Supplemental Document

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Supporting Information

Helicity-dependent metasurfaces employing Receiver-Transmitter meta-atoms for full-space wavefront manipulation

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1 Theoretical analysis of the meta-atom

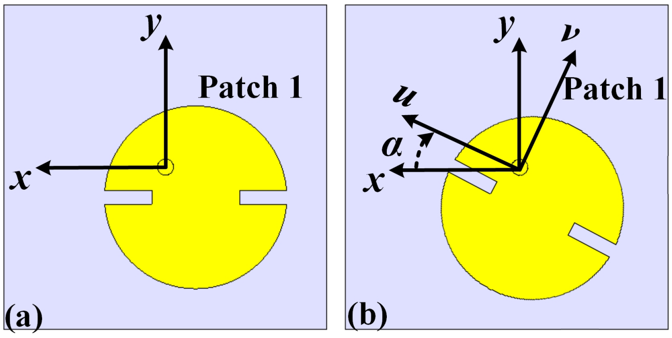

Fig. S1 Theoretical analysis of the meta-atom. (a) Receiver Patch 1 before rotation under *x*/*y* axis. (b) Receiver Patch 1 after rotation under *u*/*v* axis

Here, it can be assumed that an incident LCP wave propagates along the +*z* direction. Then the incident wave's electric field can be described as:

$$\overrightarrow{E_i} = E_0(\hat{x} + j\hat{y})e^{-jkz}e^{-j\omega t} \tag{S1}$$

According to the antenna theory, the signal received by the Receiver Patch 1can be described as:

$$\overrightarrow{E_r} = E_0(\hat{x} + j\hat{y})e^{-jkz}e^{-j\omega t}e^{-j\phi_p} \tag{S2}$$

Where Φ_p is the accumulated phase transmitted from the radiated source by optical path. Meanwhile, the transmission phase from the Receiver Patch 1 (Port 1) to the waveport (Port 2) is denoted as

$$\phi_{m21}(\alpha)_{initial} = \omega t + \phi_p \tag{S3}$$

When the Receiver Patch 1 rotate clocklwise with α angle, the incident wave under *u*-*v* axis can be described as

$$\begin{aligned}\overrightarrow{E_i} &= E_0[(\hat{u}\cos\alpha - \hat{v}\sin\alpha) + j(\hat{u}\sin\alpha + \hat{v}\cos\alpha)]e^{-jkz}e^{-j\omega t} \\ &= E_0(\hat{u} + j\hat{v})e^{-jkz}e^{-j\omega t}e^{-j\alpha}\end{aligned} \tag{S4}$$

According to the antenna theory, the signal received by the Receiver Patch 1can be described as:

$$\overrightarrow{E_r} = E_0(\hat{u} - j\hat{v})e^{-jkz}e^{-j\omega t}e^{-j\alpha}e^{-j\phi_p} \tag{S5}$$

where Φ_p is the accumulated phase transmitted from the radiated source. Meanwhile, the transmission phase from the Receiver Patch 1 (Port 1) to the waveport (Port 2) is denoted as

$$\phi_{m21}(\alpha)_{goal} = \omega t + \phi_p + \alpha \qquad \text{(S6)}$$

Therefore, the phase gradient Φ_{m21} denoted as

$$\phi_{m21} = \phi_{m21}(\alpha)_{goal} - \phi_{m21}(\alpha)_{initial} = \alpha \qquad \text{(S7)}$$

Therefore, there is a phase gradient $\Phi_{m21}=\alpha$ when rotating the Receiver Patch 1 with the angle α. This is a key point for proposed meta-atom working in the transmission mode, which is very different from the PB theory.

