Design, Fabrication and Testing of a Modulated Metasurface Antenna at 300 GHz

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***Abstract*—This paper describes the design and realization of a modulated metasurface (MTS) antenna at 300 GHz. To overcome the hurdles associated with the use of dielectric substrates in the sub-millimeter wave range, we propose an MTS structure which consists of an array of metalized cylinders placed on a ground plane. The metal cylinders are arranged in a square lattice with sub-wavelength unit cell size. This MTS topology has been successfully used to design a spiral MTS antenna. The resulting structure has been micromachined out of a silicon wafer by means of deep reactive ion etching (DRIE). The performance of the antenna has been verified by full-wave simulations, and measurements will be available at the time of the conference.**

***Index Terms*—deep-reactive ion etching, leaky-waves, metasurfaces, silicon micromachining, sub-millimeter waves, surface waves, terahertz.**

I. Introduction

Modulated metasurface (MTS) antennas [1]–[3] have recently undergone an unprecedented development as a versatile solution for deep space communications [2] and compact sub-millimeter instruments [4]. Indeed, modulated MTSs can be applied to the design of high to very-high gain antennas. Among their advantages, it should be noted their capability of beam shaping and pointing, a simple on-surface control of the aperture fields, and all this while keeping a low profile and low envelope. The latter two features are particularly appealing for compact spaceborne communication systems and science instruments.

In MTS antennas, a planar aperture with an average inductance equal to $\bar{\mathrm{X}}$ supports the propagation of a transverse magnetic (TM) surface wave (SW) with wavenumber β_{sw} given by

$$\beta_{\mathrm{sw}} = k\sqrt{1+(\bar{\mathrm{X}}/\zeta)^2}, \tag{1}$$

where k and ζ are the free-space wavenumber and impedance, respectively. Then, the power carried by the SW is gradually radiated by applying a sinusoidal modulation to $\bar{\mathrm{X}}$. Oliner and Hessel studied in [5] the canonical case of a one-dimensional modulation along x at the $z=0$ plane:

$$\mathrm{X_s}\left(x\right) = \bar{\mathrm{X}}\left(1+M\sin\left(2\pi x/d\right)\right) \tag{2}$$

where x is also the direction of propagation, M the modulation factor and d the period of the modulation. The n-indexed mode in the Floquet mode expansion of this periodic problem presents a transverse-to-z wavenumber equal to

$$k_{t,n} = \beta_{\mathrm{sw}} + \beta_{\Delta} - \mathrm{j}\alpha + 2\pi n/d \tag{3}$$

where β_{Δ} and α are perturbations in the phase and attenuation constants, respectively, due to the modulation. In turn, β_{sw} stands for the unperturbed value of k_t ($M=0$), see (1). When $|\Re\{k_{t,n}\}| < k$, the corresponding mode enters in the visible region of the spectrum, becoming a leaky-mode. The $n=-1$ mode is the dominant leaky-mode, and it radiates in a direction given by

$$\beta_{\mathrm{sw}} + \beta_{\Delta} - 2\pi/d = k\sin\theta_0 \tag{4}$$

where θ_0 is the angle with respect to the z axis. Thus, the values of $\bar{\mathrm{X}}$ and d required to obtain a single forward beam at an angle θ_0 can be related using (1) and (4). Given a free-space wavelength λ, and neglecting the effect of β_{Δ}, the period to obtain a single forward beam is

$$d = \lambda/\left(\sqrt{1+(\bar{\mathrm{X}}/\zeta)^2} - \sin\theta_0\right) \tag{5}$$

when $\bar{\mathrm{X}}/\zeta > \sqrt{4\sin\theta_0(1+\sin\theta_0)}$.

At frequencies below 100 GHz, the modulation of $\bar{\mathrm{X}}$ can be achieved by changing the shape and orientation of sub-wavelength patches on a grounded slab. However, in the terahertz (THz) range, the losses in the dielectric become prohibitive, an all-metallic structures are preferred. In addition, alternatives to coaxial SW launchers are sought, given that they are difficult to combine with the rectangular waveguide output of solid-state frequency-multiplied continuous-wave sources, which are the most common sources at THz frequencies [6]. We will first describe in Section II an all-metal structure that provides the desired modulation of the surface reactance. Then, Section III will succinctly present the final design, including the SW launcher.

II. Constituent Element for THz MTS

The proposed MTS consists in an array of metallic cylinders on a ground plane, arranged in a periodic square lattice. Such structure, which resembles a Fakir's bed of nails, has been used in the past for synthesizing artificial surfaces of inductive nature [7]. Although we will only consider here the case of cylinders with circular cross-sections, elliptical sections [4] can be used to obtain an anisotropic response. Anisotropic surface reactances are useful to enhance the cross-polar discrimination and, thus, the antenna efficiency.

