Mariano Pascale

Tutor: Carlo Forestiere

XXXIII Cycle - II year presentation

Modal Analysis of Electromagnetic Scattering from Nanostructures

What qualifies as Nanotechnology today is basic research and development that is happening in laboratories all over the world. Nanotechnology deals with the understanding and control of matter at dimensions between approximately 1 and 100 nanometers, where unique phenomena enable novel applications. Encompassing nanoscale science, engineering, and technology, nanotechnology involves imaging, measuring, modeling, and manipulating matter at this length scale. Unusual physical, chemical, and biological properties emerging in materials at the nanoscale may differ in important ways from the properties of bulk materials and single atoms or molecules, paving the way for groundbreaking developments in many branches of science, from Electrical Engineering to Physics, Chemistry to Biology, from Material Science to Medicine. Advances in the tools that allow atoms and molecules to be examined and probed with great precision, made the nanoscale truly accessible.

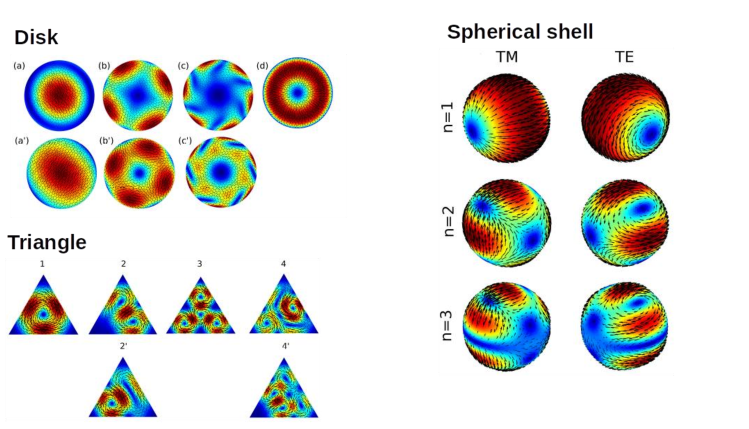
The majority of the effects at the nanoscale are mediated by electromagnetic interactions. Here the Electromagnetic Scattering Theory, which the activity of my research group is mainly focused on, plays a key role in the understanding of the electromagnetic response of nanostructures in one dimension (e.g. nanorods), two dimensions (plate-like shapes like nanocoatings, nanolayers, graphene) and in all three dimensions (nanoparticles). The scattering from metal nanoparticles has been extensively studied in literature, since their great electric field enhancement. Recently, dielectric nanostructures are gaining increasing attention in nanotechnology and many researchers suggest that high index dielectrics may be a cheaper alternative to noble metals for a variety of applications, since the enhancement of electric and magnetic fields is of the same order of magnitude of the one achievable in metal counterparts. However, the physics governing the scattering from dielectric nanoparticles is far richer than the one from metal nanoparticles and some underlying physical phenomena are still obscure.

Our approach to the solution of the electromagnetic scattering from these objects allow a rigorous explanation of the deeply different behaviors exhibited by metal and dielectric structures, whatever is their size compared to the incident radiation's wavelength.

Material Independent Modes for Electromagnetic Scattering

2D STRUCTURES

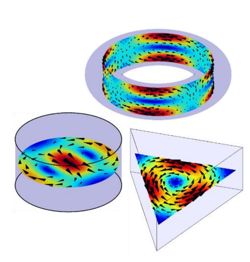
We studied the modes and resonances of arbitrary shaped surfaces.



Carlo Forestiere, Giovanni Gravina, Giovanni Miano, Mariano Pascale, and Roberto Tricarico Phys. Rev. B 99, 155423

HIGH INDEX 3D STRUCTURES

We present the general physical properties of resonances in arbitrary shaped high index resonators: we rigorously prove that they are magnetoquasistatic in nature.
A sample of the eigenmodes in a torus, cylinder and triangular prism are shown below.

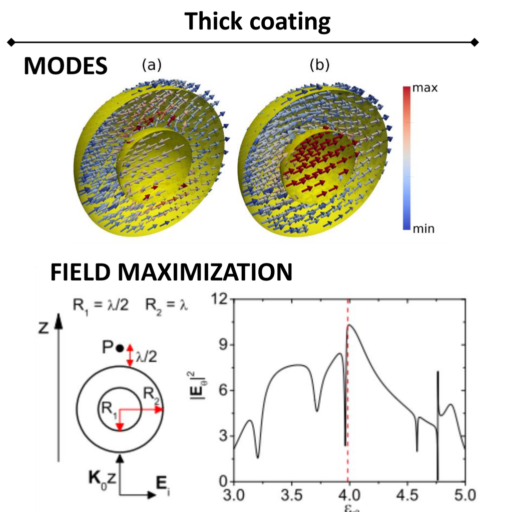


Magnetoquasistatic Resonances of Small Dielectric Objects, Forestiere C., Miano G., Pascale M., Tamburrino A., Tricarico R., Ventre S., accepted for publication in Physical Review Research.