2 Additional FDTD simulation of the designed meta-atom

The proposed meta-atom is composed of Receiver and Transmitter CP patch. For the Receiver CP patch, there are two choices: LCP and RCP. For the transmitter CP patch, can be LCP or RCP antenna. Therefore, there are four cases (Case 1, Case 2, Case 3, and Case 4) of receiver and transmitter can be denoted as **Table S1,** where r_{ij} represents the reflected wave when illuminating by *j*-polarization and receiving by *i*-polarization and t_{ij} represents the transmitted wave when illuminating by *j*-polarization and transmitting *i*-polarization Here, ＋and － denote the RCP wave and LCP wave, respectively.

For example, in Case 1, the receiver is a LCP patch antenna and transmitter is RCP patch antenna. In this case, the RCP incident wave can be reflected by Receiver and the reflected wave is still RCP wave. Therefore, r_{++} is achieved. Meanwhile, the LCP incident wave is received by the LCP Receiver (Patch 1) and is converted into guided wave signal. And then it passes through the metallized via-hole to the Transmitter (Patch 2). Due to the RCP Transmitter, the guided wave signal is radiated into RCP wave. Therefore, t_{+-} is achieved. The other cases (Case 2 , Case 3, and Case4) are depicted in **Table S1**.

Table S1 Combinations of Receiver and Transmitter

Transmitter \ Receiver	**LCP**	**RCP**
RCP	r_{++} t_{+-} (Case 1)	r_{--}, t_{++} (Case 3)
LCP	r_{++} t_{--} (Case 2)	r_{--} t_{-+} (Case 4)

Next, the Receiver-transmitter corresponding to **Table S1** is depicted in Fig. S2.

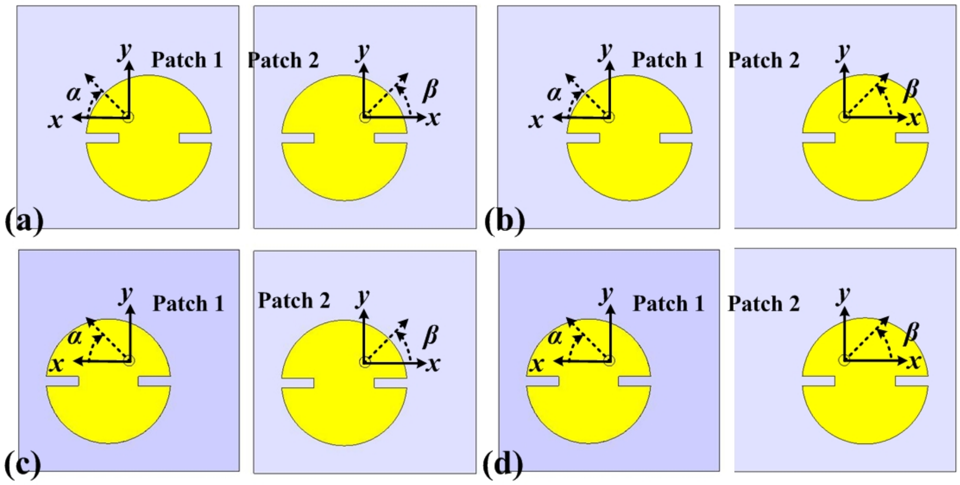

Fig. S2 Receiver and Transmitter combinations. (a) Case 1: LCP receiver Patch 1 and RCP transmitter Patch 2. (b) LCP receiver Patch 1 and LCP transmitter Patch 2. (c) RCP receiver Patch 1 and RCP transmitter Patch 2. (d) RCP receiver Patch 1 and LCP transmitter Patch 2.

Case 1 analysis:

