The simulation of the microwave shielding properties of the dual band pass frequency selective surface

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Abstract. Without proper caution, the microwave leakage from a microwave oven door can be harmful to users' health. In practice, the leaked radiation has to be blocked while the visible light is allowed to pass for a visual inspection of the cooking progress inside the oven. To fulfil the requirements, the door design based on the principle of the frequency selective surface (FSS) was proposed and the gridded square loop pattern was chosen. In the simulation conducted by COMSOL Multiphysics software, the size of the proposed FSS was given as 40.7×40.7 mm with a dielectric thickness of 2.8 mm. Two important characteristics in terms of shielding effectiveness (SE) and optical transparency (OT) of the proposed FSS configuration at normal incidence were simulated and found to be 62.7 dB and 57.5%, respectively. The simulation results indicate that the proposed FSS is applicable to a safety design of a microwave oven door in suppressing the microwave leakage. Parametric studies on the characteristics due to geometrical dimensions and glass substrate thickness were also investigated. These parameters were found to affect the shielding and transmitting performances of the proposed FSS.

1. Introduction

Microwave radiations are waves of electric and magnetic energy propagating together through space. Microwaves are a form of non-ionizing radiation meaning that they do not have enough energy to alter atoms and molecules in substances. Some familiar applications of the microwaves in daily life are telecommunications, navigations, medical treatments and especially food cooking by microwave ovens. The last activity is perhaps the most common consumer use of the microwave ovens nowadays.

Principally, the microwave radiations in microwave ovens are confined in the chamber with solid metal plates on five sides and mesh-like glass screen on the sixth side or the front door. A typical microwave oven front door equipped with a circular perforated metal sheet gives low shielding effectiveness (<27 dB) and poor visibility (<50%) [1]. In other words, the radiation is likely to leak through the door risking users' health and the visually checking progress of cooking becomes difficult. To improve the shielding effectiveness and visibility, an alternative configuration based on the principle of the frequency selective surface (FSS) for a microwave oven door was numerically studied using COMSOL Multiphysics software.

A FSS is a periodic surface with two-dimensional array of element printed on a dielectric layer. It acts like a free-space filter, exhibiting total transmission or reflection around a resonance frequency. In terms of the frequency responses, FSSs are divided into four filtering types which are low pass, high pass, band pass and band stop [2]. The geometric configurations of the mentioned spatial filters can be constructed in the pattern of patch-type array or aperture-type array. Effective FSSs are required to exhibit stable resonant frequencies, at both normal and oblique angles of incidence [3]. It is interesting to note that some FSSs, especially operating at GHz range, can simply be fabricated by the etching method which is a subtractive method used for the production of printed circuit boards.

According to the investigation of the performances for FSS in various element shapes, the square loop (SL) pattern shows the best performance characteristics in terms of having larger bandwidth and stability under various angles of incidence and polarizations in comparison to all other element shapes [3]. However, the wide bandwidth of the SL pattern becomes redundant in our required shielding property. The grid structure has to be added to the SL pattern so as to restrict the filtering response over a much narrow bandwidth. Thus, the SL pattern has to be modified to the gridded square loop (GSL) pattern. A number of previous researches on the GSL pattern were mostly studied on general characteristics in which the narrow bandwidth responses were numerically [4-6] and experimentally [7] confirmed. Besides, none of the previous works were focused on any specific applications. This, therefore, prompted us to numerically investigate the use of the GSL pattern for FSS in blocking the microwaves and passing the visible spectrum for a microwave oven door. With these two targets, we therefore employed two corresponding parameters; namely, the shielding effectiveness (*SE*) and optical transparency (*OT*), to describe properties of the proposed FSS.

In all, the aim of this paper is to design the microwave oven's door of the gridded square loop (GSL) pattern to have a high pass transmission of the visible light and block the operating frequency of the microwave oven. The investigation in terms of the shielding and transmitting properties of the proposed FSS are conducted by the COMSOL Multiphysics software. The effects of the proposed geometry on *SE* and *OT* are explored. The simulation results in terms of *SE* and *OT* from the proposed FSS, finally, will be compared to other FSSs.

