Research Networking Programmes

Short Visit Grant ☐ or Exchange Visit Grant ☒

(please tick the relevant box)

Scientific Report

Scientific report (one single document in WORD or PDF file) should be submitted online within one month of the event. It should not exceed eight A4 pages.

Proposal Title: Irregular stacked hole arrays as promising millimeter- and terahertz-wave front-ends with resonance transmission and radiation regimes

Application Reference N°: 4208

1) Purpose of the visit

The purpose of the visit to the Universidad Publica de Navarra was to work on the project dedicated to the study of resonance transmission and radiation regimes in irregular stacked hole arrays, which are considered as promising millimetre- and terahertz-wave front-ends, and build collaborations.

2) Description of the work carried out during the visit

During the research period, I worked to meet the objectives of the proposal, in close collaboration with Dr. M. Beruete, Dr. F. Falcone, and the members of their team. Thus, I benefited from the unique opportunity to combine my experience in electrodynamics of periodic structures with the host institute's experience in theory and applications of stacked hole array based (fishnet) metamaterials. The basic types of configurations that have been studied are shown in Fig. 1.

The project has been performed with the emphasis on theoretical and numerical study of the effects exerted by distance between individual arrays, size and shape of the holes, and angle of incidence. Extensive parametric study has been carried out mainly by using CST Microwave Studio, a 3D full-wave commercial solver. Some useful (semi-) analytical estimates have been obtained by using the equivalent circuit approach, which has recently been adapted at the host institute to the stacked hole arrays.

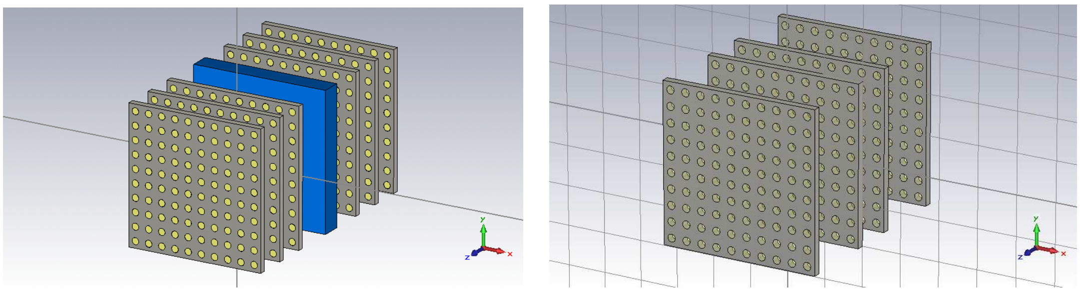


Figure 1. Examples of a stacked hole array with a single centered dielectric defect (left) and a chirped stacked hole array (right), both being symmetric with respect to the midplane z=D/2.

As entry point, (a) the recent findings of the host institution in stacked hole array metamaterials, (b) my own recent results including those obtained after submission of the proposal, and (c) recent literature on theory of single and stacked hole arrays and their applications to control of radiation have carefully been analyzed. The aim was to detect the most recent trends and points to focus on, in order to use the research period most efficiently.

3) Description of the main results obtained

The first part of the project has been dedicated to the study of regular, i.e., periodically stacked hole arrays with defects created by solid dielectric plates, see Fig. 1(a). First, the principal possibility of existence of defect modes in such structures has been demonstrated. Defect modes are considered to be conventional in resonance periodic structures with the period of the order of free-space wavelength, λ, which have structural defect(s), e.g., in photonic crystals with defects. On the contrary, their appearance at subwavelength scale is not so obvious. The estimates made by me together with the host institute members have indicated the possibility of existence of defect modes in the stacked hole arrays with axial period being substantially smaller than λ, provided that the centered "defect" has relative permittivity ε that is larger than five.

