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RESEARCH PAPER

Room shielding with frequency-selective surfaces for electromagnetic health application

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Use of frequency-selective surfaces (FSSs) is proposed to shield rooms against electromagnetic fields in order to achieve secure indoor communications and reduce human exposure to external fields. The secure room is designed using two-layer FSSs with an FR4 substrate to cover 10–12 GHz frequency band. Different elements in each layer and shift in the position of elements are the reasons for more than 3 GHz bandwidths in X band. The performance of the structure is also stable versus the misaligned position of layers. An equivalent circuit model is proposed for the structure and results show −20 dB isolation between inside and outside of the room in the desired frequency band. Bio tissue is located inside the cubic structure with FSS walls and the results of the specific absorption rate are demonstrated and compared in two rooms with FSS cover on concrete walls and a room with concrete walls. The 17 × 17 cm² two-layer FSS is fabricated for the measurement and the results are presented. The designed FSS can be used in the construction of wave-isolated room for any application.

Keywords: Secure communication, Electromagnetic hygiene, Frequency-selective surfaces

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I. INTRODUCTION

Frequency-selective surfaces (FSSs) as spatial filters have many applications these days. Thus, they are used in secure communication. Leakage of any important information is avoided by installing these surfaces inside departments. Wireless communications are not secure, since signals are available outside the departments. In fact, FSS filters the working frequency band and the waves cannot pass the walls; therefore, information remains secure. Data transmission is avoided in the desired frequency band; however, other communication systems such as Wi-Fi and cellphones could work properly.

Our new, proposed application is electromagnetic (EM) health. Specific absorption rate (SAR) limits in the body should remain <1.6 W/kg in 1 g of tissue to guarantee health [1]. Consider an apartment near high-power sources, which radiates more than standard limits. These surfaces would not let the wave enter the department and make negative effects. Bandwidths (BWs), coupling of surfaces, limitation in dimensions, and connection joints should be noticed in the design process for designing operative FSS [2].

Researchers are interested in these applications, since two main topics (i.e. security and health) are covered. Some studies have introduced the diffraction issues associated with FSS for secure building applications [3]. Other works tend to design practical surfaces; for example, reconfigurable FSS is designed to stop the transmission of GSM network protocol [4]. In this research, the second idea is considered and designing wide-band FSS with sharp transition is required in this application to cover the whole BWs. The proposed FSS is shown below: a room with internal transmission band of 10–12 GHz is considered and data transmission is studied. High-power source is also considered and biologic effects are studied by comparing SAR results. In the next steps, design, geometry, results, and measurements are expressed.

II. DESIGN AND GEOMETRY

To design FSSs, we need to focus on increasing the mechanical strength of structure against disruption as well as frequency stability versus angle of incident and variation in EM characteristic. Substrates with appropriate permittivity and thickness increase both mechanical strength and stability; therefore, we use the substrate on two sides of elements [5].

Besides, wave could propagate in both polarizations, the structure must be dual polarized. Therefore, four leg, Jerusalem cross, ring, and square loop structures are the candidates. But, other criteria such as stability of resonant frequency with angle of incident, low cross-polarization, and large band with separation are essential for implementing the shield. Four leg structures are used, since they have the best stability, BW, and band separation and their

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cross-polarization is more than that of the square loop structure, but low enough. On the other hand, four leg structure unit cells are smaller than others and the dimensions are controllable by more parameters as shown in Fig. 1 [5–8]. They have wide BWs, which are not wide enough to cover 10–12 GHz. These frequencies are chosen, since in our application, the high-power source radiates 10–12 GHz signal. Thus, multi-element FSSs are tested and the BW is increased; but, it is not enough to cover the whole BW. Finally, multi-layer FSSs are chosen to increase BW and the substrates are used to increase mechanical strength and stability [5, 6]. Other methods are combined with the multi-layer method to cover 2 GHz in X band with the minimum number of layers. FR4 with the thickness of 1 mm is selected as a substrate to design the structure. EM characteristic of FR4 is considered 4.6 relative permittivity and 0.025 conductivity.

Periodic structure is considered to design the FSS [5, 7–9]. Two layers are needed to cover the 10–12 GHz bands. Each layer resonates at different frequencies: the first resonance frequency is 10.12 GHz and the second one is 11.4 GHz. These frequencies are chosen for minimum transmission and maximum BW; in addition, positon of the layers is selected as follows to minimize misalignment impacts. The impact of misalignment on resonant frequencies is studied in the results section. Frequencies with more than 20 dB attenuation are considered BW in this paper [3, 4]. According to this definition, BW of our proposed structure is more than 3 GHz. Geometries of the first and second layers are illustrated in Fig. 1.

