Heterogeneous amplitude-phase metasurface for distinct wavefront manipulation

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ABSTRACT:

Achieving simultaneously multiple distinct wavefront manipulations using a single flat plate is pivotal in increasing the integration level and information capacity of an optoelectronic system. As of today, the state-of-the-art metadevices have been devoted to multiple functionalities by imparting two independent phase patterns triggered at two orthogonal polarization states. However, in fact, it is terribly challenging to realize individual amplitude-phase ($A$-$P$) control by using an anisotropic metasurface. Here, we demonstrate a heterogeneous strategy for achieving an $A$-$P$ manipulation by utilizing heterogeneous indium-tin-oxide (ITO) resistive films and metal patterns. By synergizing dual-layer ITO films and a sandwiched dual-mode metallic layer on a back metallic ground, the proposed meta-atom exhibits near-zero and near-unity reflections for dual orthogonal linear polarizations. Above feature can be utilized to trigger polarization-dependent functionalities by uniformly and inhomogeneously distributing the ITO and metallic pattern, respectively. Using this proposed architecture, we implement two metasurfaces with integrated radiation-absorption and integrated diffusion-absorption function. Both numerical and experimental results demonstrate that two well-designed metadevices enable to achieve a similar broadband absorptivity (above 90% within 7.8–18.5 GHz) but completely distinct wavefront manipulations triggered by two polarizations. Our heterogeneous metasurface concept paves the way towards realizing high-performance multi-functionalities with complex wavefront manipulation capabilities.
INTRODUCTION

Metasurfaces, a two-dimensional equivalence of metamaterial, have gained numerous research interests by their powerful electromagnetic (EM) wave manipulation capability [1]-[6]. With their constituent sub-wavelength meta-atoms arranged over a two-dimensional plane, metasurfaces are able to impart arbitrary wavefront manipulation for any EM wave [7]-[10]. Currently, metasurfaces have been employed in an array of applications including imaging and hologram [11], vortex beam generation [12], RCS reduction [13]-[16], ultra-thin cloak [17], [18], polarization manipulation [19]-[21], information encoding [22] and many other advanced functionalities [23]-[25]. Although excellent wavefront manipulation can be achieved by controlling phase, conventional implementations of gradient metasurfaces are typically narrow band and cannot sustain their performance over practical spectral bandwidth. To address above fundamental question, some approaches to design achromatic wavefront manipulation metasurface were proposed and verified [26]-[27]. To achieve an intelligent control, smart metasurfaces with self-adaptively reprogrammable functions were proposed [28]. In addition, some EM functionalities were also achieved by tunable metasurfaces, such as focusing [29] and vortex beam generation [30]. To further increase the integration level and information capability of an optoelectronic system, some full-space manipulation metasurfaces [31] were designed and demonstrated. Recently, some polarization-sensitive bifunctional metasurfaces have been implemented, which enable two distinct wavefront modulation dependent on distinct incident polarizations [32]-[38]. Nevertheless, most aforementioned bifunctionalities realized by imparting individual dual spatial phases at two linearly polarized (LP) or circularly polarized (CP) channels, were still only applicable for phase-only EM wave manipulation.
In addition to phase control, the amplitude manipulation as another crucial degree of freedom (Dof) of EM wave, has been widely adopted in absorbers [40]-[45] and other related applications [46]. Although fruitful progress has been achieved for A-P manipulations [47], [48], they were mostly implemented only under one LP channel. Chiral metasurfaces were demonstrated as a promising candidate for individual A-P control in two spin states [49], [50], nevertheless they suffer from considerably narrow bandwidth. To the best of our knowledge, the individual A-P control under two orthogonal LP states is rarely reported, which made the metadevices with polarization-dependent A-P manipulation still elusive and in its infancy, not to mention the A-P control in a heterogeneous frame. The pressing task prompts us to integrate both amplitude and phase control in two LP channels to realize novel EM devices with a desirable bandwidth.

