Ultrathin Dual-Band Wide-Angle Beam Scanning Metalens Based on High-Efficiency Meta-Atom

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Metasurfaces composed of planar subwavelength-scaled meta-atoms demonstrate unprecedented wavefront manipulation capabilities. However, the wavelength-dependent property of the metasurface could severely reduce the design freedom, and most metasurfaces require multilayer structure for high efficiency. Herein, a single-layered-substrate meta-atom is proposed to achieve independent phase manipulations as well as high transmission efficiencies at two frequencies. Specifically, the full $2\pi$ phase coverages can be individually realized through rotating the corresponding resonators. As a proof-of-concept demonstration, a dual-band high-efficiency metalens with wide field-of-view (FoV) under the circular polarization incidence is simulated, fabricated and measured at Ka-band for satellite communications. Both simulation and experimental results agree well with each other, demonstrating that wide scanning coverages of $\pm 60^\circ$ can be achieved at both 20 and 30 GHz. The proposed method can be a competitive candidate for designing dual-band high-efficiency meta-devices.

1. Introduction

Metasurfaces composed of engineered planar unit cells or meta-atoms present excellent local modulation capabilities on phase, amplitude and/or polarization of the incident wave at subwavelength scales.[1] Various applications such as focusing,[2,3] holography,[4–6] vortex beam generation,[7–9] optical cloaking,[10–12] and beam scanning[13–16] have been well studied by metasurface-based devices or meta-devices. Among these applications, beam scanning is highly desired by wireless communication systems such as satellite communication systems and tracking radars. Compared with the bulky reflector and the precise phased arrays, metasurface lens is considered as a promising solution for beam scanning achievement due to the ultrathin profile, light weight, low cost and easy fabrication.[17–21]

Due to the dispersion nature, most of the reported beam-scanning metalenses are limited to a single-band operation,[13,14,16] whereas dual-band or multiband operation is of great interest for improving communication capability, achieving compact integration and reducing device costs. In order to tackle this issue, the multiplexing techniques, i.e., aperture division and meta-atom interleaving are widely used for multiband achievement.[22–25] However, the former causes a discretized phase distribution among the lens aperture, the later might encounter unbalanced aperture efficiency among the operating frequencies due to the different amount of the meta-atoms. Hence the design of dual-band or multiband meta-atom is of great importance to effectively avoid the problem discussed above.[26–29] In ref. [26], a trilayer dual-band metalens was proposed, and a prototype fabricated by the standard photolith-graphic technique experimentally demonstrated a beam coverage of $\pm 25^\circ$. Matos et al.[27] proposed a new methodology to design a dual-band meta-atom, one metasurface based on six-layer unit-cell is proposed to achieve a beam coverage of $\pm 50^\circ$. By separating radiators into different layers, Liu et al.[28] presented a four-layer dual-band beam scanning metalens, where a beam coverage of $\pm 45^\circ$ has been realized through translation of the feed. More recently, a dual-band metalens based on trilayer meta-atoms was proposed in ref. [29], and a beam coverage of $\pm 30^\circ$ was experimentally verified. It can be seen that all the above-discussed works adopt multilayer structure to realize acceptable transmission efficiency, which consequently require more complicated manufacturing process and higher fabrication cost. Moreover, the beam scanning function could only be conducted in a single band within a limited angular coverage. More recently, several bilayer metasurfaces with various functions are reported in the literature. A wide-band TA based on bilayer unit-cell is proposed in ref. [30], wherein an aperture efficiency of 60.2% was experimentally demonstrated at K-band. In ref. [31], a high-efficiency full-space metasurface composed of bilayer meta-atom is proposed to act as a meta-lens and a beam-splitter at two specific bands, respectively. In ref. [32], a bilayer OAM generator consisting of N-shaped huygen’s meta-atom is proposed to achieve a conversion efficiency of...
75%. However, none of them could achieve wide-angle beam scanning at two bands. Thereafter, dual-band wide-angle beam scanning metalens based on single-layer substrate is still highly desired.

