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Frequency Selective Surface With Two Quasi-Independent Notch Frequencies

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ABSTRACT A double-layer frequency selective surface (FSS) built on FR4 substrate exhibiting two notch frequencies in the 0–10-GHz range is introduced. Recently published examples demonstrate that further research needs to be undergone for obtaining separate tuning of the resulted notch frequencies. Thus, this issue is addressed in this paper: the notch frequencies can be quasi-independently set by appropriate values given to the geometrical parameters of the two metal patterns in the unit cells of the structure. The FSS behavior is stable with respect to the angle of incidence of impinging electromagnetic waves up to 45°, as proved by simulation and validated by experiments.

INDEX TERMS Frequency selective surface (FSS), notch filter, angular stability.

I. INTRODUCTION

A plane Frequency Selective Surface (FSS) is a thin electromagnetic structure that is periodic in two independent directions [1], [2]. The transmission through the surface has band-pass nature if the metal elements of the surface are of slot type and it has a band-stop nature if the elements are dipoles. The two situations are related by the Babinet principle [2].

Initially, FSS's have found applications in antenna reflectors, radomes and (radar) absorbers [1]. Practical deployment of FSS's required a dielectric support. This added a third dimension to the structure and inspired the introduction of stacks of selective surfaces. If the dimensions of the structure along the third dimension are not large, the stack is still called an FSS. If the elements of the spatial period (called unit cell) in the third dimension are large, the term "3 D FSS" is used [2].

Selectivity featured by the transmission and reflection coefficient could be modelled by considering the FSS as a surface impedance, containing inductors and capacitors (and resistors if losses must be considered) [3]. However, these circuit elements depend on the angle of incidence and polarization of the incoming wave. Therefore, during the time, conception of FSS's with transmission characteristics insensitive to angle of incidence and polarization has become an important issue. Nowadays the topic is still challenging.

The contemporary widespread presence of wireless transmission devices fostered research in devising spatial filters for Wi-Fi, WiMax, Bluetooth, LTE, UWB, ISM-band and X-band signals [3]–[9]. Such filters are FSS's realized on printed circuit boards (PCB's) by printing and etching either one face (single layer [7]) or both faces (double layer) of the board with a periodic metal pattern. The resulting transmission coefficient of the FSS may exhibit a large stop-band [4], a pass-band [5], one stop-band [6], two stop-bands [7], [8], three stop-bands [9] or even five stop-bands [10].

Other researchers focused on implementation of (geometry) reconfigurable and tunable 2D or 3D surfaces by using devices such as MEMS, diodes and amplifiers [2], [11]–[13]. Yet another promising research field is devising FSSs that act on the polarization of the incoming wave (e.g. [14]).

However, the problem of finding FSS geometries that allow for separately setting of the resonant frequencies is less frequently addressed in the literature. Variation of geometrical parameters generally affects more than one resonant frequency, making the design process for tailoring the geometrical parameters of the structure to yield frequency

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responses according to requirements of various applications more complicated. The goal of finding a structure allowing individual control of resonant frequencies has been the main motivation for this work.

In this paper, a low-cost, double layered FSS built on an FR4 substrate is reported. One face of the PCB contains a rectangular periodic pattern of fan-shaped cross dipoles and the other face contains a pattern of rectangular rings still arranged periodically, with the same spatial period in the two orthogonal directions. The structure has been obtained by a modification of one recently proposed by the same authors in [7] and it features two notch frequencies.

It is shown in the paper that the two notch frequencies can be quasi independently controlled by the geometrical parameters of the patterns from the two faces: the dimensions of the rings mainly determine the lower frequency, while the dimensions of the cross-dipole mainly control the upper one. The separate control of the notch frequencies represents an important opportunity in design.

Secondly, it is also proved that the proposed structure features insensitivity to angle of incidence of the incoming wave up to 45°. The properties of the proposed FSS have been assessed by means of a commercial solver [15] and afterwards validated by experiments.

The rest of the manuscript is organized as follows. In Section II a comprehensive review of (recently) published papers is reported, aiming to underline the importance of the present investigation, with special attention on the control of the notch frequencies. In Section III the proposed FSS is introduced and the transmission coefficient in normal incidence and the response to incident waves at various angles are reported. In Section IV, a parametric study on the dependency of the transmission coefficient on geometrical parameters and frequency is carried over. This study is intended for providing design data for specific applications. In Section V, the experimental validation of an application-oriented design is presented for one of the parameter set previously defined. Conclusions are drawn in the last Section.

