Metamaterials lens design for microwave

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Abstract-The development of flat, low profile, and light weight metamaterial lens for microwave allows for small phase error, a wide frequency band of operation, wide angle scanning, and true-time delay beam forming. This lens design is promising for applications in remote sensing, THz imaging, and adaptive antennas in microwave regime. In this work, the comparison between the beam shaping of metamaterial lenses and the diffraction limited optical systems in extended bandwidth is provided both analytically and numerically.

Recent accomplishments in the field of metamaterials research, have developed novel metallic featured structures that allow for local control of the phase of an optical beam while it is transmitted through metasurfaces and metamaterials. These manmade subwavelength-sized materials, with their intricately designed structures, bend electromagnetic waves in ways that are impossible for naturally-occurring materials. The unusual features of metamaterial lenses can be described by using the concept of generalized Snell’s law⁵.

The basic geometry of the proposed lens consists of two distinctive interfaces: a dielectric substrate and a front metalized metasurface. Unlike the bulk dielectric material, the front metasurface is composed of sub-wavelength size resonating structures as depicted in figure 1(a), which are capable of introducing specific phase shifts at the boundary between the air and bulk materials which can be expressed by the generalized Snell’s law⁵. The refraction on the back interface between air and dielectric substrates follows the well-known form of Snell’s law.

The focusing property of this lens can be expressed:

\[ \varphi(x) = \frac{2\pi}{\lambda} f \left[ \sqrt{1 + \frac{x^2}{f^2}} - 1 \right] \]  

where \( \varphi(x) \) is the phase shift gradient of metasurface, \( x \) is the position of the unit cell along the diameter of the lens, \( f \) is the focal length, and \( \lambda \) is the wavelength of incident radiation. This expression has the same functional form as a concave graded refracted index (GRIN) lens.

Thus by introducing a series of phase shifts in the metasurface of this form, lens focusing can be achieved. To account for diffractive effects from this structure, a series of numerical simulations were performed using HFSS to determine the expected performance properties of the metamaterial lens in microwave spectral region.

To achieve the locally controlled phase shift, a 2D lattice consisting of 5 layers of coaxial rings were used.
The inner radius of the ring was adjusted to tune the phase shift at a particular unit cell. Figure 1(a) shows the geometry of the unit cell that provides the local phase shift at the interface between the air and bulk materials. Because one unit cell does not have the necessary dynamic range to span across a $2\pi$ phase shift, five layers are cascaded to form a unit column that achieves an overall $2\pi$ range of phase shift. After each unit column were designed, they were assembled into a 2D array as depicted in figure 1(b) to establish the required phase profile governed by equation (1) and shown in figure 1(c). Figure 1(c) also represented the intensity profile of light after transmitted through the metamaterials lens.

Figure 1: Unit cell with 5 layers of coaxial rings unit cells stacked together (a); 5 layer structure of metamaterial lens for microwave (b); Phase and intensity profiles of the transmitted light through the metamaterials lens (c).

In the further study, we have compared the beam-shaping performance of metamaterial lens under extended bandwidth and off-axis deployment operations to the near-diffraction limited optics, and these results show excellent agreement between analytical and numerical approaches.

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**REFERENCES**