Design of Parabola-Shaped Planar Lossy Magnetic Surface for Improved Isolation Characteristic Between GPS Array Elements With Circular Polarization Property

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***Abstract*—This letter proposes the design of a parabola-shaped planar lossy magnetic (PLM) surface for improving the isolation characteristic of Global Positioning System (GPS) arrays. The proposed surface consists of multiple parabolic grooves that are filled with lossy magnetic material that allows the resulting surface to serve as an artificial magnetic conductor. A four-element GPS array with and without the proposed surface is fabricated and measured in a full-anechoic chamber to demonstrate the feasibility of the parabola-shaped PLM surface. The results confirm that the developed surface is suitable for improving the isolation characteristic for GPS arrays while minimizing array pattern gain reduction at increased steering angles.**

***Index Terms*—Global Positioning System (GPS) array, isolation characteristic, parabola-shaped planar lossy magnetic (PLM) surface.**

I. Introduction

ANTENNA arrays have been widely employed in Global Positioning Systems (GPSs) to minimize the degradation of position estimation performance due to intentional jamming by steering pattern nulls to jamming directions [1]–[4]. Since the number of possible pattern nulls is proportional to the array element number, the antijamming performance in general can be improved by increasing the number of array elements. However, an increase in the number of antenna elements causes high mutual coupling, which distorts the radiation pattern, and such pattern distortion becomes more significant as the steering angle increases. Therefore, the isolation between adjacent elements should be considered an important design parameter to maximize the interference mitigation capability, especially in extremely small arrays. The isolation characteristic can be enhanced by inserting a soft surface consisting of perfect electric conductor and perfect magnetic conductor (PMC) plates, which reduce the tangential components of the electric and magnetic fields, respectively, on the ground surface [5]–[7]. Although such soft surfaces can improve the isolation characteristic effectively, the PMC parts require a depth of a quarter wavelength at the operating frequency, and this volume is not suitable for GPS array systems due to the resulting increase in size. Thus, a planar periodic lossy magnetic (PLM) surface that acts as an artificial magnetic conductor (AMC) by using lossy magnetic materials is introduced to reduce the volume of these soft surfaces [8]. Most studies that aim to reduce mutual coupling are focused on linearly polarized (LP) antenna elements, where single-axis tangential electric field components are predominant on the ground plane. Therefore, a more in-depth research is required to improve the isolation characteristics of other polarized antennas, such as circularly polarized GPS antennas with nonuniform field distributions on the ground plane.

In this letter, we propose the parabola-shaped PLM surface, which improves the isolation characteristic between GPS array elements having a circular polarization (CP). The proposed surface consists of multiple parabolic grooves filled with lossy magnetic materials to realize the AMC, which can reduce mutual coupling with a thin thickness. In addition, each focal point of the parabola-shaped grooves is optimized to effectively block the nonuniformly distributed near-field components between the CP antenna elements. The mutual coupling can be reduced by inserting the proposed parabola-shaped PLM surface into the ground plane; at the same time, the significant pattern distortion occurring with increased steering angles is minimized. To verify the feasibility of the proposed parabolic-shaped PLM surface, a four-element array with the proposed parabola-shaped PLM surface is fabricated. The antenna characteristics, such as the bore-sight gain, radiation pattern, reflection coefficients, and mutual coupling, are then measured in a full anechoic chamber. The results demonstrate that the proposed parabola-shaped PLM surface is suitable for reducing the mutual coupling and array pattern gain distortion of an array with the CP property.

II. Proposed Parabola-Shaped PLM Surface Design

Fig. 1 shows a four-element microstrip patch antenna array with the proposed parabola-shaped PLM surface inserted into the ground plane. The four-element patch antennas from Ant.1

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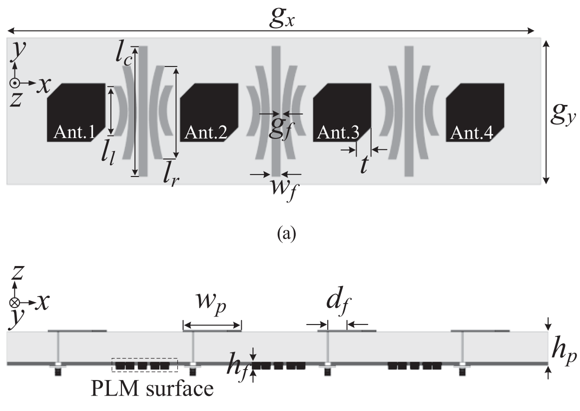

Fig. 1. Geometry of the four-element GPS array with the proposed surface. (a) Top view. (b) Side view.

