Design of a planar periodic lossy magnetic surface to improve active array patterns with enhanced isolation

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Abstract: This study proposes the design of the periodic lossy magnetic (PLM) surface with a low profile for enhanced array characteristics. The proposed PLM surface consists of multiple rectangular grooves with equal spacing, and the grooves are filled with lossy magnetic materials to increase the surface impedance between array elements to mitigate the mutual coupling. To verify its feasibility, the authors fabricate a two-element circularly-polarised patch antenna array with the PLM surface inserted into the ground plane and measure antenna characteristics in a fully anechoic chamber. The results demonstrate that the PLM surface is capable of reducing the mutual coupling so that the active array patterns can be improved with higher front-to-back ratios and lower active reflection coefficients for large steering angles.

1 Introduction

Antenna arrays have become essential in a wide range of applications to form directive active array patterns so that the array can maintain more reliable wireless communication links towards desired directions [1, 2]. The reliability of using the array, however, is often degraded by the mutual coupling between array elements that distort the active element patterns [3, 4], and this pattern distortion becomes more significant in the lower hemisphere due to an unnecessary increase of the back radiation when an array is mounted on a small finite ground [5]. From the beamforming perspectives, the distorted active element patterns also affect the active array patterns, which results in degraded beamforming performances, e.g. the low front-to-back ratio (FBR) and higher active reflection coefficients, especially for large steering angles [6, 7]. Thus, a lot of effort has been made to reduce the mutual coupling so as to achieve the enhanced active array patterns. It is well known that inserting additional slots or cavity walls into the ground platform is an effective scheme of improving the isolation characteristics, which blocks or consumes the electromagnetic (EM) energy coupled between nearby antennas [8–14]. However, the additional structure perturbs the active element pattern due to the wave reflection and diffraction, thereby increasing the fluctuation in the active array pattern. Although Kildal et al. introduced the corrugated structures in which a low-impedance perfect electric conductor and a high-impedance artificial magnetic conductor (AMC) are repeated to mitigate the effect of the mutual coupling [15–17], the corrugations require a depth of about a quarter wavelength at the operating frequency. To reduce the volume of the corrugated structure, a lot of effort has been made, e.g. metallic strips that are short-circuited to the ground using metallic vias were applied in [18]. EM band-gap structures also found their suitability for miniaturising the corrugations as proposed in [19–21].

In this study, we propose the design of the periodic lossy magnetic (PLM) surface with a low profile to improve the isolation for enhanced array characteristics in small arrays. The proposed PLM surface provides a new approach to the realisation of the AMC using lossy magnetic materials as a replacement for the corrugated structure. The proposed PLM surface consists of multiple rectangular grooves with equal spacing, and the grooves are filled with lossy magnetic materials to mitigate the mutual coupling by increasing the surface impedance between array elements. Since the increased surface impedance helps to reduce the electric currents and near-fields induced on the finite ground plate, the back radiation of the active element pattern can also be minimised, which results in increased FBR. In addition, the reduced mutual coupling minimises the variation in the active reflection coefficient, and thus the scan blindness of the active array pattern can be relieved for larger steering angles [7]. To verify the feasibility of the proposed design, we fabricate a two-element circularly-polarised patch antenna array with the PLM surface inserted into the ground plane and measure the antenna characteristics of reflection coefficients, mutual coupling, and active element patterns in a fully anechoic chamber. The results demonstrate that the PLM surface can improve the isolation, and both the active element and the active array patterns have higher FBRs with lower active reflection coefficients for large steering angles compared with the array without the PLM surface.

2 Proposed PLM surface

2.1 Magnetic properties of PLM surface

Fig. 1a shows the corrugated structure that is inserted into the ground plane between two antennas. The conducting surfaces at the top of the ridges have low impedance, and the virtual surfaces between ridges operate as the high-impedance AMC when the depth of the corrugated structure is a quarter wavelength [22]. Thus, the mutual coupling between array elements decreases because the tangential components of the electric and magnetic near-fields become close to zero at the surfaces of the ridges and the AMCs, respectively [23]. However, the one-quarter depth of the corrugation makes the structure impractical for electrically small arrays. As an alternative approach, we propose the planar PLM surface replacing the corrugated structure by a lossy magnetic material to achieve EM properties similar to the high-impedance AMC even with an extremely thin profile, as shown in Fig. 1a. Generally, the magnetic material has a higher relative permeability at low frequencies; however, the value gradually decreased as the frequency increased, while the magnetic loss tangent raised at higher frequencies. The magnetic loss tangent tan $\delta_m$ can be written as