Horizontal position of the layers is shifted to minimize coupling. The final structure, including both FSS layers and substrates is shown in Fig. 2. As can be observed, the thickness of the structure is 3 mm. In the literature, multi-layer structures are used to increase BW, in which most layers are the same and aligned well to achieve the desire BW. This method increased BW, but not to the expected amount [10, 11]. Therefore, we select elements with different dimensions and shift the layers in the horizontal axis to reduce the sensitivity of performance versus manufacturing misalignments. Both layers are combined with the Jerusalem type to adjust the resonance frequency by varying the dimensions of adjacent elements and consequently mutual capacitance. Distinct elements and shifted surfaces are null in the S_{11} parameter. This nullity helps design sharper transition in the specification of filter. Not only is made sharper transition, but also BW is improved and more than 3 GHz BW is achieved in the X band.

The value in Fig. 1 is attained by both first approximation and optimization. The approximated values of parameters such as a_1, d_1, a_2, d_2, and h are considered due to essential resonant frequency, then optimized by genetic algorithm (GA). Increase of a_1, d_1, a_2, and d_2 decreases both resonant frequencies. Decreasing h parameters increases the frequency distance between two resonant frequencies and reduces the flatness of frequency response. On the other hand, any misalignment between center of the first and second layers (SH) reduces the frequency distance between two resonant frequencies, which is minimized in our design and studied in the Results section. After the approximation of the values, dimensions are optimized to cause wide BWs, sharp transition response, and flatness of stop band. The goal of optimization is to maximize $(\Delta f/(x_1 + x_2))$ in frequency response. Δf, x_1, and x_2 are shown in Fig. 2(b) for a common bandstop filter.

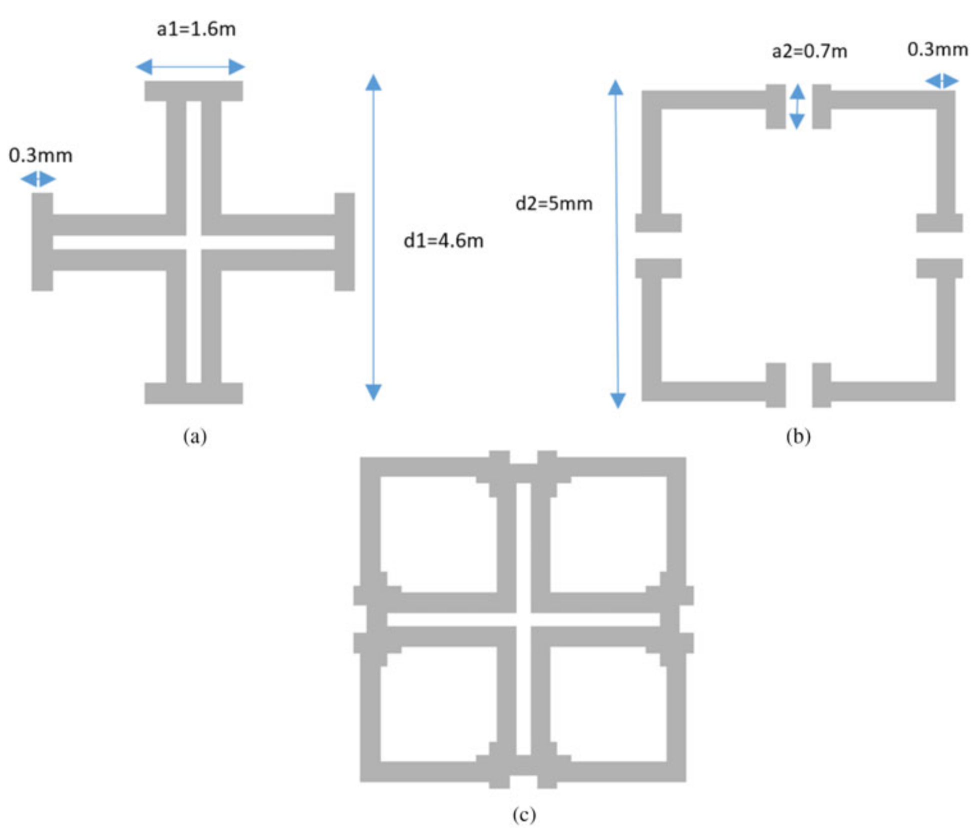

Fig. 1. Design geometries in (a) first layer, (b) second layer, and (c) both layers.

