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A Metasurface to Focus Antenna Beam at Offset Angle

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Abstract

This paper explains the design of a metasurface that tilts and focuses the broadside beam of an ordinary antenna to an offset angle. The design is based on the theory of near-field phase transformation, which has been demonstrated in our previous publications. In the final design, the metasurface is simply stacked above the base antenna within its near-field region - for the purpose of demonstration the base antenna is a classical resonant-cavity antenna (RCA). The metasurface transforms the arbitrary phase distribution of the field, radiated by the RCA, at its input into a linearly increasing phase at its output, thus tilting and focusing the RCA beam. The metasurface is made of spatially distributed printed cells for locally introducing a specific phase shift. With the metasurface, the RCA beam points at a 20^o elevation angle and is 8 dB more directive with significantly reduced 3dB beamwidth.

1 Introduction

High-gain antennas, mostly, have a focused beam in the broadside direction. In several practical scenarios, however, it is often desired to transmit or receive signals from an offset angle away from the broadside direction. As an example, consider an antenna flush mounted on a building wall and receiving from a satellite at an elevation. In such a case, a less sophisticated but a low-cost solution includes physically tilted dish-shaped reflectors and arrays. The physical tilt of antennas make them protrude, requires additional hardware and frequent maintenance [1]. An ideal solution is a flat antenna that is fixed parallel to the wall but whose beam points to the elevation of the satellite.

Our recently demonstrated near-field phase transformation methodology can be used to develop beam-tilted high-gain antennas [2–4]. These flat low-profile antennas comprise a feed (the radiator) and a metasurface in a stacked configuration. The feed radiates the electromagnetic energy and the metasurface manipulates the phase of the field. The working of the methodology has been successfully demonstrated by developing a metasurface to transform the non-uniform phase distribution of a low-gain antenna to a nearly uniform phase distribution [3].

This paper uses the near-field phase-transformation methodology to develop a beam-tilted medium-gain antenna. The final design consists of a resonant-cavity antenna (RCA) and a parasitic passive metasurface referred to as an offset-angle beam-focusing metasurface. The paper is organized such that Section II gives a brief generic overview of phase transformation. Section III discusses the design process of the metasurface and Section IV presents a design example with predicted results.

2 Phase Transformation for Antennas

It has been established from antenna array theory that the directional propagation of an array can be controlled by introducing appropriate phase shifts in the feed of the array [5]. Extending the concept, a similar phase pattern can be replicated in the field radiated by aperture antennas, thus changing their radiation characteristics including the direction of propagation. One example is that of the lenses used to enhance the broadside directivity of antennas by transforming their spherical phase fronts to planar. [6].

Using the near-field phase-transformation methodology, we have demonstrated beam focusing in the broadside direction through near-field phase-correcting structures (PCSs) [2, 3]. PCSs, in function, are similar to lenses but their operation is not limited by focal-length distance and can function in a very close proximity to antennas. These PCSs transform a given arbitrary phase distribution to a nearly uniform phase distribution in a plane parallel to the antenna aperture. Phase transformation has also been used to vary the direction of propagation through beam-tilting metasurfaces, also referred to as turning metasurfaces (TMs). The TMs transform the uniform phase to a linearly increasing phase in a plane parallel to the aperture [4, 7].

Later, in [7], the phase-correcting metasurface and TM are used in a stacked pair to focus the beam at an offset angle. The configuration of the antenna is shown in Fig. 1. The main limitation of this model is that a pair of metasurfaces are required, which makes the structure tall and costly.

In contrast to the previous work, which uses a pair of metasurfaces to focus a beam at an offset angle, this work presents a single offset-angle beam-focusing metasurface. The detailed design of this metasurface is in the following section.

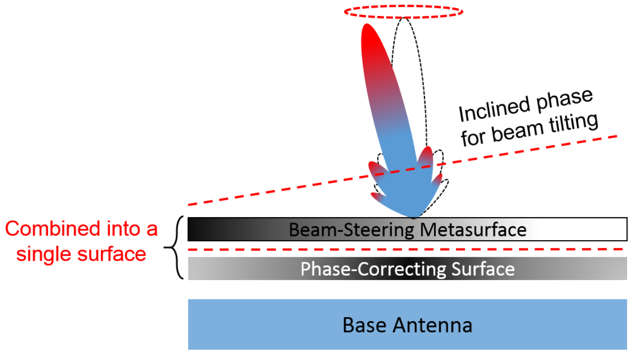


Figure 1. Cross-section of a tilted-beam antenna with a pair of phase-transforming metasurface [7].

