

Generation and deflection of dual-frequency two-dimensional microwave Airy beams on the basis of compact meta-atoms

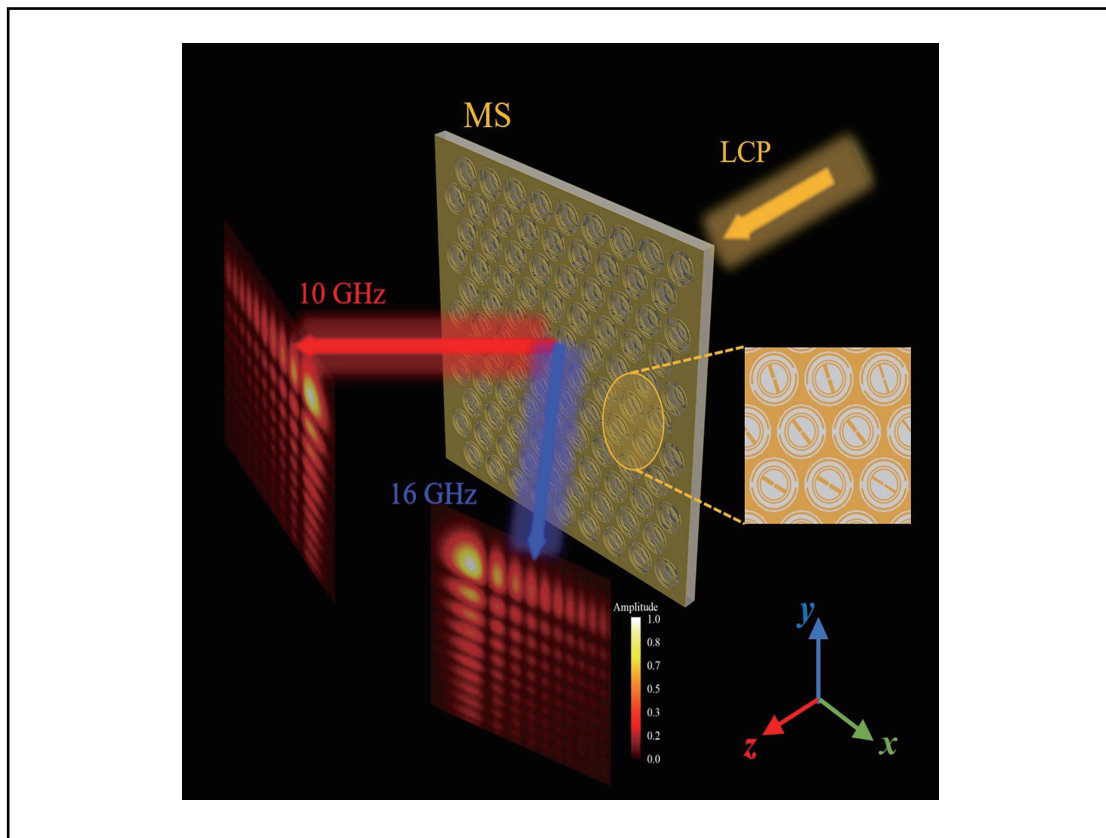
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Graphical abstract



Schematic illustrations of the dual-frequency amplitude-phase decoupled metasurface for producing a 2D Airy beam.

Public summary

- A single-layer hexagonal transmitting meta-atom is proposed, which is capable of modulating amplitude and phase independently at dual-frequency while maintaining a high transmittance.
- Based on the proposed meta-atoms, a metasurface capable of generating a two-dimensional microwave Airy beam was designed. The beam deflection angles are -20° and 20° at 10 GHz and 16 GHz, respectively.
- The deflected microwave Airy beam produced by the proposed metasurface still maintains unique self-accelerating and self-healing properties, providing a greater degree of freedom in the control of the Airy beam.

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Abstract: Airy beams have attracted much attention because of their nondiffraction, self-healing, and self-bending properties. However, the existing methods suffer from a single operating frequency and a fixed radiation direction. In this paper, a single-layer hexagonal transmissive meta-atom is proposed, which enables completely independent modulation of the amplitude and phase at dual frequencies. The compact structure has high transmittance and enables precise control of the amplitude and phase at two frequencies. As a proof-of-concept, the proposed meta-atom is applied to generate microwave two-dimensional Airy beams deflected $\pm 20^\circ$ at 10 GHz and 16 GHz. The simulation results prove that the deflected Airy beams still maintain self-accelerating and self-healing properties.

Keywords: metasurface; dual-frequency; amplitude and phase modulation; microwave Airy beam

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1 Introduction

In 1979, Berry and Balazs discovered Airy wave packets in the field of quantum mechanics^[1], verifying the unique nondiffractive, self-accelerating, and self-healing properties of Airy beams during propagation^[2–4]. However, the ideal Airy beam carrying infinite energy is physically impossible to realize. Siviloglou and Christodoulides introduced a truncation factor that made it possible to generate Airy beams experimentally^[5,6], and the truncated Airy beams still maintain their interesting properties. Moreover, after the introduction of Airy beams into the optical community in analogy with the Schrödinger equation and the even-axis Helmholtz equation, more and more research interests in the field of optics, such as particle manipulation^[7], light-sheet microscopy^[8], and plasma guidin^[9], have been reported.

