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An Alternative to Huygens' Meta-Atoms: Transmitarray with Only Electric Response

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Abstract – Huygens' meta-atoms are key elements for obtaining full power transmission through metasurfaces with full control over the transmission phase. Conventional Huygens' meta-atoms use spectrally overlapped magnetic and electric resonances. However, realization of this approach is challenging due to several drawbacks including different bandwidth and mutual coupling of the resonances. In this talk, we study metasurfaces comprised of elementary electric dipoles and discuss ways of obtaining the functionality of Huygens' meta-atoms without the use of magnetic response. We show that this approach is beneficial considering frequency bandwidth and the inclusions size. Finally, we present a design of an optical transmitarray that bends normally incident waves at 45° angle.

I. INTRODUCTION

Metasurfaces can potentially enable ultimate manipulation of light including control of wave intensity, polarization and propagation direction. Realization of inclusions that enable high transmission amplitude and full phase control of 2π is necessary for high-efficiency wave shaping in transmission. Local modulation of phase and amplitude for polarization-preserving, reflectionless metasurfaces with a complete 2π transmission phase coverage can be realized using Huygens' meta-atoms. A Huygens' meta-atom is designed so that tangential electric and magnetic moments are induced simultaneously upon external plane-wave excitation. The resonances of both induced dipoles should spectrally overlap and the dipole amplitudes should satisfy the balance condition [1–4]. However, it is challenging to design such inclusions because of strong mutual coupling of the modes. In addition to that, the origins of magnetic and electric dipole resonances are different which results in different bandwidths of the resonances. However, in Ref. [5] similarities between the response of normal and tangential electric dipoles were noticed and in Ref. [6] it was proposed to use only electric responses in order to get full power transmission with a complete phase coverage. Worth to note that among other benefits this approach allows us to reduce the physical size of the meta-atoms.

In this talk we present the main ideas of paper [6] and show, as an example, theoretical values of reflection coefficients will be obtained and compared with simulations of an array of dielectric bars. Using the approach proposed in [6], we will demonstrate meta-atoms that use only electric response meanwhile enabling full control over the amplitude and phase of transmitted waves. Finally, we will present a design of a transmitarray that bends light at 45°.

II. SCATTERING BY ARRAYS OF ELECTRIC DIPOLES

The thickness of considered metasurfaces is small compared to the wavelength and the period is subwavelength, therefore we can model them using the generalized sheet transition conditions (GSTC). These conditions relate the jumps of the tangential components of electric and magnetic fields ($\mathbf{E}_t$ and $\mathbf{M}_t$) across the metasurface with induced polarizations. In the general case, four polarization vectors should be considered: tangential and normal electric: $\mathbf{P}_t$ and P_n , and tangential and normal magnetic: $\mathbf{M}_t$ and M_n . The GSTC read:

$$\begin{aligned}\mathbf{E}_t^+ - \mathbf{E}_t^- &= j\omega \mathbf{n} \times \mathbf{M}_t - \nabla_t \frac{P_n}{\varepsilon}, \\ \mathbf{n} \times \mathbf{H}_t^+ - \mathbf{n} \times \mathbf{H}_t^- &= j\omega \mathbf{P}_t + \nabla_t \times \mathbf{n} \frac{M_n}{\mu},\end{aligned}\tag{1}$$

where ω is the angular frequency, $\mathbf{n}$ is the unit vector normal to the metasurface, ϵ and μ are the dielectric permittivity and permeability of the host medium, and superscripts $+$ and $-$ denote the field components above and below the metasurface.

Let us consider metasurfaces where only electric polarization can be induced and study separately two cases, first $\mathbf{P}_t \neq 0$, $P_n = 0$, and second $P_n \neq 0$, $\mathbf{P}_t = 0$. In the first case, the polarizability of a dipole in the array ($\hat{\alpha}$) can be expressed in terms of the interaction constant β and polarizability of a single dipole in free space α ,

$$\frac{1}{\eta \hat{\alpha}} = \frac{1}{\eta} \operatorname{Re} \left(\frac{1}{\alpha} - \beta \right) + \frac{j\omega}{2S} \cos \theta^i, \quad (2)$$

where η is the free-space intrinsic impedance, S represents the unit-cell area, and θ^i is angle of incidence. This allows to find the reflection coefficient from such an array:

