Research Networking Programmes

Short Visit Grant ☐ or Exchange Visit Grant ☒

(please tick the relevant box)

Scientific Report

Proposal Title: Controlling directivity and shaping radiation at millimeter and terahertz frequencies by using quasiplanar superstrates – front ends with strongly localized subwavelength resonances

Application Reference N: 4721

1) Purpose of the visit

The purpose of the stay at the Universidad Publica de Navarra was to work on the project dedicated to the study of quasiplanar (ultrathin) superstrates, which are based on three-layer hole array stacks and work in the localized-resonance slow-wave regime that enables performance enhancement of the antenna systems, and build long-term collaborations on the relevant research topics.

2) Description of the work carried out during the visit

During the research period, I worked on the project in close collaboration with Dr. M. Beruete, Dr. F. Falcone, and members of their team. Thus, I used the opportunity to merge rich experience acquired by the host institute in the hole-array (fishnet) metamaterials with my recent ideas and plans regarding a new class of the structures that may serve as efficient front-ends enabling enhancement of performance of the antenna systems, to which they are integrated. Thus, the emphasis has been put on practical applications. Accordingly, the parametric study has been carried out with the general aim to find the appropriate ranges of parameter variation and design the structures that may lead to a reasonable compromise between the geometrical (e.g., thickness) and electromagnetic (Q-factor, group velocity, directivity) characteristics, by taking into account fabrication and other related issues. CST Microwave Studio, a 3D full-wave commercial solver has been used as the main simulation tool. The equivalent circuit approach, which has recently been adapted at the host institute to the stacked hole arrays (SHA's), has been utilized for the initial-stage parameter choice and interpretation purposes.

As entry point, (a) the recent results obtained in the frame of collaboration between the researcher and the host institute, including those of the previous research period supported by the ESF, (b) recent literature on ultrathin Fabry-Perot type cavities and metamaterial cavities for antenna applications, (c) recent literature on directive beaming, and (d) the host institute's recent findings on metamaterials have been used. This information has carefully been analysed with the aim to detect critical features and problems and, thus, to reduce the overall efforts required for fulfilling the objectives of this project.

An alternative way of obtaining of slow waves in quasiplanar structures has been utilized that is based, in fact, on the common effect of the hole arrays working in the propagating-wave and evanescent-wave regimes. This enables defect-mode type, i.e., volumetric effects at very small total thicknesses, that makes them good candidates to be applied to shaping radiation of the antenna systems with or without connection to the leaky wave based mechanism. After the detailed numerical study, the basic ideas have been transferred to the practical design.

3) Description of the main results obtained

In the *first part* of the project, the routes to quasiplanar (ultrathin) superstrates based on SHA's with the complex shapes of the holes and small total thickness have been investigated. The goal here was to find the structures with the slow-wave Fabry-Perot type resonances than may be thinner than $\lambda/10$ and even $\lambda/25$. The attention has also been paid to the performances enabling dual- and multiband operation. The obtained results confirm the initial guess, i.e., that the key feature, which may enable performance enhancement over the known ultrathin cavities and the metamaterial based structures, concerns the peculiar spectral properties of the localized subwavelength resonances and the related possibility of decreasing group velocity. Choosing the hole shapes in the "regular" and "defect" arrays, one can control the resonance frequencies of the operation (defect type) modes, which are associated with subwavelength resonances. As shown, obtaining of the total thickness less than $\lambda/10$ is not a big problem. In the larger part of this study, hole shape in the "defect" array represents the complimentary split-ring resonators (SRRs). The possibilities of decrease of the lateral size of a unit cell have been investigated by involving the complimentary resonators of a more complex shape.