Conventional methods generate Airy beams through cubic phase modulation, which usually requires complex equipment such as spatial light modulators^[5] and lens systems^[10]. In comparison, meta-surfaces allow more flexible control of the amplitude, phase, and polarization of electromagnetic waves, which has inspired applications, such as holography^[11,12] and radar cross section (RCS) reduction^[13], and has also shown significant advantages in Airy beam generation^[14]. In particular, Airy beam emitters implemented on a metasurface are more easily operated in microwaves^[15] and can be extended to dual or multiple frequency bands.

Reshaping the electric field distribution of the incident electromagnetic wave with the help of phase-only^[16] or amplitude–phase-modulated^[17–19] metasurfaces provides a simpler and low-cost method to generate Airy beams. In recent years, hyperbolic metamaterials^[19–21] that can simultaneously

manipulate the amplitude and phase of electromagnetic waves have been proposed for linearly polarized waves, and such metasurfaces with $0/\pi$ two-phase modulation are well suited for Airy wave beam generation. For circularly polarized (CP) waves, on the other hand, a metasurface that combines the propagation phase and the geometrical phase yields a more comprehensive phase tuning range with greater application scope^[22,23].

However, most of the current studies on Airy beam generation have focused on a single frequency, and the realization of microwave and millimeter-wave Airy beams is still limited by the large processing and testing dimensions. Therefore, the realization of efficiently multiplexed Airy wave generation structures remains a challenge.

To overcome the above drawbacks, a compact dual-frequency meta-atom is proposed in this paper, and microwave two-dimensional (2D) Airy beams with specified angles are generated on the basis of the proposed meta-atom within 10 GHz and 16 GHz, as shown in Fig. 1. The Airy beam based on metasurface reconstruction in this work maintains self-acceleration and self-healing properties. In addition, the amplitude and phase of the proposed meta-atom are fully decoupled at two frequencies, which has potential for applications such as reducing the antenna side lobe and generating a high-quality hologram.

The rest of this paper is organized as follows. The meta-atom design and simulation results for independent control of the dual-frequency amplitude and phase are presented in Section 2, the theory of generation and deflection of 2D Airy beams is presented in Section 3, and the simulation results and discussion are given in Section 4. Finally, conclusions are drawn in Section 5.

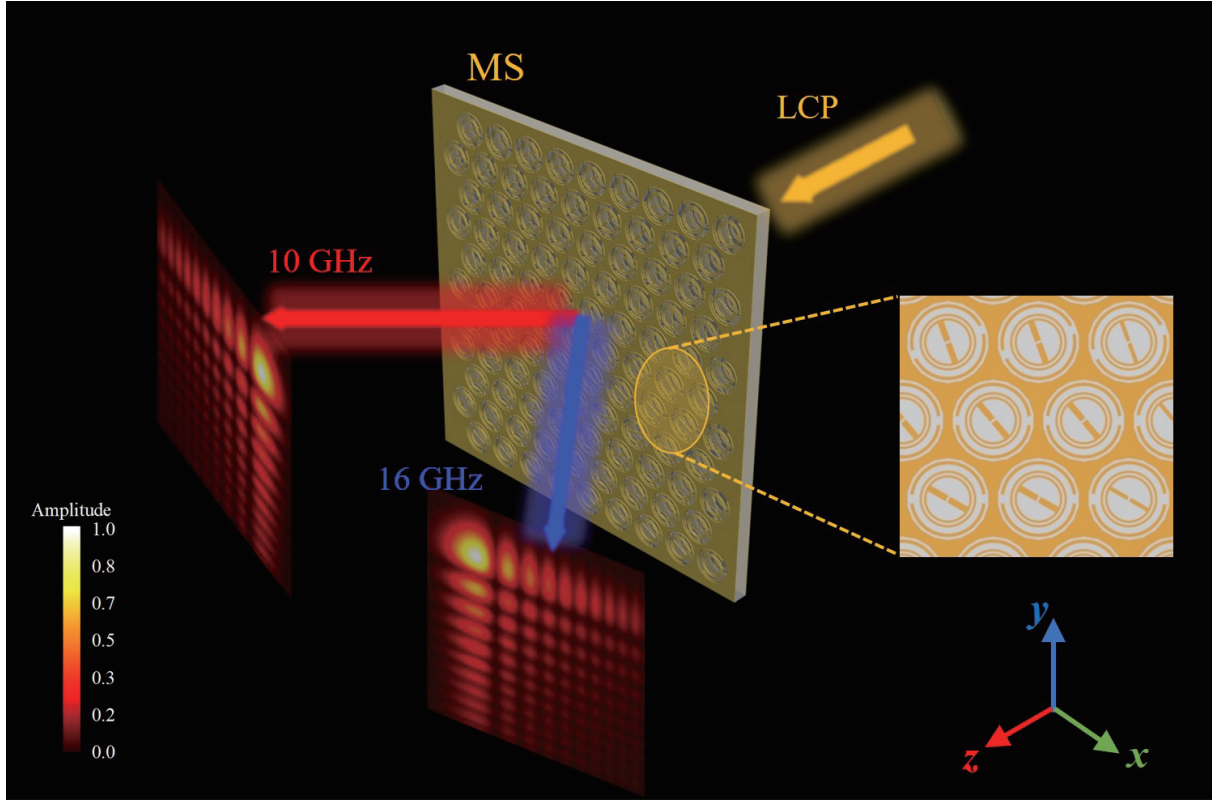


Fig. 1. Schematic illustrations of the dual-frequency amplitude-phase decoupled metasurface for producing a 2D Airy beam.