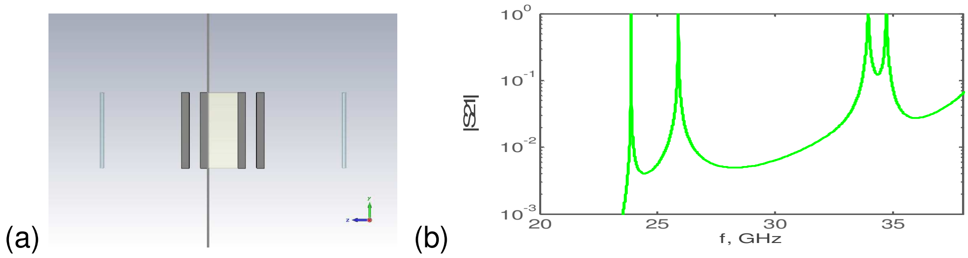


Figure 2. (a) Side view of a single lateral period of the four-array structure with a dielectric insert in the middle ("defect") and (b) transmission through this structure as a function of frequency.

A numerical study has been carried out in order to validate these estimates. As a result, several performances have been selected for the purposes of a more detailed study. Geometry and transmission results for one of them are presented in Fig. 2. The studied configuration differs from the general case shown in Fig. 1(left) in that it comprises only four hole arrays, while the entire space between the second and third arrays is filled by a homogeneous dielectric with ε=5.8. The PEC approximation has been used for the metallic plates. The first narrow total-transmission peak appears at f=23.5 GHz. It is located within a stop band of the corresponding defect-free structure consisting of five identical equidistant hole arrays and, thus, having the same thickness D. Field analysis confirms that this peak is associated with strong field localization at the dielectric defect. Note that kD=0.87π and, hence, D/λ=0.435 at the peak frequency, so that narrowband defect-mode inspired transmission is obtained at subwavelength scale, as desired. The estimate for Q-factor obtained from transmittance at the half power level gives a value larger than 3×10^3. Figure 3 demonstrates the axial distributions of the electric and magnetic fields in the structure that has a bit different geometrical parameters than in Fig. 2 (for better illustrativity). One can see that more than 100-fold enhancement can be obtained. Thus, the ability of the studied class of metastructures to confine electromagnetic field, also at subwavelength scale, is evident.

It has been found that simple removing of one array from the regular periodic structure does not lead to a similar effect. As expected, symmetry with respect to the midplane is required for obtaining interferences leading to the absence of reflections, similarly to the classical Fabry-Perot resonator. Numerical study of two problems, i.e., transmission at beam-type illumination and radiation from the source hosted by a defect has not yet been completed, since redistribution of available CPU time in favour of the third part has been required, in order to perform all simulations of that part as a (long) single series. Dependence on the angle of incidence, θ, has been studied. It has been shown that a relatively weak sensitivity to the angle varied in a wide range is possible but depends on whether TE polarization (electric field vector is parallel to y axis) or TM polarization (magnetic field vector is parallel to y axis) is used. Such a weak sensitivity is often associated with strong directivity.

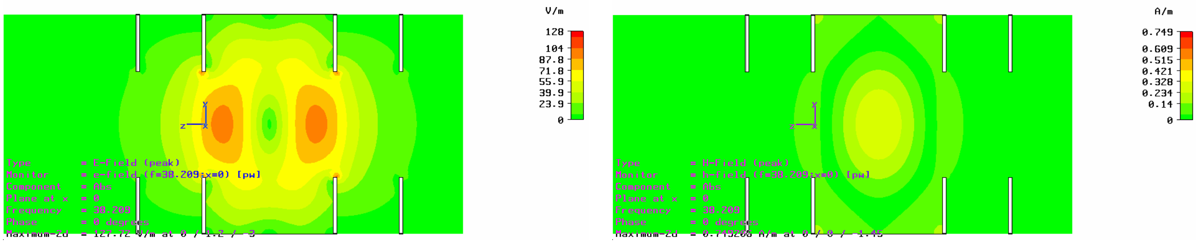
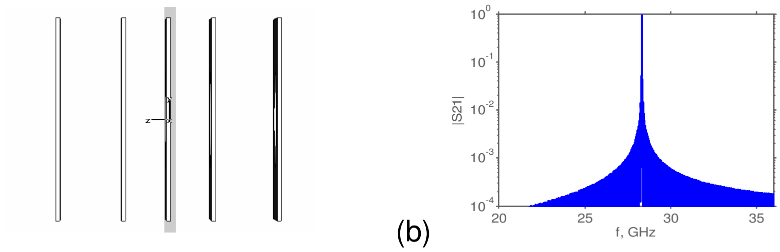


Figure 3. Examples of the electric (|E|, left) and magnetic (|H|, right) field confinement within the dielectric defect.

