Progress In Electromagnetics Research Letters, Vol. 58, 23–28, 2016

GPS Patch Antenna Loaded with Fractal EBG Structure Using Organic Magnetic Substrate

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Abstract—In this paper, a novel circularly-polarized (CP) patch antenna using organic magnetic substrate is proposed. This patch antenna works at 1.575 GHz frequency band which is for the global positioning system (GPS) application. The organic magnetic material is used to realize the miniaturization of antenna. To improve gain and axial ratio bandwidth of the antenna, fractal Hi-impedance surface electro-magnetic band gap (EBG) structures was used. The proposed antenna has been fabricated and measured. The simulation results for operating frequency band are shown to have good agreement with measurements.

1. INTRODUCTION

Circularly polarized patch antenna has the advantages of light weight, low profile, and ease of fabrication [1–3]. Because of these advantages, it is attractive in the global positioning system. However, due to surface wave losses, the CP patch antenna has a narrow axial ratio bandwidth, which is difficult to meet the requirements of the miniaturization and high performance simultaneously [4]. Some studies have reported periodic structures called electromagnetic band gap structures which suppress surface wave propagation [5–7]. So, we propose a GPS patch antenna integrated with a planar EBG structure, resulting in a significant improvement in both axial ratio (AR) bandwidth and performance. Besides, to realize the miniaturization of the GPS antenna, the patch and EBG structure use a fractal curve as the boundary, and this paper introduces a new type of organic magnetic material as substrate. The organic magnetic materials have stable magnetic performance, higher permeability and permittivity, and microstrip antennas with such materials are characterized with compact size, wide band, simple structure and easy fabrication [8]. Fractal geometries have been applied in antennas and radiators. The utilization of fractal geometries in antennas can reduce physical sizes and produce multiband response in radiation characteristics.

In this paper, we present a novel GPS patch antenna with fractal EBG structure using organic magnetic substrate, which can meet the requirements of miniaturization and high performance of GPS. The measured performances, which are in good agreement with the predicted ones, will be shown in the following sections.

2. ANTENNA STRUCTURE AND DESIGN

The geometry of the proposed microstrip patch antenna is shown in Figure 1. The antenna adopts a coaxial feed structure. The feed point fed on the diagonal, and the position of feed point's coordinate is (x_p, y_p). The antenna uses an organic magnetic material as the substrate. This material's electrical parameters are about $\mu_r \times \varepsilon_r = 14$. The relative permeability of $\mu_r = 1.4$, and the substrate thickness $h = 4\,\text{mm}$.

Received 21 October 2015, Accepted 8 December 2015, Scheduled 17 December 2015

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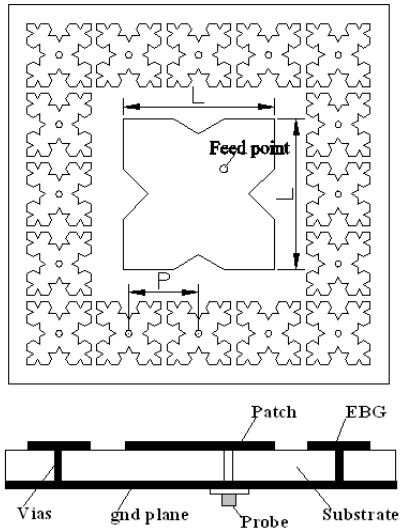

Figure 1. Structure of the GPS antenna.

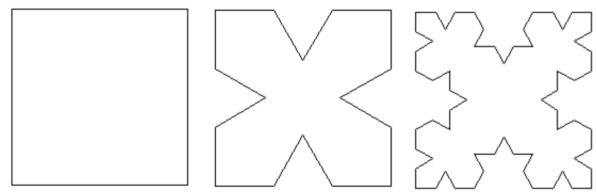

Figure 2. The first few stages in the construction of the Koch curve: (a) 0th iteration; (b) 1st iteration; (c) 2nd iteration.

In this paper, the patch and EBG structure use Koch fractal curve as the boundary. The first few stages in the construction of the Koch curve are shown in Figure 2.

The patch of this antenna uses the 1st iteration Koch fractal curve as the boundary. Circular polarization in general can be obtained when two orthogonal modes with equal amplitudes are excited within the patch. The proposed Koch fractal boundary circularly polarized antenna is obtained by replacing each pair of opposite sides of a square patch with the first iterated Koch curve using different fractal dimensions. The fractal dimensions can be changed by modifying the indentation angle θ in x- and y-directions. This makes the electrical length in two directions of the patch different, and hence the feed along the diagonal excites two orthogonal modes which are close to each other [9]. As a result, using a Koch curve as the boundary can obtain circular polarization by choosing a suitable θ in x- and y-direction. As shown in Figure 1, the patch's width is equal to its length L. The indentation angle in x-direction is θ_x, and the indentation angle in y-direction is θ_y.

