IOSUD - Universitatea Politehnica Timişoara
Şcoala Doctorală de Studii Inginereşti

CONTRIBUȚII LA PROIECTAREA SUPRAFEȚELOR SELECTIVE ÎN FRECVENȚĂ CU APLICAŢII ÎN COMPATIBILITATE ELECTROMAGNETICĂ

CONTRIBUTION TO THE DESIGN OF FREQUENCY SELECTIVE SURFACES WITH APPLICATIONS IN ELECTROMAGNETIC COMPATIBILITY

Teză de doctorat – Rezumat în limba engleză

pentru obținerea titlului științific de doctor la
Universitatea Politehnica Timișoara
în domeniul de doctorat inginerie electronică, telecomunicații și tehnologii informaționale

autor ing. Petru – Adrian BUTA
conducător științific Prof.univ.dr.ing. Aldo De SABATA

luna noiembrie anul 2022

This Ph.D. thesis is structured into 6 chapters. Chapter 1 presents an introduction to the evolution of planar period structures and metamaterials; chapter 2 presents a bibliographic study and the recorded progress in research for frequency selective surfaces; chapter 3 presents a periodic metallo-dielectric structure built in stripline technology and the effect that geometry modulation has on the wave-conduction properties of the structure; in chapter 4, various applications are presented, conceived with the purpose to selectively filter electromagnetic waves using frequency selective surfaces; in chapter 5, applications designed with frequency selective surfaces are also presented, but with fractal geometry, for the purpose of filtering and miniaturization, and in chapter 6, conclusions are drawn and contributions are reviewed.

1. Introduction

This chapter is an introduction to the content of the thesis. The evolution of planar electromagnetic structures, metamaterials, periodic volumetric electromagnetic structures (3D), and the occurence of frequency selective surfaces are presented, gradually showing the most notable achievements in this field of research.

2. Frequency selective surfaces

In this chapter, a comprehensive bibliographic study related to metamaterials in general and to frequency selective surfaces (FSSs), in particular, has been carried out. It has been presented the progress made in research carried out on FSSs in recent years worldwide, in the most important fields with applicability to miniaturization, and selective shielding against electromagnetic interference, starting from simple geometries up to the most complex structures [1, 2].

The importance and impact of the basic metallic element of the unit cell have been highlighted. In this sense, a classification has been also presented in accordance to the structure of the resonant dipoles based on which the unit cell is created, among which are mentioned: reducing the size of the structures by miniaturization, selective filtering, and shielding according to frequency and angle of incidence, providing a suitable response in dual polarization, etc. Also, the concepts of metasurface, convoluted structure, miniaturization technique based on the convolution of geometric elements, and miniaturization based on fractalization of the basic elements of the unit cell have been presented in order to reduce the size of the structures [3, 4, 5].

3. Effect of Geometry Modulation on the Full Dispersion Diagram of a 2D Periodic Structure Built in Stripline Technology

In this chapter, the impact that geometry modulation has on a periodic metallic structure, the way the band-gaps widths are modified, the wave-conducting properties, the and group velocity associated with some propagation modes have been considered [6]. Also, a bibliographic study at the beginning of the chapter related to high-impedance electromagnetic surfaces and surfaces with a forbidden frequency band has been performed.

Instead of a general theoretical presentation, easy to find in specialized literature, a description and a discussion of the simulations based on a CAD electromagnetic software simulation [7] have been proposed, as well as their evaluation from the perspective of the metamaterials theory analysis.

Also, contributions brought up to now to this topic have been described, by presenting the geometry of the proposed stripline structure: the considered unit cell was inhomogeneous, and made from an elliptical metallization, connected to the lower metallic plane by four cylinders the metal walls as reported in fig. 1 [6].

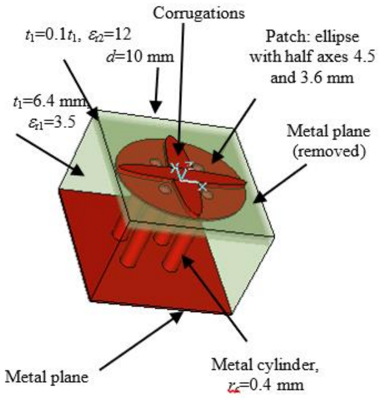

Fig. 1 Geometry of the unit cell [6]

Using the eigenmode solver of the CAD simulation program, the 2D dispersion diagram for this structure for the first five propagating modes has been constructed, obtaining a broadband EGB (between modes 1 and 2) and other smaller EBGs (between modes 2 and 3, respectively 3 and 4) as it can be seen in fig. 2.

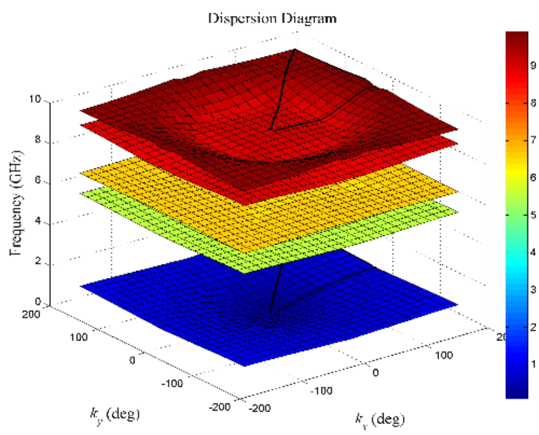

Fig. 2 Dispersion diagram for the first 5 modes [6]

An important feature that was taken into account was the group velocities of waves that occur after modulation and their significant impact. For this, two representations based on the gradient of the dispersion surfaces were used and it was found that, in both cases, group velocities are positive in relation to the phase velocity for the unmodulated structure.

It has been demonstrated that, following the application of a geometric modulation, both the wave conduction properties and the group velocities associated with some propagation modes changed their direction. In fig. 3, it can be seen that the isotropy regions of the dispersion diagram (DD) resulted larger for the modulated structure than for the unmodulated one [6].

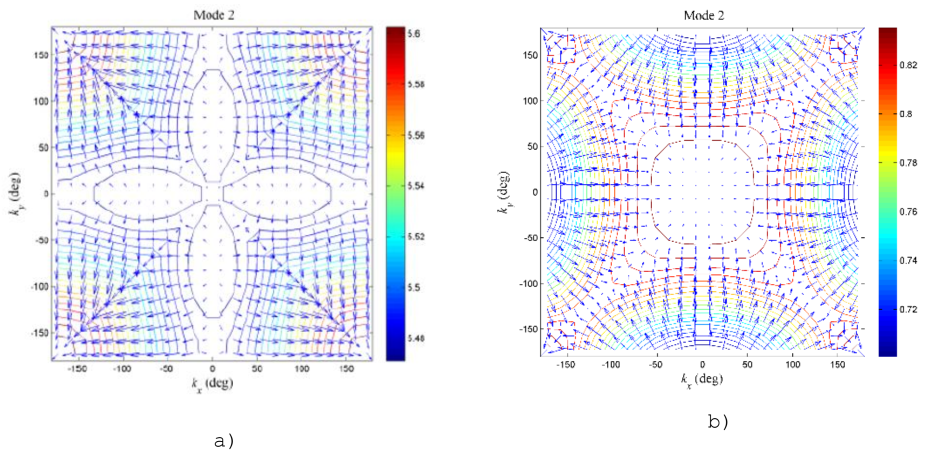

Fig. 3 Group velocities of propagation modes; a) unmodulated structure; b) modulated structure [6]

4. Aplications of frequency selective surfaces

This chapter presents applications with periodic electromagnetic structures, designed to selectively filter and shield electromagnetic waves within certain specific frequency domains, the signals crossing the structure remaining unchanged within other frequency bands, these having applicability in the field of testing motor vehicles from the electromagnetic compatibility point of view. Each design application was build on an FR4 substrate and their operation and behavior mode was analyzed by performing various parametric studies by means of an electromagnetic simulation software [7], and also confirmed by experimental measurements in some cases.