ELECTROMAGNETIC CLOAKING

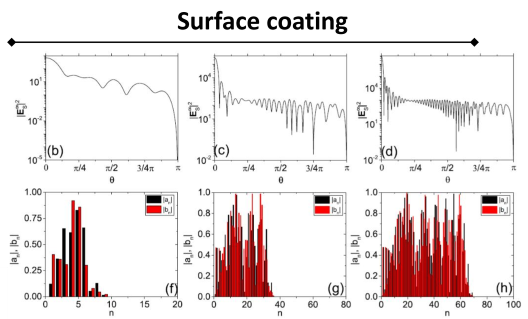
We studied the full-wave modes and resonances of a homogeneusly coated sphere, showing the effectiveness of the approach for field maximization and directional scattering cancellation, regardless of the sphere's size.

Thick coating



Mariano Pascale, Giovanni Miano, and Carlo Forestiere, "Spectral theory of electromagnetic scattering by a coated sphere," J. Opt. Soc. Am. B 34, 1524-1535 (2017).

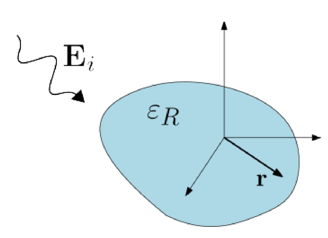
Surface coating



Radiation diagram as a function of the angle θ at φ=0 for a sphere with permittivity εr=4 and R⁄λ=1⁄4 (a), R⁄λ = 1 (b), r⁄λ = 5 (c), and r⁄λ = 10 (d), coated by a surface of finite conductivity. The value of surface conductivity σ is designed to enforce a vanishing backscattering.
The corresponding magnitude of the Mie coefficients is shown in panels (e)–(h).

Carlo Forestiere, Giovanni Miano, Mariano Pascale, and Roberto Tricarico, "Directional scattering cancellation for an electrically large dielectric sphere," Opt. Lett. 44, 1972-1975 (2019).

We develop a spectral solution of the electromagnetic scattering problem from an arbitrary shaped object:



$$\mathbf{E}_S(\mathbf{r}) = (\varepsilon_R - 1)\sum_{\alpha=1}^{\infty}\frac{\mathcal{P}_\alpha\{\mathbf{E}_i\}}{\varepsilon_\alpha - \varepsilon_R}\mathbf{C}_\alpha(\mathbf{r})$$

INCIDENT FIELD — MATERIAL — GEOMETRY

RESONANCE CONDITION $\min_{\omega}\left|\frac{\varepsilon_\alpha(\omega) - \varepsilon_R(\omega)}{\varepsilon_R(\omega) - 1}\right| = \rho_\alpha$

- The eigenvalues ε_α and the eigenmodes **C**r are material independent
- They depend only on the geometry of the object
- The permittivity appears only as multiplicative polynomial functions
- For passive materials with non-negative imaginary part of the permittivity, the quantity $(\varepsilon_\alpha - \varepsilon_R)$ does not vanish, since $Im\{\varepsilon_\alpha\} < 0$
- The amplitude of the α-th mode increases as the distance between the α-th eigenvalue and the permittivity is reduced

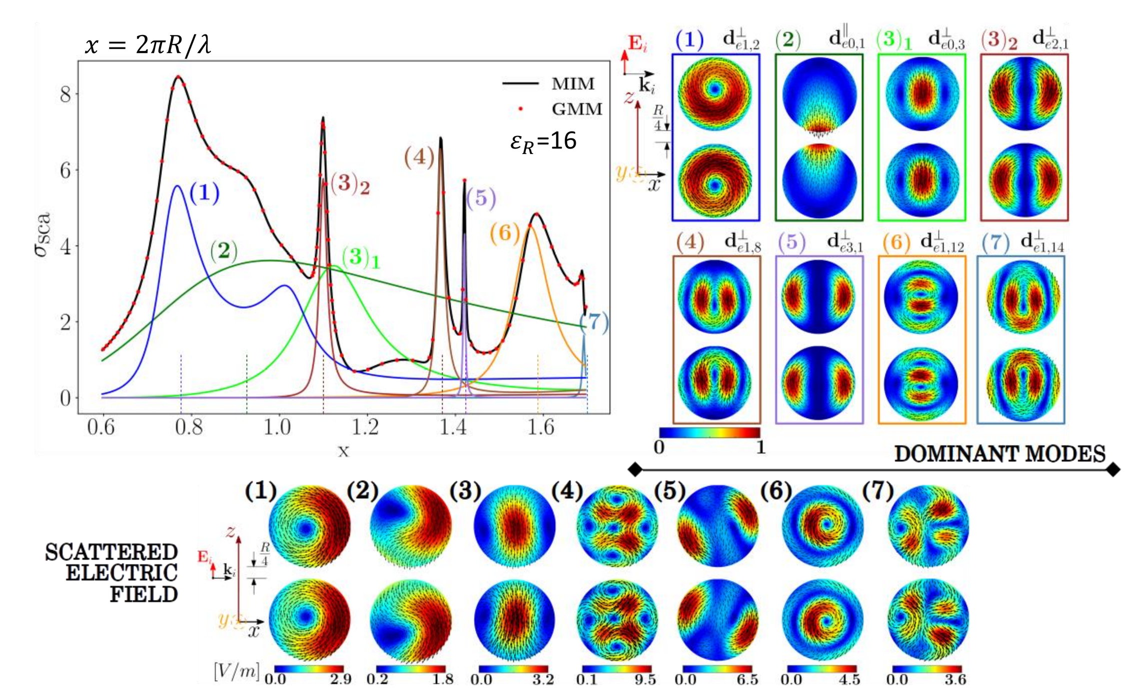
The description in terms of resonances and modes:

- offers intuitive insights into the physics of the problem
- enables the rigorous understanding of interference phenomena, including Fano resonances, in terms of the interplay among well-identified modes
- suggests how to shape the excitation to achieve an assigned electromagnetic response

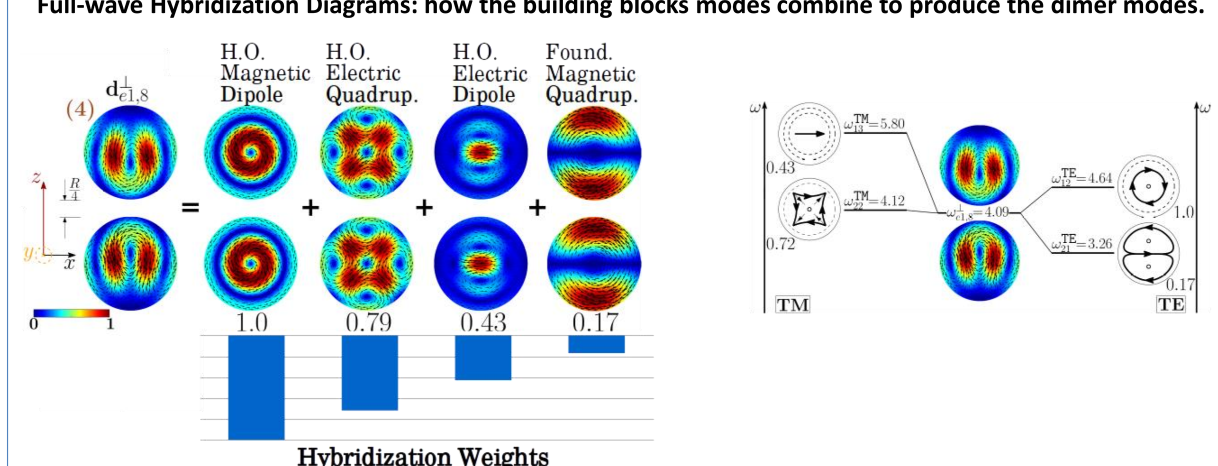
Material-independent modes for electromagnetic scattering, C. Forestiere and G. Miano, Phys. Rev. B 94, 201406

SPHERE DIMER

We investigated the full-wave hybridization mechanism in silver and silicon dimers for the modes that are excited in the scattering under longitudinal and transverse plane-wave illumination.
The analysis of the scattering efficiency of a Silicon homo-dimer excited by a longitudinally polarized plane wave is shown below.



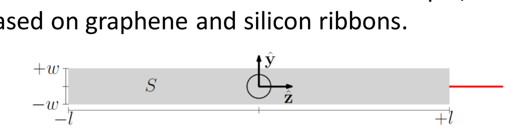
Full-wave Hybridization Diagrams: how the building blocks modes combine to produce the dimer modes.



Pascale, M., Miano, G., Tricarico, R., Forestiere, C.. Full-wave electromagnetic modes and hybridization in nanoparticle dimers. Sci Rep 9, 14524 (2019)

QUASI-1D NANORIBBONS

We analyze the resonance conditions of a long and narrow ribbon of finite length whether it is conductive or dielectric. Our method effectively allows the design of the material to obtain the desired resonances. For example, we design two quasi-1-D resonators based on graphene and silicon ribbons.



C. Forestiere, G. Miano, M. Pascale and R. Tricarico, "Electromagnetic Scattering Resonances of Quasi-1-D Nanoribbons," in IEEE Transactions on Antennas and Propagation, vol. 67, no. 8, pp. 5497-5506, Aug.

I am currently spending a one year research period in the Photonics Initiative group at the Advanced Science Research Center (ASRC) in New York, NY, United States, under the supervision of Prof. Andrea Alù.

I am currently focusing on the analysis of the electromagnetic response of plasmonic broadband nanoresonators based on geometrical singularities, such as touching spheres or cylinders. This kind of devices are theoretically capable of an efficient harvesting of light over a broad range of the frequency spectrum since the great number of excitable («bright») modes. Moreover, they proved to be an excellent platform for the description of the so called «Chu-Harrington limit» in nano-optics, which sets a lower limit on the Q factor for an antenna enclosed in a small volume. The material independent mode expansion turned out to be very effective in providing rigorous insights into the physics of the problem.

Then, I will apply the concepts developed in the study on the resonances of small dielectric objects (Magnetoquasistatic Resonances of Small Dielectric Objects, Forestiere C et al, under review) to the design and analysis of high-index structures featuring peculiar field configurations called "topological protected modes", which are field configurations very robust against fabrication disorder.