"POLITEHNICA" UNIVERSITY of BUCHAREST

ETTI-B DOCTORAL SCHOOL

PhD Thesis Summary

UTILIZAREA SUPRAFEȚELOR SELECTIVE ÎN FRECVENȚĂ PENTRU IDENTIFICAREA ȘI URMĂRIREA AUTOVEHICULELOR

APPLICATION OF FREQUENCY SELECTIVE SURFACES TO VEHICLE IDENTIFICATION AND TRACKING

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Thanks

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Content

Chapter 1

Introduction

Periodic radiant structures allow to obtain given radiation characteristics, either it is a spatial distribution imposed for the radiant field or a given variation of the intensity of the radiated field, depending on the frequency.

Antenna networks allow the synthesis of a desired radiation characteristic by an appropriate choice of the placement of the elements in space and, respectively, of the excitations.

The term frequency selective surfaces (FSS) refers to a wide range of electromagnetic structures designed to interact and modulate unguided electromagnetic radiation.

Thus, frequency selective surfaces can be considered as "spatial filters", because they filter spatially distributed electromagnetic waves, determining at certain frequencies the transmission, reflection or absorption of energy.

1.1 PhD thesis domein presentation

The applications considered in this thesis are the use of frequency selective surfaces (FSS) for the generation of identification codes when illuminating by a radar.

The individualization of these codes is done according to the chosen set of resonance frequencies. Such applications include both vehicle identification with the help of intelligent license registration plates, as well as the autonomous driving of a convoy of vehicles (towards for example, military vehicles).

1.2 The purpose of the PhD thesis

If vehicles are identified using smart license plates, those plates are, in reality, frequency selective surfaces that are "read" laterally; therefore, when illuminated by a radar their radiation will be monitored in this case, in the plane containing the radiant structure.

The purpose of the PhD thesis is to optimize the FSS structures used in such identification applications by maximizing the effective area for a set of given resonance frequencies, opting for a parametric study.

1.3 The content of the PhD thesis

The second chapter is dedicated to theoretical aspects related to antenna strings and areas.

The third chapter presents aspects related to modeling and characterization by simulation of frequency selective surfaces.

Chapter four analyzes the influence of the incidence angle and unit cell characteristics on the response in the frequency domein of multi-reasonating frequency selective surfaces.

Chapter five aims to analyze the effective area of FSS with multiresonance loop type cells.

In chapter six, the influence of the resonators shape on the frequency selectivity was analyzed.

Chapter seven examines the influence of cell and substrate size on frequency selectivity, the influence of the substrate on the effective area of an FSS cell of given size and the chapter ends with the practical measurement of a frequency-selective surface with square loops characteristic area for vehicle number plates radar interrogations.

Chapter eight is dedicated to the conclusions and perspectives for farther research.

Chapter 2

Periodic Radiant Structures

Antenna networks allow the synthesis of a desired radiation characteristic through an appropriate choice of the elements placement in space and, respectively, of the excitations.

The total field of the network is equal to the field produced by a single element originally positioned, multiplied by a factor called the network factor, dependent on network geometry and excitation phase. By changing the separation space or a phase shift between elements, the network factor and the total field can be controlled. The network factor depends on the number of elements, the geometric arrangement, amplitudes and relative phases of excitations as well as spacing. Network factor has a simpler shape if the elements are excited with the same amplitude, phase and they are equidistant. Because the factor does not depend on the characteristic directivity of radiant elements, it can be expressed by replacing real elements with punctiform sources, isotropic.

In many applications, it is desirable that the maximum radiation of an antenna network to be placed normally on the axis of the string. To optimize the design, the radiation maximums of each element and to that of the string factor, should be directed to $\theta = 90°$. To have the maximum of the uniform string factor oriented perpendicular to the string axis, it is necessary that all elements have the excitations in phase. The distance between items can have any value.

The maximum radiation can be practically oriented towards any other direction, ensuring a sweep of the main lobe. By controlling progressive phase difference between the elements, the maximum radiation can be oriented to any desired direction, resulting in a scanning network.

Other important aspects are directivity, lobe opening at -3dB and the level of the secondary lobes. In addition to placing the elements longitudinally in a row, the elements can be positioned in an array, resulting in an area of antennas that provide additional variables that can be used to control and shape the characteristic of radiation.

The term frequency selective surface (FSS) refers to a wide range of electromagnetic structures designed to interact and modulate unguided electromagnetic radiation (EM), at a certain frequency [1]. Thus, frequency selective surfaces can be considered as "spatial filters" [2], because they filter spatially distributed electromagnetic waves, determining, at certain frequencies, the transmission, reflection or absorption of energy. A frequency selective surface (FSS) is usually represented by a composite flat material, designed so that it is transparent to certain frequency bands, while reflecting, absorbing or redirecting radiation to other bands of frequency.

From a constructive point of view, FSS are manufactured in the form of flat surfaces and comprise a large number of cells acting on the electromagnetic field, designed in the form of a periodic arrangement. Unit cells are usually built of metallic and dielectric materials, so that the unit cells are excited only at certain frequencies (hence the notion of frequency selectivity). Normally,the periodicity of these unit cells is two-dimensional and the unit cells are flat,being relatively thin in relation to the third dimension (hence the term "surface"). Frequency selective surfaces are presented under a wide variety of topologies and geometries. FSS structures are used in a wide range of applications involving space electromagnetic windows or synthesis of characteristic radiations. In the first case, the spectrum of allowed frequencies in a specific spatial region is controlled, while in the second case, the spatial distribution of radiated energy in free space is controlled (as optical lenses can focus light). A very important aspect, which influences the response of a frequency selective surface is represented by the shape of the component elements of such an area, in particular that of metal surfaces.