In sub-chapter 4.2, key concepts related to FSS are commented and a bibliographic study related to their application in various fields of activity was carried out.

Looking for structures that provide filtering in bands such as WLAN or X band, in sub-chapter 4.3 a complex structure, composed of a Jerusalem cross and a circular ring has been introduced, as shown in fig. 4 [8]

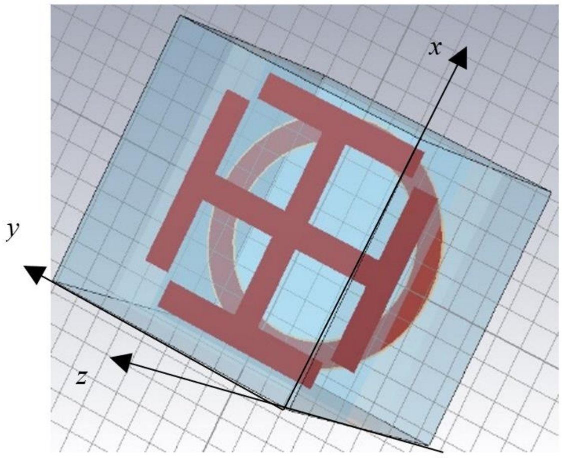

Fig. 4 Unit cell geometry, three-dimensional view [8]

In this sub-chapter, the geometry of the designed structure with the dimensions involved ahs been described the results obtained by simulating the transmission coefficient of a linearly polarized plane wave, at normal incidence have been presented. In fig. 5 it can be seen that this structure behaves like a broadband one, presenting a forbidden band that extends from 4.7 GHz up to 16.6 GHz, having a bandwidth of 11.9 GHz (depending on the dimensions of the elements of the unit cell).

Using an electromagnetic simulation environment [7] various combinations of geometric dimensions have been tested to obtain: a broadband filter, an X-band filter, and a WLAN-band filter. Previously, the two structures separately have been simulated (first the circular ring and then the Jerusalem cross) to elucidate the exact origin of the resonances that determine the existence of the filtered bands.

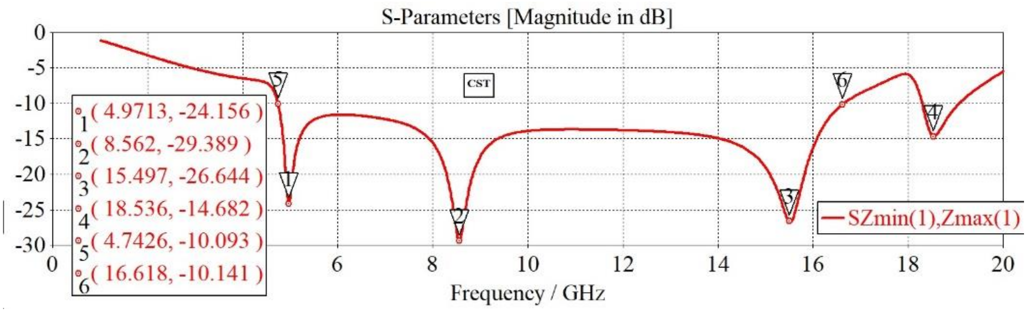

Fig. 5 The transmission coefficient for normal incidence [8]

Finally, parametric studies related to the angle of incidence θ for the proposed structures have been performed and conclusions have been reached: for the broadband filter this behavior is maintained up to an angle of incidence of 30 degrees, and for the X-band and WLAN filters up to an angle of incidence of 45 degrees.

In sub-chapter 4.4, a multiple resonator structure has been designed to answer a practical problem with the aim of designing filtering solutions for Wi-Fi, Bluetooth and X bands, which commonly used in the automotive industry [9].

This time, metal square rings have been used in the composition of the unit cell, the structure being built on only one side of the substrate. A step-by-step presentation of the evolution of the metal model to achieve the desired transmission properties has been provided, and finally a broadband filtering has been achieved.

Calculation of the transmission coefficient of the structure with a single square ring on a single side of the substrate has been tackled first, obtaining filtering in the Wi-Fi and Bluetooth bands (the center frequency was 2.1 GHz). Subsequently, obtaining the second resonator (centered on 7.8GHz) was possible by introducing an additional quadratic ring, and by changing the dimensions of the unit cell, three and four resonances were obtained.

In fig. 6 the unit cell with modified parameters in order to obtain 4 bandgaps is reported, and in fig. 7 the frequency response is shown.

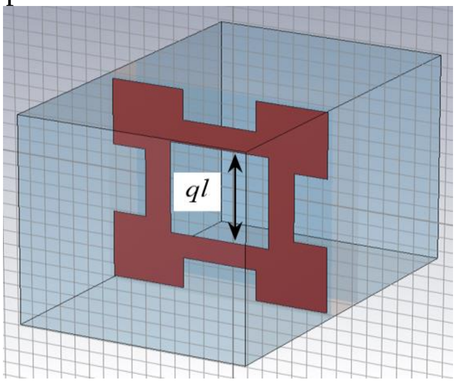

Fig. 6 Square ring structure [9]

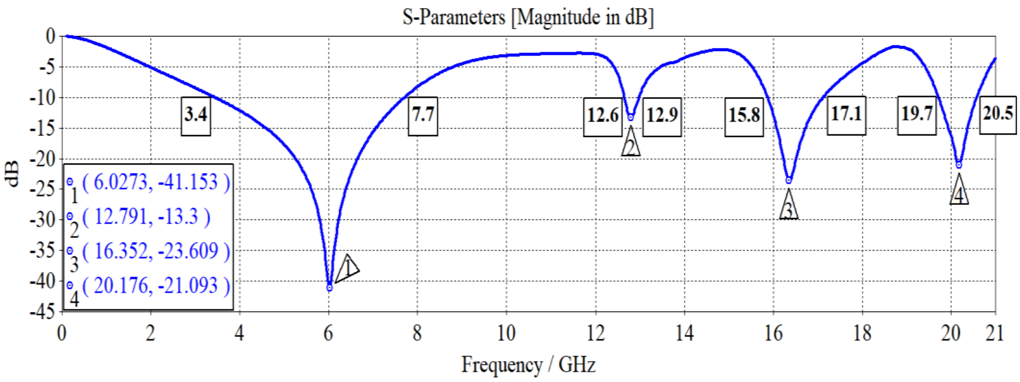

Fig. 7 Frequency response for normal incidence [9]

A detailed parametric study, related to the thickness of the FR4 dielectric substrate has been performed, thus obtaining the possibility of the frequency shift of the resonances. X-band filtering was achieved by duplicating the metal pattern on the opposite side of the dielectric substrate (fig. 8), and the variation of the incidence angle θ demonstrated a good bandpass filtering efficiency up to an incidence angle of 45 degrees when the metallic pattern was also duplicated on the opposite side as shown in fig. 9 [9].

