PhD in Information Technology and Electrical Engineering

Università degli Studi di Napoli Federico II

PhD Student: Mariano Pascale

XXXIII Cycle

Training and Research Activities Report – Third Year

Tutor: Carlo Forestiere

1. Information

- Mariano Pascale, MSc in Electronic Engineering – University of Naples Federico II
- XXXIII Cycle- ITEE – University of Naples Federico II
- Athenaeum Fellowship
- Tutor: Prof. Carlo Forestiere

2. Study and Training activities

- **Courses (credits in brackets)**

  Attended with certification

  - **Introduction to nanotechnology**, Carlo Forestiere, MSc course of Electrical Engineering (6).

- **Seminars (credits in brackets)**
  - **On the Hall effect in three-dimensional metamaterials",** Christian Kern (University of Utah), at the Advanced Science Research Center, City University of New York, NY (0.2)**.**
  - **Topological quantum photonics and novel soliton physics**, Andrea Blanco-Redondo (Nokia Bell Labs), at the Advanced Science Research Center, City University of New York, NY (0.2).
  - **Topological physics: from photons to electrons**, Mohammad Hafezi (University of Maryland), at the Advanced Science Research Center, City University of New York, NY (0.2).
  - **Plasmonics on Two-Dimensional Materials**, Dionisios Margetis (University of Maryland), at the Advanced Science Research Center, City University of New York, NY (0.2).
  - **III-V semiconductor metasurfaces: frequency mixing and all-optical tuning**, Polina Vabishchevich (Sandia National Laboratories), on-line, (0.2).
  - **How to get published with the IEEE?**, Eszter Lukacs (IEEE), on-line, (0.4).
  - **Controlling light with metasurfaces**, Franesco Monticone (Cornell University), Virtual seminar on "Metasurfaces" (0.2).
  - **Bose-Einstein condensation and lasing in plasmonic lattices**, Paivi Torma (Aalto university), Virtual seminar on "Metasurfaces" (0.2).
  - **Vortex beams generation with dielectric metasurfaces**, Antonio Ambrosio (Istituto italiano di tecnologia-CNST@poliMi), Virtual seminar on "Metasurfaces" (0.2).
  - **Ultrafast phenomena workshop** (online), Matthew Sfeir (Photonics Initiative, Advanced Science Research Center, CUNY, NY) (1).
  - **2020 CLEO Virtual Conference: Laser Science to Photonic Applications** (0.5).
  - **Radiative Cooling Under the Earth's Glow**, Jyotirmoy Mandal (UCLA) (0.2).

- **Optical metamaterials based on broken symmetries**, Andrea Alù (Photonics Initiative, Advanced Science Research Center, CUNY, NY), on-line (0.2).
- **Network Systems, Kuramoto Oscillators, and Synchronous Power Flow**, Francesco Bullo, on-line (0.3).

3. Credits Summary

	Credits year 1								Credits year 2								Credits year 3								Extension					
		1	2	3	4	5	6			1	2	3	4	5	6			1	2	3	4	5	6		7	8	9			
	Estimated	bimonth	bimonth	bimonth	bimonth	bimonth	bimonth	Summary	Estimated	bimonth	bimonth	bimonth	bimonth	bimonth	bimonth	Summary	Estimated	bimonth	bimonth	bimonth	bimonth	bimonth	bimonth	Summary	bimonth	bimonth	month	Summary	Total	Check
Modules	20	0	0	8	0	0	2.3	10.3	20	10.6	6	6.8	0	0	0	23.4	6	0	0	0	0	0	6	6	0	0	0	0	39.7	30-70
Seminars	5	0	0	1.8	0	3	0.4	5.2	5	0.6	4.3	0.4	0	1.4	0.2	6.9	5	0.6	1.4	2.9	0	0	0.3	5.2	0	0	0	0	17.3	10-30
Research	35	7	7.5	7	7	9	7	44.5	35	1	2	3.3	8	7	8.4	29.7	49	6	5	5	9	9	3.8	37.8	9	9	4	22	134	80-140
	60	7	7.5	16.8	7	12	9.7	60	60	12.2	12.3	10.5	8	8.4	8.6	60	60	6.6	6.4	7.9	9	9	10	49	9	9	4	22	191	180

4. Research activity

- **Title**

  Material-independent modes for the electromagnetic scattering from homogeneous objects: from quasistatic to full-wave formulations.

- **Study**

  Nanophotonics, Electromagnetic scattering theory

- **Research description**.

  The light manipulation at the nanoscale is the leitmotif of the research field of nanophotonics. Over the last decades, the classical limits imposed by diffraction have been largely surpassed by virtue of technological and theoretical breakthroughs in the field of light-matter interaction. Properly engineered metallic and dielectric nanostructures provide an unprecedented level of control over the electromagnetic radiation in subwavelength spatial regions. This is enabled by their resonant behavior at the optical frequencies [1-2]. Thus, the development in this research field necessarily depends on an effective electromagnetic modeling of these resonances. Hand in hand with the technological progress, there have been growing efforts in providing a complete and accurate framework for the description of resonances in metallic and dielectric nanostructures. The most powerful tools have certainly been represented by the spectral theories, in which the object electromagnetic behavior is characterized by its resonant modes. These modes are calculated as solutions of an auxiliary eigenvalue problem, i.e., the source-free Maxwell's equations. Several spectral theories have been developed, and in each of them the nanostructure geometric parameters, material, and resonant frequencies are intertwined in a different way, according to the choice of spectral parameter. For instance, the quasi-normal modes, widespread in the nanophotonics community, adopt, as the spectral parameter, the operating frequency, and hence the modes depend on both the nanostructure material and its shape [3].

