Research and knowledge transfer project

Advanced sensor based on metamaterials for multispectral imaging

Objectives

This research project aims at the development of sensors based on metamaterials and metasurfaces in order to increase the sensitivity of multi-spectral imaging systems. This project fits within Campus Iberus' research line in "Tecnologías para la salud" ("Health Technologies"). In particular, within this line, multimodal diagnostic technologies, to which multispectral sensing belongs, have been identified as one of the areas of interest in its action plan [1].

In this research line, the design of high-performance advanced sensors based on emerging technologies such as metamaterials and metasurfaces is proposed. Moreover, as an important novelty, in addition to the classic approach to the study of sensors based on metasuperficies, we will consider its use in configurations based on quantum phenomena. This dual approach, which makes use of the different nature of sensing techniques, makes it possible to use them in different frequency bands, being ideal for increasing the performance of multi-spectral image systems.

The project will be carried out in cooperation between the Institute of Smart Cities of the Public University of Navarra, by its Group of Antennas and the Multispectral Sensing Group of Navarrabiomed. Both groups possess the necessary knowledge in metamaterials and metasurfaces in the case of the ISC, and in multispectral sensing in the case of Navarrabiomed, which will be complemented with the incorporation of the Beatriz Galindo researcher, which should have expertise in quantum sensing and quantum metamaterials. This incorporation will bring a great added value to the project and will be the starting point of a new research line in cooperation between both groups.

Our generic objective of increasing the sensitivity of multi-spectrum image systems results in the following specific objectives:

- To study sensing configurations based on metasuperficies for multi-spectral image systems.
- To study sensing configurations based on quantum techniques combined with metasuperficies for multi-spectral imaging systems.
- To experimentally verify the studied sensing configurations and the achieved sensitivity increase.
- To explore the application of the analysed configurations beyond the field of multispectral imaging.

State of the art

The project will study sensing configurations for frequencies higher than the terahertz, focusing essentially on the terahertz, MIR and visible bands.

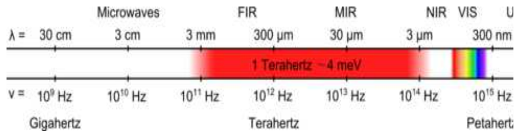

Figure 1. Electromagnetic spectrum (THz/MIR and visible bandas highlighted)

The terahertz and mid-infrared band (THz/MIR) is the spectral region between the microwave and near infrared (NIR). It is generally accepted that it ranges from 0.1 to 100 THz [2,3]. Until recently, the THz band has been known as the "THz gap" due to the difficulty of generating and detecting these frequencies efficiently. The situation has reversed thanks to the emergence of new THz generation techniques and new, cheaper and easy-to-use detectors. These discoveries have allowed to close the THz gap and these days there is an increasing research activity aiming at exploiting the technological possibilities of this so far unexplored band. As a matter of fact, the Multi-spectral imaging field is one of the areas where THz systems have been incorporated. In addition, the technological development at these frequencies has reached the adjacent upper band (MIR) so that today it is also another area of high scientific and technological interest. In this project we will refer to these bands in a generic way like THz / MIR.

THz/MIR spectroscopy field has undergone dramatic development in recent years due to the existence of large molecules of biological and biomedical interest, such as amino acids, which have a particular spectrum that allows their identification in this band. In particular, the wavelength of THz/MIR waves is comparable to the flexion, stretching, or torsion vibration movement modes of macromolecules. This makes this band crucial for applications in security [4], pharmacy [5], biomedicine [6], etc.

The detection of substances and materials in THz/MIR frequencies can be done by means of a classical analysis based on spectroscopy. With this method, the information (molecular bonds, concentration, etc.) is extracted from transmittance, reflectance and absorbance measurements, where the characteristic spectral peaks of the substance or material under test can be identified, exactly as it is done in infrared spectroscopy. Unfortunately, microorganisms and compounds of organic chemistry generally have a very similar composition (CH-, NH-), so identification with these techniques is not always simple.