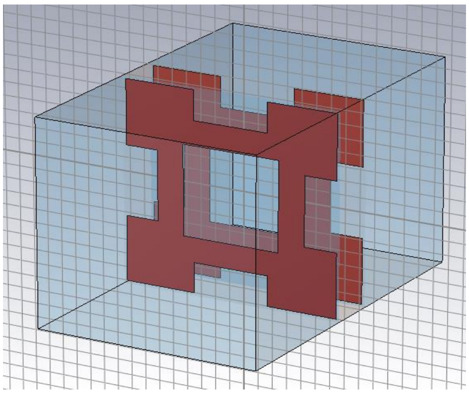

Fig. 8 Unit cell with metallization on both sides of the substrate [9]

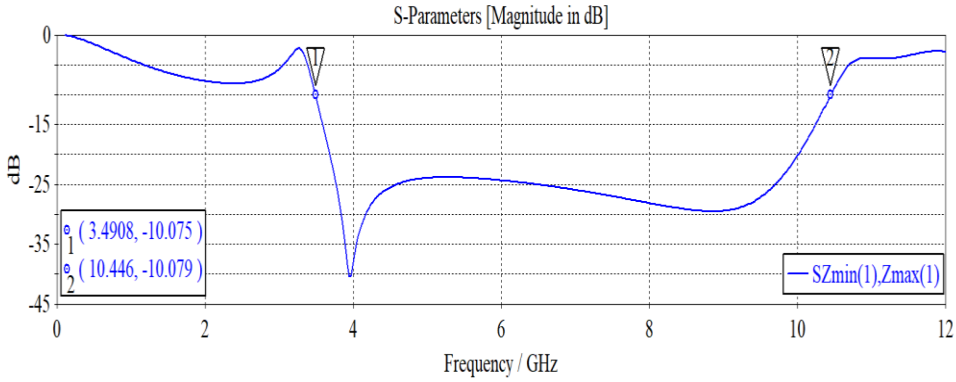

Fig. 9 Frequency response for double-sided unit cell – normal incidence [9]

Subchapter 4.5 presents a frequency-selective surface that functions as a spatial filter, designed to filter electromagnetic signals in the standardized frequency range for the UWB band (3.1 – 10.6 GHz) [10]. The proposed structure is capable of more than 10dB attenuation filtering for a bandwidth of more than 14 GHz between 1.59 GHz and 15.76 GHz (the solution has a much larger stopband than those in the literature).

A description of the structure using metallic models on both sides of the substrate has been presented first, and then, through field images of the surface current density, the way each face exhibits resonant frequencies has been illustrated

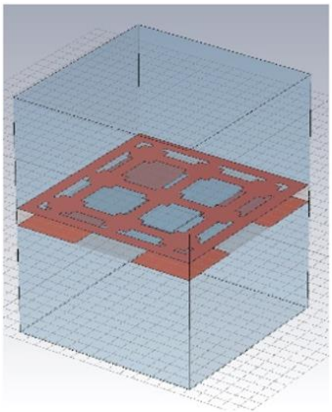

Fig. 10 Unit cell geometry – CAD model without substrate [10]

Using circuit models the operation of this FSS was explained. The incident wave was modeled by a matched voltage generator connected to the input terminals, having an internal impedance equal to the wave impedance of free space. The effect of the free space on the structure was modeled by a load impedance equal to that of the free space. The substrate was modeled as a lossy line, and the metallizations were modeled as series-selective circuits connected in parallel at the line input [10]. The simulated structure was also practically realized on an FR4 double-layer dielectric support with a thickness of 1.6mm. The unit cell occupied a surface of 15x15mm^2.

To ensure proper operation, the practically realized structure provides a greater width of the stop band in comparison with the intended range. This was initially evaluated by numerical simulation, and then practically measured in an anechoic chamber as reported in fig. 11.

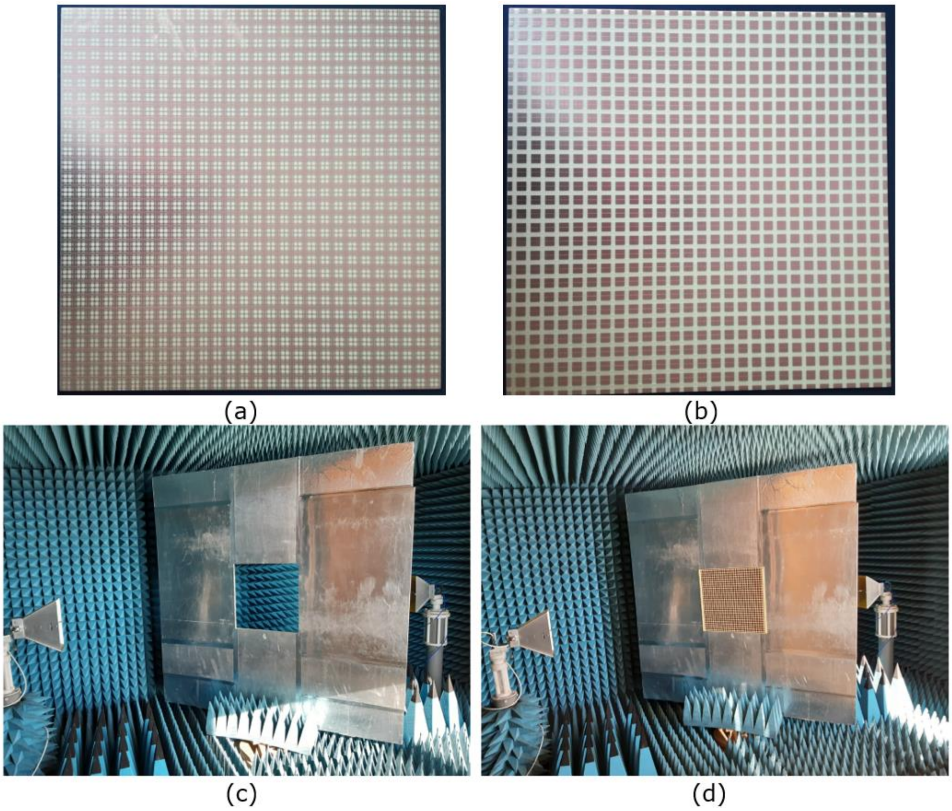

Fig. 11 Experimental validation: PBC prototype Face 1 (a), Face 2 (b); measurement setup without prototype (c) and with prototype inserted (d) [10]

Operational tests at oblique incidence have been perfomed, and an angular insensitivity was achieved over 60 degrees for TE waves, and over 50 degrees for TM waves, covering the UWB frequency range. The obtained results demonstrated a good correlation between the theory and the experiments.