In this work, a novel dual-band single-layered-substrate meta-atom with completely independent geometric phase modulations at two different operation bands is proposed to realize high efficiency metalenses for beam scanning. The meta-atom comprises two identical patterned metallic layers printed on both sides of a substrate. The patterned metallic layer is composed of a modified Jerusalem cross resonator (MJCR) seated in a circular hole, a modified complementary split ring resonators (MCSRR) and a ring connector. As an illustration for the satellite communication, the two operation frequencies are chosen as $f_1 = 20$ and $f_2 = 30$ GHz. The MJCR and the MCSRR are utilized to independently tailor the phase profiles at $f_1$ and $f_2$, respectively. The full $2\pi$ phase modulations around the two frequencies could be attained through rotation of the two types of resonators. As a proof-of-concept demonstration, a metalens composed of $27 \times 27$ meta-atoms is designed, fabricated and measured. The measured results agree very well with the simulated ones, which implies that the proposed dual-band meta-atom could be a competitive candidate for designing dual-band high-efficiency meta-devices.

2. Results and Discussions

Figure 1a illustrates the operating schematic of the dual-band beam scanning system. As shown, the metalens is placed on the $xoy$ plane with the geometric center aligned to the center of the coordinate system, and a circularly polarized (CP) patch antenna located beneath the metalens acts as the feed source. As the feed is translated by a certain distance, the outgoing beam would be steered into a certain angle with respect to the $z$ axis, where the steering angle $\theta$ and the feed displacement $L$ satisfy

$$L = f \times \sin \theta$$  \hspace{1cm} (1)

where $f$ is the focal length of the metalens.

Figure 1b,c displays the perspective and top views of the dual-band meta-atom, respectively. It can be seen from Figure 1b that the meta-atom consists of two copper layers printed on both sides of a dielectric substrate Rogers RT 5880 with a dielectric constant of 2.2, a loss tangent of 0.0009 and a thickness of 1.575 mm. The metal–insulator–metal structure is selected to the meta-atom design for the purpose of high efficiency and low fabrication complexity.[30] The metallic layer displayed in Figure 1c can be geometrically divided into three parts: the inner part is a modified Jerusalem cross resonator (MJCR), the middle part is a ring and the outer part is a modified complementary split-ring resonator (MCSRR). The inner part mainly dominates the transmission property at higher frequency band, and the outer parts mainly dominates the transmission property at lower frequency band. The middle ring not only plays as an indispensable part of the MCSRR but also acts as a physical isolator between the inner and outer resonators. It is worth noting that the resonance of the MCSRR (MJCR) is attributed to magnetic (electric) resonance, and the coupling between these two different types of resonances is theoretically ultralow, which further guarantees independent phase modulations at two frequencies for the proposed meta-atom.

The periodicity of the meta-atom is depicted as $P$, the thicknesses of the metallic layers and substrate are presented as $t_1$ and $t_2$, respectively. The inner radius of the circular hole, the outer and inner radiuses of the MCSRR are denoted as $r_1$, $r_2$ and $r_3$, respectively. The lengths of the two orthogonal bars of the MJCR are denoted as $l_1$ and $l_2$, respectively. The width of the circular hole and the MCSRR are denoted as $w_1$ and $w_2$, respectively. The orientations of the MCSRR and MJCR with respect to the $x$-axis are denoted as $\theta_1$ and $\theta_2$, respectively, which are the key parameters for achieving the required phase delays at two frequencies. The radius of the center-located ring is $r_c$ (not denoted in the figure). It should be mentioned that the two operation frequencies could be tuned by modifying the key structural parameters such as the flare angle of the curved bars of the MJCR or the flare angle of the C-shaped slots of the MCSRR.

The meta-atom property is studied by the full-wave simulation tool-Ansoft high frequency simulation simulator (HFSS). In the
simulations, a left-handed circular polarization (LHCP) wave is used to illuminate the meta-atom from the top side, where the unit cell boundaries are adopted. The transmission amplitude and the resonance frequency of the proposed meta-atom can be regulated by adjusting some key parameters such as $\alpha_1$, $\alpha_2$, $l_1$, $l_2$, $l_3$, $l_4$, and $r_c$. More specifically, the resonance frequency of the MJCR is mainly determined by the flare angle of the arcs, i.e., $\alpha_1$ and the radius of the center-located circle, i.e., $r_c$. The transmittance around 30 GHz is highly sensitive to the length of the cross bars, i.e., $l_1$ and $l_2$. The resonance frequency of the MCSRR as well as the transmission amplitude around 20 GHz are highly sensitive to the variation of $w_1$ and $w_2$ (see Figure S5, Supporting Information).

