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## Enhanced forward scattering from magnetic scatterers: design and synthesis of resonant Huygens' sources

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### Abstract

We present optical studies of nano-resonators (meta-atoms) which are designed for a specific control of their angular scattering properties in visible light. Directional scattering is obtained by adjusting the series of odd and even scattering modes. The architecture of the meta-atoms is designed to enhance the magnetic dipolar scattering which appears as the major contribution to the odd modes. Several types of meta-atoms are investigated and their scattering properties are measured. We show that the bottom-up approach enables multiple synthetic strategies and we compare their optical efficiencies.

### 1. Introduction

The manipulation of light by the simultaneous control of the electric and magnetic polarizability of an artificial nanostructure is a fundamental concept of the field of meta-materials. Whereas the electric response of materials to light is ubiquitous, the magnetic response is known to be negligible in natural materials. Enhancing its magnitude is a major challenge. In metamaterial composites, the magnetic response is due to inclusions (or meta-atoms) which are designed to behave like magnetic dipoles upon excitation by the light wave. Significant impacts on light control require electric and magnetic response of high and equivalent magnitude.

The bottom-up approach, based on nanochemistry and self-assembly, has proven its ability to produce magnetic meta-atoms on a large-scale<sup>1,2</sup>. Four different designs have been successfully investigated in our consortium, namely plasmonic raspberries<sup>1</sup>, plasmonic dodecapods<sup>2</sup>, plasmonic nanoclusters<sup>3</sup> and high-index dielectric particles<sup>4</sup>. Successive refinements of the designs and of the syntheses enabled a considerable increase of the magnetic and electric multipolar response. We report here on optical studies which have been developed to characterize the series of multipole scattering modes of these meta-atoms. The correlation between the modal distribution and the directional scattering is explored.

### 2. Optical studies

The scattering properties of the meta-atoms have been measured by a polarization-resolved static light scattering sketched in Fig.1. The scattering data are collected as a function of wavelength, scattering angle and polarization state of the input and output light.

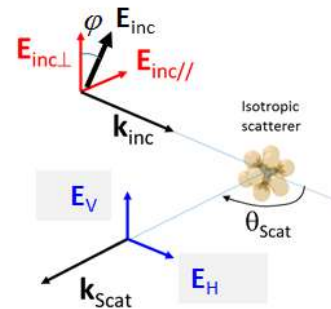


Figure 1: Sketch of the light scattering setup. The scattered light is collected along two orthogonal polarizations  $E_v$  and  $E_h$  to identify odd and even scattering modes.

The analysis of the scattering signals enabled to extract the series of scattering multipoles for the different types of meta-atoms. Figure 2 shows an example obtained for spherical clusters of gold nanoparticles<sup>3</sup>. In this example, the ratio of odd (magnetic dipole MD + electric quadrupole EQ) to even (electric dipole ED) modes reaches 0.7 over a broad frequency range while the total scattering efficiency exceeds 1. The various architectures of the nano-resonators offer some degree of control on the spectral overlap of the different modes.

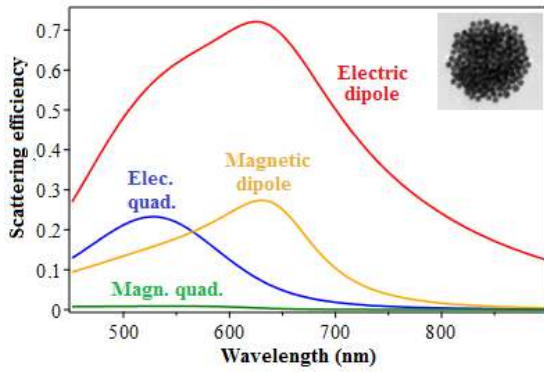


Figure 2: series of scattering multipoles measured on spherical nanoclusters of gold nanoparticles of radius  $7\text{nm}^3$ . The volume fraction of gold in the nanocluster is 46%. The leading contributions arise from the electric ED and magnetic MD dipoles and the electric quadrupole EQ. The magnetic quadrupole MQ and all higher multipoles do not contribute.

### 3. Directional scattering

The Kerker's condition on electric and magnetic dipoles for forward scattering has been worked out in 1983 and later extended to the full series of multipoles<sup>5,6</sup>. The full forward scattering (i.e. zero backscattering) requires a perfect cancellation of odd and even modes<sup>6</sup>. In our systems, the odd modes are MD+EQ and the even mode is ED.

Figure 3 shows that the forward scattering is strongly enhanced upon approaching the generalized Kerker's condition. Indeed, increasing the volume fraction of gold in the nanoclusters enhances the magnetic dipole and the electric quadrupole, hence producing a strong forward scattering. Moreover, the phenomena occur for a high total scattering efficiency, which may open the way to further applications in metasurfaces.

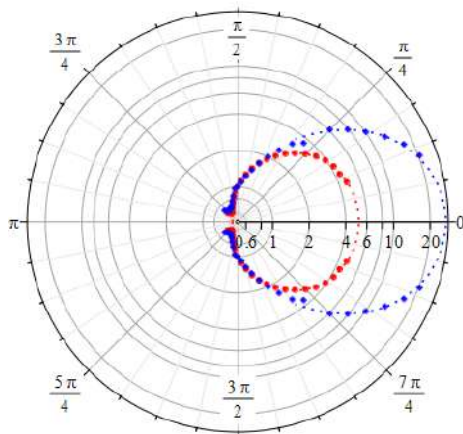


Figure 3: Polar plots in log scale of the experimental scattering from gold nanoclusters. The volume fraction of gold nanoparticles in the clusters is 27% and 46% for the red and blue symbols respectively.

### 4. Conclusions

New generations of resonant magnetic scatterers operating in visible light or near IR are currently produced by nanochemists along several synthetic strategies based on plasmonic or Mie resonances. The bottom-up approach enables a large-scale production at low energetic cost. The spectral overlap of the magnetic and electric resonances can be tuned by appropriate designs which enables a broadband control of the targeted optical property. Scattering efficiencies significantly larger than 1 are consistently obtained. These meta-atoms are intended for applications in self-assembled metasurfaces such as IR filters, phase retarders or broadband super-absorbers.

### Acknowledgements

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