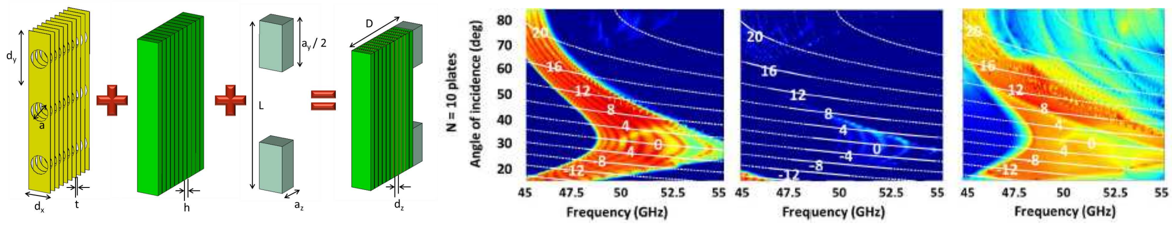
Then, I have been worked on the second part of the project dedicated to the stacks of hole arrays with a variable distance between the neighboring arrays. These structures have also been assumed to be symmetric with respect to the midplane, while all the individual arrays were identical. Although the possibilities of strong field confinement have been earlier demonstrated in some chirped structures with a resonance distance between neighbors, it has been unclear whether similar type of confinement can be obtained in the chirped stacks of hole arrays and how they should be designed. To answer these questions, a systematic numerical study has been performed. In contrast with the arrays studied in the first part of the project, dispersion simulations could not increase the overall efficiency, because there is no unambiguous correspondence to a constant-period infinite structure. Thus, despite that the time consuming simulations have been required, the performances and transmission regimes therein were found, which correspond to the initial expectations. An illustrative example is presented in Fig. 4. A single peak appears at f=28.3GHz corresponding to D/λ=0.52, i.e., this regime is slightly above the half-lambda (diffraction) limit. Note that this configuration shows no axial periodicity at all but, in spite of this, enables strong field confinement, so that the Q-value at the half-power level exceeds 10^4.

The performed study of transmission allowed to select parameter settings for the embedded-dipole radiation problem, which will be considered as a next step. Comparing to the structures studied in the first part of the project, the chirped stacks look more perspective, since they do not need special technological arrangements to host a source, allowing air instead of a high-ε dielectric at the middle. Thus, such structures can be perfect candidates to serve as compact Fabry-Perot cavities hosting a transmitter in the composite cavity based antennas. In turn, the structures from the first part are expected to require no modification, if being used as superstrates.



(a) (b)

Figure 4. (a) Side view of a single lateral period of the five-array chirped structure and (b) the corresponding transmission vs frequency.



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

Figure 5. Example of the stacked hole array with one-side dielectric grating (a), forward (b) and backward (c) transmittance, and forward-to-backward transmittance contrast (d); white lines - isolines of diffraction (deflection) angle [1].

A cross-part study, to which I contributed during the research period, has been related to the hybrid structures comprising a regular stacked hole array and a dielectric grating placed at one of the interfaces. The grating may be considered in some senses as a surface defect, although its role in the resulting mechanism differs from that of field confinement and frequency-domain localization. As a result of the common effect of diffractions and peculiar dispersion of the corresponding Floquet-Bloch mode of the stacked array, strongly pronounced asymmetric transmission may appear. It manifests itself in that only the first diffraction order transmission is possible when the grating side is illuminated at a certain nonzero θ, while transmission in the opposite direction is totally blocked [1]. This operation regime can be useful for antenna applications, enabling deflection at a desired angle. According to the obtained results, a 35° deflection with respect to the incidence direction is typical. Figure 5 presents an example that demonstrates the appearance of strong, diffraction inspired asymmetry in a stacked hole array with one-side corrugations, while zero-order transmission (which is always symmetric, i.e., the same for the two opposite directions) is vanishing.