Another important category of FSS is complementary unit cells. A complementary cell is made by retaining the same geometries, but by inverting the conductive area with the dielectric one. It is usually desirable to have a high degree of symmetry and a density as high as possible of the elements so that the grating lobes appear at high frequencies.

It can be concluded that the resonance is dependent on the shape of the elements and their size, while the distance between the elements and the symmetry of the structure affects robustness at different angles of incidence. Frequencies at which grating lobes occur depend only on the spacing of the elements and the angle of incidence and not on the type of elements used. An improved variant of FSS is the reconfigurable structures. In this case its resonant behavior and frequency response can be quickly reconfigured.

Chapter 3

FSS modeling

The characterization of FSS can be done by solving Maxwell's equations. Such analysis is easier to perform assuming that FSS is of infinite size. This approximation also gives good results in the case of large size selective surfaces.

The most common method of analyzing infinite FSS is to apply the Floquet theory for periodic structures. This approach involves solving Maxwell equations for a single unit cell; the entire FSS is characterized by imposing boundary conditions for unit cell. The method is based on Floquet's theorem, which states that a differential equation with periodic coefficients and periodic limit conditions will have a solution that is also periodic.

In practice, the determination of Floquet mode coefficients must be done numerical. One of the most common techniques is the method of moments (MoM). Numerical application of Floquet theory, either by commercial simulation software, either by dedicated codes, is the most common method of analysis for frequency selective surfaces.

The simulations in this study were performed using Computer Simulation Technology (CST) Microwave Studio Suite, which is a high performance electromagnetic simulation software. Finite Integration Technique (FIT) is used as the basic technique in CST, which is based on the integral form of Maxwell's equations [3].

The structures proposed in this paper are flat frequency selective surfaces. Because the time domain analysis can only be performed for a normal wave incidence, it was decided to solve in the frequency domain, which, although it involves a longer analysis time, can be used for angles of incidence other than 90°.The results are obtained in the form of distribution parameters.

Chapter 4

The influence of the incidence angle and the unit cell characteristics on frequency response of multi-resonant selective surfaces

In this chapter, the influence of different dimensional material parameters was studied, as well as the angle of the received wave incidence from the radar on the unit cells resonance frequencies of the frequency selective surface, for a parametric study with the help of a specialized simulation program.

The frequency response analysis was done based on the reflection coefficient at Floquet ports. In this section, a typical FSS unit cell was considered in square, circular or hexagonal loops shape to analyze how the angle of incidence influences the resonance frequency. Performing a parametric study by simulations, the effects brought about by the modification of the dimensional parameters were highlighted, on the resonance frequency and the frequency response. The copper material was initially chosen for the conductive elements, and the substrate material had a electrical permittivity of 1 because this substrate has little influence on frequency response. The unit cell can be repeated indefinitely with periodicity depending on the desired radiation characteristics. Unit cells with a square loop, with three square loops, with a circular loop and three circular loops, one hexagonal loop and three hexagonal loops were analyzed.

The purpose of the research was to observe the influence of geometric dimensions and angle of incidence on the resonant frequency of frequency selective surfaces. The results obtained and the discussions specific to each case, can be used to optimize the design of FSS unit cells. The effects of the following dimensions on the frequency response were analyzed: length and width of the loop, thickness of the copper layer and the substrate. In addition to these geometric parameters, the resonance frequency dependence was also analyzed for permittivity of the substrate used, but also the influence of the angle of incidence under which electromagnetic waves are applied to the frequency-selective surface.

The values of the initial geometric dimensions for single unit loop cells were chosen so that the initial resonant frequency is 2 GHz, and in the case of cells with three concentric loops, only the resonance frequency variation was followed depending on the thickness of the loop paths. From the comparative study of the three types of square loop FSS cells, circular and hexagonal, respectively, some conclusions can be drawn about the optimal choice of the geometric shape, in the context of the parametric studies performed for each shape of the cell in part.

Chapter 5

Effective area of frequency selective surfaces with multi-resonant type loop cells

The characterization of frequency-selective surfaces in terms of radiation can be done by analyzing their actual area. In this way, the frequency selective character can be analyzed in those directions of interest to the desired application.

If vehicles using smart license plates are identified, these plates are, in reality, frequency selective surfaces that are "read" laterally; therefore, their radiation when illuminated by a radar will be monitored in this case, in the plan in which it contains the radiant structure. The principle of tracking and identification of vehicles in an official vehicle column, using FSS number smart plates is shown in Figure 5.1.