2. Methodology

In this proposed work, the front door structure was designed and simulated by using the COMSOL program to investigate the events of the microwave and visible light incident on the FSS. We started with the creation of a unit sample FSS to represent the whole periodic structures and using boundary conditions to solve the problem and finally obtained the required characteristic values.

The proposed configuration for the FSS is the gridded square loop (GSL) arrays of copper. The metallic thin layer has the conductivity (σ) of 5.998×10^{7} S/m (represented as grey color in figure 1) and it is regularly arranged on the dielectric substrate layer (represented by white color in figure 1) with the relative permittivity (ε_r) of 6.5 (Highly UV-transmitting soft glass). Table 1 shows the optimal geometric parameters of the proposed FSS unit.

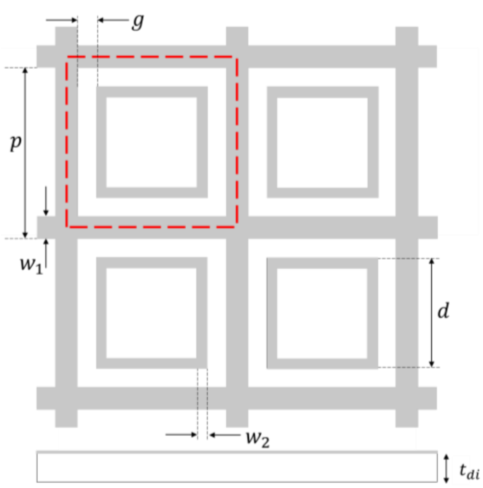


Figure 1. Gridded square loop (GSL) FSS and design parameters: top – top view with the FSS unit (red dash square) and bottom – side view. The grey and white colours represent the copper and glass areas, respectively.

Table 1. Geometric parameters of the proposed FSS unit.

t_{di} (mm)	p (mm)	d (mm)	g (mm)	w_1 (mm)	w_2 (mm)
2.80	40.7	26.4	4.65	5.00	2.50

The simulated model using COMSOL is shown in figure 2. Two ports are used at both sides of the proposed FSS unit cell located on the z-axis. The port 1 designated as the "source port" is excited by a normally incident electromagnetic (em) wave in the direction of the negative z-axis (red arrow) whereas the port 2 assigned as the "detector port" captures the transmitted em wave. Perfectly matched layers (PMLs) were applied on the top and bottom of the unit cell to absorb the excited mode from the source port and any higher order modes generated by the periodic structure. Then, the periodic boundary conditions on four sides of the unit cell were introduced to simulate the infinite 2D array. A frequency domain ranging from 0.4 to 4.3 GHz and parametric sweep solver were used for the simulation because the chosen range covered the dual band pass response of the proposed FSS.

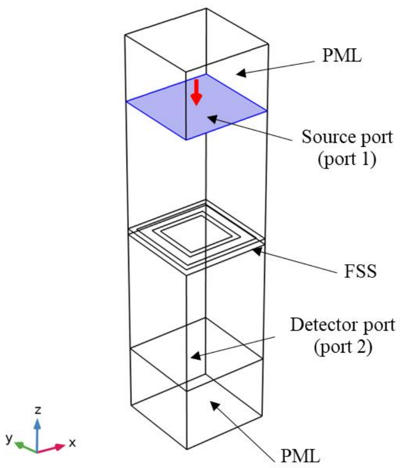


Figure 2. A model of unit cell for simulation of the proposed FSS using COMSOL.

