Steer and split electro-magnetic waves by employing ultra-thin anisotropic meta-material

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Abstract. As an ultra-thin developed form of meta-materials, metasurface does attract tremendous attention due to its flexibility in controlling wave front in different spectrums. In this paper, we propose a microwave metasurface with function of transforming spherical waves into plane waves and splitting waves according to polarized status of incident waves. By using a compact ultra-thin anisotropic element, we design a polarization beam splitter under spherical wave’s illumination. With different phase gradients for x/y-polarized waves, the anisotropic metasurface has function of gain enhancement of 12.4 dB on average and reflecting x/y-polarized waves in -x/+y direction with the same reflected angel of 33° at the operating frequency of 15GHz. For verification of simulation results, the metasurface sample with size of 102×102mm² and cells of 17×17 is fabricated and measured. Experimental results are in excellent agreement with the simulated ones, in which the high isolation of 30dB at 15GHz between x- and y-polarized waves is obtained. Due to the great performance in beam steering and thickness reduction, our design provides a promising approach of beam splitting, steering and gain enhancement in microwave region.

1. Introduction
Metamaterials have gained much attention around the world since J. B. Pendry and D. Smith proposed the concept of negative permittivity [1] and permeability [2]. But multi-layered three-dimensional metamaterials suffer from a narrow usable bandwidth, low optical efficiency as well as complicated and costly fabrication. Recently, the concept of an abrupt phase change at the interface provides a powerful solution to overcome the limitations of metamaterials, which is also called metasurface [3-5]. A metasurface is usually introduced by applying a series of periodic or quasi-periodic subwavelength antennas on a surface from which novel optical properties are achieved [6], such as negative refraction [7], subwavelength focusing [8-10]. Based on the plasmonic response of the gold V-shaped nano-antenna, phase gradient metasurface (PGM) is first proposed by Yu et al. in 2011 [3]. By imposing a hyperbolical phase profile on the interface, planar focusing metasurface (PFM) has attracted attention since they can replace lossy and bulky curved conventional focusing elements [11-12].

Among the most researches, it’s always a hot topic to manipulate polarized status of propagating waves by employing anisotropic metasurface [13-14]. For example, polarized converters as well as polarized beam splitters are commonly realized by anisotropic metasurfaces [15-16]. As for polarized converters, the study group of Shaobo Qu [16-17] and the group of Tiejun Cui [18-19] have done many in-depth researches on both cross-polarization conversion and linear-to-circular polarization conversion. But for beam splitters, as depicted in Ref. 19 and 20, only the condition of plane waves’ illumination is considered in most research articles up to now. Therefore it’s still in great desire to explore the beam splitters under the condition of spherical waves’ illumination.
In this paper, we first propose a new kind of phase distribution which contributes to both anomalous reflection and gain enhancement. Then an ultra-thin anisotropic reflected metasurface element is designed to construct a beam splitter under spherical waves illumination according to the phase distribution we proposed. By putting different phase gradients for x/y-polarized waves on the anisotropic metasurface, it has function of gain enhancement of 12.4 dB on average and reflecting x/y-polarized waves in -x/+y direction with the same reflected angle of 33°. Besides the isolates degree above 30dB between x- and y-polarized waves is obtained in both simulated and measured setup at 15GHz. The metasurface is single-layered with thickness of 1mm (0.05λ), which makes contributions in thickness reduction of microwave devices.

2. Anisotropic metasurface cell design

The structure of the metasurface cell is demonstrated in Fig.1, in which the double improved orthogonally I-shaped metallic structures are employed to control the reflection phases of x/y-polarized electromagnetic waves respectively. The detailed dimensions of the structure shown in Fig. 1(b) are p=6 mm, b=0.4mm, d= 0.2 mm and the orthogonally I-shaped metallic structures are separated from a metal grounded plane by a dielectric spacer with thickness of h=1mm. The dielectric layer is with the relative permittivity ε_r=4.3 and loss tangent 0.001. In order to illustrate the polarization-independent property for differently-polarized incident waves, we fix a_y=2mm and vary a_x from 2.2 mm to 5.6 mm. Fig.1(c) depicts the reflection phases at 15 GHz for x/y-polarized incoming waves. A desirable phase variation from -133° to -473° is unambiguously observed for the x-polarization waves, while the reflection phase is not affected for the y-polarized waves. Similarly, if a_x is fixed at 2 mm and a_y is varied from 2.2 mm to 5.6 mm, the reflection phases of y-polarized waves are changed from -133° to -473°, while the reflection phases of the x-polarized waves are not affected. In addition, the phase range does not cover 360° despite of independent phase response for differently polarized waves, which will debase the precision of phase control. But fortunately the phase range covers 340°. When designing a metasurface sample, we will choose the cells with relative phase response of 340° and 360° (0°) instead of cells with phase ranging from 340° to 350° and 350° to 360° respectively. In this way the phase compensation error will be depressed to the least, which will contribute to the satisfying performance of the designed metasurface sample.

