Engineering Nearest Neighbor Coupling in Huygens Metasurfaces

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Abstract: Nearest neighbor coupling in antenna systems tends to reduce the overall optical efficiency of the system. Here, we compare arrays of disc and donut resonators that confine the impinging beam locally. Maximum optical efficiency of 70% for anomalous refraction is achieved.

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1. Introduction

Mutual coupling is experienced when antennas are brought near each other. The coupling strength depends on their relative location and the type of resonance they are employing. In low aspect ratio nanoantenna arrays, this coupling strength is significant and can result in a decrease in the overall scattering efficiency of the array.[1] It is possible to engineer the nanoantenna geometry to localize the field such within the nanoantenna with minimal scattering to its nearest neighbors. This is beneficial towards easy production of unique nanoantenna arrays for beam steering applications.

Huygens metasurfaces are known for efficient scattering of light in a particular direction due to spectrally overlapping (leading to efficient forward scattering) or spectrally proximal (resulting in efficient backward scattering) electric and magnetic dipole resonances. This effect is seen in a homogenous periodic array of nanoantenna elements where nearest neighbors are identical. However, the nanoantennas exhibit a different behavior when nearest neighbors have a different size and shape due to pronounced mutual element coupling, making it more challenging to isolate the scattering optical efficiency and imparted phase due to each nanoantenna in a phased array. [2]

2. Design and Modeling

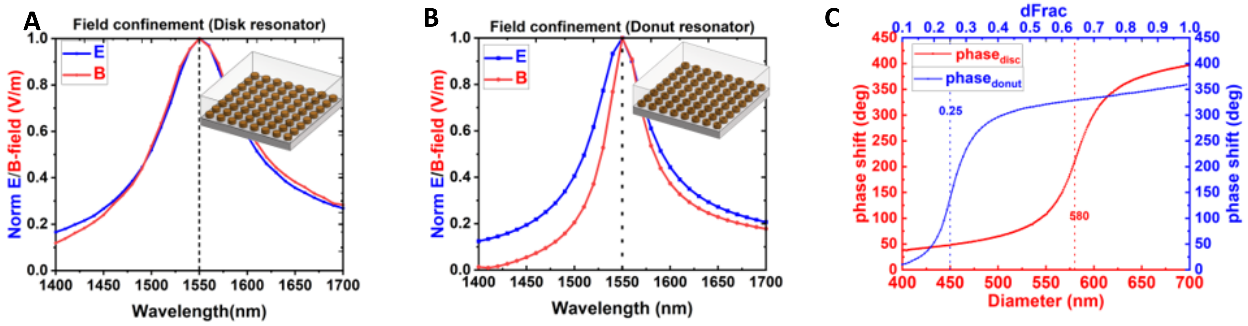

Figure 1 (A). Spectrally overlapping resonances for a homogenous nanodisk resonator array. The black dotted line at 1550 nm shows the resonant wavelength. Inset: Disk resonator array showing the encapsulant (PDMS) region, nanoantenna array (silicon), and substrate (quartz) from top to bottom. (B). Spectrally overlapping resonances for a homogenous nanodonut resonator array. Inset: Donut resonator array showing similar regions as described in Figure 1A. (C). Phase shift imposed due to varying diameter (disk array) and dFrac (donut array) respectively. dFrac indicates the inner hole diameter as a fraction of the outer diameter of the nanodonut.

Nanodisk and nanodonut geometries were selected to investigate the effect of nanoantenna design towards mitigating mutual nanoantenna coupling by comparing their forward scattering optical efficiency. The arrays are designed to be embedded in a polydimethylsiloxane (PDMS) capping layer as shown in the inset to Figure 1A. The donut geometry is of interest here because up to 2π phase shift can be obtained by varying the inner diameter of the resonators without varying the outer diameter, edge-to-edge, or unit cell dimensions, which may mitigate the deleterious effects of coupling. The geometric parameters are optimized to support spectrally overlapping (see Figures 1 A and B) resonances at 1550 nm. In the homogenous array, it is obvious that the electric and magnetic fields are well confined in the resonators. By carefully selecting the size of each antenna, a set of elements spanning a 2π phase shift range is obtained (Figure 1C). To achieve a gradient array, the geometry of nearest neighbors along the lateral dimension were varied leading to the imposition of a phase gradient on the exiting beam from the metasurface.