An alternative to classical spectroscopy consists in designing ad-hoc platforms to improve or intensify the response of the analysed material. One of the most promising architectures in this regard are the advanced sensing platforms based on metasurfaces, thin screens designed to present non-conventional refraction / reflection properties. Sensing with metasuperficies is radically different: first, a screen with an intrinsic spectral resonance is designed. Then the analyte is deposited and the effect it has on the resonance of the metasurface is observed. Analyte information can be recorded in a multitude of parameters such as frequency shift, depolarization, refraction / reflection angle, absorption, etc. (see [7, 8] and the references contained therein). Thus, the possibilities and degrees of freedom for detection of substances grow dramatically so that even ad-hoc designs adjusted to the needs of specific analytes can be proposed.

In the literature we can find works that demonstrate the potential of metasurfaces for biological sensing [9-16]. The experiments shown there correspond to proof of concept tests, in which the possibility of detection of certain compounds or microorganisms is demonstrated, reporting increases in the sensitivity of the sensors of up to 10 orders of magnitude [11]. Some examples of these structures are shown in Figure 2. Although these are just the first steps, from the previous examples it is clear that metasurface based sensing devices constitute a huge step forward towards future lab-on-a-chip high performance biosensors.

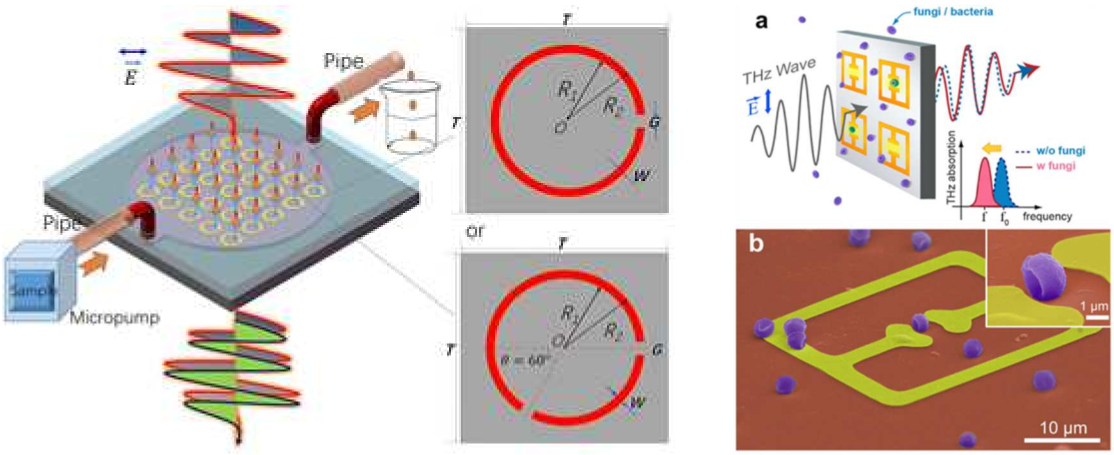

Figure 2. Left: Schematic of a microfluidics based sensor (from [10]). Right: (a) Schematic representation of a THz metasurface for microorganism detection. (b) SEM image of the metasurface, showing the microorganism positions. (Inset) Detail of the micro-hole (from [9])

However, there are several aspects that can be improved, which will be studied in this project:

(i) Study of new metasurfaces
In order to increase sensitivity, we will consider the study of new metasurfaces that allow a greater area of interaction with the analyte.

(ii) Metasurfaces with multifrequency response
To get the most out of the properties of the metasurface, it is important to control their response, so that their resonance frequencies can be adjusted, either to the analyte resonance frequencies or to the working frequencies of the test equipment. In both cases, design techniques for multifrequency metasurfaces are required.

(iii) Guided sensing configurations
Most experiments carried out so far are based on quasi-optical configurations, which can be inefficient. It is postulated that the sensitivity of the sensors could be increased if guiding structures, in which the metasurface will be implemented, were used. This approximation, followed in the microwave and millimetre-wave ranges, frequencies lower than those that will be considered in this project, is not directly scalable to said frequencies. For this reason it will be necessary to carry out adjustments that include, for example, the use of waveguides that are more suitable for high frequencies, such as those based on photonic crystals.

