Loop-Shaped Patch Antenna for Conformal Arrays to Minimize the Effects of Adjacent Conducting Skin

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ORIGINAL ARTICLE

Loop-Shaped Patch Antenna for Conformal Arrays to Minimize the Effects of Adjacent Conducting Skin

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Abstract
This article proposes a novel method of designing a loop-shaped slot patch antenna using an extended cavity structure to reduce the influence of adjacent conducting vehicle skin. The proposed antenna consists of the radiating patch, loop shaped slot, and an extended cavity structure. The radiating patch is directly connected to a hybrid chip coupler to achieve a circular polarization property, and the extended cavity structure is employed to confine the near-field within the radiating patch that allows to have less influence of the conducting skin and to increase the effective permittivity of the proposed antenna. To verify the effectiveness of the proposed conformal array antenna, we fabricate 2×2 array antenna with and without an adjacent conducting skin, and its performances, such as bore-sight gains and 2-D radiation patterns are measured in a full anechoic chamber. The results confirm that the proposed antenna structure is suitable for elements of the conformal array, which is less affected by the conducting skin of the airframe.

Keywords Conformal array antenna · Microstrip patch antenna · Array antenna

1 Introduction

Conformal array antennas have been widely used in aeronautical applications, such as military aircraft, unmanned aerial vehicles (UAVs), and missiles, to reduce aerodynamic drag and radar cross section (RCS) by incorporating antennas into the curved vehicle skin. Microstrip patch antennas are considered to be most suitable candidate for the conformal array antennas due to their low profile, light weight, and manufacturability [1]. Conformal array antennas have been typically integrated into a conducting airframe to obtain good aerodynamic characteristics and RCS reduction, however; the conducting vehicle surface on which the elements of the conformal array are mounted often affects the array antenna characteristics, such as radiation pattern, impedance matching, and mutual coupling. Therefore, from the perspective of the overall communication link, it is important to prevent such performance degradations of the conformal antenna due to the effect of the proximity conducting vehicle surface [2]. To prevent such performance degradations, various studies have been carried out on applying a structurally embedded conformal antenna to vehicles, which extracts some parts of the airframe surface and inserts array antennas into the structure. These approaches, however, make it difficult to use space effectively because portions of the airframe should be extracted much more than required space for the conformal antenna system [3, 4]. Although some papers have reported good results on space-efficient conformal array antennas, the array antenna performances can still be affected by conducting vehicle surfaces placed between the individual antenna elements [5, 6]. On the other hand, a great deal of research has also been conducted to prevent such performance degradation by inserting additional structures. For example, techniques of inserting meta-surfaces,

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conducting structures, and shorting pins between antenna elements and nearby conducting vehicle surfaces have recently been reported [6, 7]. However, these approaches are still difficult to use in practical applications in terms of manufacturing cost and design complexity.

In this paper, we propose a novel method of designing a loop-shaped slot patch antenna with an extended cavity structure to reduce the influence of adjacent conducting vehicle skin. The proposed antenna consists of the radiating patch and the extended cavity structure, while the loop-shaped slot is placed between the patch and the extended cavity. The proposed extended cavity structure can drastically reduce the influence of adjacent conducting surfaces without increasing the design complexity. The radiating patch, which is printed on the FR4 substrate, is directly connected to a hybrid chip coupler to obtain a circular polarization (CP) characteristic. The extended cavity structure is implemented to confine the near-field distributions within the radiating patch, which is significantly different from a conventional well-known cavity-backed structure, where the cavity is inserted under the ground to improve the directivity property. The extended cavity allows the antenna to be less affected by the adjacent conducting vehicle skin and to increase the effective permittivity of the substrate to reduce antenna size and height. In order to verify the effectiveness of the proposed conformal array antenna in terms of the mutual coupling and the radiation pattern, we fabricate 2×2 array antenna with and without an adjacent conducting vehicle skin, and its performances are measured in a full anechoic chamber. In addition, we also examine the operating principle of the antenna by observing the near electromagnetic fields between the radiating patch and the adjacent conducting surface. The results verify that the loop-shaped slot patch antenna is suitable for elements of the conformal array that is less affected by the conducting skin of the airframe.