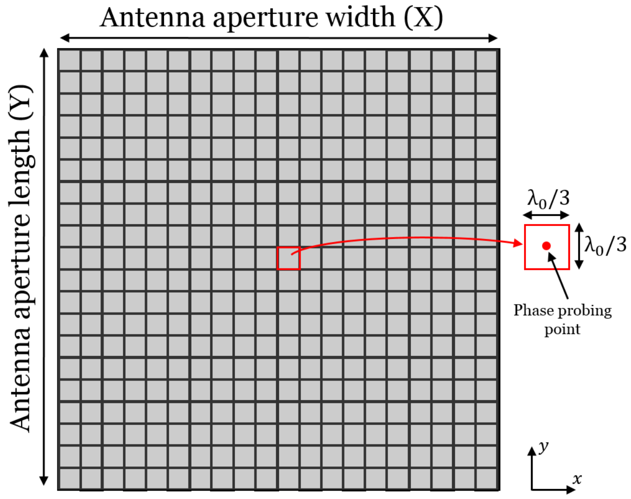


Figure 2. Aperture of an arbitrary antenna. The aperture is discretized into a 2D grid, and each of the grid points has unique index.

3 Offset-Angle Beam-Focusing Metasurface Design Process

The design process of the offset-angle beam-focusing metasurface is similar to that of a phase-correcting metasurface. The only difference is that an additional linear phase progression is added in the desired phase shift to cater for the beam tilt. To explain the process consider a base antenna with an aperture of X×Y mm^2 as shown in Fig. 2. The aperture has been discretized into a 2D grid of square cells, and each cell has a length of $\lambda_0/3$ where λ_0 is the free space wavelength at the operating frequency. The antenna is simulated with a commercial electromagnetic (EM) simulator and the phase is recorded at the aperture grid. This phase referred to as the input phase is denoted by $\theta_i(n,m)$, where n and m are the grid indices along the x- and y-axis, respectively. The phase can then be used to compute the necessary correction phase required for enhancing the broadside directivity. The complete procedure of calculating the phase for correction is given in [2] and for brevity will be discussed. The correction phase is denoted by $\phi_C(n,m)$ here. Introducing $\phi_C(n,m)$ through a shaped structure or a metasurface, simply focuses the beam in the broadside direction.

In order to tilt the beam at an elevation angle θ_0 along the radial direction of the positive x-axis, it is necessary to have a linearly decreasing phase shift along the positive x-axis and a constant phase shift along the y-axis. The step of the phase-shift value depends on: tilt angle (θ_0), the frequency of operation, and the center-to-center spacing between the discrete cells in the grid. The detailed calculation procedure is available in [4]. The necessary phase-shift pattern on the 2D grid required for tilting the beam is denoted by $\phi_T(n,m)$.

In the next step of the design process, the two phases are added together to determine the net phase shift required for the focusing and tilting of the beam together. The net phase shift denoted by $\phi_N(n,m)$ is simply the addition of correction and tilting phase shifts or $\phi_N(n,m) = \phi_C(n,m) + \phi_T(n,m)$. The net phase shift can then be introduced by a metasurface having spatially distributed phase-transforming unit cells.

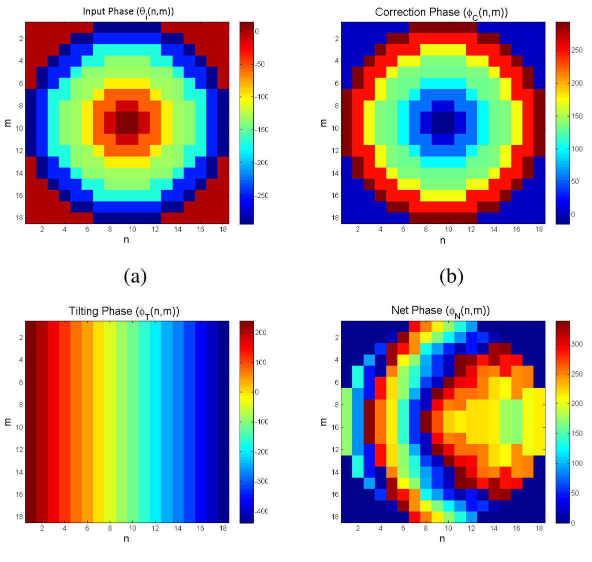
4 Design Example

The process has been validated by designing an offset-angle beam-focusing metasurface for a resonant-cavity antenna (RCA) operating at a frequency of 11 GHz. This RCA has been used as a base antenna in a design given in [2] and will not be explained here in detail. The RCA comprises a single patch antenna feed and an all-dielectric unprinted square slab of Rogers TMM4 ($\varepsilon_r = 4.5$) as a partially reflecting surface (PRS). The PRS dimensions are $6\lambda_0 \times 6\lambda_0$ or 162 mm×162 mm, where λ_0 is the free-space wavelength at the operating frequency. The PRS is physically located at a spacing of $\lambda_0/2$ from the feed.

The RCA is simulated with CST Microwave Studio and the phase ($\theta_i(n,m)$) of the dominant field component, E_y here, is recorded in a virtual plane located 7 mm above the PRS. This plane has the same physical aperture as the PRS and has a 2D grid of 18×18 square cells. $\theta_i(n,m)$ is then used to compute $\phi_C(n,m)$ using the procedure explained in [3].

