Planar wide-angle and polarisation-insensitive ultrathin frequency selective surface patch absorber design analysis and implementation

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Abstract
Single-layer ultrathin absorber patch elements are analysed under normal and oblique incidence. A compensation technique for impedance variation with an angle of incidence (θ) is proposed. An equivalent-circuit model is formulated that provides a realisation for the absorption response (in terms of resonance frequency and absorption ratio) of non-complicated rectangular patch absorbers using simple equations. The design methodology proposed is based on using multiple subcells of simple patches to add another degree of freedom for the design equations and keep the ultrathin planar feature. Previously reported techniques realising a wide angle of incidence are applied for fair comparison with the proposed methodology. The developed structure features angular stability, polarisation insensitivity, and a planar non-complicated configuration compared with that of structures reported in literature. Moreover, a prototype is fabricated and measured to validate the proposed approach.

1 | INTRODUCTION

Electromagnetic wave absorbers are used broadly in civilian and military applications; such applications include energy harvesting, stealth technology, and enhancing antenna measurements [1]. Traditional absorbers such as Salisbury, Jaumann, and Dallenbach, also known as quarter-wavelength-thick absorbers, have been used efficiently [2, 3], but limitations in size, operating frequency, and fabrications have existed. Meanwhile, ultrathin periodic frequency selective surfaces (FSSs) deployed as electromagnetic wave absorbers have been a focus of research. Those planar single-layer structures are adapted to perfectly match free space impedance within various frequency ranges [4–6]. An ideal FSS absorber for the above-mentioned applications should realise near-unity absorption independent of the polarisation angle (ϕ) and incidence angle (θ) [1]. Reference [7] introduced grounded chiral metamaterials using vias connecting stacked rings and 3-D grids. Another study proposed a polarisation-insensitive absorber using unit cells rotated by 90° with respect to one another [8]. Using symmetric structures is also widely used in electromagnetic wave absorbers as reported in [9–12].

Polarisation insensitivity was attained in the proposed structure by maintaining symmetry in the unit cell design. On the other hand, the approach to enhance angular stability proposed in [13, 14] uses different/same sized multilayer structures with gradual increases in permittivity. Another approach, reported in [15, 16], is to use 3-D hemispherical or trapezoidal substrate shapes to provide enhanced angular stability. However, those structures are subject to fabrication errors. Reference [17] suggested using active absorbers with capacitive loads to achieve stable angular performance. In addition, a square patch unit cell with a grounding metal via was proposed in [18]. The structures presented in [15, 16] resulted in only transverse magnetic (TM) performance improvement under oblique incidence and are considered complex. The independence of the angle of incidence for FSS single-layer absorbers is reported only for θ ≤ 60° or with absorbance less than 40% for incident waves with angles θ ≥ 60° [1].

The aim of this work is to improve the absorbance of ultrathin patch elements for angles up to and beyond 60° for both incident polarisations. The previous work proposed in [19, 20] establishes that a unit cell can be treated as a single antenna; hence, deploying the fields’ radiation pattern into
input impedance calculations can add more degrees of freedom for absorber design equations. Following this concept, Section 2 investigates absorber performance under normal and oblique incidence, and a compensation technique for impedance variation with the angle of incidence ($\theta$) is proposed accordingly. This modification is based on the comparable analogy of the absorbance pattern of the first incident polarisations on patch absorbers and the radiation pattern of a single-patch antenna in the H-plane and E-plane proposed earlier in [20]. In Section 3, an equivalent-circuit model formulated and presented in [19] is attuned under oblique incidence. In Section 3, an equivalent-circuit model formulated and presented in [19] is attuned under oblique incidence. Finally, Section 4 presents the design steps for a stable wide-angle polarisation-insensitive ultrathin single-layer FSS absorber. Moreover, various reported techniques are simulated under oblique incidence and compared with the implemented proposed design.

