POLITECNICO DI TORINO

Master's Degree in Electronics Engineering

Conception and Design of Tunable Frequency Selective Surfaces

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Summary

Conception and Design of Tunable Frequency Selective Surfaces

by
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Designing a spatial filter (Frequency Selective Surface) is presented in this thesis. These filters are well-known to be used extensively in communication and radars applications. Also FSS is classified in the group of resonators. Basic principal of FSS is based on transmission and reflection electromagnetic waves in specific frequency band. Designing the tunable FSS structure is a main purpose of this thesis, so for fulfilling this goal PIN diodes are used. By the means of using PIN diodes biasing network is considered. This thesis introduces a new configuration of biasing the diodes in the structure by using the microstrip lines. These lines are located separately from the main structure to overcome the increase of complexity structures. Mentioned issue for biasing diodes directly will be discussed completely in design and measurement section. Basically our work is concentrating the behavior of FSS structure for two different incidence TE and TM incidence which is responsible for (y-direction) and (x-direction), respectively.

Section 3 provides FSS simulation by the help of CST software tools. The purpose of employing this software is to be more accurate and precise in designing and simulation lumped elements in comparison with other software. Moreover, this software is more friendly and popular among other designers. Section *design and measurement* focuses on designing process of FSS structure. In the following of section 4 simulation design process and results are represented. The beginning of section 4 is to design an initial structure and analysing the behavior of FSS structure in normal incidence angle. Then in order to connect the surface with microstrip biasing network via-holes are used for this purpose. But the initial via-holes cause electrical connection we need to find the best position for via-holes. Creating cut-slots in the structure design is considered because of using PIN diodes. Finally the FSS structure is being under investigation to analyse the PIN diodes in the condition of ON and OFF state for both TE and TM incidence.

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Chapter 1

Introduction I

1.1 Interest

Frequency Selective Surface (FSS) is known as spatial filters which reflects, transmits or absorbs the electromagnetic waves. These structures are used as low-pass, band-pass,etc. filters which are more common in the use of variety applications such as Radar cross section (RCS), radoms, etc. During my research and conducting on my thesis one of the major reasons which I became more and more enthusiastic about FSS is some of its features and flexibility which makes FSS more popular among other designers. Reflection/transmission at certain frequency, wide-range of application which FSS can be used. Another reason which absorbs my attention toward this structure is ability to design different structures based on my imagination. Moreover, studying on FSS structures helps me have a deep understanding about this concept. Being involved with recent published papers about these structures and I also am interested in designing FSS structures through CST or HFSS and improve my knowledge about this stuff.

1.2 Contribution

Over the period of studying and working on FSS structures I designed an initial structure in CST Studio Suite then analyzing its behavior in both TE and TM incidence fields. Gradually I came up with an idea to design a tunable structure. For this purpose non-linear devices such as diodes and varactors are used. In this thesis for making the FSS structure tunable diodes are chosen because varactors are dependent on biasing voltage for this reason their control would be more complex. In terms of adding diodes it is needed to create cut-slots in the structure. Innovative part of this work is biasing network. With respect to other works on tunable FSS structure, diodes are not biased directly. So biasing diodes elements is done through mictrostrip lines which are located on the bottom of substrate. These lines are connected with the main structure through via-holes. The proposed initial FSS structure is being under parametric study to find the best position for via-holes. The final structure is reported with its results in both TE and TM incidence in *Simulation and Result* section.

Chapter 2

Introduction

2.1 Overview

The purpose of this research is to design and study the behavior of spatial filters (FSS). First of all it is needed to know that filters have an essential role in RF circuits. These structures are used in order to eliminate the harmful and unwanted signals which make an interference in the system. Filters are organized in different groups based on their application such as low-pass, band-pass, high-pass, etc. As for example high-pass filters which are used to stop lower frequency signals and pass higher ones.

FSS structures are known as an spatial filters which have a certain frequency [1]. These structures have ability to expose to the electromagnetic radiation. Figure. 2.1 illustrates the FSS structure which is made of a Periodic unit-cell in forms of the array (As it is mentioned, Periodic structure consists of the elements which are identical) [2].

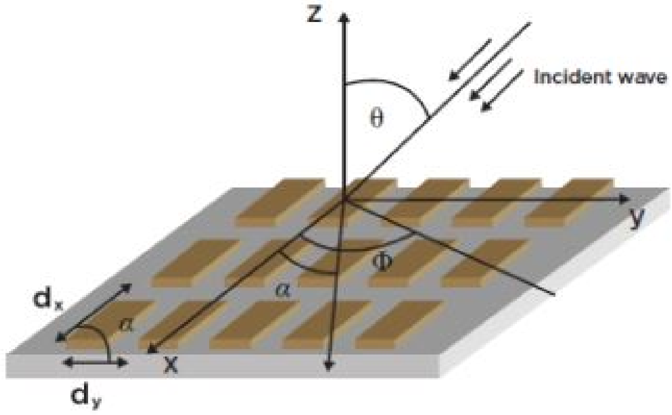

Figure 2.1: Frequency Selective Surface (FSS) structure.

Frequency selective surfaces are used in various applications as an example: reducing radar cross-section (RCS), Radoms, creating high impedance surface (HIS), reducing coupling among antennas, sensors and also in domestic ways they are used such as Microwave stoves [3].

For designing the FSS structure we need to consider some of the essential requirements as sustainability with respect to radiation pattern, sustainability in polarization, ability to separate the frequency bands, etc. Thus, some important factors are discussed as following: *i*: number of the planes are placed in a row, *ii*: choosing the type of the elements, *iii*: bandwidth and *iv*: cross-polarization level.

Some well-known FSS structures are introduced in fig. 2.2. FSS structures are designed to behave like low-pass, high-pass, band-pass filters, etc. FSS with high-pass or band-stop behavior has capacitance response, and inductance response is for FSS with low-pass or band-pass filters. These behavior is well depicted in fig. 2.3.

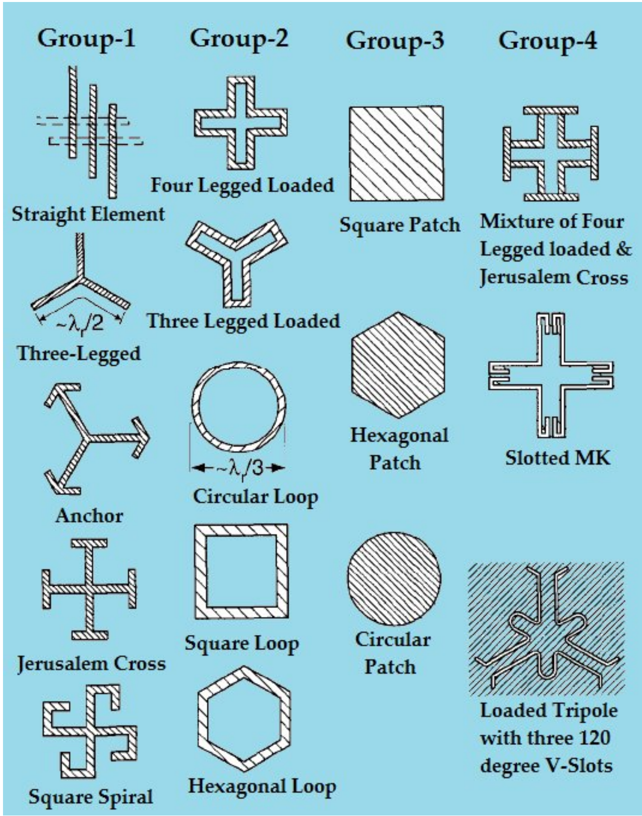

Figure 2.2: Various types of FSS structure used in design [4].

Elements which are used in design of the FSS structures are organized in four main categories.
1: The center connected or N-poles

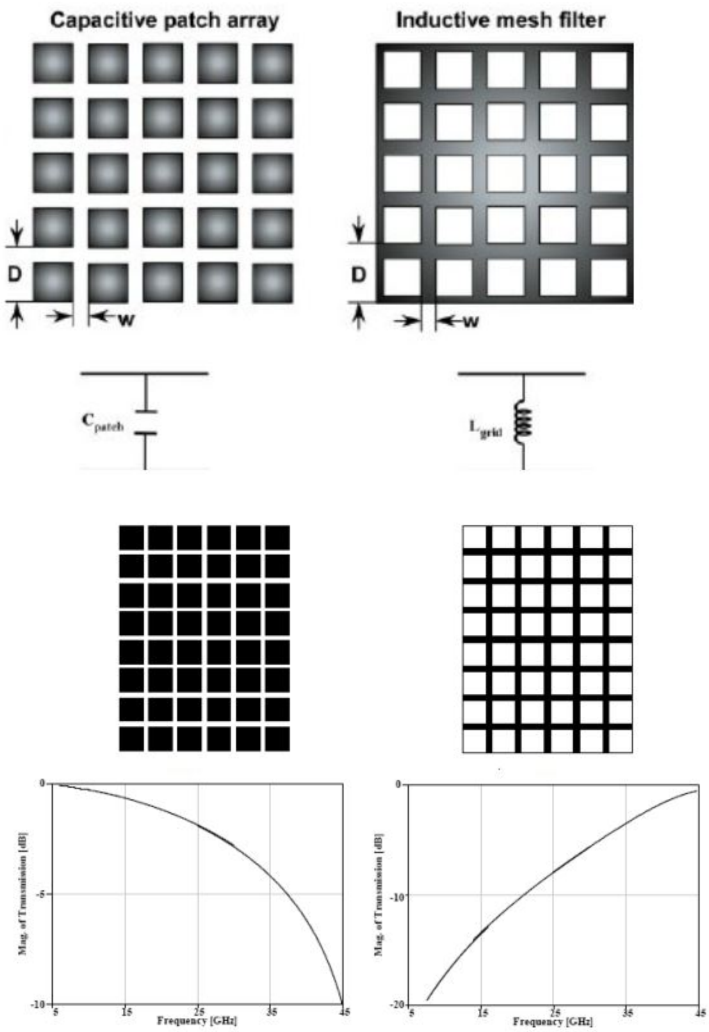

Figure 2.3: FSS structures: patches and slots (up), Response of Patches (capacitive) and Slots (inductive) (down) [5].

2: The loop types
3: Solid interior or plate types
4: Combination types
.

Table. 2.1 shows a table which compares the behavior these 4 groups. The element shape has an noticeable effect on the frequency response of the structure, even the arrangement of these elements is considered in the design process.

A short description for each four group is reported.
First group (The center connected or N-poles): This type of the elements is made

Table 2.1: Comparison between behavior of FSS elements [6].

Elements	Angle independence	Cross-polarizatio level	Larger bandwidth	Smaller band seperation
Loaded dipole	1	2	1	1
Jerusalem Cross	2	3	2	2
Rings	1	3	1	1
Tripole	3	3	3	2
Crossed dipole	3	3	3	3
Square loop	1	1	1	1
Dipole	4	1	4	1

of tripoles array fig. 2.4. These elements consist of three thin monopoles which are connected in the center. The main use of this group is to reduce the inter-element space in order to increase the bandwidth.

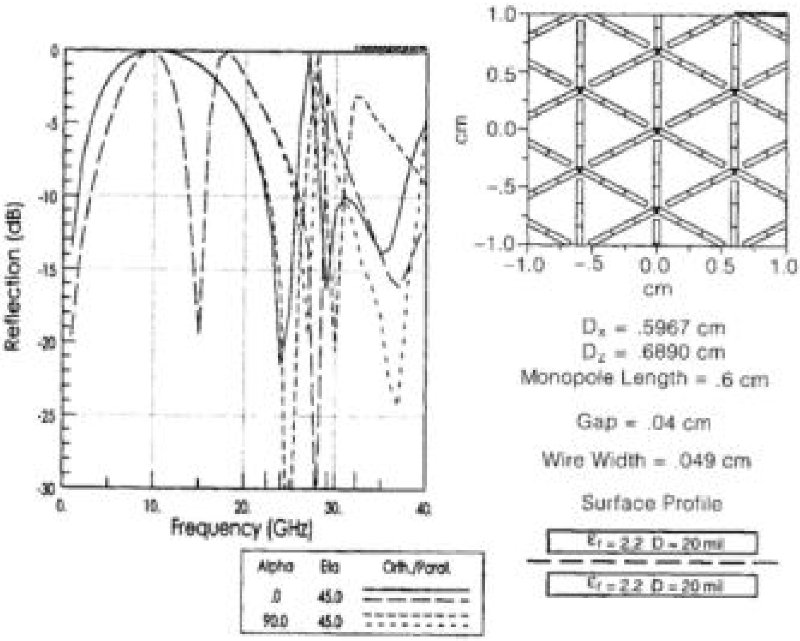

Figure 2.4: First group of elements for FSS design.

Second group illustrates the most common used elements for FSS design. As it is shown in fig. 2.5, these structures are created by connection of four-legged elements (using half-wave dipoles). The operation of this group is half-wave dipole has a similar behavior like a shorter dipole which is loaded Z_L which is a reactance.

It can compensate the effect of the shorter length.

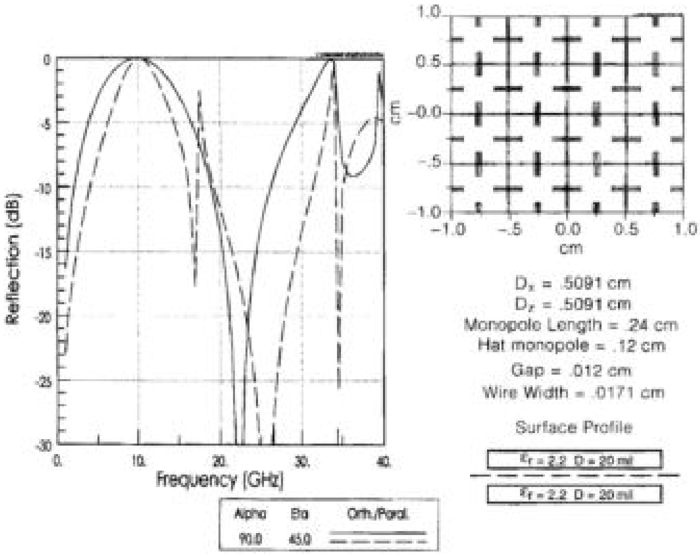

Figure 2.5: Second group of elements for FSS design.

The third group of FSS elements comprises two major parts: *i*: Metallic patches arrays like a circular disk, square, etc. which is known as reflecting arrays.
ii: Slots arrays on metallic plates such as circular, square, etc. This type corresponds to transparent as fig. 2.6 has illustrated below.

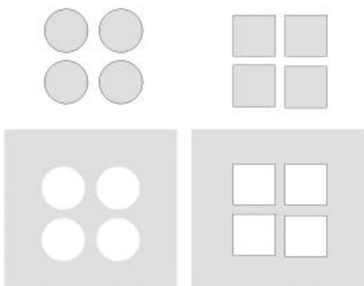

Figure 2.6: Third group of elements for FSS design.

Combination type is for group 4. This category of elements represents the combining of elements from other group in order to create a new approach. Figure. 2.7 shows this group elements.