3. Shielding and optical properties

3.1. Shielding effectiveness

The shielding effectiveness (SE) of any configuration is defined as a ratio, usually expressed in decibels, between transmitted and incident EM powers, i.e., electric field or magnetic field values. The SE is computed from the modulus of the total transmission scattering parameter s_{21} between two transmission lines separated by the device under test as follows [8]:

$$SE = 20\log_{10}\left(\left|s_{21}\right|\right). \quad (1)$$

3.2. Optical transparency

The theoretical optical transparency (OT) is the percentage of light transmitted through the proposed FSS determined by the ratio between transparent area and total area. The shape of the periodic array is shown in figure 1. p is the length of the grid, and each square aperture has sides of length $p-w_1$ with the square loop of length d and width w_2. So, the transmission percentage OT_{GSL} of the configuration can be calculated from

$$OT_{GSL} = \frac{(p - w_1)^2 - 4(dw_2 - w_2^2)}{p^2}. \quad (2)$$

As a metal layer is deposited on a dielectric substrate, the Fresnel losses due to air/glass interface have to be considered. The optical reflectance R is given by

$$R = \frac{(n_{glass} - n_{air})^2}{(n_{glass} + n_{air})^2}. \quad (3)$$

In this study, the value of n_{glass} = 1.505 for the highly UV-transmitting soft glass, then R = 0.0406. Therefore, the theoretical transparency OT of GSL unit is given by the formula:

$$OT(\%) = (1 - R)^2 OT_{GSL} \times 100. \quad (4)$$

4. Results and discussions

When the plane waves were incident on the proposed FSS, the reflection and transmission were investigated. The frequency and parametric studies were thought to affect the shielding and optical performance of the proposed FSS.

4.1. Transmission and Reflection

This is obvious that some parts of the proposed FSS structure are metallic and the remaining parts are dielectric. They react to the electromagnetic waves differently. Generally, when the electromagnetic waves are incident on this surface, they are partly be transmitted in the forward direction and partly reflected in the specular direction. The quantity of the reflectance or transmittance depends on the areas of these materials. This should be noted that, in this study, the thickness of the metallic surface is assumed to be negligible as compared to the wavelength used. Consequently, such a structure can be estimated as a perfect conducting element. The effect of the penetration from the microwave below the conducting surface leading to the absorption can be ignored.

If the waves propagate in the z-axis, normal incident to the FSS, the electric field is laid on the plane of the structure. Then, the metals can induce the electric fields to cancel out the incident fields in the forward direction. As a result, the waves cannot penetrate through the structure. In addition, as the electric field interacts with a dielectric part, the material responds with a shift in charge distribution with the positive charges aligning with the electric field and the negative charges aligning against it. The event leads to the induction of the internal field and the overall field is decreased. If the field is high enough, these waves can penetrate the dielectric layer. Under the resonant condition, the amplitude of the transmitted waves may be equal to the incident waves and the reflected waves becomes zero. This situation is described as the total transmission.

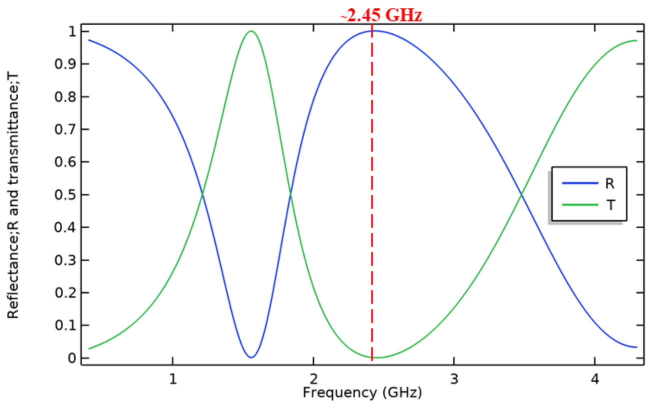


Figure 3. Reflection and transmission of the proposed FSS.

The simulation results of transmission and reflection responses for the proposed FSS are presented in figure 3. The optimization process was carried out step by step using the fine tuning. In the transmission pattern, there are two peaks around $f_{c,1}$ = 1.5 GHz and $f_{c,2}$ = 4.3 GHz of the total transmission. These peaks result from the matching incident waves to the size of the grid and square shapes respectively. In other words, the gridded square loop pattern works as a band pass filter and responds to two distinct frequencies. In the reflection mode, the structure shows a total reflection at 2.45 GHz which is the operating frequency of a microwave oven. This clearly indicates that the proposed FSS has a high potential to shield the microwave radiation.

