High-index dielectric Huygens metasurface

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***Abstract*— We describe a dielectric Huygens metasurfaces capable to manipulate light in the visible regime with 100% transmission efficiency. The metasurface is comprised of TiO_2 cylindrical nanoparticles embedded in a medium with lower refraction index. The interaction between dielectric disks is considered and it is used as a parameter to optimize the optical properties of the metasurface.**

Keywords—metasurfaces; dielectric particles; Huygens surface; flat lenses; MEMS;

I. Introduction

Metasurfaces offer unique possibilities to manipulate light by controlling the amplitude, phase and polarization of an impinging electromagnetic wave. They work by introducing local discontinuities in the wavefront of a propagating electromagnetic wave, thus altering its behavior to constitute a new wavefront [1]. In its most recent implementation [1], metallic resonant nanoscale antennas were used to introduce local phase shifts determined by the size and shape of the nanoscale antenna. By choosing the length and shape of the metallic antenna it is possible to control the phase of the resonator's current and thus to tune the phase of the local scattered wave between 0 and 2π. Although metallic resonators have been very useful to demonstrate the feasibility of the concept, the intrinsic dissipative losses of metals in the IR and visible wavelength region make these metasurfaces very inefficient for light manipulation [2]. High-index dielectric nanoparticles are an interesting alternative to metallic particles because they exhibit strong electric and magnetic optical resonances in the IR and visible range with the advantage of not having metallic losses. Moreover, it has been shown [3] that when the spectral characteristics of both resonances are the same, dielectric particles will produce perfect forward scattering with no light reflected back. In this work, we study a dielectric metasurfaces consisting of TiO_2 cylinders that act as a Huygens' surface when illuminated with visible light. We describe the effect that the resonator geometry and its surrounding medium have on the optical response of the metasurfaces, and the possibilities that can be achieved by integrating them onto MEMS devices.

II. Huygens metasurface

A. Hyugens' resonators

Huygens' principle, that every point on a wavefront can be considered a secondary source of spherical wavelets, has helped to understand a large variety of optical phenomena, including diffraction problems, antenna design, imaging and communications [4]. It has been demonstrated that when each individual point source emits a radiation pattern corresponding to an electric dipole oscillating perpendicularly to a magnetic one, the integrated emitted radiation propagates exclusively in the forward direction [5]. Since dielectric nanoparticles exhibit strong electrical and magnetic resonances in the visible, they can be use to implement nanostructured metasurfaces that will act as Huygens' surfaces in this wavelength region. A high-index dielectric cylindrical particle, when illuminated along its axis of symmetry, will exhibit an electric dipolar (ED) and magnetic dipolar (MD) resonance whose spectral position can be controlled by changing the geometry of the particle [6]. By modeling the dielectric cylindrical particle as having an electrical dipole in the x-direction and magnetic dipole in the y-direction, it is possible to calculate the intensity and phase of the scattered light after illumination by a plane wave propagating along its symmetry axis [7].

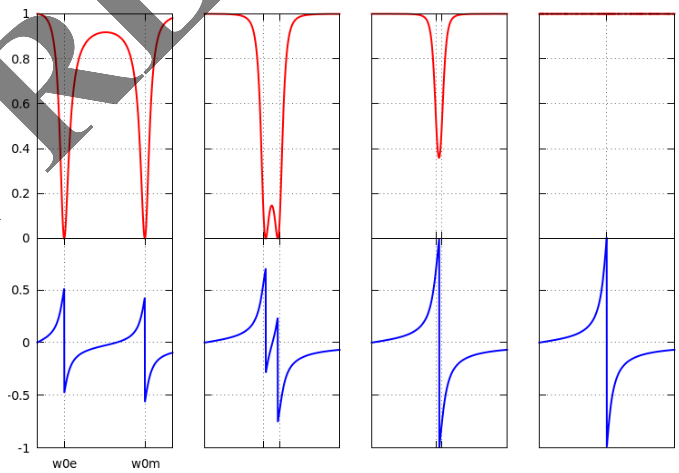

Fig. 1. Intensity (red curves) and phase (blue curves) of the light transmitted by a dielectric nanoparticle having different relative position of its ED and MD resonances. Each column represents a sititation where the resonances occurs at different frequency. When the spectral response of the ED and MD are the same, right side panel, 100% transmission of the light is observed and a 2π phase shift is imposed.