In the recent years, a spectral method that uses the object relative permittivity as spectral parameter, has proved very useful in the modeling of the electromagnetic scattering from homogeneous isotropic nanostructures. This method relies on modes, called material-independent modes, that depend on the object geometry and the operating frequency, but not on the nanostructure dielectric permittivity [4]. My research activity dwelt on the description of the electromagnetic scattering by homogeneous objects in terms of material-independent modes, either in the quasistatic or full-wave regime.

When the object is much smaller than the operating vacuum wavelength, its resonances and resonance modes are well described by the electro- and magnetoquasistatic approximations of the Maxwell's equations [5-6]. These (quasistatic) modes are found as eigenfunctions of compact and self-adjoint integral operators. Through means of a perturbative approach, my research group provided an extension to the quasistatic analysis, linking the radiation corrections to the frequency shift and radiation quality (Q) factor of the quasistatic modes, through closed-form expressions [7]. In the derived expressions, the dependencies on the material and the size of the object are factorized.

During my stay at the Photonics Initiative at the Advanced Science Research Center, in New York, under the supervision of Prof. Andrea Alù, together with my research group I developed a new method, based on the quasistatic mode expansion, for the calculation of the optimal current distribution supported by an object of dimension smaller than the wavelength, yelding the minimum Q factor. The provided representation leads to analytical and closed form expressions of the electric and magnetic polarizability tensors of arbitrary shaped objects, whose eigenvalues are known [8] to be linked to the minimum Q factor. This method has also proved effective in the analysis of the Q factor-bandwidth relation in singular plasmonic nanostructures. These results are included in papers currently under preparation.

The quasistatic approaches fail when the object size is comparable to the incident wavelength, and thus a full-wave formulation is needed. The analysis of the object full-wave material-independent modes and eigenvalues provides a systematic classification of resonances and interference effects. In this framework, we are able to justify the differences in the power spectrum scattered by dielectric and metal nanoparticles [9]. These modes have also been employed in the design the permittivity of the object to pursue a prescribed tailoring of the scattered field, including the cancellation of the backscattering, the suppression of a given multipolar order, and the maximization of the scattered field in the near-field zone [10,11,12].

The resonances and resonance modes in the electromagnetic scattering from metallic and dielectric sphere dimers in the full-wave regime have also been investigated [13]. Along the lines of the well-known plasmon hybridization model [14], the dimer modes are seen as the result of the hybridization of the modes of the two constituent spheres, whose importance is quantified by hybridization weights. In this way, as the spheres arrangement is varied, although the dimer modes change, they are still represented in terms of the same set of single sphere modes, but with different hybridization weights. This study represents the first full-Maxwell theory of hybridization in dielectric dimers, and it also constitutes an extension of the plasmon-mode hybridization theory.

References

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- [2] A. B. Evlyukhin, C. Reinhardt, A. Seidel, B. S. Luk'yanchuk, and B. N. Chichkov. **Optical response features of Si-nanoparticle arrays**. In: Phys. Rev. B 82 (2010).
- [3] Philip Trøst Kristensen, Kathrin Herrmann, Francesco Intravaia, Kurt Busch, and Kurt Busch. **Modeling electromagnetic resonators using quasinormal modes**. In: Advances in Optics and Photonics 12.3 (Sept. 30, 2020). Publisher: Optical Society of America, pp. 612–708. issn: 1943-8206
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- [14] P. Nordlander, C. Oubre, E. Prodan, K. Li, and M. I. Stockman, **Plasmon Hybridization in Nanoparticle Dimers**, Nano Letters 2004 4 (5), 899-903.

- **Collaborations**

  We collaborate with Andrea Alù's group, the Photonics Initiative, Advanced Science Research Center at City University of New York , with the Electrical Engineering group from the University of Cassino (Profs. Tamburrino, Ventre), with groups from physics (Profs. d'Ambrosio, Tagliacozzo, Pepe, Tafuri).

5. Products

- **Publications**
  - **Full-wave electromagnetic modes and hybridization in nanoparticle dimers**. Pascale, Mariano and Miano, Giovanni and

Tricarico, Roberto and Forestiere, Carlo, Scientific Reports, Nature Publishing Group, 2045-2322, vol. 9, pag. 1–21, n 1.

- **Magnetoquasistatic resonances of small dielectric objects**, Carlo Forestiere, Giovanni Miano, Guglielmo Rubinacci, Mariano Pascale, Antonello Tamburrino, Roberto Tricarico, and Salvatore Ventre, Phys. Rev. Research 2, 013158
- **Quantum theory of radiative decay rate and frequency shift of surface plasmon modes**, Carlo Forestiere, Giovanni Miano, Mariano Pascale, and Roberto Tricarico, Phys. Rev. A 102, 043704
- **Material-independent Modes for the Design of Electromagnetic Scattering**, Carlo Forestiere, Giovanni Miano, Mariano Pascale and Roberto Tricarico, In: Compendium on Electromagnetic Analysis. 5 vols. World Scientific, June 18, 2020, pp. 345–384. isbn: 978-981-327-029-9.

- **Publications in preparation**
  - **On the Q factor of Singular Plasmonic Resonators: Lower Bounds and Relation with Fractional Bandwidth** M. Pascale, S. Mann, C. Forestiere, A. Alù.
  - **Lower bounds to quality factor of small radiators through quasistatic scattering modes**, M. Pascale, D. Tzarouchis, G. Miano, S. Mann, A. Alù, C. Forestiere.

6. Conferences and Seminars

- **Details**
  - **The fourteenth international congress on engineered material platforms for novel wave phenomena, Metamaterials 2020,** Advanced Science Research Center, City University of New York, NY, 28/09/-01/10/2020.
- **Presentations made**
  - **Modal analysis of 2D broadband plasmonic resonators,** on-line, 28/09/-01/10/2020.