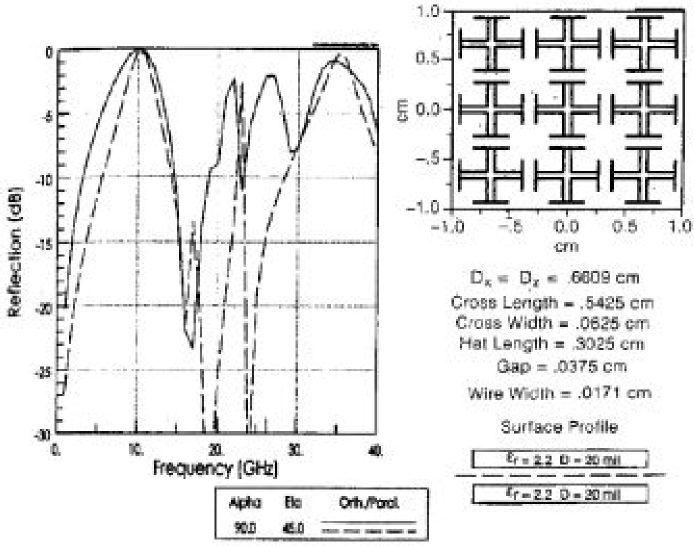

Figure 2.7: Fourth group of elements for FSS design.

2.2 Model for Frequency Selective Surfaces

As already mentioned, FSSs are considered as a spatial filters which are located on the surface [7]. Any microwave filters are based on three main steps; *i*: number of the resonators which are needed to use in a filter; *ii*: resonator design; and *iii*: controlling the interaction between resonator.

First of all, it is important to understand how to design a resonator for our filters. For having resonant characteristics both capacitor and inductor are needed [8, 9]. According to electrostatic theory, by having two conductive objects which are connected to different DC voltage make a capacitance in order to store the electric energy. While, the effect of current flow on a surface it can construct magnetic field which keep the magnetic energy inside of itself which implies the inductive concept. Figure. 2.8 illustrates the capacititve and inductive construction as it is mentioned above.

If the gap distance between two patches is smaller than the dimension of the patch, we can declare that generated capacitance has an inverse relationship with gap width and direct relationship with overlap area. Also, in a thin surface carrying the current if the length of the surface is long our inductor is big, but if the width of the surface is wide the value of inductor is small.

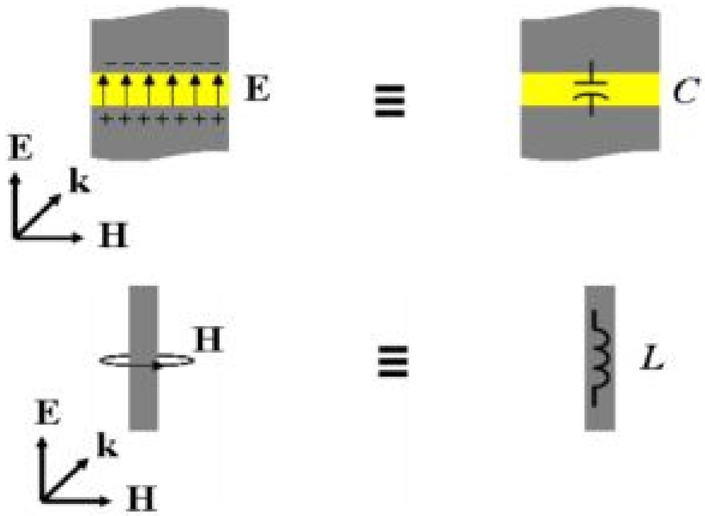

Figure 2.8: Construction of capacitive and inductive junctions [10]

The value of capacitance and inductor can be evaluated by the formulas below:

$$C = \epsilon_0 \epsilon_{eff} (2l/\pi) \log[csc(\pi s/2l)] \tag{2.1}$$

$$L = \mu_0 (p/2\pi) \log[csc(\pi w/2p)] \tag{2.2}$$

according to above equations for obtaining the capacitance and inductance of a resonator, ϵ_0 is relative permittivity of the air, ϵ_{eff} is dielectric Constance of a substrate, and μ_0 is air permeability.

In fig. 2.9 some equivalent circuits of FSSs are shown. The equivalent circuits of each element depends on geometry and reflection wave polarization.

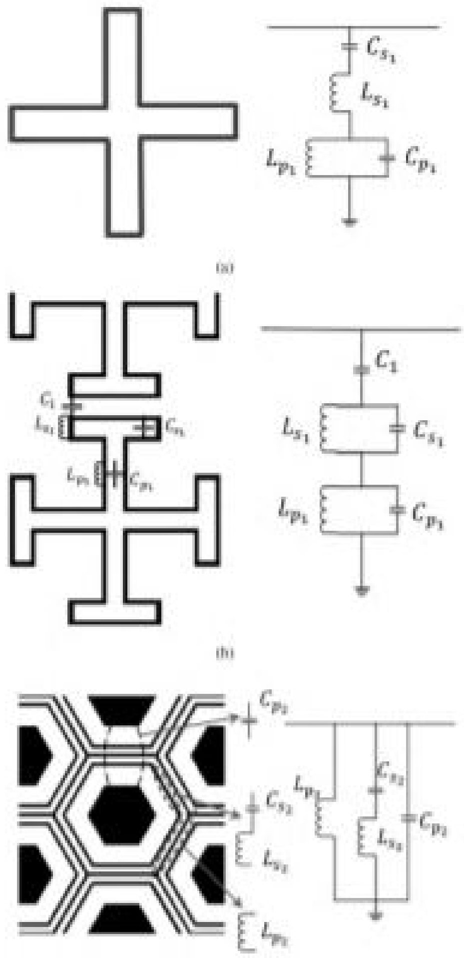

Figure 2.9: Equivalent circuits of FSS structure [11]

Chapter 3

Simulation and Results

3.1 Chapter Introduction

In this section every single step of FSS structure design is reported. Related figures and results for each design is completely discussed in this chapter. The main of this part is noticeably allocated to design of the FSS structure. As it is mentioned above in this thesis a multiband and tunable FSS is demonstrated. The innovative part for this work is presented a new configuration in feeding part by applying three parallel microstrip lines at the bottom of the structure which are connected with FSS through via-holes. While, before coming with this idea to use this type of configuration for biasing FSS structure there are other possibilities which are used by other authors. For example, in [12] by inserting a coplanar transmission line in the structure tries to modify the dispersion diagram of a high impedance surface. Also, [13] presents a biasing network with an active part as a high impedance surface. By considering all these possibilities for biasing network we decided to follow a new concept which is proposed above.

All proposed structures are designed on FR-4 substrate with $\epsilon_r = 4.3$ and $\tan = 0.025$. Simulation of these structures are accomplished by the means of the CST software tool. Moreover, the major purpose of this thesis is working on a tunable structure in comparison with the passive configuration in which is used in the past [14]. So for this purpose we need to use such a structure design to fulfill this goal. Thus, it is required to use some elements to make our structure tunable [15]. Conventional FSSs have some major limitation as unchangeable reflection and transmission characteristics. So designers are attracted to find some solution in order to overcome to this limitation.

There are various solutions for this issue which the most important of them can be included as multiplexing of frequencies [16], harmonics generation [17], etc. Although there are some solutions, using lumped elements such as diodes and varactors received more attention [18, 19].

For biasing active elements such as PIN diodes or varactors using DC bias network is highly required. But it is clear that inserting DC biasing in the structure will cause two main issues: first complexity of the structure would increase and the second issue is an alternation in response of incidence waves would be appeared. In order to solve these major problems using the microstrip lines as feeding parts in the bottom of the structure is proposed [20, 21].

Also in this thesis the purpose is to use PIN diodes. The idea of choosing these non-linear elements in comparison with varactors elements is the behavior of varactors change due to the voltage variation. Moreover, PIN diodes are used for this thesis work in a frequency range between 100 MHz and 30 GHz. Also required time for this type of diode is 2 ns in order to switch from ON-state to OFF-state.

In the following of this chapter the equivalent circuit of PIN diode are shown. The PIN diode which is used is (MADP-0009.7-14020) [22].

3.2 Initial design of FSS

As it is discussed the first structure which is illustrated in fig.3.1. This structure consists of a large circle and the small one which is embedded with two cross microstrip lines. This FSS is located on a dielectric with a thickness of $h1 = 1.58$ mm. Also as it is shown in fig. 3.1 these is another dielectric inside of the main one with the thickness of $h2 = 0.8$ mm. The initial geometry of this structure is reported in table. 3.1.

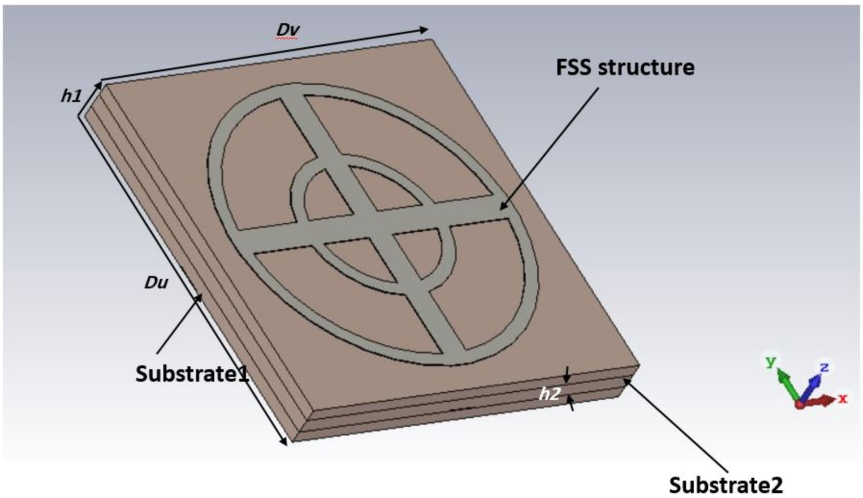

Figure 3.1: Frequency Selective Surface (FSS) structure.

Table 3.1: Geometry of the initial FSS structure.

Parameter	**Value**	**Unit**
Du	14	mm
Dv	14	mm
L	12	mm
W	1	mm
R1	6	mm
R2	3	mm
h1	1.58	mm

According to fig. 3.2, the geometry of FSS structure is reported with respect to table. 3.1. Also by considering the fig. 3.2 it is clear that two microstrip lines are used in this structure which is connected to main FSS structure. The main goal of these microstrip lines are to bring DC for biasing the structure.

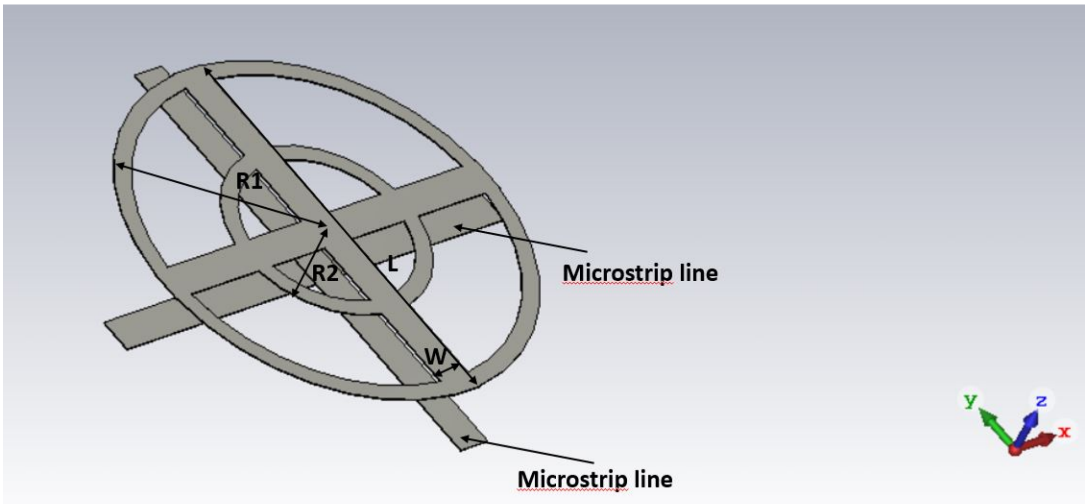

Figure 3.2: Geometry of Frequency Selective Surface (FSS) structure.

After designing the initial structure as it is shown before, the results for both TE-incidence ($y - direction$) and TM-incidence ($x - direction$) are illustrated in fig. 3.3 and fig. 3.4, respectively. These result are obtained in normal incidence when $\phi = 0$ and $\theta = 0$ ($\phi = 0$ and $\theta = 0$ are the angles of sperical coordinates with respect to the reference structure fig. 3.2).
As it is shown in both mentioned figures for the initial structure transmission coefficient for TE incidence indicates two frequency bands: first from 6.59 GHz to 9.72 GHz is referred to -10 dB stop-band, and for the second band the frequency range is 12.05 GHz to 12.64 GHz. The notch frequency is -35.54 dB and -17.61

dB for two frequency bands, respectively. Also, the same result for TM incidence is reported as follow: in the first frequency band the structure covers 6.59 GHz to 10.49 GHz which its notch frequency is placed at −37.21 dB. Then from 12.63 GHz to 12.92 GHz is allocated for the second frequency band with −13.08 dB notch.

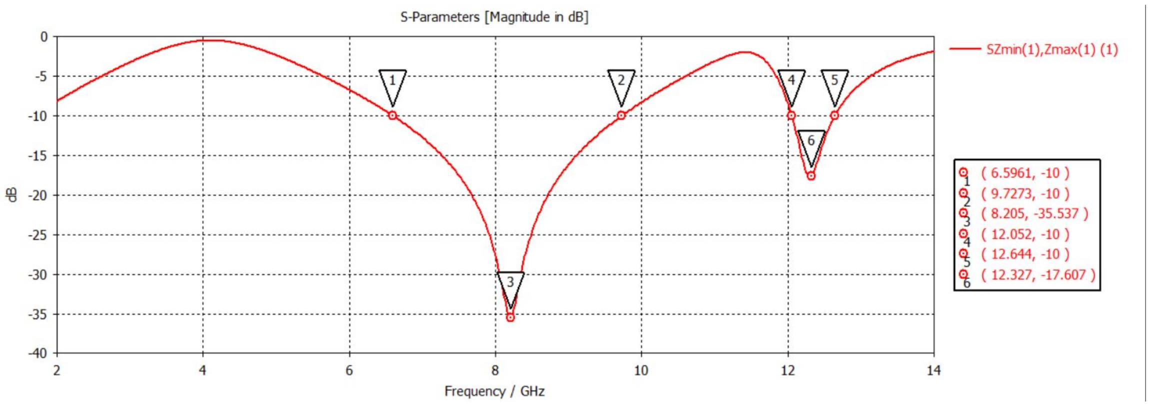

Figure 3.3: Result in TE-incidence for intial FSS.