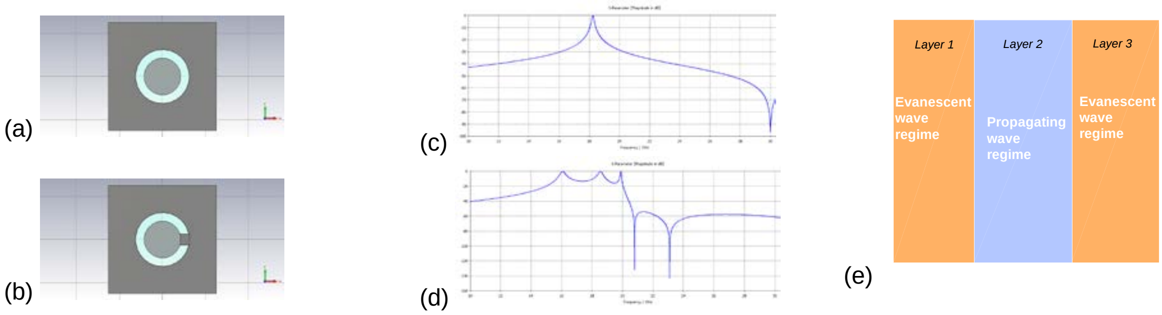


Figure 1. Example of geometry of unit cell of (a) regular and (b) defect array; transmission ($|S_{21}|$) vs frequency for (c) three-layer sandwiched configuration and (d) three-layer structure composed of defect arrays; (e) schematic demonstrating the general transmission mechanism, Ku-/K-band.

The basic class of the studied configurations represents a stack of three arrays, two of which are regular arrays and the middle array is defect one, see Figs. 1(a) and 1(b), respectively. Moreover, three layers are really enough to obtain strong localization and high Q-factor, although it can be even more enhanced if using five or seven layers at the price of increasing the total thickness. The parameters of the defect array are chosen so that the lowest resonance frequency is lower than the frequency threshold, above which the "regular" array can itself transmit electromagnetic waves. In other words, the general scheme is based on sandwiching an element showing a subwavlength resonance between those working in the evanescent-wave regime, as shown in Fig. 1(e). As a result, the resonance fields can be strongly localized in space, whereas transmission represents narrow defect-mode type peaks and corresponds to small group velocity, see Fig. 1(c). For the comparison, Fig. 1(d) shows transmission through the corresponding three-layer structure comprising only defect layers. The total-thickness-to-wavelength and lateral-period-to-wavelength ratios are equal here nearly to 0.07 and 0.3 that is typical for the considered class of the structures. CST Microwave Studio, a commercial software based on the finite integration method has been used for simulations aimed to find the performances with very small total thickness. The assumption of PEC metallic parts was adopted.

A semi-analytical approach based on the equivalent LC circuit model has been utilized for the fast estimation of the resonance frequencies and initial-stage design without time consuming simulations. On the other hand, the tight-binding theory did not lead to the expected improvements, probably, because of the specifics of the considered class of the structures. Generally, the combination of rigorous and semi-analytical model provided the possibility of obtaining the useful results within a limited time frame.