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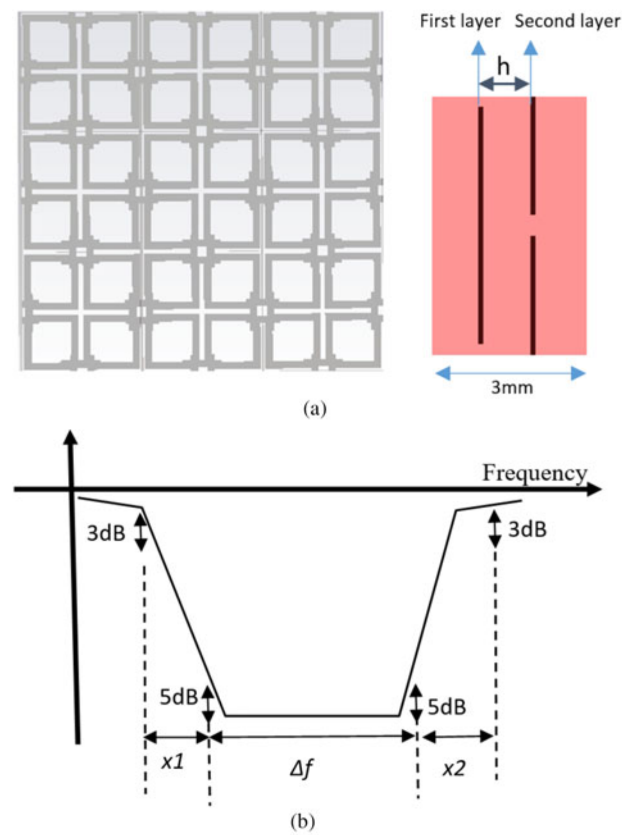

Fig. 2. (a) Geometry of periodic structure from the front and side views. (b) Bandstop filter response.

Equivalent circuit is a common method to analyze FSSs [6, 10]. Therefore, equivalent circuit of the design is proposed in Fig. 3, which explains shielding effectiveness (SE) as follows. Mutual coupling add extra-capacitive and -inductive elements and explain the extra null in frequency response and shifts at resonant frequency. This circuit is concluded from the results. SE of the structure shows resonant frequencies, null frequency, low- , and high-frequency responses. Thus, the circuit model is proposed by considering series and parallel branches to follow the mentioned frequencies. Frequency response of the circuit is compared in the results section and a good agreement is found with full-wave analysis. This circuit is important in designing multi-layer FSSs by circuit models or cable models. Equivalent model of different structures is used to design a new structure. The circuit is designed by following resonant frequencies, null frequency, low-, and high-frequency responses of the structure. Each element of the model is explained in Table 1. This model is proposed for researchers who want to use this structure in their multi-layer designs.

Initial values of the model are determined by considering each branch as an independent circuit with the same resonant frequency as respective resonant frequency in SE diagram. The values are determined by GA algorithm for the minimum least square of difference between frequency response of full-wave and circuit model analysis. Briefly 1000 points of SE diagram are considered as references and the same 1000 points in frequency respond of the circuit model are matched to the mentioned points by minimizing *G-function*. *G-function* is started at 0.12, reached to 0.044 after 400 iterations and converged to 0.031 at 2000th iteration.

G-function is defined by (f_i means ith frequency point):

$$G - function = \frac{\sum_{i=1}^{1000} (Full\ wave_{frequency.respond}(f_i) - Circuit_{frequency.respond}(f_i))^2}{\sum_{i=1}^{1000} (Full\ wave_{frequency.respond}(f_i))^2}. \quad (1)$$