2 | OBLIQUE INCIDENCE INVESTIGATION FOR SINGLE-LAYER ABSORBER ELEMENTS

For near-unity absorbers at normal incidence, the absorber input impedance is 377 $\Omega$ with a zero-reflection produced only at $\theta = 0^\circ$. A mismatch between free space and the absorber surface is usually observed at oblique incidence [13]. Consequently, reflection significantly increases with the incidence angle ($\theta$). Therefore, to constantly match free space impedance, absorber input impedance ($Z_{in}$) should be varied by a factor relative to the angle of incidence ($\theta$). The concept of introducing a compensation factor to $Z_{in}$ was reported earlier in reference [13]. The modification was based on Snell’s law, in which the absorber impedance should be lowered by the cosine of angle of incidence and increased by the inverse for parallel and orthogonal polarisations, respectively [13]. An ideal compensation technique is then implemented by adding a matching slab in front of the resistive sheet of the absorber (forming a multilayer structure). The work suggested in [13] has given an approximate optimum value for the matching slab dielectric constant under oblique incidence but only for thick absorbers (minimal height slightly thicker than one-fourth of the wave length). The aim of this paper is to introduce a compensation technique for near-perfect ultrathin absorbers ($h < \lambda/10$) while retaining the ultrathin single-layer feature. The absorption mechanism of ultrathin absorbers has been studied in detail under normal incidence ($\theta = 0^\circ$), and an equivalent-circuit model has been formulated accordingly for the ultrathin grounded patch elements [19]. As demonstrated in [19], for an incident TM plane wave in z-direction ($E_x$ & $H_y$ field components), the patch absorber can be represented by two anticipated absorbing slots of width ($W_p$) and height ($h$) separated by the distance ($L_p$). These two slots can give an approximate account for structure resonance absorption following the equations incorporated in this section.

The total input impedance $Z_{in}$ calculated at the angular frequency $\omega$ of the ultrathin patch absorber is verified in [19] as a series combination of two identical parallel RLC circuit models and is given by Equation (1):

$$Z_{in}(\omega) = \frac{2}{\frac{1}{RRLC} + \frac{1}{j\omega LRLC} + j\omega CRLC}$$

(1)

where $R_{RLC}$, $L_{RLC}$, and $C_{RLC}$ are the circuit model resistance, inductance, and capacitance. Based on transmission line model equations and basic concepts of electromagnetic theory [15, 21], those lumped parameters are related to absorber physical dimensions using the non-rigorous equations verified in [19] and given by Equations (2-4):

$$C_{RLC} = \frac{W_p}{\eta\lambda\omega} [1 - 0.636 \ln(kh)]$$

(2)

$$L_{RLC} = \frac{L_p}{W_p} \frac{\eta \sqrt{\varepsilon_{eff}}}{\cos \theta}$$

(3)

$$R_{RLC} = \frac{h}{\sigma L_s W_s}$$

(4)

where $\lambda$ is the material space wavelength, $k$ is the wave number, $\eta$ is the characteristic impedance for the dielectric material, $\varepsilon$ is the velocity in free space, $\sigma$, and $\varepsilon_{eff}$ is the conductivity of the effective substrate permittivity of the substrate calculated using the formulas presented in [21]. $L_p$ and $W_p$ are the patch length and width, and $L_s$ and $W_s$ are the periodic cell length and width. Hence, the input impedance can be analytically calculated for minimal reflection at free space matching ($Z_{in} = Z_0$) and max absorption accordingly at the resonance frequency ($f_0 = 1/2\pi\sqrt{LC}$). However, no dependence on the angle of incidence can be observed. Therefore, absorber cell input impedance ($Z_{in}$) should be varied by a factor relative to the angle of incidence ($\theta$) to be able to analytically calculate an equivalent value under oblique incidence. The oblique compensation factors introduced in the next section are guided by comparable analogy to the absorption response and patch antenna far-field pattern reported earlier in [20]. The outcome of the work presented in the next sections aids in the design implementation of a non-complicated planar single-layer ultrathin absorber with enhanced angular stability and polarisation insensitivity.

