Exploring light-matter interactions & forces in complex particle arrays (LIGHTCOMPAS)

Long description of the PhD proposal

The aim of the present proposal is the development (based on previously acquired experience and knowledge) of new theories, conceptual models, and computational tools, linked to experimental activities, able to explain and understand the rich phenomenology that emerges from the interaction of light with complex systems exhibiting various optical responses, including the optical forces exerted on them. Complexity may arise from a peculiar arrangement (arrays of nano- and micro-structures), a singular response (non-reciprocal, reactive or thermally activated) or a unique illumination (structured or fluctuating radiation). The response emerging from these interactions will be analyzed in cutting-edge experimental work, performed in collaboration international groups. These subject matters are nowadays at the forefront of Physics in general, and Optics/Photonics and Condensed Matter in particular.

Specifically, the present coordinated project intends to achieve several objectives, focused on understanding light-matter interaction and forces in systems consisting of: complex arrays, particles presenting unconventional responses and non-trivial fields. The arrays are, in practice, planar arrays (metasurfaces) of sub-wavelength entities with an inherently peculiar response where the lattice arrangement modifies the emerging fields. On the other hand, the unconventional optical responses considered arise mostly from a magneto-optically induced non-reciprocal behavior or a thermal non-trivial response. In general, the elements considered possess nanometric dimensions and thus fall into the scope of the fields of nanoscience and nanotechnology, although not limited to this scale. The interaction of light (ranging from planewave illumination to more complex structured or fluctuating fields) with such nanostructured matter is characterized by the appearance of a rich phenomenology stemming from the complex morphology, structure, and/or electromagnetic response.

The work will be developed in a cooperative environment, consequently, it is very attractive for the teams involved the use of common languages, formalisms and techniques to study the optics of such complex systems exhibiting plasmonic, Mie-resonant, chiral, magneto-optical, electro-optical, and thermo-optical responses, from its fundamental properties (scattering, absorption, electrodynamic forces, spin) to more elaborate collective phenomenology arising in complex particle arrangements (lattice-resonances, bound-states-in-the-continuum, optical binding networks). During years, the researchers forming the team have developed key fundamental contributions, internationally recognized, to the advancement of the above areas, covering a wide range of subjects. Furthermore, the main objectives pursued in this proposal have in turn direct connection with challenges relevant to Nano- & Biotechnology:
Nano-Optoelectronics, Optical Microscopy, Nano/Bio-sensing, Optical Communications, (Bio-)Optical Manipulation, etc. Some examples of possible applications in the mid or long term are: nanolasers & flat-optical devices, robust optical interconnections, nondestructive optical microscopes at the nanometric scale using electromagnetic forces, particle tracking tools, nanosensors, etc.

Main objectives to be addressed during the predoctoral period:

O.1. Metasurfaces
To introduce mechanisms both passive (geometry and optical source) and active (external agents) controlling the optical response of complex planar arrays, we propose to extend our Coupled Electric-Magnetic Dipole (CEMD) approach to account for a variety of complex geometries and active media. Care has to be taken to incorporate certain optical responses in the dipolar response of the meta-atom (particles). In principle, we plan to address magnetic, electric and thermal control through various materials.
T1.1. Dipolar or multipolar responses of particles.
Determine suitable means to extract the dipolar (or higher) polarizabilities (even if not diagonal, as in the case of magneto-optic materials or chiral), from the intrinsic scattering properties of the isolated particles.
T1.2. Extension of the CEMD model to complex particle response and to arbitrary substrates and 3D unit cells.
Extend the CEMD formalism to incorporate such complex dipolar/multipolar responses of the metal-atoms. Incorporate multilayered substrates with multiple reflections as corrections to the free space Green function. Extend the formalism to place particles (meta-atoms) in the unit cell in arbitrary 3D positions.
T1.3. Extension of the CEMD model to arbitrary sources.
Incorporate near-field sources using a spatially varying dipole density. For far-field sources, use the angular momentum representation, which enables the description of structured light beams under both paraxial and nonparaxial conditions, including the important case of HG beams carrying OAM.
T1.4. Lattice resonances and Bound states In the Continuum (BICs) in 2.5-dimensional arrays.
Study the effect on the response of the displacement of particles in the direction perpendicular to the array. Search for chiral and directional responses in 2.5 dimensional arrays.
T1.5. BICs in active arrays: electric/thermal and magnetic control.
Analyze first the impact on BIC when the active mechanism leads to a change in the dielectric functions of the constituents through electric means or thermal means (graphene, phase change materials, etc.) and/or magneto-optical means (YIG, InSb).
T1.6. Time-varying metasurfaces.
This challenging task aims at exploring the optical properties of time-varying arrays of particles through our CEMD model with the abovementioned extensions if required.
T1.7. VO2 oxides.
In this task we aim to analyze whether VO2 oxides may be considered as building blocks of chiral structures in a thin film by a local variation of the temperature and whether these chiral structures are reversible.

