

The main purpose of my visit to Dr. Musken's lab was to carry on with the recently established collaboration (between the Nanophotonics Group in the CFM of San Sebastian and the Quantum Light and Matter Group of Dr. Muskens in the University of Southampton). I planned to provide theoretical support in situ to tackle all the ongoing projects that our groups share, as well as getting an overview of the experimental arrangements and techniques.

Within the projects we proposed to tackle were the following:

- Study of the influence of the high-index silicon substrate and space charge layers on the plasmonic modes in the antenna-MOSFET designs they are currently developing. Our expertise will fill a theoretical gap, providing simulation capabilities not accessible in Southampton currently.
- We also want to investigate the possibility of using ITO as a material for antennas and work on multiple nanoring structures as an efficient design to extend the working spectral range of sensors with extreme importance in biosensing.
- We will also use our simulation capabilities to investigate the combination of plasmonic structures/antennas on waveguides, ring resonators or MMI splitters.

Along this visit we satisfactorily worked on two out of the three, and we postponed the third project for a future interaction in our collaboration.

The first project we focused on was the study of the coupling between higher order modes in asymmetric dimer antennas. We did a full study of interference and coupling of the multipolar modes for nanorods, as well as the evidence of interference and coupling between dark and bright modes in asymmetric dimers. We also investigated how the high sensitivity of these more complex antenna designs can be exploited in the nonlinear regime to achieve plasmonic switches.

We numerically studied in detail the hybridization between bright and dark modes results in anticrossing of resonances, often referred to as Fano interferences. We discussed the properties of asymmetric dimers in relation to nonlinear control of spectral modes, and demonstrated nonlinear modulation of a hybrid asymmetric dimer - ITO antennas.

These results are now being written in a manuscript entitled: "Interference, coupling and nonlinear response of higher order modes in asymmetric dimers" and will be sent for publication to a high impact journal.

The second project we tackled was the study of multiple nanoring structures as an efficient design to extend the working spectral range of sensors with extreme importance in biosensing. We looked at different designs and performed calculations to model the response of such structures. After a rigorous study of the concentric rings geometry we concluded that a spiral like geometry would provide with similar electromagnetic response but with the advantage of being easily experimentally implementable.

The numerical study was based on simulations performed with use of finite-difference time-domain software (Lumerical). This numerical method is broadly established in computational electromagnetism to calculate the optical response of different nanostructures. It consists of a direct implementation of the Maxwell time-dependent curl equations to solve the temporal variations of electromagnetic waves within a finite space that contains an object of arbitrary shape and properties. In practice, the space including the scatterer is discretized into a grid that contains the basic element of this discretization, the Yee cell. The precision of the results depend both on the number of the cells used in the simulation, as well as on the appropriate selection of the simulation time. The presented results are fully converged, thus they can be considered an exact solution of Maxwell's equations. Additionally, some of the results shown here have been tested with another solving method, the discrete dipole approximation (DDA), producing very good agreement.

There is still some more work to do on this, but we did establish a working planning for this, so these results can end up also in an interesting publication.

The support received from the European Science Foundation (ESF) within the framework of the ESF activity 'New Approaches to Biochemical Sensing with Plasmonic Nanobiophotonics (PLASMON-BIONANOSENSE)' will be acknowledged in these two publications and a reprint will be forwarded to the ESF Secretariat as soon as available.

Also mention that during this stay I had the chance to give a seminar related to numerical methods for solving electromagnetic problems.

We also had several scientific discussions in connection with the field of nanophotonics, specially applied to bio-sensing, which have led to several new ideas that will be studied further in our collaboration.

In summary, this visit to Dr. Musken's lab, apart from offering me the possibility of getting introduced to the ultrafast experimental techniques they have developed, it has helped to develop further our collaboration regarding the use of nanoantennas for biosensing and optical switching (e.g. waveguide sensors, new design, tuneable sensors), which can provide a unique platform to obtain high-impact results.