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Water-Based Microwave Reflectarrays

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***Abstract*— Control of transmission/reflection of waves continues to be a task of great importance. Especially, 2-D structures such as metasurfaces, with imprinted spatial phase variation coming from arrays of small metallic/dielectric scatterers, are of increasing interest for microwave as well as optical frequencies. In this work, we demonstrate alternative and simple metasurface reflectarrays based on distilled water. The reflectarrays are composed of water-filled cylinders which are operated around their magnetic dipole resonance. The cylinders reside in a Rohacell 51HF host, and their size varies in order to span a 360º interval in the reflection phase. They reflect a normally incident plane wave at an angle of 51.34°. The numerical results predict a total reflected power of 36.9% with the reflection in the desired direction being more than 13 times larger than the reflections in other directions. A prototype was fabricated, with the measurements being in excellent agreement with the numerical results.**

***Index Terms*—reflectarray, metasurface, water-based.**

I. INTRODUCTION

Although electromagnetic wave front control has been studied for decades, it continues to be of great scientific and technological importance [1]–[5]. In particular, flat structures modifying the wave front over a fraction of the wavelength have seen an increased interest due to the introduction of metasurfaces (MSs). Initially, these structures were designed primarily for optical frequencies. However, several designs for microwave frequencies have also been demonstrated. Important realized functionalities included the so-called anomalous wave reflection and transmission in accordance to the generalized Snell's laws; these are also known as reflect- and transmitarrays. In all cases, the MSs consist of arrays of scatterers (inclusions) which introduce required spatial phase shifts across their surface in order to control the directions of scattered waves. In many instances, the scatterers were made of metals, while several all-dielectric versions have been reported recently due to their low losses [1]–[3]. These all-dielectric MSs make use of Mie-resonances which can be effectively induced in high-permittivity inclusions of small size.

In optics, the range of high-permittivity materials is limited, whereas plenty exists at microwave frequencies [3]. Still, expensive and low-loss ceramic-like dielectrics are normally chosen for microwave systems. On the other hand, a cheap, abundant and natural material like distilled water can also be used. Its frequency- and temperature-dependent permittivity makes it an interesting material for many microwave technologies like metamaterials (MMs) [6] and MSs [7]–[10], dielectric resonator antennas [11] and heating systems [12], to mention a few.

The present work investigates simple water-based MS reflectarrays operating at 1 GHz and at room temperature (20 °C). The reflectarrays consist of arrays of water cylinders with varying sizes contained in a Rohacell 51 HF foam block and being backed by a conducting ground plane. The desired phase shift across the reflectarray is achieved around a magnetic dipole resonance induced in the water cylinders. Two designs are considered: one with the cylinder height variation and another with the cylinder radius variation. The two reflectarrays are designed to reflect a normally incident wave at a reflection angle of 51.34°, and they both exhibit a pronounced reflection in the desired direction. The total reflected power is 36.9 % for both reflectarrays with the reflection in the desired direction being more than 13 times larger than the reflections in all other directions. The power that is not reflected is dissipated as heat in the water. The highly resonant cylinders reduce the total reflection efficiency of the reflectarray due to the water losses. A prototype of the reflectarray with varying cylinder heights was fabricated and the measurements exhibit an excellent agreement with the numerical results.

The paper is organized as follows. Section II introduces the water-based MS reflectarray. Section III presents the numerical and experimental results. Section IV includes a summary and conclusions of this work. Throughout the work, the time-factor exp($j\omega t$), where ω is the angular frequency, and t is the time, is assumed and suppressed.

II. CONFIGURATION

The reflectarrays are composed of a rectangular lattice of cylinders filled with water in a Rohacell 51 HF medium. One period (super cell) of a reflectarray consisting of N cylinders with varying heights is sketched in Fig. 1. A Cartesian coordinate system is introduced as shown in Fig. 1. Each cylinder is displaced by a and the lattice constants are a in the y–direction and Na in the x–direction. The generalized Snell's law of reflection yields $\sin\theta_{\rm r} - \sin\theta_{\rm i} = \Delta\phi/k_0 a$ with $\theta_{\rm r}$ and $\theta_{\rm i}$ being the reflected and incident angles, respectively, k_0 being the wavenumber and $\Delta\phi = 360°/N$ being the phase-jump between the cylinders in the super cell. We introduce a total phase shift of 360° across the super cell by varying either the height ($h_{\rm cyl}$) or the radius ($r_{\rm cyl}$) of cylinders. To enhance the reflection, the transmission is cancelled by backing the cylinders with a conducting ground plane, cf., Fig. 1.