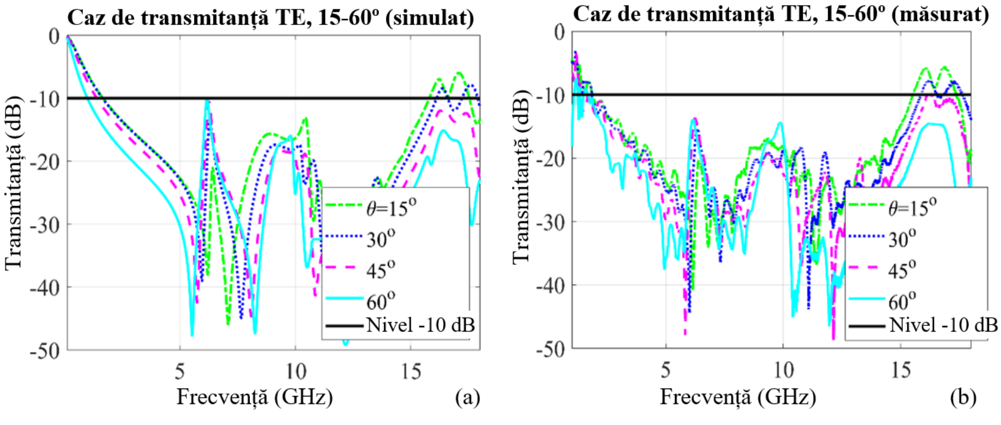

Fig. 12 Transmittance at oblique incidence of TE waves: (a) simulated; (b) measured [10]

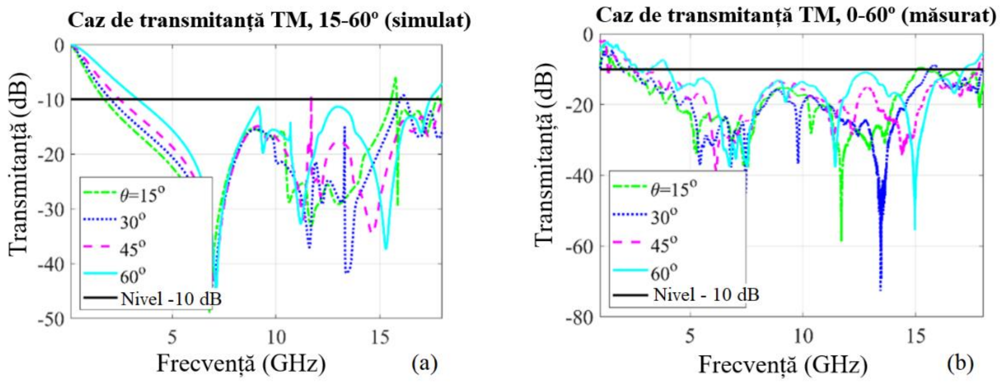

Fig. 13 Transmittance at oblique incidence of TM waves: (a) simulated; (b) measured [10]

Sub-chapter 4.6 presents the construction of a frequency-selective surface on an FR4 substrate that achieves a different linear polarization compared to the transmitted incident electromagnetic waves, more specifically the incoming plane waves are filtered into orthogonally linearly polarized waves in two adjacent frequency bands [11]. The frequency range below 10 GHz, which is of interest for applications in the automotive industry, has been considered.

Initially a pattern on one side of the PCB has been considered, having a narrowband behavior, which was later transformed into a wideband one by replicating the metal pattern on the other side of the substrate, as shown in fig. 14.

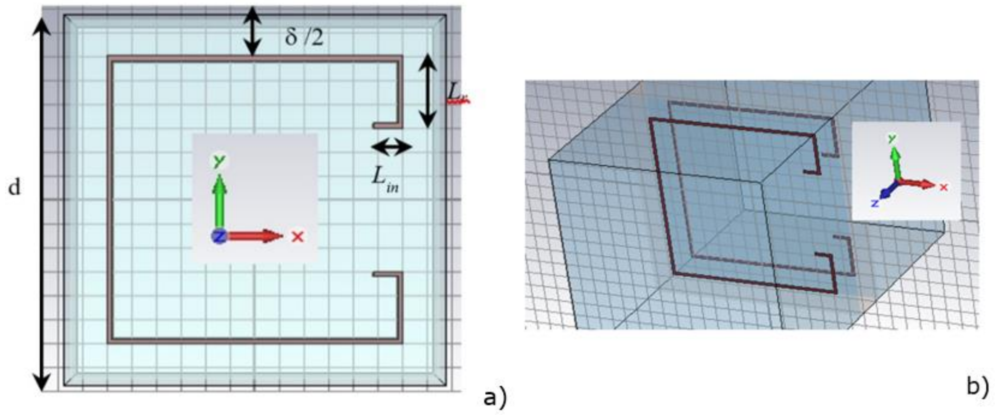

Fig. 14 Unit cell of the FSS: a) front view; b) 3D view (dielectric substrate was removed to ensure visibility) [11]

The electromagnetic properties of the proposed FSS were evaluated using a numerical simulation software, and in fig. 15 transmittance of the frequency selective surface can be seen.

The transmittance obtained showed the occurrence of the polarization phenomenon in normal incidence: if the electric field vector E is parallel to the x-axis, a stop band with a limit of -10 dB can be observed at a central frequency f_c = 4.78 GHz (a plane wave incident on the surface of the structure, arbitrarily polarized, in this frequency band, will leave the surface (in the opposite direction to the incident one) normally polarized with E||y), and if the electric field vector E is parallel to the y-axis, two central frequencies are present: f_{c1} = 2.34 GHz and f_{c2} = 6.31 GHz (this time an incident plane wave on this structure, arbitrarily polarized in this frequency band, will be transmitted being characterized by an orthogonal polarization compared to the first case, i.e. E||x).

Further, aiming to obtain a broadband operation for this polarizer, the metal pattern has been duplicated on the other side of the substrate. Fig. 16 illustrates the obtained transmittance result [11].

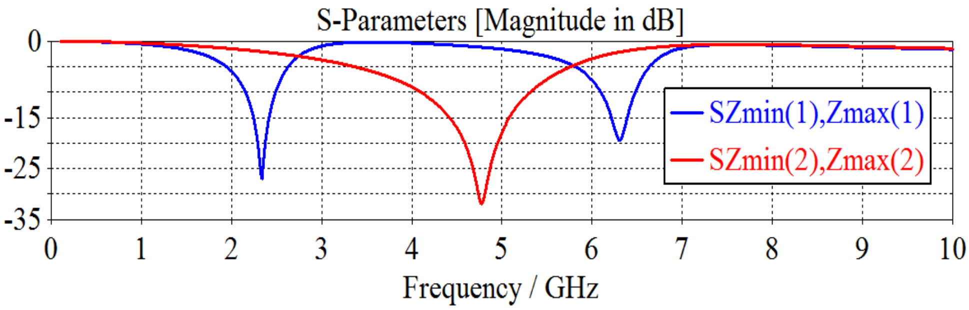

Fig. 15 Transmittance of the FSS with one patterned surface [11]

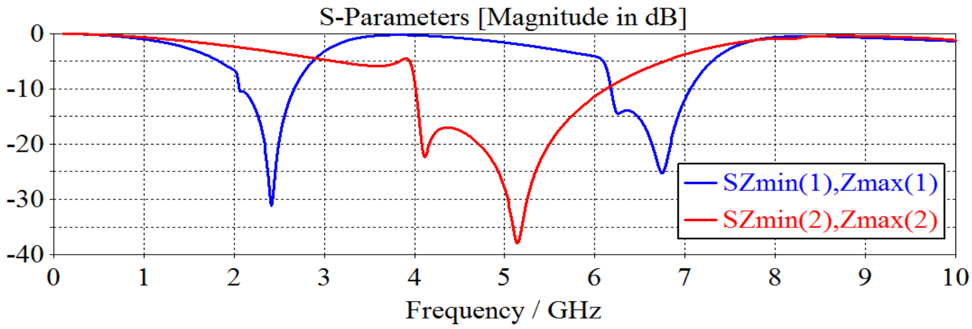

Fig. 16 Transmittance of the FSS with both faces patterned. [11]

Also, a parametric study related to the dimensions of the unit cell (length and width) was performed, which demonstrated the possibility of using the structure in various frequency bands.

