SCIENTIFIC REPORT: PLASMON-INSPIRED METASTRUCTURE FOR SENSING APPLICATIONS "METAPLASMONSENSING"

Purpose of the visit

Extending the range of materials' electromagnetic properties is currently one of the main driving forces behind the development of metamaterials [1] and plasmonics [2]. In their infancy, they grew independently, but recently, a great scientific effort has been put forth to combine both disciplines so as to take advantage of the best features of each field. On the other hand, engineer community has successfully employed for quite a long time equivalent circuit models to develop its work.

Taking advantage of this engineering machinery based on equivalent circuit models and transmission lines, the researcher Dr. Miguel Navarro-Cía developed during his last internship at Imperial College London in 2009 (under the principal supervision of Prof. S.A. Maier) an explanation of both classical spoof plasmons (slit arrays and hole arrays) and Sievenpiper mushroom geometries by linking the surface plasmon frequency with the resonant frequency of the effective surface impedance [3]. Moreover, stimulated by metamaterials and keeping this useful engineering perspective, we designed another geometry based on complementary split ring resonators [4] in such a way that the supported electro-inductive fundamental mode exhibits tight confinement and resembles a TM-polarized surface plasmon polariton at the same time [3]. The qualitative analysis was supported by numerical results based on dispersion diagrams, field distribution, and electric energy density.

The surface plasmon-like wave aforementioned may become a platform for biosesing at terahertz frequencies where surface plasmon polaritons develop into loosely bound Sommerfeld-Zenneck surface waves.

As it was described in the application process, the aim of the visit was to address the following two points:

- Fundamentals and optimization:

  To extend the analysis based on engineering concepts to higher order modes (so as to exploit it for dual band response, for instance) as well as to magnetic (TE) surface plasmon polariton like modes.

  To investigate and optimize the metamaterial-inspired unit cell for surface plasmon mimicking based on resonant approaches. In the literature there are a wide range of metamaterial unit cells and a deep analysis as well as modification of them is required to improve the performance of planar routing that may lead to new sensing technique. Particular effort will be paid to size reduction, bandwidth enhancement and multiband response. The main tool for that would be the commercial software CST Microwave Studio™ together with the transmission line concepts.

- Fabrication and measurement:

  Indeed, this is the core of the project because the main aim of the internship would be to move to the experimental validation of our previous numerical work [3]. The development of proof of concept demonstrators in micromachining technology as well as contact photolithography technology is foreseen. Firstly, a straight plasmonic-like planar waveguide is intended to be measured and then, a Y-splitter configuration to the potential of the approach. To this end, the candidate will possibly need to receive some training in the instrumentation available at Imperial College London such as the Teraview [5].

Description of the work carried out during the visit

The work carried out during the visit can be sorted into three categories:

- Theoretical and computation effort:

At the beginning of the internship it was identified of primary importance the modelling of annular hole arrays because of the interest surged after the experimental demonstration of the dual-band response of this structure [6]. To this end, transmission line concepts were employed to describe the electromagnetic response of the first two propagating modes of annular hole arrays. This theoretical framework founded on engineering concepts became the platform to propose optimized surface plasmon-like dual-band operation. The theoretical calculations were confirmed numerically with the finite-integration time domain commercial software CST Microwave Studio™. Finally, the potential of the optimized dual-capability of the structure was demonstrated by designing a straight planar waveguide (Fig. 1), and a Y-splitter.