3 | INPUT IMPEDANCE COMPENSATION UNDER OBLIQUE INCIDENCE

Absorption deterioration results from the mismatch between free space and absorber input impedance as discussed earlier. A correlation can be considered between the decaying response of the absorbance TM/ transverse electric (TE) pattern and the far-field E/H plane [20]. The compensation factors are then suggested ($F_{TM}$ and $F_{TE}$) following the analytical equations
reported in [21] for the E-plane ($\varphi = 0^\circ$) and H-plane ($\varphi = 90^\circ$), respectively:

\[
F_{TM} = \left(\frac{\sin \left(\frac{\omega L_p}{2}\sin(\theta)\right)}{\omega L_p \sin(\theta)}\right) \left(\frac{\sin \left(\frac{\omega b}{2}\cos(\theta)\right)}{\omega b \cos(\theta)}\right)
\]

\[
F_{TE} = \cos(\theta) \left(\frac{\sin \left(\frac{\omega L_p}{2}\sin(\theta)\right)}{\omega L_p \sin(\theta)}\right) \cos \left(\frac{\omega b}{2}\cos(\theta)\right)
\]

where $k$ is the wave number, $b$ is the substrate height, $L_p$ is the patch length, and $\theta$ is the angle of incidence. Variation of the input impedance with the incidence angle $\theta$ can be estimated by multiplying the unit cell impedance $Z_{in}$ (see (1)) under normal incidence by $F_{TM}$ and $F_{TE}$. Therefore, the formulated RLC equations are now extended for oblique incidence, where the reflection coefficient $S_{11}$ and the absorption value $A_1$ can be calculated analytically for each polarisation at the design resonance frequency. The absorption is only affected by the reflection parameter due to the presence of the ground metallic layer blocking any transmission effect:

\[
Z_{in-\text{oblique-TM}}(\omega) = Z_{in}(\omega)F_{TM}
\]

\[
Z_{in-\text{oblique-TE}}(\omega) = Z_{in}(\omega)F_{TE}
\]

\[
S_{11-\text{T M}}(\omega) = \frac{Z_{in-\text{oblique-TM}}(\omega) - Z_0}{Z_{in-\text{oblique-TM}}(\omega) + Z_0}
\]

\[
S_{11-\text{TE}}(\omega) = \frac{Z_{in-\text{oblique-TE}}(\omega) - Z_0}{Z_{in-\text{oblique-TE}}(\omega) + Z_0}
\]

\[
A_{TM}(\omega) = 1 - (S_{11-\text{T M}}(\omega))^2
\]

\[
A_{TE}(\omega) = 1 - (S_{11-\text{TE}}(\omega))^2
\]

where $Z_0$ is the free space impedance (377 $\Omega$) and $\omega$ is the design angular frequency ($2\pi f$). Following the proposed approach, control of the real impedance value $R$ (see Equation (4)) to achieve free space impedance matching for each angle of incidence $\theta$ at a certain resonance frequency ($f_0$) can be realised. In order to verify this concept, a variation in cell size using a square substrate dimensions ($L_0 = W_0$) is held for the grounded FR-4 single-layer patch element (see Figure 1) with physical dimensions $L_p = W_p = 8$ mm, $b = 0.8$ mm, $\varepsilon_r = 4.3$, and $\tan \delta = 0.025$ at resonance $f_0 = 8.5$ GHz. The lumped parameters ($L$ and $C$) are calculated at resonance to be 2.5607 nH and 0.13775 pF, respectively—see Equations (2) and (3)—while control of the real impedance value $R$ is calculated according to the substrate size variation; see Equation (4). The reflection coefficient $S_{11}$ is then calculated (see Equations (9) and (10)) under oblique incidence with increasing $\theta$. As shown in Tables 1 and 2, for $\theta = 0^\circ$, a cell size of 1.754 is required to achieve near-unity absorption for both polarisations. However, for $\theta = 80^\circ$, the cell size differs for each of the two polarisations, and it also differs for the values $0^\circ < \theta < 80^\circ$. Two fundamental conclusions can be drawn from the preceding tables: each angle can achieve high absorption response with a corresponding specific substrate size, and each of the two polarisations (TE/TM) responds differently.