At the end of the sub-chapter, another parametric study was carried out, this time according to the angle of incidence θ (varied between 0 and 45 degrees), setting the azimuthal angle φ = 0 or 90 degrees (the structure not being symmetrical). Therefore, four possible combinations for the two propagation modes TE and TM resulted, all demonstrating good stability of the proposed structure.

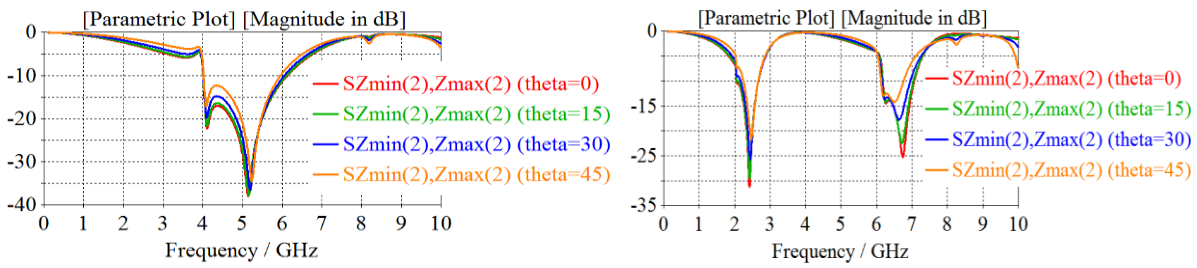

Fig. 17 Transmittance parametrized by theta, with phi=0 (left) and phi=90 (right), E||x incidence [11]

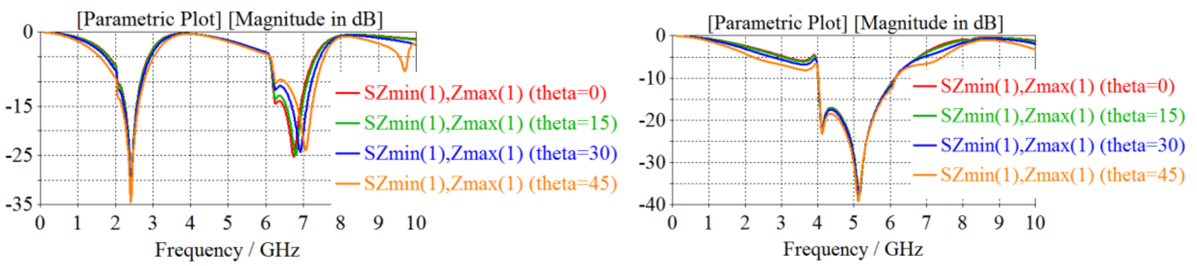

Fig. 18 Transmittance parametrized by theta, with phi=0 (left) and phi=90 (right), E||y incidence [11]

5. Aplications of frequency-selective surfaces with fractal geometry

This chapter presents some convenient solutions for applications that require miniaturization, filtering, and selective shielding in the 1 – 12 GHz frequency range. The presented solutions have been implemented using periodic fractal structures with aim at filtering the Wi-Fi, LTE, C-band, and X-band bands.

Frequency control of bandgaps, successive iterations of fractals, and frequency response following cascading of metallic geometries on both sides of the unit cell have been pursued, and also parametric simulations have been performed on particular cases and various parameters of interest have been analyzed using CST Microwave Studio [7].

In sub-chapter 5.2, a bibliographic study on frequency-selective surfaces was carried out with an emphasis on the fractal paradigm.

In sub-chapter 5.3 a structure for fractalization has been designed, namely a crossed dipole located on the diagonals of a quadratic unit cell as represented in fig. 19.

Parameters and dimensions of the designed structure have been described, and for each case, the transmission coefficient of a linearly polarized plane wave with normal incidence has been represented.

The first result illustrated the achievement of a resonance centered at 9 GHz having an attenuation of nearly 20dB. In order to increase the attenuation, fractalization of the structure had to be done, achieving a shift of the bandgap to lower frequencies (to 5.8 GHz) and with an increased attenuation of almost 32 dB, as represented in fig. 21. In addition, a modification of the structure to exhibit broadband behavior was pursued, which was achieved through the second iteration of fractalization of the metallization.

Therefore, a second forbidden band appeared, opening the way to transform the structure into a broadband filter [12].

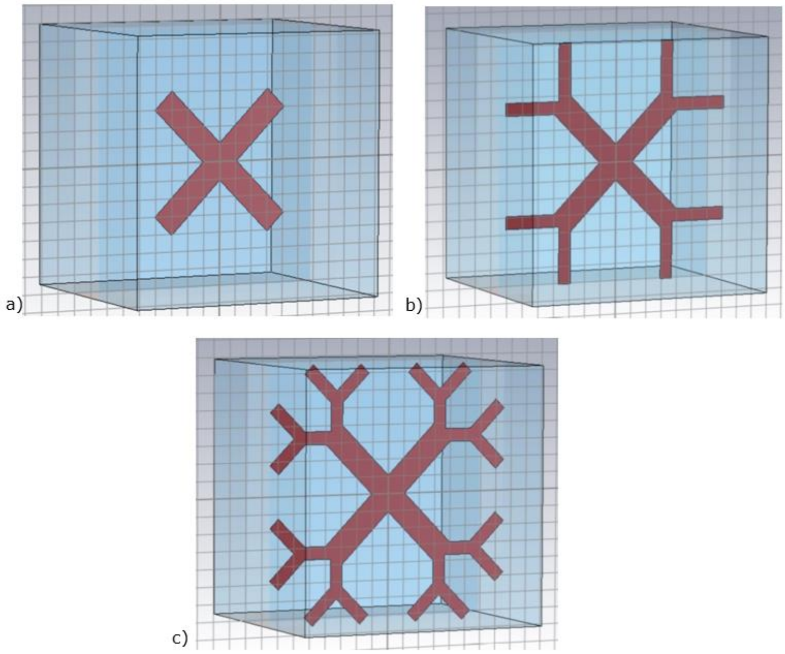

Fig. 19 CAD model for the unit cell: a) initial; b) first iteration; c) the second iteration [12]