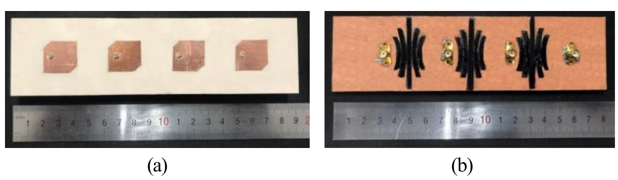

Fig. 2. Photographs of the four-element GPS array with the proposed surface. (a) Top view. (b) Bottom view.

to Ant.4 are designed to resonate at 1.575 GHz, and two corners of each element are truncated by length t to achieve the CP property. These elements are printed on a high-dielectric substrate ($\varepsilon_r = 20$, tan$\delta_m = 0.0035$) that has a height of hp and size of $g_x \times g_y$, and are arranged with an edge-to-edge distance (d) of 0.1 wavelength. The proposed parabola-shaped PLM surface consists of four parabola-shaped materials that are symmetric with the central stick shape of the material. This parabola-shaped surface is adopted to effectively block near-field components that are nonuniformly distributed between the array elements with CP properties. Note that the long-strip shape is also effective in case of the LP antennas having either vertical or horizontal components since the field, which is incident at a right angle to the long-strip surface, can be effectively blocked. The employed material is an FSF 501 commercial ferrite plate ($\mu_r = 8$, tan$\delta_m = 2$), which is manufactured by MARUWA, Owariasahi, Japan. These properties can realize the AMC characteristic in the PLM surface, as confirmed in [8]. The focal points (p_1 and p_2), lengths (l_c, l_l, and l_r), width (w_f), and gap (g_f) of the proposed parabola-shaped PLM are important parameters for blocking the nonuniformly distributed near-field components in arrays with the CP property. The detailed design parameters are optimized by a genetic algorithm in conjunction with the FEKO electromagnetic simulator [9], [10], and the optimized values are listed in Table I. As can be seen, the focal point of the ferrite material located on the outside is (13,0), which is smaller than the inside material value of (26,0). The optimized width (w_f) of the ferrite material is ten times greater than the gap (g_f), thereby satisfying the soft surface condition [5]–[7].

Fig. 2 shows photographs of the fabricated four-element array printed on the high-dielectric ceramic substrate ($\varepsilon_r = 20$, tan$\delta_m = 0.0035$). The high-dielectric substrate is used to confirm the feasibility of enhancing the isolation by inserting the

TABLE I
OPTIMIZED VALUES OF THE FOUR-ELEMENT GPS ARRAY WITH THE PROPOSED SURFACE

Parameters	Values
w_p	20.1 mm
d_f	4.8 mm
t	4.4 mm
w_f	3 mm
g_f	0.25 mm
g_x	180 mm
g_y	50 mm
h_p	5 mm
l_c	48 mm
l_l	32 mm
l_r	22 mm
p_1	(13,0)
p_2	(26,0)

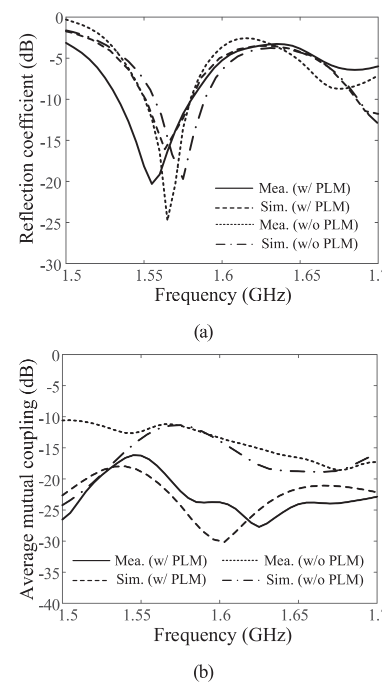

Fig. 3. S-parameters of the proposed array. (a) Reflection coefficient of the Ant.1. (b) Average mutual coupling.

proposed parabola-shaped PLM surface in an environment with strong mutual coupling. The ferrite plates are attached to the parabola-shaped slots into the ground plane to derive the AMC characteristic. The antenna characteristics, such as the bore-sight gain, radiation pattern, reflection coefficients, and mutual coupling, are measured in a full anechoic chamber, and the results are discussed in Section III.