For the Case 1, Receiver Patch 1 is a LCP patch and Transmitter Patch 2 is RCP patch. Therefore, RCP reflected wave and RCP transmitted wave can be obtained under the illumination of RCP and LCP incident wave. After that, the meta-atom is simulated and analyzed using FDTD. And the simulated results are shown in Fig. S3. From the Fig. S3, relative phase $\Phi(r_{++})$, phase Φ_{m21} of transmitted coefficient from Port 1 to Port 2, the phase Φ_{m32} of transmitted coefficient from Port 2 to Port 3, and transmitted phase $\Phi(t_{+-})$ can be described as:

$$\Phi(r_{++}) = -2\alpha \tag{S8}$$

$$\Phi_{m21} = \alpha \tag{S9}$$

$$\Phi_{m32} = \beta \tag{S10}$$

$$\Phi(t_{+-}) = \Phi_{m21} + \Phi_{m32} = \alpha + \beta \tag{S11}$$

To demonstrate the operation process of the reflection mode clearly, we scan α from 0° to 360° with *a* step of 22.5° while scan *β* from 0° to 360° with a step of 22.5°. The reflected phase and amplitude versus *α* and *β* are shown in Figs. S4 (a) and S4(b), respectively. At the same time, we can obtain the transmitted phase and amplitude versus *α* and *β* are shown in Figs. S4 (c) and S4(d), respectively. It is obvious that $\Phi(r_{++})$ is able to realize the range of -2*α* degree with *α* varying from 0° to 180° and $\Phi(r_{++})$

does not change with β varying from 0 to 360 degree in Fig. S4(a). It indicates that phase of reflected wave r_{++} is controlled only by α not β. Therefore, we can manipulate the phase of r_{++} by changing the α from 0° to 180° to obtain the reflected phase from 360° to 0°. Fig. S4(b) demonstrates that the amplitude of r_{++} is almost a constant about 0.95 with varying α and β, leading to manipulate wavefront of r_{++} with very high efficiency.