The third part of the project has been dedicated to the stacked arrays of the holes of a more complex shape. First, a study has been performed for the regular (periodic) finite-thickness stacks, in order to validate the expected effect of changing shape and size of the holes. Two basic classes of the stacked arrays have been considered: (i) with annular holes and (ii) with complimentary split ring resonator shaped holes. There have been two main aims: to shift the regular transmission bands significantly towards smaller frequencies, as compared to the case of circular holes and, hence, further decrease the D/λ ratio, and obtain sensitivity to polarization, which cannot be achieved in case of circular holes. Note that the principal possibility of such a shift has been known earlier, but matching with the specific objectives of this project was required. Changing the hole shape, one changes the equivalent circuit parameters. From this perspective, both coaxial and complimentary split ring resonator shapes of the holes look very promising. Figure 6 presents two examples of the transmission spectra (c,d), for the two stacked arrays that have either (a) annular or (b) complimentary split ring resonator shaped holes. The inner and outer radii are connected as d_i=0.69d_o, in the both cases. In case (a,c), transmission is *insensitive* to polarization change, while the observed transmission band corresponds to D/λ varied from 0.42 to 0.56, so that its most part is located below the half-lambda limit. In case (b,d), transmission strongly depends on polarization of the incident wave. Furthermore, for TM-polarization, the entire passband is located below the half-lambda limit: here D/λ is varied nearly from 0.22 to 0.27.

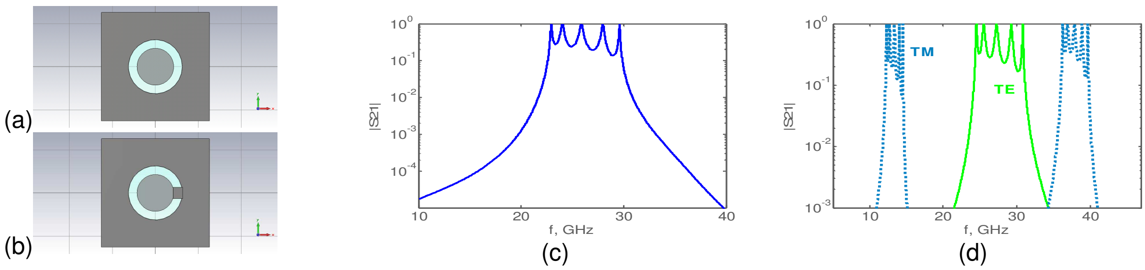


Figure 6. Front view of a single lateral period of (a) the annular-hole array and (b) the complimentary split ring resonator shaped hole array, and (c,d) transmission in the corresponding regular (periodic) five-array stacks.

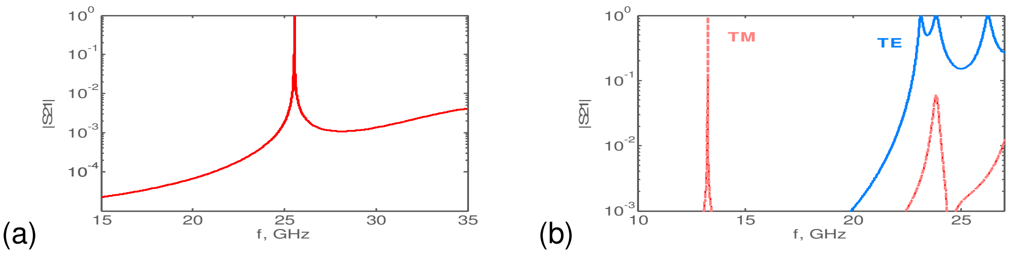


Figure 7. Transmission in (a) the stack of the circular hole arrays with the central defect that represents the annular hole array, and (b) the stack of the annular hole arrays with the central defect that represents the complimentary split ring resonator shaped hole array; both structures are composed of five equidistant arrays.

