A Huygens' Metasurface Lens for Enhancing the Gain of Frequency-Scanned Slotted Waveguide Antennas

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***Abstract*—Lenses at the microwave/millimeter-wave frequencies can be used to improve the performance of antennas. However traditional dielectric lenses suffer from high reflections and large physical thickness. To combat these issues, we propose a Huygens' metasurface lens design which can perform the desired lensing effects while minimizing reflections and keeping a low profile. The proposed metasurface utilizes a wide variety of unit cells to accurately model the theoretical boundary conditions necessary for a focusing wave transformation. An example of a metasurface cylindrical lens is designed to improve the gain of a 40λ long frequency-scanned slotted waveguide antenna operating in the frequency range of 33.4GHz to 35.2GHz. The proposed metasurface is designed to increase the gain of the feed antenna while maintaining its scanning capabilities.**

I. Introduction

Lenses are crucial devices for manipulating electromagnetic waves. By utilizing the material properties and geometry of lenses, electromagnetic energy can be focused from a diverging source. While traditional utilization of lenses often occurs at optical frequencies, microwave/millimeter-wave frequency lenses are also sought after. One utilization of such lenses is their application in enhancing antenna radiation patterns. These lens antennas utilize a feed antenna at the focal plane of the lens. Similar to optical lenses, microwave lenses can be realized from dielectric materials with curved geometries. However, some disadvantages of using pure dielectric lenses include their typical bulky size and reflections which occur due to the mismatch at their air and dielectric interfaces. While techniques exist to reduce the thickness and mismatch of dielectric lenses [1], [2], a true matched and thin dielectric lens is still difficult to achieve.

Metasurfaces, which are the 2D equivalent of metamaterials, are thin structures composed of electrically small scatterers [3], [4]. These scatterers or unit cells are electrically small and can manipulate incident electromagnetic waves to produce desired effects. Such metasurfaces can achieve a variety of wave manipulations, such as refraction and polarization control, with minimal reflections, while maintaining a low profile [3].

In this paper, we propose the design of a metasurface lens to collimate a 40λ long frequency-scanning slotted waveguide antenna centered at 34.3GHz. The waveguide antenna which produces a fan beam has a bandwidth of 1.8GHz which scans continuously with frequency from 0° to -20° in the H-plane. To improve the gain of the waveguide antenna, a metasurface lens is designed to collimate the fan beam into a pencil beam without disturbing its scanning capabilities. The lens is composed of a three-layer printed design placed at the focal plane of 3λ at 34.3GHz away from the waveguide antenna and has a width of 15λ in the E-plane or collimation plane.

II. Unit Cell Design and Physical Realization

The design of the metasurface can be broken down into two steps. The first step involves finding the desired theoretical response of the metasurface. To approximate the radiation profile of the waveguide antenna, an equivalent magnetic line source can be used. By stipulating the cylindrical wave profile of the equivalent magnetic line source and the desired output plane wave, the electric/magnetic surface impedance/admittance required to produce the wave transformation can be obtained [3], [4]. The second step is to then find appropriate unit cells which can model these spatially varying surface constituents to produce the desired wave transformation.

Following the derivations in [5], the spatially dependent electric impedance $\mathrm{Z_{se}}$ and magnetic admittance $\mathrm{Y_{sm}}$ can be determined by stipulating the wave profile of the equivalent magnetic line source and the desired output plane wave. These are surface impedances/admittances required to transform the cylindrical wave from the magnetic line source to the output plane wave with small reflections. For a physical realization, the surface impedances/admittances can be translated into a microwave equivalent [**Z**] or [**S**] matrix [6]. Thereafter, physical structures can be designed by matching their response to the translated [**Z**] or [**S**] matrices.

To design physical structures to model the ideal [**Z**] or [**S**] matrices, three-layer unit cells with etched metallic scatterers are proposed. The proposed unit cells consist of 3 copper layers (1/2 oz. thick) etched on two 25mil Rogers 3010 substrates. The two substrates are bonded using a 2mil Rogers 2929 bondply producing a total unit cell thickness of 1.32mm ($\approx \lambda/7$ at 34.3GHz). The lateral dimensions of the unit cells are 1mm x 1mm ($\approx$ $\lambda/9$ x $\lambda/9$). To produce the desired response with the unit cells, the metallic features are varied geometrically. Specifically, to accommodate for the entire required phase range, a variety of metal structures including dogbones and meander lines are used (see inset Fig. 1).