2 Proposed Antenna Structure

Figure 1 shows a proposed loop-shaped slot patch antenna for individual elements of a conformal array that can effectively reduce the influence of the adjacent conducting vehicle skin. The proposed antenna structure consists of a radiating patch, a loop-shaped slot, and an extended cavity structure, where the open side of the cavity is located on the same layer as the radiating patch to obtain good aerodynamic characteristics. The radiating patch is printed on the FR4 substrate ($\varepsilon_r = 4.4$, $\tan\delta = 0.018$) with a height of h, and a length of the radiating patch (w) is designed be about a half wavelength (λ_g). To achieve a circular polarization (CP) characteristic, the radiating patch is connected to the two output ports of a chip coupler (XC1400P-03S

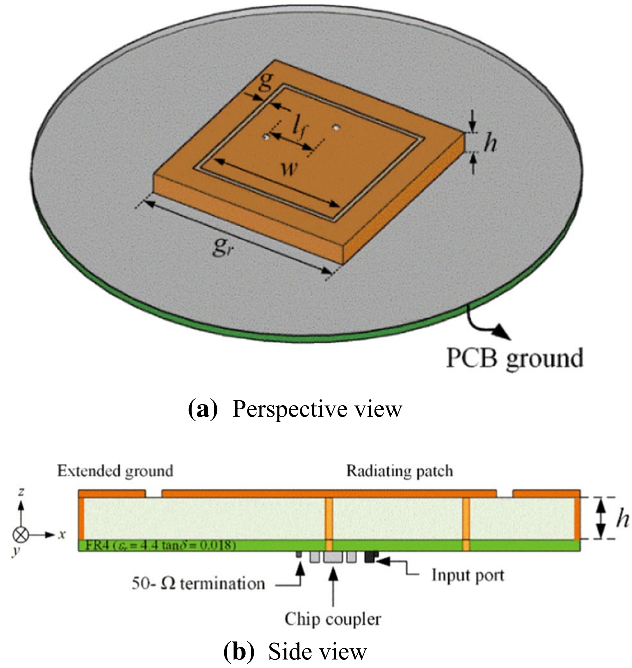


Fig. 1 Geometry of the proposed antenna

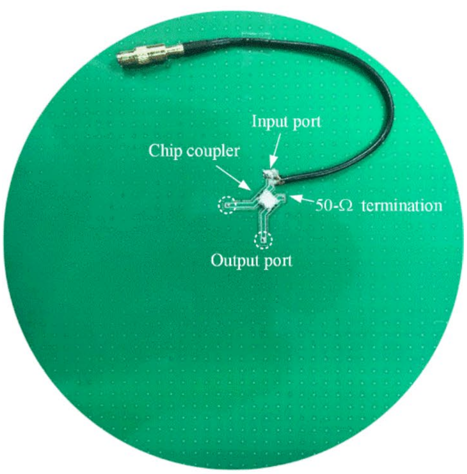
Table 1 Optimized values of the proposed antenna

Parameters	Values (mm)
w	45
g	1
h	6
l_f	15
g_r	52

from Anaren), and the feeding network, denoted as l_f, is embedded on a printed circuit board (PCB) with a radius of 100 mm on the bottom of the antenna. The cavity structure extends from the ground to the top of the proposed antenna to confine the near-field distributions within the radiating patch, which allows the antenna to be less affected by the adjacent conducting skin and to reduce antenna size by the increased effective permittivity of the substrate. The loop-shaped slot is placed between the radiating patch and the extended cavity structure on the top layer, and the slot width (g) is carefully adjusted to induce a strong E-field distribution for minimizing the antenna size. The optimized design parameters, such as g, w, l_f, and h, are obtained by using a genetic algorithm (GA) conjunction with the FEKO EM simulator [9], and the optimized values are listed in Table 1. As can be seen, the proposed antenna has a narrow slot g of 1 mm for inducing a strong E-field to obtain high effective permittivity and a thick substrate thickness (h) of 6 mm to enhance the radiation gain with improvement of the matching bandwidth.