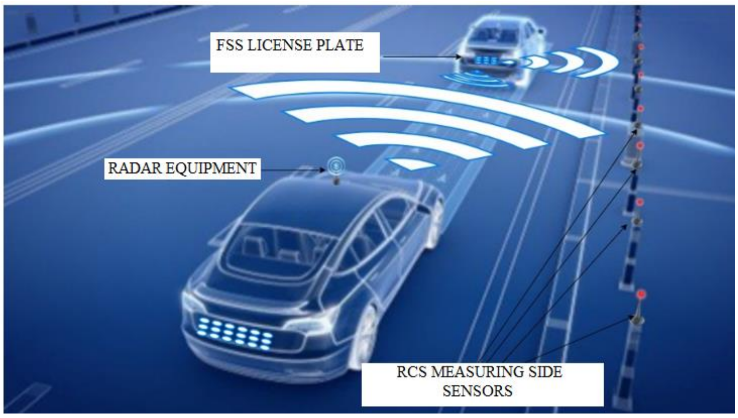

Fig. 5. 1 *Principle of tracking and identification of vehicles in a column using smart FSS license plates*

As shown, the set of resonant frequencies (at which a structure presents maximum effective area) is, in practice, the code to be read in order to be radio identified. In this chapter, the following FSS unit cells were compared comparatively by simulation: square, circular and hexagonal loops.

The variation of resonance frequencies was analyzed depending on the angle of incidence of electromagnetic waves on the surface of the FSS cell and the spatial variation of the effective area for different values of incidence angle (0°, 30°, 60°), at each of the resonant frequencies.

The results obtained from the simulations were compared for similar types of unit cells, respectively with one, two or three square, circular or hexagonal. It was observed that the change in the angle of incidence to 0°, 30°, 60°, produced changes in the values of the resonant frequencies, the most accentuated being noticed in the case of inner loops. Regarding the effective area, it could be observed that its value is influenced by the variation of the angle of incidence and that the results obtained in simulations have different values for each type of loop.

Chapter 6

The influence of the resonators shape on the frequency selectivity

In this chapter, the study focused on the analysis of the effective area values obtained at flat wave illumination of closed-loop polygonal unit cells, characterized by a different number of sides. The purpose of the comparative analysis was to identify the geometric shape of closed loop type which ensures the highest values of the effective area, expressed in decibels relative to an area of one square meter [4], [8], [9].

It is desired to obtain peak values as high as possible at the resonant frequencies chosen in the previous chapter: 2 GHz, 2.5 GHz and 3 GHz. It is also desirable that the level of the peaks of the effective area corresponding to the three resonant frequencies to be as close as possible. As factors of merit was chosen the RCS peak values on the resonant frequencies, as well as a dip as low as possible between two resonant peaks [10]. This difference ensures good selectivity in frequency.

Unlike other papers on similar topics in the literature, in this paper it was imposed as an objective to maintain along optimizations of 2 GHz, 2.5 GHz and 3 GHz resonant frequencies for all studied geometric shapes [5], [6], [7]. As a matter in fact, there is a limitation of dimension adjusting possibilities of the proposed loops for analysis, because the values chosen for these frequencies of resonance are close enough, the practical realization of the loops becoming difficult in some cases. The difficulty lies in the fact that the space between the neighboring loops becomes very reduced, two adjacent loops coming to behave from the electromagnetic point of view as a single loop. In these cases, instead of the two distinct resonance frequencies, a single resonance frequency is obtained. In the happiest case, there are two peaks of the effective area, but the selectivity is very low, making difficult to identify them. In a previous chapter it was approached to adjust the frequencies of resonance by changing the width of the loop path, but this technique is not effective for path widths of 1mm. Such a technique would reduce the space between two neighbor loops, which could even lead to their merging and an inappropriate frequency response.

Most of the works in literature in this domein is oriented towards identification and the development of methods to reduce RCS [4], [8], [9], [10], [12-20]. For radio identification applications, however, it is desirable to obtain values such as higher for the effective area at resonant frequencies, which makes the optimization be different from the approaches in the literature. As previously presented, the applications covered in this paper refer to car license plates that encodes the information by a resonant frequency code.

In this chapter, the substrate used was FR4, with an electrical permittivity of 4.3. The width of the loops did not allow a satisfactory margin of adjustment, this being maintainedat at 1 mm for all geometric shapes analyzed. The size of the studied unit cells was maintained at 40 mm because this value allowed a good framing of concentric loops for all studied geometry shapes. From the comparison of the results obtained it follows that the structure with concentric square loops oriented along the vertical axis of the cell, provides the best values of the effective area between all the studied geometric shapes, these being around value of -55 dBm^2. Values close to these results were also obtained for the unit cell with concentric hexagonal loops. The FSS unit cell with octagonal loops is highlighted through its best selectivity. This ensures a good selectivity and facilitates the separation of resonant frequencies by radar equipment, though the values of the effective area are not among the highest.

Chapter 7

The influence of cell and substrate size on frequency selectivity

In this chapter, having as a point of reference the results obtained in the previously chapter, the influence of the spatial period of the frequency selective structures will be studied (cell size), respectively the type of substrate on the effective radar area. The influence of the use of an FR4 substrate with electrical permittivity of 4.3 and an alumina substrate with an electrical permittivity of 9.9 over the effective area values, will be also analyzed. The alumina substrate allows a miniaturization of the structure, its permittivity being higher than FR4. Instead, the losses of the alumina substrate are higher, which affects the radiation efficiency of a frequency selective surface made with such a material. For both substrate types, analysis was made for two existing thicknesses in practice, 1 mm and 2 mm.