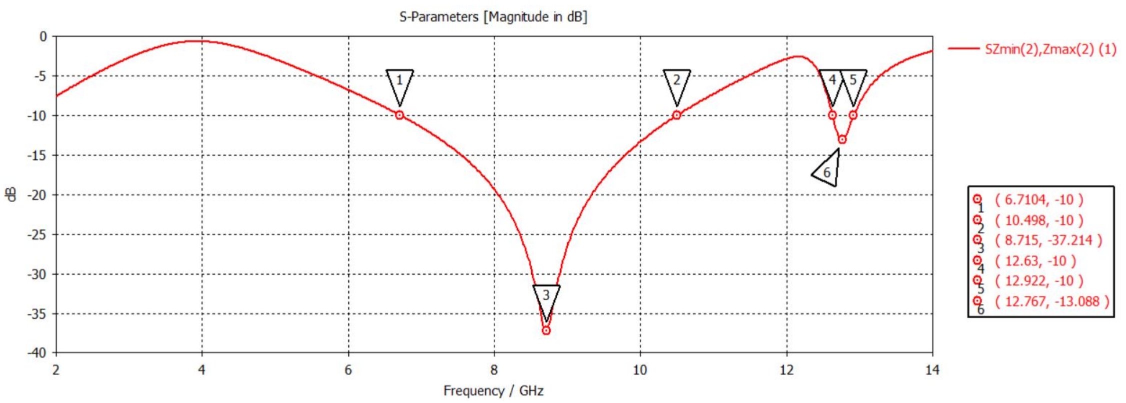

Figure 3.4: Result in TM-incidence for initial FSS.

For understanding the effect of each element in the result of the structure, the parametric analysis is done. Parametric study for different values of incidence angles for TE and TM incidence are presented in fig.3.5 and fig.3.6. This parametric study is done on ϕ= 0° and $\theta = [0° - 45°]$

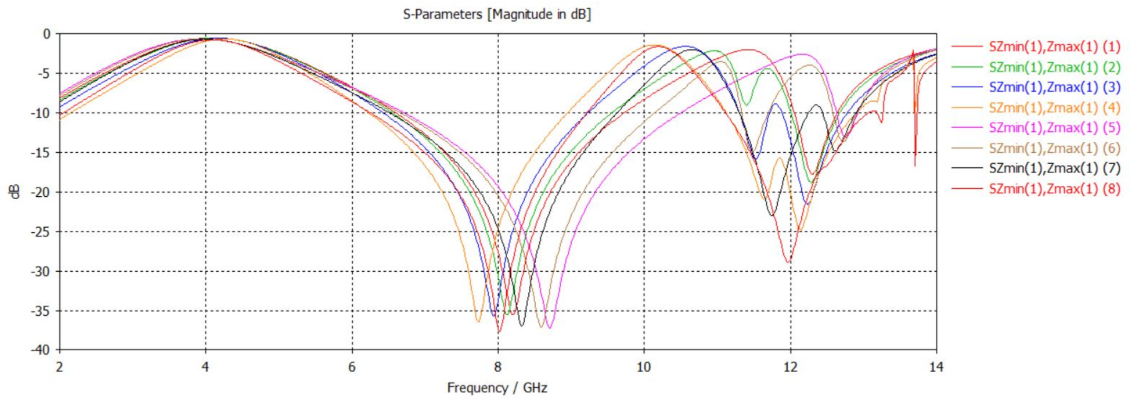

Figure 3.5: Parametric study for different incidence angles (TE-incidence).

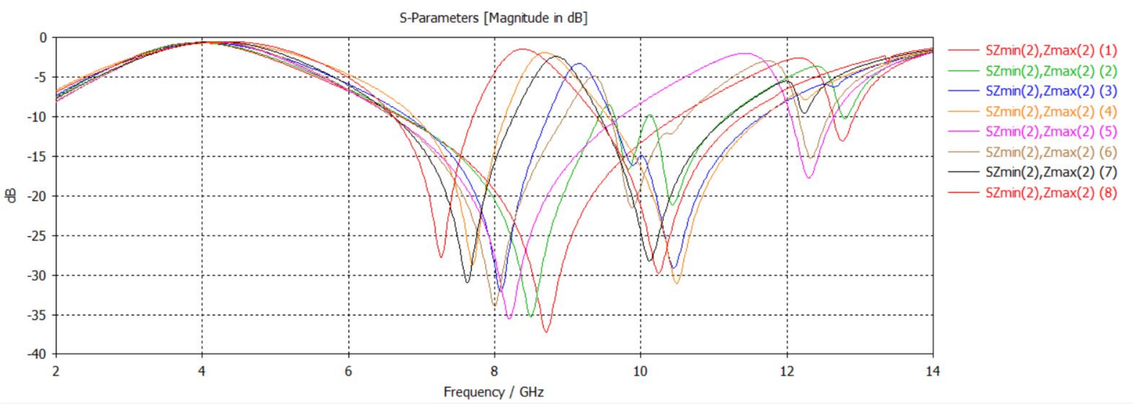

Figure 3.6: Parametric study for different incidence angles (TM-incidence).

3.3 Structure with Via-holes

As already mentioned in this work, the main purpose of this thesis is to design a multiband and tunable FSS structure by the means of diodes. To fulfill this goal it is necessary to bias the diodes. Biasing the diodes are not done directly because the complexity of the structure increases. That is why we use a new concept of biasing by the means of the microstrip lines to do this task. But, in order to make this biasing possible through these lines, via-holes are highly sensed to connect the FSS to the microstrip lines as it is shown in fig.3.7. The initial places for via-hole position are $op1 = 2$ mm and $op2 = 2$ mm.

Also the results for adding via-holes in the structure are presented in fig.3.8 and fig. 3.9 for TE and TM incidence, respectively.
In TE incidence based on the result in fig.3.8 by adding the via-holes in the structure

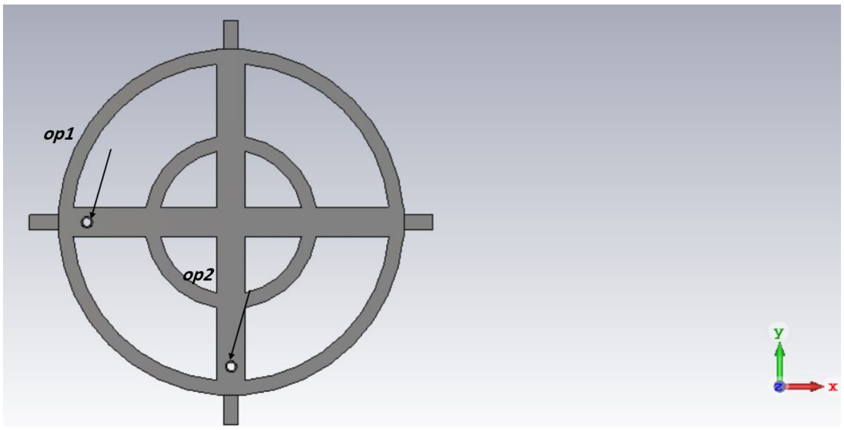

Figure 3.7: Via-hole position in FSS structure.

we have three frequency bands. First the transmittance level at −26.17 dB occurs from 3.56 GHz 4.92 GHz (1.36 GHz bandwidth), the second −10 dB stop-band is from 8.77 GHz to 9.98 GHz (−24.37 dB). The third frequency band covers from 11.21 GHz to 12.36 GHz with −21 dB transmittance level.

The result for TM incidence as it is shown in fig. 3.9 is reported. According to TM incidence three frequency bands are presetned. First, the transmittance level at −26.25 dB happens in 1.3 GHz bandwidth, second frequency band covers from 8.75 GHZ to 10.79 GHZ with −29.39 dB, also the third frequency band is between 11.52 GHz and 12.37 GHz (−19.78 dB).

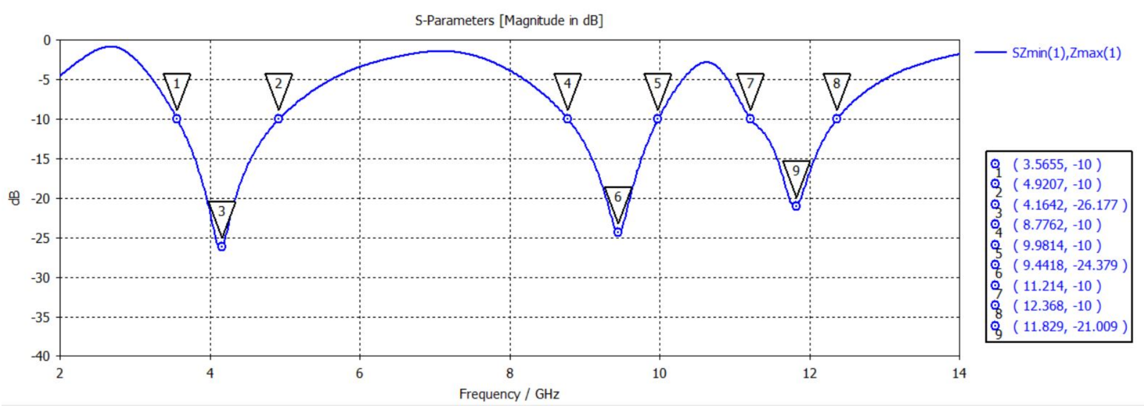

Figure 3.8: Result for via-hole position in FSS structure (TE-incidence).

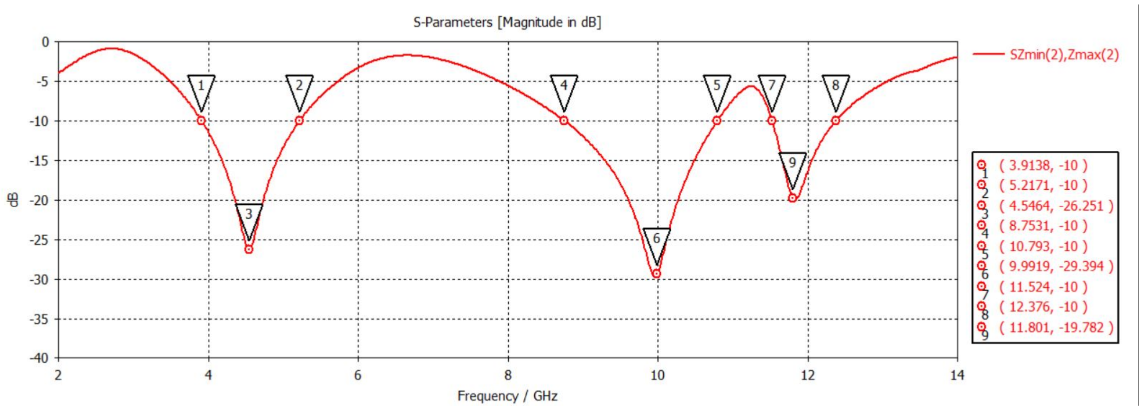

Figure 3.9: Result for via-hole position in FSS structure (TM-incidence).

By obtaining the results for via-hole positions, parametric study has been done on via-hole positions to find the best place for them. This related result for this parametric study is shown in fig. 3.10 and fig. 3.11.

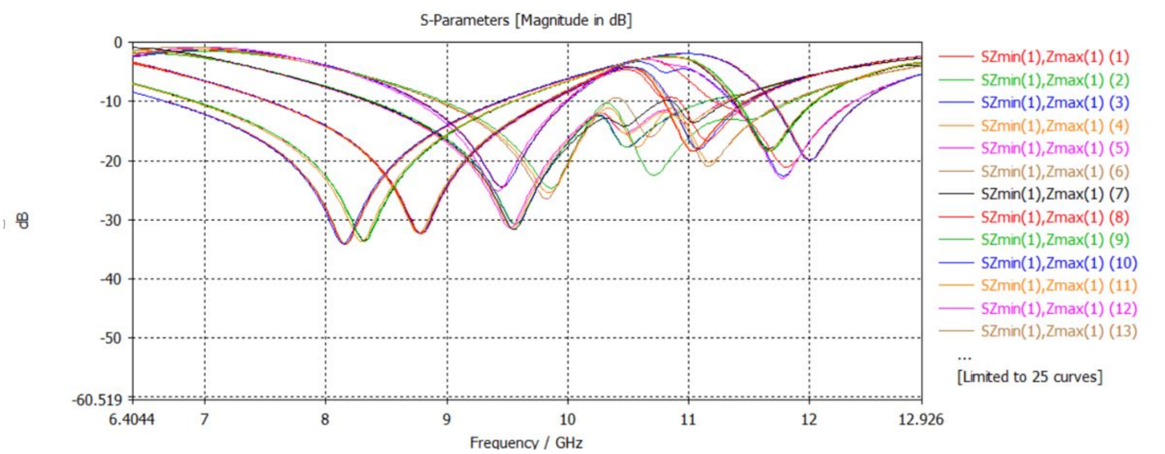

Figure 3.10: Parametric study on via-hole positions (TE-incidence).

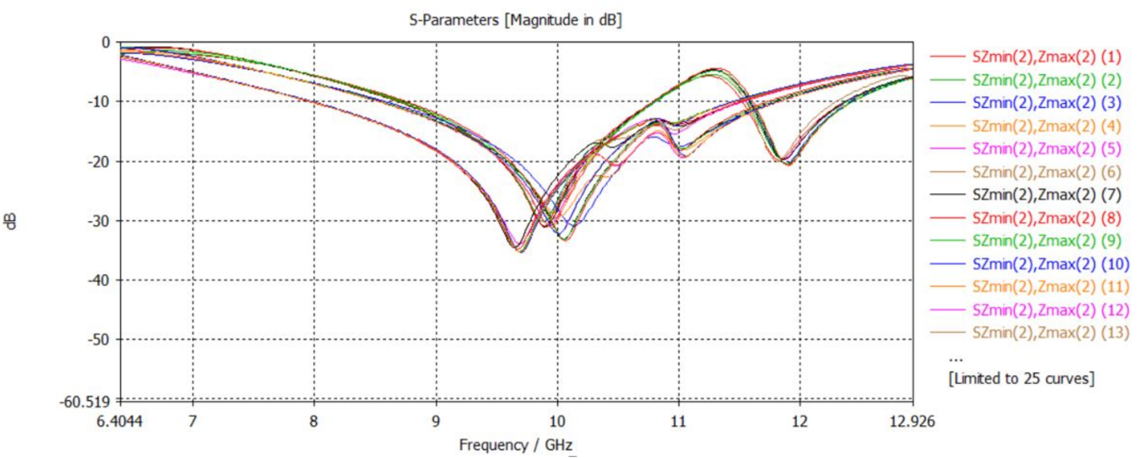

Figure 3.11: Parametric study on via-hole positions (TM-incidence).

According to this parametric study the best position for via-holes are $op1 = op2 = 3$ mm which the result is shown in below figures for both TE and TM incidence (fig. 3.12 and fig. 3.13).

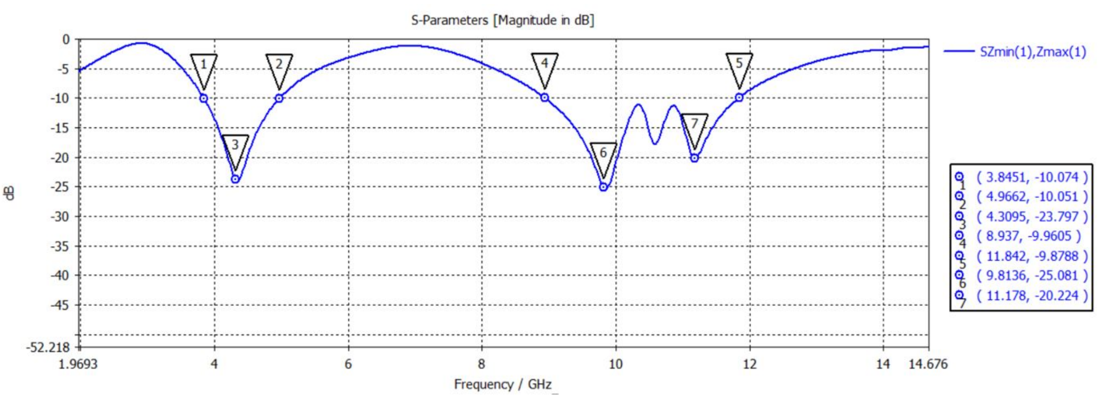

Figure 3.12: Result for via-hole positions $op1 = op2 = 3$ mm (TE-incidence).