III. MEASUREMENT AND ANALYSIS

Fig. 3(a) shows the measured and simulated reflection coefficients of Ant.1 with and without the parabola-shaped PLM surface when the other ports are terminated by 50 Ω loads. The measured values of Ant.1 with and without the proposed surface, which are indicated by solid and dotted lines, are −11.7 and −13.5 dB, respectively, at 1.575 GHz. The dashed and dash-dotted lines present the simulated reflection coefficients

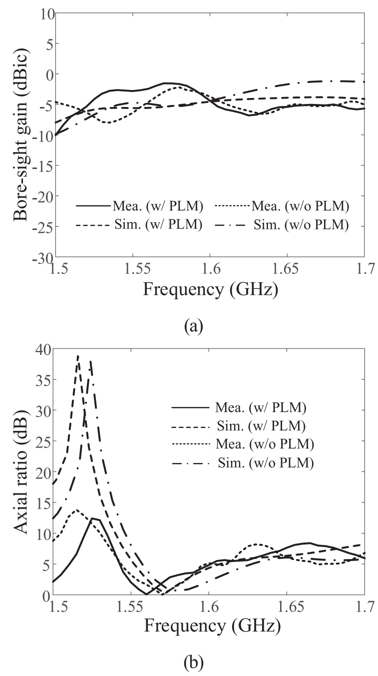

Fig. 4. Bore-sight gain and AR of the Ant. 1. (a) Bore-sight gain. (b) AR.

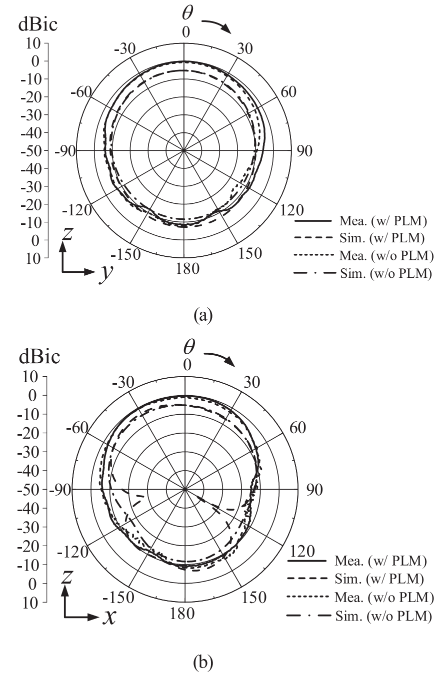

Fig. 5. Comparison of simulated and measured radiation patterns of the Ant.1 at 1.575 GHz. (a) *zx* plane. (b) *zy* plane.

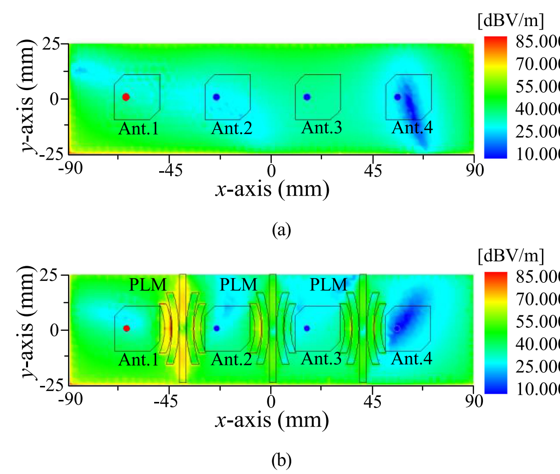

Fig. 6. Electric field distributions on the ground plane. (a) Distributions without the proposed surface. (b) Distributions with the proposed surface.

of the antenna element with and without the proposed surface, and the values are −12.3 and −19.7 dB, respectively, at the operating frequency. These results confirm that the proposed parabola-shaped PLM surface does not cause any serious negative effect on the reflection coefficient characteristic of the antenna element. Fig. 3(b) shows the average mutual coupling of the elements according to the existence of the parabola-shaped PLM surface in the ground plane. The measured and simulated average mutual coupling strengths of the antenna element without the proposed surface are −11.4 and −11.3 dB, respectively, at 1.575 GHz. These isolation characteristics are improved by 10.5 and 12.9 dB for measurement and simulation by employing the proposed parabola-shaped PLM surface. To verify the effect of the proposed surface on the bore-sight gain of the antenna element, we confirm the bore-sight gain according to the existence of the parabola-shaped PLM surface, as shown in Fig. 4(a). The measured bore-sight gains are −1.6 and −2.0 dB with and without the proposed surface, respectively. The variation according to the PLM surface agrees well with the simulated result of less than 0.5 dB. This gain reduction can be compensated by other advantages, such as the enhanced isolation and array pattern gain obtained at increased steering angles. The severe gain reduction occurs when the proposed parabola-shaped PLM surface is inserted on the upper plane near the radiator since the proposed surface uses a lossy material. If the PLM surface is employed into the upper plane near the radiating elements, the gain reduction of more than 2 dB is observed because the radiator and proposed surface are almost in contact with each other. Fig. 4(b) shows the simulated and measured axial ratio (AR) values of the antenna with and without the parabola-shaped PLM surface at $\theta = 0°$. The simulated and measured ARs with and without proposed surface are maintained below 3 dB at 1.575 GHz. Fig. 5(a) and (b) shows the two-dimensional patterns in the *zx* and *zy* planes, respectively, at 1.575 GHz. The half-power beamwidths of the measured and simulated values are 110.7° and 105° with the parabola-shaped PLM surface, respectively, and 109.2° and 105° without the proposed surface. From these active element patterns according to the existence of the proposed surface, we can confirm that the proposed surface does not affect the pattern distortion in the upper hemisphere. As mentioned in Section I, the current distributions on the ground plane are not uniform when the antenna elements have CP property. To interpret the operating mechanism of the proposed parabola-shaped PLM surface, we analyzed the electric field distributions induced on the ground plane of the four-element array with and without proposed surface as shown in Fig. 6. As observed in the E-field distributions, the maximum field strength near the port of Ant.2 is reduced from 37.8 to 25.7 dBV/m by employing the proposed parabola-shaped PLM surface. These

