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Abstract. Here we report results on numerical investigation of the all-dielectric metasurfaces based on water. Two different functionalities of the water-based metasurfaces are shown: focusing an anomalous reflection of the electromagnetic wave. Metasurfaces are comprised of dielectric bianisotropic resonators and operate at microwave frequency.

1. Introduction

The metasurfaces made of high-index materials attracted a lot of attention due to their high efficiency in wave manipulation, diversified functionality, relatively simple fabrication and compact size [1]. Moreover all-dielectric metasurfaces exhibit no Ohmic losses and are fully compatible with standard industrial semiconductor technology. All-dielectric metasurfaces are usually made of sub-wavelength dielectric particles exhibiting Mie resonances. Combination of different Mie modes and Fabry-Perot resonances make it possible to use all-dielectric metasurfaces in controlling emitted radiation in both forward and backward directions, near-field engineering, enhancement of linear and nonlinear effects [2, 3].

In order to form homogeneous metasurface with closely packed sub wavelength resonant particle,s high-permittivity material should be used for resonators. While semiconductor is most common material for optical range [4], in microwave region high-index ceramics is usually used. It was recently shown that even usual water can be used as a constituent material for microwave metamaterials [5]. Water-based metasurfaces were shown be able to act as microwave absorbers [6, 7], tunable filter [8], exhibit torroidal response [9].

In this work we demonstrate water-based reflective metasurfaces with two different functionalities: a metasurface for focusing the reflected incident wave (focusing metamirror) and a metasurface anomalously reflecting normally incident waves (reflective metamirror).

2. Focusing metamirror

The focusing metamirror is composed of the dielectric bianisotropic particles arrange in a square array (Fig. 1). The shape of each particle has a form of cylinder of the height $H$ and radius $R$ with a notch inside having the depth $h$ and the radius $r$ (see inset to Fig. 1). The dielectric properties of the particles are the same as for distilled water at the temperature $25^\circ$: $\varepsilon = 78$, $\mu = 1$, electric conductivity $\sigma = 1.59$ [S/m]. The period of the array is $a = 15$ mm. Note that period should be less than half of the operating wavelength to avoid undesired reflection.
Figure 1. Focusing metamirror comprised of the array of 21x21 bianisotropic dielectric water particles. Inset is showing a quarter cut-off of a single particle.

Figure 2. $|E_x|$-field component in the $yz$-plane in the middle of the metamirror. Focal spot is clearly visible at the distance $3\lambda$ from the metamirror which is positioned in the $xy$ plane at $z = 0$.

Metasurface achieves focusing functionality by incorporating parabolic profile of the reflection phase on its surface providing constructive interference of the reflected field at a focal point in front of the metasurface:

$$\varphi(r_0) = \varphi_0 + \frac{2\pi}{\lambda}\sqrt{r_0^2 + F^2}, \quad (1)$$

where $\varphi$ is a desired phase shift, $r_0$ is the distance from the lens center to the point at the surface of the lens, $F$ is focal distance, $\lambda$ is the operational wavelength and $\varphi_0$ is an arbitrary constant phase.

In order to get required phase shift the dimensions or permittivity of the particles should be varied. For given particle geometry the most convenient is to change the outer $R$ and the inner $r$ radii while keeping height constant. Required phases can be calculated by numerical simulation of the single particle with imposed unit cell boundary conditions. The final geometry of the each particle is defined by two conditions: minimum difference between required and obtained phase and maximum value of the reflection coefficient. The operation frequency of the was chosen to be 4 GHz. Corresponding calculated dimensions are $H = 5.2$ mm and $h = 2.8$ mm with the radii varying in the range $r = 0.5 \div 6.4$ mm and $R = 6 \div 7.4$ mm.

Finite size metasurface consisting of 21x21 particles has been then numerically simulated with the time integral equation solver of CST Microwave Studio. Open boundaries have been imposed from all directions and plane wave has been chosen as the excitation source. The performance of the designed optical metamirror is demonstrated in Fig. 2 where $|E_x|$-field component of the reflected incident field is plotted. The reflected field has a maximum at a distance $3\lambda$ from the metasurface.

3. Reflective metamirror

Next we have designed a metamirror to reflect normally incident plane wave to an chosen angle $\vartheta = 45^\circ$ from the normal. From the generalized Snell’s law [10] we can define the angle $\vartheta_r$ of the reflected wave for the case of normally incident wave and the periodic structure with the
period $a$:
\[
\sin \theta_r = \frac{\lambda_0}{aN}
\]  
(2)

where $N$ is the number of cells within the range of wavelength, and $\lambda_0$ is the wavelength in vacuum. According to Eq. (2), the reflection angle $\theta_r$ can be tuned only by changing the number of elements $N$ and the unit period $a$. To design the metasurface similar bianisotropic elements as in previous section have been used arranged with the period $a = 15$ mm. Correspondingly 7 elements with different dimensions were chosen to provide required set of phases changing from $0^\circ$ to $360^\circ$ (Fig. 3). An array consisting of 9 supercells has been numerically simulated under TE-polarised plane wave excitation. To reduce calculation time periodic boundaries have been imposed along $y$-direction. The results in a form of the real value of $H_z$ field component is shown in Fig. (4) for the frequency $f = 4$ GHz. The white arrow represents the reflected wave which is equal to $\theta_r = 45^\circ$ corresponding to the designed value.

Figure 3. Distribution of the reflection phase over metasurface (for 3 supercells).

Figure 4. $z$-component of the magnetic field of the reflection metasurface (9 supercells) in the $xz$ plane at $z = 0$.

4. Conclusion

It was shown by numerical simulation that simple distilled water can be used as a material to design all-dielectric metasurfaces. Two common features has been demonstrated including focusing and anomalous reflection of the reflected waves. There are no fundamental limitations in using water as a dielectric for different types of metasurfaces. This material opens an opportunity to design out-of-band transparent tunable cheap large-scale microwave metasurfaces.

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