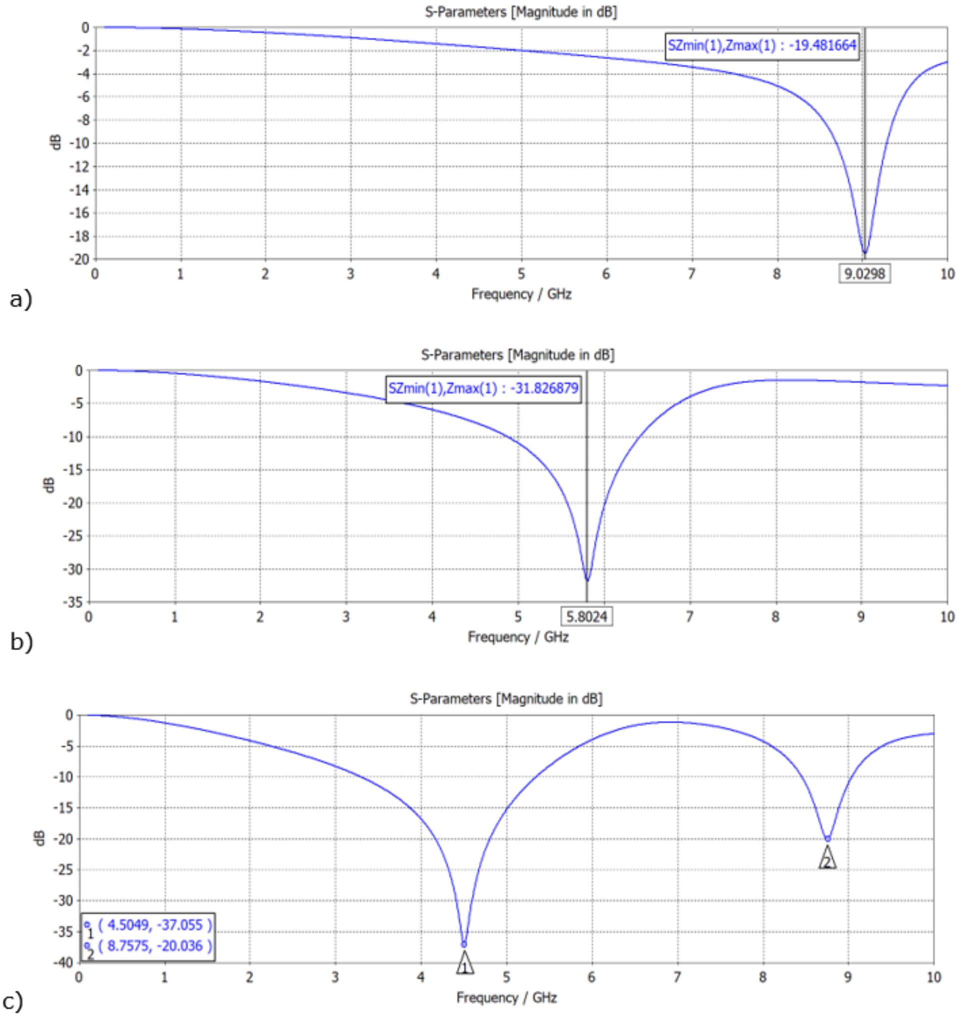

Fig. 20 Transmission properties of the structures from Fig. 19. The notations of the sub-figures are in corespondence [12]

Finally, a broadband screen was designed, but having different geometric patterns on one side and the other of the dielectric substrate, one of these geometric patterns being designed by fractal iteration, therefore obtaining a stopband of almost 3.5 GHz, in the frequency range of 4.1 – 7.5 GHz.

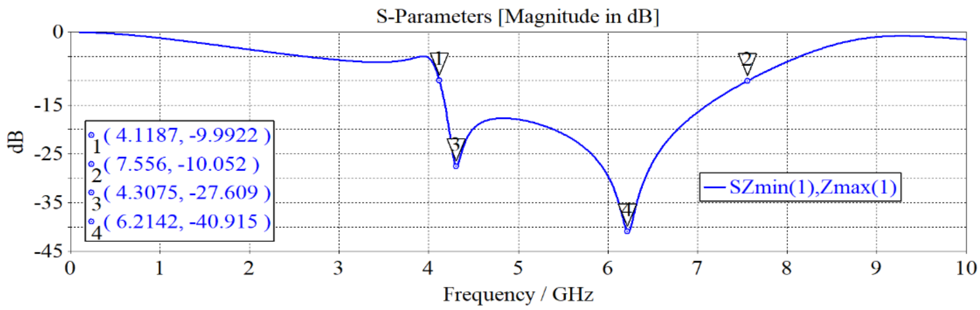

Fig. 21 Transmission properties for the unit cell which contains a fractal with two iterations and a metallic cross on the opposite side. [12]

Furthermore, parametric studies have been carried out for the broadband structure, therefore demonstrating that the proposed structure is insensitive to angular variation of the direction of incidence of the electromagnetic wave (tested angles were comprised between 0 and 60 degrees).

The results of the parametric studies demonstrated that the positions of the stopband edges can be controlled by geometry, this solution being convenient in applications that require filtering and selective shielding.

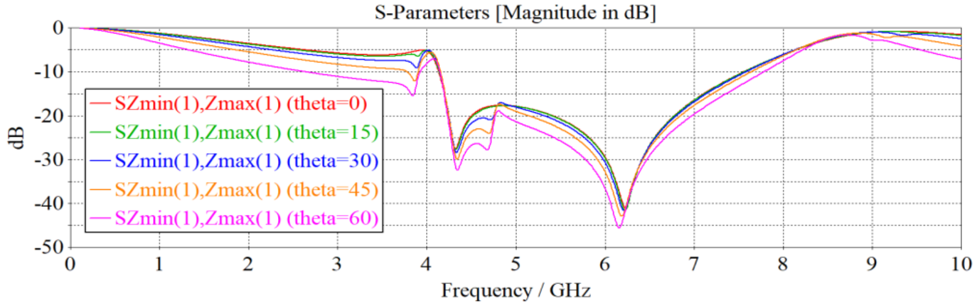

Fig. 22 The transmission coefficient at various angles of colatitude theta (TE mode) [12]

In sub-chapter 5.4, it is presented how the stop band position of a spatial filter based on an FSS can be shifted to lower frequencies by fractalization and how by duplicating the metal pattern on both sides of the substrate the stop band is increased. It has been demonstrated that the proposed structure can work as a spatial filter for X-band, Wi-Fi, and LTE band [13]. The construction of the structure was initiated by modeling a copper square on a single-layer dielectric substrate of FR4 type to obtain a tuned filter on the LTE band. Afterwards, the structure was fractalized as can be seen below (fig. 13).

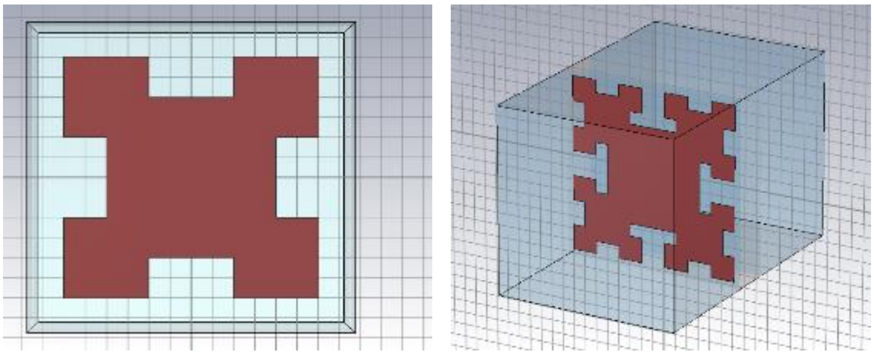

Fig. 23 Fractal with one iteration (left), fractal with two iterations (right) – single layer [13]

Through successive geometric iterations of the metallic model, a pre-fractal structure that presents a stop band that partially covers the C band and the X band has been obtained. By duplicating the metallic model and on the other side of the dielectric substrate, a broadband filter was obtained, operational in the frequency range 5.29 – 12.17 GHz and two resonance frequencies at 5.72 GHz, respectively 11.48 GHz (with a bandwidth of approximately 7 GHz), as the result shown in fig. 24 demonstrates. This frequency range includes applications aimed for WI-FI wireless communication, but also weather surveillance radar systems, satellite communication applications, applications associated with TLPR (radiolocation, radio detection, radio navigation, aeronautical, satellite earth exploration) both civilian and military.