II. MOTIVATION

As a stimulus of the investigation described in the present paper, one can observe that in the literature, there are different reported solutions of multiple resonances FFS's devised for screening applications in the frequency range up to 12 GHz. However, the possibility of distinct alteration of the resonant frequencies is much less recurrent. In the following, a short, review-kind presentation follows with special focus on the recent findings on tunable FSSs, aiming to further demonstrate the necessity of investigations similar to that proposed in the present work.

A 2-notch FSS based on a rectangular periodic pattern with canonical circular loops in the unit cell has been proposed in [8]. The pattern with a period of 39.5 mm has been etched on one face of an FR4 board having a thickness of 1.5 mm. Geometrical dimensions have been chosen to provide a 2.4 GHz and a 5.2 GHz notch (or pass bands in the case of slots in place of conducting traces) and it has been proven that both frequencies were proportional to r^{-1}, where r is a radius parameter associated to the loops. Therefore, modification of the parameter affects both frequencies.

The 3-notch FSS proposed in [9] has been intended to filter frequencies in WiMAX, WLAN and X band. A solution with stop frequencies of 3.5, 5.2 and 10.2 GHz has been devised, based on periodic patterns imprinted on both sides of an FR4 board of 1.6 mm thickness. The square-shaped unit cells, of side 10 mm, contain rectangular loops. For tuning assessment, only one parametric study has been reported in function of a certain length parameter D, whose modification affected all three notch frequencies, one of which vanished for some values of the parameter.

A single layer FSS with five notch frequencies has been devised on one side of an FR4 substrate of 1.6 mm thickness [10]. The unit cell contained five square and modified square metal rings that determined the occurrence of the five notch frequencies in the range 1.5-5.5 GHz for a 27 mm side length of the unit cell. No parametric study has been reported for assessing tunability. Nevertheless, it has been shown by field simulation that more than one ring played a role in establishing the value for each of the five frequencies.

The situation in [4] is different, since the authors propose a FSS featuring a large 10 dB stop-band in the range 6.5-14 GHz. However, the stop band is based on the interaction of two notches corresponding to patterns imprinted on the two faces of an FR4 substrate of thickness 3.2 mm. The notch frequencies are introduced by a unit cell with a cross metal shape on one face (arms of the cross parallel to the sides of the square unit cell) and a circular metal loop on the other face. The side length of the unit cell has been of 12 mm. The authors have shown that decreasing the substrate thickness makes notch frequencies pull out one from another (making larger bandwidth) and explain this by increase of mutual coupling between elements on the two faces. The patterns on the two faces of the substrate impact differently the notch frequencies, the cross arms length having a larger impact on the lower frequency and the loop radius having a larger impact on the higher frequency. However, these impacts have been tested separately, i.e., by simulation with only one of the patterns being present, so that exact information for tunability with impact of geometrical parameters in the actual structure on notch frequencies is missing. A parametric study in function of the dielectric constant of the substrate has been reported, which showed that modification of this parameter affects both frequencies simultaneously.

A stack of two FSS's printed on one-sided 0.76 mm Arlon Di 880 substrate, with square unit cell having 7.7 mm side size and incurved cross dipole metallization (for miniaturization of the straight dipole) is reported in [16]. The device features two notch frequencies in the X band that can be combined to create a frequency response with a large stop-band, equivalent to an eighth-order filter. The two notch frequencies are determined by the geometrical parameters of the two layers respectively. However, the proposed device is built on two different boards with certain separation in between, which reduces the coupling between the two surfaces but complicates fabrication.

A single-sided FSS with hexagonal periodicity, maximum transmission at 9.41 GHz (X-band) and maximum reflection at 14.5 GHz (Ku band) and 35 GHz (Ka band) is proposed in [17]. The compact packing of linear dipoles allowed for miniaturization (5 mm hexagonal cell spacing) and consequently side lobe suppression. The prototype has been built on 0.508 mm thick Rogers4003C substrate. The three critical frequencies (one for a pass-band and two notches) could be controlled individually by different geometrical parameters. Actual variation intervals and sensitivities of the three frequencies to parameter variations are not reported However, these frequencies are widely separated and the higher frequencies necessitated a higher quality substrate.

The authors in [18] have proposed a 2.5 D periodic structure realized by knitting modified metal square loop elements on a 2-mm thick PTFE substrate for shielding both GSM bands (900/1800 MHz). Two meandered loops on the two faces of the substrate have been connected by vias in a 24-mm unit cell. The loops control the notch frequencies and geometrical parameters of loops and vias can be used to adjust these frequencies. However, apparently the adjustments cannot be applied individually to each frequency (exact data on this issue are not reported).