O.2. Dichroism in structured materials
In this objective we will consider systems in which dichroism is induced by complex structures (chiral) like, for instance, triskeles. Also, we aim to analyze how structural chirality affects the mechanical response, in particular, to the optical torque. Additionally, this objective deals with the calculation of the optical force exerted on a MO dipole when embedded in a constant magnetic field and an isotropic random electromagnetic field.
T2.1. Dipole Modelling of the chiral structure and comparison with full numerical simulations.
We will analyze if the dichroic response in these systems may be understood by considering the multiple interactions between different dipolar subunits of the system. We will compare with scattering results from FDTD and Comsol simulations.
T2.2. Mechanical response of the chiral structure.

Once the dipolar decomposition is known we will use it to calculate the mechanical response of the systems (optical torque) and its relation with chirality.
T2.3 Handedness detection with non-reciprocal particles.
In this task we will analytically calculate the optical response of a MO electric dipole when embedded on an isotropic fluctuating field and in the presence of a constant magnetic field. We will calculate the response depending on the magnetic field strength and the degree of circular polarization of the isotropic field.
T2.4 Analytical calculation of the force.
In this task we will analytically calculate the optical interactions on a MO electric dipole when embedded on an isotropic fluctuating field and in the presence of a constant magnetic field. We will calculate the optical force and torque depending on the magnetic field strength and the degree of circular polarization of the isotropic field.

Training program planned in the context of the project.

-The post-graduate students will be enrolled in the PhD program of the Department of Condensed Matter Physics (Condensed Matter Physics, Nanoscience and Biophysics), or in the PhD program of the Department of Material Physics (Advanced Materials and Nanotechnology), both at Universidad Autónoma de Madrid (UAM). Short- to mid-term duration **stays** of the students will be encouraged with other collaborators abroad for a minimum of three months to obtain the International Mention in the degree of doctor. At least two in any of the collaborating groups: Technical University (Eindhoven), Imperial College (London), University of Fribourg (Switzerland), IMRE-A*Star (Singapore), LPEM-CNRS (Paris), C2N-CNRS (Palaiseau), KU Leuven (Belgium), NYCU (Taiwan), Los Alamos National Laboratory (USA); or some other groups related to the project. Also, as the project progresses, *students are expected to attend and present their research in several national or international conferences and workshops*.

-Attendance to **CSIC postgraduate courses**: especially the course given annually at our institutes (IEM Course and IO Course on Introduction to Research in the Structure of Matter and Optics, respectively). The CSIC also provides training courses/workshops on basic and advanced techniques such as Matlab, Python, HPC, etc.