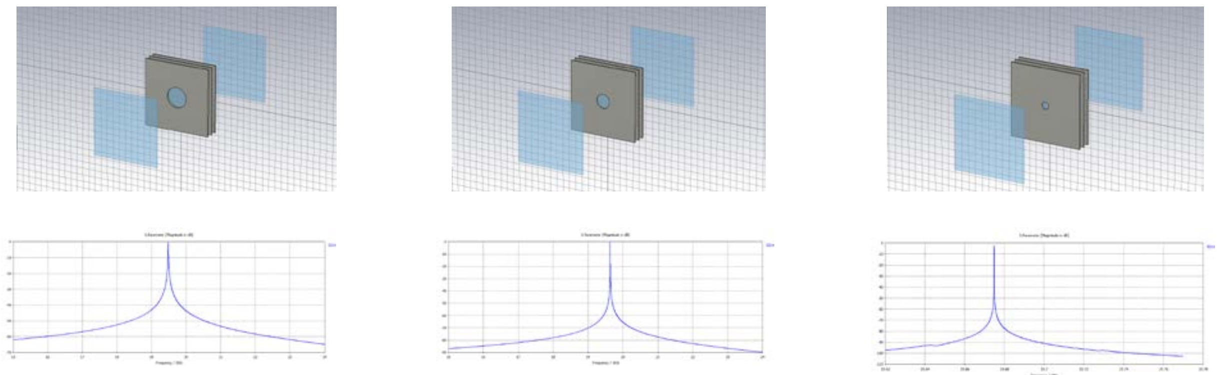
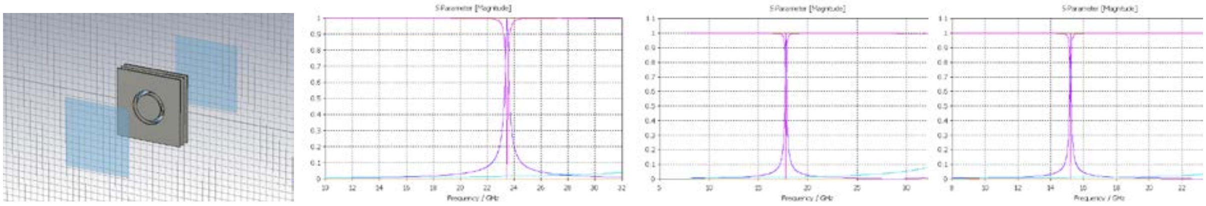


Figure 2. Top - geometries with complimentary SRR defect (middle) array and circular-hole regular (outer) arrays: left - large, middle - intermediate, and right - small diameter of the holes of the regular arrays; bottom - the corresponding transmission ($|S_{21}|$), Ku-/K-band.

Figure 2 shows geometry and transmission results for three structures, which only differ in the diameter of the holes in the regular (outer) arrays. It is seen that the spectral location remains the same, whereas the peak width tends to decrease, i.e., the higher Q-factor can be achieved. Thus, the resonance frequency and Q-factor are mainly determined by the properties of the defect and regular array(s), respectively. Thus, choosing characteristics of these layers in a proper way, it is possible to obtain the desired resonance properties, while the entire structure remains very thin. The observed features make the suggested structures advantageous as compared to the known ultrathin Fabry-Perot type and metamaterial based cavities. Moreover, these structures are thinner than those suggested earlier in the framework of collaboration between the researcher and the host institute. The observed resonance transmission has a slow-wave nature, since it corresponds to the nearly flat dispersion. It is worth noting that the perfect transmission can be achieved even for very small holes. Thus, the incident wave is perfectly squeezing into significantly subwavelength holes.

Finally, *nonsymmetric* three-layer hole array stacks have been investigated. These structures differ from the similar structures studied earlier by the researcher and at the host institute in that they have a substantially smaller thickness. As a result of the work on this part of the project, seven most promising performances were selected to be studied in detail in the next parts of the project at the beam-type illumination corresponding to radiation of a microwave antenna.

The *__second__* *__part__* of the project has mainly been dedicated to the adaptation of the results and ideas generated in the frame of the first part to the practical antenna systems. The focus has been the choice of quasiplanar (ultrathin) structures enabling desired directive properties, e.g., directive beaming that can be integrated with patch and horn antennas. Since the main mechanism exploited is based on subwavelength resonances, the choice of the laminate placed between the hole arrays can strongly affect the resonance, i.e., operation frequencies and some properties of the resonance fields that are critical for the performance. Using the results of the first part of the project as entry point, simulations were carried out in order to take into account permittivity of the laminate. The study has been performed for the permittivity ranging from 2.1 (teflon) to ~12 (GaAs, silicon), i.e., for the materials that are commonly usable and easily implementable in practical design.



(a) (b) (c) (d)

Figure 3. (a) Unit cell of the structure with coaxial-shaped holes of regular arrays and complimentary SRR defect array; Transmission ($|S_{21}|$, peak) and reflection ($|S_{11}|$, dip) at different permittivity of dielectric layers between the hole arrays: (b) $\varepsilon=1$, (c) $\varepsilon=2.1$, (d) $\varepsilon=11.4$, Ku-/K-band.

