Research Networking Programmes

Short Visit Grant ☐ or Exchange Visit Grant ☒

(please tick the relevant box)

Scientific Report

The scientific report (WORD or PDF file – maximum of eight A4 pages) should be submitted online within one month of the event. It will be published on the ESF website.

Proposal Title: Gradient Metasurfaces with Interwoven Patterns for Wave Shaping and Focusing Functionalities with Improved Bandwidth and Resolution Performance

Application Reference N°: 5093

1) Purpose of the visit

The main objective of this exchange visit was to investigate the feasibility of creating phase gradient discontinuity of scattering by using metasurfaces (MSs) composed of constituent elements with interwoven and tessellated topologies and their potential application to realize anomalous reflect/transmit beams across broad bandwidth and for wave shaping. The concept of interleaving conductor patterns of doubly periodic arrays underpins a class of MSs with miniaturized unit cells and highly stable angular and polarisation response across wide fractional bandwidth. These unique properties are enabled by convoluted strips or slots in conductor sheets extended beyond a single unit cell and interspersed in adjacent unit cells of substantially subwavelength size. In particular, multifilar spirals and Brigid's crosses have been proposed as alternative constituent elements of the conductor patterns which can be not only interleaved but also nested and tessellated.

The idea behind this research is that the use of interwoven patterns with substantially subwavelength constituents as the building block of novel gradient MSs can facilitate the achievement of improved performance in terms of angular and polarization stability over possibly broader frequency bands. Moreover, the very subwavelength size of such interwoven scatterers implies that the near-field is closely confined and the interfacial phase shift is a smoother quasi-continuous function owing to the pattern interleaving between adjacent unit cells. The higher duty cycle and quasi-continuous phase shift are expected to strongly suppress excitation of the spurious diffracted modes and significantly increase the conversion efficiency of the incoming wave to anomalously scattered dominant outgoing waves. In other words, MSs with interwoven patterns should enable engineering the spatial distribution of amplitude, phase and polarization response with finer resolution, making it possible to achieve higher wave conversion efficiency. The larger range of spatial frequency components provided by the proposed MSs with higher subwavelength resolution enables the control of the near-field and meso-field. Moreover, wavefront shaping by the MSs with interwoven patterns could be accomplished within a distance much smaller from the interface than with other kind of scatterers as the incident wave traverses or is reflected by the thin MS.

2) Description of the work carried out during the visit

The introduction of an abrupt phase shift, denoted as phase discontinuity, at the interface between two media has been recently shown to require the generalization of Snell's laws of reflection and refraction in accordance with Fermat's principle. Generalized Snell's laws indicate that the transmitted and reflected waves can be bent into arbitrary directions in their respective half space, depending on the direction and magnitude of the interfacial phase gradient, as well as the refractive indices of the surrounding optical media. The elemental constituents of the MS must be able to controllably alter the phase of the scattered waves. Phase shifts covering the 0 to 2π range are needed to provide full control of the wavefront.

In our work we concentrated on reflectarray-type structures, consisting of an array of intertwined spirals and a ground plane, separated by a thin dielectric spacer, which is also the common approach for realizing a high-impedace surface (HISs). The essence of reflectarrays is to use resonators coupled with their dipolar images in the ground plane to achieve a reflection phase coverage of 2π. This approach has the advantage that the MS scattering efficiency could be significantly enhanced due to the ground plane completely suppressing transmission, whereas to boost the efficiency of MSs used to control the transmitted light one has to match their impedance with that of free space. An additional advantage is that the polarization of the reflected light is the same as that of the incident light. In this work, we have assumed for simplicity that the illuminating field is impinging at normal incidence on an interface and that a gradient MS is developed to efficiently reflect the normally incident plane wave to a given angle from normal. Since the incident and reflected waves are plane waves, the phase gradient must be constant and exhibit periodicity in the direction of the field polarization to which the surface is designed to respond. Each period corresponds to a macro-cell, whose 2D periodic translation in the plane forms the entire planar MS which is discretized into a number of resonant subunits designed to have a constant phase difference between neighbours.

As the first step, we have investigated different strategies to realize the required variable reflection phase along the interface. The first option that we have considered was to spatially tailor the geometry of the intertwined spirals across each macro-cell of the array, and hence their frequency response, based on the significant change of the phase shift between the incident and the scattered waves near a resonance. By using approximate analytical models and rigorous full-wave simulations, we have demonstrated that the phase response of intertwined spiral elements can be controlled, for example, by changing the degree of intertwining or tailoring the length of spiral arms with the introduction of breaks at different locations along them. However, while with this approach it is possible to obtain a variable phase of the reflection coefficient of the individual spiral elements, it has been observed that two related issues may arise: i) the range of reflection phases actually realizable by simply varying the geometrical parameters of the spiral elements; ii) the connection at the boundaries of the array macro-cell of spiral elements with significantly different layouts without interupting the monotonic variation of the reflection phase gradient, which is connected to the fact that the interweaving of the patterned conductors implies that each element is actually extended beyond a single unit cell. To address these issues, we have tried to more effectively realize the desired phase gradient by assembling each macro-cell with spiral elements having identical layout and loading the resonators with lumped elements of suitably variable values. In particular, we have investigated the use of lumped inductances, connected in series across breaks in the spiral conductors, and capacitances, placed in shunt between adjacent spiral arms. Such lumped elements incorporated into the scatterers can provide the desired large reflection phase variability, close to 2π, while simplifying the topology of the scatterers to form the macro-cell of the gradient MS. While these lumped components do not need to be tunable, and could possibly be realized by changing the conductor width or introducing interdigital capacitances between spiral arms, the adoption of varactor diodes as voltage controlled variable capacitances could lead to the further advantage of reconfigurability and beam steering capabilities of the proposed gradient MSs.