Figure 2a illustrates a photograph of the proposed loop-shaped slot patch antenna, and Fig. 2b exhibits the PCB that includes the chip coupler, the coplanar wave guides, and a 50-Ω termination chip for quadrature phase excitation. Figure 2c shows the proposed antenna when the conducting skin is placed between the individual antenna elements on the top layer to examine the influence from the adjacent vehicle conducting surfaces. The antenna characteristics, such as the reflection coefficient, bore-sight gain, axial ratio (AR), and 2-D radiation patterns, are measured in an anechoic chamber.

(a) Top view



(b) Printed circuit board embedding the coupler circuit

(c) Proposed antenna with the conducting skin.

Fig. 2 Photograph of the fabricated antenna

3 Measurement and Analysis

Figure 3 represents the simulated and measured reflection coefficients according to a function of frequency. To obtain the simulated reflection coefficients, we calculate the scattering matrix of the two-port antenna by using the FEKO EM simulator [8], and the two-port scattering matrix is connected to the four-port network of the chip coupler in Advanced Design Software (ADS) [9]. The dashed and solid lines show the simulated and measured values, respectively. Both results show a good agreement with a measured value of – 25 dB at 1.575 GHz and a simulated value of – 21.9 dB.

The reflection coefficient is less than – 10 dB from 1 to 1.645 GHz. Figure 4 presents the measured bore-sight gain compared with the simulated result. The dashed line shows the simulated value, and the measured result obtained from the full-anechoic chamber is specified by '+' symbol. We also represent the measured data obtained from the semi-anechoic chamber, as a solid line, to observe the overall trend of results within the operating frequency range. As can be seen, the measured data with the conducting skin is similar to that without conducting skin, which confirms that the proposed antenna is insensitive to the adjacent conducting skin.

