A Dual stopband two-sided frequency selective surface for mobile shielding applications

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Abstract. A two-sided frequency selective surface (FSS) is proposed to shield two bands of the mobile frequencies (EGSM-900 and DCS-1800). The FSS consists of an array of square concentric rings cells printed on both sides of the substrate to offer better shielding of the two mobile frequencies. The CST Microwave suit is used for the simulations. The equivalent circuit model for the two-sided FSS is analysed and the transmission frequency in terms of the two stop frequencies is estimated. The obtained shielding is better than 40 dB across the two bands. The proposed FSS can be used to reduce mobile radiation or to isolate halls from nearby mobile base stations. The bandwidth of the FSS cell can be increased by using ring pairs of unequal sizes on the two sides of the substrate.

1. Introduction
Many issues and problems of spectrum management have arisen due to the increasing use of devices and applications that operate at many frequencies. The radiation due to the mobile phone can cause many issues, such as the annoyance or interference of the device ringing tones. In some locations, like hospitals, examination halls, and places of worship, mobile equipment, tablet, and phones need to be inactivated. Thus, shielding or isolating a building or some parts of it from the mobile signals is of increasing concern. The use of jamming devices to overlay the interference of the mobile signals has become illegal in many countries, due to health issues. Another solution is by rejecting the unwanted mobile bands by employing Frequency Selective Surfaces (FSS). With the use of large glass windows in modern buildings, where waves can easily penetrate, adding an FSS can be a simple and cheap solution, while the use of window curtains [1-2] will offer a solution and isolate the mobile waves. FSS have been extensively studied in the literature [3] and many applications were presented, such as shielding at certain frequencies [1-6]. The FSS were also used for transmitting waves of a certain band of frequencies through a conducting screen as in [7], or enhancing the transmission of mobile frequencies through the energy-saving glass windows [8], or to offer a bandpass property in a conducting screen [9]. The presented shape of the unit cell of the FSS had various geometries such as square [1-4], circular [5], hexagons [6], strips, U-shaped slots [7], crossed dipoles [8], and intertwined slots [9]. In [4], the GSM frequencies were shielded by a form of a wallpaper FSS, where square loops were used in the unit cell to provide a 20 dB attenuation. A double-ring FSS showed more than 20 dB of mobile frequencies shielding [5]. A curtain of FSS which has a double square loop unit cell on one side showed more than 35 dB attenuation [1]. A fractal square loop FSS printed on FR-4 substrate

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provided a dual bandstop in the frequencies of GSM900, GSM1800, and IMT2000 [6]. The FSS unit cell of square, hexagonal, and circular loops were analysed for the purpose of a passband of the dual frequencies of GSM 900 & 1800MHz [10]. This paper investigates an FSS of double square rings printed on both sides of a dielectric sheet for GSM900 and GSM1800 bands shielding. The proposed two-sided design is aimed to increase the shielding of the single-sided FSS. The shielding of the e.m. wave is aimed for use as a curtain to provide the shielding at the wanted frequencies. The CST microwave suit is used in the simulations, where the filtering or blocking of certain frequencies is explained by the surface current distribution on the copper rings. Moreover, an equivalent circuit for the FSS unit cell having four rings is proposed, and formulas for the blocked and transmitted frequencies are derived. The effects of the shift in the alignment of the rings, and using rings of different sizes on the two sides of the FSS cell are investigated.

2. FSS Design

The concentric double-square rings that are known for their dual-band or wideband operation and having the same response for vertical and horizontal polarizations [11] were used on both sides of the FSS. The frequency bands of EGSM-900 (880-960 MHz) and the DCS1800 (1710-1880 MHz) are aimed at as they are used for mobile communications in Iraq. The designed element structure of the FSS is shown ‘in Figure 1’. The structure of the FSS is in the form of a fabric curtain with double copper rings printed on both sides of the sheet. The permittivity of the woven-fabric curtain (substrate) was chosen as 2.2 [12], and the thickness of 1 mm was assumed in the simulations. The ring resonance happens when the guided wavelength \( \lambda_g \) equals the ring average perimeter \( L_{av} \), where

\[
L_{av} = \lambda_g = \frac{\lambda_0}{\sqrt{\varepsilon_{eff}}}
\]

Where curtain effective dielectric constant \( \varepsilon_{eff} \) is given by:

\[
\varepsilon_{eff} = \frac{\varepsilon_r+1}{2}
\]

The calculated dimensions of the double ring on each side of the substrate are shown in Table 1, where the width of the rings is 1.4 mm. In this design, the centers of the two GSM mobile bands were set at 0.920 GHz and 1.795 GHz. The outer ring and inner ring dimensions were chosen according to the above equations to block the lower and upper mobile bands, respectively.