$$\tan \delta_m = \frac{\sigma_m}{\omega \mu}, \quad (1)$$

where $\sigma_m$ is the magnetic loss conductivity, $\mu$ is the magnetic permeability, and $\omega$ is the angular frequency.
where \( \sigma_m \) and \( \omega \) represent the magnetic conductivity and the angular frequency, and \( \mu' \) and \( \mu'' \) are the real and imaginary parts of the permeability. Note that the permeability of the lossy magnetic material can be written as

\[
\mu = \mu_0 \mu_r \left(1 - j \tan \delta_m \right),
\]

where \( \mu_0 \) indicates the vacuum permeability and \( \mu_r \) represents the relative permeability. To explore the EM properties of the magnetic material, we calculate the reflection coefficient (\( \Gamma \)) for a plane-wave source that normally incidents from the free space to a medium filled with the magnetic material, as

\[
\Gamma = \frac{\eta_1 - \eta_0}{\eta_1 + \eta_0},
\]

where \( \eta_0 \) and \( \eta_1 \) indicate the intrinsic impedances of the free space and medium, as defined in (4) and (5), respectively.

\[
\eta_0 = \sqrt{\mu_0 / \varepsilon_0},
\]

\[
\eta_1 = j \alpha_\mu / \gamma
\]

and the values of \( \Gamma \) are obtained by varying \( \mu_r \) from 1 to 20 and \( \tan \delta_m \) from 1 to 22, as shown in Fig. 2a. Since a value of \( \Gamma \) close to +1 indicates that the magnetic material used in the proposed PLM surface has similar EM properties to the AMC of the corrugated structure, we maintain an absolute permeability value (defined as \( |\mu| > 5 \times 10^{-5} \) H/m) by increasing the value of either \( \mu_r \) or \( \tan \delta_m \). For instance, \( \Gamma \) has the value of >0.5 when \( \mu_r \geq 8 \) or \( \tan \delta_m \geq 2 \). Fig. 2b examines the value of \( \Gamma \) by varying \( \tan \delta_m \) for a given \( \mu_r \), and Fig. 2c shows variations of \( \Gamma \) for a given \( \tan \delta_m \) according to the \( \mu_r \) values. From these observations, we verify that the value of \( \Gamma \) increases logarithmically as the values of \( \mu_r \) and \( \tan \delta_m \) become greater. In our approach, we realise EM properties similar to the AMC using an off-the-shelf ferrite sheet, manufactured by E-song EMC (Model: SRA34), having the properties of \( \mu_r = 8 \) and \( \tan \delta_m = 2 \) [24]. These properties are suitable to achieve the reflectivity of \( \Gamma = 0.66 \), and the product is thin and flexible so the sheet can be easily fitted into desired shapes. The isolation improvement converges when \( \Gamma > 0.66 \), which implies that the magnetic properties of SRA34 are effective to achieve a similar behaviour as the AMC in the PLM surface due to the power dissipation within the lossy magnetic materials.

Fig. 1 Conceptual geometry of the periodic structure
(a) Corrugated structure, (b) PLM surface

Fig. 2 Reflection coefficients of the plane wave incident to the lossy magnetic medium
(a) Reflection coefficients according to the EM properties of the lossy magnetic material, (b) Reflection coefficients according to \( \tan \delta_m \) for various \( \mu_r \) values, (c) Reflection coefficients according to \( \mu_r \) for various \( \tan \delta_m \) values
Table 2 Variations of the antenna characteristics according to the material properties

<table>
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<th>$\tan \delta_m$</th>
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</tr>
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<td>-30.1</td>
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</table>

2.2 Geometry of two-element array with PLM surface

To confirm the feasibility of the PLM surface, we apply the proposed structure to controlled reception pattern antenna arrays for mitigating the effect of intentional interferences, where multiple global positioning system antennas are often adopted in extremely small aperture areas as discussed in [25–28].