2 Meta-atom design and analysis

To generate the initial Airy beam profile and control the deflection angle of the beam, it is critical to design a meta-atom that can independently control the transmitted amplitude and phase. We first characterize the functions achieved by the metasurface through the Jones matrix. When electromagnetic waves are incident on the metasurface, assuming that there is no cross-polarized transmission component, the transmission matrix can be expressed as:

$$T = \begin{pmatrix} T_{xx} & T_{xy} \\ T_{yx} & T_{yy} \end{pmatrix} = \begin{pmatrix} t_{xx}e^{j\varphi_{xx}} & t_{xy}e^{j\varphi_{xy}} \\ t_{yx}e^{j\varphi_{yx}} & t_{yy}e^{j\varphi_{yy}} \end{pmatrix} = \begin{pmatrix} t_{xx}e^{j\varphi_{xx}} & 0 \\ 0 & t_{yy}e^{j\varphi_{yy}} \end{pmatrix}, \quad (1)$$

where t_{xx} and t_{yy} represent the copolarized transmission amplitudes for the x - and y -polarizations, respectively, and φ_{xx} and φ_{yy} are the corresponding transmission phases. The coordinate form is transformed with the transformation matrix $\Lambda = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & 1 \\ j & -j \end{pmatrix}$ to obtain the transmission Jones matrix in CP form as:

$$T_{\text{cir}} = \begin{pmatrix} T_{rr} & T_{rl} \\ T_{lr} & T_{ll} \end{pmatrix} = \Lambda^{-1} T \Lambda. \quad (2)$$

When Pancharatnam-Berry (P-B) phase manipulation is applied to incident CP waves by rotating the meta-atom, a rotation matrix $S(\alpha)$ is introduced. At this point, the transmission matrix is obtained:

$$T_{\text{cir}}(\alpha) = S(-\alpha) T_{\text{cir}} S(\alpha) = \begin{pmatrix} \cos(\alpha) & -\sin(\alpha) \\ \sin(\alpha) & \cos(\alpha) \end{pmatrix} \begin{pmatrix} T_{rr} & T_{rl} \\ T_{lr} & T_{ll} \end{pmatrix} \begin{pmatrix} \cos(\alpha) & \sin(\alpha) \\ -\sin(\alpha) & \cos(\alpha) \end{pmatrix} = \begin{pmatrix} T'_{rr} & T'_{rl} \\ T'_{lr} & T'_{ll} \end{pmatrix}, \quad (3)$$

in which

$$\begin{cases} T'_{rr} = \frac{1}{2}(t_{xx}e^{j\varphi_{xx}} + t_{yy}e^{j\varphi_{yy}}); \\ T'_{rl} = \frac{1}{2}(t_{xx}e^{j\varphi_{xx}} - t_{yy}e^{j\varphi_{yy}})e^{-2j\alpha}; \\ T'_{lr} = \frac{1}{2}(t_{xx}e^{j\varphi_{xx}} + t_{yy}e^{j\varphi_{yy}}); \\ T'_{ll} = \frac{1}{2}(t_{xx}e^{j\varphi_{xx}} - t_{yy}e^{j\varphi_{yy}})e^{2j\alpha}. \end{cases} \quad (4)$$

If $t_{xx} = t_{yy} = t$, the cross-polarized transmission amplitude can be written as:

$$t_{rl} = \left| t \sin \frac{\Delta\varphi}{2} \right|, \quad (5)$$

where $\Delta\varphi = \varphi_{xx} - \varphi_{yy}$. Eq. (5) shows that the maximum efficiency of polarization conversion can be achieved by ensuring that $t_{xx} = t_{yy}$ and that the phase difference $\Delta\varphi$ is 180° . Therefore, under the incidence of CP waves, the modulation of the cross-polarized transmission phase is based on the rotation of the meta-atom, whereas the amplitude can be modulated in terms of both the transmission amplitude t_{xx}/t_{yy} and the phase difference $\Delta\varphi$.

The structure of the proposed meta-atom operating at 10 GHz and 16 GHz is shown in Fig. 2a and b. Unlike common