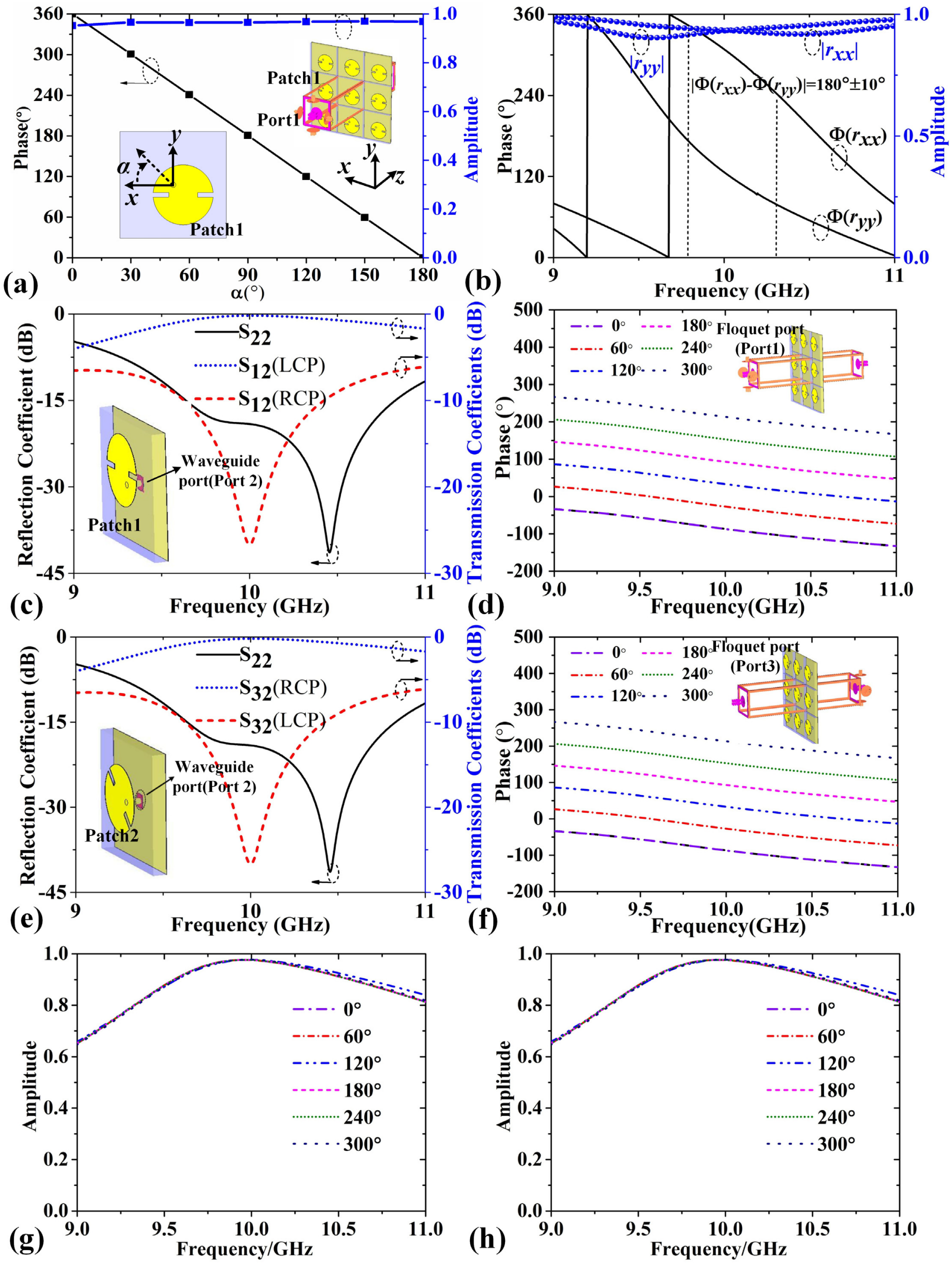

Fig. S3 FDTD simulation results. (a) The phase and amplitude of reflected wave under RCP plane wave illumination at 10GHz. (b) Amplitude and phase of reflected wave under x-polarized and y-polarized wave illumination. (c) Receiver Patch 1 characteristics: Reflection magnitude of S_{22} and transmission coefficients between Port 1 and Port 2. (d) Φ_{m21} with the rotation angle of α. (e) Transmitter Patch 2 characteristics: Reflection magnitude of S_{22} and transmission coefficients between Port 2 and Port 3. (f) Φ_{m32} with the rotation angle of β. (g) Transmission amplitude from Port 1 to Port 2 when rotating angle of α. (h) Transmission amplitude from Port 2 to Port 3 when rotating angle of β.

To demonstrate the operation process of the transmissive mode clearly, we scan β from 0° to 360° with a step of 22.5° while scan α from 0° to 360° with a step of 22.5°. The transmitted phase and amplitude versus α and β are shown in Figs. **S**4(c) and S4(d), respectively. Fig. S4(c) demonstrates that $\Phi(t_{+-})$ can cover the range of 0°-360° by rotating α, or β, or both of them. More interesting, the same $\Phi(t_{+-})$ can be achieved by totally different combinations of rotation angle α and β, which means our receiver-transmitter meta-atom can control the CP waves with different chirality freely in the full space. And $\Phi(t_{+-})$ agrees well with the theatrical one based on Equation (S9). As shown in Fig. S4(d), the amplitude of t_{+-} is almost a constant about 0.94 with the variation of α and β, which means a very high transmitted efficiency.