A model of the reflectarray is built in COMSOL Multiphysics 5.3 [13], which is used for the numerical calculations. The model consists of one super-cell placed in PML-supported free-space and backed by a Perfect Electric Conductor (PEC) as the conducting ground plane. Floquet periodic boundary conditions are used to render the periodicity of the structure, and the incident field is defined by a background field. The permittivity of water is described by the Debye model [14] and the permittivity of the Rohacell 51 HF medium is set to 1.075 [9]. In this work, we consider a linearly x–polarized plane wave illumination at normal incidence (θ_i = 0); the field magnitude is 1 V/m and the frequency is set to 1 GHz.

III. Results

Two reflectarrays have been designed: In Design A, the height of the cylinders is varied, whereas in Design B the radius is varied. First, we identify the height and radius values which introduce the required reflection phase variation. This is done by reducing the array to a square lattice of identical cylinders (N = 1) and sweeping the height (while keeping r_{cyl} = 20 mm) and the radius (while keeping h_{cyl} = 20 mm) of the cylinders. The lattice constant is a = 48 mm and the water temperature is set to 20 °C. The resulting reflection coefficients (S_{11}) are shown in Fig. 2(a). Nearly 360° phase evolution is achieved, albeit with a varying magnitude. This is attributed to a magnetic dipole excited within each cylinder. At resonance, the absorption is maximum causing the reduction in the reflection observed in Fig. 2(a). The magnitude of the total electric field is shown in the xy–plane for the resonant cylinder with r_{cyl} = 20 mm and h_{cyl} = 10.7 mm in Fig. 2(b).

With the data in Fig. 2 we can engineer the reflectarrays for many different reflection angles. Presently, we use a super cell with 8 cylinders, i.e., $\Delta\phi$ = 45°, which according to the generalized Snell's reflection law give a reflection angle of 51.34°. The respective height and radius values are found in Table 1. The performance of the reflectarrays is evaluated through the plane wave spectrum of the instantaneous scattered field which is shown in Fig. 3(a) as a function of the reflection angle. The calculation is done by performing a Fourier transform of the amplitude of the instantaneous scattered field along a line parallel to the x–axis. We observe reflections in three angular directions: one at 0° (normal) and two at ±51.34°. The total reflected power is 36.9 % for both reflectarrays with the reflection at 51.34° being more than 13 (260) times larger than the reflection at 0° (–51.34°). The power that is not reflected is dissipated as heat in the water. In addition, the instantaneous scattered electric field in the xz-plane for Design A is shown in Fig. 3(b) confirming the dominant reflected wave in the desired direction. Arrows showing the direction of the normalized time-average reflected Poynting vector are included.

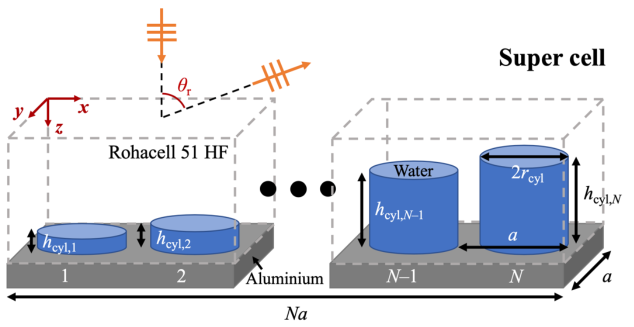

Fig. 1. Sketch of one super cell of the reflectarray with varying cylinder height (Design A).

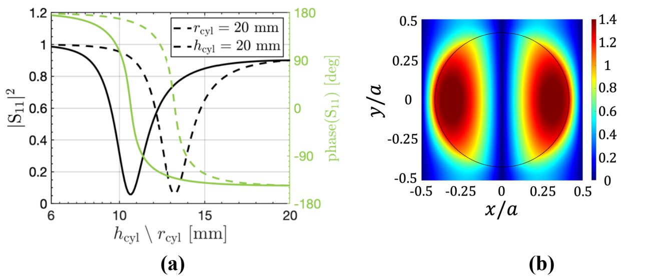

Fig. 2. Numerical results for the square lattice of identical cylinders. In (a) the magnitude squared and phase of the reflection coefficient is shown as a function of h_{cyl} (constant r_{cyl}) and r_{cyl} (constant h_{cyl}). In (b) the electric field magnitude is shown in the xy–plane (just above the aluminium plate) for the resonant cylinder with r_{cyl} = 20 mm and h_{cyl} = 10.7 mm.