To establish a systematic framework for the design of the intertwined spiral gradient MSs, a simple pseudo-analytical approach, based on the tranmission line model (TL) of plane wave propagation across the spiral arrays and the principle of local periodicity, was developed. This approach essentially consists in retrieving the equivalent impedance of uniform spiral arrays from the full-wave simulation of a single unit cell of the array with periodic boundary conditions. Then, by inserting the equivalent impedance of the spiral elements into the TL model of the MS backed by the ground plane and loaded by the lumped elements, the reflection phase of the individual resonators can be represented in analytical form. As a result, the problem of finding the values of lumped elements to be inserted into the intertwined spiral resonators in each macro-cell of the MS to realize the prescribed phase gradient and associated beam steering response at a given operating frequency is reduced to the solution of a system of nonlinear equations, which can be easily treated numerically. The hypothesis of local periodicity of the MS underlying this approach seems to be justified by the slow variation of the scattering characteristics of the individual resonant elements across a macro-cell.

A few sample gradient MSs have been designed by using the above TL approach, and their performance has been characterized by simulating their single macro-cells with periodic boundary conditions. As a result only well identified modes, known as Floquet harmonics, are permitted to propagate. From simulations, a fraction of the incident power scattered into the various propagating Floquet harmonics was estimated. It was verified that the developed gradient MSs based on the intertwined spiral arrays with embedded lumped elements can couple most of the incident power into the desired reflected harmonics. However, the conversion efficiency was lower than expected, and some residual excitation of other harmonics was observed. In fact, from the analysis of the phase of the currents induced in the intertwined resonant elements forming the MS macro-cells, it has emerged that the realized phase gradients were not completely congruent with the theoretical profiles. These discrepancies are attributed to the simplifying assumptions of the used design method and, in particular, the hypothesis of local periodicity. While substantially valid in the central part of the macro-cells, it is not held near their boundaries, where the impedances of the resonant elements undergo abrupt changes to provide the required reflection phases. In particualr, this effect is non-negligible for MSs formed by the intertwined spirals due the strong distributed coupling between the interleaved spiral arms extended from adjacent unit cells. The development of a more sophisticated design technique, capable of taking into account the inherent aperiodicity of the macro-cells of gradient MSs and the resulting variable coupling of the constituent intertwined elements, will be part of future research on this topic.

3) Description of the main results obtained

Among the main results of the work carried out during this 8-week visit are the identification and numerical characterization of different strategies to control the reflection phase response of the intertwined spiral arrays backed by a metallic ground plane, by either changing their geometrical parameters and degree of intertwining or incorporating lumped elements or varactor diodes at specific locations on the surfaces. A simplified design methodology combining the TL model with the hypothesis of local periodicity was also developed and applied to demonstrate feasibility of creating phase discontinuity of scattering by interwoven spirals with incorporated lumped elements. This design approach was used to develop proof-of-concept gradient MSc whose performance was then verified by rigorous numerical simulations. While the simulations substantially confirmed the desired beam steering capability of the designed gradient MSs made of interwoven spiral scatterers, they have also revealed inaccuracies in the realized profile of the reflection coefficient phases of the individual scattering elements. Such discrepancies were traced back to the simplying assumption of local periodicity exploited in the initial designs, and it is envisaged that improved performance could be achieved by developing a more sophisticated and precise design technique.

4) Future collaboration with host institution (if applicable)

This exchange visit has permitted to initiate a collaborative research activity between the Laboratory of Applied Electromagnetism of the University of Siena and the Institute of Electronics, Communications and Information Technology (ECIT) of Queen's University Belfast, in the field of MSs and their application to the development of novel ultrathin beam steering and wave shaping devices.

The visit has constituted an opportunity to exchange knowledge and cooperate on a research topic of common interest with mutual benefits in terms of cross-fertilization of research experiences and scientific backgrounds. It is expected that research on this topic, and more generally in the field of MSs, will proceed in the future in a more coordinated way between the two institutes, while new opportunities to support closer interaction and cooperation will be actively sought for.

5) **Projected publications / articles resulting or to result from the grant *(ESF must be acknowledged in publications resulting from the grantee's work in relation with the grant)***

Results achieved during this visit are still preliminary and, as mentioned above, further developments and improvement of the design methodology for the proposed MSs with interwoven patterns are still necessary. However, it is foreseen that initial outcomes of this research could be the subject of a contribution that will be submitted to the next European Conference on Antennas and Propagation, to be held in Davos, Switzerland, on 11-15 April 2016.

6) Other comments (if any)