Angular stable frequency selective wallpapers for mitigating indoor wireless interference

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1. Introduction

With the rapid growth in the use of wireless technology, especially in the general license (or unlicensed) bands, wireless systems are increasingly likely to operate in close proximity to each other and suffer mutual interference as a consequence. Signals received from a competing wireless system degrade reception quality and lower throughput. Moreover, the security of those signals is compromised [1]. Interference between wireless systems can be reduced if the signal attenuation in the radio propagation channel between the systems can be increased. For indoor wireless systems, frequency selective surfaces (FSSs) can be used for this purpose. Studies [2,3] have shown that by applying a custom-designed frequency selective surface as covering, a frequency selective wall (FS-wall) can be created. A FS-wall has been demonstrated to successfully reduce potential interference by 15dB [2,3]. Designing effective FS-wall coverings is a significant engineering challenge. Normally, the performance of an FSS will be affected by the electromagnetic properties of the wall itself, especially when the FSS is attached directly to the wall. Providing an intervening air space between the wall and the FSS will reduce mutual coupling effects so that the FSS response and the uncovered wall response can be cascaded to determine the combined response [3]. Nonetheless, it is appealing to have a FS-wallpaper that can be applied to the wall directly without any air spacing in between. Ideally, the FS-wallpaper should also have a stable performance with signals arriving at different incident angles (θ).

This paper presents the development of an angularly stable FSS that operates in the X-band. Focus has been placed on comparisons between the FSS (namely FSS-I) which was presented previously in [3,4] and a newly designed X-band FSS (namely FSS-II). The performance of the new FSS wallpaper is very promising, particularly the angular stability. Design guidelines are proposed for the creation of angularly stable FS-wallpapers for other operating frequencies.

2. FSS design

In the development of an FSS design which provides attenuation largely independent of the angle of signal incidence, the square loop element shape was retained from earlier designs. The original X-band FSS-I square loop offers a desirable bandstop response [3,4]. In [5,6] it is suggested that a reduction in element size will yield an improved frequency response over a wider range of incident angles. Therefore, with a similar target resonant frequency (f_r) at 0º incidence, the new FSS (FSS-II) was deliberately designed with small square loop element size and spacing. Element dimensions of FSS-I and FSS-II are illustrated and summarised in Fig. 1 and Table 1.

Table 1: The square loop element dimensions and the theoretical resonant frequencies of FSS-I and FSS-II.

<table>
<thead>
<tr>
<th>Parameters (m)</th>
<th>FSSs</th>
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<tbody>
<tr>
<td></td>
<td>FSS-I</td>
</tr>
<tr>
<td>p</td>
<td>0.016</td>
</tr>
<tr>
<td>g</td>
<td>0.004</td>
</tr>
<tr>
<td>d</td>
<td>0.012</td>
</tr>
<tr>
<td>s</td>
<td>0.002</td>
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Theoretical resonance (0º incidence) 11.1GHz 10.7GHz
3. FSS performance

The original FSS design (FSS-I) suffered a 2GHz shift in the resonant frequency, $f_r$, with varying angles of incident signal, namely $0^\circ$ (normal) to $60^\circ$. This response, calculated by equivalent circuit modelling [4], is illustrated in Fig. 2(a). In comparison FSS-II exhibits only a 0.5GHz shift in the resonant frequency, $f_r$, as illustrated in Fig. 2(b). This confirms that by reducing the element dimensions, especially the inter-element spacing ‘$g$’, an FSS can be made less angle dependent. Also note that with the smaller square loop element size (element dimension ‘$p$’) of FSS-II, the criterion for avoiding grating lobes [5], $p(1 + \sin \theta) < \lambda$, can be obtained within the incident angle and frequency range considered here. In contrast, for FSS-I the presence of grating lobes can be observed in Fig. 2(a), namely the cusps in the response curve at points A and B. Such cusps imply a dispersion of energy, and undesired complicated wave propagation close the FSS surface.