Fig. 3 shows a two-element microstrip patch antenna array with the proposed PLM surface inserted into the ground plane. The PLM surface consists of $N$ rectangular ferrite strips of the width $w_f$, length $l$, and gap $g_f$, respectively. The radiating patches are fed by coaxial probes at $d_t$ off-centre and are designed to resonate at 1.575 GHz with an edge length $w_p$. The edge-to-edge distance between the two patches is denoted as $d$, and two corners of each patch are truncated by length $t$ to achieve circular polarisation. The patches are then printed on a high-dielectric ceramic substrate with the EM properties of $\varepsilon_r$ and $\tan \delta$, and the substrate has a size of $g_x \times g_y$ and a thickness of $h_p$. The initial values of $g_x$ and $w_t$, which indicate the interval and width of the ferrite strips, are estimated to be 0.4 and 4 mm to satisfy the soft surface condition [15]. The length of the ferrite strips ($l$) is determined to be about $\lambda_0/2$, which is half the size of the finite ground ($g_y$). For more effective isolation improvement with an increased FBR in the active array pattern, these parameters are optimised by a genetic algorithm in conjunction with the FEKO EM simulator [29, 30], and the optimised values are listed in Table 1. The optimised PLM surface has five ferrite strips, and the optimised values of $w_f$, $l$, and $g_f$ are 2, 36, and 0.5 mm, respectively. The width $w_f$ of the ferrite strips is four times greater than the gap $g_f$, which implies that the high-impedance surface should be larger than that of the low-impedance conducting surface for improved active element patterns with the enhanced isolation.

To further verify the validity of the lossy properties in the PLM surface, we observed variations in the mutual coupling and the active element patterns by changing the value of $\tan \delta_m$ from $10^{-5}$ to 6, as listed in Table 2. The mutual coupling is $<-26$ dB when $\tan \delta_m > 1$ with the maximum improvement of 7.3 dB (from −23.4 to −30.7 dB) at $\tan \delta_m = 5$. Note that the bore-sight gain is maintained to be $>1.5$ dBiic throughout the entire range of the loss tangent. Therefore, the magnetic material of the proposed PLM surface should have $\tan \delta_m$ values $>1$ to operate effectively as the high-impedance AMC. Table 3 provides the relation between the bandwidth and the periodicity of the PLM surface. We calculate the frequency bandwidth with the isolation improvement of $>10$ dB compared with the array without the PLM surface. As can be seen, the bandwidth tends to broaden as the number of ferrite strips increases, e.g. the bandwidth is 12 MHz with $N=1$ and improved to 29 MHz when $N=7$. It is important to note that the electrical sizes, determined by $w_f$ and $g_f$, also help to enhance the bandwidth of the isolation improvement.

3 Measurement and analysis

3.1 Fabrication and measurement

Fig. 4 shows photographs of the two-element array fabricated on the high-dielectric ceramic substrate that is produced by sintering the moulded ceramic powder with the dielectric properties of $\varepsilon_r = 20$ and $\tan \delta = 0.0035$ [31]. This high-dielectric substrate is employed for miniaturising the aperture size of the array to verify the feasibility of the isolation improvement in such harsh environments with strong surface waves. The shape of the patch and the ground with five rectangular grooves is printed on the ceramic substrate through the thermal decomposition of copper, and the ferrite sheets are tailored to fit the size of the rectangular grooves to realise the high-impedance areas of the PLM surface. We also fabricate a two-element array without the PLM surface to...
validate its effectiveness in terms of antenna properties, such as the impedance matching, mutual coupling, bore-sight gain, and active element patterns.

Fig. 5 presents a comparison between the measured and simulated s-parameters and bore-sight gain. Fig. 5a is the impedance matching characteristics of Ant. 1 according to the existence of the PLM surface between antennas. The results are obtained when Ant. 1 is fed by a coaxial probe, while the port of Ant. 2 is terminated by a 50-Ω load. The simulated results that are indicated by dashed and dash-dotted lines have values of −9.3 and −13.7 dB with and without the PLM surface, respectively, at 1.575 GHz. The solid and dotted lines indicate the measured results, and the values at 1.575 GHz are −16.2 and −13.3 dB, which implies that the PLM surface does not cause a negative effect on the impedance matching characteristics of individual array elements. Fig. 5b shows a comparison of the mutual coupling between array elements according to the PLM surface. Without the PLM surface, a resonant behaviour appears at 1.55 GHz due to the finite ground with the antenna spacing of \( d = 40 \) mm. The simulated and measured coupling strengths are −18.94 dB at 1.575 GHz and −14.8 dB at 1.575 GHz, respectively, and these values are decreased to −28.99 and −29.48 dB by inserting the PLM surface. Consequently, the isolation is improved by 10.05 dB for simulation and 14.68 dB for measurement with the use of the PLM surface. This isolation improvement can be achieved when the periodic structure is accompanied by the lossy magnetic material. The high-refractive index is not the major cause of the isolation improvement since the SRA34 that is modelled in our simulation has no dielectric loss and its relative permittivity is assumed as \( \varepsilon_r \approx 1 \).