An example is presented in Fig. 3. One can see that, in spite of the fivefold increase of the laminate permittivity, the resonance frequency has been downshifted only by 55 per cent, i.e., from 23.5GHz to 15.2GHz. The performed analysis of the field distributions shows that the characteristics of the dielectric material placed *inside* rather than *around* the open subwavelength resonators is most critical. Hence, a reasonable design solution can be based on the use of a proper dielectric filling in the volumes, where the fields might be especially strong.

Next, possible ways to multiband operation have been investigated. They include the advanced performances that contain different subwavelength resonance elements with different resonance frequencies in the same defect array and ultrahigh-permittivity layers between the individual hole arrays. The peculiarities of the choice of the laminate material and related design steps have been considered and the corresponding numerical results obtained for different radar bands, i.e., from C-band to W-band, with an extension up to 2 THz. As has been demonstrated by the obtained simulation results, choice of the laminate material and dielectric filling can be important for microwave and millimeter-wave applications. However, miniaturization in this case is more efficient when using subwavelength resonators that have ultrasmall size due to the specific geometrical features. On the contrary, restrictions related to Ohmic losses may be more important at terahertz frequencies, whereas miniaturization is not so important as at the lower frequencies. In spite of this, rescaling remains an efficient design tool within the entire frequency range of interest. Several selected performances with a small number of the stacked hole arrays, which have earlier been designed by the researcher and his colleagues at the host institute, were carefully examined by taking into account the above-mentioned reasons.

Within the PEC assumption, resonance absorption enhancement, which may appear at terahertz frequencies, cannot be taken into account. Thus, the PEC performances that look most promising for these frequencies were checked by repeating simulations by using lossy metallic parts. The equivalent LC-circuit model has been utilized for interpretation of the rigorous numerical results. The routes to its further modifications, which would take into account the specifics of the studied structures, were indicated. Four millimeter-wave pre-prototypes of the layered superstrates have been selected, which were the focus at the next steps of the project. At the same time, two terahertz pre-prototypes have been selected, in which the peculiarities of this frequency range are taken into account.

Up to now, it has not been a big problem to perform CST simulations, because the assumption of lateral periodicity was used together with the frequency-domain solver. Next, finite-size structures at a beam-type illumination were simulated in order to come from the simplified theoretical to more realistic performances. The time-domain solver has been used together with the standard CST tools of the near field visualization and retrieval of the far-field characteristics. The structure was assumed to be composed of 10X10 to 20X20 unit cells, while excitation was simulated by a waveguide port. In order to get use CST for this kind of the problems, simpler three-layer stacks have first been used, in which both regular and defect arrays show a simple circular shape. Even for these simple structures, simulations have been more time consuming than expected. This led to some delays and deviations from the initial work plan. Experience of the host institute in CST simulations and access to the supercomputer at one of the collaborating institutions have been utilized to partially mitigate these deviations. Based on the experience acquired due to these simulations, a proper strategy of using CST for large quasiplanar structures has been found that enables reasonable efforts and efficiency of design at the available computational resources.

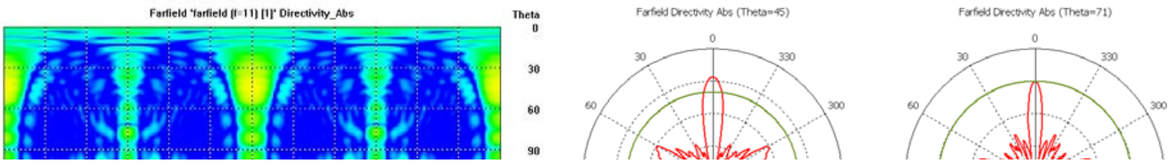


Figure 4. Left - example of directivity map in (Phi,Theta)-plane; middle - example of directivity at fixed Theta, corresponding to directivity map on the left; regular (outer) layers - arrays of circular holes of a smaller radius, defect (middle) layer - arrays of circular holes of a larger radius; right - example of directivity at fixed Theta for the similar structure with the middle layer having a single hole of the same radius as in the middle array for the remaining plots; X-band.