![Figure 2: Angular responses calculated based on equivalent circuit model for (a)FSS-I & (b)FSS-II.](image)

3.1 Measured angular response in freespace

By suspending the FSS in freespace between a (rotatable) pair of X-band horn antennas, as described in [7], angular performances of FSS-I and FSS-II with incident angles varying from $0^\circ$ to $60^\circ$ were determined. These are illustrated in Fig.3. FSS-II presents a more stable angular response compared to FSS-I, which agrees with the results from modelling shown in Fig. 2. For FSS-II, which was made with densely packed small square loop elements, $f_r$ shifts only slightly around 9GHz, by 200MHz, when $\theta$ changes from $0^\circ$ to $45^\circ$. In comparison, for FSS-I, $f_r$ varies by approximately 1.2GHz, shifting from 10GHz to 8.8GHz, as shown in Fig. 4(a).

![Figure 3: Measured angular responses for (a)FSS-I & (b)FSS-II stand alone in freespace. The vertical dotted lines are where the FSS-I and FSS-II performance were monitored for producing Figure 4(b).](image)
By monitoring the attenuation experienced at a particular fixed frequency (as indicated by the vertical dotted lines in Fig. 3(a)(b)), Fig 4(b) illustrates that FSS-II offers a reasonably constant attenuation (in the order of 40dB) across a range of incident angles, while the attenuation provided by FSS-I varies from approximately 30dB to 2dB. The attenuation (isolation) consistency provided by FSS-II is considered to be sufficient for the intended indoor wireless application. The results show that the stability of an FSS angular response can be improved by appropriate FSS design, as in this case where densely packed small elements have been used.

### 3.2 FSS-II on wallboards with varying air spacing

Applying a FSS directly to a wall can alter the response of the FSS, because its response is coupled with that of the wall. This was demonstrated in [3], where an FSS-I covered plasterboard wall had a much lower resonant frequency than the FSS considered in isolation. In other words, the FSS-I characteristics were not preserved when it was applied to the wall with zero air spacing. The FSS and the wall interact with each other in a complicated manner. Such interaction detunes the FSS-I performance and prevents the FS-wall being modelled by cascading the effects of the FSS and the wall individually, which presents a serious design difficulty. It has been found that by increasing the air spacing to 10mm, the FS-wall performance can then be predicted well by cascading the FSS-I and the wall responses. This implies that with sufficient air spacing (10mm in the FSS-I case), interaction between the FSS and the wall becomes insignificant; hence the wall and the FSS can be considered independently.

For the intended indoor wireless system isolation application it would be ideal if FSS-wallpaper could be applied directly to a wall (like ordinary wallpaper) without any intervening air spacing between the FSS and the wall. Given that FSS-II does not generate grating lobes within the incident signal angle and the frequency range considered here, Fig.5 demonstrates that wave
propagation through the FSS-II and the wall is simple enough to allow the two to be modelled independently, even with 0mm air spacing. Both plots in Fig.5 show strong frequency selective characteristics with $f_r$ at approximately 9GHz, which is the same as the $f_r$ value when FSS-II stands alone in air, as shown in Fig.3 (b). Although at some incident angles, the frequency response diverges from the FSS-II freespace response (possibly due to measurement imperfections), in general, the designed characteristics of the FSS-II response was preserved.

As a consequence of the small element size used in FSS-II, the onset frequency of the grating lobes was outside the operating band investigated here. This brings the benefit of minimal interaction between the wall surface and the FSS even with no intervening air spacing. Consequently, modelling for the combined FS-wall structure is less complicated. This is an encouraging result for the development of practical FS-wallpapers.

4. Conclusions

It has been demonstrated that the modification in element dimensions (as represented by FSS-II) is a practical and effective technique for creating an angle-insensitive FS structure. Only a single layer of FSS is required to achieve the desired stability in angular response, which suggests that a practical low-cost FS-wallpaper is feasible. Such a wallpaper can transform a typical wall (e.g. made from, say, plasterboard) into a FS-wall. With the suppression of grating lobes within the operating band, FSS-II can be directly applied to an ordinary office wall as wallpaper while preserving the FSS’s original frequency selectivity (i.e. not detuned by the wall properties). As a result, designers can focus on the FSS design without requiring knowledge of the specific properties of each wall. The resultant response of the FS-wall can be approximated by cascading the individual responses of the wall and the FSS considered independently of the other.

The results presented in this paper suggest that effective FS-wallpapers can be designed by keeping FSS elements small and densely packed without compromising the target resonant frequency. Although only X-band FSS responses were presented in this paper, the results have also been found applicable to the design of FS-wallpaper for lower frequency applications, such as the provision of isolation between WLAN systems (operating at 2.4GHz or 5.8GHz).

References