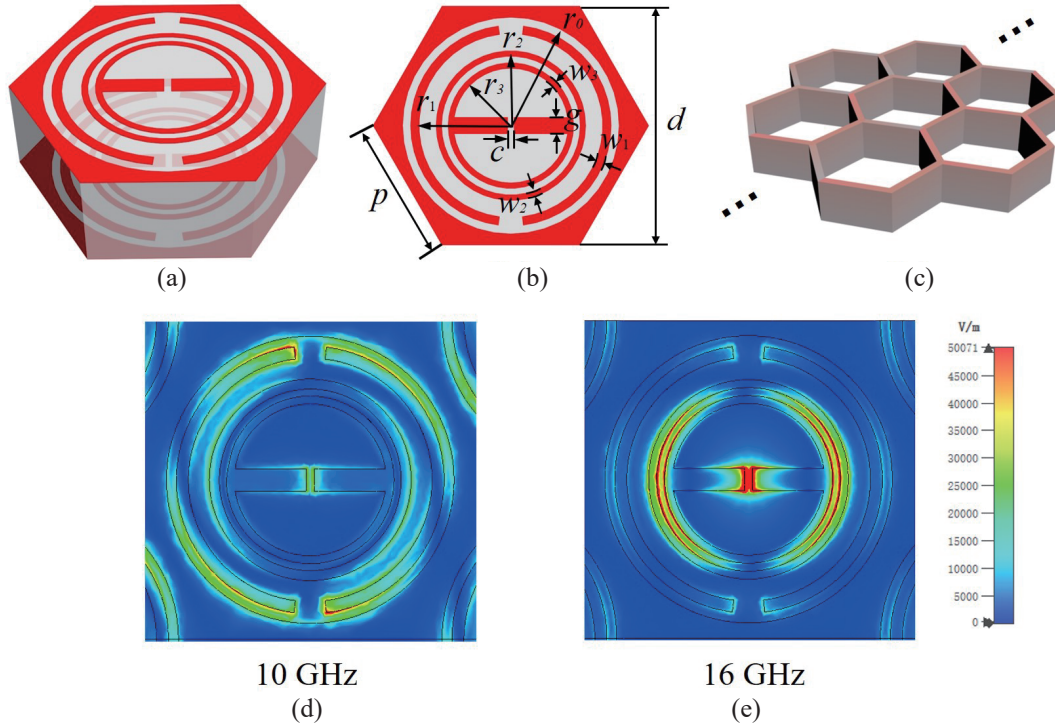


Fig. 2. Configuration and performance of the proposed meta-atom. (a) Stereogram of the meta-atom, (b) top view of the meta-atom, (c) schematic of the honeycomb-shaped arrangement, and (d) simulated electric fields under left-handed CP incident waves at 10 GHz and (e) 16 GHz.

square meta-atoms, meta-atoms adopt a hexagonal topology to obtain a more compact honeycomb-shaped metasurface array, as shown in Fig. 2c. On the one hand, the hexagonal meta-atom provides more stable performance with smaller variations in transmission phase and amplitude than the parameter-optimized square meta-atom does. On the other hand, the use of hexagonal meta-atoms can accommodate more meta-atoms within the same size of the metasurface, resulting in more precise phase control. Identical metal layers are printed on both sides of a single-layer F4B substrate with a dielectric constant of 3.5 and a loss angle tangent of 0.001. The metal layer consists of a hexagonal shape with a circular hole, a split-ring resonator, a circular ring, and a central strip structure. The preliminary optimized structural parameters are $p = 4.62$ mm, $d = 8$ mm, $h = 3$ mm, $r_0 = 3.6$ mm, $r_1 = 3.2$ mm, $r_2 = 2.4$ mm, $r_3 = 2.1$ mm, $w_1 = 0.3$ mm, $w_2 = 0.2$ mm, $w_3 = 0.2$ mm, and $c = 0.1$ mm, and the thickness of the copper is 0.018 mm. The split-ring resonator and the strip structure resonate at 10 GHz and 16 GHz, respectively, as shown by the electric fields in Fig. 2d and e, demonstrating good isolation between the dual frequencies.

The meta-atom is simulated and optimized in the CST Microwave Studio Software, and Fig. 3a–c and d–f show the results of amplitude and phase modulation at 10 GHz and 16 GHz, respectively. At 10 GHz, as shown in Fig. 3a and b, the directional angle α_1 of the split ring controls the transmission phase of the CP wave, and the cross-polarized wave transmission coefficient is consistently greater than 0.8 while obtaining complete 360° transmission phase coverage. Fig. 3c depicts the variation in the transmission amplitude t_{rll} with $\Delta\phi$. Since the variation in the split tensor angle θ affects the transmission phase difference $\Delta\phi$ between the x -polarized and

y -polarized waves, θ can independently modulate the transmission amplitude according to Eq. (5). The transmission coefficient can vary from 1 to 0.1 as θ increases from 14° to 50°.

Fig. 3d and e illustrate the variation in the cross-polarization transmission phase and amplitude with α_1 and α_2 at 16 GHz. The transmission phase is regulated by the rotation angle α_2 of the central strip structure, and the transmission coefficient is always greater than 0.85 during phase modulation. Unlike the amplitude modulation method of the meta-atom at low frequency, on the basis of the theoretical analysis presented earlier, the CP wave transmission coefficient is controlled at 16 GHz by simultaneously adjusting t and $\Delta\phi$, as shown in Fig. 3f. In a specific realization, varying the width g of the strip allows arbitrary magnitude values between 0.1 and 0.95 to be obtained. In summary, the four parameters of the amplitude and phase at two frequencies are independent of each other, and the excellent characteristics of the meta-atom make it highly promising for various applications.