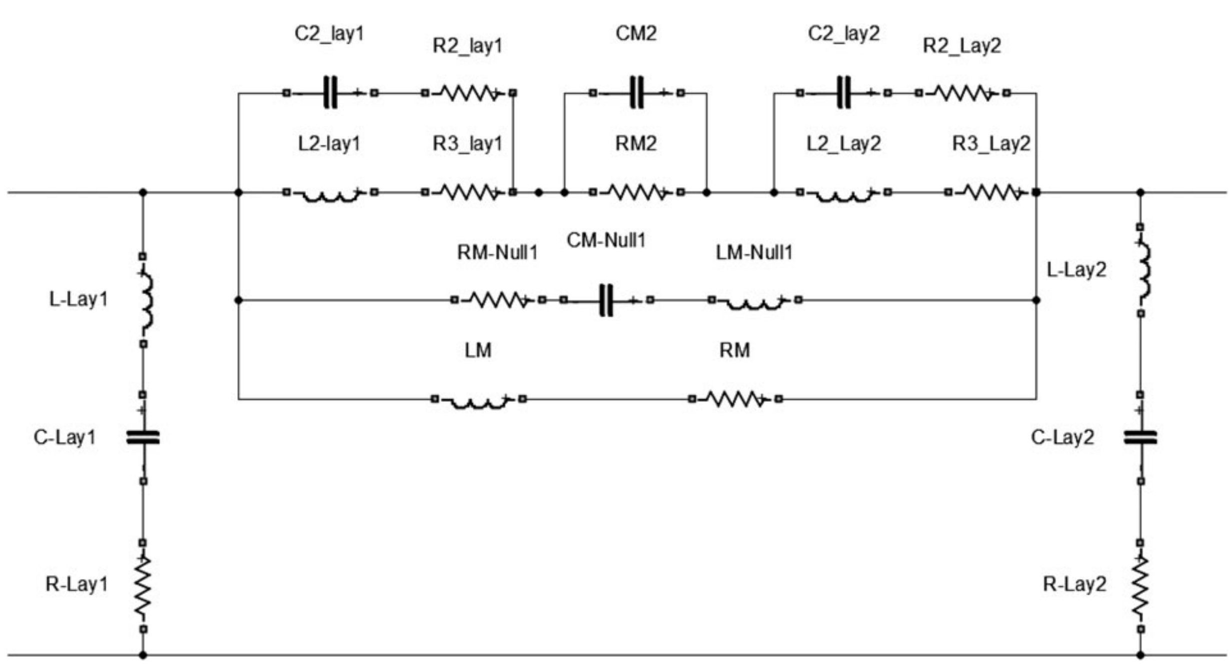

Fig. 3. Equivalent circuit of the design.

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Table 1. Elements of the circuit model.

Element	Explanation	Unit	Value
L_Lay1	Inductance in parallel resonator of the first layer	nH	18.4
C_Lay1	Capacitance in parallel resonator of the first layer	fF	12.5
R-Lay1	Resistance in parallel resonator of the first layer	Ω	55
L2-lay1	Inductance in series resonator of the first layer	nH	1.9
C2_Lay1	Capacitance in series resonator of the first layer	fF	138.8
R2_Lay1	Resistance of capacitance in series resonator of the first layer	Ω	1.8
R3_Lay1	Resistance of inductance in series resonator of the first layer	Ω	1.73
L_Lay2	Inductance in parallel resonator of the second layer	nH	7.6
C_Lay2	Capacitance in parallel resonator of the second layer	fF	25
R-Lay2	Resistance in parallel resonator of the second layer	Ω	15
L2-lay2	Inductance in series resonator of the second layer	nH	0.394
C2_Lay2	Capacitance in series resonator of the second layer	fF	500
R2_Lay2	Resistance of capacitance in series resonator of the second layer	Ω	1.1
R3_Lay2	Resistance of inductance in series resonator of the second layer	Ω	1.1
CM2	Mutual capacitance	fF	25
RM2	Resistance of mutual capacitance	Ω	1200
LM	Mutual inductance	nH	37.8
RM	Resistance of mutual inductance	Ω	1
LM-Null1	Inductance related to null frequency	nH	150
CM-Null1	Capacitance related to null frequency	fF	2
RM-Null1	Resistance related to null frequency	Ω	100

III. EM-HEALTH APPLICATION AND SIMULATION

To achieve an isolated room versus EM exposure, it is necessary to cover a room completely by the designed FSS. The proposed structure is usable for wall, ceiling, and floor. Since the substrates are considered thick enough, the structure is stable with frequency inside or on the wall. Simulations show that, if the structure is applied between two layers of concrete with the thickness of 10 cm, then the shift at frequency resonance is <1.1% which is stable. SE of the structure inside and on the 20 cm concrete wall is shown in the Results section in Fig. 5. The only possible issue is covering glass, in the case of rooms with windows; however, transparent structures with the same design for glass could be attached on the glasses and solve the problem. Transparent FSSs are introduced in the literature and many methods such as printing and sketching could be used on transparent substrates

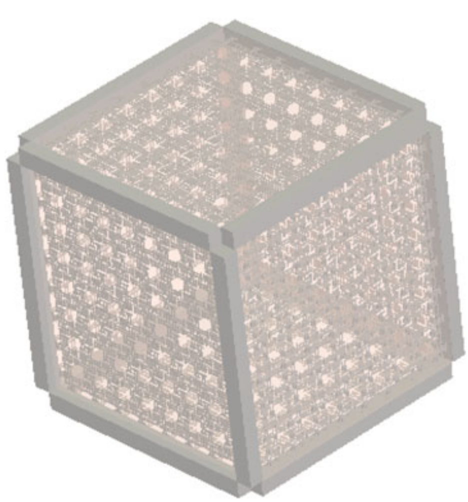

Fig. 4. Cubic FSS structure as the equivalent model of a room.

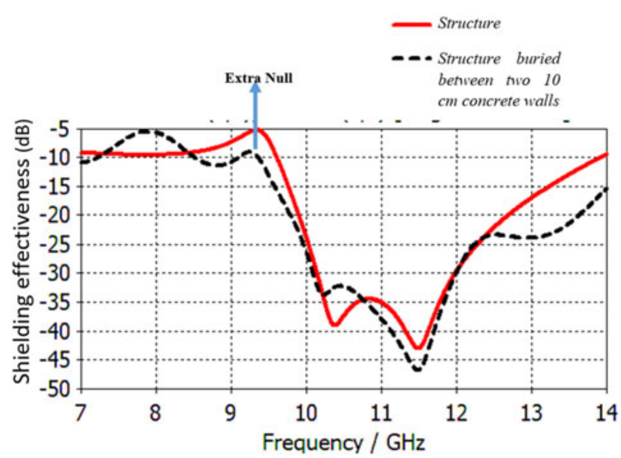

Fig. 5. SE of periodic FSS for both TE and TM polarizations.

