Isotropic Huygens sources made of clusters of nanoparticles for metasurfaces applications

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Abstract. We present spherical clusters, composed by spherical dielectric or metallic inclusions, as a new kind of efficient and isotropic Huygens sources. We demonstrate that this design can allow a large and multimode overlapping of the electric and magnetic resonances excited at visible frequencies. They may also serve as building blocks for metasurface applications. We investigate their possible uses in high transmittance devices requiring a local phase control, and in thin absorber metalattices. They are particularly suited to bottom-up fabrication and self-assembly, offering an alternative to the classical lithography compatible Huygens meta-atom.

1. Introduction

Huygens sources have, during the last years, experienced a renewed interest as they open new possibilities for light manipulation at the nanoscale. Acting as nanoantennas, those objects are characterized by a highly asymmetrical scattering resulting from interferences between their optically induced modes. Dielectric nanoparticles of high refractive index were first proposed as promising candidates for Huygens sources realizations as they can exhibit strong electric and magnetic Mie resonances in the visible or infrared domain. Experimental investigation on Si, GaAs... dielectric spheres [1,2] has indeed demonstrate that unidirectional forward scattering was obtain at the Kerker condition, when the particle possess electric and magnetic dipolar response equal in both magnitude and phase.

However, for those spherical objects, as the involved modes do not spectrally overlap, Kerker condition is satisfied far from the resonances, where light is only weakly scattered. One solution to overcome this low efficiency is to consider anisotropic particles such as ellipsoids, nanodisks, nanobars, cones,... [3-5]. Tuning the aspect ratio of those structures can bring the resonances at the same wavelength, but, because of the break of symmetry, their properties then become dependent on the polarization and incident angle of the light. On the other hand, metallo-dielectric core-shell particles [6] or multi-layered spheres [7] were shown to work as isotropic resonant directional sources.

Our work [8] presents an alternative structure, acting as an efficient isotropic Huygens source, consisting of compact spherical nanoclusters of particles. In section 2, We demonstrate that this design allows spectral overlap of the electric and magnetic resonances of same order in the visible domain or IR. We provide different examples to illustrate that dipolar or extremely broadband sources can be achieved with either metallic or dielectric inclusions. Furthermore, by considering arrays of clusters, we show in section 3, that those elements might constitute interesting building blocks for metasurfaces.
Indeed, silicon clusters in the IR can be used to locally control the phase shift, in a range close to the full interval of $2\pi$, while conserving high transmission, opening the path to the design of wavefront shaping devices. On the other hand, dissipative losses in silicon doubly resonant clusters in visible can be exploited to obtain perfect absorption in this spectral range.

2. Clusters of particles as resonant or broadband Huygens sources with high efficiency

As previously mentioned, we investigate the optical properties of spherical clusters of nanospheres, generated by considering the closest packing of small inclusions interacting repulsively into a large sphere. The scattering of those object is calculated using the T-matrix solver provided by Mackowski [9], based on generalized Mie theory.

Both dielectric and plasmonic clusters can exhibit optically induced magnetic response as well as an electric answer in the visible. In fact, an effective medium theory approach of the problem reveals that such clusters behave as a bulk dielectric homogenous medium which refractive index is mostly determined by the volume fraction of particles. Although it is known that high-refracted index spherical structures possess spectrally isolated resonances, recent work have shown that those resonance can spectrally merge for spherical particles with low index [10,11]. As the effective refractive index can deliberately be engineered in a cluster structure, it is indeed possible to target an optimum value of this parameter to ensure overlapped resonances while keeping a high value of the scattering efficiency. Such a cluster structure also provide more flexibility in term of choice of dispersion compare to the limited choice of natural material of low index for which dispersion are fixed.

Following this idea, we target a peak resonance wavelength of 500 nm, and explored the size and density parameters for the cases of silver and silicon inclusions with the aim of getting overlapped electric and magnetic dipolar resonances. Two examples of designs are presented in figure 1. The first, is a 60-cluster made of silver inclusions in water of radius $r = 15$ nm, with a filling ratio $f = 20\%$. The cluster radius is $R \approx 100$ nm. The second is a 13-cluster with radius $R \approx 123$ nm made of silicon inclusions of radius $r = 41$ nm, with $f = 47\%$ in air. For both designs, Maxwell Garnett effective medium theory indicates an effective refractive index for the structure close to $n+ik = 2+0.1i$.