3 Microwave two-dimensional Airy beam generation and deflection

3.1 2D Airy beam generation

The ideal 2D Airy wave packet can be derived directly from the one-dimensional Airy wave equation, which can be observed as a parabolic trajectory in the 2D plane that is nondiffractive along the propagation direction. However, the ideal Airy beam carrying infinite energy could not be realized experimentally, and Siviloglou et al.^[9] solved this problem by introducing a truncation factor. The 2D Airy beam propagation equation carrying a truncation factor can be described as:

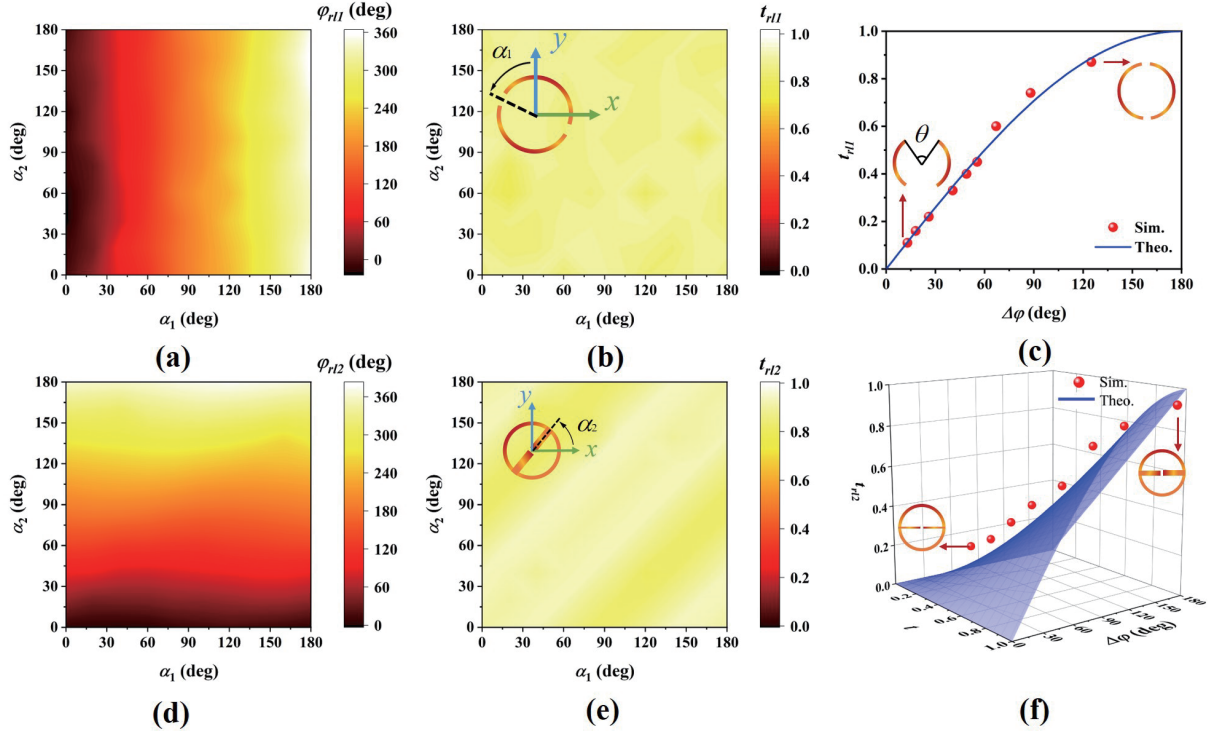


Fig. 3. (a) Transmission phase responses and (b) transmission amplitude responses by rotating angles α_1 and α_2 at 10 GHz, (c) transmission amplitude responses at 10 GHz versus $\Delta\phi$ under LCP incidence. (d) Transmission phase responses and (e) transmission amplitude responses by rotating angles α_1 and α_2 at 16 GHz, (f) transmission amplitude responses at 16 GHz versus $\Delta\phi$ and t under LCP incidence.

$$\phi(x, y, z) =$$

$$Ai\left(\frac{x}{x_0} - \frac{\xi^2}{4} + ia\xi\right) \exp\left(\frac{ax}{x_0} - \frac{a\xi^2}{2} - \frac{i\xi^3}{12} + \frac{ia^2\xi}{2} + \frac{ix\xi}{2x_0}\right) \times \quad (6)$$

$$Ai\left(\frac{y}{y_0} - \frac{\xi^2}{4} + ia\xi\right) \exp\left(\frac{ay}{y_0} - \frac{a\xi^2}{2} - \frac{i\xi^3}{12} + \frac{ia^2\xi}{2} + \frac{iy\xi}{2y_0}\right),$$

where Ai is the Airy function, and a represents the truncation factor, which takes values in the range of 0–1. x_0 and y_0 approximately represent one-half of the Airy main-lobe half-power beam width, $\xi = z/(kx_0^2)$ represents the normalized propagation length, and $k = 2\pi/\lambda$ and z represent the propagation distances along the propagation direction. When $z = 0$, the initial Airy wave profile can be simplified to:

$$\phi(x, y, z = 0) = Ai\left(\frac{x}{x_0}\right) e^{ax/x_0} \times Ai\left(\frac{y}{y_0}\right) e^{ay/y_0}. \quad (7)$$

The desired Airy beam profile can be simply realized by arranging meta-atoms with different amplitudes and phases.