In light of the above challenging, here we propose for the first time a strategy by synergizing metallic and semiconductor meta-structures in a heterogeneous frame. The key paradigm is to sandwich dual-layer I-shape ITO resistive films orthogonally by a single-layer I-shape metallic resonator. The meta-atom exhibits different reflections dependent on the surface resistance ($R_s$) of ITO patch for polarization parallel to it due to the triggered ohmic loss [51]-[53]. While for orthogonal polarization, the metallic I-shape pattern manifests a near-unity reflection with substantial phase change through parametric variation, which is promising for wavefront shaping. For experimental demonstration, two types of heterogeneous metadevices composed of spatially varied meta-atoms were investigated. One device exhibits a polarization-selective broadband absorption for one LP state and quad-beam radiation for its orthogonal counterpart, whereas the other demonstrates a similar broadband absorption behavior but a uniform diffusive scattering pattern at the two orthogonal LP states. Our strategy successfully realizes separate A-P manipulation under two LP
channels, which distinguishes a lot from previously reported dual-phase metadevices \cite{32-38}. Such a distinct strategy promises many fascinating applications in stealth with polarization-shifted invisibility mechanism and should open up an alternative avenue for devices with multiplexed functionalities in high integration.

RESULTS AND DISCUSSION

1. Principle and heterogeneous meta-atom design

As is shown in Figure 1a, our proposed metadevice exhibits a broadband absorption behavior for \( x \) polarization while manifests an arbitrary pattern control (i.e., quad-beam radiation patterns and spatial diffusive patterns) under \( y \) polarization. The key to achieve above predicted functional patterns is to identify a collection of meta-atoms that enable distinct polarization-dependent birefringent EM response, i.e., \( A-P \) manipulation with negligible polarization cross-talking. To begin with, we first briefly introduce a basic principle to guide the design. For a co-polarization reflective meta-atom with mirror symmetry, its EM properties can be described according to diagonal Jones matrices \( R = \begin{pmatrix} r_{xx} & 0 \\ 0 & r_{yy} \end{pmatrix} \). Here, \( r_{xx} \) and \( r_{yy} \) denote the reflection coefficients with polarization along two principal axes \( x \) and \( y \), respectively. Here, we expect a controllable \( |r_{xx}| (|r_{yy}|) \) while requiring \( |r_{xx}| (|r_{yy}|) = 1 \) within a broad bandwidth. In such case, the system exhibits a controllable reflection amplitude for \( x(y) \)-polarized wave and a near-unity reflection for \( y(x) \)-polarized wave. Moreover, the reflective phase profile \( \phi_{yy} (\phi_{xx}) \) can be freely and individually adjusted by structural parameters. To the best of our knowledge, it is not easy to implement above criterion based on the resonate feature of a full metallic anisotropic meta-atom. In the following, we propose an alternative strategy using a composite scheme (metal & ITO), which is still of anisotropic geometry, to achieve separate \( A-P \) manipulation under two LP channels.

The basic building block utilized for \( A-P \) manipulation is depicted in Figure 1b, it is comprised...
of a backed metallic ground and three pattern layers (layer I, II and III from top to bottom) separated by two F4B spacers with a relative permittivity $\varepsilon = 2.65 + i0.001$, and $h_1$ and $h_2$ denote the substrate’s thickness. The continuous metallic ground is placed at the bottom to guarantee a reflection mode. To characteristic its EM behavior, finite-difference-time-domain (FDTD) calculations are performed in CST Microwave Studio. The I-shape ITO patch in layer I was oriented along $x$-axis and deposited on the polyethylene glycol terephthalate (PET) substrates with $\varepsilon = 3 + i0.003$ and thickness of 0.175 mm. It is maintained exactly the same as that in layer III to assist dual-mode broadband absorption (see Figure 1c) due to high ohmic loss of ITO and low dielectric loss of PET. As shown in Figure 1d, we expect a magnetic resonance and an electric resonance generated at low and high frequency, respectively, which is evidenced by the anti-parallel currents between layer I and III, and the parallel currents between layer I and ground. Consequently, layer I and III form a circulating loop for the incident magnetic field and a magnetic resonance is generated in the former case, whereas, the induced parallel currents between layer I and III resemble that of an electric dipole in the latter case, facilitating an electric resonance. For sharp comparison, the surface currents for other two meta-atoms containing only single layer ITO in layer I and III is analyzed in Supplementary Figure S1, supporting the proposed working mechanism.