3. Simulation

The CST Microwave Studio was used to tune the double square rings dimensions and investigate the performance of the FSS that have been designed in the previous section. A linearly-polarized plane wave whose electric field is directed along the Y-axis is assumed normally-incident on the FSS. Figure 2 shows the simulated S-parameters of the double square rings, for the two cases of two-sided and single-sided designs. The response shows two stopbands at 0.935 GHz (transmission coefficient \( S_{21} \) of -40.6 dB, and reflection coefficient \( S_{11} \) approaching 0 dB) and at 1.9 GHz (\( S_{21} \approx -40.9 \) dB, and \( S_{11} \approx 0 \) dB) frequencies. These two resonance frequencies correspond to the two concentric rings. It can be seen that the two-sided FSS has a better blocking by about 3 dB. As seen in Figure 3, the surface current variation along the perimeter of the large rings forms one wavelength at the lower band, while that on the smaller ring forms one wavelength at the upper band. Such variations express that when a ring resonates the transmission through the FSS is blocked. The other frequency at 1.382 GHz, which is seen in Figure 2, represents a transmission of the incident wave, \( S_{21} \approx 0 \)dB and \( S_{11} = -33.3 \)dB. At 1.382 GHz frequency, as seen in Figure 4, the opposite
directions of the currents on both rings result in almost elimination of the current effect and thus leads to transmission (no blocking) through the FSS at the 1.382 GHz frequency.

Table 1. The calculated dimensions of the FSS cell compared to those obtained from the simulations.

| Parameter     | L_1  | L_2  | W_1  | W_2  | D   |
|---------------|------|------|------|------|-----|
| Calculated    | 65.65| 1.4  | 46   | 1.4  | 70  |
| Found from CST| 65.5 | 1.4  | 46.5 | 1.4  | 70.5|

Figure 1. The two-sided FSS unit cell showing the double-square rings printed on both sides of the substrate (curtain). (a) front view, (b) side view.

Figure 2. The S-parameters of the one-sided FSS compared to those of the two-sided FSS cells. The rings on the two sides are of similar sizes.
The two-sided FSS cell as shown in Figure 2 has a slight shift in the stopbands (0.86% and 6.44% at the first and second one respectively). The shift in the stop frequencies can be attributed to the mutual coupling between the double rings on one side with those on the other side. Table 2 lists the resonance frequencies that were obtained for the following designs of the unit cell:

a) double-square ring on one side only,
b) double-square ring on one side, and the inner ring on the other,
c) double-square ring on one side, and the outer ring on the other,
d) two-sided design having double-square ring on both sides.

Table 3 shows a comparison between the obtained S-parameters of the four FSS cells which are listed in Table 2. It can be seen that better shielding is obtained for the two-sided cell which has a lower $S_{21}$ value by about 3dB as compared with the one-sided cell, and this is also evident in Figure 2.
Table 2. Values of the stop and pass frequencies for the shown four investigated FSS cells.

|                        | 1st stop frequency (GHz) | pass frequency (GHz) | 2nd stop frequency (GHz) |
|------------------------|--------------------------|----------------------|--------------------------|
| double-square ring on one side | 0.927                    | 1.327                | 1.782                    |
| double-square ring on one side + outer ring on the other | 0.935                    | 1.357                | 1.777                    |
| double-square ring on one side + inner ring on the other | 0.932                    | 1.355                | 1.897                    |
| two-sided double square ring | 0.935                    | 1.382                | 1.9                      |

Table 3. Reflection and transmission coefficients at the stop and pass frequencies for the shown four investigated FSS cells.

|                        | @ 1st stop frequency | @ Pass frequency | @ 2nd stop frequency |
|------------------------|----------------------|------------------|----------------------|
| S-Parameter (dB)       | S_{11}               | S_{21}           | S_{11}               | S_{21}           | S_{11} | S_{21} |
| double-square ring on one side | -0.12                | -36.8            | -30.7                | -0.24            | -0.12  | -37.4  |
| double-square ring on one side + outer ring on the other | -0.08                | -40.2            | -24.5                | -0.26            | -0.13  | -36.3  |
| double-square ring on one side + inner ring on the other | -0.12                | -36.8            | -41.7                | -0.19            | -0.07  | -41.1  |
| two-sided double square ring | -0.08                | -40.6            | -33.3                | -0.18            | -0.07  | -40.9  |