3.2 Theory of beam deflection

The control of the trajectory of the Airy beam is also important for meeting the demands of applications in complex scenarios. On the basis of the generalized Snell's law of refraction, the phase required for beam deflection can be calculated as^[24]:

$$\phi_d = -\frac{2\pi}{\lambda}(x \sin \theta \cos \varphi + y \sin \theta \sin \varphi), \quad (8)$$

where θ and φ are the pitch and azimuth angles separately. Finally, the desired phase distribution on the metasurface can be superimposed by the initial phase of the Airy beam and the phase of beam deflection.

3.3 Metasurface design for 2D Airy beam generation

On the basis of the above theoretical analysis, the proposed dual-frequency meta-atom is well suited to constitute a dual-frequency 2D Airy beam generator, which can realize Airy beams with different deflection angles at two frequencies, as shown in Fig. 1. To validate the proposed concept, we present a metasurface that generates Airy beams with a deflection angle of $(\theta, \varphi) = (20^\circ, 0^\circ)$ at 10 GHz and with a deflection angle of $(\theta, \varphi) = (-20^\circ, 0^\circ)$ at 16 GHz. The metasurface consists of a total of 1672 meta-atoms with physical dimensions of 310 mm $\times$ 310 mm. Moreover, a major factor that restricts the generation of Airy beams in the microwave and millimeter wave bands is the bulky structures required for fabrication and testing, whereas the dimensions of the proposed compact meta-atoms have more precise phase control of a limited size while meeting the Nyquist sampling rate required to reconstruct the Airy beam. Compared with a metasurface composed of square meta-atoms of the same size, the proposed arrangement can accommodate 151 more meta-atoms.

The amplitude distributions of the initial Airy beam at 10 GHz and 16 GHz are obtained as illustrated in Fig. 4a and b for $x_0 = y_0 = 25$ and attenuation factor $a = 0.1$. The Airy wave beams are reconstructed at different positions of the metasurface at low and high frequencies, characterizing the independent phase modulation function of the metasurface. The phase of the beam deflection of 20° at 10 GHz and the phase required to generate the Airy beam are presented in Fig. 4c and d, which are superimposed to obtain the final phase distribution in Fig. 4e. Similarly, the phase distribution at 16 GHz is calculated as shown in Fig. 4f–h.