In this study, hexagonal and square loops unit cells were studied and simulated, in the second case, these being oriented along the vertical axis of the unit cell, or at 45° to this axis. In the case of alumina substrate, for maintaining the three resonant frequencies at 2 GHz, 2.5 GHz and 3 GHz was necessary reducing the width of copper paths from 1 mm to 0.5 mm. Following the comparative study it was found that an alumina substrate determines considerably better effective area values and offers the possibility of resonator dimensions reduction. An increase in the effective area values can be obtained by increasing the size of the unit cell, but it has proven to be effective within certain limits. Size change in steps of 1 mm it does not have a uniform effect on the three resonant frequencies simultaneously, because there were few cases in which a good balance of peak area values for all three resonant frequencies was obtained. The width of the copper paths for the FR4 substrate was 1 mm, and for alumina substrate, it was necessary to reduce the width of the paths from 1 mm to 0.5 mm.

To study the influence of the substrate on the effective area of an FSS cell of given size, cell dimensions and cell size 42 mm were maintained, substrate thickness 1 mm and copper layer 0.018 mm , and frequencies of resonance at 2 GHz, 2.5 GHz and 3 GHz. To maintain these frequencies were adjusted the lengths of the square loops and possibly the thickness of the copper paths, if space of these was too small or if they overlapped. The FSS cell was chosen with three concentric square loops, this geometric shape offering the best peak values of the effective area between the previously studied geometric structures. By choosing a suitable substrate, the peak values of the effective area can be increased by more than 10 dB in some cases. Among the obtained results, the ones corresponding to the substrates like Mica with a relative permittivity of 6 and Rogers RO3003 with a relative permittivity of 3 stand out. These offered the highest values of the effective area.

Within the same chapter, the effective area of a frequency selective surfaces with square loops, for radar interrogated license plates was measured. In the case of radar interrogation license plate applications, the scenario considered is the following:

the license plate, which contains a frequency selective surface is illuminated by the vehicle's rear radar, but the information must be readable by a receiver on the side of the road. Therefore, the radar configuration will be, in this case, a bistatic one [21], [22]. In order to performe xperimental determinations, the frequency selective area was made, presented in figure 7.1.

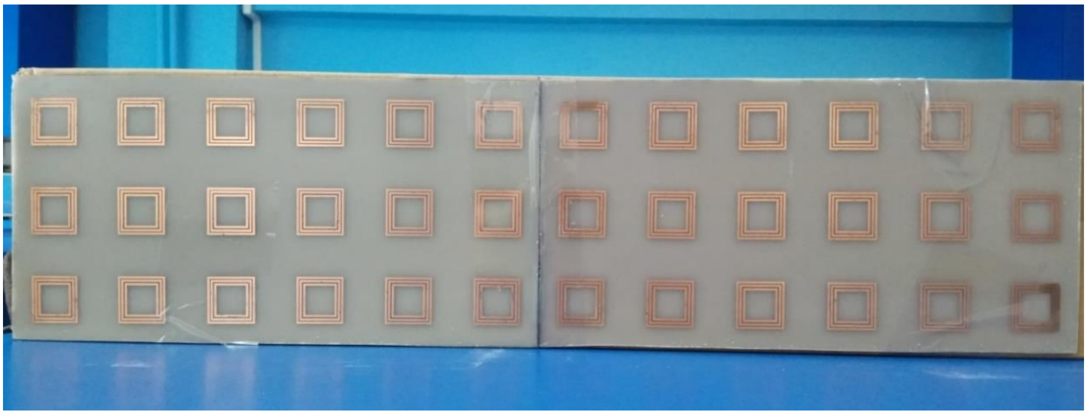

***Fig. 7. 1** Effective area characterized experimentally, on FR4 substrate, thickness 1 mm*

The experimentally characterized frequency selective surface consists of 36 resonators on a FR4 substrate measuring 47.5x11.5 cm (standard registration plate format). The resonators were designed to resonate at the chosen frequencies. The bistatic radar configuration used for measurement is shown in figure 7.2.

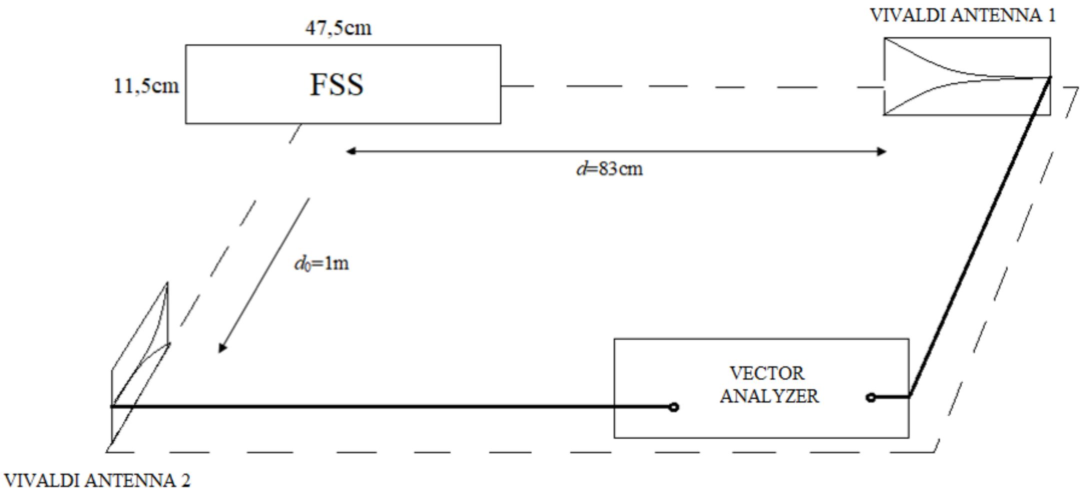

***Fig. 7. 2** Configuration of the effective area measurement system.*

Figure 7.3 shows the practical system for measuring the effective area, in which you can see the two Vivaldi antennas and the frequency selective board.