The metallic structure utilized in layer II is a quasi-I-shaped pattern oriented along $y$-axis. It is composed of a metallic I and two metallic bars aside which assisted to generate dual operation modes and thus considerably extended phase cover and bandwidth, which has been verified by previous reported works [37]. Our alternative distribution of ITO patch and metallic pattern in different layers will suppress the crosstalk significantly, which completely distinguishes from previously reported anisotropic meta-atoms in full metallic scheme [35]. It is worth noting that due to the semiconductor characteristic of ITO, we can extend this design to achieve polarization-exchange functions for above polarization-dependent EM response by optimizing the surface resistance and geometric parameters, see Supplementary Figure S2.
To further gain a physical insight to the amplitude control under $x$ polarization, we study the meta-atom from the perspective of transmission line (TL) theory. Since the methods describing resonant mode of metallic pattern are well established by a series of equivalent circuit model (CM) \cite{38}, here we only retrieve the equivalent CM for dual-layer ITO on a backed ground (Figure 2a), as shown in Figure 2b. The dual-layer ITO is modeled by a parallel connection of two series connected resistance ($R$) and inductance ($L$), while the dielectric substrate and bottom ground are characterized by a TL section and an equivalent short, respectively. The $R_1$ ($R_2$) and $L_1$ ($L_2$) denote equivalent resistances and inductances of ITO in layer I (III), respectively. The $C_1$ represents the sum of capacitive coupling between the layer I and III, and that between layer I and ground, while $C_2$ represent the capacitive coupling between the layer III and ground. These circuit parameters are then determined by using a curve fitting technique in ADS to match the FDTD calculated scattering parameters. As shown in Figure 2c, the CM calculations are in good agreement with the full-wave simulation, which strongly validates the reasonability of the established CM. Moreover, as expected, the reflectivity decreases as $R_s$ increase from 5 $\Omega$/sq to 35 $\Omega$/sq owing to high ohmic loss induced by the resistive film, indicating controllable reflection amplitude ($A$ manipulation) can be achieved by changing $R_s$. When $R_1$ is selected as 35 $\Omega$/sq, the reflectivity is less than -10 dB within 7.8~18.5 GHz, indicating a broadband absorptivity according to $A = 1 - |S_{11}| - |S_{21}|$.

For $y$ polarization, the I-shape metallic pattern orienting along $y$-axis is expect to manipulate individually a controllable reflection phase ($\varphi_{yy}$). Since the ITO patch not only dissipates the scattered energy under $x$ polarization but also decreases the reflection rate under $y$ channel, in the following we not only concentrate on the controllable $\varphi_{yy}$ but also the near-unity reflection amplitude $r_{yy}$ to ensure the metadevice’s high-efficiency. Numerical results show that $r_{yy}$ degrades as the width of ITO increases and the effect of the ITO bar to $r_{yy}$ is negligible by controlling the width of it within an appropriate value (i.e., $w_2 \leq 0.8$ mm), see Supplementary.
Figure S3. Nevertheless, $w_2$ cannot be infinitely small otherwise the absorption in $x$ channel will be discounted (i.e., $0.6 \leq w_2 \leq 1$ mm to guarantee a broadband absorption of more than 90%). As shown in Figures. 2d-2f, the reflection phase $\varphi_{yy}$ cover is only 150° by altering length ($a$) from 4 to 8 mm when only a bare I-shape metallic pattern is adopted. However, a full $2\pi$ phase cover is fulfilled when two short metallic bars are added along two sides of I pattern as $a$ varies from 4 to 8 mm, as shown in Figures. 2g-2i. Therein, dual operation modes, i.e., principal and parasitic modes are formed at low and upper frequency bands, facilitating a low quality-factor resonator. Such a mode-cascading strategy has significantly broken the initial dispersion and enhanced the bandwidth at upper frequency, and the relevant theory has been demonstrated in [39]. As a consequence, we observe a high reflection rate ($r_{yy} > 0.9$) and a satisfied phase cover. In the following, we select the dual-mode I-shape pattern to engineer the predesigned spatial phase profile under the incidence of $y$-polarized wave.