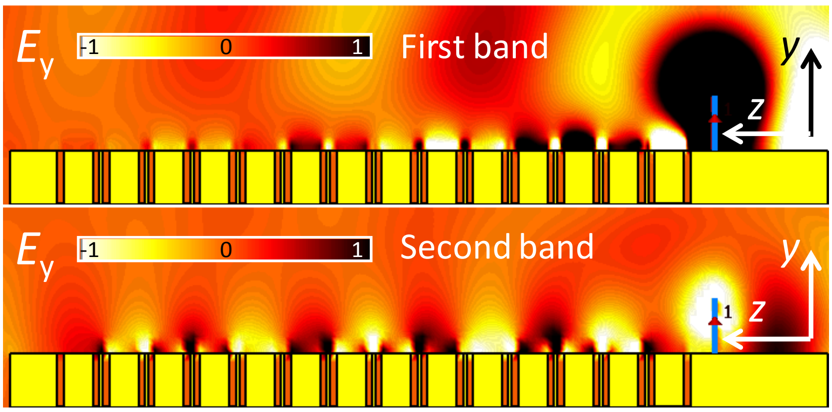

Fig. 1. Cross sectional view (*zy*-cutting plane) of the electric field E_y at f = 1.11 THz (0.98f_{SSPP_TEM}) (top) and f = 1.72 THz (0.98f_{SSPP_TE11}) (bottom) in the planar waveguide formed by a straight chain of annular holes.

After this first task, the researcher embarked on the design of complementary split ring resonators-based planar terahertz waveguide to be measured in collaboration with CIC nanoGUNE Consolider at 30 THz (near-field characterization). Neither Imperial College London nor Universidad Pública de Navarra is equipped to perform such kind of characterization. This is still an ongoing task.

- Lab activities:

Intensive training was focused on the equipment and software not familiar to the researcher. Namely:

- Teraview (a semiconductor based terahertz pulsed technology that gives full access to the 0.06 – 4 THz spectral region) [5]
- 85070E Dielectric Probe Kit [7]

For the training, pure distilled water, ionized water and some aqueous solutions were measured with the second equipment which covers up to 40 GHz; see Fig. 2. The experimental results of pure distilled water were compared successfully against the single Debye model, which is enough to describe the properties of water at such frequencies. In addition to liquids, and indeed in connection to other research lines carried out at Imperial College London, graphene samples and nanoantennas were measured with Teraview.

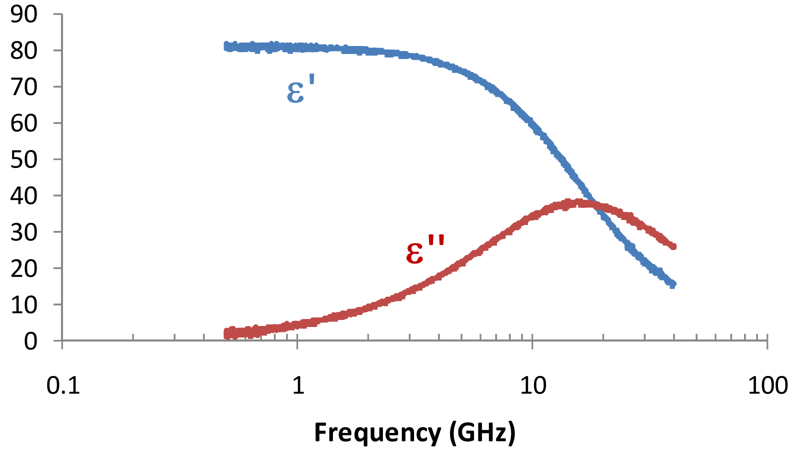

Fig. 2. Water permittivity at 18 ° C, experimental data over the range 0.5 - 40 GHz.

- Writing of paper and communications:

  The theoretical as well as numerical analysis developed to explain and optimize the dual-band response of pierced metallic surface with annular holes was considered to be worth publishing. The paper was submitted to "Plasmonics" and has been recently accepted (see "publications" section of the report).

  Also, founded on this work, three communications to international conferences taking place in 2011 have been written (see "publications" section).

In addition, the researcher has attended one of the conferences presenting a poster based on the work of the visit (NANOMETA 2011), and with regard to non-grant-related work, he has attended several seminars and has been involved in the Plasmonics group meetings as well as Materials group meetings.

Description of the main results obtained

In short, the main result obtained so far has been the modelling of metallic surfaces textured by annular apertures exhibiting highly-confinement surface waves at two frequencies. This dual-band surface plasmon-like-supported structure enables to extend the sensing techniques founded on surface plasmon polariton to terahertz frequencies.