In the next step, $\phi_T(n,m)$ is calculated on the 2D grid for a 20^o tilt angle - detailed procedure of calculation is given in [4]. $\phi_C(n,m)$ and $\phi_T(n,m)$ are used to calculate $\phi_N(n,m)$. The color map of the four phase distributions $\theta_i(n,m)$, $\phi_C(n,m)$, $\phi_T(n,m)$, $\phi_N(n,m)$ are given in Fig. 3.

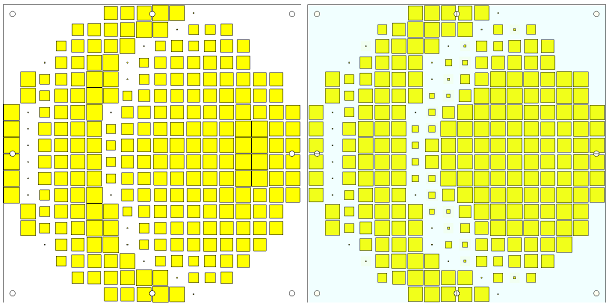
The value of net phase ($\phi_N(n,m)$) is utilized to realize the offset-angle beam-focusing metasurface by integrating phase-varying cells [3]. These phase-varying cells have two dielectric layers sandwiched between three printed layers. Each of the printed layers has a square patch with different size; the top and bottom patches are identical while the middle patch has a different size. The process is simply to find a cell with a phase shift $\phi_N(n,m)$ and place it on the appropriate grid location. The two layers, top and middle, of the resulting metasurface are shown in Fig. 4. The 3D models of the RCA and the metasurface are shown in Fig. 5.



(a) (b)

(c) (d)

Figure 3. Phase distributions: (a) input (b) phase shift required for correction (c) phase shift to tilt beam by 20^o in elevation plane and (d) net phase shift obtained by combining a and b, mapped on the 2D aperture grid.



(a) (b)

Figure 4. Top and middle layers of the offset-angle beam-focusing metasurface.

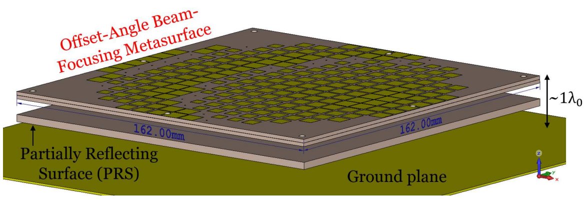


Figure 5. 3D models of the RCA and the beam-focusing metasurface.

The metasurface was simulated with the RCA in CST Microwave Studio. The main parameter of interest, the far-field pattern, was computed at the operating frequency. The elevation plane cut, taken at a 0^o azimuth angle, is plotted in Fig. 6. For the reference, the pattern of the RCA in the same plane but without the metasurface is added in the same figure. The peak directivity of the RCA with metasurface is approximately 8 dB higher, with a beamwidth of 15.3^o. The 3dB beamwidth is almost 20^o less than that of the RCA without the metasurface. Additionally, the main beam is not in the broadside direction or at 0^o elevation angle but instead points to 20^o elevation angle. The elevation angle can be further increased by using a corresponding $\phi_N(n,n)$ in the design process. The sidelobe level of the antenna in the elevation plane is around -17 dB.

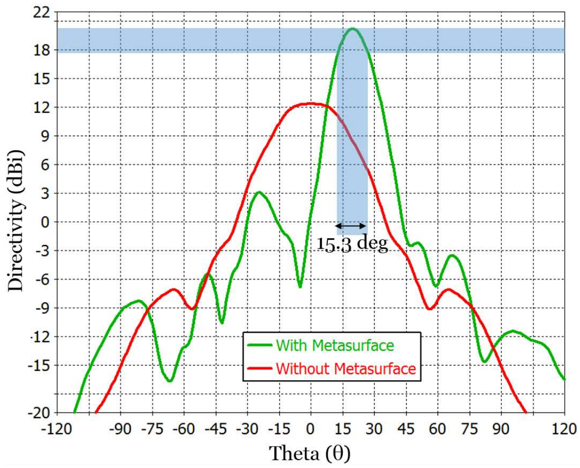


Figure 6. Elevation plane cuts taken at 0^o azimuth angle or $\phi = 0^o$.

The total height of this antenna is only 27 mm or $1\lambda_0$. The majority of the height is because of the $\lambda_0/2$ spacing between the feed antenna and the PRS, which is necessary for the RCA resonance. The height can be further reduced by using a thin flat antenna such as an array of patches.

5 Conclusion

The paper presented a metasurface design that tilts and focuses the beam of a base antenna at a predefined offset angle in the elevation plane. The base antenna used for demonstration is a medium-gain resonant-cavity antenna (RCA) but the concept can be applied to high-gain antennas as well. The metasurface is in the near-field region of the RCA and operates by transforming its normal phase distribution to a linearly increasing phase pattern. With the metasurface, the directivity is enhanced by 8 dB and the beam is tilted by 20^o in the elevation plane. The overall thickness of the antenna is only a single free-space wavelength or $1\lambda_o$.

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