![Figure 1](image)

**Figure 1.** (a), (b), and (c) are the scattering efficiencies for 3 different clusters. The black curve is the total efficiency, the blue (red) curve is the efficiency of the electric (magnetic) modes. (d), (e) and (f) are the corresponding fractions of total energy scattered in the forward direction.

Figures 1(a) and 1(b) show the total scattering efficiency of both systems. We see that an ideal Huygens dipole is reached in both cases near the designed wavelength, with a total efficiency at the peak around $\sim 2.5$ for the silver cluster and a higher value of $\sim 5$ for the silicon cluster. Figs. 1(d) and 1(e) shows that the scattered energy is radiated in the forward direction on a range of wavelength of about 100nm around the targeted wavelength.
For numerous applications, it is also interesting to maximize the forward scattering over a broad range of wavelengths. This can be realized by exploiting larger amount of mode all interfering destructively. Figure 1(c) and 1(f) present the optical properties of a cluster working as a broad Huygens multipole on a range of 1000 nm covering the visible and near infrared domain. The structure consists on a cluster of radius 300nm of 80 Si inclusions in water, of 50 nm in radius each. The volume fraction is f = 37%. Compare to the 13Si-cluster presented in figure 1(b), the radius of the full cluster has been increased leading to the excitation of much more multipole. At the same time, the volume fraction has been decreased, which induce a lower effective refractive index for the structure which in turn guarantee that electric and magnetic multipole of same order, up to the octupole, overlap two by two.

3. Metasurfaces applications: transparent devices with phase control and perfect absorber

Due to their directional scattering, Huygens sources open the possibility to manipulate transmitted wave, when organized into metalattices [12]. Functionalities such as focusing, beam deflection, vortex beam generation, holography,... are widely explore in the literature [13]. Such metasurfaces rely on the local spatial modulation of the phase, at the scale of a resonator, in order to shape the wavefront of the transmitted wave. At the same time, high transmission is conserved due to the absence of backscattering from the constituent meta-atoms.

![Figure 2. Beam shaping. Map of the electric field normalized to the incident field. Each box is a capture of a unit cell of an array of clusters with a given lattice spacing. Pitch takes value from 1585nm to 1305nm from left to right.](image1)

![Figure 3. Perfect absorber. Absorption, transmission and reflection for an array of silicon Huygens clusters organized in a square lattice.](image2)

The mapping of the norm of the electric field presented in Figure 2, demonstrate that a cluster structure might be a suitable building block for such applications as it is possible to change the phase of the transmitted wave when varying the lattice spacing in an array of clusters. In this situation, we used silicon clusters at a wavelength of 1590nm as silicon exhibit no losses in the IR domain. The radius of the clusters are 390nm and the 13 Si inclusions composing the objects have a size of 129nm in radius. The full wave simulation were performed under COMSOL Multiphysics. The variation of phase in this situation cover a range of 1.7π when changing the pitch of the array from 1305nm to 1585nm, while the transmission is kept to value above 90% due to the overlapped resonances of the clusters at the working wavelength. Other numerical simulations not presented here indicates that it is also possible to obtain a variation of phase of 2π when varying the size of the clusters through a homothetic transformation.

Although high transmittance metadevices rely on lossless elements, it is also well known that lossy Huygens sources can be exploit to build perfect absorbers [14]. In our case, Silicon clusters in the visible domain are suitable candidates as the imaginary part of bulk silicon refractive index is quite high for wavelength below 500nm. Figure 3 present the transmission, reflection and absorption of an array of
clusters designed as a Huygens dipole at the wavelength of 450nm. The cluster radius is 142nm and consist on 13 Si particles of radius 41 nm organized in a lattice with a pitch of 331nm. High intrinsic losses combines to Huygens source behavior allow us to obtain an absorption of nearly 100% at 450nm.

4. Conclusion
We proposed compact assemblies of particles into spherical clusters to fill the lack of Huygens sources with isotropic properties operating at optical frequencies. Both dipolar or broadband multipolar Huygens sources can be achieved with cluster of dielectric or metallic particles. The approach rely on the engineering of the refractive index of the structure rather than its geometrical shape. We believe the cluster structure is a rich system as it is scalable and its optical properties can be tuned by varying the nature, amount, size, and volume fraction of inclusions. We have as well explore ability of silicon cluster to control transmission, in both magnitude and phase, and absorption when organized into metalattices.

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