4.2. Shielding performance

The simulated *SE* dependence on the frequency response is shown in figure 4 at the normal incidence. The proposed FSS provides a maximum shielding ability of around 62.7 dB at the resonance frequency of 2.45 GHz indicating that the proposed FSS is capable to provide the microwave shielding property.

Figure 5 shows the electric field distribution on the side view of the simulated FSS model. At the resonance frequency around 2.45 GHz, the weak field appears at the detector port while the strong field is seen at the source port. In other words, the incident waves just slightly went through the structure and most portions were reflected. These results again confirm that the proposed FSS can effectively shield the microwave at the frequency of 2.45 GHz.

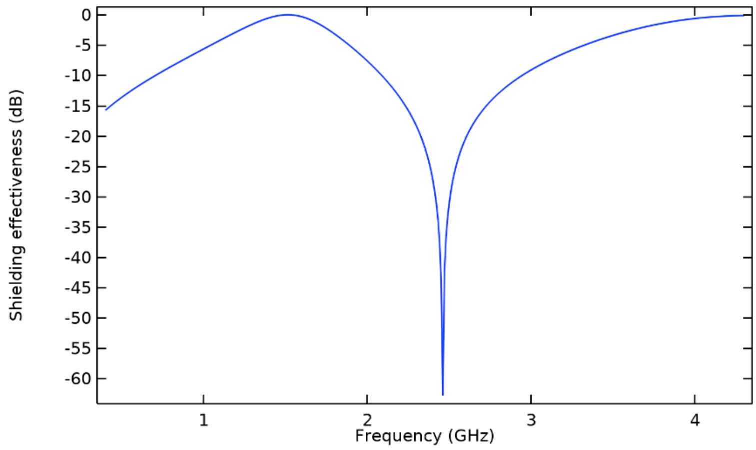


Figure 4. The simulated *SE* dependence on frequency at the normal incident angle.

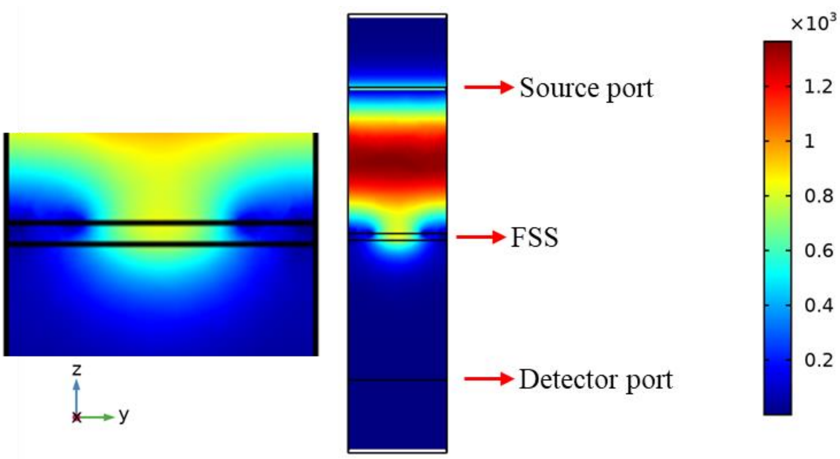


Figure 5. The electric fields distribution at 2.45 GHz.

The grid width (w_1) of the GSL pattern was varied from 4.0 – 6.0 mm, in 1 mm steps, at normal incident angle. The influence of w_1 on the SE of the FSS is shown in figure 6(a). The SE slightly changes with the increase in the width. On the contrary, the resonance points seem unchanged. This shows that the small increasement of the metal area cannot cause any significant effect to the reflection. We can also observe the effect from the square loop width (w_2) variations in figure 6(b).