Fig. 5c shows variations in bore-sight gains obtained from active element patterns of Ant. 1. The simulated bore-sight gains are 0.85 dBiC (without the PLM surface) and 0.71 dBiC (with the PLM surface). These values agree well with the measured results that are slightly decreased from 1.91 to 1.76 dBiC due to the PLM surface. The simulated bore-sight gains are 0.85 (without the PLM surface) and 0.71 dBiC (with the PLM surface) with the total efficiency of 49 and 45%, respectively. This gain reduction of <0.2 dB is caused by the increase of the axial ratio that is slightly raised from 2.3 to 3.6 dB and can be compensated by the other advantages of using the PLM surface, e.g. reduced mutual coupling, lower active reflection coefficients, improved active array patterns, and higher FBRs, which will be discussed in Section 3.2.

Figs. 6a and b present the active element patterns in the \( zx \)- and \( zy \)-planes at 1.575 GHz. The simulated and measured half-power beam widths averaged in the \( zx \)- and \( zy \)-planes are 102.7° and 105° with the PLM surface, and 104.6° and 105° without the PLM surface, which demonstrates that the PLM surface does not affect...
the patterns in the upper hemisphere. In addition, the back radiation at \( \theta = 180^\circ \) is reduced from \(-8.3\) to \(-9.8\) dB for simulation and from \(-6.2\) to \(-7.8\) dB for measurement; thus, the simulated and measured FBRs for active element patterns are improved by 1.25 and 1.33 dB, respectively.

### 3.2 Analysis

Fig. 7 shows the H-field distributions of the two-element array at a cross section: \(-50\) mm \( \leq x \leq 50\) mm, \(y = 0\) mm, \(-5\) mm \( \leq z \leq 15\) mm, when the Ant.1 is excited with an amplitude of 1 V while the port of Ant. 2 is terminated by a 50 \( \Omega \) load. The H-field distribution without the PLM surface is shown in Fig. 7a and the distribution with the PLM surface is shown in Fig. 7b. Without the PLM surface, strong fields are observed near the patch of Ant. 2 at \(P_1 (x = 2.5, \ z = 4.9)\) with a value of 9.4 dBA/m, and the strength in the centre of the ground surface at \(P_2 (x = 0, \ z = 0)\) is calculated as \(-4.7\) dBA/m. Since the mutual coupling is improved by the increased surface impedance, the strengths of the fields propagated from Ant. 1 are decreased to 6.6 and \(-7.5\) dBA/m at \(P_1\) and \(P_2\), respectively. It should also emphasise that the field strength below the ground plate at \((x = 0, \ z = -30)\) is reduced from \(-13.8\) to \(-15.2\) dBA/m which allows for such improved FBRs.

Fig. 8 shows the distribution of electric current induced on the ground plane with and without the PLM surface at 1.575 GHz. The positions of radiating patches are specified by dotted lines, and the location of the PLM surface is indicated by a dashed line. As observed in the H-field distributions, strong electric currents are induced on the PLM surface, which lowers the current intensity in proximity to Ant. 2. For example, the maximum current strength near the port of Ant.2 is reduced from 29.13 to 23.67 dBA/m due to the PLM surface, while the current intensity near the port of Ant. 1 is maintained as 45 dBA/m for both results. Fig. 8 shows the distribution of electric current induced on the ground plane with and without the PLM surface at 1.575 GHz. The positions of radiating patches are specified by dotted lines, and the location of the PLM surface is indicated by a dashed line. As observed in the H-field distributions, strong electric currents are induced on the PLM surface, which lowers the current intensity in proximity to Ant. 2. For example, the maximum current strength near the port of Ant.2 is reduced from 29.13 to 23.67 dBA/m due to the PLM surface, while the current intensity near the port of Ant. 1 is maintained as 45 dBA/m for both results.

Fig. 9a shows FBR variations of active array patterns according to the steering angles from \( \theta = 0^\circ \) to \( \theta = 80^\circ \). At each steering angle, the FBR of the active array pattern is calculated as the gain difference between the main lobe and the back lobe placed at an angular difference of 180°. Without the PLM surface, the FBR tends to increase gradually from 9.1 to 16.3 dB as the steering angle increases. Since the PLM surface reduces the back radiation without significant gain reduction, as discussed in Section 3.1, the average FBR is improved by 5.1 dB with the use of the PLM surface. In addition, the maximum improvement of 11.3 dB is observed when the steering angle is increased to 70°. Fig. 9b
Comparison of the simulated FBRs, (b) Comparison of the measured and simulated active reflection coefficient

\[ u = k_0 \sin \theta, \quad (6) \]