2. Design of polarization-selective heterogeneous metadevice

In this section, we implement two polarization-selective heterogeneous metadevices based on the merit of individual $A-P$ manipulation in two orthogonal LP states and the meta-atom library established in Figure. 2i. Both FDTD calculations and microwave experiments of far-field and near-field results are performed to characterize their performance. Detailed numerical and experimental setup can be referred to Supplementary Figure S4 and Figure S5, respectively.

2.1 Radiation-absorption integrated metadevice design

Recently, an increasing demand has been devoted to the design of multi-beam antenna arrays \cite{38}, \cite{54}, \cite{55}. Here, as a demonstration of the above concept, we design an integrated metadevice that is capable of high-directive quad-beam emissions (reflectarray) with uniform intensity under $y$ polarization state and complete broadband absorption in $x$ polarization channel by employing aforementioned meta-atom. Such a scenario is indeed a fact of gaining invisibility to an antenna, where the scattering under the polarization orthogonal to that of antenna is typically extremely large.
Since the excited amplitude of each meta-atom is determined by the feeding source \( \cos^4(\theta) \), here, \( q = 8.6 \) is the modulation factor of the beam) and its location \([58]\), we only adopt a phase-only synthesis approach to engineer the spatial phase profile of the multi-beam reflectarray. In such case, the alternating projection method (APM) is utilized to synthesize the phase pattern. The main purpose of utilizing APM to optimize the aperture phase distribution of quad-beam reflectarray is to search for the intersection between two sets, \( i.e., \) the set of possible far-field radiation patterns (set \( A \)) and the set of the target idealized patterns (set \( B \)), by employing a closed-loop iterative procedure. Here, to improve high directivity of main beam and suppress the side-lobe level, two mask requirements need to be satisfied \([38][59]\).

The quad-beam reflectarray is composed of \( 28 \times 28 \) meta-atoms and occupies a square area of side length \( D \) of 238 mm. The designed frequency is targeted at \( f_0 = 12.5 \) GHz. A \( y \)-polarized conical feed horn containing a standard X-band BJ-100 waveguide and an open-end tapered waveguide with an aperture of \( 44 \times 24 \) mm is positioned \( F = 142 \) mm away above the metasurface (see Supplementary Figure S4). Such a configuration is very beneficial to avoid the spillover radiation. For the convenience of experimental characterization without loss of generality, four pencil beams with uniform amplitude are directed to \((\varphi, \theta) = (0^\circ, 30^\circ), (90^\circ, 30^\circ), (180^\circ, 30^\circ), (270^\circ, 30^\circ)\).