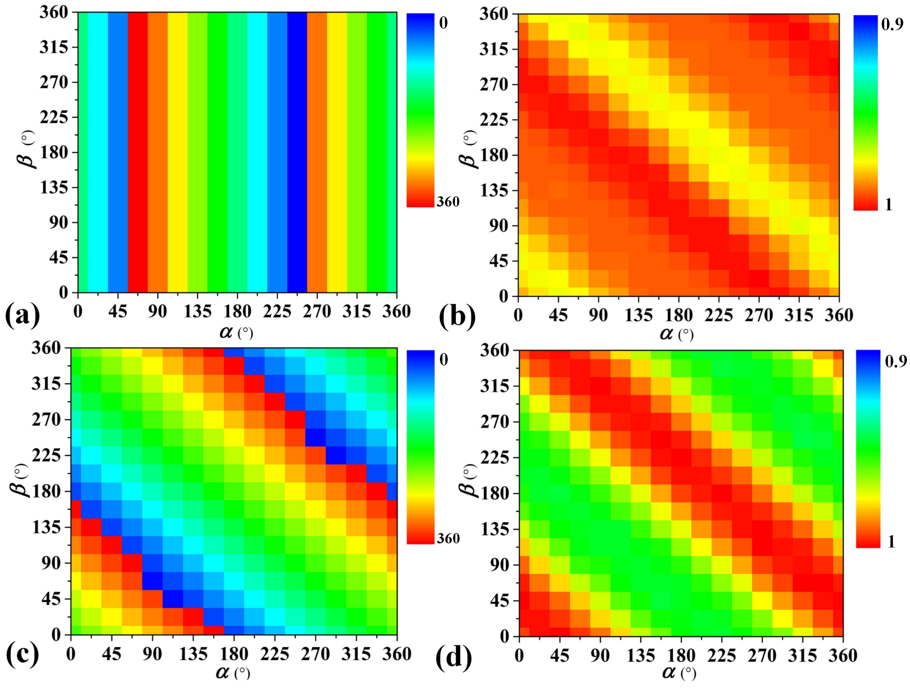

Fig. S4 Characteristics of the meta-atom with rotating the receiver patch1 and transmitter patch 2. (a) Phase of r_{++}. (b) Amplitude of r_{++} .(c) Phase of t_{+-} . (d) Amplitude of t_{+-}

Case 2 analysis:

For the Case 2, Receiver Patch 1 is LCP patch and Transmitter Patch 2 is LCP patch. Therefore, RCP reflected wave and LCP transmitted wave can be obtained under the illumination of RCP and LCP incident wave. According to the Case 1 analysis, the same methods are used to demonstrate the characteristics of meta-atom in Case 2. By FDTD simulation, reflected phase $\Phi(r_{++})$, phase Φ_{m21} of transmitted coefficients from Port 1 to Port 2, the phase Φ_{m32} of transmitted coefficients from Port 2 to Port 3, and transmitted $\Phi(t_{--})$ can be described as:

$$\Phi(r_{++}) = -2\alpha \tag{S12}$$

$$\Phi_{m21} = \alpha \tag{S13}$$

$$\Phi_{m32} = -\beta \tag{S14}$$

$$\Phi(t_{--}) = \Phi_{m21} + \Phi_{m32} = \alpha - \beta \tag{S15}$$

We scan α from 0° to 360° with a step of 22.5° while scan β from 0° to 360° with a step of 22.5°. The reflected phase and amplitude versus α and β are shown in Figs. S5 (a) and S5(b), respectively. At the same time, we can obtain the transmitted phase and amplitude versus α and β are shown in Figs. S5 (c) and S5(d), respectively. The simulated results are in good agreement with the theatrical calculation based on Equations (S12)-(S15).