After optimization, a meta-atom featuring both high transmission efficiencies and independent $2\pi$ phase modulations at the two preset frequencies is obtained. The parameters are finally fixed as: $l_1 = 1.9$ mm, $l_2 = 1.6$ mm, $l_3 = 0.2$ mm, $l_4 = 0.9$ mm, $w_1 = 0.4$ mm, $w_2 = 0.2$ mm, $r_1 = 1.4$ mm, $r_2 = 2$ mm, $r_3 = 2.4$ mm, $r_c = 0.4$ mm, and $P = 4.95$ mm. As the width of all the bars, the arcs and the slots are fixed as 0.2 mm, the number of parameters that need to be optimized has already been greatly reduced. The period of the meta-atom, i.e., $P$ is fixed smaller than half wavelength to avoid grating lobes appearance. Although the rich geometric parameters might increase the complexity of the optimization process of the proposed meta-atom, it also provides a high degree of freedom in meta-atom design.

Figure 2a (Figure 2b) depicts the geometric phase shift at $f_1 = 20$ GHz ($f_2 = 30$ GHz) of the transmitted RHCP wave by rotating $\theta_1$ ($\theta_2$) with a fixed $\theta_2$ ($\theta_1$) under the incidence of LHCP plane wave. It is seen from Figure 2a (Figure 2b) that the phase shift varies almost linearly with the rotation of $\theta_1$ ($\theta_2$) and the full $2\pi$ phase coverage could be achieved at $f_1$ ($f_2$) by varying $\theta_1$ ($\theta_2$) from 0 to $\pi$. The variation of $\theta_1$ ($\theta_2$) shows very little influence on the transmission phase shift at $f_2$ ($f_1$). Additionally, Figure 2c (Figure 2d) presents that a high cross-polarized transmission amplitude higher than 0.8 (0.9) could be maintained at $f_1$ ($f_2$) except for some slight fluctuations. Therefore, Figure 2 certifies the proposed meta-atom could provide independent $2\pi$ phase controls at the two preset frequencies with high transmission efficiencies. It should be noted that the $2\pi$ phase coverage is achieved by rotating the resonator with an angle of $\pi$, as indicated by the Berry phase principle. The highly independent phase modulating capability of the proposed meta-atom is attributed to low coupling between the MJCR and the MCSRR. The low coupling is mainly due to the different resonance types of the two resonators, respectively.

For array formation, the angle stability of the proposed meta-atom is investigated by HFSS. As described in ref. [13], for the metalens with Fourier phase profile, the effective aperture keeps as a shape of circle with radius of $F$. Hence the largest effective incidence angle for the meta-atom on the metalens is arctan ($F/R$) = 45°. Figure 3 plots the transmission phase as a function of the incidence angle at two bands, and the maximum phase fluctuation of about 39° and 38° are recorded, respectively. Although such phase fluctuation deteriorates the ideal phase distribution, the focused efficiency is still acceptable because the gradual phase distribution of the transmission wave is maintained.

![Figure 2](image-url)  
Figure 2. a,b) The geometric phase shift at $f_1 = 20$ GHz by rotating $\theta_1$ with a fixed $\theta_2$ and $f_2 = 30$ GHz by rotating $\theta_2$ with a fixed $\theta_1$ under illumination of LHCP plane wave. c,d) The corresponding cross-polarized transmission for (a) and (b).
To verify the property of the proposed dual-band meta-atom, one dual-band beam scanning metalens is designed and simulated. Firstly, the required phase profile of the metalens for achieving wide FoV is discussed.
Two genetic illustrations of the light path that passes through metalens with different phase profiles are presented in Figure 4a, b. Assuming that both metalens are illuminated by normally and oblique incident monochromatic light in succession. For the metalens populated with the parabolic phase distribution in Figure 4b, the normal incidences could be converged well to the focal plane, but the oblique incidences are converged off the focal plane due to the obvious spherical aberration. While for the one with Fourier phase distribution in Figure 4a, both the normal and oblique incidences could be well converged to the focal plane.\[31\] Hence the FoV of the metalens is effectively extended due to the aspherical property of Fourier phase distribution. Formula of such phase distribution can be derived from a general case of oblique incidence by geometry optics (GO) method.\[32\]

\[
\phi = \frac{kr^2}{2f}
\]

where \( k \) is the free space wave number at the operating frequency, \( r \) is the distance from the meta-atom to the center of the metalens, and \( f \) is the focal length.