Future collaboration with host institution

In addition to the ongoing work in collaboration with CIC nanoGUNE Consolider to design and measure the near-field of complementary split ring resonator based spoof surface plasmon, during the internship it has been identified the potential of a long-term collaboration between the host institution (Imperial College London) and the institution of Dr. Miguel Navarro-Cía (Universidad Pública de Navarra). The main reason behind the common interest relies on the fact that the equipment of each institution complements to each other in terms of techniques (frequency domain vs. time domain) and frequency band as follows:

- Materials laboratory at the Imperial College London: vector network analyzer (frequency technique) covering microwaves (0 – 40 GHz) and pulsed-technique for terahertz (from 0.06 to 4 THz).
- Millimetre and Terahertz Waves Laboratory, Universidad Pública de Navarra [8]: quasi-optical vector network analyzer covering millimetre-waves (from 45 to 670 GHz) [9].

This complementary instrumentation will allow broadband characterization of bio-substances (mainly molecules dissolved in water) – which is of interest of this network – as well as other substances/materials: from microwaves to terahertz.

In order to establish a long-term collaboration two strategies are going to be followed:

- To arrange visits/internships:
  On the one hand, Prof. Norbert Klein (chair in Electromagnetic Nanomaterials in the Department of Materials) is likely visiting the Universidad Pública de Navarra in 2011 to discuss common objectives in the field of biosensing. The intended date is May 2011.
  On the other, it is being explored that Dr. Miguel Beruete (member of the Millimetre and Terahertz Waves Laboratory at the Universidad Pública de Navarra) will do a co-funded one-month internship at Imperial College London to reinforce the collaboration sometime during the second half of 2011.
- To explore the viability of appointing a person for at least one year at Imperial College London:
  To this end, Dr. Miguel Navarro-Cía has applied for the Imperial College London Junior Research Fellowship (3-year fellowship) starting in the academic year 2011-2012.

Projected publications/articles resulting or to result from the grant

Communications in conferences:

1. **M. Navarro-Cía**, M. Beruete, M. Sorolla, and S.A. Maier, "Coaxial-cable-based planar THz waveguide: optimizing performance," IEEE AP-S International Symposium on Antennas and Propagation 2011 and USNC/URSI National Radio Science Meeting 2011 (2011 IEEE AP-S/URSI), Spokane, U.S.A., July (2011).
2. **M. Navarro-Cía**, M. Beruete, F. Falcone, M. Sorolla, and S. A. Maier, "Optimizing geometrically-induced plasmon-like waves by equivalent circuits," Progress In Electromagnetics Research Symposium (PIERS 2011), Marrakesh, Morocco, March (2011).
3. **M. Navarro-Cía**, M. Beruete, M. Sorolla, and S.A. Maier, "Analysis of surface-plasmon-like modes under an engineering perspective," The 3rd International Topical Meeting on

Nanophotonics and Metamaterials, NANOMETA 2011, Seefeld ski resort, Tirol, Austria, January (2011).

Journal papers:

1. **M. Navarro-Cía**, M. Beruete, M. Sorolla, and S.A. Maier, "Enhancing the dual band guiding capabilities of coaxial spoof plasmons via use of transmission line concepts," to be published in Plasmonics. DOI: 10.1007/s11468-011-9203-x.

References

[1] L. Solymar and E. Shamonina, *Waves in Metamaterials*, (2009).

[2] S.A. Maier,Plasmonics: Fundamentals and Applications, (2007).

[3] M. Navarro-Cía, M. Beruete, S. Agrafiotis, F. Falcone, M. Sorolla and S.A. Maier, "Broadband spoof plasmons and subwavelength electromagnetic energy confinement on ultrathin metafilms," Opt. Express 17, 18184 (2009).

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[5] http://teraview.com

[6] Editor's choice, "Plasmons on Separate Paths," Science 327, 505 (2010).

[7] http://www.home.agilent.com/agilent/product.jspx?pn=85070E&lc=eng&cc=US

[8] http://www.csm.unavarra.es/defaultE.asp

[9] http://abmillimetre.com