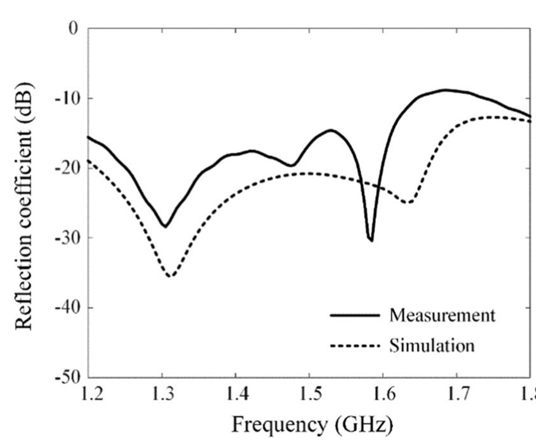


Fig. 3 Reflection coefficients of the proposed antenna

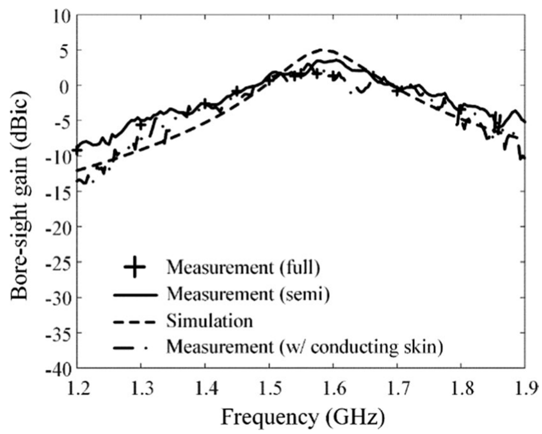


Fig. 4 Bore-sight gain of the proposed antenna

Figure 5 provides a comparison between the simulated and measured AR results in the bore-sight direction. The measured AR is 2.8 dB at 1.575 GHz and the AR values are maintained below 3.3 dB in a wide frequency range in 400 MHz (1.2–1.6 GHz), which demonstrates that the proposed antenna can avoid a significant CP gain reduction caused by the distorted polarization properties. The measured results, such as reflection coefficient, bore-sight gain, and AR, are slightly different with the simulation values due to the fabrication tolerance, such as effective dielectric permittivity and loss tangent of the PCB board.

Figure 6 illustrates the 2-D radiation patterns in the zx- and zy-planes at 1.575 GHz. The measured half power beam width (HPBW) are 74.8° (zx-plane) and 72.4° (zy-plane), respectively. The simulated results are 74.6° and 74.7°, which shows good agreement compared to the measured values. The results show that the proposed antenna does not present any serious pattern distortion with HPBWs of greater than 72°.

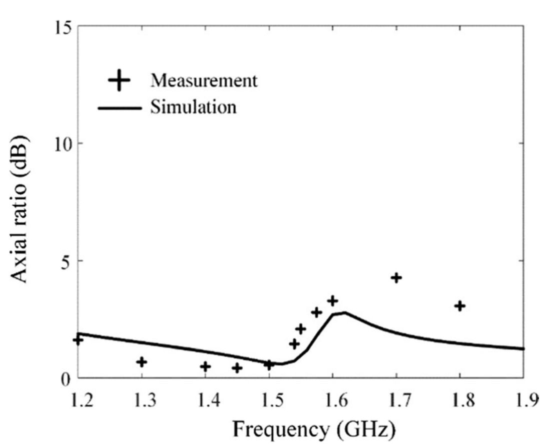
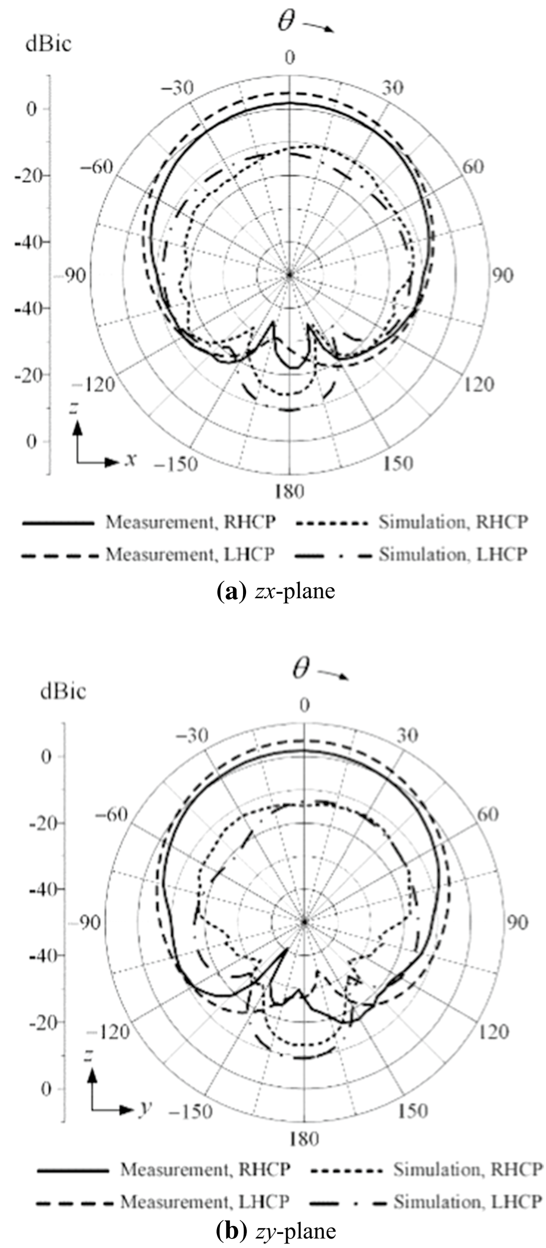