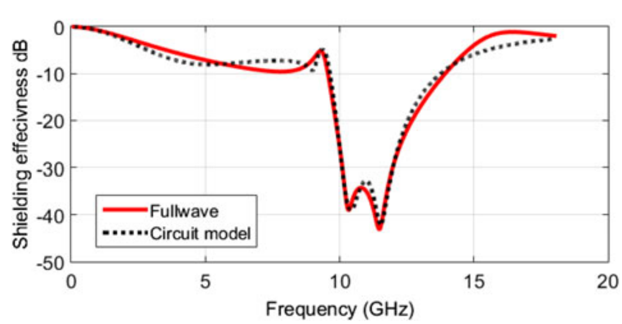

Fig. 6. Frequency response of the proposed circuit model and full-wave analysis.

[12, 13]. Although dimensions of our design can be optimized for transparent substrates for glass, we focus on the presented design below.

The best scenario for studying this idea is considering a real dimension room in $4 \times 5 \times 3\ m^3$ with concrete walls and

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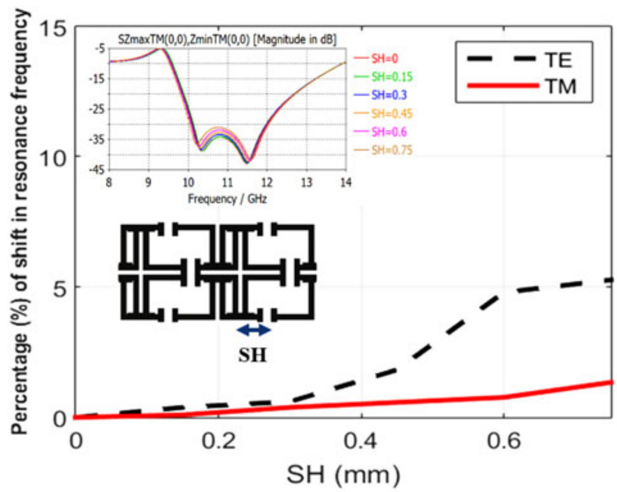

Fig. 7. Percentage of shifts at resonant frequencies versus misaignment.

cover it with the proposed FSS, place a human voxel inside the room, illuminate EM wave to room with and without FSS cover, and simulate the whole scenario. Comparison of the results shows the impact of cover on EM hygiene.

Since FSSs are resonant structures, high meshes are needed to simulate the structures. For example, the mentioned structure needs 140 TB RAM for simulation, which is not applicable. Therefore, we propose to consider a small box with 3 cm thickness concrete walls in order to study the impact of FSS cover. Six faces are used as walls, roof, and ceiling in a cubic structure. Dimensions of the cubic structure are 12 × 12 × 12 cm^3 and its geometries are illustrated in Fig. 4. Rooms are cubic and EM waves incident to each wall in different angles. This geometry helps to investigate the effect of cubic shape of covered box on shielding.

Since the considered box is not big enough to cover the whole body, an organ of body is considered to investigate SAR reduction inside the tissue. A finger is small enough to fit inside the proposed box and it contains skin, fat, muscle, and bone tissues. Therefore, an equivalent voxel of a finger inside a box is considered in two scenarios. In the first scenario, FSS cover is not applied on the concrete walls of the box; but, in the second scenario, FSS cover is attached to the concrete walls of the box. Plane wave incident to both boxes and SAR inside the tissue is computed for both scenarios and compared in the Results section. SAR is a standard for showing the absorbed power inside human tissue and comparison of both cases illustrates the reduction of absorbed power inside the tissue.

IV. RESULTS

Performance of the design in two cases of original structure and structure inside the 20 cm concrete wall is illustrated by the SE of FSS in Fig. 5. Diagrams in Fig. 5 show two resonant

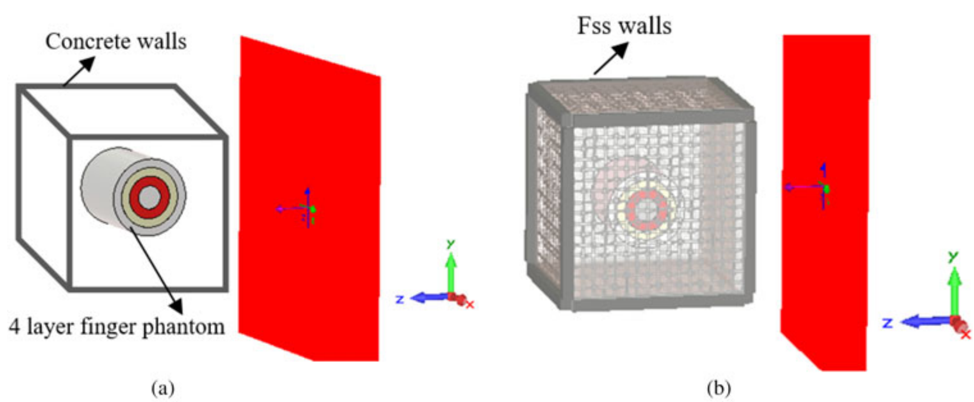

Fig. 8. Plane wave radiation to biologic tissue. (a) A room with 3 cm concrete walls. (b) Inside room with FSS cover on 3 cm concrete walls.