Fig. 7. 3 *Practical configuration of the measuring system for the effective area*

Figure 7.4 shows the normalized transfer functions and the average transfer function.

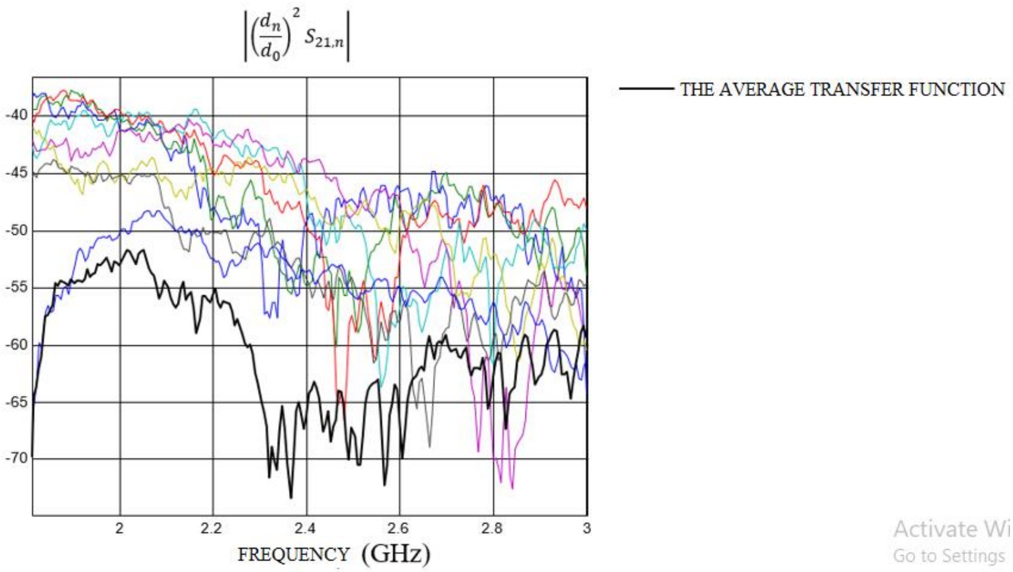

Fig. 7. 4 *Standard transfer functions and corresponding average transfer function at distance d_0 = 1 m.*

The measurements were carried out, in this case, at eight distances between 30 cm and 1 m. In figure 7.5, the variation of the effective area with the frequency was represented. May notes a slight deviation for the second resonant frequency (about 200 MHz),mainly due to the limited manufacturing accuracy of the experimental device.

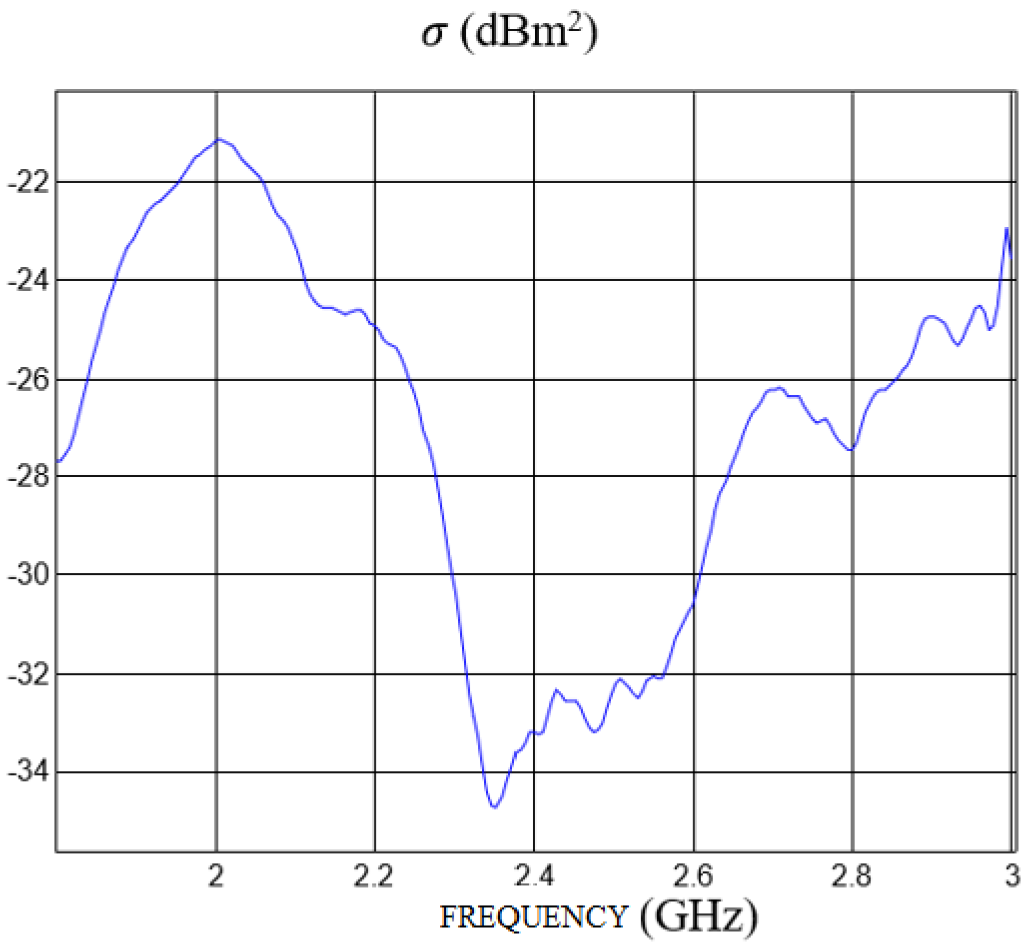

Fig. 7. 5 *Variation of the measured effective area with frequency*

Although the number of cells is relatively small, the peak values of the effective area are between -26 dBm^2 and -22 dBm^2.