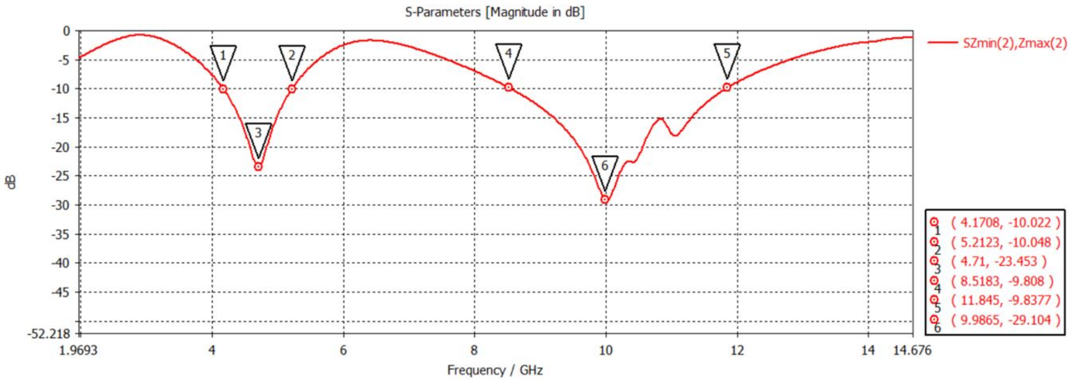

Figure 3.13: Result for via-hole positions $op1 = op2 = 3$ mm (TM-incidence).

3.3.1 Tackling the problem of electrical connection

But by analysing the structure by creating cut-slots into the structure to use diodes we face electrical connection which causes sever problems in our FSS. Thus, regarding to avoid any electrical problems we need to move via-hole $op2$ to the center of FSS. Figure. 3.14 shows the final positions for via-holes in the structure. In following figures the result for the structure in both TE and TM incidence is represented in fig. 3.15 and fig. 3.16.

Based on the results are achieved in figures above, it is clarified that by moving the via-hole $op2$ the issue of electrical problems is tackled. For TE incidence there are two frequency bands, the first -10 dB band-stop is between 6.68 GHz and 9.46 GHz, also the second notch frequency happens at -19.86 dB in 750 MHz (11.69 GHz - 12.44 GHz).

For TM incidence as it is shown in fig. 3.16 four frequency bands are reported. First frequency band is in range of 3.82 GHz - 4.84 (transmittance level -31.30 dB), second frequency band covers 5.075 GHz and 5.42 GHz at -17.89 dB notch frequency. Third frequency band is between 8.67 GHz and 10.78 GHz with -30.91 dB transmittance level, finally the last frequency band is from 11.71 GHz to 12.38 GHz at notch frequency -19.28 dB.

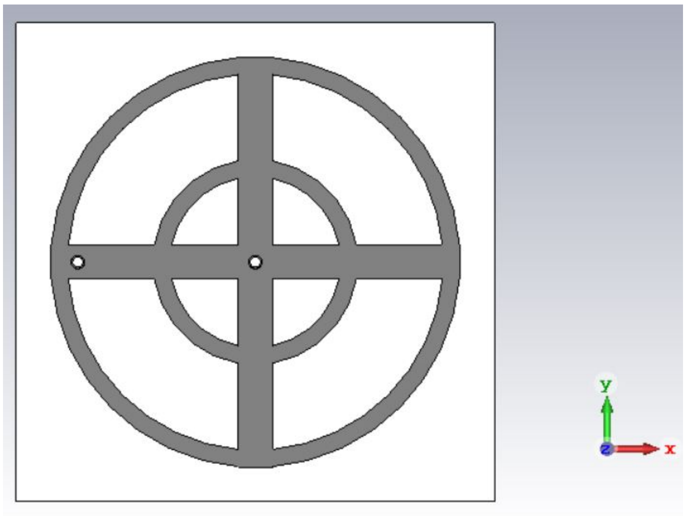

Figure 3.14: Schematic for Structure with center via-holes.

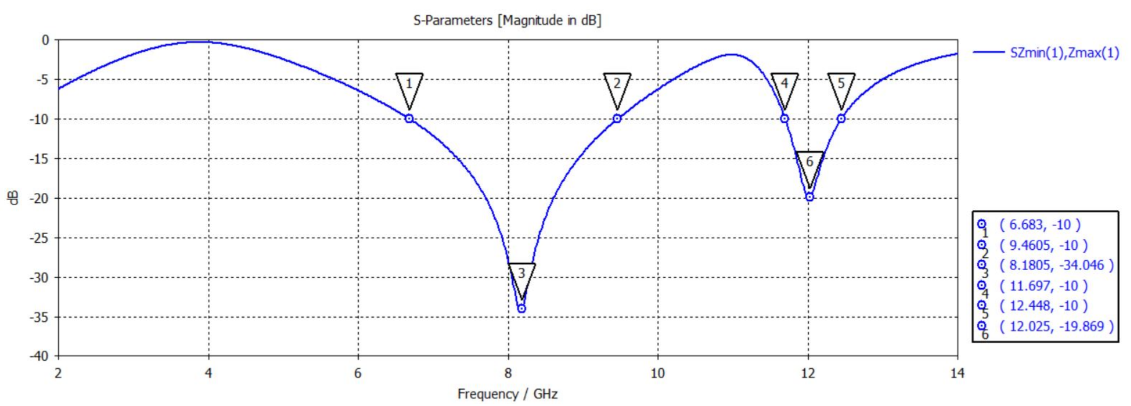

Figure 3.15: Result for TE incidence for center via-hole.

3.4 Structure with Cut-slot

By achieving a final structure in terms of the position of via-holes in order to make the FSS structure tunable, some cut-slots are created in the structure. The dimension of these cut-slots are selected by the means of diodes instruction which is proposed by the manufacturers (In this thesis the dimension of cut slots are 1 mm in width and 0.47 mm in length).
Figure.3.17 reports the structure with creating cut-slots in the structure. After applying mentioned modifications to the structure, following results are obtained which are shown in fig.3.18 and fig.3.19 for both TE and TM incidence, respectively.

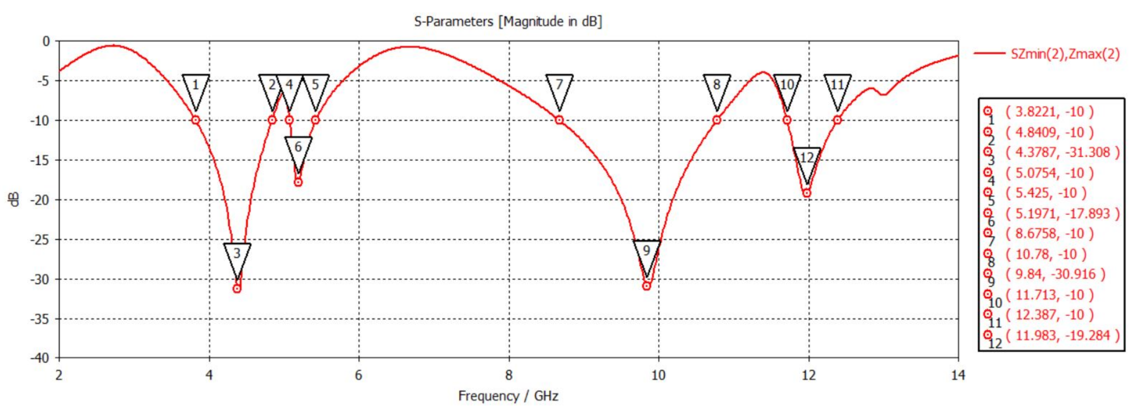

Figure 3.16: Result for TM incidence for center via-hole.

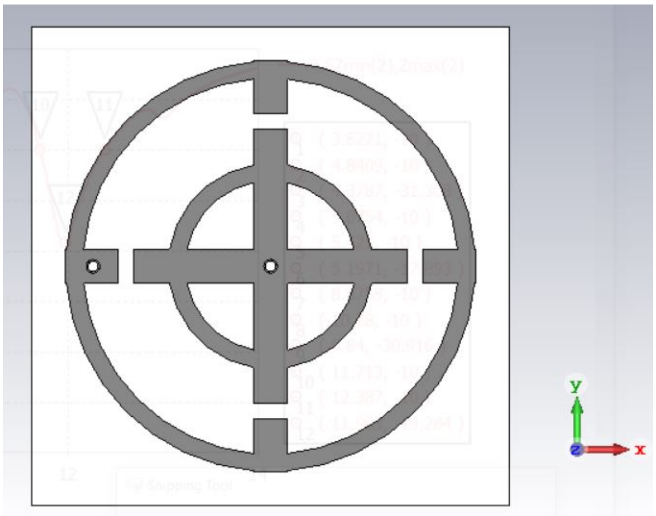

Figure 3.17: Schematic for Structure with cut-slots.

3.5 Structure by adding diode

Here by considering cut-slots our structure is ready for adding diodes in order to analyze the behavior of our structure by the means of these active elements.

First of all, the equivalent circuit of diode is shown in fig. 3.20. The final structure of diode in simulation area is represented in fig.3.21.

When the diode is in ON-state condition, it works as a RL circuit which the nominal values for R is 7.8Ω and L is $30pH$, while the diode is in OFF-state acts as a LC which the capacitance is parallel with a large R ($C = 28fF$ and R (OFF-state) is $30k\Omega$).

After introducing the PIN diode which is used in the structure, results for both

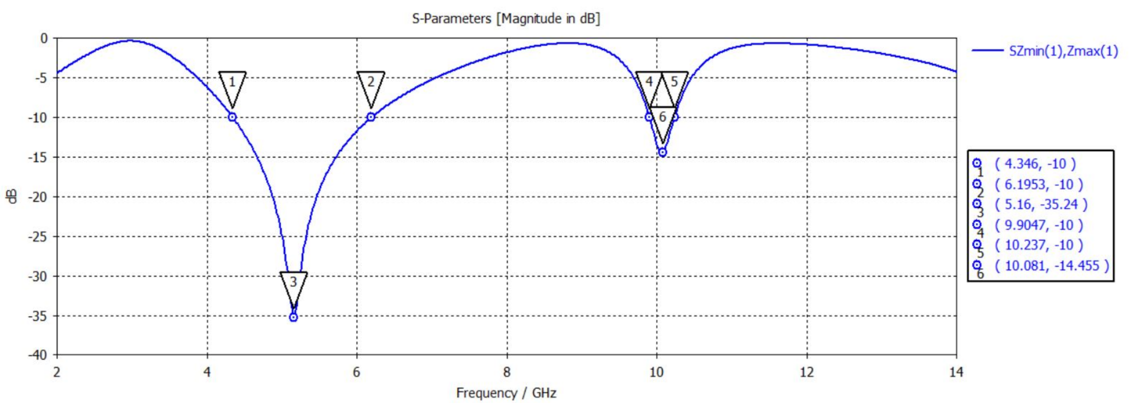

Figure 3.18: Result for cut-slot structure (TE incidence).

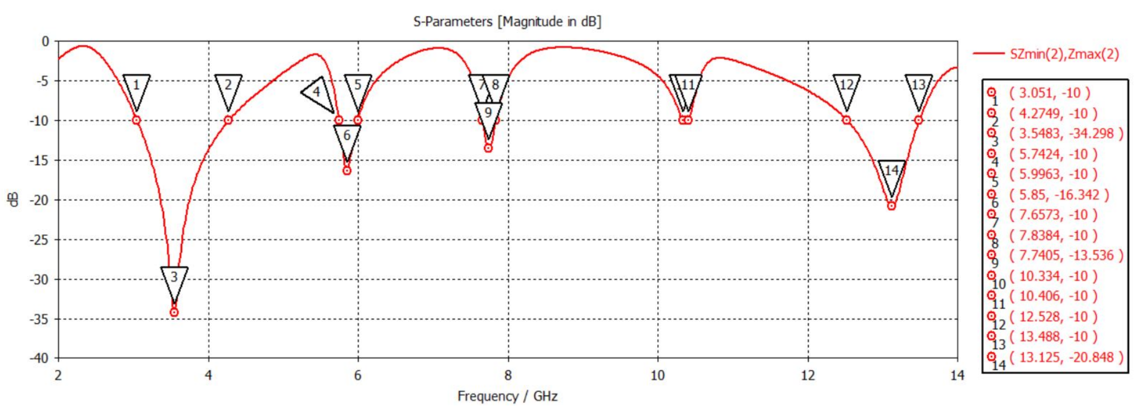

Figure 3.19: Result for cut-slot structure (TM incidence).

TE and TM incidence are shown in fig.3.22 and fig.3.23. The results are prepared for both conditions of diode in ON-state and OFF-state.

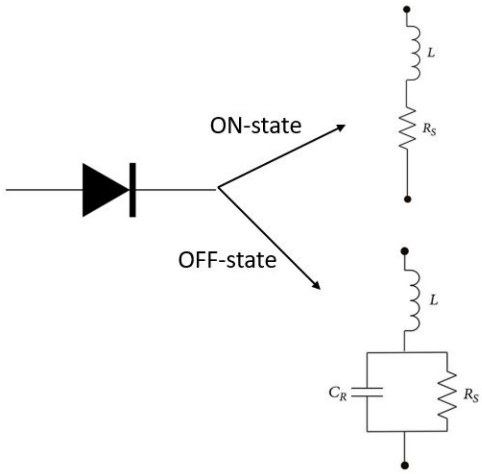

Figure 3.20: Equivalent circuit of diodes.

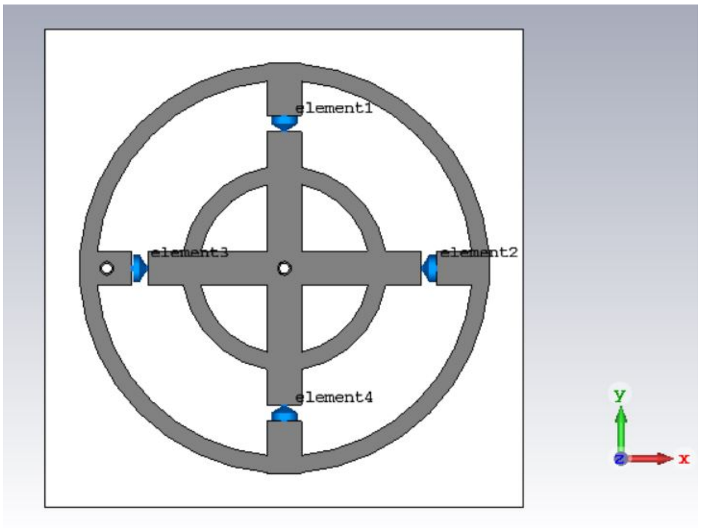

Figure 3.21: Schematic for Structure with diodes.

3.25.