The diameter was varied for the disk geometry while the inner diameter was varied for the donut geometry (with the outer diameter of the donut held constant), providing an additional degree of freedom for obtaining a basis nanoantenna set spanning a 2π phase shift range. Eight elements of each of these geometries were arranged along the lateral dimension. All 8 antenna elements chosen for the disc geometry were above 90% transmission in their homogenous array; in the donut geometry, six were above 90% transmission, while the other two elements were ~86% and ~70% efficient in their homogenous array models, respectively.

3. Beam Deflection

To investigate the optical deflection, or anomalous refraction, efficiency of the phased array metasurface, a Fast Fourier transform algorithm was developed to extract the fraction of the transmitted beam at each outgoing angle. Multi-modal analysis was done to capture the optical efficiency at different deflection angles for a swept incident angle. Optical efficiency is defined as the intensity of the deflected light exiting the encapsulated nanoantenna array divided by the intensity of light exiting the encapsulant into the substrate without the nanoantenna array. It can be seen in Figure 2 A and B that the disc geometry yields its highest efficiency deflecting a beam by ~6.3° with ~70% efficiency (-4° incident angle). The nanodonut geometry yields its highest efficiency deflecting a beam by ~8.8° with ~47% efficiency (4° incident angle). However, further analysis must take into account the initial efficiency of the chosen elements in their homogenous array formats to compute a composite figure of merit that fully accounts for the effect of nearest neighbor coupling. Other geometries are also being investigated towards achieving optimal designs for Huygens metasurface phased arrays with minimal deterioration in performance due to nearest neighbor coupling.

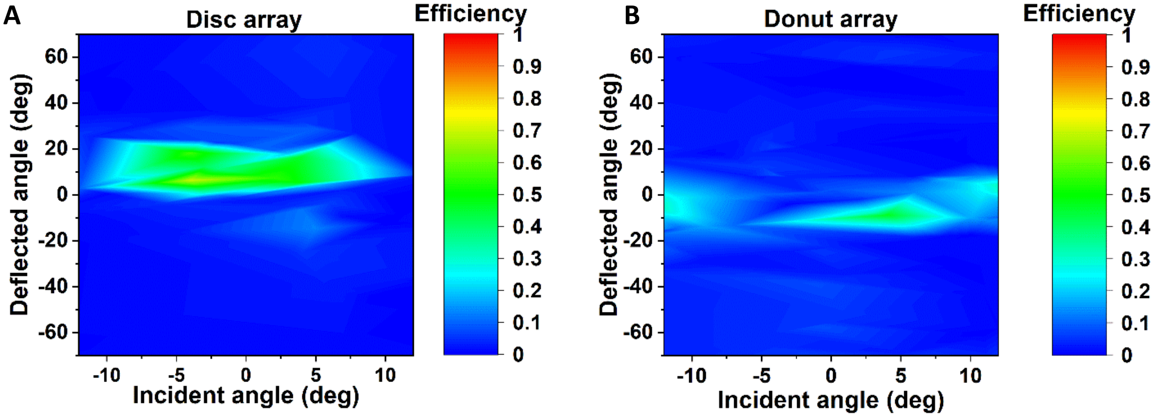

Figure 2 (A). Beam deflection optical efficiency of the disc nanoantenna phased array vs. incident angle. (B). Beam deflection optical efficiency of the donut nanoantenna phased array vs. incident angle.

Conclusion

Huygens metasurface disc and donut nanoantenna arrays were designed for high efficiency beam deflection to study the impact of geometry on nearest neighbor coupling. Further efforts will quantify the nearest neighbor coupling and its impact on the efficiency of phased arrays.

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References

[1]. J.L. Allen and B.L. Diamond, "Mutual Coupling in Antenna Arrays" *Technical Report ARPA,* 1966

[2] A. Ollanik, J. Smith, M. Belue, and M. Escarra, "High-Efficiency All-Dielectric Huygens Metasurfaces from the Ultraviolet to the Infrared," *ACS Photonics*, 2018, doi: 10.1021/acsphotonics.7b01368.