The theoretically calculated radiation pattern and phase distribution are shown in Figure 3a. It can be clearly seen that the desired quad pencil beams are precisely directing toward four distinct directions at \( f_0 \). Moreover, the side-lobes remained a satisfied low level of below -30 dB, indicating effectiveness of our approach. According to the phase pattern, we readily construct the final reflectarray layout based on an automatic phase mapping according to the established meta-atom library shown in Figure 2i. For experimental characterization, we utilize standard printed circuit board (PCB) technology and commercially available ITO resistive patch to fabricate the sample.
occupying an area of $238 \times 238 \text{ mm}^2$, as shown in Figure 3b. As portrayed in Figure 3c, four highly directive pencil beams with uniform intensities are clearly observed at $f_0$ from FDTD calculated 3D radiation pattern, coinciding well the theoretically calculated patterns shown in Figure 3a. Detailed cross-section radiation patterns are quantitatively described in Figure 3d, where a reasonable agreement of results is observed between the FDTD calculations and experiments. Two main beams are symmetrically directing toward two distinct directions ($\theta = \pm 30^\circ$) in two principal planes and the level of side-lobes is better than −10 dB at $f_0$. The physics for the quad-beam radiation lies in the efficiently formed four spots with highly localized fields, see the measured field map depicted in Figure 3e. The far-field and near-field patterns of reflectarray at others frequencies can be found in the Supplementary Figure S6, in where almost the same radiation behavior was observed within 12~13.5 GHz. In addition, we can also select other frequency as the target $f_0$ by the same strategy according to practical applications, which is also a solid evidence to broadband wavefront manipulations. As shown in Figure 3f, the peak gain and aperture efficiency ($\eta$) are 20.8 dB and 38% at $f_0$ according to $\eta = \sum \lambda^2 G_i / 4\pi A$ ($N$ denotes the number of beams and $A$ is the aperture area).

The aperture efficiency degrades as the frequency goes beyond $f_0$. The undesirable reflection modes induced by the distorted phase profile gives rise to the efficiency deterioration.

Under x-polarized state, since the ITO patch exhibits resistance $R_s$, the incident EM wave can be absorbed owing to strong ohmic loss. Therefore, a broadband absorption behavior is expected by selecting appropriate $R_s$ according to the reflectivity shown in Figure 2c. Here, the dual-layer ITO pattern with $R_s = 35 \Omega/\text{sq}$ is homogeneously arranged on the layer I and III of metadevice. The width ($w_2$) and length ($l$) of dual-layer ITO bar is designed as 0.8 and 8 mm, respectively, aiming to reduce the absorption effect of the ITO bar to $r_{yy}$ and achieve a broadband absorption. As shown in Figure 3g, the scattered energy is considerably dissipated by examining the extremely weak FDTD calculated $E_x$ intensities above the metadevice with respect to that of the equal-sized flat

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PEC sheet. As depicted in Figure 3h, it’s obvious that the backward RCS of our designed metadevice has a significantly reduction of more than 10 dB. As shown in Figure 3i, numerical and experimental results coincides well, indicating a broadband absorptivity above 90% within 7.8~18.5 GHz (a fractional bandwidth of 81.2%). A slight deviation between measured and calculated results are possibly induced by the finite size effect, fabrication errors and experimental instrument limitations. In a word, all results verify the predesigned dual functionalities of the metadevice under both polarization states, which promises great potentials in stealth of a multibeam antenna in a desirable bandwidth.

2.2 Diffusion-absorption integrated invisible metadevice design

Integrating versatile invisibility of different mechanisms in one single metadevice is vital and yet is rarely reported. Here, we proposed a metadevice that is capable of achieving polarization-shifted invisibility mechanism under two orthogonal LP states. For \( y \)-polarized wave, the random phase profile shown in Figure 4a is utilized to realize the near-uniform diffusive scattering. Here, we utilize MATLAB to generate a random matrix with a dimension of \( 28 \times 28 \) within 0~360° as the random phase profile of metasurface. It is worth noting that due to the fact that diffusive scattering performance is insensitive to accurate random phase distribution, such a performance can be also expected at other frequencies, which is beneficial for a broadband RCS reduction. While at its orthogonal polarization state, similar broadband absorption behavior is achieved. Here, similar design method as that of the first heterogeneous metadevice is adopted to engineer the metadevice layout shown in Figure 4b. As expected in Figure 4c, our metadevice redistributes the scattering waves uniformly toward countless directions in the whole upper half-space, significantly reducing the backscattering of metadevice with respect to that of the equal-sized flat PEC sheet. The metadevice reduces both monostatic and bistatic RCS by more than 10 dB in a broad band within 8~19.2 GHz (a fractional bandwidth of 80%), see Figure 4d. As shown in Figure 4e, experimental results correspond well with the FDTD calculations, which confirms the low-scattering behavior.
within 8~19.2 GHz and a broadband wavefront manipulation. The slight deviation was attributed to
the finite size effect and inevitable fabrication tolerances. As expected in Figure 4f, the near-field
intensity \( E_x \) in xz plane above our metadevice is significantly weaker than that of the equal-sized
PEC sheet. Therefore, we envision a significantly reduced far-field backward scattering of our
metadevice by more than 10 dB relative to the PEC sheet, see Figure 4g. The consistent FDTD and
experimental results in Figure 4h indicate an absorptivity above 90% bandwidth within 7.6~18.5
GHz (a fractional bandwidth of 83.5%). In a word, the almost constant absorption behavior under
\( x \)-polarized wave for the two metadevices exhibiting two completely distinct wavefront controls at
\( y \)-polarized state further illustrate a solid evidence of polarization-independent \( A-P \) manipulation
with low cross-talking.