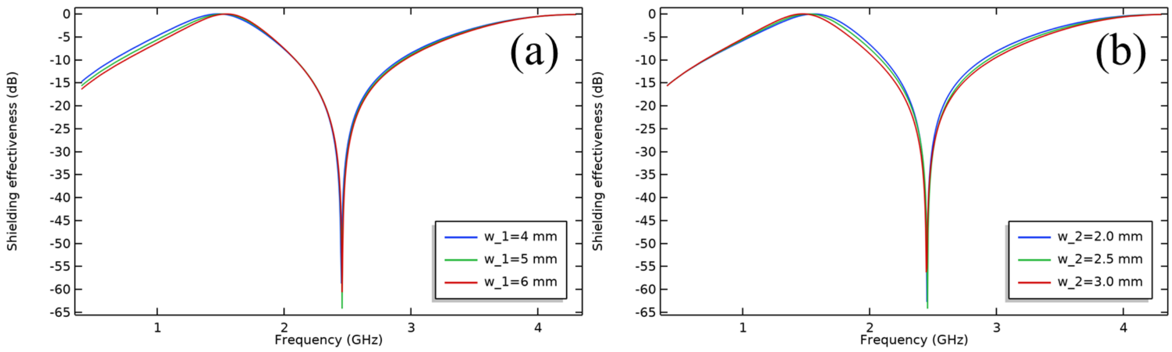


Figure 6. Influence on SE from (a) grid width and (b) square loop width of FSS.

The grid length (p) of the GSL pattern was studied and varied from 39.7 – 41.7 mm, in 1 mm steps, at normal incident angle. The influence of p on the SE of the FSS is shown in figure 7. The SE as well as the resonance point are changed due to the variation of p. This suggests that the shielding ability to the microwave at the specified frequency can be ineffective as the grid length varies.

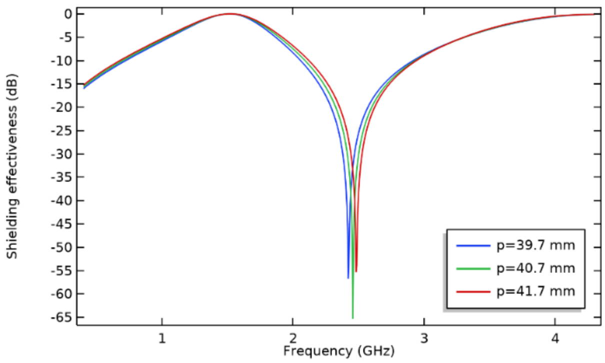


Figure 7. Influence of grid length of FSS on SE .

The square loop length (d) of the GSL pattern was studied from 25.4 – 27.4 mm, in 1 mm steps, at normal incident angle. The influence of d on the SE of the FSS is shown in figure 8. The SE and resonant frequency decrease with the increase in d . This can alternatively be explained in terms of the equivalent circuit of the gridded square loop [9,10]. The parametric change affected the magnitude of the electrical characteristics of the structure and subsequently, the resonant point was changed. The frequency response of the structure to the incident waves occurs at lower resonance frequencies. Then, the shielding ability is accordingly altered.

We can conclude that the dimension of the structure directly affects to the shielding effectiveness SE . It was found that the length of square loop has more influence on the SE with a large shifting resonance frequency than any other parameters.

The thickness of the dielectric substrate was also found to affect the resonant frequencies in the transmission and reflection responses of the FSS. The resonance frequency exponentially decreases and subsequently converges to a value of $\left(0.5(\varepsilon_r+1)\right)^{-1/2} f_0$ for the thickness greater than $\lambda/4$ where f_0 is the resonance frequency of the FSS without the substrate and λ is the wavelength in the substrate at the resonance frequency [11].