On the other hand, quantum technologies leverage basic aspects of quantum mechanics like entanglement to boost the performance of computation and communication systems beyond their classical limits. Other applications of quantum technologies include quantum sensing, where quantum field correlations enable sensitivities unattainable with classical systems and, in particular, beyond the standard quantum limit (see the recent review [17]). This technology is particularly relevant for the field of health and life sciences, where constraints in terms of sensitivity are crucial to determine the feasibility of a given application.

The success of quantum technologies is linked to the development of nonclassical light sources, since quantum light states feed and ultimately enable the processes underpinning these technologies. Therefore, the development of nonclassical light sources based on metasurfaces can have an important impact in different sensing systems, as well as their applications in health and life sciences.

Specifically, we proposed the following research lines:

(i) High-N00N state generation
One of the main areas of application of quantum optics for sensing systems relies of the use of entangled states to boost the sensitivity beyond classical limits. For instance, when a N00N state is distributed on the two arms of an interferometer, the phase advanced experienced by this state is N times larger than that obtained under the usual operation mode of the interferometer [18]. This effect has a multiplicative impact on the phase sensitivity, with direct application in the analysis of biological and chemical samples. In fact, this technique can be particularly useful in the analysis of samples with very low concentrations, where the impact of the on the refractive index of the sample is very small. N00N-state-enhanced biological sensing has already been successfully demonstrated experimentally, for example, in measuring protein concentration [19]. However, a bottleneck in the further application and development of this technology is that there is no deterministic procedure for the preparation of N00N states for N>2. In fact, state-of-the-art sources of N00N states require from projection measurements and postelection [20], or approximate approaches to their generation [21], which limits the scope of these systems. Therefore, the development of metasurface-based nonclassical light sources allowing for the preparation of N00N states with a higher probability, or even deterministically, would have an important impact on the development of this technology.

(ii) Squeezing
Another approach in the use of quantum light states to improve the resolution of an interferometer relates to the use of squeezed light to reduce the noise level [22]. In particular, squeezed states can be used to suppress shot noise, inherent to the quantization of the electromagnetic field, by transferring the uncertainty between the quadratures of the signal. In this manner, it is possible to improve the signal to noise ratio of the system without increasing the signal power. In turn, this allows for minimizing the action of the interrogating signal on the sample, including heating and/or motion induced by optical forces.
This methodology is currently used in gravitational wave observatories [23], and it has been demonstrated in biological samples in combination with optical tweezers [24]. Squeezed states of light can be generated with different nonlinear processes. Nowadays, the best results are obtained with cavity-enhanced optical-parametric amplification (OPA), with squeeze factors as high as 15 dB (which is associated with 32 enhancement factor on the signal to noise ratio for with classical light of the same power) [25]. Current limitation factors for the squeeze factor are imposed by the influence of decoherence processes. In addition, only a few proof-of-concept demonstrations of on-chip squeezed light sources have been presented. Using metasurface and metamaterials concepts can assist in the

development of this technology in both aspects. For example, nonlinear phenomena is intrinsically enhanced in zero-index (ZI) media (a medium whose refractive index approaches zero), allowing for the observation of effects beyond the usual perturbative description [26, 27]. Moreover, physical realizations of all-dielectric (and thus low-loss) and on-chip integration of ZI media have been experimentally demonstrated [28].

(iii) Quantum absorption

One of the main challenges associated with the realization of quantum technologies is that entangled states are extremely sensitive to decoherence phenomena. Although this effect is one of the main difficulties in the development of quantum computing and quantum simulations, we suggest that the extreme sensitivity of entangled states can be harnessed to enhance the performance of sensing systems. In this regard, recent experimental demonstrations of nonlinear quantum absorption in lossy beam-splitters opens the door of exploiting absorption as an additional resource in quantum interference [29]. For example, the sensitivity of entangled states with respect to decoherence can be used to analyze weakly absorbing samples. With this perspective, the numerous degree of freedom offered by metasurfaces for the selective control of light-matter interactions could be used to tailor the desired absorption channels.