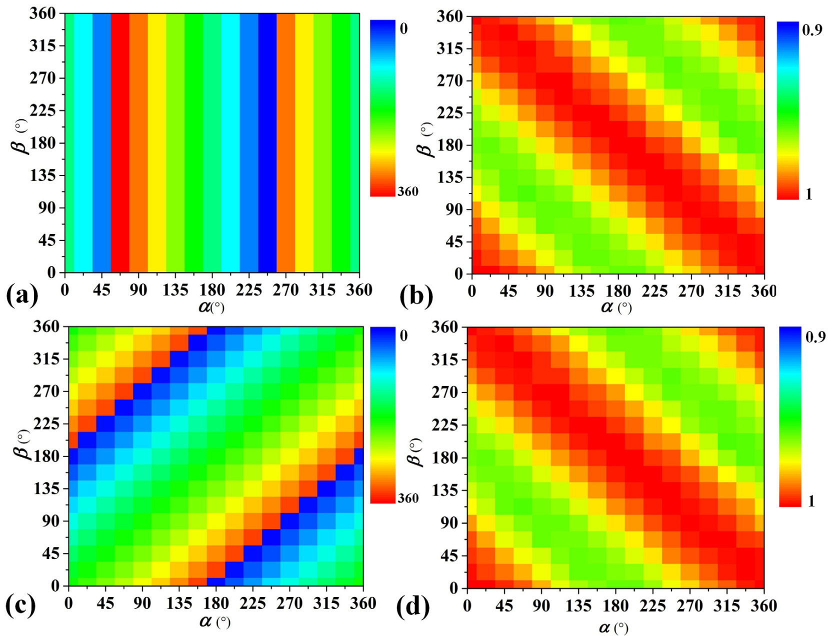

Fig. S5 Characteristics of the meta-atom with rotating the receiver patch1 and transmitter patch 2. (a) Phase of r_{++} . (b) Amplitude of r_{++} . (c) Phase of t_{--} . (d) Amplitude of t_{--}

Case 3 analysis:

For the Case 3, Receiver Patch 1 is RCP patch and Transmitter Patch 2 is RCP patch. Therefore, LCP reflected wave and RCP transmitted wave can be obtained under the illumination of LCP and RCP incident wave According to the Case 1 analysis, the same methods are used to demonstrate the characteristics of meta-atom in Case 3. Reflected phase $\Phi(r_{--})$, phase Φ_{m21} of transmitted coefficient from Port 1 to Port 2, phase Φ_{m32} of transmitted coefficient from Port 2 to Port 3, and transmitted phase $\Phi(t_{++})$ can be described as:

$$\Phi(r_{--}) = 2\alpha \tag{S16}$$

$$\Phi_{m21} = -\alpha \tag{S17}$$

$$\Phi_{m32} = \beta \tag{S18}$$

$$\Phi(t_{++}) = \Phi_{m21} + \Phi_{m32} = -\alpha + \beta \tag{S19}$$

We scan α from 0° to 360° with *a* step of 22.5° while scan *β* from 0° to 360° with a step of 22.5°. The reflected phase and amplitude versus *α* and *β* are shown in Figs. S6(a) and S6(b), respectively. At the same time, we can obtain the transmitted phase and amplitude versus *α* and *β* are shown in Figs. S6 (c) and S6(d), respectively. The simulated results are in good agreement with the theatrical calculation based on Equations (S16)-(S19).

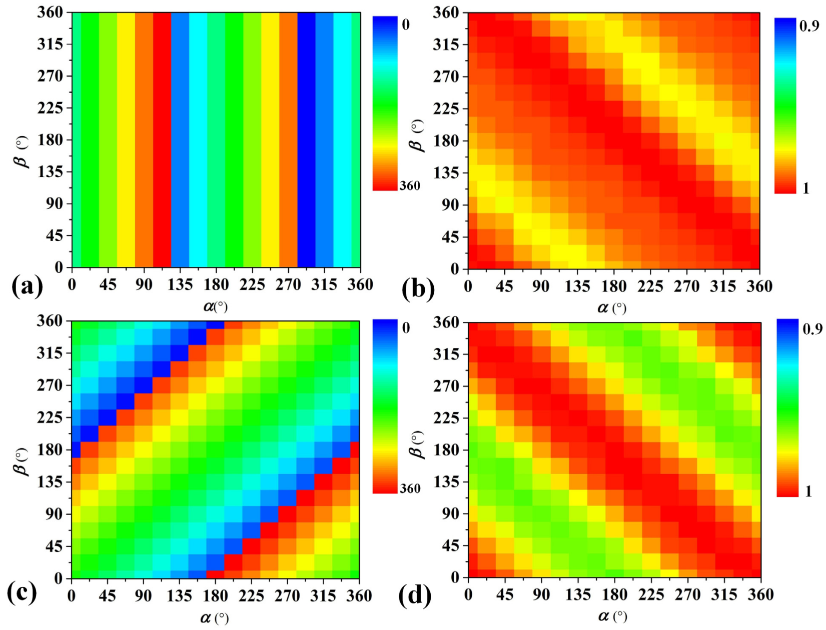

Fig. S6 Characteristics of the meta-atom with rotating the receiver patch1 and transmitter patch 2. (a) Phase of r_{--} . (b) Amplitude of r_{--} . (c) Phase of t_{++}. (d) Amplitude of t_{++}