As a proof-of-concept demonstration, one metalens composed of 27 \( \times \) 27 meta-atoms is designed and simulated. The focal length is set as \( F_1 = F_2 = 28 \) mm at both frequencies. The discrete phase profiles of the metalens at \( f_1 \) and \( f_2 \) are depicted in Figure 4c,d, respectively, where 3-bit phase modulation is adopted into the phase discretization. A gradient distribution of the color map could be observed at both figures. The focusing performance of the metalens is studied by full-wave simulations via HFSS. In the simulations, the metalens is placed on the xoz plane and the LHCP plane wave with tilt angles of 0° and 60° is applied to illuminate on the metalens. The observing plane is chosen to locate on the xoz-plane with a size of 50 \( \times \) 60 mm\(^2\) at the focal length. The simulated electric-field intensity on the observing plane at \( f_1 \) (\( f_2 \)) is depicted in Figure 4e (Figure 4f). Hot spots in the two figures indicate good focusing performances of the metalens at both frequencies even with a tilt angle of 60°. Moreover, obvious horizontal shifts of the focal spot could be observed in both Figure 4e,f. According to Equation (1), the theoretical value of foci offset for both frequencies is 24.2 mm. The simulated foci offset at \( f_1 \) is 25 mm, which is close to the theoretical value of 24.2 mm. For the case at \( f_2 \), the simulated foci offset is found to be 26 mm, slight larger than the theoretical value of 24.2 mm. The slight discrepancy between the simulated the theoretical value of foci off-set could be caused by the property of the meta-atoms under oblique incidences.

The beam scanning function of the metalens is verified by using the HFSS. In the simulations, the metalens is placed on the xoy plane and the feed source is located on the focal plane and horizontally translated along the x-direction. The simulated radiation patterns at 19, 20, 21, 29, 30, and 31 GHz is plotted in Figure 5a–f, respectively. As seen in each figure, nine radiation beams pointing to different directions are all normalized to the maximum value of the broadside beam, and each beam direction corresponds to a predesigned feed displacement. To get a clearer view on the scanning performance at two central frequencies, main indicators are summarized in Table 1, where \( \alpha_{beam} \) is the main beam pointing direction, \( G \) is the gain and \( \Delta G \) is

![Figure 5](image-url). The simulated radiation patterns at a–f) 19, 20, 21, 29, 30, and 31 GHz.
the scan loss (SL). It should be noted that although radiation pattern is displayed in a normalized form, the absolute values of the simulated gain at broad side direction are provided in Table 1. For the sake of simplicity, $x = 0$ mm is defined as the original position of the feed. As the feeds are placed at the original position, the simulated gains of the lens antenna at $f_1$ and $f_2$ are 18.9 and 17.7 dBi, respectively. The gain enhancement for two bands is found to be 13.5 and 12.1 dB, respectively, as compared with the gain of the corresponding feeds (i.e. 5.4 and 5.6 dBi). As the feed is displaced $x = -40$ mm to $x = 40$ mm, the radiation beam could be scanned from $60^\circ$ to $-60^\circ$ at $f_1$. While for the case at $f_2$, the radiation beam could be steered to $\pm 15^\circ$, $\pm 30^\circ$, $\pm 45^\circ$, $\pm 60^\circ$ when the feed is positioned at $x = \pm 9$ mm, $\pm 18$ mm, $\pm 25$ mm, $\pm 30$ mm, respectively. For the maximum beam steering angle, the simulated SL is found to be 3.7 dB (3.5 dB) at $f_1$ ($f_2$). It should be noted that although the proposed metalens is optimized at $f_1$ and $f_2$, the beam scanning function within the coverage of $\pm 60^\circ$ could be well achieved with a fractional bandwidth of about 10% and 6.7% for bands centered around $f_1$ and $f_2$, respectively.