(iv) Ultra-wideband (UWB) photon sources

Classical radar and imaging technologies benefit from ultra-wideband pulses to enhance spatial and temporal resolution [30]. Similarly, the use of UWB photons would benefit and increase the resolution of quantum optical sensing and imaging systems. During recent years, there has been great advances in the field of integrated single-photon sources, leading to an important improvement in their performance in terms of purity, indistinguishability and on-demand operation [31]. However, state-of-the-art single photon sources do not offer much control over the bandwidth of the emitted photons and, importantly, there is no efficient methodology for the generation of UWB photons. Therefore, the design of UWB photon sources based on metasurfaces would enable an improvement on the resolution and functionalities of nonclassical light sensing and imaging systems.

(v) Efficient narrowband photon sources

Contrary to UWB photon sources, efficient sources of narrowband photons would provide and enhanced frequency resolution of interest for spectroscopy. Specifically, efficient narrow band photon sources would enable single photon activation of biological and chemical processes, while maintaining spectral resolution. In turn, this would improve the selectivity among the many transitions of biological entities. In this regard, most solid-state quantum emitters exhibit narrowband spectral lines that could be employed for spectroscopy applications. However, narrowband quantum emitters are usually inefficient, particularly for solid-state systems operating at room temperature. Typically, the efficiency of these emitters is improved by coupling them to a photonic nanostructure that accelerates the desired decay process [32]. Usual strategies like Purcell enhancement are based on enhancing the decay rate and thus they also lead to a broadening of the bandwidth. Consequently, there is a compromise between narrowband operation and efficiency in the design of a quantum emitter. Therefore, the development of metasurface-based alternative strategies enabling a simultaneous enhancement of the efficiency and reduction of the bandwidth will enable efficient narrowband photon sources for spectroscopy systems.

The ISC group holds a long and consolidated research track in the field of metamaterials and metasurfaces, as well as in the development of applications of terahertz frequencies in different fields: security (FP7-SEC-2012-1 -312496, IPT-2011-0960-390000, IPT-390000-2010-3), communications (TEC2016-76997-C3-1-R, TEC2013-47753-C3-1-R), radioastronomy (TEC2014-61817-EXP), radar (RAFF – Radar for Flight, 0011-1365-2016-000084), agro (Gobierno de Navarra, PI025, 2016/PI014 e IIM14244.RI1) and industrial (RTC-2014-2110-2). It is worth mentioning the applications in the biomedical arena, where in cooperation with Navarrabiomed, they have work on fungal infection detection by means of THz and MIR spectroscopy in the framework of projects YEDIS (Yeast Detection by Infrared Spectroscopy, 0011-1365-2016-000081) and EIFFEL (Early invasive fungal infection detection with Terahertz sensor systems, IIS14618.RI1)

Moreover, focussing on the metamaterial and metasurface field the group at ISC has work in several research projects. Among them we can highlight projects Consolider EMET (CSD2008-00066) and TEC2014-51902-C2-2-R, devoted to investigating metamaterial structures. First steps in the field of THz sensing have already been given, so that the group has already a published journal paper [16] and several conference papers in this area.

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Impact

In the scientific field, the main impact of the project will be the improvement of sensitivity of the sensors thanks to the specific design of metamaterials/metasurfaces. It is expected that the use of these specific metamaterial/metasurface configurations will allow increases in sensitivity of several orders of magnitude.

The project will serve to complement the existing research lines of the ISC, opening the line of quantum sensing. This will be possible thanks to the incorporation of the Beatriz Galindo researcher, who must have a profile oriented to quantum sensing and quantum metamaterials. This incorporation will provide a great added value to the ISC and will be the starting point of this new research line in this field.