This concept provides a physical understanding of absorption performance; rectangular substrate cells ($L_a = W_a$) can achieve better response for each of the two polarisations, and multiple adjacent ($N$) subcells forming the absorber unit cell can provide more stable performance. A wide-angle planar ultrathin absorber configuration is implemented in the next section following the guidelines for oblique incidence enhancement for both modes simultaneously.

### Table 1
Calculated $S_{11}$ (dB) for transverse electric mode with variable cell size ($L_a = W_a = m\lambda$) under oblique incidence

| $\theta$ (°) | $\theta = 0^\circ$ | $\theta = 20^\circ$ | $\theta = 40^\circ$ | $\theta = 60^\circ$ | $\theta = 80^\circ$ |
|------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| $m = 0.75$ | -3.2            | -3.4            | -4.3            | -5.67           | -8.61           |
| $m = 1.25$ | -10.1           | -11.3           | -17.33          | -15.27          | -4.13           |
| $m = 1.75$ | -26.5           | -21.96          | -10.86          | -2.9            | -0.9            |
| $m = 2.25$ | -9.2            | -8.3            | -2.3            | -0.03           | -0.009          |

### Table 2
Calculated $S_{11}$ (dB) for transverse magnetic mode with variable cell size ($L_a = W_a = m\lambda$) under oblique incidence

| $\theta$ (°) | $\theta = 0^\circ$ | $\theta = 20^\circ$ | $\theta = 40^\circ$ | $\theta = 60^\circ$ | $\theta = 80^\circ$ |
|------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| $m = 0.75$ | -3.2            | -3.28           | -3.57           | -3.34           | -1.6            |
| $m = 1.25$ | -10.1           | -16.46          | -15.14          | -10.7           | -7.19           |
| $m = 1.75$ | -26.5           | -25.34          | -17.2           | -5.44           | -3.52           |
| $m = 2.25$ | -9.2            | -7.28           | -1.87           | -0.03           | -0.43           |

### 4. SINGLE-LAYER WIDE-ANGLE ULTRATHIN PATCH ABSORBER DESIGN IMPLEMENTATION

The developed analysis has concluded that for given substrate parameters ($\varepsilon_r$, $\tan \delta$, and $b$), the absorption resonance
frequency is controlled through the metallic patch dimensional variations \(L_p\) and \(W_p\), while the absorption amplitude ratio is controlled through substrate dimensional variations \(L_s\) and \(W_s\) with no significant effect on the resonance frequency (see Equations (1)–(4)). The design methodology proposed in this section is based on using multiple adjacent subcells \(N\) add another degree of freedom for the input impedance parameter. The total effective input impedance of the \(N\) subcell pattern of the absorber structure can be calculated as an average effective impedance \(Z_{\text{in-average}}\) using Equation (13):

\[
Z_{\text{in-average}}(\theta_0) = \frac{1}{N} \sum_{n=1}^{N} Z_{\text{in-oblique}-n}(\theta_0)
\]  

(13)

where \(Z_{\text{in-oblique}-n}\) is the \(n\) subcell input impedance calculated under oblique incidence for each polarisation separately (see Equations (7) and (8)). For all \(n\) subcells, \(L\) and \(C\) parameters are kept constant at this point to achieve similar resonance frequency, and hence the patch dimensions \(L_p\) and \(W_p\) are fixed values. Starting with two adjacent \((N = 2)\) subcell patterns, the lumped parameters \((L\) and \(C\)) are calculated to be 2.5607 nH and 0.13775 pF, respectively, at resonance \(f_0 = 8.5\) GHz. At resonance, following the proposed equations (see Equations (1)–(13)), the inductive reactance is cancelled by its capacitive counterpart, thus leaving the total effective input impedance purely resistive. The real part of the average effective impedance \((R_0)\) is then considered to achieve free space matching under oblique incidence. Achieving the required values for real impedances (for minimal reflection) at the design frequency \(f_0\) under oblique incidence \((\theta_0)\) results in different substrate dimensions \((L_s\) and \(W_s\)) for each \(\theta\). The real impedance variation \((R_0)\) with different values of \((\theta_0)\) for the proposed design is plotted (see Figure 2).