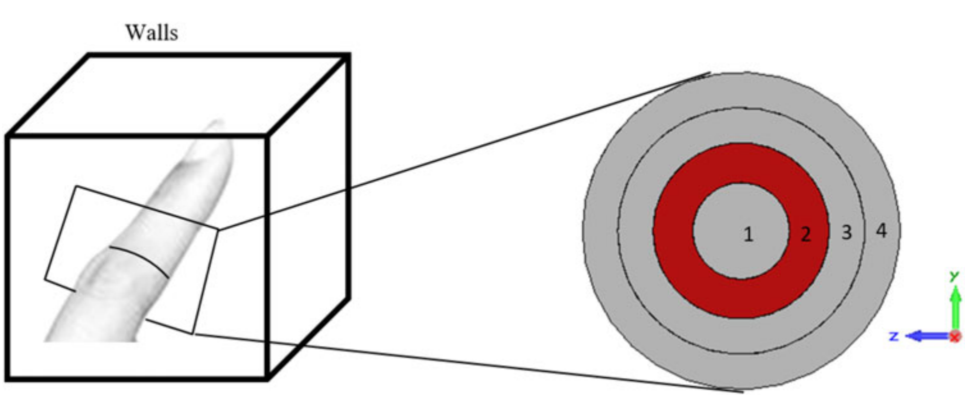

Fig. 9. Vertical cut plane of the equivalent phantom of finger. (1) Bone with the radius of 5.5 mm, (2) muscle with 2.5 mm width, (3) fat with 2 mm width, and (4) skin with 2 mm width.

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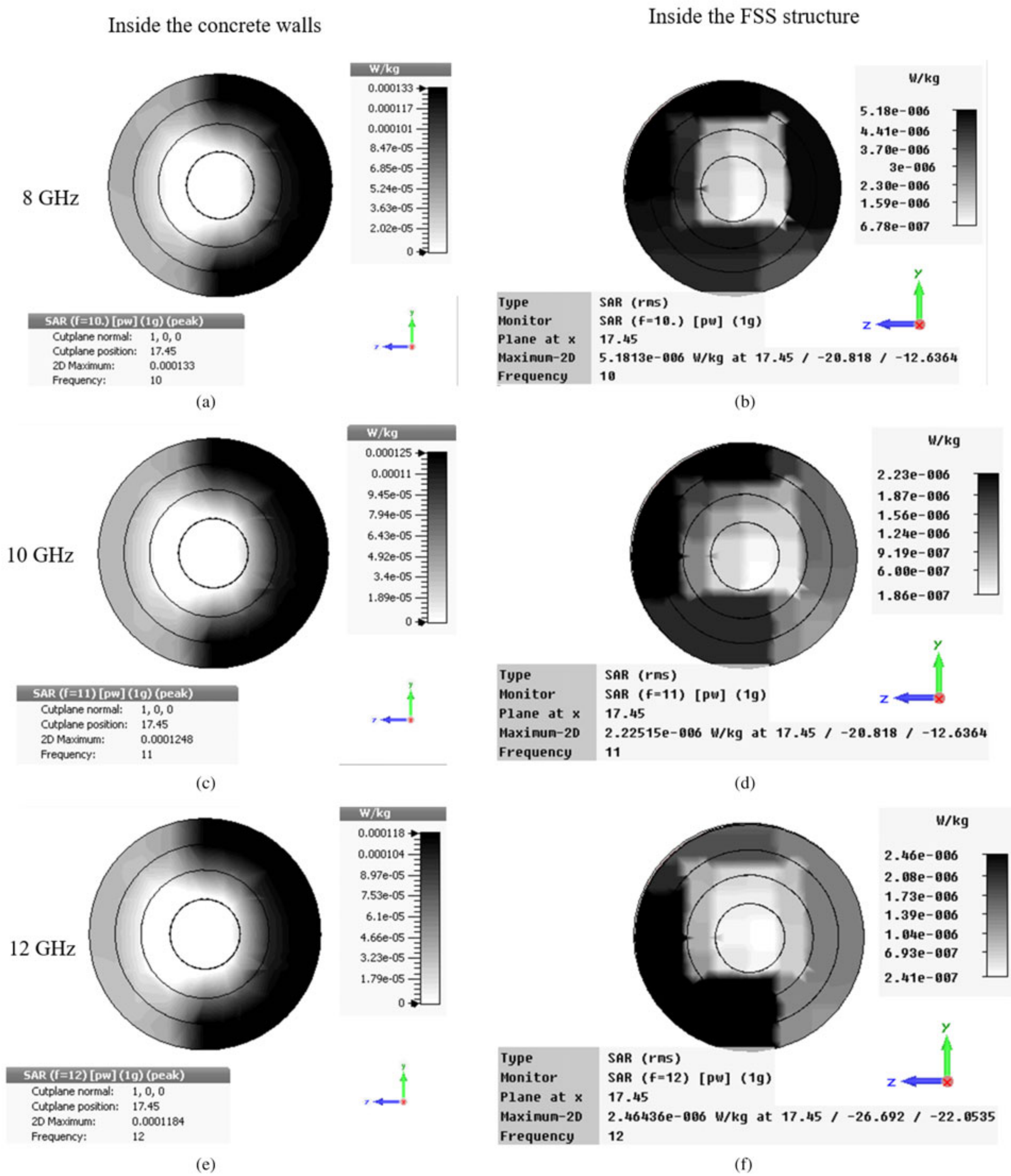