$$R = -\frac{j\omega\eta}{2S} \hat{\alpha} \cos \theta^i. \quad (3)$$

Array of normally oriented dipoles represents the case when $P_n \neq 0$ and $\mathbf{P}_t = 0$. Considering excitation by obliquely incident plane wave of TM polarization, the polarizability of a dipole in the array can be expressed in a similar way:

$$\frac{1}{\eta \hat{\alpha}} = \frac{1}{\eta} \operatorname{Re} \left(\frac{1}{\alpha} - \beta \right) + \frac{j\omega \sin^2 \theta^i}{2S \cos \theta^i}. \quad (4)$$

Fig. 1: (a) - Reflection spectrum of an array of infinitely long dielectric bars illuminated obliquely at the angle of $\theta^i = 45^\circ$. Refractive index of the dielectric material is $n = 6$, the periodicity is $a = 730$ nm, the width is $w = 300$ nm and the height is $h = 360$ nm. Insets show electric field distributions at the resonances (157 THz and 177 THz). The arrows show directions of the induced dipole moments. (b) and (c) - Transmission amplitude and phase for varied dimensions of the bars made of amorphous silicon ($n = 3.48$). (d) - Design of a transmitarray formed by silicon bars, operating at the wavelength $\lambda = 1.55 \mu\text{m}$. The width and the height of the left bar are 478 nm and 712 nm; of the central one - 417 nm and 501 nm; of the right one - 728 nm and 214 nm.

Under given conditions, the reflection coefficient can be derived from the GSTC in Eq. 1 as

$$R = \frac{j\omega\eta}{2S} \hat{\alpha} \frac{\sin^2 \theta^i}{\cos \theta^i}. \quad (5)$$

Reflection coefficients in Eqs. (3) and (5) allow to study the phase of reflected waves of such arrays. On this basis it is possible to draw an analogy between an array of lossless tangential electric dipoles at resonance and an electric wall, because the phase of the reflected wave in both cases is π . An array of resonant normal electric dipoles mimics a magnetic wall, because the phase of the reflected field is 0. Thus, an array of normally oriented electric dipoles can play the role of magnetic dipoles in Huygens' metasurfaces.

Let us now consider a model structure composed of dielectric bars with refractive index $n = 6$. Illuminating this structure obliquely by a plane wave of TM polarization, both tangential and normal electric dipoles can be induced. Figure 1(a) shows reflection spectrum of such structure and electric field distributions at the resonant frequencies, which confirm our theoretical predictions.

III. WAVEFRONT SHAPING

Overlapping both electric dipole resonances it is possible to achieve full power transmission with 2π phase coverage enabling full control over transmitted light [6]. In addition to identical bandwidth of the resonances there is one more advantage. Considering dielectric structures in the optical domain, this approach allows us to reduce the physical dimensions of the inclusions, since electric resonances occur at higher frequencies. Let us now show applicability of this approach by designing a transmitarray operating at the wavelength $1.55 \mu\text{m}$ based on only electric response. Amorphous silicon ($n = 3.48$) will be used as a dielectric material for bars. According to the generalized law of refraction, transmission phase imparted to the incident wave should be varied in the 2π range. Varying dimensions of infinitely long dielectric bars it is possible to adjust the desired phase ensuring high transmission amplitude. The black line in Figs. 1(b) and (c) marks dimensions of the bars suitable for the transmitarray design. Choosing three bars with appropriate dimensions a transmitarray operating at the wavelength of $1.55 \mu\text{m}$ is obtained. The following optimization of the transmitted power adjusts the dimensions of the bars. Figure 1 shows electric field distribution cast by the optimized structure. The efficiency of 88% for the final design was achieved, meaning that 88% of the incident power at the angle $\theta^i = 45^\circ$ couples to the desired mode at the angle of $\theta^t = 0^\circ$.

IV. CONCLUSION

In conclusion, we have drawn an analogy between an array of resonant normal electric dipoles and a magnetic wall. It has been shown that utilizing this approach allows designing meta-atoms that provide high transmission amplitude with a complete 2π -phase coverage. Furthermore, we have presented an example of new optical transmitarrays that allows full wave control. In our talk we will demonstrate the fabricated structure and present experimental results on its performance.

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