All the considered examples provided good incidence angle stability and polarization insensitivity due to 90° rotation symmetry or other features. However, the same examples, published quite recently, demonstrate that easy tunability (control of the critical frequencies) is an issue that necessitates further research. In this context, devising a structure that allows for prescribing each of the notch frequencies separately, by the appropriate choice of a geometrical or material parameter is a desirable goal.

III. PRESENTATION OF THE STRUCTURE AND ITS TRANSMISSION PROPERTIES

The proposed FSS is built on an FR4 substrate ($\varepsilon_r = 4.3$, $\tan(\delta) = 0.025$). The unit square-shaped cell consists of a metal fan-shaped cross located on one side of the board, Fig. 1 (a) and a square ring on the opposite one, Fig. 1 (b). As it will be shown in the following, two notch frequencies are present in the transmission coefficient of the FSS in the frequency range of interest, i.e., 0-10 GHz. The adjustment of the notch frequencies by variation of geometrical parameters is the main interest in this paper.

The considered structure has similarities with [4] and [7]. However, unlike [4], the cross has been rotated by 45° such that the diagonally positioned dipoles can achieve longer extension. Furthermore, the newly introduced fan shape allows for supplementary degrees of freedom by introducing new geometrical dimensions, that if appropriately varied can have a positive impact on the tunability opportunities of the device. As for the ring, the square shape has been selected for similar reasons as above, since it allows for a greater perimeter length than the circular one for the given space (footprint of the unit-cell).

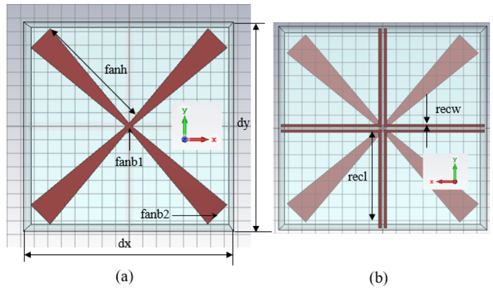

FIGURE 1. Geometry of the unit cell of the FSS and relevant geometrical dimensions (a) top side; (b) back side.

The combination fan - square ring has already been considered by the same authors in [7]. However, the symmetry center of the fan was positioned above the symmetry center of the square ring in that work. Unlike this disposition, in the present solution the ring has been displaced by one half of the spatial period in both x and y directions with respect of the reference frame depicted in Fig. 1. It will be shown that this displacement improves the (quasi)independent adjustment of the two notch frequencies. Furthermore, in this paper, an experimental validation of the operation of the proposed structure is reported.

Each of the patterns on the two faces of the unit cell can be represented individually in a quasi-static analysis by a surface impedance consisting of periodic arrangements of simple LC circuit with resonant frequency $f = \frac{1}{2\pi\sqrt{LC}}$ (resistors can be added to account for losses) [1-3]. The circuit parameters depend on the geometry and materials entering in the composition of the FSS. When the two patterns are cascaded like in the proposed solution, the LC circuits on the two faces of the printed circuit board become coupled in general, which can be modeled either by a mutual inductance or a mutual capacitance or both. Coupling modifies the resonance frequencies of the two circuits and modification of parameters of one circuit impacts the resonant frequency of both. In the proposed design, the coupling between the resonant circuits is very weak, so that each one acts (almost) independently.

The small values of the coupling elements are due to the proper arrangement, as follows: a small common area of the metal patterns of the two faces of the PCB, obtained by using different resonant elements (dipoles versus loops), that in this case have electrical and magnetic moments that are (reciprocally) orthogonal, reduce the near-field coupling by capacitive effect. This latter is further enhanced by the displacement of the centers of the loops with respect to the centers of the dipoles, giving rise to a structure, where a zero electric current corresponds to the maximum moment of the magnetic dipole, and vice-versa. Currents in the dipoles induce linked magnetic flux of opposite directions in different regions of the loops, making a small mutual inductance in this way (and vice-versa by the reciprocity theorem [19]).

Another feature provided by the low coupling between the cascaded patterns is the insensivity to angle of incidence inherited by the cascaded structure from same property exhibited by the dipole and loop patterns (see e.g. [1]).