-Presentations in: group meetings, seminars and *national or international conferences*.
The candidate is expected to become familiar with the **basic tools** in the first six months (which include technical capabilities of interest also outside the scientific field), such as:
-Mathematical and numerical calculation: Matlab, Mathematica, COMSOL and SCUFF;
-Computation: handling of calculation nodes in Linux and desktop iMac of the group;
-Processing of images: Origin, InkScape, POVRay, Adobe Illustrator;
-Processors of texts and presentations: Word, LATeX, PowerPoint, Keynote, and online platforms (Google Docs and Overleaf).
-Analytical and numerical methods of propagation and dispersion of electromagnetic waves, within Classical and Quantum Electrodynamics, in connection with the interaction of light with matter at the nanoscale (NanoPhotonics).
-Optical microscopy (transmission, darkfield, fluorescence widefield, confocal) and optical trapping.

-Another objective of this project will be to explore the possible implementation of a line of research on Optics/Photonics within the **joint Doctoral Programme between CSIC and the Universidad Internacional Menéndez Pelayo (UIMP)** (see http://www.csic.es/lineas-de-investigacion for more information). This initiative will involve several members of this project as well as CSIC researchers active in this field.

CURRICULUM VITAE ABREVIADO (CVA)

IMPORTANT* – *The Curriculum Vitae cannot exceed 4 pages. Instructions to fill this document are available in the website.

Part A. PERSONAL INFORMATION

First name	Antonio		
Family name	García Martín		
Gender (*)	Male	Birth date (dd/mm/yyyy)	14/09/1971
Social Security, Passport, ID number	51408254B		
e-mail	a.garcia.martin@csic.es	URL Web	
Open Researcher and Contributor ID (ORCID) (*)		0000-0002-3248-2708	

(*) Mandatory

A.1. Current position

Position	Scientific Researcher		
Initial date	13/02/2015		
Institution	Consejo Superior de Investigaciones Científicas		
Department/Center	Instituto de Micro y Nanotecnología		
Country	Spain	Teleph. number	918372216
Key words	Light-Matter interaction, Nanophotonics, Plasmonics, magneto-optics, magneto-plasmonics, near-field optics		

A.2. Previous positions (research activity interruptions, indicate total months)

Period	Position/Institution/Country/Interruption cause
06/2000-01/2000	Contratado Doctor at Universidad Autónoma de Madrid
02/2001-02/2003	PostDoctoral Position at University of Karlsruhe (Germany)
03/2003-05/2005	“Ramón y Cajal” Scientist at IMN-CSIC
06/2005-02/2015	Tenured Scientist at IMN-CSIC

A.3. Education

PhD, Licensed, Graduate	University/Country	Year
Ms Sc Physics	Universidad Autónoma de Madrid	1996
PhD Physics	Universidad Autónoma de Madrid	2000

(Include all the necessary rows)

Part B. CV SUMMARY *(max. 5000 characters, including spaces)*

During my already 27 years of scientific career I have been involved in the development of a number of novel theoretical tools and numerical codes in the framework of wave propagation in complex systems. These tools are focused on the theoretical analysis of optical properties of resonant nanoscale systems (plasmonics, photonic crystals, magnetoplasmonics, radiative heat transfer), with a considerable link with actual experiments. The starting point was in the period 1996-2000, where I realized the PhD in Physics at the Condensed Matter Department of the Universidad Autónoma de Madrid. In that period, we analyzed the properties of metallic systems all the way from very small to very long. The PhD Thesis entitled “Theory of wave transport in complex systems: from ballistic transport to localization induced by rough surfaces” got the highest mark, unanimous Sobresaliente Cum Laude, and received the ***Outstanding PhD Thesis award***.

After the PhD, I moved for a two-year postdoctoral stay to the Condensed Matter Department at the University of Karlsruhe to undertake theoretical studies on the properties of photonic crystals with intended defects and on continued the transport properties in disordered wires. There, I developed numerical codes specially adapted to defect computations based on highly localized basis sets. The methodology is still in use at the group and the review paper (K. Busch et al., J. Phys.: Condens. Matter (Topical Review) **15**, R1233-R1256 (2003)) is a reference work in the field.