The calculated geometrical dimensions for the proposed enhanced design structure (see Figure 3) are extracted using the proposed equations (see Equations (1)–(13)). Note that a \((2 \times 2)\) rather than \((2 \times 1)\) subcell pattern is used to create a symmetrical absorber configuration to achieve the polarisation insensitivity property [7, 8, 12].

Furthermore, a prototype is fabricated for theory validation. The measurement test setup is held where two horn antennas were used to measure the reflections from the absorber (see Figure 4). The distance from horn antennas is considered as far as possible to realise normal incident plane wave. The horn antennas are then rotated to achieve oblique incidence. The measurement setup is usually done in two steps: firstly, the reflection coefficient is calculated for a full ground plane (total reflection); then, the ground plane is replaced with the absorber prototype, and the reflection coefficient is measured relative to that of the ground plane.

The frequency response of scattered samples was measured for both polarisations (see Figures 5 and 6) up to \(45^\circ\) due to measurement setup limitations (cable rotational movements).

The results demonstrate better performance and a more stable multicell \((2 \times 2)\) absorber configuration under oblique incidence than those for a single-cell \((1 \times 1)\) configuration (see Figure 7 and 8). The wide-angle polarisation-insensitive planar ultrathin absorber configuration proposed features 51% and 58% absorption up to \(80^\circ\) oblique incidence for TE and TM polarisations, respectively, with a fractional bandwidth of 5% at 8.5 GHz. Even though a slight deviation between the calculated and the measured samples is noted, a better physical insight can be realised on the absorption performance for both polarisations. This deviation might go back to the assumption of a lossless metallic layer \(R\) only represents a lossy substrate) and the existence of fabrication errors as well.

The proposed design has shown relatively enhanced absorbance for both polarisations. Furthermore, previous techniques that realised wide angles of incidence were applied for fair comparison (see Table 3).

Following reference [13, 14], the multilayer absorber shows improved performance for both polarisations. The via structure reported in reference [16] provides better results for the TE polarisation and worse performance for the TM polarisation. The 3-D configuration following reference [18] showed stable performance for both polarisations. However, the simplicity of the proposed planar single-layer design has an additional feature when compared to the complexity of the reported structures. Of note, increasing the number of cells may lead to enhanced stable performance under oblique incidence. But with a greater number of cells, the matching condition for the total average of the input impedance may not be fulfilled. Finally, this work is being combined with previous studies to further investigate and achieve a scalable wideband patch absorber with optimised angular stability for both TE and TM polarisations.

5 | CONCLUSION

An equivalent-circuit model analysis is formulated for an ultrathin grounded absorbers under oblique incidence. A compensation technique for the impedance variation with the
angle of incidence ($\theta$) is proposed. This modification is based on a comparable analogy for the absorbance pattern of patch structure and the far-field radiation pattern of a single-patch antenna. The wide-angle polarisation-insensitive planar ultra-thin absorber configuration proposed features 51% and 58% absorption up to 80° oblique incidence for TE and TM polarisations, respectively. The design methodology proposed is based on using multiple subcells ($N$) of simple single-layer patches to add another degree of freedom for the design equations and retain the ultrathin planar feature. Moreover, a prototype was fabricated for verification, and a comparison summary with previously reported techniques is presented to validate the competence of the proposed work.
Figure 8: Comparison between proposed calculated response and measured samples for transverse electric polarization.

Table 3: Summary of various design simulation results under oblique incidence.

| Absorber configuration | Angle of incidence (θ) | TM Absorbance (%) | TE Absorbance (%) |
|------------------------|------------------------|-------------------|-------------------|
| Conventional pattern (1 × 1) | 0° | 99 | 78 |
|                        | 60° | 99 | 62 |
|                        | 80° | 99 | 62 |
|                        | 80° | 99 | 62 |
|                        | 80° | 99 | 62 |
| Proposed pattern (2 × 2) | 0° | 99 | 80 |
|                        | 60° | 99 | 60 |
|                        | 80° | 99 | 60 |

Abbreviations: TE, transverse electric; TM, transverse magnetic.

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