For further insight into the operation of the 2-sided FSS cell, the FSS was modelled by an equivalent circuit comprising four parallel RLC circuits (each for one ring), as seen in Figure 5. The equivalent circuit is further developed by deriving formulas for the blocked and transmission frequencies. The substrate is represented here by a short section of transmission line having length h that is separating the two pair of rings that are printed on the two sides of the substrate. As the substrate is thin (h=1 mm), then his transmission line is very short (of length ≈ 0.01λe). Therefore, the impedance $Z_{in}$ seen by the incident wave can be approximated by the parallel combination between $Z_1$ and $Z_{p2}$ (see Figure 5). The input impedance ($Z_{in}$) can thus be found as:

$$Z_{in} = \frac{Z_{p2}Z_1}{Z_{p2} + Z_1}$$

(3)

After some algebraic manipulations, the derived frequencies at which transmission is blocked through the FSS are:

$$\omega_1 = \frac{1}{\sqrt{L_1C_1}} \quad \omega_3 = \frac{1}{\sqrt{L_3C_3}}$$

(4)
\[ \omega_2 = \frac{1}{\sqrt{L_2 C_2}} = \omega_4 = \frac{1}{\sqrt{L_4 C_4}} \]  

(5)

Where the double rings (outer and inner rings) on the right side of the FSS has the stop frequencies \( \omega_1 \) and \( \omega_2 \), while the left side rings (outer and inner rings) of the FSS has stop frequencies of \( \omega_3 \) and \( \omega_4 \). The derivations were developed to find the two transmission frequencies for the right side and left side of the FSS cell which are \( \omega_5 \) and \( \omega_6 \) respectively. The FSS cell can be designed to have similar pair of rings on the two sides, so that:

\[ \omega_5 = \omega_6 = \omega_t \]

\[ \omega_t = \sqrt{2 \cdot \frac{\omega_1 \omega_2}{\sqrt{\omega_1^2 + \omega_2^2}} = \sqrt{2 \cdot \frac{\omega_3 \omega_4}{\sqrt{\omega_3^2 + \omega_4^2}}} \]  

(6)

**Figure 5.** Equivalent circuit representing the two-sided double-square ring FSS cell (a), Equivalent lumped-element circuit of the FSS (b).

In the fabrication of the two-sided FSS cell, the rings on both sides may not be aligned perfectly, and there may be a shift, whose effect is investigated here. Figure 6 shows the scattering parameters of the FSS cell that were obtained from the simulations when there is a shift of 1 mm and 2 mm in the diagonal direction to the rings, compared to the case where there is no shift. The first stop frequency is shifted slightly from 0.935 GHz to 0.917 GHz, and then to 0.892 GHz as the shift was increased from 0 mm, to 1 mm, and then to 2 mm. Thus, the spatial shift in the rings results in a small shift in the stopband frequency and a small increase in the response bandwidth.
Figure 7 shows the transmission coefficient ($S_{21}$) for (the double-square ring on each side) two-sided FSS cell for cases of:

a) the two sides have similar rings,
b) the rings on the other side are larger by 1%,
c) the rings on the other side are smaller by 1%.

The figure shows that the bandwidth has increased for both cases when the rings on the other side larger or smaller sizes. The bandwidth slightly changed (3.15%), which can be attributed to the two resonances corresponding to the rings on both sides. Figure 7 also shows a slight change of about 2% in the first stop frequency when the size of the rings on the other side was changed by 1%. As there are two pairs of rings with different sizes, then each pair resonate at a different frequency. The overall response is a combination of the responses of the two pairs, and thus it will have an increase in the bandwidth and a shift in the centre frequency. The 2% and 4% differences in the sizes of the rings have shown the same trend, as can be seen from Figures 8 and 9, which show the S-parameters for the FSS cell for the two-sided FSS.

To explore the effect of farther differences in the size of the rings, the sizes of the rings on the backside were reduced by 15% and 20%, and the obtained S-parameters are shown in Figure 10 and Figure 11, respectively. The single passband in between the two stop frequencies has now split into two adjacent passbands. As the reduction factor was increased from 15% to 20%, the former two passbands have become three bands as shown in Figure 11. These results show that the sizes of the double rings on the other side can be chosen to obtain more than one passband while preserving the two reject bands.