Chapter 8

Conclusions

One of the aims of the research was to observe the influence of geometric dimensions and angle of incidence on the resonant frequency of frequency selective surfaces. The results obtained and the discussions specific to each case, can be used to optimize the design of FSS unit cells. The effects of the following resonator dimensions on the frequency response were analyzed: length and width of the loop, thickness of the copper layer and the substrate. In addition to these geometric parameters, the resonance frequency dependence with permittivity of the used substrate, but also of the angle of incidence below which electromagnetic waves are applied to the frequency-selective surface was also analyzed.

The multi-resonant FSS unit cells with three circular loops were analyzed for effect which is produced by the variation of the width of the copper paths on the resonant frequencies of the three concentric loops and the influence of the spacing between the three loops. The values of the initial geometric dimensions for single loop unit cells were chosen so that the initial resonant frequency is 2 GHz, and in the case of cells with three concentric loops, only the resonance frequency variation was followed depending on the thickness of the loop paths. For closed-loop FSS cells, a loop length approximately equal to the wavelength leads to the first resonant frequency.

8.1. Obtained results

From the comparative study of the three loop type FSS cells, (square, circular and hexagonal, respectively), some conclusions can be drawn about the optimal choice of the geometric shape, in the context of the parametric studies performed for each shape of the unit cell. FSS unit cells with square, circular and hexagonal loops were also studied and compared comparatively, by simulation. The resonance frequencies variation was analyzed depending on the angle of incidence of electromagnetic waves on the surface of the FSS cell.

Another parameter that was the subject of the study was the spatial variation of the effective area for different values of the angle of incidence (0°, 30°, 60°), at each of resonant frequencies. The results obtained from the simulations were compared for similar types of unit cells, respectively with one, two or three square loops, circular or hexagonal. It was observed that the change in the angle of incidence to 0°, 30°, 60° produced changes in resonant frequencies values, the most accentuated being notified in the case of inner loops.

Regarding the effective area, it was observed that its value is influenced by the variation of the angle of incidence and that the results obtained afterwards simulations have different values for each loop type. From the comparison of the obtained results it is observed that the structure with concentric square loops oriented along the vertical axis cell values provide the best effective area values of all studied geometric shapes, these being located around -55 dBm^2. Approximate values of these results were also obtained for the unit cell with hexagonal concentric loops. The FSS unit cell with octagonal loops is highlighted by the best selectivity, ensuring a good separation of resonant frequencies by a radar equipment, although the effective area values are not among the highest.

Following the comparative study it was found that an alumina substrate determines considerably better effective area values and offers the possibility of resonator dimensions reduction. An increase in the effective area values can be obtained by increasing the size of the unit cell, but it has proven to be effective within certain limits. Size change in 1mm steps it does not have a uniform effect on the three resonant frequencies simultaneously, because there were few cases in which a good balance of peak area values for all three resonant frequencies were observed. The width of the copper paths for the FR4 substrate was 1 mm, but for alumina substrate, it was necessary to reduce the width of the paths from 1 mm to 0.5 mm.

As other authors have observed [11], cell size (periodicity),it influences to some extent the resonance frequency, but it mainly has an effect on the effective area. Switching from a substrate of FR4 to alumina with an electrical permittivity of 9.9 caused a significant reduction of loops size, which implicitly leads to a reduction in the size of the cells they belong to and thus a larger number of unit cells can be used on a given surface.

From the point of view of effective area peak values, it was found that between studyed structures on a FR4 substrate, the cell with square loops positioned parallel to the vertical axis of the cell determines the best values, followed by the FSS unit cell with hexagonal loops, both on the substrate with a thickness of 1 mm and a cell size of 40 mm. If alumina substrate was used, the best results have been recorded for the unit cell with squares rotated 45° to the cell vertical axis, followed by the unit cell with hexagonal loops, both on a substrate with 2 mm thick and a cell size length of 40 mm. It should be noted that for all shapes of resonator simulated on the alumina substrate, the peak values of the effective area were above -55 dBm^2 (maximum obtained value at the unit cell with square loops on FR4 substrate). Overall, it was found that the values obtained for the alumina substrate are between -45 dBm^2 and -40 dBm^2, considerably higher than for the FR4 substrate. However, the alumina substrate leads to a lower radiation efficiency, having the loss tangent higher than FR4. By choosing a suitable substrate, the peak values of the effective area can be increased by more than 10 dB in some cases.

Among the obtained results, stand out the ones corresponding to the substrates of Mica with a relative permittivity of 6 and Rogers RO3003 with a relative permittivity of 3. They provided the highest values of the effective area.