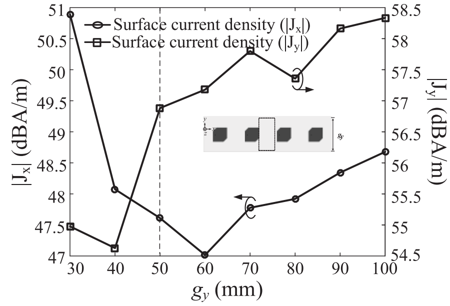

Fig. 7. Surface current density according to the ground size (gy).

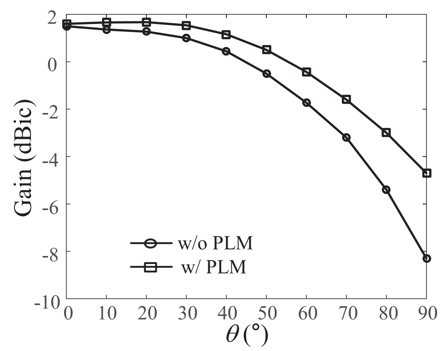

Fig. 8. Array pattern gain according to the variations in steering angle (θ).

TABLE II
COMPARISON OF ISOLATION IMPROVEMENTS TO EXISTING RESULTS IN THE LITERATURE

No.	[11]	[12]	[13]	Proposed
Frequency (GHz)	2.1	1.6	5.75	1.575
Number of elements	2	2	2	4
Antenna spacing (λ_0)	0.6	1	0.5	0.1
ε_r	4.4	10.2	10.2	20
Polarization	LP	LP	LP	CP
Material shape	Long-strip	Square	Square	Parabola
Improvement (dB)	9	8	10	12.9

resulting improvements in the isolation characteristic can also be verified by the induced near-field distributions. To verify this nonuniform current distribution, we analyze the surface current density of the *x*- and *y*-components according to the ground size (g_y), as shown in Fig. 7. As can be seen, the current densities of the *x*- or *y*-component do not dominantly exist, and the strength variation is less than 5 dB according to the limited range of the ground size. The ground size (g_y) of the proposed array is 50 mm, as denoted by the dashed line, and the *x*- and *y*-components are approximately 47.7 and 49.5 dBA/m, respectively. Fig. 8 shows the simulated array pattern gain according to the variations in steering angle from $\theta = 0°$ to 90°. Without the parabola-shaped PLM surface, the gain tends to decrease gradually from 1.8 to -8.2 dBic as the steering angle increases. This reduction of 10 dB is minimized to 6.3 dB by inserting the proposed parabola-shaped PLM surface in the ground plane. We also compared the proposed research with the previous research to further demonstrate the effectiveness of the proposed parabola shape as shown in Table II [11]–[13]. The previous research has dealt with isolation of the only two LP antenna elements with half wavelength or more antenna spacing. The proposed surface is applied to four CP array elements with an antenna spacing of 0.1 λ_0, which has nonuniform near-field components on the ground plane. The average isolation improvement of the proposed parabola-shaped surface is 12.9 dB and is greater than previous research.

IV. CONCLUSION

The parabola-shaped PLM surface was proposed to reduce the mutual coupling between GPS array elements with a CP property. The proposed surface consists of four parabola-shaped ferrite materials that are symmetric with the central stick shape of the ferrite. We fabricated a four-element GPS array to verify the feasibility of the proposed surface, and the antenna characteristics, such as reflection coefficients, radiation pattern, mutual coupling, and bore-sight gain, were measured in a full anechoic chamber. The average mutual coupling between the GPS array elements was decreased from -11.3 to -24.2 dB, which indicated an enhancement of 12.9 dB at 1.575 GHz. The bore-sight gain reduction of the array element by inserting the proposed surface was less than 0.5 dB, and this decrease was compensated by enhanced isolation and array pattern gain. In addition, the array pattern distortion of the GPS array was examined at increased steering angles, and the array pattern gain was increased from -8.2 to -4.4 dBic at a steering angle of $\theta = 90°$. These results demonstrated that the proposed surface can improve the isolation characteristics of GPS arrays that have nonuniformly distributed near-field components on the ground plane.

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