4. Conclusions

A two-sided FSS formed of concentric double square conducting rings has been demonstrated to shield the GSM900/1800 MHz frequency bands. The FSS is built by printing copper rings on a fabric sheet that represents a curtain for offering a shield across windows. The CST simulations show an attenuation of better than 40 dB at the two GSM bands. The FSS was represented by an equivalent circuit comprising four parallel resonating-circuits, and the estimates of the blocked and transmit frequencies are in agreement with those found from the simulations. The bandwidth of the stopbands can be increased by employing rings of slightly different sizes on the two sides of the substrate. The larger difference in the size can lead to split the passband into two or three sub-bands.
**Figure 7.** The obtained transmission factor of the 2-sided FSS cell for; the two pairs on both sides have similar sizes (---), the rings on the backside are 1% larger (-----), the rings on the backside are 1% smaller (-----).

**Figure 8.** The obtained reflection coefficient of the 2-sided FSS cell for; the two pairs on both sides have similar sizes (---), the rings on the backside are 2% smaller (-----), and 4% smaller (-----).

**Figure 9.** The obtained transmission factor for the 2-sided FSS cell for; the two pairs on both sides have similar sizes (---), the rings on the backside are 2% smaller (-----), and 4% smaller (-----).
5. References

[1] Mayouf A, Sayidmarie K H, and Ali Y 2020 A dual stopband frequency selective surface for mobile shielding applications 2020 Proceedings of the 1st International Multi-Disciplinary Conference Theme: Sustainable Development and Smart Planning, Cyberspace, pp.818-827, 28-30 June 2020.

[2] Mayouf A, 2020 Investigation of Frequency Selective Surfaces (FSS), MSc Dissertation, University of Mosul, Iraq.

[3] Munk B A 2000, Frequency Selective Surfaces: Theory and Design 2000, (Wiley and Sons).

[4] Sohail S I, 2016 Wi-Fi transmission and multi-band shielding using single-layer frequency selective surface, IEEE Int. Symp. Antennas Propag., pp. 963–964.
[5] Manaa Y, and Aldhaheri R W, 2017 Dual-Band frequency selective surface for GSM shielding in modern buildings. Aljouf University Science and Engineering Journal (AUSEJ), Vol. 4, No. 2.

[6] Al-Atrakchii M A, Sayidmarie K H, Abd-Alhameed R A, 2020 Frequency selective surface using the metamaterial property of the U-Shaped strip 2020, Proceedings of the 1st International Multi-Disciplinary Conference Theme: Sustainable Development and Smart Planning, IMDC-SDSP 2020, Cyperspace, pp.818-827, 28-30 June 2020.

[7] Al-Atrakchii M A, Sayidmarie K H, Abd-Alhameed R A, 2021 A band pass frequency selective surface using U-shaped slots, 2021 International journal of microwave and optical technology, Vol. 16, No. 1, 2021, pp. 36-43.

[8] Kiani G I, Olsson L G, Karlsson A, Esselle K P, and Nilsson M 2011 Cross-dipole bandpass frequency selective surface for energy-saving glass used in buildings, IEEE Transactions on Antennas and Propagation, Vol. 59, No. 2, pp. 520-525, Feb. 2011.

[9] Vallecchi A, Langley A, and Schuchinsky A, 2017 Bi-state frequency selective surfaces made of intertwined slot arrays”, IEEE Transactions on Antennas and Propagation, Vol. 65, no. 6, pp. 3093-3101.

[10] Singh J, Najim M, Agarwala V, Singh D, and Varma G D 2016 Critical analysis of frequency selective surfaces for dual band GSM-900 & 1800 MHz transmission. Proceedings of Recent Advances in Electronics and Computer Engineering Conference RAEECE 2015, 13- 5 Feb. 2015, pp. 207–210.

[11] Bialkowski M E, and Sayidmarie K H, 2008 Investigations into phase characteristics of a single-layer reflectarray employing patch or ring elements of variable size, IEEE Transactions on Antennas and Propagation, Vol. 56, No. 11, PP. 3366-3372.

[12] Bal K and Kothari V K, 2010 Permittivity of woven fabrics: A comparison of dielectric formulas for air-fiber mixture, IEEE Transaction on Dielectric Electrical Insulation, vol. 17, no. 3, pp. 881–889.