Case 4 analysis:

For the Case 4, Receiver Patch 1 is RCP patch and Transmitter Patch 2 is LCP patch. Therefore, LCP reflected wave and LCP transmitted wave can be obtained under the illumination of LCP and RCP incident wave According to the Case 1 analysis, the same methods are used to demonstrate the characteristics of meta-atom in Case 4. Reflected phase $\Phi(r_{--})$, phase Φ_{m21} of transmitted coefficient from Port 1 to Port 2, the phase Φ_{m32} of transmitted coefficient from Port 2 to Port 3, and transmitted phase $\Phi(t_{-+})$ can be described as:

$$\Phi(r_{--}) = -2\alpha \tag{S20}$$

$$\Phi_{m21} = -\alpha \tag{S21}$$

$$\Phi_{m32} = -\beta \tag{S22}$$

$$\Phi(t_{-+}) = \Phi_{m21} + \Phi_{m32} = -\alpha - \beta \tag{S23}$$

We scan α from 0° to 360° with *a* step of 22.5° while scan *β* from 0° to 360° with a step of 22.5°. The reflected phase and amplitude versus *α* and *β* are shown in Figs. S7 (a) and S7(b), respectively. At the same time, we can obtain the transmitted phase and amplitude versus *α* and *β* are shown in Figs. S7 (c) and S7(d), respectively. The simulated results are in good agreement with the theatrical calculation based on Equations (S20)-(S23).

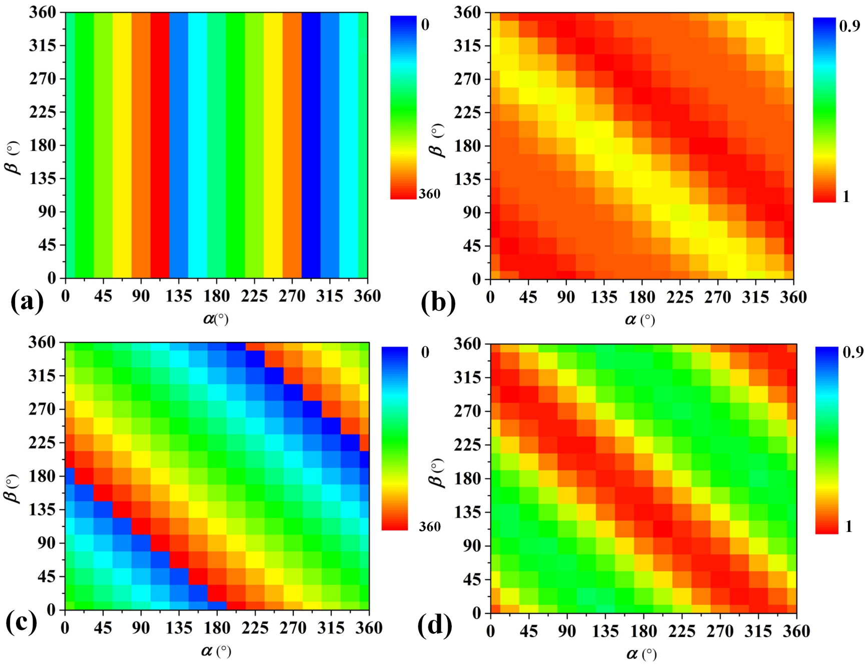

Fig. S7 Characteristics of the meta-atom with rotating the receiver patch1 and transmitter patch 2. a) Phase of r_{--} b) Amplitude of r_{--} c) Phase of t_{-+} d) Amplitude of t_{-+}