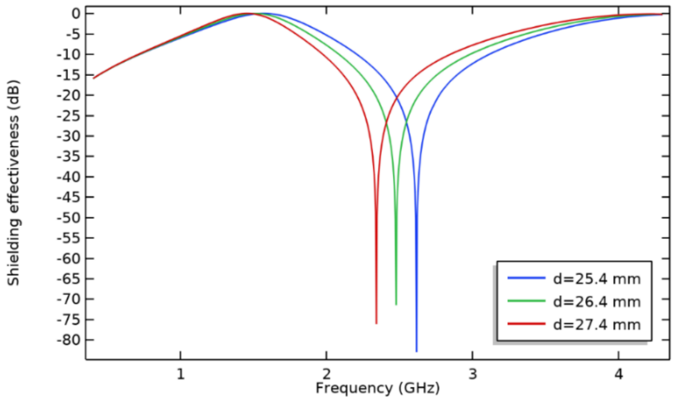


Figure 8. Influence of square loop length of FSS on SE .

The substrate thickness (t_{di}) was studied from 2.4 – 3.2 mm, in 0.4 mm steps, at normal incident angle. The influence of t_{di} on the SE of the FSS is shown in figure 9. The SE decreases with the increase in the substrate thickness. Meanwhile, the resonance points clearly moved backward. The reason of the shifting is that the increment of the dielectric layer with the value lower than $\lambda/4$ makes a rapid decrease of the resonance frequency [11]. The low-frequency transmission of the incoming waves is revealed.

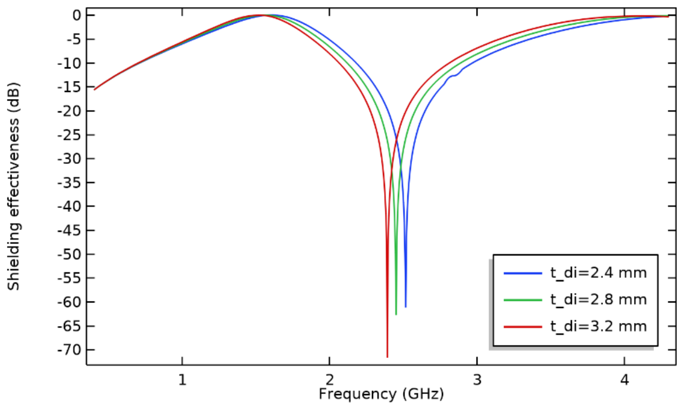


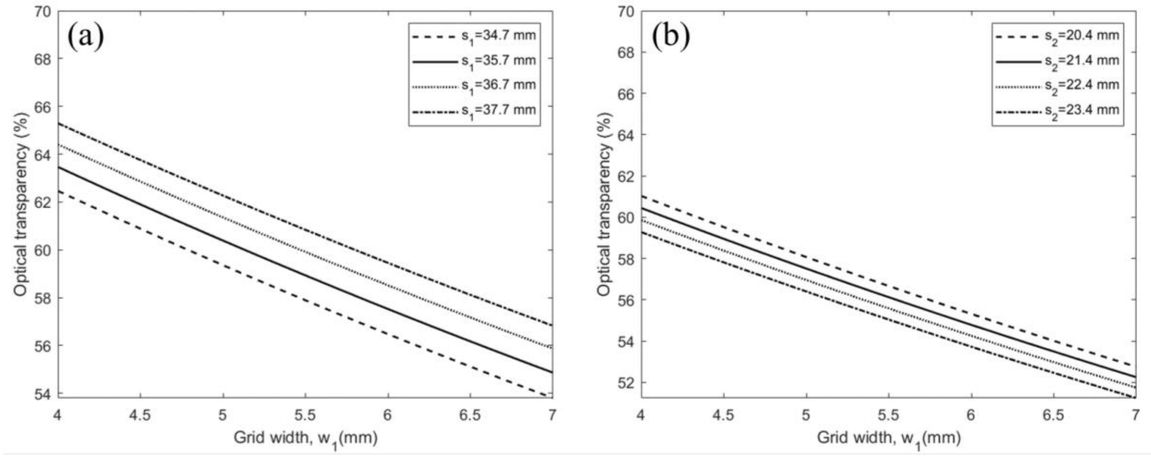
Figure 9. Influence of glass thickness substrate on SE .