CONCLUSIONS

We have proposed and successfully demonstrated a strategy for individual \( A-P \) control based on
heterogeneous hybrid material of ITO and metallic pattern at two orthogonal LP states. The
different mechanism relative to available full metallic birefringent metasurface is studied based on
equivalent circuit model and current distributions. The individual \( A-P \) control under two
polarizations can be employed for distinct functionalities. As a proof of concept, two well-designed
heterogeneous metadevices that exhibit similar broadband absorption at one polarization but
completely distinct wavefront manipulations at the orthogonal polarization were experimentally
demonstrated. Both numerical and experimental results show that our strategy is able to achieve
predesigned functions with high efficiency and broad operation band under two orthogonal
polarizations. The amplitude-assisted control opens new possibilities and degrees of freedom for
novel polarization-dependent metadevices with complex bifunctionalities.

METHODS

Numerical section

All numerical designs and characterizations are performed through FDTD simulations in
Full-wave simulation software CST Microwave Studio. As shown in Figure S4a, in calculations of
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the reflection phases/amplitude of the metasurface, we only calculate the basic meta-atom with unite cell boundary conditions imposed at its four bounds, and with a Floquet port placed at a distance 20 mm away from the meta-atom plane. Here, the surface resistance of the ITO can be modelled by an ohmic sheet in CST and can be assigned to arbitrary value. In $z$ direction, the electric boundary ($E_z = 0$) is applied to emulate the PEC ground plane. In Figure S4b, to investigate near-/far-field characterizations, open boundary is applied at metadevice’s four bounds of plane. The quad-beam emission is generated by illuminating the metadevice with a $y$-polarized feed horn placing above it, see Figure S4c. The distance between feed horn and metadevice center is $F=142$ mm, which is beneficial to avoid much spillover from the source.

**Experimental section**

Figure S5 shows the experimental setup for far-field and near-field measurements. All EM signals were recorded through an AV3672B vector network analyzer. In far-field measurements, the feed horn was aligned with the metadevice, and rotated freely. To ensure the accurate position of the feed horn, the feed horn is fixed at the center of a foam plate with the same size as metadevice and the parallel distance between the foam plate and metasurface is $F$. The feed horn and metasurface were fixed on a foam platform rotated freely along foam’s axial center, as shown in Figure S5a. A $y$-polarized standard-gain horn working in 8–18 GHz is selected as receiver placed 10 m away from the sample to record the far-field signals. In near-filed measurements, the metadevice and feed horn were fixed with a distance of $F$. A 6 mm-long monopole antenna was selected as a receive placed 70 mm away from the feed horn and connected with a 2D electronic step motor which can move automatically in a maximum area of 0.4 m×0.4 m with a step resolution of 5 mm (see Figure S5b.). The local $E_y$ field was recorded (with both phase and amplitude) by distributing the monopole along $y$ axis.