Back in Spain, I joined the Instituto de Microelectrónica de Madrid in March 2003 (from July 2017 is the Instituto de Micro y Nanotecnología), where I got a permanent position, in 2005, and a promotion to Investigador Científico in 2015.

My scientific interests lie in the area of nanophotonics, in particular in the optical properties of *complex nanostructures possessing simultaneously magneto-optical activity and resonant excitations* (**magneto-plasmonic or magneto-dielectric materials**):

• Tunable and/or chiral nano-antennae: resonant elements (either dielectric or metallic) with magneto-optical properties and/or exhibiting chirality, optical forces and radiative heat transfer.

• Tunable metasurfaces: periodic systems composed of tunable/chiral nano-antennae and hybrid versions.

• Plasmonic nano-antennae: enhanced performance in energy harvesting devices and control of the near-field.

Supervision of Students: Four PhD Thesis have been successfully carried out with me as supervisor (three in the last 10 years), all with the highest mark. Additionally, two Master Thesis have been carried out under my guidance.

Reseach Publications/Patents/Conferences/Projects: 127 (121 ISI) publications (around 80% in Q1) with 4697/6568 citations, giving an h index h=36/44 (ISI/Scholar), giving an average of ~375/500 citations per year in the last five years' period. Co-author of two patents – ES2368287, and P201531817. Co-author of more than 200 conference participations (65% talks of which more than 42 are invited or keynotes). PI in 6 research projects (in particular PI-Coordinator of a EU-FP7 project involving 11 groups from 5 countries and a budget of ca. 3M€). Participation in another 20 local, national and international projects.

Other:

- Responsible for the outreach activities (science week) of the Institute of Micro and Nanotechnology for the years 2005-2007, 2009-2022.
- Speaker at the Nanofestival 10alamaneos9: 2017, 2018 and 2019.
- Project evaluator: ANEP and MINECO, FET-OPEN and Marie Skłodowska Curie (EU), National Agency for Scientific and Technological Promotion (Argentina), The Engineering and Physical Sciences Research Council (EPSRC – England), Agency Nationale de la Recherche (ANR - France), The Icelandic Research Fund (IRF-Iceland), The Austrian Science Fund (ASF-Austria).
- Associated Editor of Nanomaterials (MDPI), SN Applied Sciences (Springer-Nature)
- Regular "Referee" for different international journals: Nature Photonics, Nature Nanotechnology, Nature Communications, Nano Letters, Nanoscale, Physical Review Letters, Physical Review X, Advanced Materials, Small, ACS Photonics, Advanced Optical Materials, Scientific Communications, Physical Review B , Optics Letters, Optics Express, Journal of Physics Cond. Matter, Nanotechnology, IEEE OSA Journal of Lightwave Technology, and Optics Communications.

I have also held some administrative duties as Head of the Department of Fabrication and Characterization of Nanostructures (June 2009 to May 2013), Deputy Director from May 2013 to May 2021, and Director of the IMN from May 2021- December 2022).

Part C. RELEVANT MERITS *(sorted by typology)*

C.1. Publications *(see instructions)*

121 ISI publications (**Researcher ID E-5283-2010)**

4697 citations h = 36

Among the 121 indexed publications, 17 of them are correspond to the last five years and are connected with the current Project proposal: **note that 11/17 are international collaborations.**

1. A. Kimel, A. Zvezdin, S. Sharma, S. Shallcross, N. de Sousa, A. García-Martín, G. Salvan, J. Hamrle, O. Stejskal, J. McCord, S. Tacchi, G. Carlotti, P. Gambardella, G. Salis, M. Münzenberg, M. Schultze, V. Temnov, I. V. Bychkov, L. N. Kotov, N. Maccaferri, D. Ignatyeva, V. Belotelov, C. Donnelly, A. Hierro Rodriguez, I. Matsuda, T. Ruchon, M.