Design A is not only superior in terms of performance, but also from a fabrication point of view as drilling/milling cylindrical cavities of different radii is more challenging. Furthermore, Design A is also more flexible as the number of cylinders in the super cell can be increased/decreased through control of the heights, and hence, the reflection angle can be tuned. We envision that the height control of the water cylinders can be done by using pistons, but this tunability was not investigated in this work. Presently, a prototype of Design A was fabricated with the total structure consisting of 4 super cells. The reflectarray was realized by simply milling identical cylindrical cavities in a Rohacell 51 HF block, and then filling them with the required amount of distilled water. A photograph of the reflectarray is shown in Fig. 4(a). To measure the reflection properties, we have built an experimental setup consisting of two horn antennas mounted on an aluminum beam positioned above the reflectarray as sketched in Fig. 4(b). A two-port system was defined with the antenna directly above the reflectarray being Port 1 (P_1) and the other being Port 2 (P_2). By moving the antenna of P_2 along the beam, the obliquely reflected power was measured at different angles. The measurement result is shown in Fig. 4(b) by the reflected power at different angles. The values have been normalized with the background reflections, where the reflectarray was removed. Even

TABLE I. Design A (**A**) with height variation (r_{cyl} = 20 mm) and Design B (**B**) with radius variation (h_{cyl} = 20 mm).

Cylinder no.		**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
A	h_{cyl} [mm]	6.0	9.6	10.2	10.5	10.7	10.9	11.5	14.7
B	r_{cyl} [mm]	6.0	12.1	12.8	13.1	13.3	13.5	14.0	16.3

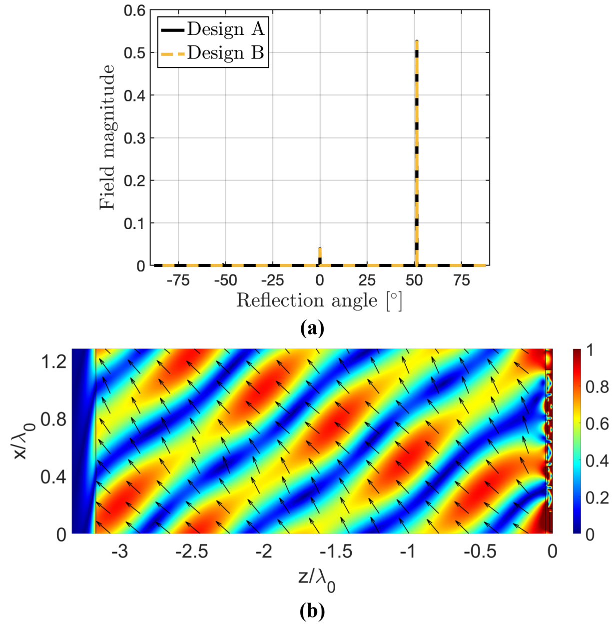

Fig. 3. (a) Plane wave spektrum of both reflectarrays. (b) Magnitude of the instanteneous reflected field (colors) in the *xz*–plane of one super cell of Design A. The arrows show the direction of the normalized time-average reflected Poynting vector.

though the reflectarray only consists of 4 super cells, we were still able to measure a pronounced reflection at an angle of 52° confirming the numerical predictions. The reflected power in the desired direction is approximately 4 times higher than that in the normal direction.

Additional details on the numerical and experimental mode, as well as on the numerical results showing an improved performance with the increase of water temperature will be discussed at the presentation.

IV. Summary and Conclusions

Two water-based MS reflectarrays were investigated exhibiting a strong reflection in the desired direction of 51.34° with a normal plane wave incidence. The reflectarrays were based on water cylinders operated around their magnetic dipole resonance; the cylinders resided in a Rohacell 51 HF host medium. The only difference between the reflectarrays was the geometrical variation of the cylinders (height vs. radius) used to achieve the spatial reflection phase shift across the array. The numerical results predicted a total reflected power of 36.9 % for both reflectarrays with the reflection in the desired direction being more than 13 times larger than the reflections in all other directions. A prototype of the reflectarray with varying cylinder heights was fabricated, and the measurements confirmed the strong reflection in the desired direction. At last, we discussed how the water-based reflectarray easily can be reconfigured for other reflection angles by employing a piston system. We believe that the proposed reflectarrays may serve as cheap and easy–to–fabricate tunable alternatives for VHF and UHF bands.

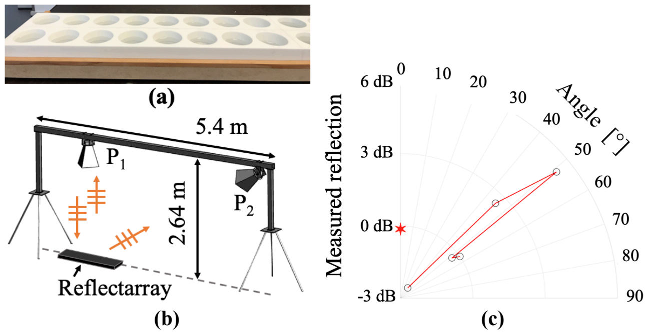

Fig. 4. (a) Photograph of the fabricated reflectarray (Design A), (b) sketch of the experimental setup and (c) measured normalized reflected wave shown in the logarithmic scale.

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