The general idea that has been utilized here for obtaining defect modes and relevant transmission and field confinement effects without using thick dielectric inserts or chirping, as in Figs. 2-4, is to use as a defect a hole array taken from a regular stack having the first pass band at lower frequencies than the host stacked structure. Accordingly, structures of two types have been designed. First of them represent the stacked arrays of circular holes, except for the central (third) array, which has annular holes, i.e., it is taken from Fig. 6(a). Second of them represent the stacked arrays of annular holes, except for the central array, which has the complimentary split ring resonator shaped holes, i.e., it is taken from Fig. 6(b). The transmission results are presented in Figs. 7(a) and 7(b), respectively. The single narrow transmission peaks are observed in Figs. 7(a) and 7(b) at f=25.5GHz and f=13.4GHz, respectively, i.e., they correspond to the pass bands of the regular arrays, from which the defects were “taken”. In Figs. 7(a) and 7(b), subwavelength defect modes correspond to D/λ=0.47 and D/λ =0.25, respectively.

Symmetry with respect to the midplane remains the necessary condition for obtaining of total transmission at the PEC approximation. The configurations in Fig. 7 can be utilized rather as superstrates and should be re-designed to host a dipole or monopole transmitter. For that one in Fig. 7(a), effect of θ has been studied in detail. It has been shown that the defect-mode relevant transmission peak remains almost *insensitive* to the variations in θ at least up to 60° for TE-polarization, while a relatively weak sensitivity for TM-polarization remains up to 30°

only. Thus, hybrid operation regimes are possible if using two polarizations at both large and small values of θ.
Since most of simulations have been performed at the PEC approximation for microwave frequencies, the possibility of utilizing the obtained results for higher, e.g., terahertz frequencies has been considered, based on the analysis of a testing problem. It has been concluded that they are usable at terahertz frequencies, because the observed features are kept, in spite of that the unavoidable losses in metal may decrease efficiency.

[1] P. Rodriguez-Ulibarri, M. Beruete, M. Navarro-Cia, and A.E. Serebryannikov, Wideband unidirectional transmission with tunable sign-switchable refraction and deflection in nonsymmetric structures, *Phys. Rev. B*, submitted.

4) Future collaboration with host institution (if applicable)

Collaboration with the host institution will undoubtedly be continued. Results of this project can be considered as a good starting point for development of lasting collaboration. Completing numerical study that is relevant to radiation from the source embedded into and possible beam shaping due to passing through the stacked hole arrays working in the defect mode regime will be the nearest goal. As the next step, we plan to consider adaptation of the operation regimes, which have been found during the work on this project, to practical antenna problems like highly directive radiation and wavefront control, including all-stage design and experimental validation. Reasonability of continuation of this study is confirmed by the most recent trends and findings, e.g., see [1,2]. Progress in this direction will depend on the support available. A joint research proposal may be submitted in case if a proper call will be found. Regardless of this, some of research activities are planned to be synchronized.

[1] A. Ourir, R. Abdeddaim, and J. de Rosny. Planar metamaterial based on hybridization for directive emission, *Opt. Express*, vol. 20(16), pp. 17545-17551 (2012).
[2] T. Matsui, T. Nomura, A. Miura, et al. Wavefront control by stacked metal-dielectric hole array with variable hole shape, *Opt. Express*, vol. 21(5), pp. 6153-6161 (2013).

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)*

A part of the obtained results, e.g., those related to asymmetric transmission, have already been submitted as a regular paper to *Phys. Rev. B* (P. Rodriguez-Ulibarri, M. Beruete, M. Navarro-Cia, and A.E. Serebryannikov, Wideband unidirectional transmission with tunable sign-switchable refraction and deflection in nonsymmetric structures).
Results of study of defect modes arising at subwavelength scale, will be presented in a paper, which we are working on and going to submit to *Opt. Express*, *IEEE Trans. Antennas Propag*., or another highly reputed journal, depending on the final content. A part of results is planned to be presented as a joint conference paper.

6) Other comments (if any)

I would like to thank ESF for support of this research and for the opportunity to network and build collaborations under the NEWFOCUS Programme.