One can achieve the MTS modulation by changing the radius or height of the cylinders in a unit cell with constant

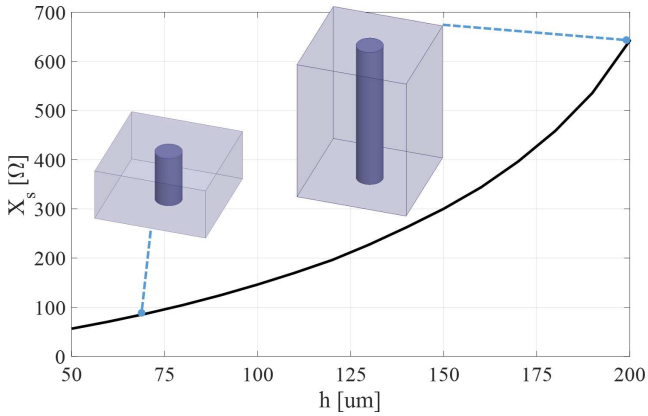

Fig. 1. Equivalent surface reactance of an infinite array of cylinders on a ground plane and arranged on a square lattice at 300 GHz, as a function of the height h of the cylinders. The radius of the cylinders is $r = 17.5\,\mu$m, and the side of the unit cell is $a = 138.5\,\mu$m.

dimensions. The latter approach is preferred, given that one can get a broader range of reactances. In order to retrieve the inductance value that corresponds to a cylinder's height, we make a local periodicity assumption and retrieve the frequency-β_{sw} pair of interest from the dispersion curves obtained with an eigenmode solver for a periodic problem made of cylinders with constant height. Then, imposing the transverse resonance condition between jX and the free-space TM impedance ($-\text{j}\zeta\sqrt{\beta_{\text{sw}}^2 - k^2}/k$, $\beta_{\text{sw}} > k$ for SWs), we obtain $\text{X} = \zeta\sqrt{\beta_{\text{sw}}^2 - k^2}/k$. Fig. 1 shows the reactance values obtained by changing the height of 17.5 μm radius cylinders in a 138.5 μm side square unit cell. The value of a has been obtained as $a = d/N$, where $N = 6$ cells per period and d has been obtained using (5) for $\bar{\text{X}}/\zeta = 0.7$ and a pointing angle $\theta_0 = 1^o$. It is important to note that long cylindrical rods are difficult to realize with DRIE while keeping a good precision and a simple process. Therefore, one has to verify that the required heights satisfy $h/r \leq 10$ in the design phase.

III. Modulated Metasurface Antenna at 300 GHz

The design consists in a spiral modulated MTS antenna. The center frequency is 300 GHz and the spiral antenna provides a broadside pencil beam with circular polarization. The expression of the synthesized surface reactance is

$$X_s(\rho, \phi) = \bar{\text{X}}\left(1 + M\sin\left(2\pi\rho/d - \phi\right)\right) \tag{6}$$

where ρ and ϕ represent the position on the MTS plane in polar coordinates. The periodicity of the modulation along each radius is equal to $\lambda_{\text{sw}} = 2\pi/\beta_{\text{sw}} \approx 2\pi/\beta_0 = \lambda_0$. Therefore, two SW rays separated by 90° intercept a spiral line $X_s(\rho, \phi)$ =constant at distances from the origin that differ $\lambda_{\text{sw}}/4 \approx \lambda_0/4$. Thus, two sectors separated by 90° give rise to orthogonal and quadrature-phased components, which results in a broadside circular polarization. The reader is referred to [2, Sec. IV-A] for further details. In our case, $\bar{X} = 0.7\zeta$, $M = 0.65$, $N = 6$ and $a = 138.5\,\mu$m. The 4 mm radius aperture is discretized in square unit cells with side a, and the heights of the cylinders in each unit cell are obtained using