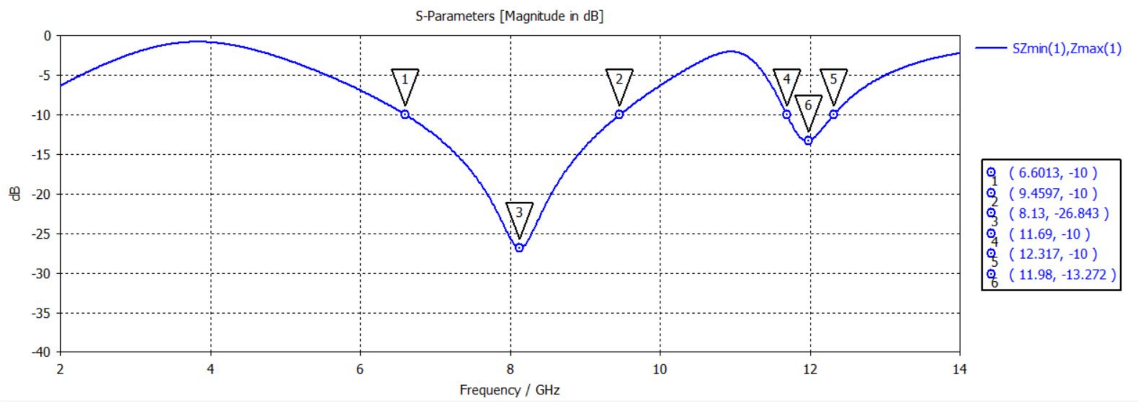

Figure 3.22: Result for TE incidence (ON-state).

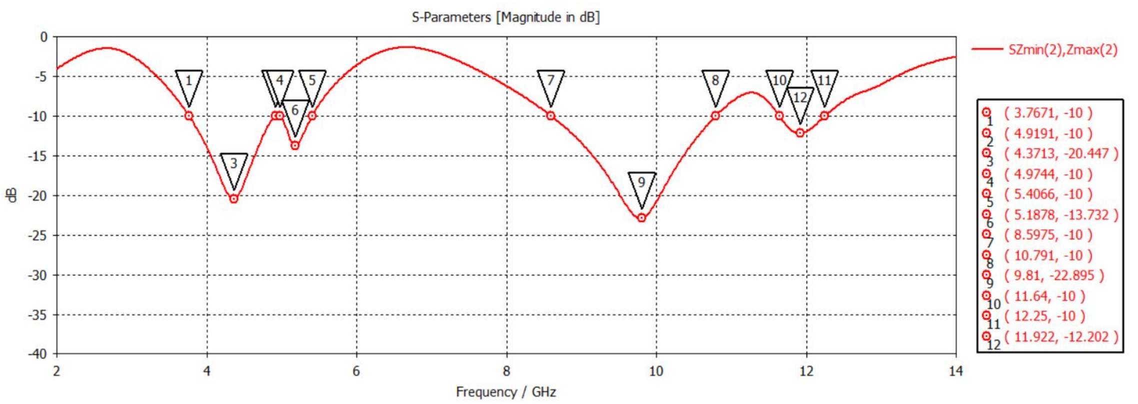

Figure 3.23: Result for TM incidence (ON-state).

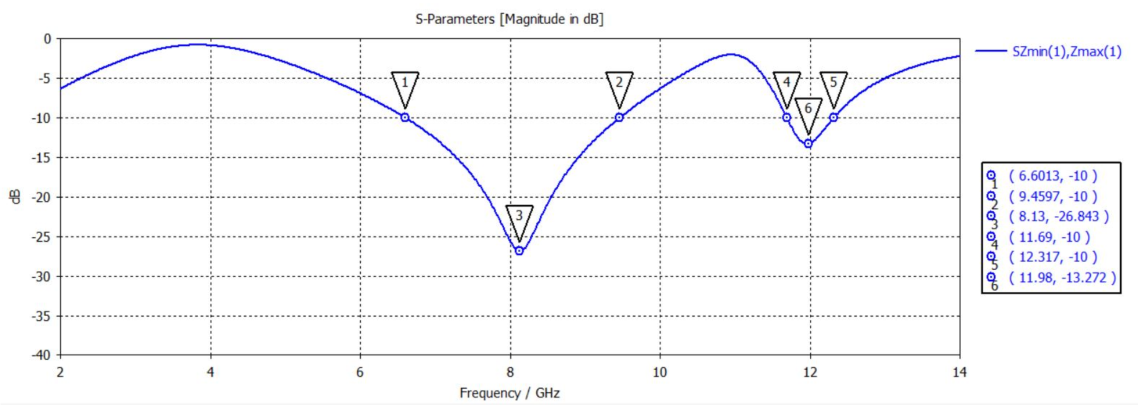

Figure 3.24: Result for TE incidence (OFF-state).

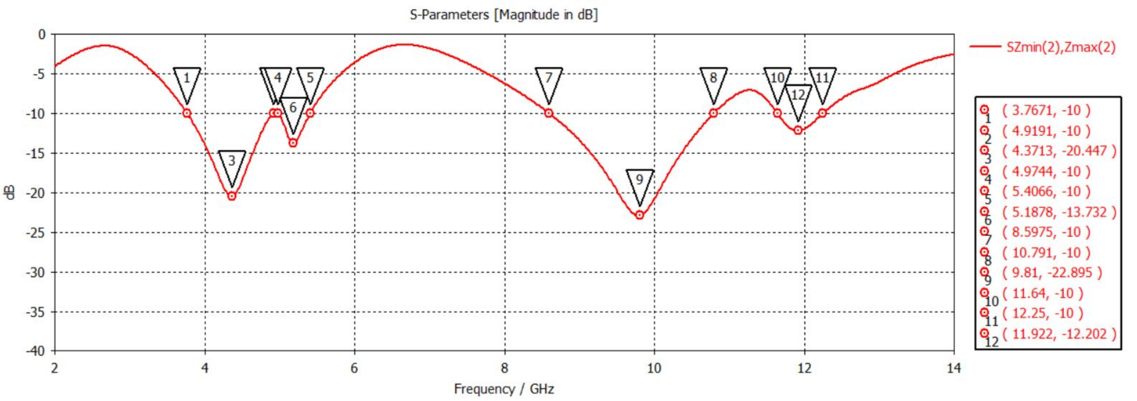

Figure 3.25: Result for TM incidence (OFF-state).

According to the results which are reported in figures above, in the situation when the diode is ON for TE incidence behaves in two frequency bands, the first one is between 6.60 GHz and 9.46 GHz with notch frequency at -26.84 dB. Second frequency band covers from 11.69 GHz to 12.32 GHz (transmittance level -13.27 dB).
While, For TM incidence the behavior of structure in ON-state situation is reported as follow: The first transmittance level occurs at -20.45 dB in the frequency band from 3.76 GHz to 4.92 GHz, the second frequency band is between 4.97 GHz and 5.41 GHz with a notch level at -13.73 dB. the third notch is at -22.89 dB in 8.59 GHz - 10.79 GHz frequency band, finally the last frequency band is from 11.64 GHz to 12.25 GHz (with notch frequency at -12.20 dB).

The same analysis is done for FSS structure in OFF-state condition and the result is reported as follow: For TE incidence 6.60 GHz - 9.46 GHz is referred to the first frequency band (notch frequency is -26.84 dB), the second frequency band covers from 11.69 GHz to 12.32 GHz with transmittance level at -13.27 dB.

For TM incidence in OFF-state, the result is presented in four frequency bands. First frequency band of the structure covers from 3.78 GHz to 4.92 GHz with the notch frequency at -20.45 dB. Second notch frequency is at -13.73 dB from 4.97 GHz to 5.40 GHz. Frequency band which covers from 8.59 GHz to 10.79 GHz with the transmittance level at -22.89 dB is related to the third frequency band of the structure. the final frequency band is between 11.64 GHz and 12.25 GHz with a notch frequency at -12.2 dB.

3.6 Structure with right hand via-hole

In this part, our purpose is to make our FSS structure symmetric. For fulfilling this goal another via-hole is created on the right side of the structure with respect to the first via-hole which is placed at the same position in the opposite of first via-hole (all via-holes in this thesis posses the same dimension).
The structure by considering the third via-hole on the right side of the structure is illustrated in fig.3.26, Also, the results for TE and TM incidence are reported in fig.3.27 and fig.3.28, respectively.

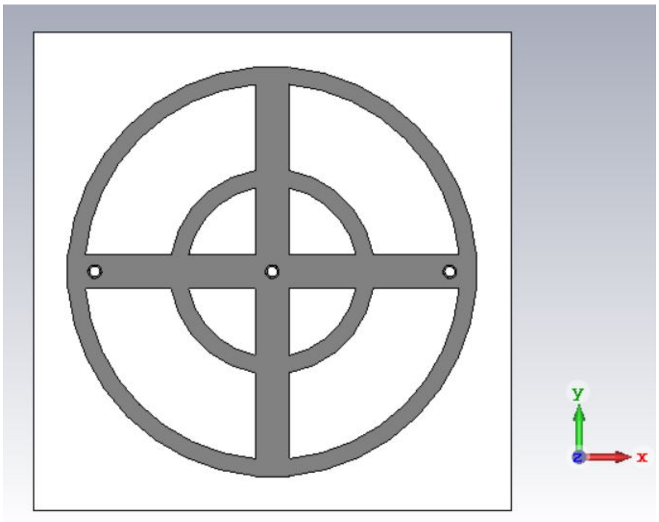

Figure 3.26: Schematic for Structure with added via-hole.

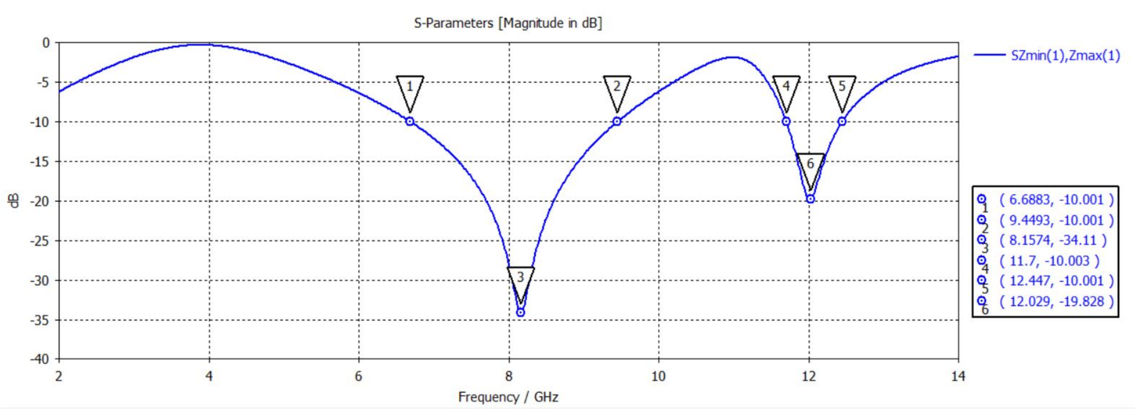

Figure 3.27: Result for TE incidence in structure with 3 via-holes.

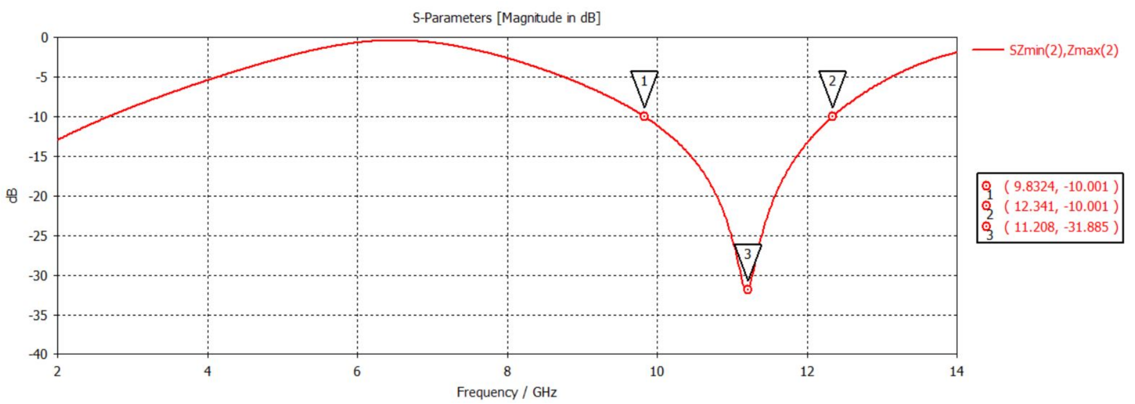

Figure 3.28: Result for TE incidence in structure with 3 via-holes.

As it is reported in fig.3.27 for TE incidence the first frequency band is between 6.68 GHz and 9.45 GHz with notch frequency at −34.11 dB, and second transmittance level is at −19.83 dB in the frequency range from 12.45 GHz to 12.029 GHz. The behavior of FSS structure with 3 via-hole for TM incidence is presented as follow: 9.83 GHz - 12.34 GHz is related to a frequency notch at −31.88 dB.

3.6.1 Creating cut-slot for three via-hole structure

In the Following of the section cut-slots are added to the structure which is shown in fig. 3.29 and its results are represented in fig.3.30 and fig.3.31 for both TE and TM incidence, respectively.

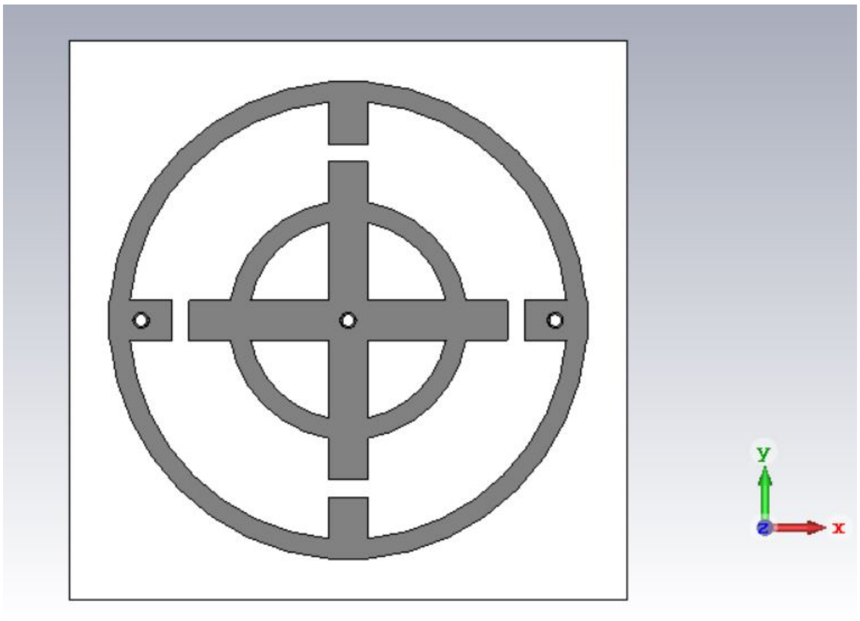

Figure 3.29: Schematic for Structure with cut-slots for 3 via-hole FSS structure.