Figure 4 presents the examples illustrating the principal possibility of obtaining of angular width (3dB) less than 10 degrees. The obtained beams represent rather conical type beams. Similar behavior has been obtained for the tunneling mechanism, i.e., when evanescent-wave layer is placed between two propagating-wave layers, see Fig. 5. The obtained results generally indicate a wider band width than that associated with slow (transverse) waves, so that its connection to leaky (lateral) waves should be studied in more detail.

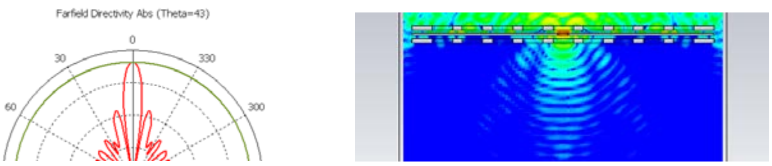


Figure 5. Examples of directivity (left) and field distribution (right) for the structure with larger-radius circular hole arrays as the outer layers and smaller-radius circular hole arrays as the middle layers, Ku-band.

In the frame of the *third part* of the project, the practical design of the prototypes and preparations to the experiments have been carried out. The targeted frequency range mainly corresponds to X-, Ka- and V-bands. The studied structures represent, in fact, finite-size analogues of the laterally periodic structures, which are selected on the basis of the results of the first part, but are distinguished from the finite-size structures in the second part in that they are designed to be integrated to the practical antenna systems. The criteria of selection include but are not restricted to the commonly used antenna characteristics (beam width, gain, directivity), available equipment including resolution of the experiment setup, and costs required for fabrication.

The basic type of the studied three-layer structures represents the complimentary SRR array sandwiched between the circular hole arrays. The former shows a subwavelength resonance and works in the propagating-wave regime, while the latter work in the evanescent-wave regime. The obtained results show that the electromagnetic characteristics, e.g., Q-factor and group velocity can be controlled by varying geometrical parameters of the individual arrays. The structures here are similar to those in the first part of the project, but now they have a finite size of 10X10 to 20X20 unit cells and are excited with a beam-type source. Thus, the experience acquired during the work on the second part of the project has been extensively utilized.

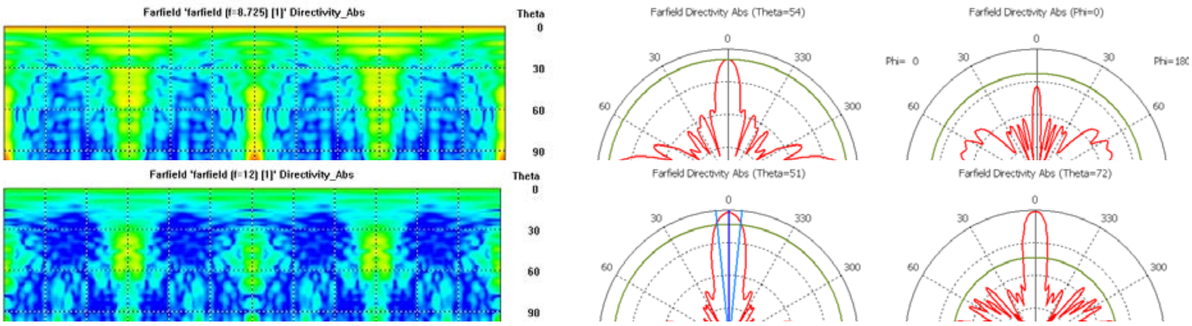


Figure 6. Left - examples of directivity map in (Phi,Theta)-plane; middle and right bottom - examples of directivity at fixed Theta; right top - example of directivity at Phi=0, the plots in the middle correspond to directivity maps shown on their left; regular (outer) layers - arrays of circular holes, defect (middle) layer - arrays of complimentary SRRs; X-band.