To experimentally verify the performance of the proposed dual-band metalens, one prototype is fabricated and characterized. Figure 6c shows the photo of the fabricated metasurface by using standard printed circuit board technique. Both the dielectric substrate and the metallic layer extend 30 mm beyond the total meta-atom array to leave a gripping area for the measurement, as shown in Figure 6d. The far-field measurement setup in the anechoic chamber is shown in the left of Figure 6a, where a standard gain horn antenna operating from 18–40 GHz, a Vector Network Analyzer (PNA N5227A), and CP

| Position | $\alpha_{\text{beam}}$ E-plane at 20 GHz | $\Delta G$ [dB] | Position | $\alpha_{\text{beam}}$ E-plane at 30 GHz | $\Delta G$ [dB] |
|----------|----------------------------------------|----------------|----------|----------------------------------------|----------------|
| 0 mm     | $0^\circ$ | 18.9 | 0 | 0 mm | $0^\circ$ | 17.7 | 0 |
| 11 mm    | $15^\circ$ | 18.4 | 0.5 | 9 mm | $15^\circ$ | 17.1 | 0.6 |
| 20 mm    | $30^\circ$ | 18.2 | 0.7 | 18 mm | $30^\circ$ | 16.2 | 1.5 |
| 30 mm    | $45^\circ$ | 17.5 | 1.4 | 25 mm | $45^\circ$ | 15.4 | 2.3 |
| 40 mm    | $60^\circ$ | 15.2 | 3.7 | 30 mm | $60^\circ$ | 14.2 | 3.5 |

Figure 6. a) Measurement setup in the anechoic chamber. b) The perspective view of the lens antenna. c–d) The top and zoomed views of the fabricated metalens.
patch antennas are used to characterize the fabricated meta-lens. The perspective view of the lens antenna is presented in Figure 6b. It is noted that a guide rail is etched on the supporting board to enable horizontal shift of the feed as well as to keep the distance between the feed and lens aperture equal to the focal length. Two corner truncated CP patch antennas with central operating frequencies of $f_1$ and $f_2$ are designed as the feed sources of the meta-lens.

Figure 7a–f presents the measured radiation patterns at 19, 20, 21, 29, 30, and 31 GHz, respectively. It can be observed that the $\pm 60^\circ$ beam coverage could be realized by translating the feed sources for all the frequencies. Table 2 summarizes the major performance indicators at $f_1$ and $f_2$. The maximum measured gains at $f_1$ and $f_2$ are 18.6 and 17.5 dBi, respectively. The SLs corresponding to the most tilted beams at $f_1$ and $f_2$ are 4 and 3.8 dB, respectively, which are slight larger than the simulated ones of 3.7 and 3.5 dB. It can be seen from Figure 5 and 7 that the measured results agree very well with the simulated ones. The small discrepancy between the measurement and simulation results could be caused by the measurement errors and fabrication tolerance. The total efficiency of such beam scanning system should be the produce of the four parts: the efficiency of the feed, the illumination efficiency, the spillover efficiency and the transmission efficiency of the meta-atom. It can be calculated by using equation of $\eta = \frac{G \lambda^2}{4 \pi A}$, where $A$ is the physical aperture of the TA, $G$ is the maximum broadside gain and $\lambda$ is the operating wavelength.

Different from traditional parabolic metalens that utilizes nearly whole aperture to scan the beam, the beam scanning function of proposed metalens with Fourier phase profile is achieved by horizontal shift of the effective radiation region. The effective radiation region in shape of circle occupies only 14.5% of the