4.3. Optical performance

According to the theoretical OT in equation (4), definition of the quantity is the ratio of the transparent area and the total area of the FSS. Then, we will define the parameters to readily describe the effect on the OT .

As shown in figure 10, the theoretical OT according to the grid aperture ($s_1 = p - w_1$), square loop aperture ($s_2 = d - 2w_2$), and square loop width (w_2) are plotted versus grid width (w_1). The OT decreases as w_1 and s_2 increase because the transparent area decreases. The increasement of s_1 makes the area of transparent increases, then the OT increases. In case of increasing w_2 , the OT decreases and so do w_1 and s_2 . However, the latter case is more significant than the former because of more metal area involved.

The low OT leads to a low quantity of the visible light transmission. For the optimal dimension, the theoretical OT of the proposed FSS is around 57.5%.



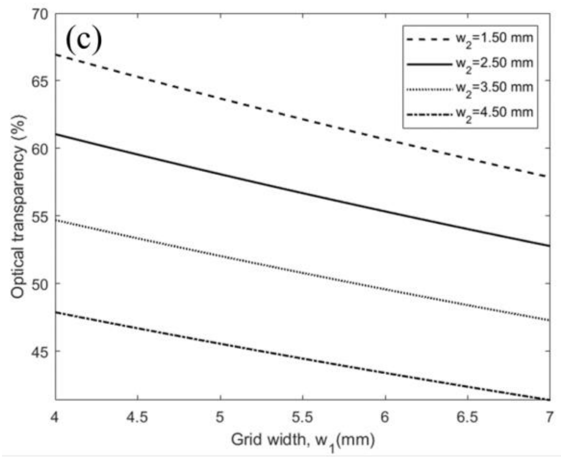


Figure 10. Influence on theoretical OT due to (a) grid aperture, (b) square loop aperture, and (c) loop width versus grid width.

In conclusion, improved shielding effectiveness can be obtained by altering the dimensions of the proposed FSS unit and glass substrate thickness. The simulation results of these parametric studies can be used to optimize the performances of the proposed FSS to achieve the expected goals of the design.

4.4. Comparison to other FSSs

The shielding effectiveness and optical transparency of this work, a metal mesh film (MMF), and a circular perforated metal sheet (PCS) at the generated frequency of 2.45 GHz from a microwave are listed in table 2.

Table 2. SE and OT of the proposed FSS, MMF, and PCS at operated frequency of microwave oven of 2.45 GHz

FSSs	SE (dB)	OT (%)
This work	62.7	57.5
MMF, [1]	32.4	73.0
PCS, [1]	26.6	48.5

These results show that the proposed FSS has the highest SE although the OT is lower than the MMF. This result indicates that the GSL pattern is a promising candidate for the microwave shielding designed for protecting users from an over-exposure of microwaves.

5. Conclusions

We have designed a FSS which is used for shielding the microwave and permitting the light transmission. The configuration of the proposed FSS is the gridded square loop pattern with the transmitting properties being in line with the band pass filters on the glass substrate. The design has been optimized according to the parametric studies by using the COMSOL software. The characteristics of the designed FSS fit the requirements which are the strong reflection of the microwave and ample transmission of the visible light at normal incidence.

To complete a whole spectrum of this research, some interesting points worth further investigating include (1) the study of some realistic effects of the interaction between the microwave and the proposed FSS such as the penetration depth [12] which is relevant to the absorbing properties of the FSS and the thermal insulation [13] which relates to the heat loss through the FSS while working, (2) the response of the proposed FSS to the oblique incident angles because, in practice, the incident waves can come from any angular directions, (3) the performance of the proposed FSS in terms of a well-known parameter, the Figure of Merit (FoM): a quantity describing the efficiency of the FSS [14], which is a parameter for a practical comparison and (4) the experimental study of the designed FSS structure in which the potential practical use of the proposed structure can be verified.

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