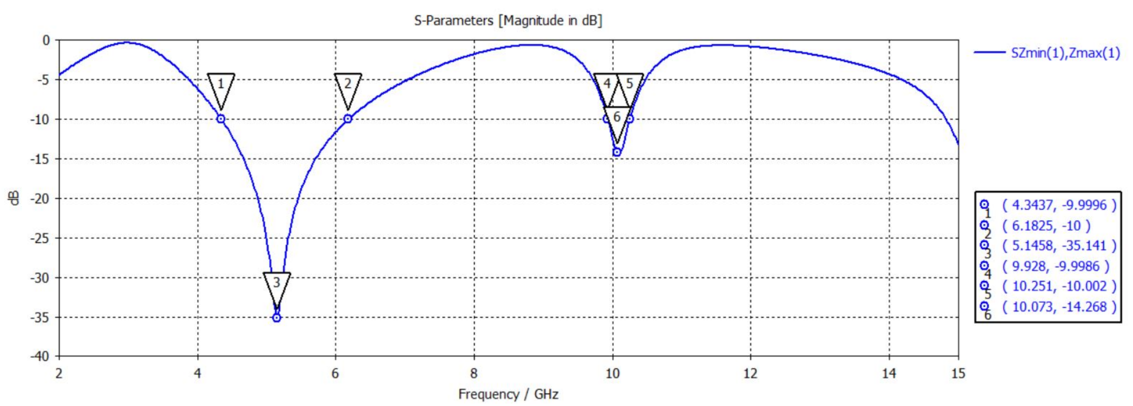

Figure 3.30: Result for structure with cut-slots and 3 via-holes TE incidence.

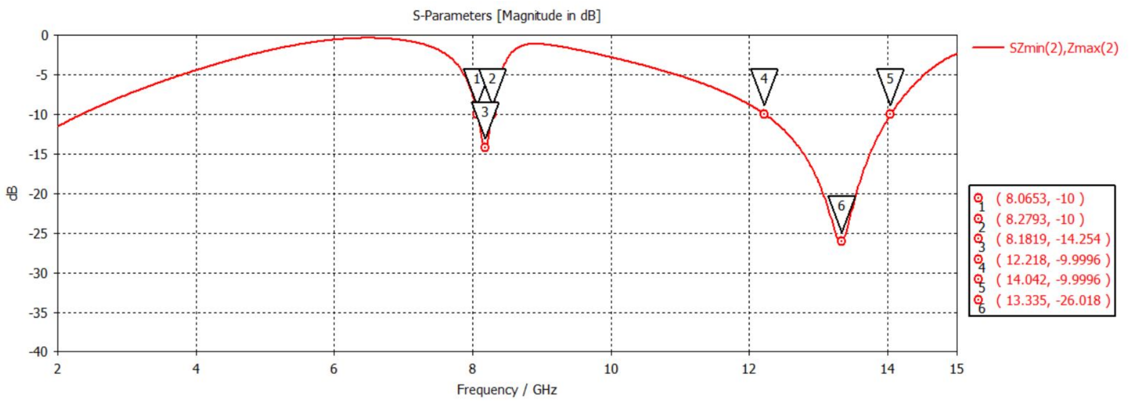

Figure 3.31: Result for structure with cut-slots and 3 via-holes TM incidence.

In the following design process after considering the right hand cut-slot for FSS structure, diodes are used in the structure to analyze the FSS design in both ON and OFF-state conditions.

Figure.3.32 shows the FSS structure with 3 via-holes. Also fig.3.33 and fig.3.34 represent the results for TE and TM incidence for FSS structure of using diode in ON-state condition, respectively.

The results for TE and TM incidence for OFF-state condition are reported in fig.3.35 and fig.3.36. According to the result which is prepared from the simulation analysis in TE incidence when the diode is behaving as ON-state, the first frequency band is between 6.61 GHz and 9.44 GHz with the transmittance level at −26.74 dB, and the second notch frequency at −13.27 dB happens from 11.69 GHz from 12.32 GHz.

For TM incidence there is only one frequency band which covers the frequency range from 9.78 GHz to 12.31 GHz (transmittance level at −24.98 dB).

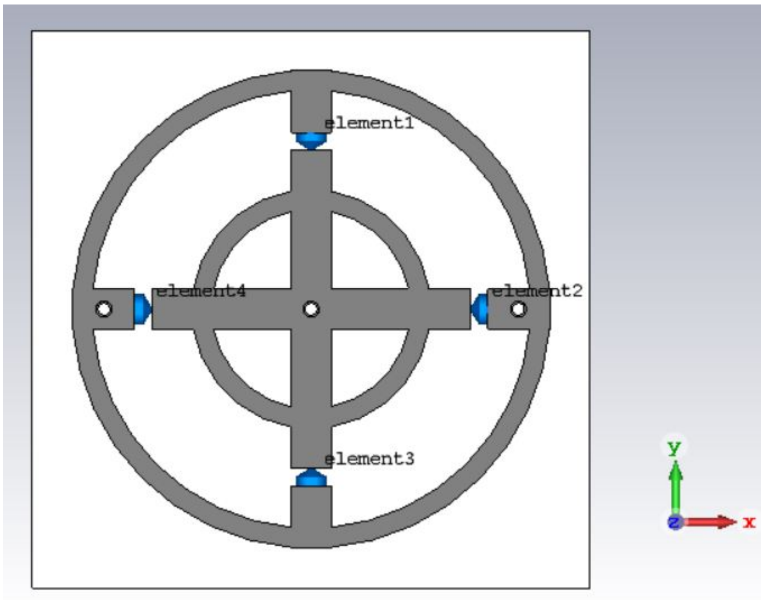

Figure 3.32: Schematic for Structure with diode.

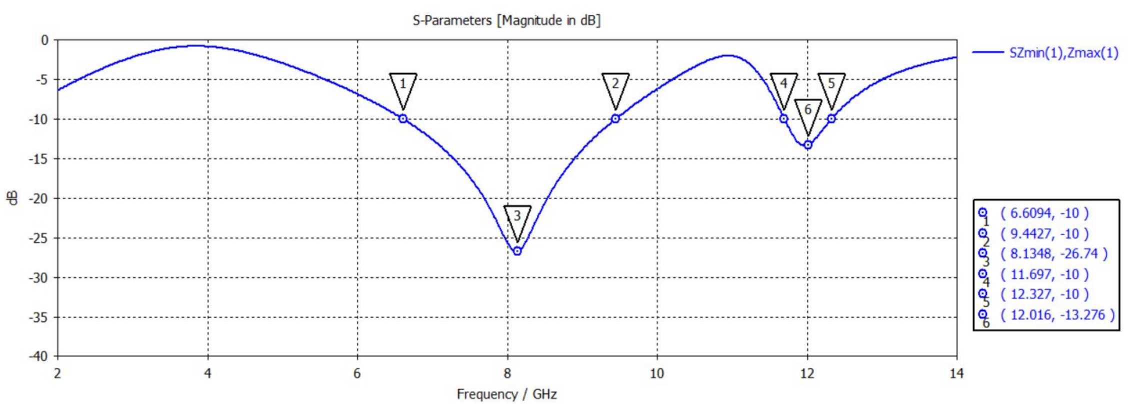

Figure 3.33: Result for TE incidence with 3-via-holes and diode (ON-state).

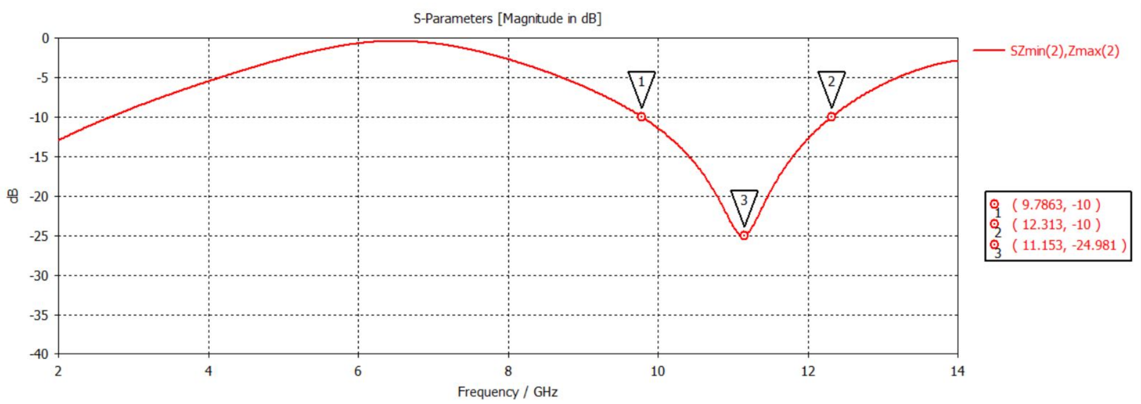

Figure 3.34: Result for TM incidence with 3-via-holes and diode (ON-state).

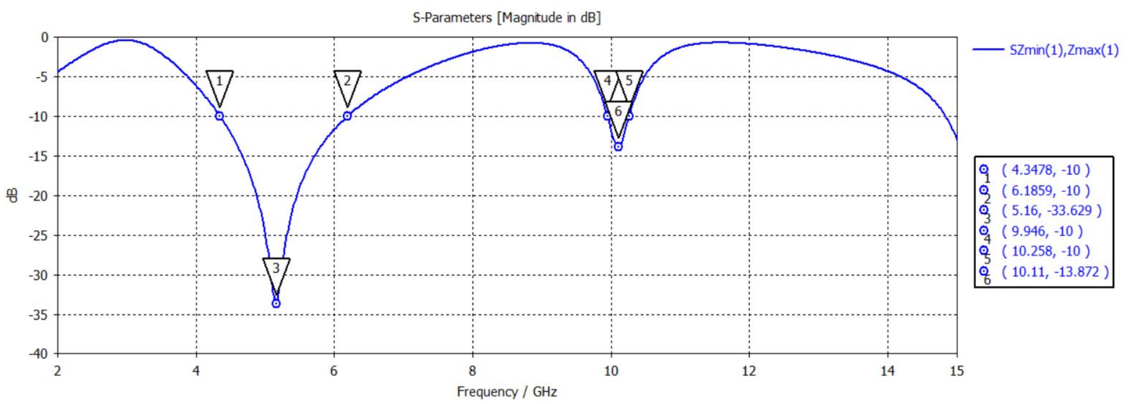

Figure 3.35: Result for TE incidence with 3-via-holes and diode (OFF-state).

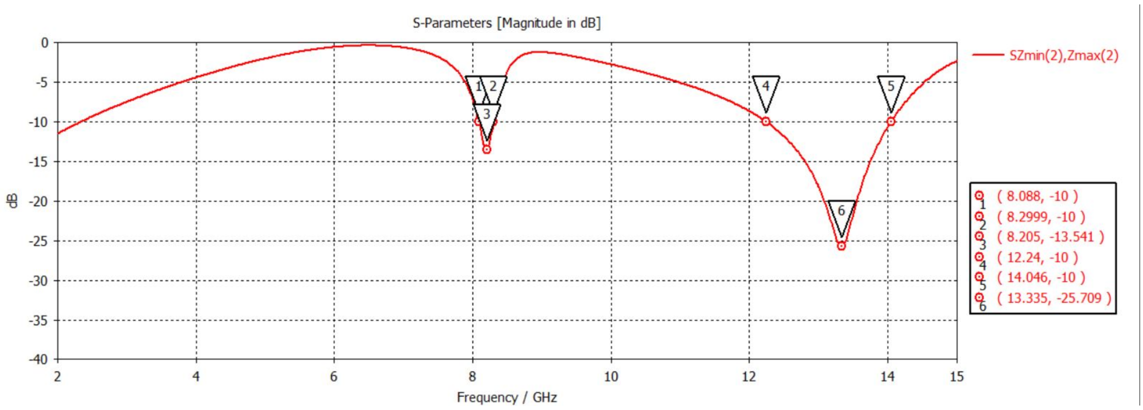

Figure 3.36: Result for TM incidence with 3-via-holes and diode (OFF-state).

Chapter 4

Conclusion

4.1 Summary of thesis

Designing and analyzing the Frequency Selective Surfaces (FSS) is reported in this thesis. FSS structures are organized in the group of resonators structures. The arrangement allows to transmit and reflect and in some cases absorb the electromagnetic waves in a given frequency band. These structures are widely used in radoms, reducing radar cross-section (RCS), etc. In this work it is concentrated to design a FSSs by the incorporation PIN diodes to make three structures tunable. The purpose of using diodes is to overcome the difficulty of FSS structures in terms of reflection/transmission characteristic which is dependent on the incidence angle. Implementing PIN diodes is one way among other solutions, which have been attracted the designers‘ attention. Using active elements as the PIN diode implies the need of biasing. In this thesis it is decided to use a microstrip line based on biasing network, aiming to reduce its effect on the electromagnetic answer of the initial structure, and because of its reduced complexity.

This work is focusing on the analyzing the behavior of the FSS structure for two different incidences: Firstly, TE incidence corresponding to y-directed electric field vector, and secondly a TM incidence (corresponding to x-direction). The initial design is created by two different circles and crossed microstrip lines, which are named as the main structure. It is built on FR-4 substrate with 1.58 mm thickness. Parameter analysis over the main dimensions of the structure has been performed aiming to find the best results in terms of bandwidth. Also, it is tried to analyze the behavior of the FSS in terms of linear to circular polarization conversion, which additionally to the equal amplitude also requires $-90°$ or $+90°$ phase difference between transmission coefficient in both TE and TM incidence cases. By considering this feature the initial structure turns into the ellipsis FSS structure to fulfill this goal.

Chapter 5

Future Work

After studying and analyzing the behavior of transmission and reflection FSS structure which is proposed in section 2, three main features of the structures which are namely as *i*: polarization filtering, *ii*: polarization converter and *iii*: full notch need different symmetries. In order to have polarization and polarization converter it is highly required that both components of incidence field must interact in a different way with the structure. For fulfilling this purpose asymmetric structure is needed. Besides, for having full notch frequency both components should reject completely at notch frequencies. With respect to previous unequal answers our work would be faced with a major problem in the case of linear polarized (LP) to circular polarized (CP) conversion. In this type of conversion there must be a $+90°$ or $-90°$ phase difference between TE and TM incidence. Another issue is the presence of control network (CN) which is responsible to bias an active device. It is clear both CN and active device have a strong effect on the symmetric structure. As it is discussed in this thesis the main goal is exploit the symmetry breaking structure. So in section 2 FSS structure by the means of two circles are considered. In order to have a FSS structure to fulfil above requirements it is sensed to turn the circles in FSS structure in section 2 into ellipses components.
Also another work which is planned to be accomplished is to make an array structure by putting single unit-cells next to each other to study the behavior the reflection/transmission of FSS structure. Designing and studying over this new configuration is under investigation to have a different FSS structure. Also for control network which is going to bias the active elements of the FSS structure we are trying to find a new concept for this purpose. The initial investigation is done and we come up with this idea to reduce the complexity of the structure and avoid response alternation of incident waves three microstrip lines which are paralyzed with each other are implemented on the surface. Then these lines would be connected directly to bottom biasing lines through via-holes.

Chapter 6

Appendix

6.1 Simulation of FSS structure with CST

In this thesis an overview of simulation Frequency Selective Surface is presented by the means of CST Studio Suit. As already mentioned in this work FSS structures are literally described by their reflection and transmission characteristics. For this purpose CST Studio Suit is chosen because CST is based on Finite Integration in Technique (FIT) which is more popular among antenna designers and also this kind of software is more friendly and easy to use.
Every step of designing FSS structure is provided by an example in this section.