Fig. 10. SAR values inside the tissue at 10, 11, and 12 GHz. (a) Inside a room with 3 cm concrete walls at 8 GHz, (b) inside FSS structure at 8 GHz, (c) inside a room with 3 cm concrete walls at 10 GHz, (d) inside FSS structure at 10 GHz, (e) inside a room with 3 cm concrete walls at 12 GHz, and (f) inside FSS structure at 12 GHz.

frequencies as expected, −20 dB cut-off point starts at 9.6 GHz and finishes at 12.7 GHz. About 3 GHz BW is needed, because in real measurements, BW decreases as follows.

Frequency response of the proposed circuit model and full-wave analysis is shown in Fig. 6. Both responses are in good agreement at 1 MHz to 18 GHz. This model is useful for the future design.

As mentioned before, variation in the dimension or position of unit cells affects the resonant frequency, which is discussed before. One of these parameters is horizontal distance between two layers (SH). In our design, we have stable frequency response. Percentage of shifts at resonant frequencies is depicted versus misalignment in Fig. 7 for both incident polarization. Even at 0.7 mm misalignment, the worst resonant shift is $<5\%$. This stability is achieved using different unit cells for each layer. If the same four leg unit cells are used for both layers, then we need at least 4.5 mm thickness for the same results. By differentiating two layers, we design

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a shield with 3 mm thickness. Higher thickness increases the weight of cover and consumed material.

To investigate the EM-health application of design, consider EM plane wave radiates to both boxes with the tissues inside. Amplitude of an electrical field in incident plane wave is considered as 1 v/m. In the first case, the tissue is located in a room with 3 cm concrete walls and, in the second one, it is located in the cube structure with the designed FSS cover on 3 cm concrete walls. SARs are calculated in both cases and presented. CST software is used to calculate SAR. Structures are illustrated in Fig. 8.

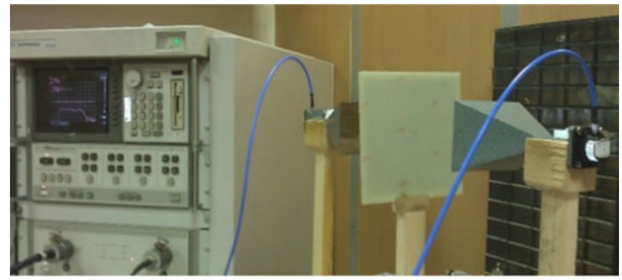
Since the structure needs accurate mesh to compute the resonances, consequently huge RAM storage is needed. Small box and small tissue are considered to prove the performance. Box dimensions are $12 \times 12 \times 12\ cm^3$ and a simple phantom of a finger with skin, fat, muscle, and bone layers is considered for the simulation shown in Fig. 9.

In Fig. 10, SAR results of two cases of Fig. 8 are compared at 10, 11, and 12 GHz frequencies. SAR is a standard for showing absorbed power inside human tissue and comparison of both cases illustrates the reduction of absorbed power inside the tissue. Figure 10 shows SAR inside the tissues of a finger inside the box for both cases. More than 90% of EM power is absorbed at the first 1.5 cm of body due to penetration depth at the frequencies of more 10 GHz. Therefore, the presented results for an organ with the size of a finger are appropriate and extendable to the whole body. Figure 10 shows good isolation between inside and outside of the boxes. At 11 GHz, maximum value of SAR is 2.23×10^{-6} W/kg in the tissue located in a room with 3 cm concrete walls and maximum SAR is 1.25×10^{-4} W/kg in the sheltered tissue. Therefore, using rooms with FSSs, a high-power source with 56 times more power can be used near the apartments and the health standards remain satisfied. However, every other device, out of working frequency band, works fine such as cellphones and WiMAX. Even SARs at the frequencies out of the working band are similar in the room with 3 cm concrete walls and room with FSS. These results approve the application of FSS in secure communications and EM health.