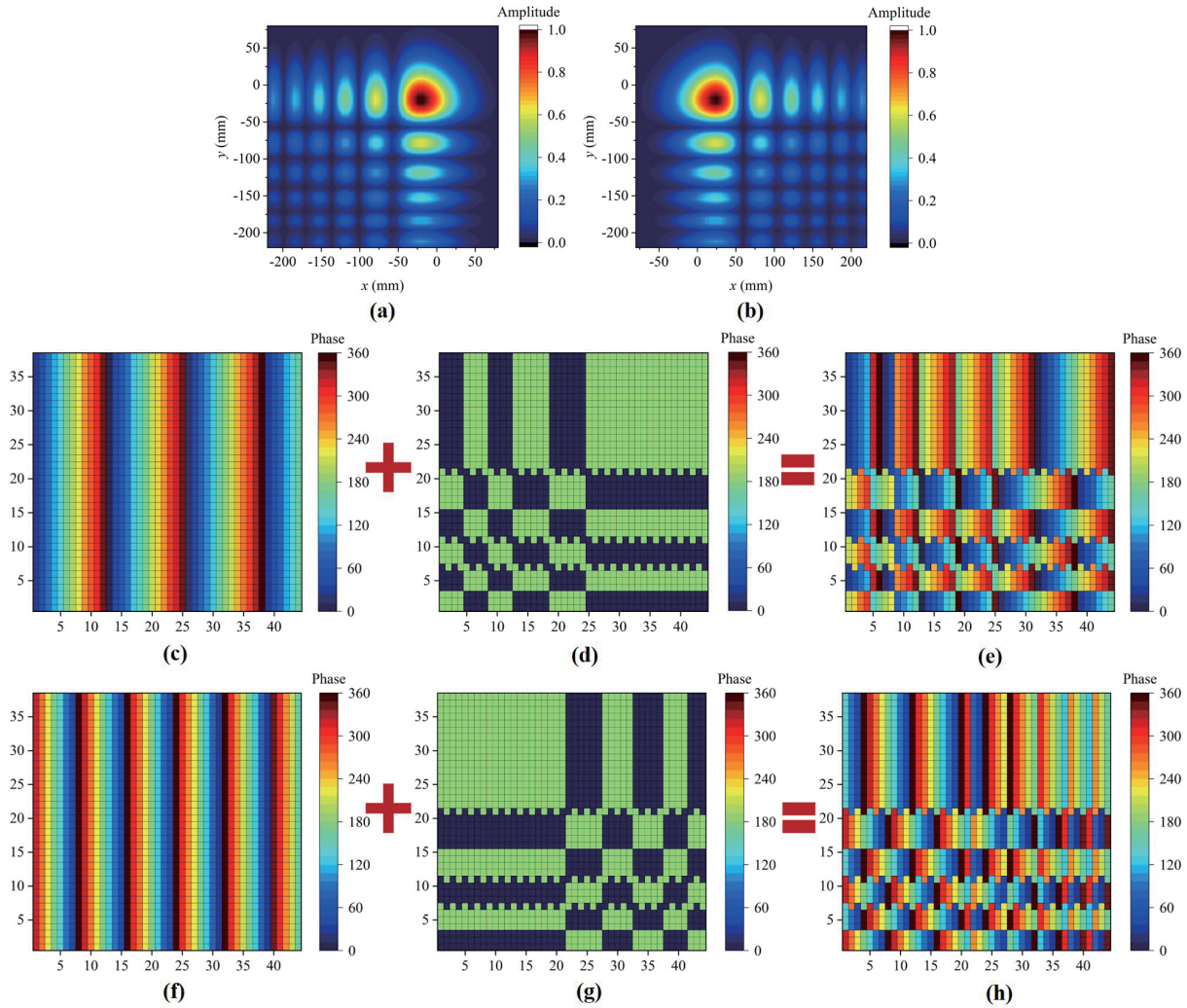


Fig. 4. (a) Theoretical values of the normalized electric field distribution of the initial microwave 2D Airy beam at 10 GHz and (b) 16 GHz. (c) Deflection phase distribution for beam angles of $(0^\circ, -20^\circ)$. (d) 2D Airy beam phase distribution and (e) final phase distribution of the metasurface at 10 GHz. (f) Deflection phase distribution for beam angles of $(0^\circ, 20^\circ)$. (g) 2D Airy beam phase distribution and (h) final phase distribution of the metasurface at 16 GHz.

4 Results and discussion

The validity of the design is verified in CST Microwave Studio. CP horns operating in the X-band and Ku-band are used as dual-band feeds, and the maximum realized gain achieved by the horns is approximately 10 dBic for both. Considering the aperture efficiency and the simulated plane wave incidence effect, the distance between the horns and the metasurface is optimized to 0.3 m.

In the simulation, the tilted Airy beam is conveniently observed by rotating the metasurface with the corresponding deflection angle of the beam. Specifically, the metasurface is rotated by 20° and -20° along the y -axis with the center of the metasurface as the origin at 10 GHz and 16 GHz, respectively, and the electric field in the xoy plane is observed at different distances. The normalized CP electric field distributions observed at 10 GHz in the plane at $z = 200$ mm, 250 mm, 300 mm, and 350 mm from the metasurface are shown in Fig. 5a–d, and the main-lobe and side-lobe of the Airy beam are clearly visible, which meets the design requirements. The normalized electric field distribution at 16 GHz along different

propagation planes ($z = 150$ mm, 200 mm, 250 mm, and 300 mm) is shown in Fig. 5e–h. Compared with those at 10 GHz, some of the electromagnetic waves at 16 GHz are scattered to the surrounding area but still exhibit clear Airy beams in the propagation path of $\theta = 20^\circ$. Furthermore, the graphical results characterize the self-accelerating behavior of the Airy wave along the x - and y -directions. The full-width half-maximum (FWHM) is used to evaluate the nondiffractive properties of the Airy beam, and according to the theory of optical ABCD systems, the propagation of the Airy wave inevitably diverges because of the spherical wavefront excitation provided by the horn^[25]. The FWHM at 10 GHz is approximately 62 mm and 80 mm at 200 mm and 350 mm, respectively, and the FWHM also gradually increases along the propagation direction at 16 GHz, maintaining the nondiffractive properties only to some extent.

Furthermore, the self-healing properties of the Airy beam can be demonstrated by placing a spherical barrier in front of the metasurface. At low frequency, we place a metal sphere with a radius of 15 mm on the main flap transmission path at $z = 150$ mm from the metasurface. The exact position of the

metal sphere was carefully adjusted in the simulation with the aim of observing a significant main flap masking effect in the observation plane at $z = 200$ mm. Fig. 6 shows the normalized electric field observed at different lengths from the metasurface. In the plane of $z = 200$ mm, the main flap is affected by the obstruction of the metal sphere, whereas a better recovery is obtained at 250 mm. For high frequencies, the same metallic sphere with a radius of 15 mm is placed at a distance of 120 mm from the metasurface, and the beam rapidly recovers with increasing propagation distance, characterizing the unique self-healing ability of self-accelerating waves.

5 Conclusions

To summarize, we propose a design strategy for generating microwave 2D Airy beams at dual frequencies with an amplitude-phase modulation metasurface. The proposed hexagonal single-layer meta-atom can manipulate the transmission phase and amplitude of the CP electromagnetic wave independently at 10 GHz and 16 GHz, whereas the transmission characteristics at both frequencies can be completely decoupled. Microwave Airy beams with different pointing angles can be efficiently generated via amplitude and phase modulation of electromagnetic waves at different frequencies.