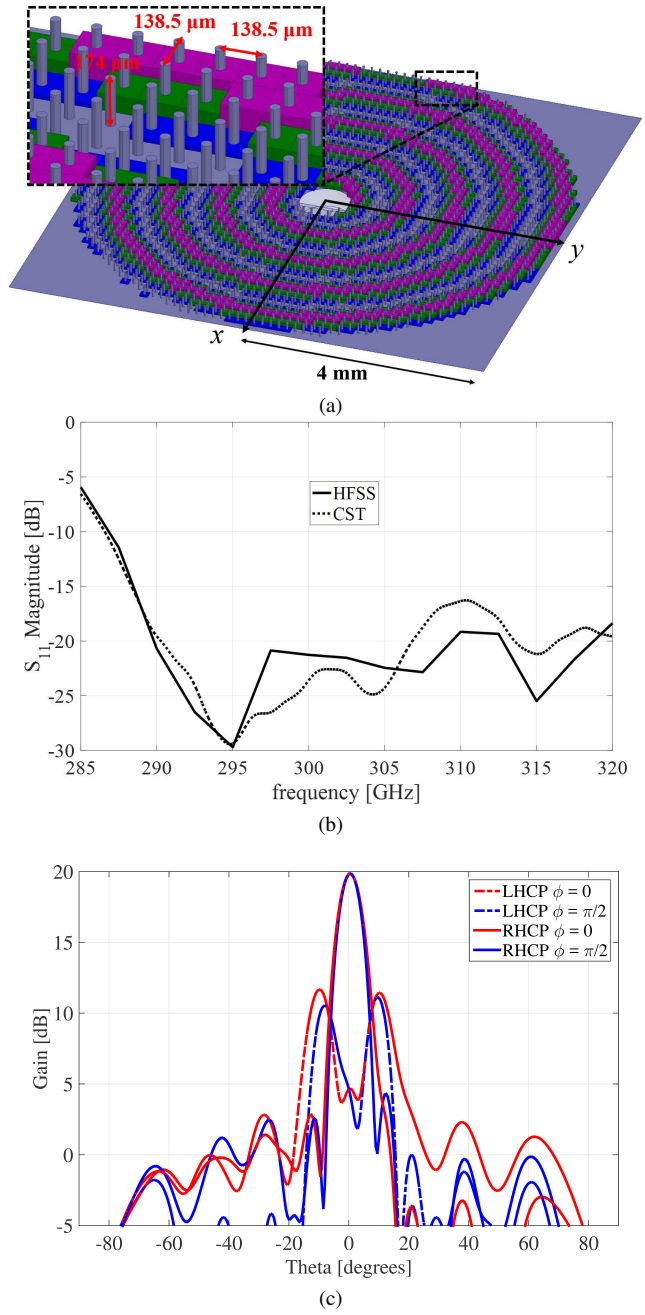

Fig. 2. (a) Simulated spiral modulated MTS antenna, (b) Magnitude of the S_{11} in dB at the input RW port of the antenna, HFSS (solid) and CST (dots) simulation results, (c) Right-handed circular polarized (RHCP) and left-handed circular polarized (LHCP) gain patterns at 300 GHz plotted with solid and dashed lines, respectively, on two orthogonal cuts.

(6) and the data in Fig. 1. The structure is shown in Fig. 2a, where each color represents a different height of the cylinders.

The antenna is fed with a overmoded CW with only the TM_{01} mode propagating, this mode provides an efficient excitation of the TM surface wave on the MTS plane, while avoiding the use of a coaxial feed. The feeder (not shown here) is placed underneath the MTS and it transforms the TE_{10} mode in the input RW to the TM_{01} in the CW. The S_{11} obtained with the aforementioned feeding structure is shown in Fig. 2b. CST Microwave Studio [8] and HFSS [9] have been

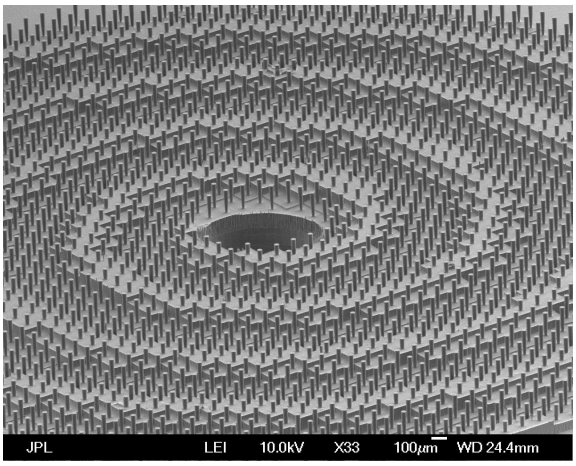

Fig. 3. SEM picture of the DRIE fabricated antenna.

used to simulate the antenna, the obtained results are in good agreement. The far-field gain patterns have been computed with HFSS [9] and they are shown in Fig. 2c for two orthogonal planes at 300 GHz. A similar performance has been verified for the patterns in the rest of the 290-315 GHz band.

The structure shown in Fig. 2a has been fabricated at the Microdevices Laboratory (MDL) of the Jet Propulsion Laboratory using deep reactive ion etching (DRIE). DRIE has been applied in the past to manufacture silicon micromachined waveguide components, which provided an excellent performance in the sub-millimeter wave range [10]. To render the DRIE fabrication of the spiral antenna possible, we have sampled the cylinder's heights so to have just four etching steps. Since the process is based on etching, one may argue that it is challenging to maintain straight sidewalls and uniform depth across the wafer for each depth step. Nevertheless, these drawbacks can be overcome by extensive process development as shown in [11]. Fig. 3 depicts a scanning electron microscope (SEM) picture of the central region of the antenna. After carrying out the desired number of etching steps, 2 μm of gold has been deposited by sputtering to metalize the structure. The MTS antenna is then assembled in a fixture that will allow one to mount it in the measurement set-up. Measured radiation patterns will be available by the time of the conference.

IV. Conclusion

A bed of nails MTS made of metallic cylinders with circular cross-section has been used to design a spiral modulated MTS antenna at 300 GHz. By using a fully metallic structure, we overcome the losses of conventional dielectric substrates in the sub-millimeter wave range. The proposed antenna is excited by means of an original feeding scheme, which is compatible with rectangular waveguide output of solid-state frequency-multiplied sources. The performance of the bed of nails MTS antenna has been verified using full-wave commercial software, and a prototype has been micromachined out of a silicon wafer by means of deep reactive ion etching (DRIE) using the Microdevices Laboratory facilities at the Jet Propulsion Laboratory. This prototype will be shortly tested, and the measured radiation patterns presented at the conference.

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