Fig. 5 Axial ratio of the proposed antenna



(a) *zx*-plane

(b) *zy*-plane

Fig. 6 2-D radiation patterns of the proposed antenna at 1.575 GHz

To verify the effectiveness of the extended cavity structure of the proposed antenna, the bore-sight gain is observed according to the design parameters (w and g) as shown in Figs. 7 and 8.

As can be expected, the resonant frequency shifts to the lower side when the radiating patch becomes larger from 43 to 47 mm. The gap, specified as *g*, between the radiating patch and the extended cavity is a key design parameter to confine the field strength in the substrate of the antenna, and the resonant frequency shifts to the upper frequency with increasing the gap from 1 to 5 mm.

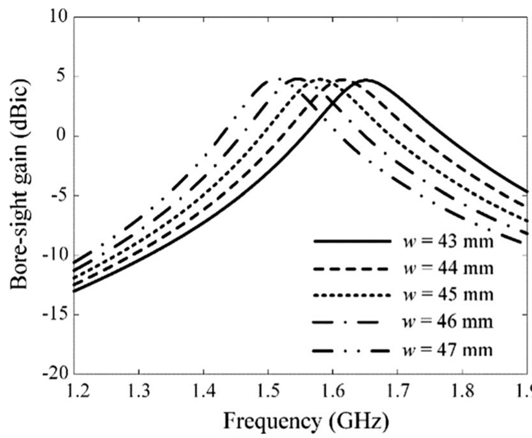


Fig. 7 Variations of the simulated gain according to *w*

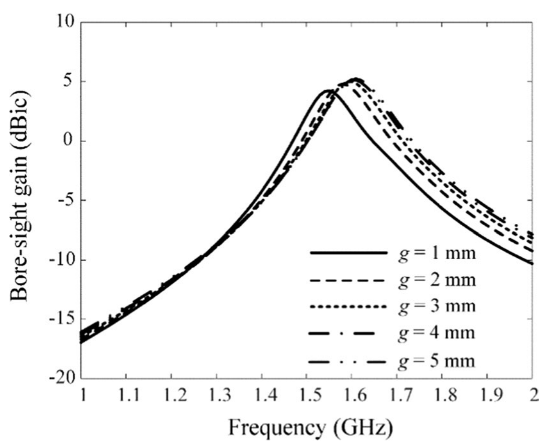
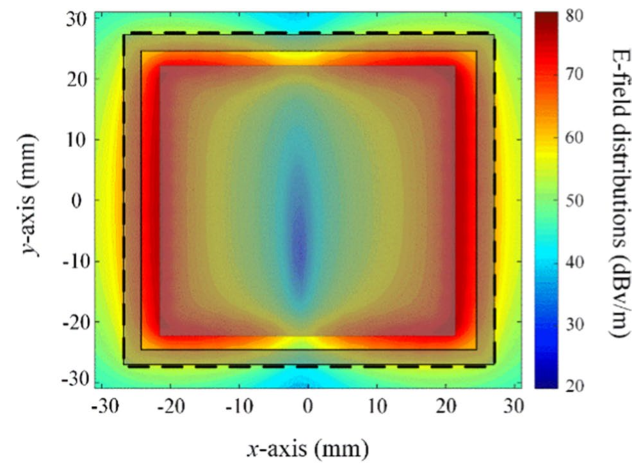
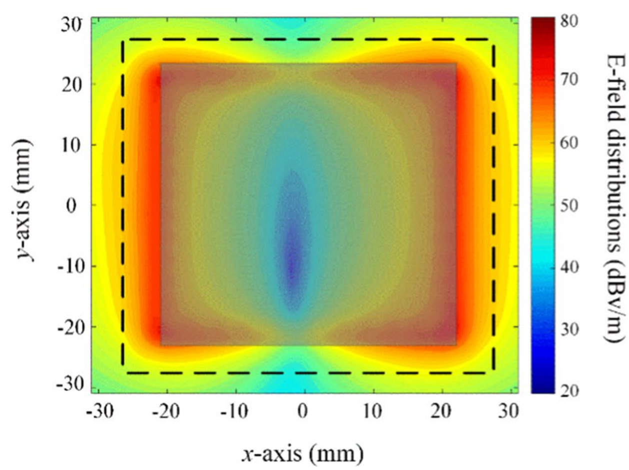