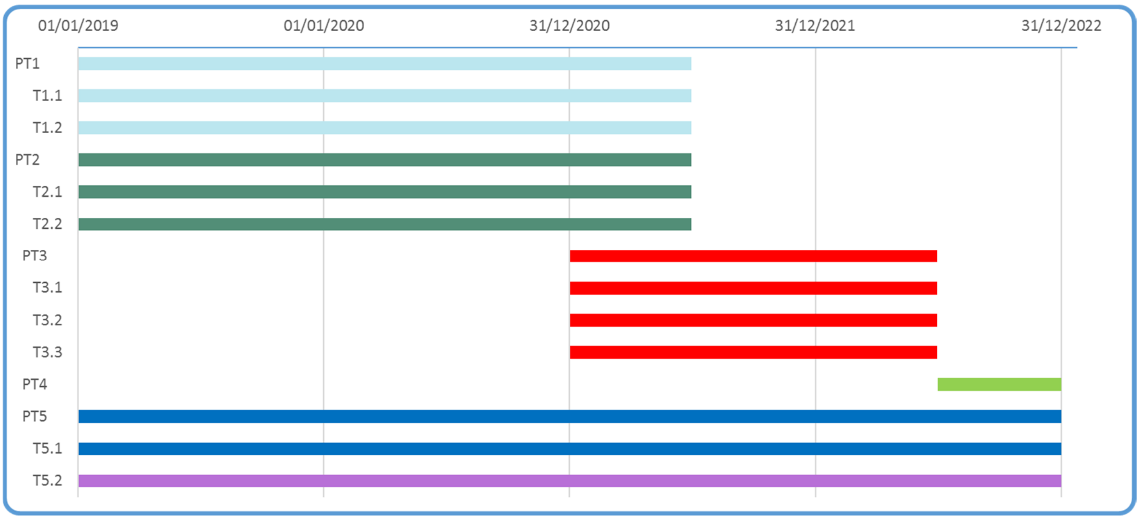
On the other hand, this project is part of one of the areas of interest identified by Campus Iberus within the line of research "Health Technologies". The project will develop sensors based on metamaterials and metasurfaces that will improve the sensitivity of the sensors currently used within multispectral imaging systems. In this way, the project will contribute to the Campus Iberus goal of developing the Health Technology area as a way to promote the application of new technologies in biomedical research and in clinical and healthcare practice.

Finally, medical imaging technologies are very useful for the early detection and diagnosis of diseases. Any contribution in this area would have an impact in the diagnosis procedures, since it would offer new possibilities to health professional. Hopefully, this project will therefore contribute to the generic goal of prolonging life and improving the quality of life of patients.

Workplan

The proposed workplan is based on a series of interconnected workpackages. WP1 and WP2 workpackages are the main core of the project, given that they will study the different sensor configurations based on metasurfaces. Once completed, the experimental verification will be carried out in WP3. Finally, dissemination activities will be implemented in WP4, while WP5 will be devoted to project management.

The project is structured over 4 years. The temporary distribution of the different work packages and their tasks are represented in the following Gantt chart:



Workpackage description:

WP1	**Design of metamaterial/metasurface based sensors**	
In this workpackage the design activities of the different configurations of metasurfaces that will be explored in the project for its application in hyperspectral imaging systems will be carried out. Given the technological limitations imposed by the different frequency bands, different tasks associated with the targeted frequency bands are proposed.		
T1.1	**Design of metamaterial based sensors in the terahertz band** In the terahertz band, it is possible to work with both free space and guided sensing configurations. Both will be studied within this task, and appropriate metamaterials and metasurfaces will be developed for each of them.	
T1.2	**Design of metamaterials in the MIR band** In this band different configurations of metasurfaces will be proposed for their use both in free space and in Attenuated Total Reflection (ATR) sensing configurations.	
Milestone	**Month**	**Milestone description**
M1	M30	Design of metamaterial/metasurface based sensor

WP2	Design of metamaterial based quantum sensors	
The goal of this working package is the investigation of different approaches towards the improvement of quantum sensing techniques based on the use of metasurfaces. We propose two main lines of research with applications in the visible regime.		
T2.1	**Entanglement-enhanced optical sensors** This task will focus on the generation of entangled light states and their application to boost sensitivity. This will include the preparation N00N states, squeezed light, and research on quantum absorption effects.	
T2.2	**Bandwidth-controlled photon sources** This task will deal with the development of photon sources with unprecedented bandwidth functionalities. This will include both ultra-wideband (UWB) photons and efficient narrowband photons.	
Milestone	**Month**	**Milestone description**
M2	M30	Design of quantum sensors using metamaterials