Figure 1. (a) Top view and (b) perspective view of the reflected MS element, (c) phase response for x- and y-polarized incident waves with a_y=2 mm and a_x varying from 2.2 mm to 5.6 mm.

3. Beam Splitters under Plane Waves’ Illumination

As we know the gradient phase distribution shown in Eq. (1) contributes to anomalous reflection according to the general reflection law as depicted in Eq. (2). Considering the element we proposed has independent phase response for orthogonally polarized waves, we can set the different phase
gradients for the orthogonally polarized beams. In this way, the designed metasurface sample will reflect the orthogonally polarized waves in different deflection angles.

\[
\Phi(x) = \xi \cdot x + \Phi_o
\]  

\[
\sin \theta_x - \sin \theta_y = \frac{\lambda}{2m} \frac{d\Phi}{dx}
\]  

Based on above designed procedure, we propose a one-dimensional phase gradient metasurface (a supercell) as shown in Fig. 2(a). The parameters of the cells along +x axis are demonstrated in Table I, in which the phase response of the six distributed cells are also depicted. Moreover \(\Phi_x(\Phi_y)\) in the table corresponds to the phase response for \(x(y)\)-polarized incident waves. Unanimously the phase gradient is fixed for 60° between adjacent cells. By fitting 3×3 supercells together as shown in Fig. 2(b), the constituted metasurface is simulated in CST Microwave Studio, in which periodic boundary condition is set in y direction while open boundary condition is set in x and z directions. Fig. 3(c) depicts the simulated reflection coefficients of the metasurface under \(x\)- and \(y\)-polarized waves’ illumination. As shown, the valley lies at 15GHz, which demonstrate that the incident beams are mostly reflected anomalously at 15GHz. In order to detect the operating procedure of the anomalous reflection, the E-field distribution on \(xoz\) plane is calculated and shown in Fig. 3. Thereinto Fig. 3(a) and (b) depict the cases under \(x\)- and \(y\)-polarized waves’ illumination respectively. In addition, the deflection angles for \(x\)- and \(y\)-polarized beams are denoted by 33.7° and 32.9° which are in good accordance with theoretic ones calculated by Eq. (2).

![Figure 2](image1.png)

**Figure 2.** (a) The designed 1-dimensional phase gradient metasurface, (b) the simulated setup for the metasurface constituted by 3×3 supercells.

![Figure 3](image2.png)

**Figure 3.** The E field distribution on \(xoz\) plane for (a) \(x\)-polarized and (b) \(y\)-polarized waves, (c) the reflection coefficients of the metasurface under \(x\)- and \(y\)-polarized waves’ illumination.
4. Beam Splitters under Spherical Waves’ Illumination

As we know, the phase distribution as depicted in Eq. (3) is capable of converting spherical waves into plane waves and vice versa. Besides, it’s the basic phase distribution for a planar focusing metasurface (PFM). According to the general reflection law as depicted in Eq. (2), the plane waves impinging on the PGM normally will be reflected to a certain angle in x direction. Moreover, seeing that the spherical waves will be converted into plane waves by PFM effectively, an additional gradient phase can be attached on the PFM lens to get the plane waves converted by spherical waves reflect to an anomalous angle. In addition, if different phase gradients are set for x/y-polarized waves, the spherical waves will be split into x/y-polarized plane waves with different deflection angles. 

\[ \Phi(x, y) = \frac{2\pi}{\lambda} \left( \sqrt{x^2 + y^2 + L^2} - L \right) + \Phi_0 \]  

According to this point, the phase distributions for x/y-polarized incident waves should meet the phase relationship as described in below:

\[ \Phi_i(x, y) = \frac{2\pi}{\lambda} \left( \sqrt{x^2 + y^2 + L^2} - L \right) + \xi_x \cdot x + \Phi_0 \] (4)
\[ \Phi_j(x, y) = \frac{2\pi}{\lambda} \left( \sqrt{x^2 + y^2 + L^2} - L \right) + \xi_y \cdot y + \Phi_0 \] (5)

where \( \Phi_i(x, y) \) and \( \Phi_j(x, y) \) represent the phase distributions for x- and y-polarized waves while \( \xi_x \) and \( \xi_y \) correspond to the extra linear phase gradients. In addition, \( \lambda \) is the wavelength in vacuum and \( L \) is the designed focal length. Deduced from above description, the reflection angles of the x/y-polarized waves are only related to the linear phase gradients \( \xi_x \) and \( \xi_y \), which can also be calculated according to generalized reflection law as below:

\[ \theta_{r, x} = \sin^{-1} \left( \frac{\lambda}{2\pi} \xi_x \right) \] (6)
\[ \theta_{r, y} = \sin^{-1} \left( \frac{\lambda}{2\pi} \xi_y \right) \] (7)