The EBG structure uses the 2nd iteration Koch fractal curve as boundary. As shown in Figure 3(a), the width of EBG unit in vertical view is equal to its length $L1$. The periodicity of the EBG structure is P, and via radius is r. The operation mechanism of this EBG structure can be explained using an effective medium model with equivalent lumped LC elements [10], as shown in Figure 3(b). The capacitor represented by the gap between the metallic patches and the inductor represented by the vias and the current along adjacent patches [11]. The surface impedance of the mushroom EBG structure is given by

$$Z = \frac{jwL}{1 - w^2 LC} \tag{1}$$

The resonance frequency of the EBG structure is calculated as following

$$w_0 = \frac{1}{\sqrt{LC}} \tag{2}$$

The edge capacitance for the narrow gap situation is given by the following equation

$$C = \frac{w\varepsilon_0(1+\varepsilon_r)}{\pi} \cosh^{-1}\left(\frac{P}{P - L1}\right) \tag{3}$$

The inductance is expressed as below

$$L = \mu h \tag{4}$$

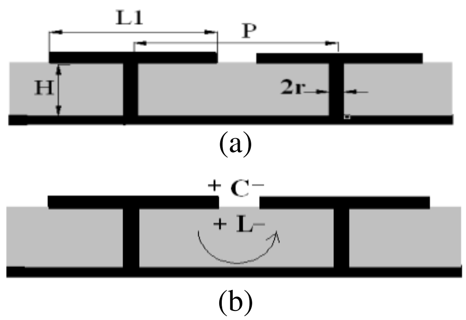

Figure 3. LC model for the mushroom-like EBG structure: (a) EBG parameters and (b) LC mode.

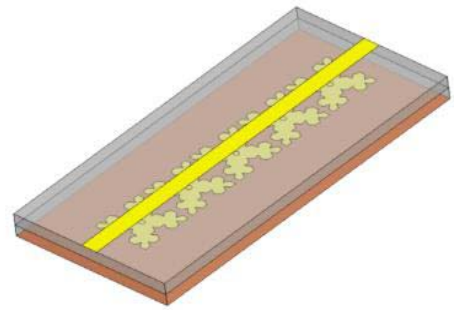

Figure 4. Model of suspending microstrip line method.

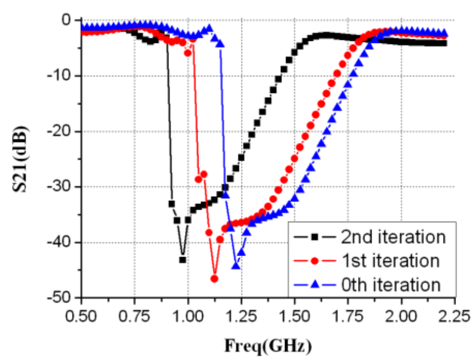

Figure 5. Effect of the fractal boundary on stop band.

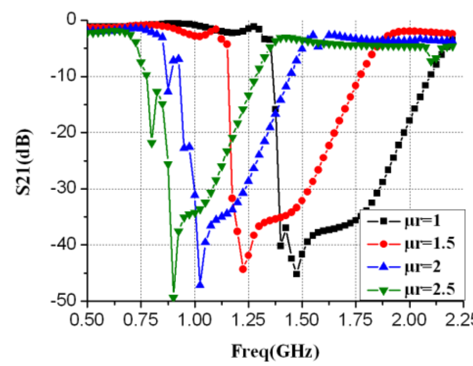

Figure 6. Effect of the fractal boundary on stop band.

where Z is the surface impedance of EBG structure; w_0 is the resonant frequency of EBG structure; C is the capacitance of EBG structure; L is the inductance of EBG Structure; P is the periodicity of the EBG structure; $L1$ is the width of uint-cell of EBG structure; ε_r is the relative permittivity of substrate; μ is the permeability of substrate.

Suspending microstrip line method can be applied to predict the stop band characteristics of the EBG structure [12], so we used suspending microstrip line method to individuate the stop band of different structures. The model of suspending microstrip line method is shown in Figure 4. The suspending microstrip line is hanging on the EBG structure, and S_{21} is calculated across the transmission line. The distance of microstrip line above the EBG is 1.6 mm, filled with air layer, and the width of microstrip line is 3 mm. The EBG is printed on an organic magnetic substrate with thickness h (4 mm) and relative dielectric constant ε_r (10). The loss of this substrate is 0.003, the size of a single EBG cell 10 mm, the gap between two cells 1 mm, and the number of EBG cells is 5.