In Fig. 1, we plot the intensity (red lines) and phase (blue lines) of the wave scattered by a dielectric cylinders having ED and MD resonances occurring at different frequencies. When the resonances are well separated spectrally, corresponding to the left panel of Fig. 1, at each particular resonance the intensity of the transmitted light become zero and the phase changes in π [8]. As the spectral position of the resonances gets closer, the transmitted light still is suppressed at each

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resonance, but the change in phase increases gradually from π to 2π, as seen in the central panels of Fig. 1. When both resonances coincide spectrally, i.e., same frequency and quality factor Q, the incident light undergoes a full 2π phase shift and is completely transmitted (Fig. 1- right panel).

B. Huygens' metasurface design

In order to design a Huygens metasurfaces that can efficiently work at visible wavelengths we need to identify a dielectric material whose optical response can be tailored to have an ED and MD resonance at the same spectral position. TiO_2 is an oxide with larger refraction index (2.5) in the visible that is fully compatible with standard fabrication processes, making it a good candidate to implement Huygens' metasurfaces.

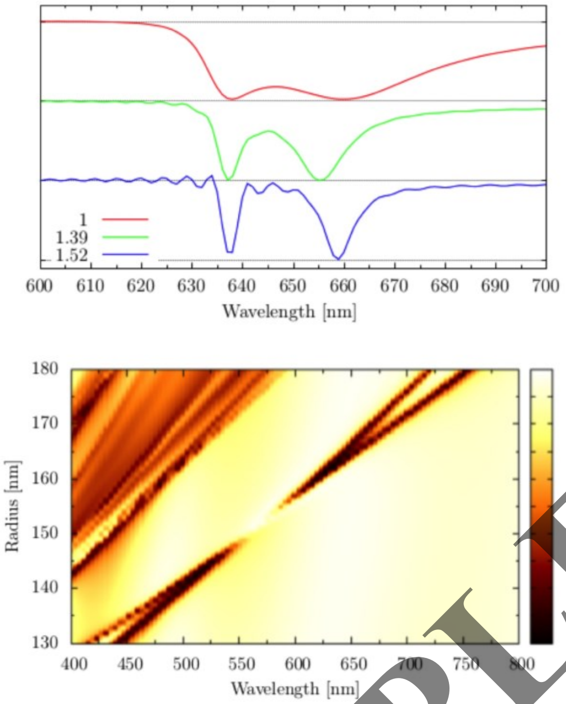

Fig. 2. Upper panel: Intensity of the light transmitted by a square array of TiO_2 cylindrical resonators for different enclosing materials. Lower panel: Intensity of the light transmitted by a square array of TiO_2 resonators immersed in a medium with n_m=1.39. The disc height is fixed at 142nm.

The optical response of TiO_2 cylindrical particles in air presents a single broad resonance typical of low Q resonators dominated by radiative losses. While radiative losses represent an important source of dissipation in single dielectric particles in air, they can be use to control the interaction between nanoparticles in arrays. This effect is clearly seen in Fig. 2 (upper panel) where we show the intensity of the transmitted light by a metasurface consisting of a square array of TiO_2 cylindrical resonators embedded in a medium of refraction index n_m. As the index of the medium surrounding the dielectric particles increases, the electromagnetic fields of each resonator extend beyond each single nanoparticle volume and the near-field coupling between resonators needs to be taken into account. This interaction between resonators is extremely beneficial since it increases the Q of the dipolar resonances and allows precise identification between the ED and the MD response (Fig. 2 – upper panel). Results like the ones shown in the upper panel of Fig. 2 can be used to identify the location of the Huygens' condition for specific arrays of dielectric resonators. An example is shown in the lower panel of Fig. 2, where we show the spectrum of the transmitted light for an array of TiO_2 cylindrical nanoparticles embedded in a medium of n_m=1.52, for particles of different radius. The dark lines in this figure represent situations where the intensity of the transmitted light is greatly reduced due to the existence of ED and MD optical resonances. It can be clearly seen that by changing the radius of the TiO_2 cylinders, the relative spectral position of these resonance can be modified and eventually merged for wavelengths near 555nm and particles radius of about 150nm. At this particular point, the Huygens' condition is fulfilled and full transmission efficiency is observed.

III. CONCLUSIONS

We have studied the feasibility of designing a Huygens dielectric metasurface operating in the visible region of the optical spectrum. Metasurfaces like the one studied in this work have tremendous potential to replace conventional bulky optics by creating flat optical components with thickness much thinner than the wavelength of the impinging light. The possibility of integrating them onto MEMS devices would enable flat and agile optical elements with ultra-fast reconfiguration time. Reconfigurable metasurfaces may be achieved using MEMS based spatial light modulators in which individual pixels are patterned with nanostructures having different optical response. By actuating specific sub-sets of pixels, the far-field response of the adaptive metasurfaces can be manipulated.

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