. Grigoropoulos, J. Wu, and J. Yao, Flat bands in magic-angle bilayer photonic crystals at small twists, Phys. Rev. Lett. **126**, 223601 (2021).

[36] E. Galiffi, G. Carini, X. Ni, G. Alvarez-Perez, S. Yves, E. M. Renzi, R. Nolen, S. Wasserroth, M. Wolf, P. Alonso-Gonzalez, A. Paarmann, and A. Alu, Extreme light confinement and control in low-symmetry phonon-polaritonic crystals, Nat. Rev. Mater. **9**, 9 (2023).

[37] G. Hu, A. Krasnok, Y. Mazor, C.-W. Qiu, and A. Alu, Moiré hyperbolic metasurfaces, Nano Lett. **20**, 3217 (2020).

[38] S. Xiao, T. Wang, T. Liu, C. Zhou, X. Jiang, and J. Zhang, Active metamaterials and metadevices: A review, J. Phys. D: Appl. Phys. **53**, 503002 (2020).