The examples that demonstrate the potential of three-layer structures with complex shape of the defect-mode layer holes are presented in Fig. 6. It is seen that angular width (3dB) about 10 degrees can be obtained for conical type beams. However, parameter adjustment allows obtaining of directive on-axis beaming. Furthermore, the angular width of 6 degrees and narrower can be obtained, as shown in the right upper plot in Fig. 6.

For the sake of comparison, the structures have also been studied, in which (i) the defect (middle) array was replaced with a metallic layer having a single subwavelength hole and (ii) the defect (middle) array and a regular (outer) array are replaced with each other, so that the tunneling mechanism is realized instead of the defect-mode type transmission. Finally, possible connections between the beam shaping and the asymmetric transmission phenomenon have been investigated. It has been shown that these two regimes may require the same dispersion and resonance field properties and, hence, can be obtained in one configuration. This feature is very advantageous, because it allows to extend functionality, e.g., by enabling off-axis beaming.

Based on the obtained results, two microwave and millimeter-wave performances were selected, refined, and then finally prepared for fabrication, that will be done in the next weeks.

Simultaneously, the Ka-/V-band experiment has been planned. It will be carried out in the laboratory of the host institute and only needs the standard equipment, i.e., the horn antennas and the spectrum analyzer. The experiment session is preliminary scheduled for the end of November - beginning of December, 2014. Besides, one terahertz performance was selected that still invokes the final refinement before fabrication, which should be carried out with the help of one of the collaborating institutions working in nanophotonics. The first contacts have been established with an Austria based SME, whose activities are focused on practical design of microwave and millimeter-wave antennas and communication systems. The discussions were arranged that helped to evaluate the selected prototypes and match them to the industrial requirements. The acquired experience can be used in future proposals of industrial projects.

4) Future collaboration with host institution (if applicable)

Collaboration between the researcher and the host institute is planned to be continued. Results obtained during the work on this project can serve a good starting point for development of lasting bilateral collaborations and their possible evolution to multilateral one. Completing the studies that are required to fulfil the objectives of this project, which include the detailed experimental study of the three selected ultrathin superstrate performances and clarifying possible interactions between the leaky (lateral) wave and slow (transverse) wave mechanisms, should be done in the framework of collaborations in the next 3-4 months. As the next step, the problem of highly directive antenna radiation will be attacked by implementing the phase discontinuity approach to the ultrathin Fabry-Perot type and metamaterial cavities that promises advanced performances and functionalities [1,2]. The perspectiveness of this study is also connected with possible future extensions toward infrared-range applications. A joint research proposal may be submitted when a proper call will be found. Regardless of the formal side, the relevant research activities of the researcher and the host institute will be synchronized.

[1] N. Yu et al., *Science* **334** (6054), 333-337 (2011).
[2] A. Ourir, A. de Lustrac, and J.-M. Lourtioz, *Appl. Phys. Lett.* **88**, 084103 (2006).

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 of the theoretical study of the subwavelength localized modes, which are obtained in the framework of this project, will be combined with a part of the results obtained during the work on the previous project funded by the ESF in a single paper. The work on this paper is now in progress. It is planned to be submitted to a highly reputed journal, e.g., *Opt. Express* or *Phys. Rev. B* within the next two months. The second paper that will mainly be dedicated to the practical implementation and technical aspects will be written and submitted to *IEEE Trans. Antennas Propag.* or *J. Electromag. Waves Appl.* once the experimental study is finished. To the time, one joint talk dedicated to the asymmetric transmission in the thin hole array based structures, P. Rodriguez-Ulibarri et al., *Diffraction inspired unidirectional transmission with sign-switchable refraction and deflection*, has been presented at the Metamaterial Congress in Copenhagen, Denmark in August 2014. One more paper has just been submitted to EuCAP2015.

6) Other comments (if any)

The researcher is very thankful to ESF for support of this project and opportunity to network and build collaborations in the framework of the NEWFOCUS Programme.