Fanciulli, M. Sacchi, C. Rita Du, H. Wang, N. P. Armitage, M. Schubert, V. Darakchieva, B. Liu, Z. Huang, B. Ding, A. Berger, P. Vavassori, *The 2022 magneto-optics roadmap,* Journal of Physics D: Appl. Phys. 55, 463003 (2022).

2. S. Edelstein, A. García-Martín, P.A. Serena, M.I. Marqués, *Circular dichroism in magneto-optical forces,* Optics Express 30, 28668-28685 (2022).
3. J. Rodríguez-Álvarez, A. García-Martín, A. Fraile Rodríguez, X. Batlle, A. Labarta, *Tunable circular dichroism through absorption in coupled optical modes of twisted triskelia nanostructures*, Scientific Reports 12, 1-10 (2022).
4. Z. Hu, M. U. González, Z. Chen, P. Gredin, M. Mortier, A. García-Martín, L. Aigouy, *Luminescence enhancement effects on nanostructured perovskite thin films for Er/Yb-doped solar cells*, Nanoscale Advances 4, 1786-1792 (2022).
5. D.R. Abujetas, N. de Sousa, A. García-Martín, J.M. Llorens, J.A. Sanchez-Gil, *Active angular tuning and switching of Brewster quasi bound states in the continuum in magneto-optic metasurfaces*, Nanophotonics 10, 4223-4232 (2021).
6. S. Edelstein, A. García-Martín, P.A. Serena, M.I. Marqués. *Magneto-optical binding in the near field*, Scientific Reports 11, 1-10 (2021).
7. M. Testa-Anta, A. Sousa-Castillo, A. López-Ortega, M. A Correa-Duarte, A. García-Martín, P. Vavassori, V. Salgueiriño, *A caging strategy for tuning the magneto-optical properties of cobalt ferrite using a single plasmonic nanoparticle*. Journal of Materials Chemistry C 9, 5098-5104 (2021).
8. HJ. Lin, H. Xiang, Ch. Xin, Z. Hu, L. Billot, P. Gredin, M. Mortier, Z. Chen, M. U. González, A. García-Martín, L. Aigouy, *Direct imaging of fluorescence enhancement in the gap between two gold nanodisks*, App. Phys. Lett. 118, 161105 (2021).
9. Z. Hu, J. M. Garcia-Martin, Y. Li, La. Billot, B. Sun, F. Fresno, A. García-Martín, M. U. González, L. Aigouy, Z. Chen, *TiO_2 Nanocolumn Arrays for More Efficient and Stable Perovskite Solar Cells,* ACS Applied Materials & Interfaces 12 , 5979-5989 (2020).
10. SD Pappas, P. Lang, T. Eul, M. Hartelt, A. García-Martín, B. Hillebrands, M. Aeschlimann, and E. Th. Papaioannou, *Near-field mechanism of the enhanced broadband magneto-optical activity of hybrid Au loaded Bi: YIG,* Nanoscale 12, 7309-7314 (2020).
11. S. Edelstein, R. M. Abraham-Ekeroth, P. A. Serena, J. J. Sáenz, A. García-Martín, and M. I. Marqués, *Magneto-optical Stern-Gerlach forces and nonreciprocal torques on small particles.* Physical Review Research 1, 013005 (2019).
12. C. de Dios, A. Jiménez, F. García, A. García-Martín, A. Cebollada, and G. Armelles, *Mueller matrix study of the dichroism in nanorods dimers: rod separation effects.* Optics Express 27, 21143 (2019).
13. L. Aigouy, M.-U. González, H.-J. Lin, M. Schoenauer-Sebag, L. Billot, P. Gredin, M. Mortier, Z. Chen and Z. García-Martín, *Mapping plasmon-enhanced upconversion fluorescence of Er/Yb-doped nanocrystals near gold nanodisk,* Nanoscale 11, 10365-10371 (2019).
14. R. M. Rowan-Robinson, E. Melander, I.-A. Chioar, B. Caballero, A. García-Martín, E. Th Papaioannou, and V. Kapaklis. *Thickness dependent enhancement of the polar Kerr rotation in Co magnetoplasmonic nanostructures.* AIP Advances 9, 025317 (2019).
15. M. G. Manera, A. Colombelli, A. Taurino, A. Garcia-Martin, and R. Rella. *Magneto-Optical properties of noble-metal nanostructures: functional nanomaterials for bio sensing*. Scientific Reports 8, 12640 (2018).
16. R. M. Abraham Ekeroth, P. Ben-Abdallah, J. C. Cuevas, and A. García-Martín. *Anisotropic Thermal Magnetoresistance for an Active Control of Radiative Heat Transfer*. ACS Photonics 5, 705−710 (2018).