Besides, since the extra phase gradients \( \xi_x \) and \( \xi_y \) are appended in x and y direction, x- and y-polarized beams will be reflected along x and y direction with deflection angles of \( \theta_{r, x} \) and \( \theta_{r, y} \) respectively. Based on above designed principle, we propose a metasurface sample with size of 102×102 mm² and cells of 17×17 as shown in Fig. 4(a). With phase distributed as Eq. (4) and (5), Fig. 4(b) and (c) depict the relative phase distribution for x- and y-polarized waves on the metasurface. The focal length \( L \) is set for 40mm and the wavelength is denoted by 20mm (at 15GHz). In addition, the extra linear phase gradient \( \xi_x \) and \( \xi_y \) are set for \( \pi/3p \) and \( -\pi/3p \). The feed source of the designed metasurface is shown in Fig. 5, in which the patch antenna radiates omnidirectionally with an operating bandwidth from 14.4GHz to 15.5 GHz. With the feed source placed at the focal point of the metasurface, the constituted system is shown in Fig. 6(b), in which the patch antenna is set obliquely as shown in Fig. 6(a) in order to get both x/y-polarized incident waves at the same time. Furthermore, the polarized status of incident beam can be described as

\[ E = e_x |E| \cos \phi + e_y |E| \sin \phi \] (8)

Here we set \( \phi=45^\circ \) in order to keep the amplitudes of x- and y-polarized incident waves equal. And then we set the assembly metasurface sample simulated in CST Microwave Studio where open
boundary conditions are set in all directions. In Fig. 6(c) is demonstrated the simulated far-field pattern of the system. Obviously, double pencil shaped beams with the maximum gain of 17.6 dB on

**Figure 4.** (a) The designed metasurface sample, (b) the relative phase distribution for $x$-polarized waves, (c) the relative phase distribution for $y$-polarized waves.

**Figure 5.** (a) The reflection coefficient and (b) the far-field pattern of the patch antenna

**Figure 6.** (a) The placement of the patch antenna; (b) the constituted metasurface sample, (c) the far-field pattern of the designed metasurface system.
Figure 7. E-field distribution on (a) xoz plane and (b) yoz plane.

xoz and yoz plane are achieved. In order to illustrate the operating mechanism, the E-field distributions on xoz and yoz plane are calculated and shown in Fig. 7(a) and (b). Unanimously, the spherical waves emitted from the feed source have been converted into plane waves with reflection angle of 33.2°, which are in good accordance with the theoretical ones calculated by the general reflection law.

In order to further verify the design, the metasurface sample is fabricated and then measured in a microwave anechoic chamber as shown in Fig. 8. The test setup is consistent with the simulated one. The numerical and measured far-field patterns on xoz and yoz plane are plotted in Fig. 9. It’s obvious that the x-polarized waves are reflected in −x direction with deflection angle of 33.2° while y-polarized waves are reflected in +y direction with reflection angle of 33.1°. Besides, the isolation degrees at the peak value between x- and y-polarized waves surpass 30dB, which is revealed about perfect beam splitting performance. Thus by designing and assigning a fire-new phase distribution on the reflected metasurface, the fabricated sample is capable of converting spherical waves to plane waves as well as splitting different polarized waves into diverse directions.

Figure 8. (a) The fabricated metasurface sample and (b) the measured setup
5. Conclusion and perspectives
In conclusion, a new method to design beam splitter under spherical waves’ illumination is proposed. By adding additional linear phase profile on hyperbolic phase distribution, the combined phase profile on surface contributes to both gain enhancement and anomalous reflection. With different phase profiles for orthogonally polarized waves, the accordingly designed metasurface is capable of improving the patch antenna gain above 12.4dB and splitting $x/y$-polarized waves in $-x/y$ directions with deflection angle of 33.4$^\circ$ at 15GHz. With thickness reduction, the proposed metasurface has great application in the region of beam splitting, steering and gain enhancement in microwave spectrum.

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