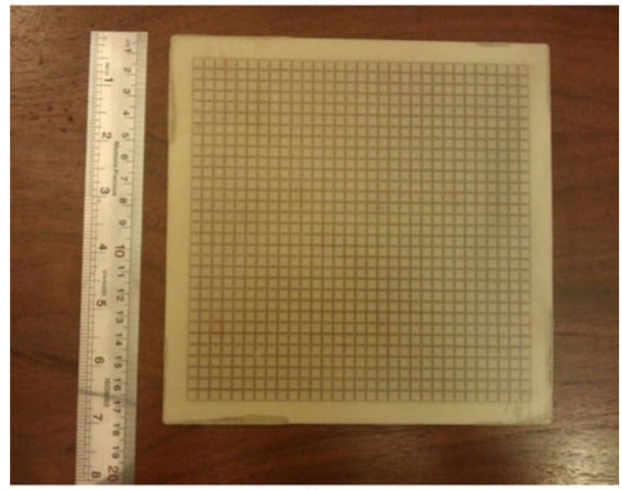
V. MEASUREMENTS

To validate the simulations, the $17 \times 17\ cm^2$ plate of designed FSS is fabricated and the S_{21} parameter was measured. SE and S_{21} parameter are identical. In each one of them, different parameter is measured and divided to a reference incident parameter. But since the measured parameters are proportional, dividing them to their references make them the same. Agilent Network analyzer 8517B and horn antennas are used to measure S_{21} of two antennas while the plate is located between them [11]. Measurement setup and fabricated plate are shown in Fig. 11 and S_{21} parameter is illustrated in Fig. 12.

Central resonant frequency is shifted due to the non-ideal substrate, since the relative permittivity of the utilized Fr4 in the fabricated surface is not 4.6, as expected. Permittivity of the available FR4 is more disperse than what is expected. Relative permittivity of the substrate is measured after the test and ε_r is found to be approximately between 2.8 and 3 at 10–16 GHz. Therefore, we simulate the designed FSS with $\varepsilon_r = 2.9$ to compare the simulated and experimented results and present them in Fig 12. The same structure as measurement is considered for the simulation and the results are in good agreement with the test; therefore, it validates the simulations. The test shows the satisfaction of our demands such as the required BWs and attenuation.



(a)



(b)

Fig. 11. Measurement. (a) setup and (b) fabricated plate.

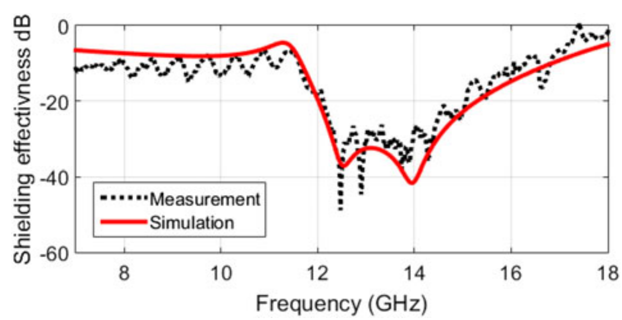


Fig. 12. S_{21}or shielding efficiency parameter of measurement.

VI. CONCLUSION

Two layers FSSs with FR4 substrate is designed to cover 10–12 GHz frequency band. Shifted layers are used to reduce the sensitivity of the structure to misalignment and add extra null in the reflection diagram to obtain sharper transition in filtering diagram. Different elements are used in each layer to increase BW; however, earlier works have used the same elements in both layers. Similar elements with mutual coupling could not sufficiently attenuate 2 GHz at X band.

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Thus, using different elements is proposed in this research to increase BW. Equivalent circuit model is proposed for the structure and results show at least −20 dB isolation at more than 3 GHz BW in the X band. Design is suitable for secure communication system when wireless transmission of secret information is required. Using FSS in EM health is also proposed and discussed. Six faces of the design are used to make cubic structure in order to simulate a room. Tissue is located inside the structure and SAR is calculated inside the cube. The results are presented and −20 dB isolation is approximately obtained in the SAR diagram. This test shows the ability of FSS to be used in EM-health applications. The existence of high-power RF source in the proximity of every apartment is worrisome for the residents. FSS could reflect wave at the selected frequencies and SAR standards remain satisfied; however, other devices such as Wi-Fi and cellphones work properly. The designed FSS is fabricated in $17 \times 17\ cm^2$ dimensions and then tested. Slight shift in the resonant frequency is observed which is normal due to the non-ideal substrate. More than 2 GHz BWs are achieved in measurement which shows the potentials of the designed FSS in secure communication and EM-health applications.

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