To analyze the effect of the fractal boundary on stop band, the iteration of fractal EBG structure is varied from the zero to the second, and other parameters, such as the gap width, substrate permittivity, and substrate thickness, are kept the same. The simulated results are shown in Figure 5.

Results illustrated in Figure 5 show that the stop band's center frequency of 2nd fractal EBG is lower than the one observed for the 0th and 1st iterations, which proves that this technique is effective in realizing miniaturization of the structure.

In order to evaluate the effect of the relative permeability μ_r of substrate on the stop band, the relative permeability μ_r of the substrate is varied from 1 to 2.5, and other parameters are kept the same. The simulated results are shown in Figure 6.

From Figure 6, it is observed that the center frequency of stop band decreases as the relative permeability of substrate is increased. This can be explained from the LC model. When the permeability of substrate is increased, the equivalent inductance L increases, thus, the frequency reduces. Because the relative permeability of the organic magnetic materials is greater than 1, using organic magnetic materials as substrate can also reduce the EBG structure effectively.

The patch sizes were chosen to achieve resonance at the 1.575 GHz band. The detailed antenna parameters are: $L = 22.62\,\text{mm}$, $L_1 = 10\,\text{mm}$, $P = 11\,\text{mm}$, $r = 0.5\,\text{mm}$, $\theta_x = 53\,\text{deg}$, $\theta_y = 30\,\text{deg}$ and the feed location $x_p = 3.5\,\text{mm}$, $y_p = 3.5\,\text{mm}$.

3. SIMULATION RESULTS AND DISCUSSION

Figure 7 shows the simulated return loss for the GPS antenna with and without EBG structure. At resonant frequency, the antenna with EBG has return loss at $-17\,\text{dB}$, and the return loss of the antenna with EBG is greater than 10 dB from 1550 MHz to 1620 MHz. A 50% wider bandwidth is achieved. The simulated axial ratio is shown in Figure 8. From the results, the simulated axial ratio of the antenna with EBG is less than 3 dB from 1.563 MHz to 1.595 MHz, and the axial ratio bandwidth of the antenna with EBG is wider than that of the same patch without EBG by 68%. Besides, Figure 9 shows that a considerable improvement of 2 dB in terms of gain is obtained compared to the same antenna without EBG. Due to surface waves and dielectric loss, the gain of the conventional antenna is low on a high permittivity substrate. From above comparisons, the EBG structure improves the bandwidth and radiation performances of the patch antenna while maintaining its compact size.

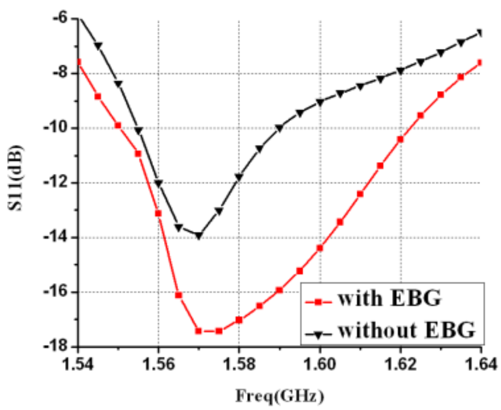

Figure 7. Simulated return loss of GPS antenna with and without EBG structure.

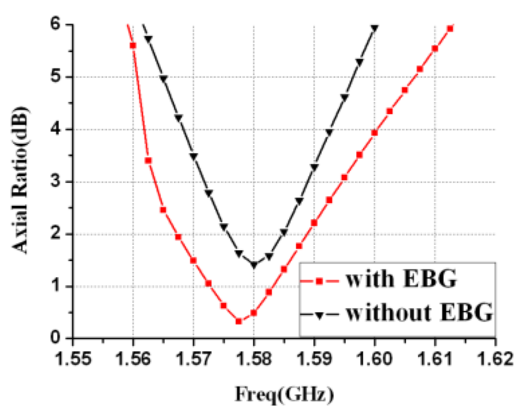

Figure 8. Simulated axial ratio of GPS antenna with and without EBG structure.

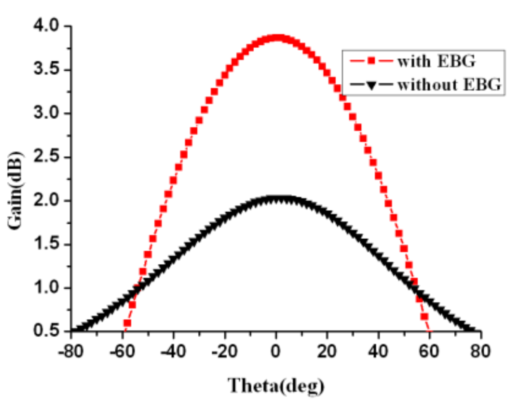

Figure 9. Simulated gain of GPS antenna of GPS antenna with and without EBG structure.