17. P. Rodríguez-Sevilla, K. Prorok, A. Bednarkiewicz, M. Marqués, A. García-Martín, J. García-Solé, P. Haro-González, and D. Jaque. *Optical Forces at the Nanoscale: Size and Electrostatic Effects.* Nano Letters, 18 602-609 (2018).

C.2. Congress, indicating the modality of their participation (invited conference, oral presentation, poster)

- **Workshops' Co-organizer**:
  (i) Trends in Nanotechnology (Local Committee or Scientific Advisory Committee) from 2001 to 2013;
  (ii) Photonics, Plasmonics and Magneto-Optics (Organizer) 3PM2018, 3PM2020, 3PM2021.
  (iii) Conferencia Española de Nanofotónica – CEN (Scientific Committee) (2010-2016 biannual) – Steering Committee (2023)
- **More than 220 contributions to International Conferences**: **42 INVITED/KEYNOTE**.

C.3. Research projects, indicating your personal contribution. In the case of young researchers, indicate lines of research for which they have been responsible.
PI in 6 research projects (in particular PI-Coordinator of a EU-FP7 project involving 11 groups from 5 countries and a budget of ca. 3M€). Participation in another 20 projects.
Projects active during the last five years:
(PI)

- SolarNano - New Applications of Upconverting Fluorescent Nanoparticles: Solar Cells Improvement and Nano-Antenna Characterization (CSIC-CNRS),
- Photonic Advanced Materials (PhaMA-CAM),

(Participant)

- Bound-states-In-the-Continuum-based PLANar photonic devices towards 6G (BIGPLAN-6G)-TED2021-131417B-I00.
- Diagnóstico Rápido de infección basado en resonadores optomecánicos(RAINDROPs)-PDC2021-121833-I00.
- Symmetry breaking emerging phenomena in Photonic and Electronic Devices (SymPED)-PID2019-109905GA-C22.
- Plasmónica Activa Mediante Túnel Electrónico Dependiente de Espín-FIS2015-72035-EXP.

C.4. Contracts, technological or transfer merits, Include patents and other industrial or intellectual property activities (contracts, licenses, agreements, etc.) in which you have collaborated.

- Inventors (i.o. signature): Ceferino López Fernández, Juan Galísteo López, Martín López García, Álvaro Blanco Montes, Antonio García Martín
  Title: Dispositivo electroluminiscente y procedimiento de fabricación del mismo – concession ES2368287
  Application No.: P201030547
  Priority country: Spain
  Priority date: 04/15/2010
  Owner entity: Consejo Superior de Investigaciones Científicas

- Inventors (i.o. signature): Antonio García Martín, Blanca Caballero, and Juan Carlos Cuevas
  Title: Sensor magnetoplasmónico basado en matrices híbridas perforadas, procedimientos y usos asociados
  Application No.: P201531817
  Priority country: Spain
  Priority date: 12/16/2015
  Owner entity: Consejo Superior de Investigaciones Científicas 2/3 y Universidad Autónoma de Madrid 1/3