The relevant dimensions that define the geometry of the unit cell are shown in Fig. 1 (a) and (b). The fan wings have the shape of a trapeze with bases fanb1 and fanb2 and height fanh. The composition of four such elements leaves room for a small square, of edge fanb1 that must be added at the center of the top side of the unit cell, Fig. 1 (a), aiming to guaranty the flow of the surface currents along the arms. The two squares on the back side are defined by the half length of the edges ringl and the width of the trace ringw. Note that the traces in Fig. 1 (b) extend up to the boundary of the unit cell in order to form the squares with the traces on the adjacent unit cells.

A common design goal for a FSS intended for filtering applications is to achieve as small as possible notch frequencies for a given dimension of the unit cell. This generally requires providing long metal traces with small width. In view of this goal, we have chosen the following initial dimensions for the elements of the structure: dx = dy = 15 mm, fanh = 9 mm, fanb1 = 0.3 mm, fanb2 = 2 mm, recl = 7.2 mm, recw = 0.2 mm. The device has been built on an FR4 substrate of thickness st = 3.2 mm.

The FSS has been firstly tested under normal incidence of a plane electromagnetic wave incoming from the positive z axis (i.e. normally incident on the top side of the unit cell, Fig. 1 (a)). The magnitude of the transmission coefficient is reported in Fig. 2. Due to the symmetry of the unit cell, the azimuthal dependence of the transmission coefficient can be neglected in normal incidence. The results have been obtained by means of a commercial EM solver [15].

The markers labelled as 1 and 2 in Fig. 2 indicate the notch frequencies. The rest of the markers indicate the boundaries of the -10 dB bandwidths, which are considered relevant for spatial filtering applications [4]. The lower relative bandwidth is 46.56% and the higher one is 38.90%.

The modification of the angle of incidence (co-latitude) can have a great impact on the transmission coefficient. A properly designed FSS must present a reduced sensitivity of the transmission coefficient with respect to this angle. In the present case, the transmission coefficient versus frequency, for various incidence angles, up to 45° is reported in Fig. 3 for TE waves. The variation of the lower notch frequency with respect to the normal incidence case is of 3.20%, while the similar figure for the upper notch frequency is 1.09%. For the TM case (not reported), values of 7.81% and 0% (i.e. not measurable), respectively have been obtained. It can be concluded that the proposed FSS met its goal from this point of view.

In the next section, a parametric study is reported aiming to assess the design capabilities provided by the proposed structure.

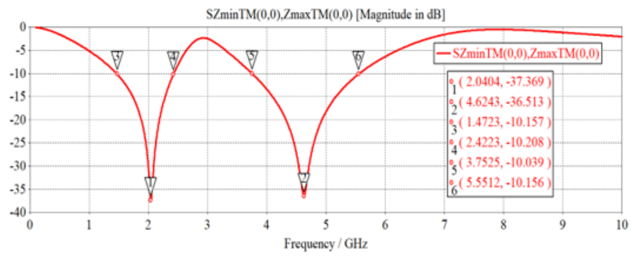

FIGURE 2. Transmission coefficient in normal incidence of a plane wave.

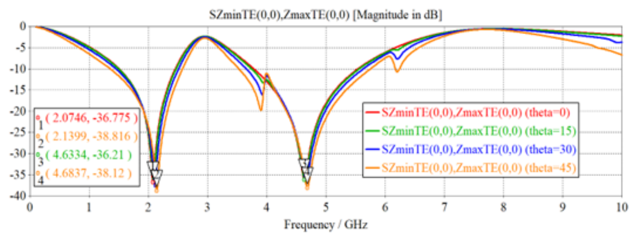

FIGURE 3. Transmission coefficient at various co-latitudes theta.

IV. PARAMETRIC ASSESSMENT

The conception of a FSS must allow designs that meet the requirements raised by various applications. The electrical parameters, such as the notch frequencies and the bandwidths can be set by selecting appropriate values for the geometrical parameters. Some important goals are to provide large ranges of variations of the electrical parameters and the possibility to tune the notch frequencies separately. Since geometrical modifications alter the electrical parameters globally, the last goal can be only approximately met in general.

The effect of the length of the edge of the rectangle recl on the transmission coefficient is reported in Fig. 4 (the incidence is normal and the incident electric field is parallel to one of the edges of the unit cell). For a relative variation of this parameter of 8.70% (with respect to the center value of the variation interval), the lower notch frequency varies by 46.48%, while the upper one varies only by 2.97%.