8.2. Original contributions

1. Analysis of how it influences the angle of incidence and unit cell characteristics on the frequency response of the multi-resonant selective surfaces, for unit cells with one and three square, circular and hexagonal loops [LO1].
2. Study of the effective area of frequency selective surfaces with loop type multi-resonant unit cells, for unit cells with one, two and three concentric square, circular and hexagonal loops [LO2].
3. Analysis of the influence of resonator shape on frequency selectivity and identification of geometric shapes in terms of peak effective area values. Unit cells were simulated with three concentric triangular, square,hexagonal, octagonal and decagonal loops, respectively [LO3].
4. Analysis of the influence of cell size and substrate on frequency selectivity, being studied the peak values of the effective area for the square and hexagonal unit cells, on FR4 and alumina substrates [LO4].
5. Studying the influence of different substrate materials used on the peak values of the effective area of a given size FSS unit cell in order to optimize substrate choice [LO5].
6. Measurement of the effective area of a frequency selective surface.
7. Measurement in bistatic configuration of the effective area of a frequency selective surface with square loops, for license plates interrogated by radar, using distance mediation method.

8.3. List of original papers

[LO1] Adrian Androne, Razvan D. Tamas, *"Impact of the angle of arrival on the response of a multi-resonant frequency selective surface,"* Proceedings Volume 10977, 2018 SPIE Advanced Topics in Optoelectronics, Microelectronics, and Nanotechnologies IX; 109772X (2018) https://doi.org/10.1117/12.2324694

[LO2] Adrian Androne, Razvan D. Tamas, "*A parametric study on the frequency-domain response of multi-resonant frequency selective surfaces with loop-type unit cells,* " Proceedings Volume 10977, 2018 SPIE Advanced Topics in Optoelectronics, Microelectronics, and Nanotechnologies IX; 109772Y https://doi.org/10.1117/12.2324698

[LO3] A. Androne and R. D. Tamas, *"Comparative Analysis for Different Loop-Type Frequency Selective Unit Cells,"* 2019 IEEE International Symposium on Signals, Circuits and Systems (ISSCS), Iasi, Romania, 2019, pp. 1-4, doi: 10.1109/ISSCS.2019.8801766.

[LO4] A. Androne and R. D. Tamas, *"Influence of the Substrate and Cell Dimensions on the Radar Cross Section of Closed Loop Type Frequency Selective Surface Unit*

Cells," 2019 IEEE International Symposium on Signals, Circuits and Systems (ISSCS), Iasi, Romania, 2019, pp. 1-4, doi: 10.1109/ISSCS.2019.8801817.

[LO5] A. Androne, R. D. Tamas and S. Tasu, *"Influence of the Substrate Material on the Radar Cross Section of Square Loop Unit Cells for Frequency Selective Surfaces,"* 2020 IEEE International Workshop on Antenna Technology (iWAT), Bucharest, Romania, 2020, pp. 1-4, doi: 10.1109/iWAT48004.2020.1570612531.

[LO6] L. Anchidin, R. D. Tamas, A. Androne and G. Caruntu, *"Antenna gain evaluation based on weighting near-field measurements, "* 2017 International Workshop on Antenna Technology:Small Antennas, Innovative Structures, and Applications (iWAT), Athens, 2017, pp.78-81, doi:10.1109/IWAT.2017.7915322.

Research project:

"Holistics of the impact of the renewable energy sources on the environment and climate" (ref. PN-III-P1-1.2-PCCDI-2017-0404) funded by the Romanian Executive Unit for Financing Higher Education, Research, Development and Innovation (UEFISCDI).

Research reports:

1. A. ANDRONE, „Studiu privind principiile care stau la baza funcționării suprafețelor selective în frecvență. Arhitecturi de suprafețe selective în frecvență", Research report no. 1, "POLITEHNICA" University of Bucharest, internal use.
2. A. ANDRONE, „Studiu parametric privind răspunsul în domeniul frecvență al suprafețelor selective multirezonante cu celule unitate de tip buclă", Research report no. 2, "POLITEHNICA" University of Bucharest, internal use.
3. A. ANDRONE, „Influența unghiului de incidență asupra răspunsului în domeniul frecvență al suprafețelor selective multirezonante", Research report no. 3, "POLITEHNICA" University of Bucharest, internal use.
4. A. ANDRONE, „Analiza comparativă a ariei efective pentru diferite celule unitate selective în frecvență cu o geometrie de tip buclă închisă", Research report no. 4, "POLITEHNICA" University of Bucharest, internal use.
5. A. ANDRONE, „Influența dimensiunii celulei și a substratului asupra ariei efective a suprafețelor selective în frecvență cu bucle închise", Research report no. 5, "POLITEHNICA" University of Bucharest, internal use.

8.4. Further development perspective

Research on frequency selective surfaces with applicability in identification and self-driving of vehicles may be continued with experimental validation analysis of all structures developed and optimized in this paper.

Another direction for further research in this field is studying various frequency selective structures, resonating at much higher frequencies, of the order of tens of GHz, typical for radars autonomous vehicles.

A validation of such a system on a real vehicle is also required radar identification, equipped with a frequency selective surface, to observe the quality of the response in real conditions, including for moving within a column.

A very important aspect is also the security of information (codes) transmited between two vehicles in the column, taking into account methods of protection against disturbance or interference.

The research can be continued in the direction of elaborating more complex shapes of resonators to ensure better frequency selectivity, but also higher peak values of RCS.