III. Lens Physical Realization and Simulation Results

The realized metasurface contains 131 unit cells in the collimation plane yielding a total width of 131mm ($\approx 15\lambda$ at 34.3GHz). These unit cells are then repeated 350 times in the scanning plane to cover the entirety of the 40λ long slotted waveguide antenna. A 1D periodic simulation via HFSS of the lens cross section excited with a magnetic line source is conducted as shown in Fig. 1. Although there are edge effects due to the finite size of the metasurface, the overall transformation from a cylindrical wave to a plane wave is clearly seen. Additionally the overall antenna directivity pattern, line source with metasurface, for the entire frequency band is shown in Fig. 2. As seen, the metasurface lens is able to collimate the isotropic radiation of the magnetic line source into a narrow beam for the desired frequency range. Furthermore, the achieved directivity improvement of the metasurface is maintained for the entire frequency band of 33.4GHz to 35.2GHz.

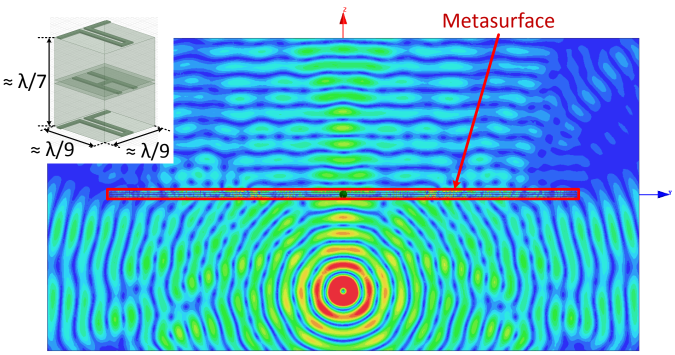

Fig. 1. Fullwave simulation of a 15λ metasurface above a magnetic line source. **Inset:** An example of a unit cell used for realizing the metasurface.

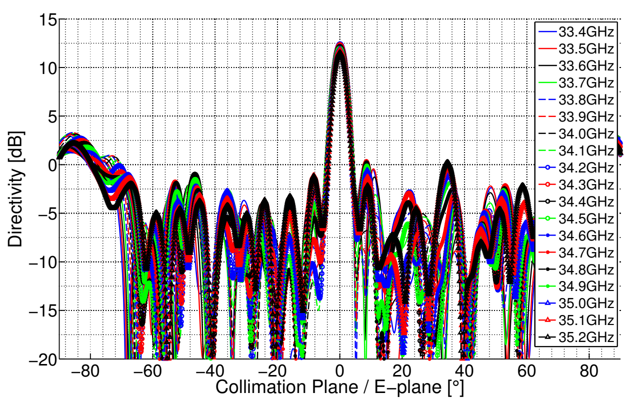

Fig. 2. Fullwave simulation of metasurface lens antenna directivity vs. frequency.

IV. Far-field Measurements

Following the verification of the metasurface lens from simulation, a prototype was fabricated and tested (see inset Fig. 3). Utilizing an anechoic chamber, the far-field realized gain pattern of the overall antenna, slotted waveguide antenna and metasurface lens, were characterized. Comparison of a few measured E-plane patterns of the standalone waveguide antenna and the waveguide antenna with the metasurface lens can be seen in Fig. 3. Examining the experimental results, it is clear that the metasurface lens is able to collimate the wide fan beam from the slotted waveguide antenna into a narrow pencil beam. As a result of the collimation, the gain of the waveguide antenna was increased by upwards of 10dB. Throughout the frequency range and the corresponding beam angles, the metasurface is able to increase the gain by 6dB to 10dB. While the losses were not possible to be quantified due to experimental difficulties, based on the measured gain improvements, the overall losses are expected to be low.

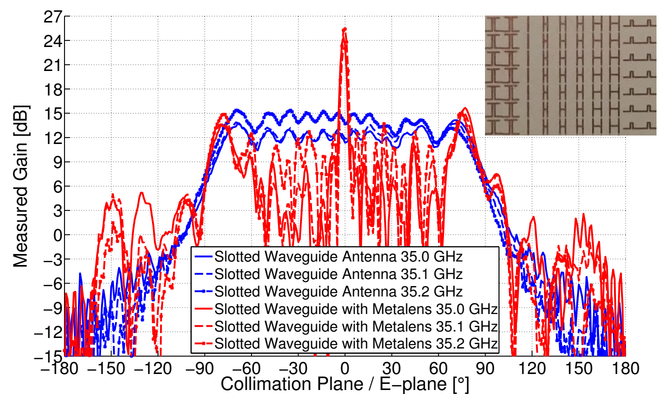

Fig. 3. Far-field measurement of the realized gain pattern of the colimation plane (E-plane). **Inset:** Close-up of a section of the fabricated metasurface.

V. Conclusion

Lenses are very useful devices in all regions of the electromagnetic spectrum. However, traditional microwave/millimeter-wave lenses suffer from high reflections and large thickness. In this paper we have presented a method of alleviating these issues by proposing a Huygens' metasurface lens design. An example of a metasurface cylindrical lens designed to improve the gain of a frequency scanned slotted waveguide antenna in the range of 33.4GHz to 35.2GHz was demonstrated. More results including the scanning-plane characteristics will be presented at the conference.

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