6.2 Setup for simulating a FSS Model

In this example before going through the design process, it is highly recommended to carefully check the setup of software. In fig.6.1 a starting point for designing FSS structure is represented. In order to design our structure *Periodic Structures* should be selected to lead into specific environment for designing full-wave analysis. Then in a project template *FSS, Metamaerial- Unit cell* is chosen as it is shown in fig.6.2. In the following of design process *Phase Reflection Diagram* and *Frequency domain* are selected as represented in fig.6.3 and fig.6.4, respectively.

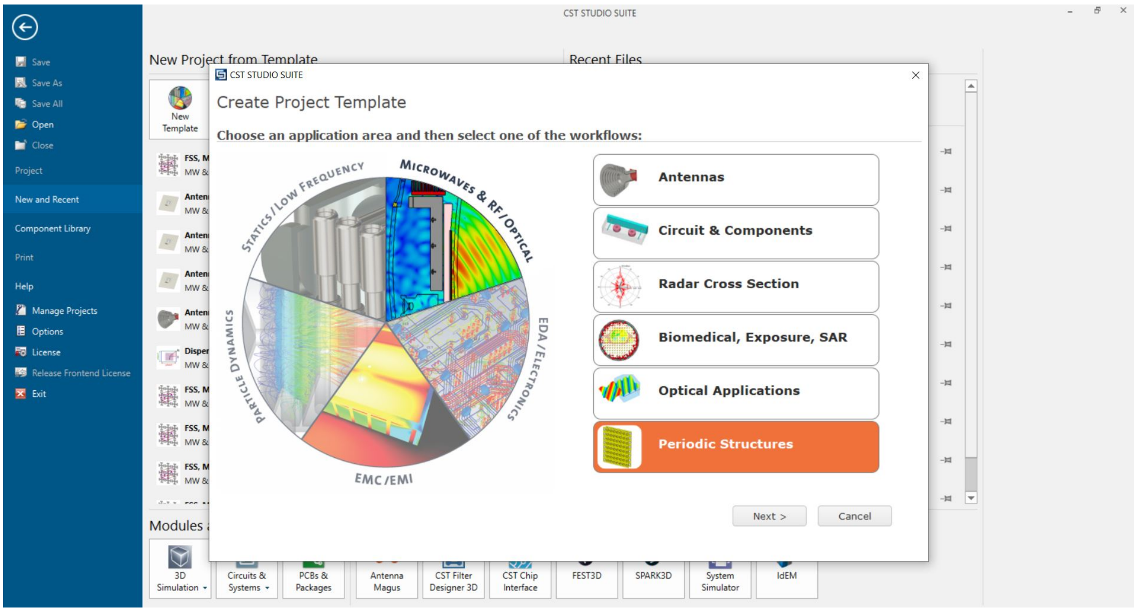

Figure 6.1: Initial setup for FSS design.

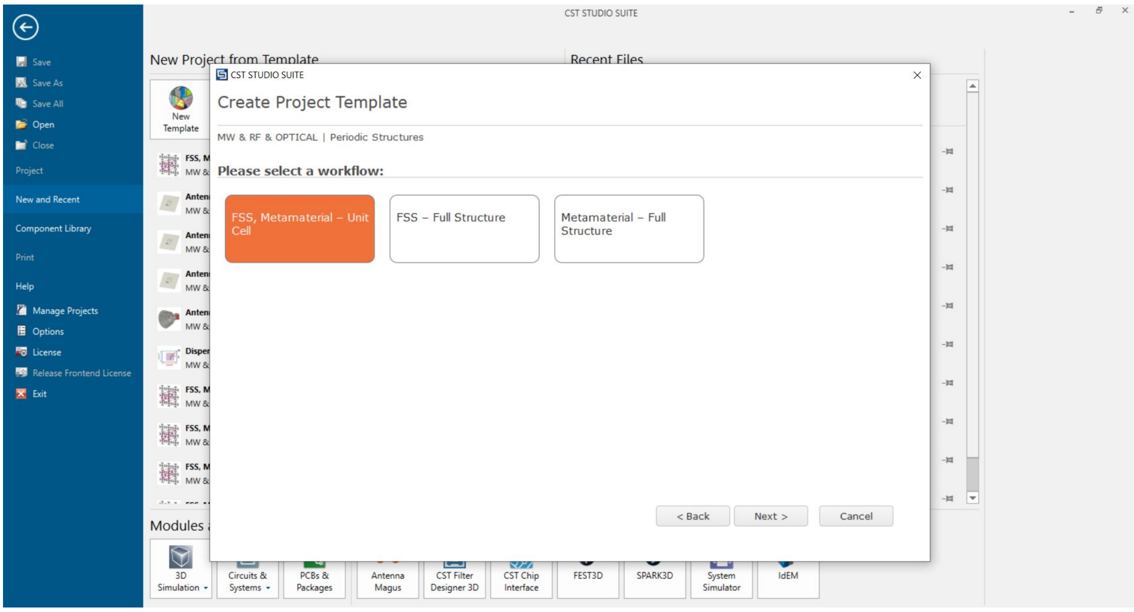

Figure 6.2: Selecting workflow for FSS design process.

After setup completion, CST environment appears, then checking the boundary in fig.6.5 and background properties in fig.6.6 are considered. By the means of these setup process we create a required condition for our design purpose.

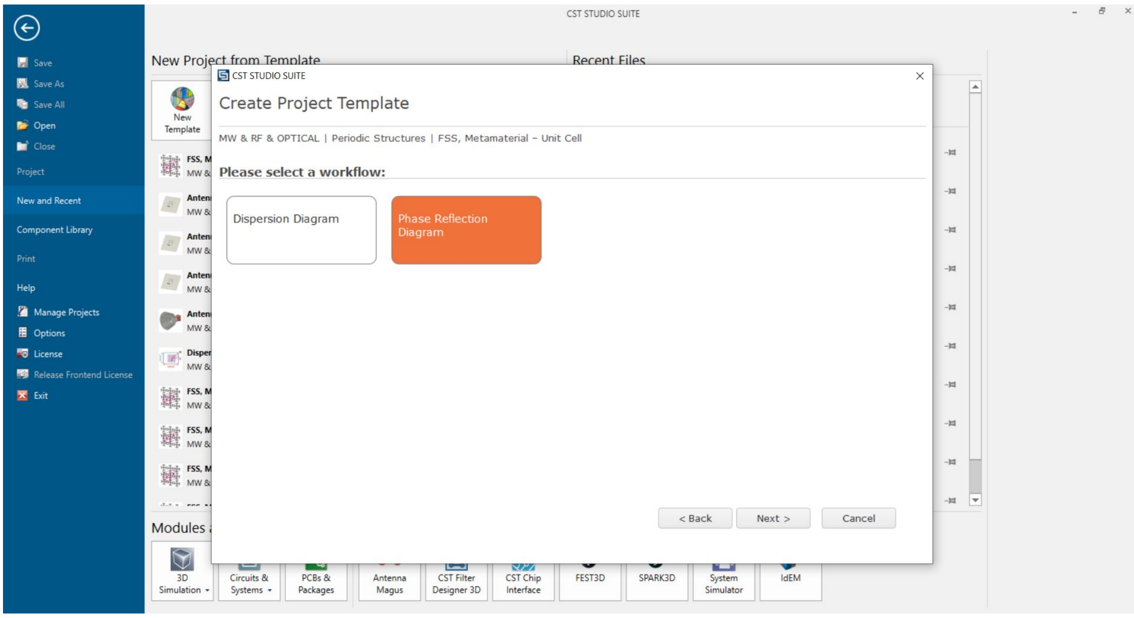

Figure 6.3: Selecting workflow for FSS design process.

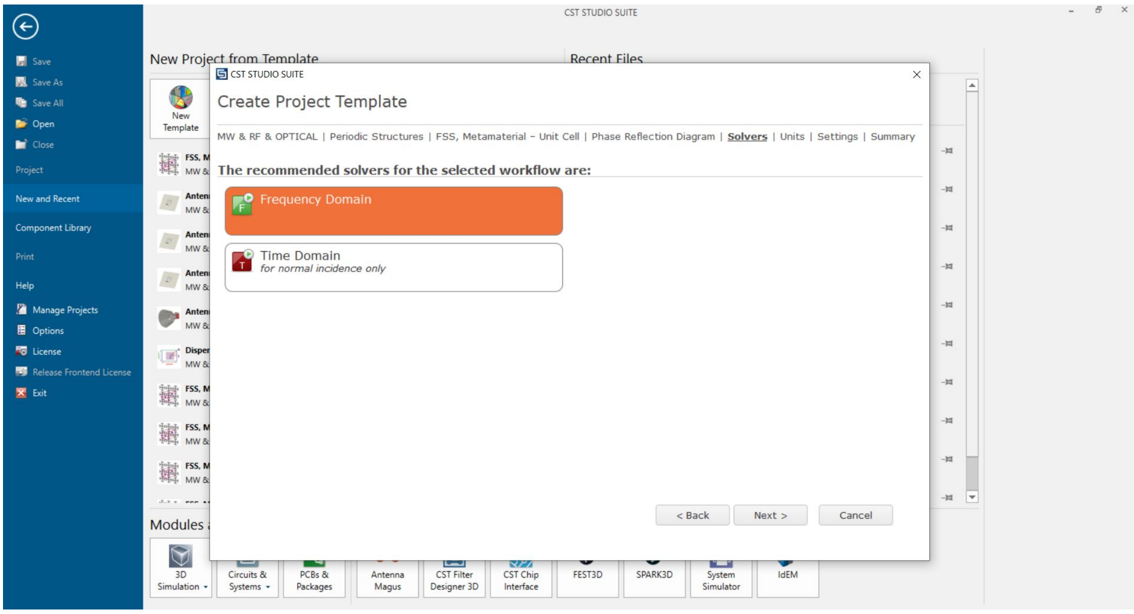

Figure 6.4: Selecting workflow for FSS design process.

The main part of FSS design is to consider *Floquet ports* fig.6.7. The reason is this type of port is essentially required to produce TEM wave. Zmin and Zmax are

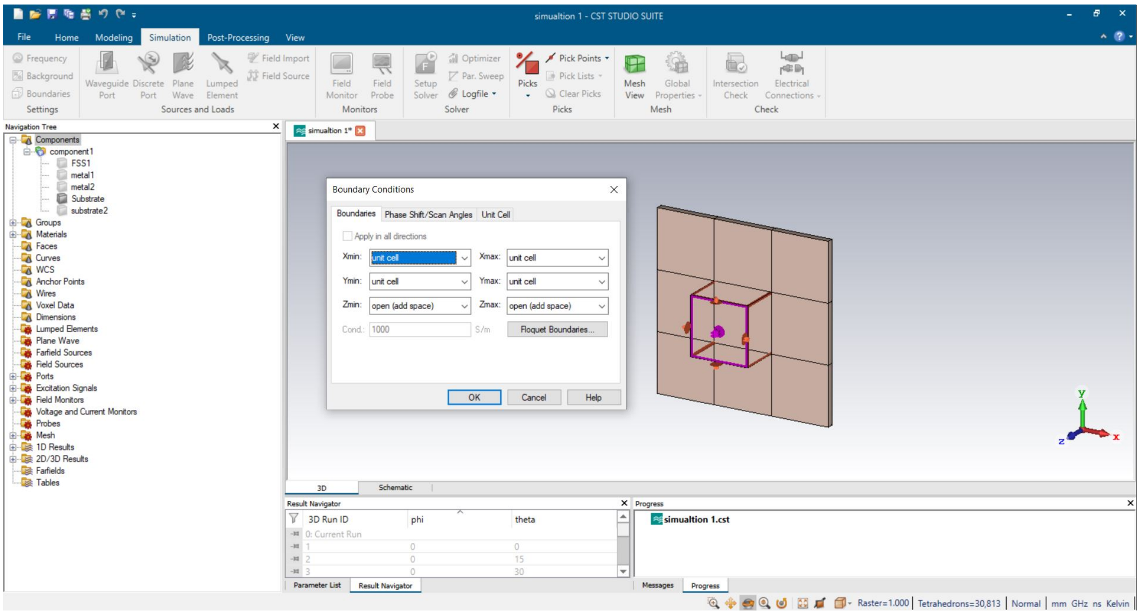

Figure 6.5: Boundary condition in FSS design proce.
ss

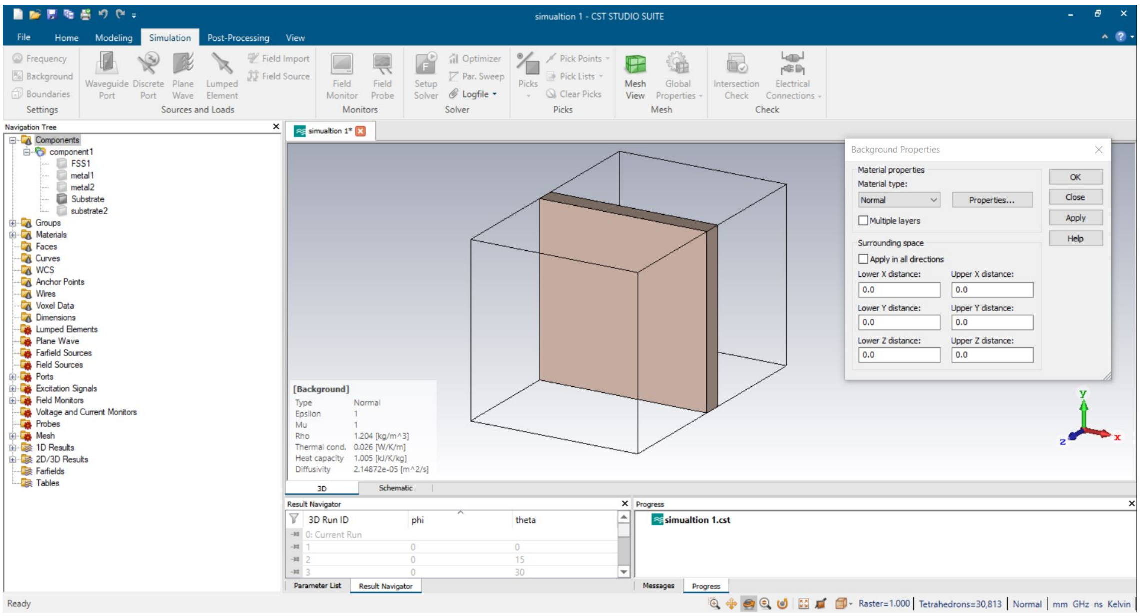

Figure 6.6: Background properties in FSS design process.

regarded as two ports which are used for the mentioned design process.
The main focus in our FSS design process is on TE and TM incidence. TE incidence

refers to *y-direction* which is responsible for Zmin(1)-Zmax(1) and TM incidence is for *x-direction* which shows Zmin(2)-Zmax(2). This step is illustrated in fig.6.8 and fig.6.9.