A similar behavior is observed when the width of the square ring trace is varied (keeping the spacing of 0.2 mm between adjacent rings constant). For a variation of recw from 0.2 to 1.0 mm (i.e. 133.33% with respect to the center of the interval), the lower notch frequency varies by 17.59% (the center frequency being 2.28 GHz), while the upper one varies by 2.82% (the center frequency being 4.57 GHz). The graphical representation of the transmission coefficient in this case resembles the one in Fig. 4 and is omitted for the sake of brevity.

Going now to the impact of varying the dimensions of the fan, the transmission coefficient in normal incidence parameterized by fanh is reported in Fig. 5. At a parameter variation of 57.14%, the upper notch frequency varies by 41.68%, while the lower one varies by only 1.91%.

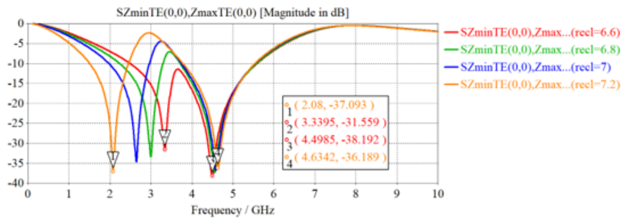

FIGURE 4. Transmission coefficient versus frequency for various values of the geometrical parameter recl.

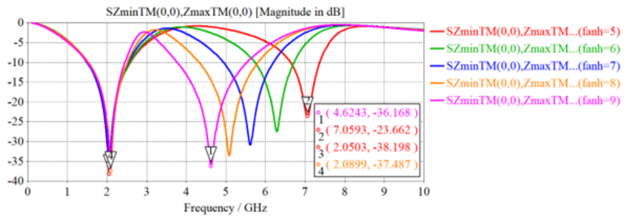

FIGURE 5. Magnitude of transmission coefficient versus frequency, in normal incidence, parameterized by fanh.

Similar simulations have been carried over by varying the parameters fanb1 and fanb2 defined in Fig. 1. The small base of the trapeze fanb1 has been given a variation of 160%, from 0.1 to 0.9 mm. The upper notch frequency varied by 9.13% around 4.68 GHz, while the variation of the lower one has been too small to be measured with precision. For assessing the impact of varying fanb2 on a sufficiently large interval, we reduced fanh to 0.7 mm. Then fanb2 has been varied from 0.3 to 4.3 mm (173.91% with respect to the center of the interval). The upper notch frequency varied by 15.38% around 5.78 GHz, while the variation of the lower one has been again too small to be measured. In both cases, the graphical representations of the parameterized transmission coefficient are similar to the one in Fig. 5 and have been omitted.

It is worth mentioning that the two notch bands can be merged into a wideband -10 dB band stop by a suitable choice of the geometrical parameters, like in [7].

In the case of the structure proposed here, it turned out that the square ring has a dominant effect on the lower notch frequency, while the fan-shaped structure controls the higher one. The weak interaction between the patterns on the two faces of the FSS might be motivated by the complementary shapes (dipoles versus loops) and by the small region where the metal patterns have common areas. Also, the displacement of the rings by half a period with respect to the structure in [7] in both x and y directions enhanced the isolation between the two faces.

V. EXPERIMENTAL VALIDATION

In this Section, the experiments performed in order to confirm the results obtained by simulation and reported in the preceding Sections are presented.

A low-cost prototype on an FR4 substrate, of dimension 45×45 cm^2, containing 30 unit cells on each of the two orthogonal directions has been built. The dimensions of the metallic elements on the surface of the substrate were those listed in Section II, so that the predicted magnitude of the transmission coefficient had to be the one represented in Fig. 2.

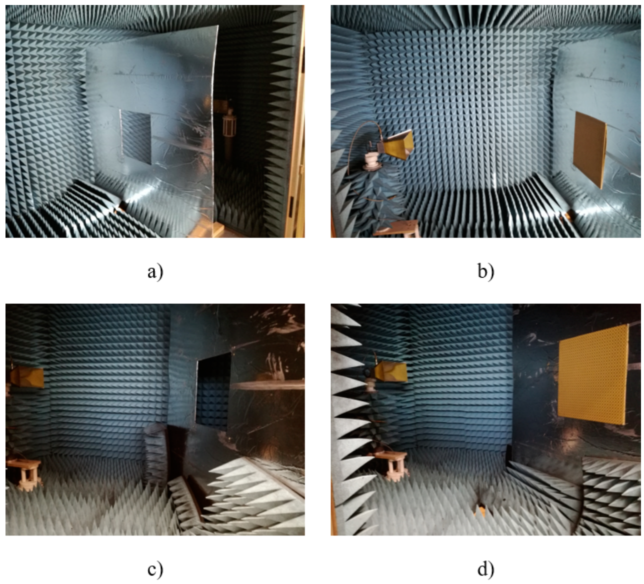

FIGURE 6. Experimental set-up. (a) Anechoic room with the tinfoil covered plywood, the place for the sample and the receiving antenna. (b) Experimental setup with the PCB: testing at 0 incidence. (c) Experimental setup without the PCB: testing at 30° incidence. (d) Experimental setup with the PCB: testing at 45° incidence.