where \( k_0 \) is the propagation constant in free space, and \( a \) is the inter-element spacing between antennas. The active reflection coefficient, introduced in [3], is often used as a figure-of-merit of phased antenna arrays and is defined by

\[ \Gamma_{\text{Active}}(\theta) = \frac{\sum_{m=1}^{N} S_{mm} e^{-j\mu m - j\mu n}}{e^{-j\mu m - j\mu n}} = \sum_{n=1}^{N} S_{nn} e^{-j\mu m - j\mu n}, \quad (7) \]

where \( N \) is the number of antenna elements, and \( S_{mn} \) represents a component of the \( N \times N \) scattering matrix in the \( m \)th column and \( n \)th row. The steering angle is adjusted from \(-90^\circ\) to \(90^\circ\) at an angular interval of \(1^\circ\), and the active reflection coefficients are calculated for each steering angle to evaluate the effectiveness of the PLM surface. The simulated value of \( \Gamma_{\text{Active}} \) drastically increased from \(-20\) to \(-12.7\) dB without the PLM surface when the steering angle is \(\theta \geq 30^\circ\), which reduces the gain of active array patterns. On the other hand, \( \Gamma_{\text{Active}} \) values to prevent the scan blindness in the active element pattern [3, 4].

Figs. 10a and b provide parametric studies of the bore-sight gain and the mutual coupling according to the width \( w_f \) and gap \( g_f \) of the PLM surface. The bore-sight gain tends to decrease as the values of \( w_f \) and \( g_f \) increase, and the gains become even \(<0\) dBic when \( w_f \geq 3 \) mm or \( g_f \geq 2 \) mm. Such gain reduction is caused when the overall width of the PLM surface in the longitudinal direction exceeds the edge-to-edge distance between antennas because the PLM surface is placed in close proximity to the radiating edge of the antenna. In terms of the mutual coupling, a drastic drop appears at \( w_f = 2 \) mm and \( g_f = 0.5 \) mm with the minimum coupling strength of \(-28.99\) dB, which is due to the resonance behaviour of the PLM surface. The frequency response of the resonance can be adjusted by tuning the values of \( w_f \) and \( g_f \) and the bandwidth of the resonance is closely related to the periodicity \( N \). These results indicate that the PLM surface should have wider high-impedance areas with narrow low-impedance conducting surfaces, and its overall width should fit within the edge-to-edge distance for more effective improvement in the mutual coupling without the distortion of active element patterns. Table 4 shows the operating frequency, antenna spacing \( d \), relative permittivity \( \varepsilon_r \), the polarisation of the antenna, and isolation improvements in comparison with other existing works presented in [18–21]. The papers dealt with \( d > 0.5\lambda_0 \) and focus on the linear polarisation (LP) with lower \( \varepsilon_r \) values to prevent the surface waves. The isolation improvement of the adjacent element with circular polarisation (CP) is more challenging compared with that with LP because the electric currents of the CP antenna array are induced in the ground plane by both transverse electric (TE) and transverse magnetic (TM) wave components, while those of the LP antenna array are caused by either TE or TM wave. The proposed PLM surface is applied for an array with \( d = 0.1\lambda_0 \) and \( \varepsilon_r = 20 \), and each array element is circularly polarised. The isolation improvement of the PLM surface is \(14.68\) dB and is greater than the improvements found in other papers, which supports the effectiveness of the proposed approach.
4 Conclusion

We investigated the design of the PLM surface to improve the active array patterns with enhanced isolation characteristics. To realise the high-impedance AMC surface, we inserted the lossy magnetic material in multiple rectangular grooves of the ground, and the feasibility of the proposed structure was then verified by fabricating the two-element circularly-polarised patch antenna array with PLM surface. Antenna characteristics were measured in the full anechoic chamber to compare the results with the simulation. The mutual coupling between array elements was improved by 14.68 dB at 1.57 GHz, and the gain reduction due to the PLM surface was <0.2 dB. From the active array pattern standpoint, the back radiation in the active element patterns was reduced by 1.48 dB, which improved the FBR with the maximum enhancement of 11.3 dB at the steering angle of 70°. The scan blindness was also relieved because the active reflection coefficients were decreased from ~12.4 to ~14.1 dB for the large steering angle of θ = 90°. The results demonstrate that the PLM surface is more suitable for small antenna arrays due to its low profile and allows for achieving the reduced mutual coupling with higher FBRs in the active array patterns.

5 Acknowledgments

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6 References


Table 4 Comparison of isolation improvements to existing results in the literature

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