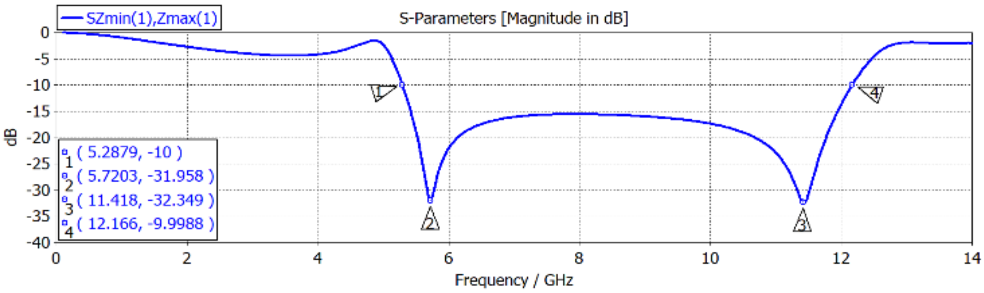

Fig. 24 Transmission coefficient for the single-iteration fractal, metallic geometry on both sides of the FSS [13]

To evaluate the sensitivity of the frequency response to the variation of the parameters of interest, a parametric study was performed on two fractal structures, the fractal with a single iteration, and the fractal with two double-layer iterations respectively.

The results obtained from the numerical analyzes obtained by means of a CAD electromagnetic simulation package [7] demonstrated that fractalization of a unit cell represents an excellent miniaturization solution, by moving the relevant filter bands towards lower frequencies while keeping the same spatial periods of the unit cell (therefore, by increasing the electrical length of the metallization), and by duplicating the metallic pattern on both sides of the dielectric layer, additional resonance frequencies are introduced that contribute to the enlargement of the stop bands.

Also, it has been shown that reducing the thickness of the substrate has the effect of increasing the degree of coupling between the metallizations on the two sides of the unit cell, which can lead to a higher attenuation in the working band and the solution can be used to position this band according to some requirements, depending on the application considered [13].

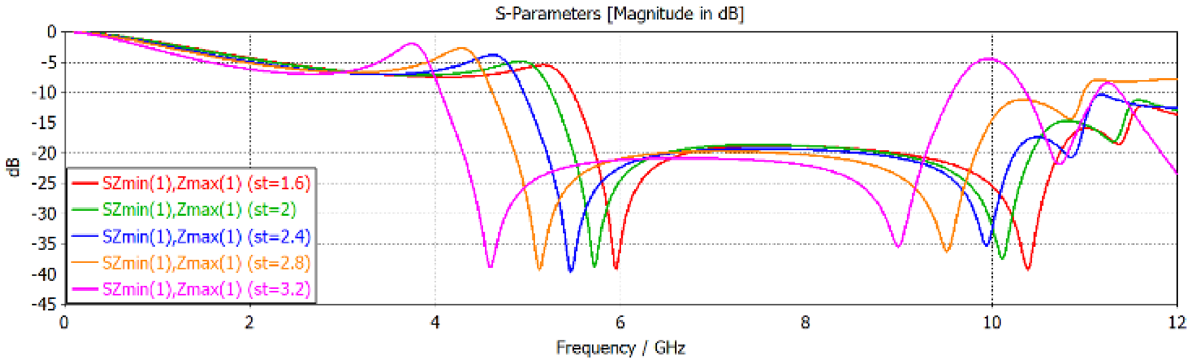

Fig. 25 Parametric study for substrate thickness for the two-iteration fractal, metallic pattern on both sides of the FSS [13]

6. Contributions

During the doctoral program I studied 85 bibliographic titles and also published 1 article in an ISI journal (in an ISI Q2 journal – MDPI Sensors), 10 articles in ISI Proceedings indexed conferences, and 4 articles in BDI indexed conferences. I would like to note that a thesis article was quoted in IEEE Transactions on Electromagnetic Compatibility (ISI journal indexed Q3). I enumerate below my own contributions to this thesis.

In chapter 2:

- I presented and commented an extensive bibliographic study related to metamaterials in general and frequency-selective surfaces in particular.
- I presented the concepts of metasurface and frequency-selective surface, and classified them according to the importance of existing functionalities and applications, underlining the parameters of operation and frequency responses.
- The most important advantages of the FSS were highlighted: selective filtering and shielding of signals depending on the frequency range and high incidence angles, as well as the processing of the plane electromagnetic wave polarization.
- Also, the concept of convoluted and fractal structures for applications that require the reduction of structural dimensions was presented.

In chapter 3:

- The particular topic of a planar periodic structure was presented and commented on: the impact of using a geometry modulation on the dispersion diagram of the respective structures.
- Also, a bibliographic study at the beginning of the chapter was presented, related to electromagnetic surfaces with high surface impedance, i.e. surfaces that present forbidden bands.
- Instead of a general theoretical presentation, easily found in the specialized literature, I chose to describe and comment on the simulations based on an electromagnetic CAD simulation software that I took part in, as well as their evaluation from the perspective of metamaterials theory analysis.

I also presented my contributions related to this subject:

  - I described the geometry of the proposed stripline structure: the unit cell was considered not to be homogeneous, it was made of an elliptical metallization, connected to the lower metal plane through four cylinders with metal walls.
  - Using an electromagnetic simulation environment, a dispersion diagram for the first five propagation modes was constructued, obtaining one broad-band EBG and two small-band EBGs (using the eigenmode solver mode of the electromagnetic CAD simulation software).
  - The group velocities for the first two modes of propagation has been calculated.
  - Further the stripline structure has been modulated (with a modulation index of 50%), and the result was visible in the new dispersion diagram, each mode of the unmodulated structure being split into four modes after modulation.

In chapter 4:

- In this chapter, it was presented periodic frequency selective structures (FSS), designed with the purpose of filtering and shielding electromagnetic waves within certain frequency domains, having applicability in the automotive testing field from the electromagnetic compatibility point of view.
- In sub-chapter 4.2 key concepts related to FSSs were commented and a bibliographic study related to their application in various fields of activity was carried out.