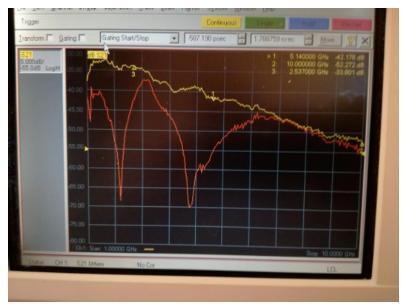

FIGURE 7. Traces on the VNA for the normal incidence case with (red) and without (yellow) the FSS surface.

The transmission coefficient has been measured with an Agilent E8361 vector network analyzer (VNA) and two horn antennas in an anechoic room. The transmitting and receiving antennas have been separated by a tinfoil covered plywood having an empty window for inserting the sample (for the different configurations see photos in Fig. 6). Then, the sample has been inserted and the transmission coefficient has been measured again. The transmission coefficient in dB of the device resulted by taking the difference between the two measurements.The two traces for the normal incidence case are reported in Fig. 7, as it has been observed on the screen of the VNA.

Measurements have been firstly made in normal incidence. The result is represented in Fig. 8 (a), together with the

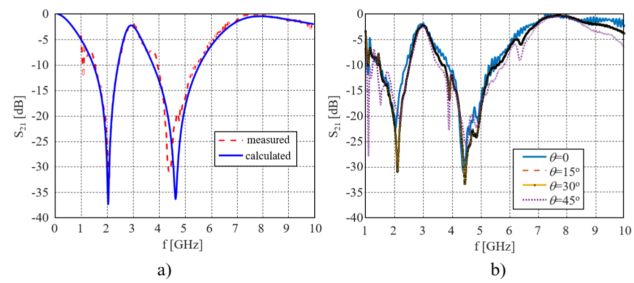

FIGURE 8. Experimental results. (a) Magnitude of the transmission coefficient: calculated (red) and measured (blue). (b) Measured transmission coefficient for various incidence angles.

simulation result (reproduced from Fig. 2). Then, measurements have been made with the sample and screening board rotated by 15°, 30° and 45°. The results are compared in Fig. 8 (b) to those obtained in normal incidence case.

Both Figs. 8 (a) and (b) indicate that the predictions made by relying on simulation results were correct. Measurements are affected by speckle caused by radiation of currents reaching discontinuities at the edges of the PCB and by non-uniformities in the FR4 material which impact results at smaller wavelengths, as expected and visible in the high frequency part of Figs. 8 (a) and (b). Nevertheless, results reported in Fig. 8 (a) indicate a coincidence between predicted and acquired notch frequencies and bandwidths and results presented in Fig. 8 (b) confirm insensitivity of the response of the device to the angle of incidence of the incoming wave up to at least 45°.

VI. CONCLUSION

A double layer FSS, built on FR4 substrate, consisting of a fan-shaped cross dipole on one face and a square ring on the other face has been proposed. The transmission coefficient has been demonstrated to possess two notch frequencies that could be quasi-independently set by geometric design. The proposed FSS has been devised with the main goal to allow quasi-independent control of the notch frequencies by means of geometrical parameters of the structure, and to present variation intervals and sensitivities for each notch. This topic has found great interest in the literature of the past years, however the bibliographic study undergone shows that achieving a separate tunability of each notch frequency is not an easy task. In most of the recent papers, the results obtained show simultaneously modification of all notch frequencies, not an independent control and if a quasi-independent control was indeed obtained, parametric variation intervals on how these can be tuned were not reported. The low frequency notch is mainly determined by the ring, while the higher notch frequency is mainly determined by the cross-dipole. This behavior is explained by the small coupling of the equivalent selective circuits that model the two faces of the PCB as surface impedances. The transmission coefficient of the proposed FSS has been proved to have a very good independency with respect to the angle of incidence of the incoming wave up to 45°. The results obtained by simulation with an EM solver have been confirmed by experiment in an anechoic room.

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