Bibliografie

[1] B. A. Munk, *Frequency Selective Surfaces: Theory and Design*, New York, NY: John Wiley & Sons, Inc., 2000.

[2] A. E. Farahat and K. F. A. Hussein, *Spatial Filters for Linearly Polarized Antennas Using Free Standing Frequency Selective Surfaces*, Progress in Electromagnetics Research, vol. 2, pp. 167-188, 2008.

[3] De Jichun Li, Yunqing Huang, *Time-Domain Finite Element Methods for Maxwell's Equations in Metamaterials*, Vol. 43 Springer Series in Computational Mathematics, Springer Berlin Heidelberg, 2012

[4] E. Martini, F. Caminita, M. Nannetti, S. Maci, *Fast analysis of FSS radome for antenna RCS reduction*, IEEE Antennas and Propagation Society International Symposium, 2006

[5] Mei Li, ShaoQiu Xiao, Yan-Ying Bai, Bing-Zhong Wang, *An Ultrathin and Broadband Radar Absorber Using Resistive FSS*, IEEE Antennas and Wireless Propagation Letters (Volume: 11),748 - 751, 2012

[6] Deng Shuhi, Ruan Yingzheng (University of Electronic Science and Technology of China, Chengdu 610054), *Radar Cross Section Analysis of Slot-Array Antennas*, Acta Electronica Sinica;1992-06

[7] Deng Shuhui;Ruan Yingzheng(Dept.of Electromagnetic Fields Eng.), *Radar Cross Section of Reflector Antenna*, Journal of University of Electronic Science and Technology of China;1990-05

[8] Ruan Yingzheng,Feng Ling,Han Xiaoying(University of Electronic Science and Technology of China,Chengdu 610054), *FSS Reflector Antennas with Small RCS*, Acta Electronica Sinica;1993-09

[9] H. Li, B.-Z. Wang, G. Zheng, W. Shao, and L. Guo, *A Reflectarray Antenna Backed on FSS for Low RCS and High Radiation Performances*, Progress In Electromagnetics Research C, Vol. 15, 145-155, 2010

[10] N. Misran, R. Cahill, V.F. Fusco, *RCS reduction technique for reflectarray antennas*, Electronics Letters , Volume: 39, Issue: 23, 13 Nov. 2003

[11] Mohyuddin W, Kim DH, Choi HC, Kim KW, *Comparative Study of Square and Circular Loop Frequency Selective Surfaces for Millimeter-Wave Imaging Diagnostics Systems*, Sensors (Basel), 2018;18(9):3079

[12] Costa, Filippo & Monorchio, Agostino, *Use of Frequency Selective Surfaces For Reduction of Radar Cross Section of Antennas and Scattering*, 2nd ESA Antenna Workshop on Antennas for Space Applications, January 2010, 882-885

[13] Y. Li, H. Zhang, Y. Fu, and N. Yuan, *RCS Reduction of Ridged Waveguide Slot Antenna Array Using EBG Radar Absorbing Material*, IEEE Antennas Wireless Propag. Lett., vol. 7, pp.473-476, 2008.

[14] J. L. Volakis, A. Alexanian, and J. M. Lin, *Broadband RCS reduction of rectangular patch by using distributed loading*, Electron. Lett., vol. 28, no. 25, pp. 2322-2323, 1992.

[15] W.-T. Wang, S.-X Gong, X. Wang, H.-W. Yuan, J. Ling, and T.-T. Wan, *RCS Reduction of Array Antenna by Using Bandstop FSS Reflector*, Journal of Electrom. Waves and Appl., vol. 23, no. 11, pp. 1505-1514, 2009

[16] Wang, Fuwei & Li, Ke & Ren, Yuhui & Zhang, Yunqi, *A novel reconfigurable FSS applied to the antenna radar cross section reduction*, International Journal of RF and Microwave Computer-Aided Engineering, vol. 29, e21729

[17] Jingjing Xue, Wen Jiang, and Shuxi Gong, *Wideband RCS Reduction of Microstrip Array Antenna Based on Absorptive Frequency Selective Surface and Microstrip Resonators*, International Journal of Antennas and Propagation Volume 2017, Article ID 1260973

[18] Y. Zheng, J. Gao, X. Cao, Z. Yuan, and H. Yang, *Wideband RCS reduction of a microstrip antenna using artificial magnetic conductor structures*, IEEE Antennas and Wireless Propagation Letters, vol. 14, pp. 1582–1585, 2015

[19] M. Zahir Joozdani, M. Khalaj Amirhosseini, and A. Abdolali, *Wideband radar cross-section reduction of patch array antenna with miniaturised hexagonal loop frequency selective surface*, Electronics Letters, vol. 52, no. 9, pp. 767–768, 2016

[20] C. Huang, W. Pan, X. Ma, and X. Luo, *Wideband radar cross-section reduction of a stacked patch array antenna using metasurface*, IEEE Antennas and Wireless Propagation Letters, vol. 14, pp. 1369–1372, 2015

[21] I. V. Mihai, R. D. Tamas and A. Sharaiha, *A Technique for Radar Cross Section Measurements in the Fresnel Region*, IEEE Antennas and Wireless Propagation Letters, vol. 18, no. 6, pp. 1149-1153, June 2019.

[22] R. D. Tamas, D. Deacu et al., *A method for antenna gain measurements in nonanechoic sites*, Microwave and Optical Technology Letters 56.7 (2014), pp. 1553–1557, doi: 10.1002/mop.28386