**ASSOCIATED CONTENT**

**Supporting Information**

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Current distribution of two meta-atoms with single-layered ITO; effect of $w_2$ on $|r_{xx}|$ and absorption; additional results for quad-beam emission

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Figure 1. Illustration of the (a) schematic functionality of our metadevice based on the basic building block shown in the inset. (b) Geometry of the anisotropic meta-atom. The meta-atom is comprised of a backed metallic ground and three pattern layers (layer I, II and III from top to bottom) separated by two F4B spacers. The layer I and III contain exactly the same I-shape ITO pattern placed on PET substrate, while the layer II is a metallic dual-mode I-shape pattern (bottom panel). The other parameters are listed as: $p = 8.5$, $H = 3.35$, $h_1 = 1$, $h_2 = 2$, $g = 0.2$, $w_1 = 0.4$, $t = 2.4$, $w_2 = 0.8$ and $l = 8$ (unit: mm). FDTD calculated (c) reflection coefficient and (d) current distributions on dual-layer ITO and ground under x-polarized wave normal incidence for $R_\text{s} = 35 \Omega/$sq.
Figure 2. The EM behavior for our proposed different meta-atoms of (a-c) type I, (d-e) type II and (g-i) type III. (a) Layout of the meta-atom I with double-layer ITO. (b) Equivalent circuit model. (c) Comparison of reflection spectrum between FDTD calculation and circuit simulation under \(x\)-polarization for different \(R_s\). Layouts of the (d) meta-atom II with bare I-shape metallic pattern in layer II and (g) meta-atom III with composite dual-mode metallic pattern in layer II. FDTD calculated reflection amplitudes of (e) meta-atom II and (h) meta-atom III for different \(a\) under \(y\)-polarization. FDTD calculated reflection phase of (f) meta-atom II and (i) meta-atom III as functions of \(a\) under \(y\)-polarization at 12.5 GHz.
Figure 3. Characterization of the radiation-absorption integrated metadevice by integrating (c-f) quad-beam radiation and (g-i) broadband absorption under normally incident $y$- and $x$-polarized wave, respectively. (a) Theoretically synthesized radiation pattern (left panel) and aperture phase distribution (right panel) for the quad-beam reflectarray. (b) Magnified view of the final fabricated sample. (c) FDTD calculated 3D far-field radiation patterns at $f_0$. (d) Comparison of FDTD calculated and measured cross-section radiation patterns in xz plane (H plane) and yz plane (E plane). (e) Measured near-field $E_y$ intensities in xy plane placed 70 mm away from feed horn at $f_0$. (f) Comparison of FDTD calculated and measured gain and aperture efficiency. FDTD calculated (g) near-field $E_x$ intensities and (h) far-field cross-section scattering patterns in xz plane for both the metadevice and equal-sized flat PEC at 16 GHz. (i) Comparison of FDTD calculated and measured absorptivity.
Figure 4. Characterization of the polarization-shifted invisible metadevice with two distinct mechanisms under (c-e) y-polarized and (f-h) x-polarized normally incident EM wave. (a) Rand phase distribution. (b) Magnified view of the final fabricated sample. FDTD calculated (c) 3D scattering patterns of the metadevice (top panel) and equal-sized flat PEC (bottom panel) at 10, 13 and 16 GHz and (d) comparison of monostatic and bistatic RCS reduction. (e) FDTD calculated and measured monostatic RCS reduction. FDTD calculated (f) near-field $E_x$ intensities and (g) far-field cross-section scattering patterns in xz plane for both the metadevice and equal-sized flat PEC at 16 GHz. (h) FDTD calculated and measured absorptivity.

This work demonstrates a heterogeneous strategy for achieving an amplitude-phase ($A$-$P$) manipulation by utilizing heterogeneous indium-tin-oxide (ITO) resistive films and metal patterns. Both numerical and experimental results demonstrate that two well-designed metadevice enables to achieve a similar broadband absorptivity (above 90% within 7.8~18.5 GHz) but completely distinct wavefront manipulations triggered by two polarizations.

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