Fig. 8 Variations of the simulated gain according to *g*



(a) Proposed antenna



(b) Conventional antenna without the extended cavity

Fig. 9 E-field distributions in *xy*–plane

Figure 9 a and b represent the E-field distribution in *xy*-plane at each resonance frequency with and without the extended cavity structure at 1.575 GHz and 1.605 GHz. The average E-field strength of the proposed antenna has a value of 78.3 dBV/m, which is approximately 15 dB larger than that of the conventional antenna (without the extended cavity). As can be seen, the proposed extended cavity structure obtains more the confined field strength of the antenna to achieve the miniaturization of the antenna and the high effective permittivity of the antenna substrate, which implies that the proposed antenna with the extended cavity structure can minimize the physical sized of the antenna. These results demonstrate that proposed extended cavity structure allows the antenna to be less affected by the nearby conducting skin of the airframe when it is applied to an array of conformal structure.

To further verify the effectiveness of the proposed extended cavity structure from the conformal array antenna point of view. The proposed 2×2 array antenna is fabricated with the distance between individual elements of 75 mm, and the conducting skin is placed on the same layer as the top layer of the proposed antenna. Figure 10 shows the array antenna gains in the bore-sight direction with and without the conducting skin, and both results are similar (less than 1 dB deviation) at operating frequency. The results verify that the performances of the proposed antenna are not seriously distorted due to the adjacent conducting skin, and the proposed antenna structure is suitable for elements of conformal array that is less affected by the conducting skin of the airframe.

4 Conclusion

We have investigated the novel design of a loop-shaped slot patch antenna with an extended cavity structure for minimizing the influence of adjacent conducting skin of the airframe.

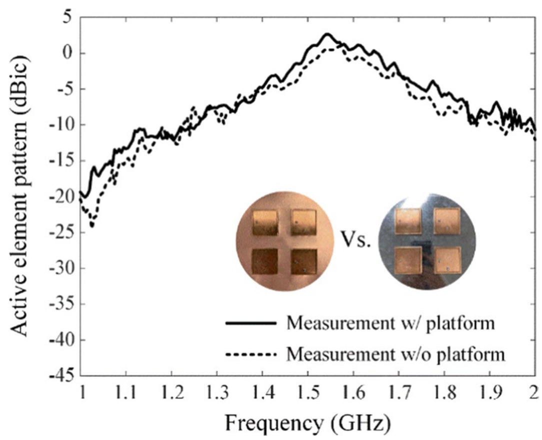


Fig. 10 Comparison of the active element pattern with and without the conducting skin

The proposed antenna consists of the radiating patch, loop-shaped slot, and the extended cavity structure, which confines the EM field distribution within the radiating patch. The measured bore-sight gain was 3.5 dBic at 1.575 GHz with AR of 2.8 dB, and the measured results with the conducting skin was similar to that without conducting skin. The average E-field strength of the proposed antenna has 78.3 dBV/m, which is approximately larger than 15 dBV/m than that of the conventional antenna, which implies that the concentrated fields allow the antenna to be less affected by the adjacent conducting skin with high effective permittivity. The results confirmed that the proposed antenna was suitable for elements of conformal array that is less affected by the conducting skin of the airframe.

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