3 Additional FDTD simulation setup of the Deflector 1

For the redesigned Deflector 1, reflected/refracted angle θ_r / θ_t were set to 45° and 0°, corresponding to the phase gradient 119° and 0°, respectively. Therefore, the target phase distribution of the reflection wave is $\Phi(r_{++})$ = -2$\alpha(n)$ (α scanning from 0° to 360° with a step of 59.5° and n ranging from 1 to N), while the target phase distribution of the transmitted wave was $\Phi(t_{+-})$ = 0. Here, n is the element number along the x-axis. According to Eq. (2), it can be deduced that $\alpha(n)$ =59.5(n-1). According to Eq. (1), $\beta(n)$ can be denoted as $\beta(n)$ = -$\alpha(n)$. As shown in **Figs. S8**(c) and **S8**(d), Receiver Patch 1 and Transmitter Patch 2 are arranged on the linear array according to the relative target phase distribution $\Phi(r_{++})$ and $\Phi(t_{+-})$. A periodic boundary is applied in the y direction, and an open boundary is applied to the x and z directions. RCP and LCP illuminate the array along the z direction, respectively. The target phase of $\Phi(r_{++})$ and $\Phi(t_{+-})$, corresponding to the rotation angles α and β, are plotted in **Fig. S8**(a). The normalized simulated radiation pattern (normalized with the PEC Deflector) for Deflector 1 is shown in **Fig. S8**(b). The reflected wave r_{++} is reflected to θ = 135° and the transmitted wave t_{+-} is not anomalously refracted, with reflected angle θ_r = 45°, which agrees well with the target reflection angle.

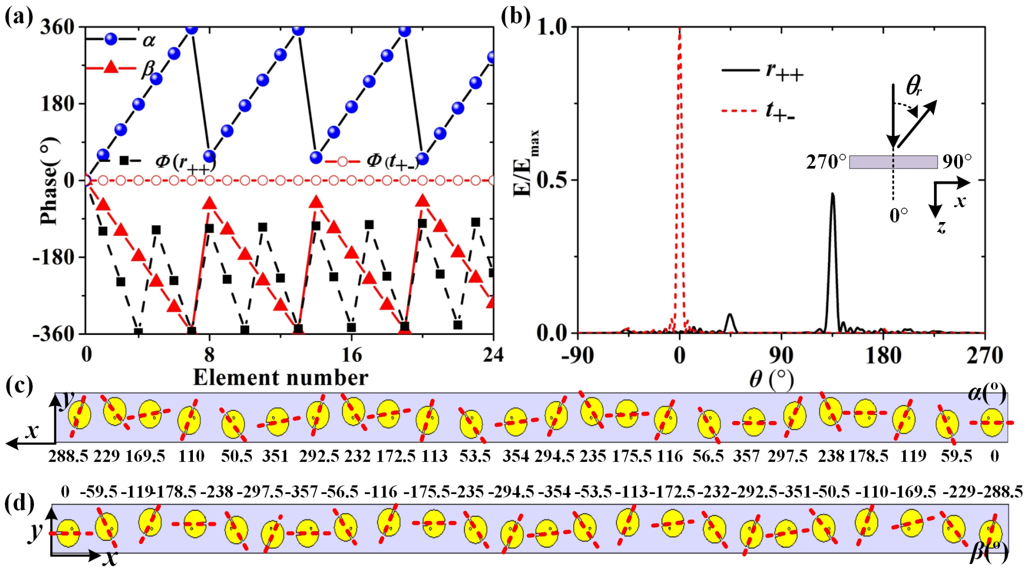

Fig. S8 Design of full-space deflector using receiver-transmitter metasurfaces (a) Linear distribution of $\Phi(r_{++})$ and $\Phi(t_{+-})$ corresponding to rotation angles α and β, which all the phases are normalized to -360° to 360°. (b) linear scaling radiation patterns of r_{++} and t_{+-}. (c) simulation model and rotation angles α for Patch 1. (d) simulation model and rotation angles β for Patch 2.