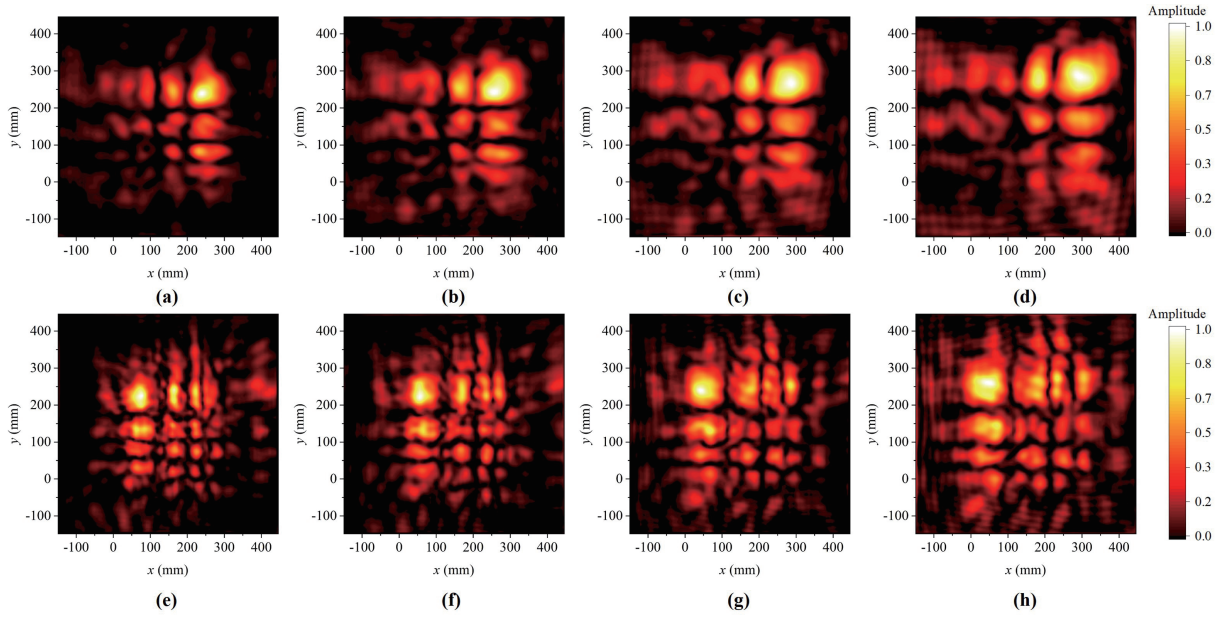


Fig. 5. Simulated normalized electric field of the microwave 2D Airy beam for different propagation distances. (a) $z = 200$ mm, (b) $z = 250$ mm, (c) $z = 300$ mm, and (d) $z = 350$ mm at 10 GHz; (e) $z = 150$ mm, (f) $z = 200$ mm, (g) $z = 250$ mm, and (h) $z = 300$ mm at 16 GHz.

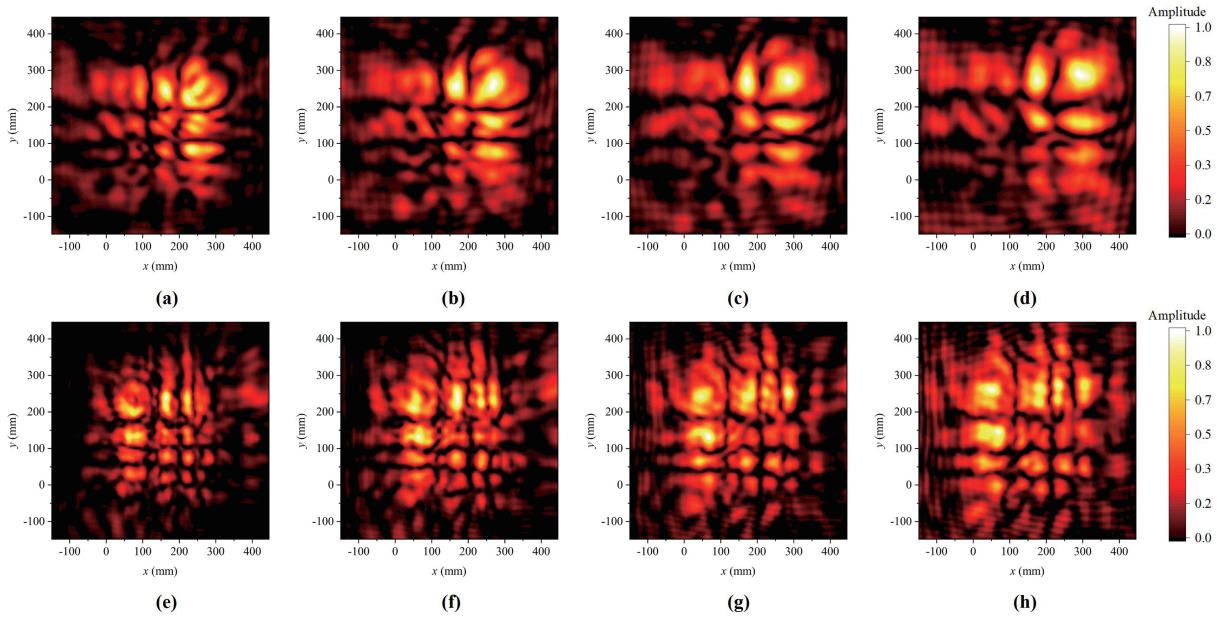


Fig. 6. Simulated normalized electric fields of microwave 2D Airy beams at different propagation distances for self-healing property verification. (a) $z = 200$ mm, (b) $z = 250$ mm, (c) $z = 300$ mm, and (d) $z = 350$ mm at 10 GHz. (e) $z = 150$ mm (f) $z = 200$ mm, (g) $z = 250$ mm, and (h) $z = 300$ mm at 16 GHz.

The unique nondiffractive, self-accelerating, and self-healing properties of Airy beams are also verified via numerical and simulation results, confirming the correctness and superiority of the proposed design approach.

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Conflict of interest

The authors declare that they have no conflict of interest.

Biographies

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