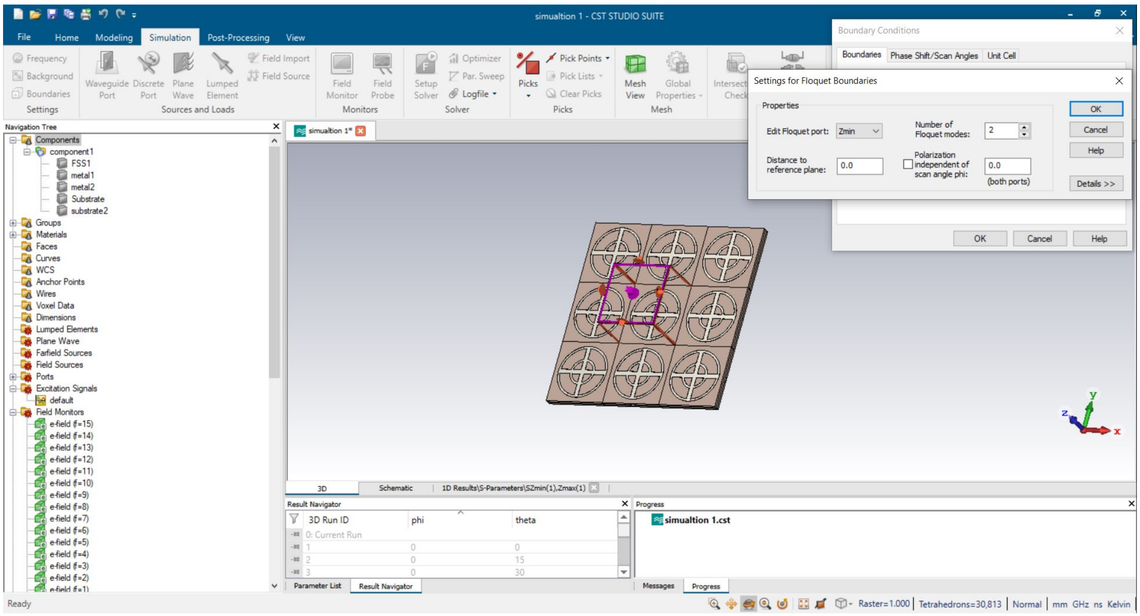

Figure 6.7: Floquet ports in FSS design process.

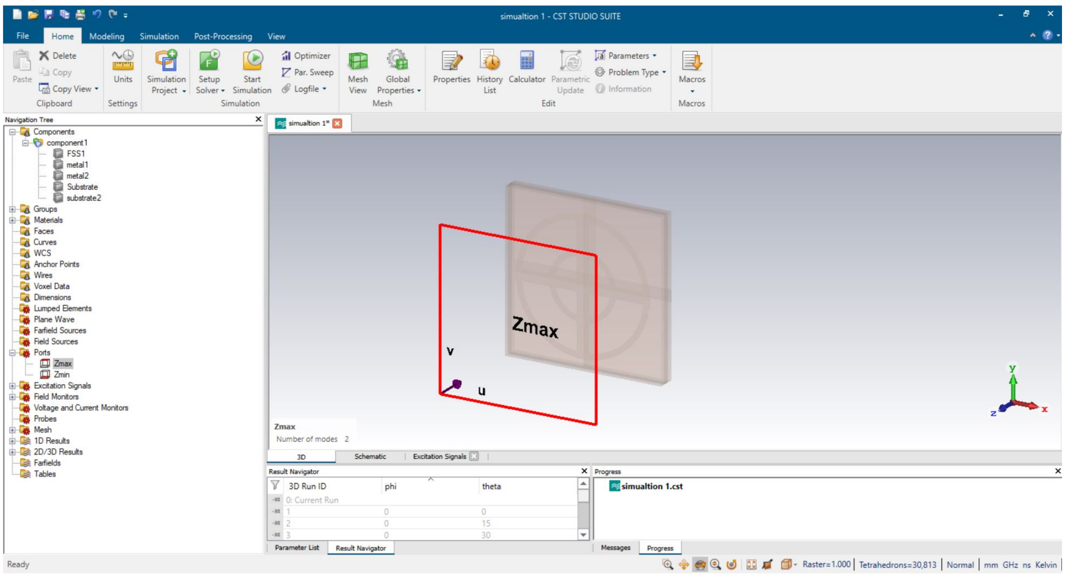

Figure 6.8: Zmin port in FSS design process.

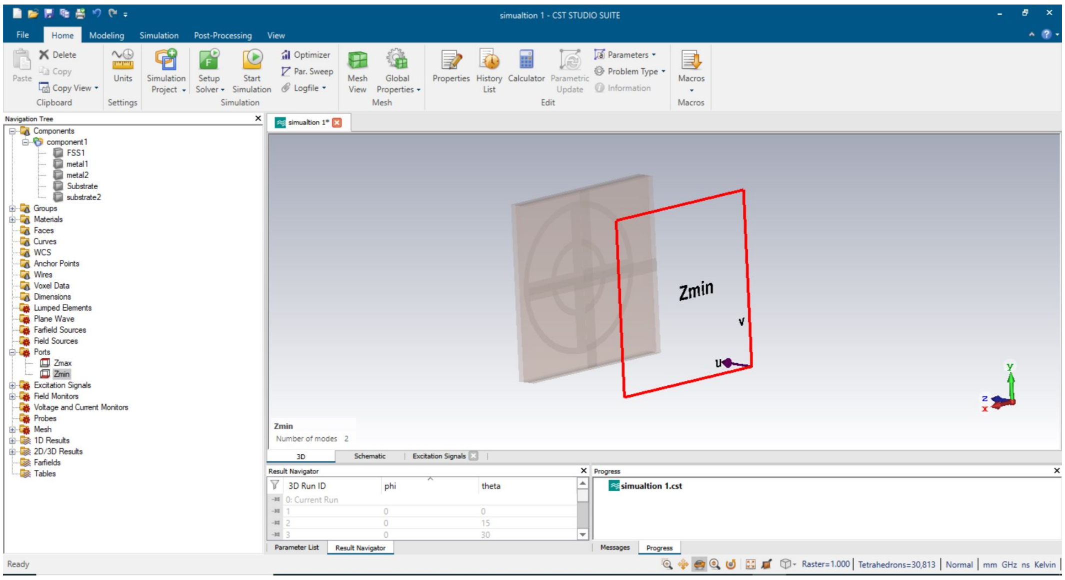

Figure 6.9: Zmax port in FSS design process.

CST Studio Suite provides a condition for FSS design that it is not needed to create an *airbox* separately also for assigning the ports just we need to follow the above setups, while in HFSS software we need to assign master boundary and slave boundary to define Zmin and Zmax ports.

Chapter 7

Publications

1. F. Mir, L. Matekovits, L. Kouhalvandi and E. O. Gunes, "Optimization for Wideband Linear Array Antenna through Bottom-Up Method," 2020 IEEE International Conference on Electrical Engineering and Photonics (EExPolytech), 2020, pp. 51-54, doi: 10.1109/EExPolytech50912.2020.9243969.

2. F. Mir, L. Kouhalvandi, L. Matekovits and E. O. Gunes, "Electromagnetic Bottom-Up Optimization for Automated Antenna Designs," 2020 IEEE Asia-Pacific Microwave Conference (APMC), 2020, pp. 792-794, doi: 10.1109/APMC47863.2020.9331411.

3. F. Mir, L. Matekovits, A. De Sabata, "Symmetry-breaking Manipulation in the Design of Multifunctional Tunable Frequency Selective Surface ", AEUE - International Journal of Electronics and Communications, 2021, Manuscript Number: AEUE-D-21-00679R1, (Passed first review, Under major review).

4. F. Mir, L. Kouhalvandi, L. Matekovits and E. O. Gunes, "Automated Optimization for Broadband Flat-Gain Antenna Designs with Artificial Neural Network", IET Microwaves, Antennas Propagation, 2021, DOI: 10.1109/LAWP.2019.2903787 (paper is accepted and in the list of publishing)

5. F. Mir, L. Kouhalvandi, L. Matekovits, "Frequency Selective Surface Design UsingAutomated Random Optimization", URSI GASS 2021, Confirmation Code : QYP5PXV7RL, 2021, (paper is accepted for the conference)

Bibliography

[1] «Frequency Selective Surfaces: Theory and Design [Book Review]». In: *IEEE Circuits and Devices Magazine* 21.1 (2005), pp. 36–36. DOI: 10.1109/MCD.2005.1388768 (cit. on p. 1).

[2] Ladislau Matekovits, Guillermo Carlos Vietti Colome, and Mario Orefice. «Controlling the Bandlimits of TE-Surface Wave Propagation Along a Modulated Microstrip-Line-Based High Impedance Surface». In: *IEEE Transactions on Antennas and Propagation* 56.8 (2008), pp. 2555–2562. DOI: 10.1109/TAP.2008.927524 (cit. on p. 1).

[3] Xiayuan Yao, Bingyuan Liang, and Ming Bai. «Quasi-optical frequency selective surface with phase compensation structure correcting the beam distortion». In: *Opt. Express* 25.19 (Sept. 2017), pp. 23014–23023. DOI: 10.1364/OE.25.023014. URL: http://www.opticsexpress.org/abstract.cfm?URI=oe-25-19-23014 (cit. on p. 2).

[4] Rana Anwar and Huansheng Ning. «Frequency Selective Surfaces: A Review». In: *Applied Sciences* 8 (Sept. 2018), p. 1689. DOI: 10.3390/app8091689 (cit. on p. 2).

[5] Ravi Panwar and Jung Ryul Lee. «Progress in frequency selective surface-based smart electromagnetic structures: A critical review». In: *Aerospace Science and Technology* 66 (2017), pp. 216–234. ISSN: 1270-9638. DOI: https://doi.org/10.1016/j.ast.2017.03.006. URL: https://www.sciencedirect.com/science/article/pii/S1270963816306952 (cit. on p. 3).

[6] Te-Kao Wu. «Frequency Selective Surfaces». In: Apr. 2005. ISBN: 9780471654506. DOI: 10.1002/0471654507.eme133 (cit. on p. 4).

[7] W.S. Park. «Design of novel thin frequency selective surface superstrates for dual-band directivity enhancement». English. In: *IET Microwaves, Antennas Propagation* 1 (1 Feb. 2007), 248–254(6). ISSN: 1751-8725. URL: https://digital-library.theiet.org/content/journals/10.1049/iet-map_20050318 (cit. on p. 6).

[8] Filippo Costa, Agostino Monorchio, and Giuliano Manara. «An Overview of Equivalent Circuit Modeling Techniques of Frequency Selective Surfaces and Metasurfaces». In: *Applied Computational Electromagnetics Society Journal* 29 (Dec. 2014) (cit. on p. 6).

[9] Aaron Stein, Phyo Aung Kyaw, and Charles Sullivan. «High-Q self-resonant structure for wireless power transfer». In: Mar. 2017, pp. 3723–3729. DOI: 10.1109/APEC.2017.7931234 (cit. on p. 6).

[10] Xingcun Colin Tong. «Metamaterials Inspired Frequency Selective Surfaces». In: *Functional Metamaterials and Metadevices*. Cham: Springer International Publishing, 2018, pp. 155–171. ISBN: 978-3-319-66044-8. DOI: 10.1007/978-3-319-66044-8_8. URL: https://doi.org/10.1007/978-3-319-66044-8_8 (cit. on p. 7).

[11] Y. Ma, W. Wu, Y. Yuan, W. Yuan, and N. Yuan. «A High-Selective Frequency Selective Surface With Hybrid Unit Cells». In: *IEEE Access* 6 (2018), pp. 75259–75267. DOI: 10.1109/ACCESS.2018.2878941 (cit. on p. 8).

[12] Ladislau Matekovits, Aldo De Sabata, and Karu P. Esselle. «Effects of a Coplanar Waveguide Biasing Network Built Into the Ground Plane on the Dispersion Characteristics of a Tunable Unit Cell With an Elliptical Patch and Multiple Vias». In: *IEEE Antennas and Wireless Propagation Letters* 10 (2011), pp. 1088–1091. DOI: 10.1109/LAWP.2011.2170653 (cit. on p. 1).

[13] A. De Sabata and L. Matekovits. «Reduced complexity biasing solution for switched parallel plate waveguide with embedded active metamaterial layer». In: *Journal of Electromagnetic Waves and Applications* 26.14-15 (2012), pp. 1828–1836. DOI: 10.1080/09205071.2012.716148. eprint: https://doi.org/10.1080/09205071.2012.716148. URL: https://doi.org/10.1080/09205071.2012.716148 (cit. on p. 1).

[14] Saptarshi Ghosh and Kumar Vaibhav Srivastava. «A Dual-Band Tunable Frequency Selective Surface With Independent Wideband Tuning». In: *IEEE Antennas and Wireless Propagation Letters* 19.10 (2020), pp. 1808–1812. DOI: 10.1109/LAWP.2020.3019584 (cit. on p. 1).

[15] L. Matekovits, M. Heimlich, and K. Esselle. «Tunable periodic microstrip structure on GaAs wafer». English. In: *Progress in Electromagnetics Research* 97 (2009), pp. 1–10. ISSN: 1070-4698 (cit. on p. 1).

[16] Weimin Ye et al. «Spin and wavelength multiplexed nonlinear metasurface holography». In: *Nature Communications* 7 (June 2016), p. 11930. DOI: 10.1038/ncomms11930 (cit. on p. 1).

[17] X. Guo, Y. Ding, and X. Ni. «Electrically Tunable Second Harmonic Generation Enhancement on a Parametrically Excited Metasurface». In: *2020 Conference on Lasers and Electro-Optics (CLEO)*. 2020, pp. 1–2 (cit. on p. 1).

[18] L. Zhang, G. Yang, Q. Wu, and J. Hua. «A Novel Active Frequency Selective Surface With Wideband Tuning Range for EMC Purpose». In: *IEEE Transactions on Magnetics* 48.11 (2012), pp. 4534–4537. DOI: 10.1109/TMAG.2012.2202099 (cit. on p. 2).

[19] Mehdi Kiani, Majid Tayarani, Ali Momeni, Hamid Rajabalipanah, and Ali Abdolali. «Self-biased tri-state power-multiplexed digital metasurface operating at microwave frequencies». In: *Opt. Express* 28.4 (Feb. 2020), pp. 5410–5422. DOI: 10.1364/OE.385524. URL: http://www.opticsexpress.org/abstract.cfm?URI=oe-28-4-5410 (cit. on p. 2).

[20] Wenting Li et al. «Polarization-Reconfigurable Circularly Polarized Planar Antenna Using Switchable Polarizer». In: *IEEE Transactions on Antennas and Propagation* 65.9 (2017), pp. 4470–4477. DOI: 10.1109/TAP.2017.2730240 (cit. on p. 2).

[21] Xi Gao, Wan Li Yang, Hui Feng Ma, Qiang Cheng, Xin Hua Yu, and Tie Jun Cui. «A Reconfigurable Broadband Polarization Converter Based on an Active Metasurface». In: *IEEE Transactions on Antennas and Propagation* 66.11 (2018), pp. 6086–6095. DOI: 10.1109/TAP.2018.2866636 (cit. on p. 2).

[22] Mehdi Kiani, Ali Momeni, Majid Tayarani, and Can Ding. «Spatial wave control using a self-biased nonlinear metasurface at microwave frequencies». In: *Opt. Express* 28.23 (Nov. 2020), pp. 35128–35142. DOI: 10.1364/OE.408622. URL: http://www.opticsexpress.org/abstract.cfm?URI=oe-28-23-35128 (cit. on p. 2).