![Figure 7. The measured radiation patterns at a–f) 19, 20, 21, 29, 30 and 31 GHz.](image)

| Position | E-plane at 20 GHz | E-plane at 30 GHz |
|----------|------------------|------------------|
|          | $\alpha_{\text{beam}}$ | $G$ [dBi] | $\Delta G$ [dB] | $\alpha_{\text{beam}}$ | Gain [dBi] | $\Delta G$ [dB] |
| 0 mm     | 0$^\circ$        | 18.6            | 0               | 0 mm     | 0$^\circ$        | 17.5          | 0               |
| 11 mm    | 16$^\circ$       | 18              | 0.6             | 9 mm     | 15$^\circ$       | 16.8          | 0.7             |
| 20 mm    | 31$^\circ$       | 17.7            | 0.9             | 18 mm    | 30$^\circ$       | 15.8          | 1.7             |
| 30 mm    | 46$^\circ$       | 17              | 1.6             | 25 mm    | 45$^\circ$       | 14.9          | 2.6             |
| 40 mm    | 60$^\circ$       | 14.6            | 4               | 30 mm    | 60$^\circ$       | 13.7          | 3.8             |

Table 2. Summary of measured results.
whole aperture consistently, while the aperture efficiency is calculated based on the whole metalens area. In other words, a small portion of radiation area inherently limits the total efficiency of such beam scanning system to a low level. It is also a trade-off between high efficiency and wide beam coverage, just as faced by works in.\cite{26} The measured efficiency of the proposed beam scanning system at 20 and 30 GHz is calculated to be 6.6\% and 2.3\%, respectively.

Furthermore, Table 3 compares the performances of the proposed metalens and some previously reported works in terms of center frequency, polarization, substrate layer, and scanning coverage. Although transmission coefficient greater than 0.8 could be achieved by all the proposed unit-cells, the metal shielding vias in refs. 28-29, the multilayer structure in ref. 27, and the air-spaced structure in ref.26 unavoidably add to the fabrication cost and processing complexities. In contrast, the cost of the proposed metalens is obviously reduced for the reason that only single-layer substrate is used. Although single-layer substrate is also used in refs. 13,16,30-32, none of them focus on the wide-angle beam scanning function at two bands simultaneously. Moreover, the scanning coverages in other works are less than 4.5°, which requires at least four sections for realizing the full 360° scanning. While the ± 60° beam coverage of this work is of great importance for achieving full 360° scanning with only three sections. Overall, the proposed metalens features a large scanning coverage, a minimalist substrate and the dual-band CP radiation characteristic, which could be beneficial for satellite communications.

### 3. Conclusion

To summarize, we have proposed a single-layered-substrate meta-atom for meta-devices featuring dual-band and wide-angle beam scanning functions. In spite of the high transmission efficiency, the whole 2π phase modulations could be individually realized at two arbitrary bands. As an illustrative example, a dual-band metalens fed by the CP patch antennas is designed, fabricated and measured, wherein ±60° beam coverages can be achieved at two preset satellite communication bands (i.e., 20 and 30 GHz) via translation of the feeds. The measured results agree very well with the simulated results. The wide scanning coverage together with only one-layer substrate structure makes the proposed method a promising candidate for beam scanning applications.

### Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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### Conflict of Interest

The authors declare no conflict of interest.

### Data Availability Statement

The data that support the findings of this study are available in the supplementary material of this article.

### Keywords

beam scanning, dual bands, metalens, ultrathin metalens

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**Table 3. Comparison between the proposed bilayer metalens and other similar works.**

| Study            | Center frequency [GHz] | Polarization | Substrate layers | Scanning coverage [°] |
|------------------|------------------------|--------------|------------------|-----------------------|
| Ref. [13]        | 19                     | CP           | 1                | ±60                   |
| Ref. [14]        | 26                     | CP           | 2                | ±33                   |
| Ref. [16]        | 10.1                   | LP           | 1                | ±48                   |
| Ref. [26]        | 20/30                  | CP           | 3                | ±26                   |
| Ref. [27]        | 20/30                  | CP           | 6                | [0, 50]               |
| Ref. [28]        | 16.5/33                | LP           | 4                | ±45                   |
| Ref. [29]        | 19.5/30                | LP           | 3                | ±20                   |
| Ref. [30]        | 20                     | CP           | 1                | /                     |
| Ref. [31]        | 8.3/12.8               | CP           | 1                | /                     |
| Ref. [32]        | 10                     | CP           | 1                | /                     |
| This work        | 20/30                  | CP           | 1                | ±60                   |

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