WP3	Experimental verification of the sensing configurations	
The objective of this work package is to design and experimentally verify sensing configurations based on the structures studied in the previous work packages. For classical metasurface based sensors, characterization of different configurations will be carried out at the measurement facilities of Public University of Navarra and Navarrabiomed. For quantum sensing, being a new research line to these institutions, most of the efforts will focus on the design and development of a quantum optical experimental set-up extending their measurement capabilities.		
T3.1	**Manufacture and characterization of sensor configurations in the terahertz band** The final sensor design will be made taking into account the particularities of the manufacturing procedures available at the Public University of Navarra. Once manufactured, the characterization of the sensors will be carried out.	
T3.2	**Manufacturing and characterization of sensor configurations in the MIR band** For this frequency band, external manufacturing will be subcontracted in case it were not possible to carry it out in house. Finally, the designed sensors will be characterized.	
T3.3	**Design of quantum sensor characterization experiments based on metasurfaces** In the case of quantum sensors, most of the efforts will be focused on the design and development of an experimental setup for their characterization, extending current measurement capabilities.	
Milestone	**Month**	**Milestone description**
M3	M42	Experimental demonstration of metamaterial/metasurface based sensors.

WP4	**Dissemination, IP management and technology transfer**	
The objectives of this work package are to disseminate the results of the project and the management of intellectual property rights. The dissemination of information and results will involve several sub-tasks, such as publications in specialized journals and international conferences, or organization of seminars and focussed sessions in the main conferences in the field. Special attention will be paid to the exploitation of the results generated, through workshops and personalized meetings with companies or research centres that might be interested in the results obtained.		
T4.1	**Dissemination** This task is devoted to making public the results obtained in the project.	
T4.2	**IP management** The objective of this task is the management of intellectual property rights and of the know-how developed within the project.	
T4.3	**Transfer of results** The database of companies generated by Campus Iberus will be used to disseminate the main results obtained and to facilitate their commercial exploitation. In addition, workshops will be organized within Navarrabiomed to promote the use of the techniques developed beyond the field of multispectral imaging.	
Milestone	**Month**	**Milestone description**
M4	M48	End of dissemination activities

WP5	**Project management**	
This work package deals with the operational and technical management of the project. It covers management activities in contractual, financial, legal, technical and administrative matters. The main objective is to carry out an efficient management process, as well as the provision of an effective risk management strategy, which will avoid deviations from the work plan and will allow complying with the project's objectives.		
T5.1	**Project management** Management of contractual, financial, legal, technical and administrative issues.	
T5.2	**Risk management** Management of the risk strategy.	
Milestone	**Month**	**Milestone description**
M5	M48	End of the Project

Knowledge transfer

This research project is part of Campus Iberus in the area of Health Technologies. Within this field, it belongs to the multimodal diagnostic area, specifically to the Medical Image area.

The development of the project will have a direct scientific impact, since it will mean a significant advance in the state of the art of the sensors based on metamaterials and metasurfaces. This will bring about new possibilities within this field that should be disseminated among the companies and centers that may benefit from these advances. In this sense, it is worth noting that the participation in the project of Navarrabiomed, a reference center in biomedical research, makes it possible to contact the most relevant agents in this field.

In addition, regarding the transfer of knowledge to the industrial sector, Campus Iberus is carrying out a series of actions to enhance collaboration with industry and enable transferring of technology developed in the field of Health Technologies. These actions include:

- Identify the main companies of interest for the development of projects in the field of Health Technologies.
- Generate a database of early demand for the technological needs of the identified companies.
- Disseminate the detected needs among the stakeholders of the Campus Iberus.
- Establish a database with the solutions of stakeholders to the needs raised.
- Promote a workshop between stakeholders and companies to foster cooperation and build collaborative projects.

All these actions are underway and by the time the project is completed, it is expected that we could benefit from them to carry out the transfer of the project results effectively.

Beyond these actions, the Public University of Navarra through its Institute of Smart Cities keeps contact with several companies that will act as observers of the project. Although these companies are not directly linked to the health sector, their areas of work are related to electromagnetism and terahertz image technologies, so they would be interested in the final results of the project.