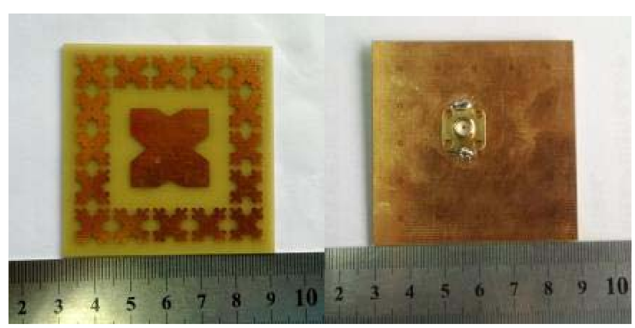

Figure 10. Photographs of the antenna prototype.

4. ACTUAL MEASUREMENT RESULTS

The proposed antenna was fabricated and measured to validate the design. Photographs of the antenna prototype are shown in Figure 10.

Performances of the fabricated GPS antenna was measured and compared with simulated results. Figure 11 is the XoZ plane radiations pattern of the GPS antenna with EBG at 1.575 GHz. Figure 12 gives simulated and measured axial ratios of this antenna, and the simulated and measured results of S_{11} are shown in Figure 13. As shown in these figures, the measured performances are in good agreement with the simulated results.

Comparison with other normal substrate antennas [13–15], the organic magnetic substrate antenna has smaller size, which can be seen from Table 1.

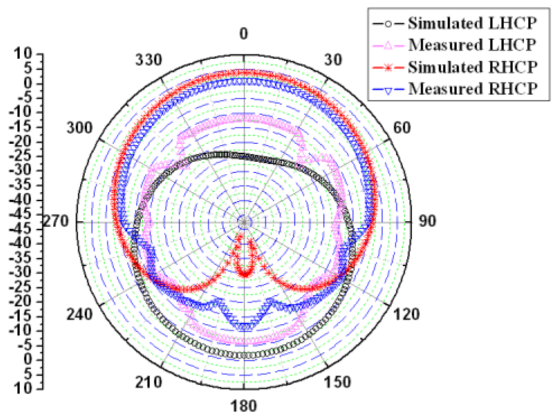

Figure 11. Simulated and Measured radiation patterns of GPS antenna with EBG at 1.575 GHz (the unit of vertical axis is dB).

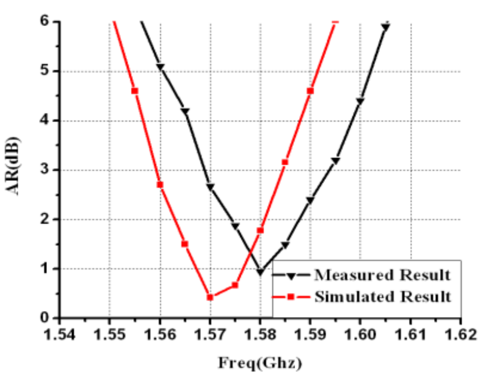

Figure 12. Simulated and Measured axial ratios.

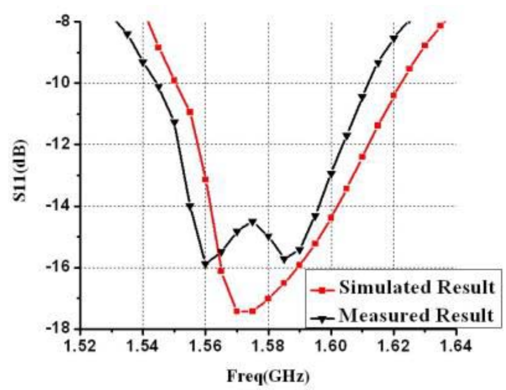

Figure 13. Simulated and Measured S_{11}.

Table 1. Size comparison of normal substrate antenna, the organic magnetic substrate antenna.

Comparison item	Ground plane (mm)	L or W (mm)	Working frequency	ARBW	Gain
This paper	$60 * 60$	22.62	1575 MHz	31 MHz	4 dBi
Literature [13]	$80 * 80$	66	1575 MHz	13 MHz	6.3 dBi
Literature [14]	$100 * 100$	17.2	1575 MHz	31 MHz	3.03 dBi
Literature [15]	$50 * 80$	46	1575 MHz	17 MHz	4.1 dBi

5. CONCLUSIONS

A novel GPS patch antenna loaded with fractal EBG structure using organic magnetic substrate is presented in this paper. The simulation and experiment results of the antenna show a significant improvement in both axial ratio (AR) bandwidth and performance by using fractal EBG structure. This antenna has smaller size. It is seen that the proposed antenna achieves good performance, which well meets the requirements of GPS applications with smaller size.

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