- Related to my contribution in this chapter, I started in sub-bchapter 4.3 with the presentation of a structure consisting of a circular ring and a Jerusalem cross. I continued with details of the geometry and dimensions of the unit cell, adapted to filter in the 1-12 GHz frequency band.
- Using an electromagnetic simulation environment, I designed various combinations of structures to achieve: a broadband filter, an X-band filter, and a WLAN-band filter.
- Previously, the two structures have been simulated separately (first the circular ring and then the Jerusalem cross) to present the exact origin of the resonances that determine the existence of the filtered bands.
- In sub-chapter 4.4 a structure with multiple resonators, has been designed. In this way, filters in bands used intensively in the Automotive field have been obtained: Wi-Fi, Bluetooth, and the X band.
- Again, I started with a description of the initial unit cell (dimensions and materials used in the simulation) and with the analysis of the transmission coefficient corresponding to a linearly polarized plane wave at normal incidence.
- At this moment, I chose as the form of the metallization inside the unit cell a square ring, with different dimensions than those existing in the literature, therefore obtaining a resonator element. By inserting a new square ring inside the original one, I managed to increase the number of resonator elements (2,3,4 elements).
- I also performed a parametric study related to the thickness of the dielectric substrate and duplicated the metal pattern on the other side of this substrate, obtaining broadband filtering.
- In sub-chapter 4.5, an ultra-wideband frequency selective surface has been proposed, simulated, and practically implemented. Therefore, a filter with an attenuation of more than 10dB for a bandwidth of more than 14 GHz between 1.59 GHz and 15.76 GHz has been achieved (the solution has a much larger stopband than those in the literature).
- I have also presented my contributions made so far regarding this topic:
  - Circuit models to explain in detail the frequency response of the proposed FSS have been proposed;
  - The stability of the structure at the oscillation of the angle of incidence: in TE mode over 60 degrees and for the TM over 50 degrees has been demonstrated;
  - A prototype of the structure has been implemented and tested in an anechoic chamber, demonstrating a good matching between simulation and experimental results.
- In the final subchapter of chapter 4 (4.6), a broadband linear polarizer-type structure has been designed and demonstrated by electromagnetic simulation.
- Own contributions can be summarized as follows:
  - Design by simulation of an FSS structure built on an FR4 substrate, where the incident plane waves were filtered into linearly polarized waves with orthogonal polarization in two different frequency bands;
  - For the situation where the electric field vector is parallel to the x-axis, a stopband with a central frequency of 4.78 GHz has been obtained, and for the case where the electric field vector is parallel to the y-axis, the presence of two stopbands centered on 2.34 GHz, respectively on 6.31 GHz have been noticed;
  - To achieve a broadband operation, the metallic pattern has been duplicated on the other side of the frequency-selective surface;
  - A parametric study related to the dimensions of the unit cell has been performed, through which the structure can be adapted for different applications;
  - Finally, the stability of the structure at various angles of incidence has been tested, obtaining good behavior up to an angle of 45 degrees.

In chapter 5:

- I have presented and commented on other types of applications for FSS, namely the use of the fractal paradigm.
- According to the requirements, I started the exposition of the subject, in subchapter 5.2, through a bibliographic study, related to the use of fractalization in the field of frequency-selective surfaces.
- In sub-chapter 5.3, a broadband FSS through a fractalized structure has been expected to be obtained, the model using only a metal cross on one side of the substrate, the other side remaining initially empty (the arms of the cross being rotated 45 degrees for sides of the unit cell to ensure sufficient sizing possibilities).
- With the initial structure, a resonance frequency centered on 9 GHz has been obtained. It was demonstrated that by using the first iteration of the fractal, the resonance can be shifted to lower frequencies (below 6 GHz) and by using a second iteration a new resonance was introduced.
- Broadband structures were obtained using one or two iterations replicated on the opposite side of the dielectric substrate, and through the parametric studies performed on the dimensions of the metalized elements, the possibility of changing the frequency of the resonances has been demonstrated.
- In sub-section 5.4, different fractalized structures have proposed with the aim of filtering signals in the LTE, C, and X bands; the initial design used was a "T-square" shape, achieving first filtering between 7 and 9 GHz (part of the X-band).
- A broadband filter (approximately between 5 – 12 GHz) for the case of fractalized FSS structure has also been obtained by replicating the pattern on the opposite side of the substrate.
- Continuing the fractalization process, stop bands in the C and LTE bands have been obtained.
- At the end of the sub-chapter, parametric studies for the thickness of the substrate and to test the stability of the structure at various angles of incidence for the previously exposed cases have been performed.

7. References

1. B.A. Munk, Frequency-Selective Surfaces – Theory and Design, Wiley, New York (2000),] [R.S. Anwar, L. Mao, H. Ning, “Frequency selective surfaces: a review”, Appl. Sci., 8, 1689, 47 pp., 2018.

2. Vardaxoglou, J.C. Frequency Selective Surfaces: Analysis and Design; Research Studies Press: Boston, MA, USA, 1997.

3. Glybovski, SB.;Tretyakov, S.A.;Belov, P.A.;Kivshar, Y.S.;Simovski, C.R. Metasurfaces: From microwaves to visible. Phys.Rep.2016, 634, 1-72.

4. Panwar, R.; Lee, J.R. Progress in frequency selective surface-based smart electromagnetic structures: A critical review. Aerosp. Sci. Technol. 2017, 66, 216–234.

5. J. A. Mackay, B. Sanz-Izquierdo, E.A. Parker, “Evolution of Frequency Selective Surfaces”, Forum for Electromagnetic Research Methods and Application Technologies (FERMAT), vol. 2, pp. 1-7, Mar-Apr. 2014.

6. L. Matekovits, A. De Sabata, O. Lipan, A. Silaghi, S. Baderca, **A. BUTA**, "Effect of geometry modulation on the Full Dispersion Diagram of a 2D Periodic Structure built Stripline Technology", 2016 IEEE Antennas and Propagation Society International Symposium (AP-S/URSI 2016), 26 June -1 July 2016, Fajardo, Puerto Rico, pp. 1961-1962, 2016.

7. Computer Simulation Technology, Microwave Studio.

8. **A. BUTA**, A. De Sabata, A. Silaghi, C. Iftode, L. Matekovits, „Applications of a Frequency Selective Surface based on a Combination of the Jerusalem cross and circular ring”, 2018

International Conference on Communications (COMM 2018), 14-16 June 2018, Bucharest, Romania, pp. 239-242, 2018.
9. **A. BUTA**, Andrei Silaghi, Aldo De Sabata, Ladislau Matekovits, “Multiple-Notch Frequency Selective Surface for Automotive Applications”, 2020 International Conference on Communication (COMM 2020), 18-20 June 2020, Bucharest, Romania, pp. 439-442, 2020.
10. A. De Sabata, L. Matekovits, **A. BUTA**, G. Dassano, A. Silaghi, „Frequency Selective Surfaces for UWB Filtering and Shielding”, MDPI Sensors, 22(5), 1896, pp. 1-16, February 2022 (FI 3.847, revistă indexată Q2, WOS:000773637200001).
11. A. De Sabata, L. Matekovits, A. Silaghi, **A. BUTA**, “Wide-Band Linear Polarizer Based on a Frequency Selective Surface”, URSI 2021, 28 August - 4 September 2021, Rome, Italy, pp. 1-4, 2021 (Scopus).
12. **A. Buta**, A. Silaghi, A. De Sabata, L. Matekovits, “Fractal Based Frequency Selective Surface with Broadband Characteristics”, 2019 International Symposium on Signals, Circuits and Systems (ISSCS), 11-13 July 2019, Iasi (Romania), 2019.
13. **A. BUTA**, A. Silaghi, A. De Sabata, L. Matekovits, “LTE Band Filtering Applications of a Fractal based Frequency Selective Surface”, 2020 14th International Symposium on Electronics and Telecommunications (ISETC 2020), 5-6 November 2020, Timisoara, Romania, pp. 1-4, 2020.