High-Directive Patch and Dipole Antennas using Biased Grounded Ferrite

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Abstract **─** In this paper, a new perfect magnetic conductor (PMC) substrate for improving the directivity of patch and dipole antennas is introduced. We used biased grounded ferrite to construct this new substrate. The most important difference between this substrate and the other artificial magnetic conductor (AMC) structures is the homogeneity. A conventional electromagnetic AMC has a periodic nature and as a result it is not homogenous but this novel substrate is homogenous. The results show that the directivity of both the patch and the dipole antennas is improved surprisingly in the presence of this novel homogenous PMC substrate. The physical reasons for the improvements are also given. Moreover, at the last section, we have calculated the magnetic loss of this magnetic anisotropic substrate.

Index Terms **─** Biased-grounded ferrite, dipole antenna, directivity, Faraday rotation, magnetic loss, patch antenna.

I. INTRODUCTION

Gyrotropic and magnetic materials have brought a lot of advantageous such as antenna miniaturization or beam squint for antenna applications [1-3]. Biased ferrites or magnetic photonic crystals are some examples for these types of materials.

A perfect magnetic conductor (PMC) is a concept, dual to the perfect electric conductor (PEC), but the nature did not provide a PMC material due to lack of magnetic charges [4]. Too many attempts were made to design artificial PMCs using electromagnetic band-gap (EBG) structures [5-6]. Suppression of surface waves by a PMC surface results in higher efficiency, smoother radiation pattern, and less back lobe and side lobe levels in antenna applications particularly for microstrip antennas [7-9] like patch antenna.

A dipole antenna with low profile configuration is a main aim in wireless communications. In such a design, the overall height of the dipole antenna structure is usually less than one tenth of the operating wavelength [10]. Due to reverse image of antenna produced by a PEC ground plane the dipole antenna radiation efficiency encounters a dramatic reduction. [10]. To solve this problem, dipoles are located at a height of $0.25\lambda_{free\ space}$ or higher from the ground plane which is not practical for the wireless communication systems [10]. But in this paper we have reduced this height to $0.005\lambda_{free\ space}$.

Shahvarpour et al, in [11] has shown that the surface of a grounded biased ferrite can be used as a PMC surface. In this paper we have used this idea and asserted that a grounded biased ferrite can function as a new substrate for the patch antenna and as a new ground for the dipole antenna to solve the deficiencies of these antennas.

In Section II, we briefly explain the role of Faraday rotation in a grounded biased ferrite for creation of a PMC surface. In Section III, we explain the application of this PMC surface for increasing the directivity of patch antenna and furthermore, in Section IV, we use the property of grounded biased ferrite to increase the directivity of a dipole antenna and at last in Section V, we discus and calculate the magnetic loss of this magnetic anisotropic substrate.

II. GROUNDED BIASED FERRITE

A grounded ferrite is a ferrite which is backed with a PEC plane. As it is stated in [11], at the first, consider an electromagnetic wave with E and H directed along the $+y$ and $+z$ respectively as it

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is shown in Fig. 1a. When this electromagnetic wave illuminates the interface of the biased ferrite and the air as shown in Fig. 1b, it will experience Faraday rotation because both the wave propagation and the bias have a same direction along the x. With the respect to characteristics of the biased ferrite, we can design h (the thickness of the ferrite) such that the wave senses a 90° rotation through the ferrite. Therefore, the E and the H will be directed along $-z$ and $+y$ respectively as it is shown in Fig. 1c. When the wave hits the PEC at the back of the ferrite the electric field undergoes phase reversal and the new direction of E will be $+z$ as it is shown in Fig. 1d. The reflected wave from PEC will experience same 90° Faraday rotation again and the tangential magnetic fields will cancel out each other on the ferrite-air surface and at last the PMC condition will be satisfied as shown in Fig. 1e.

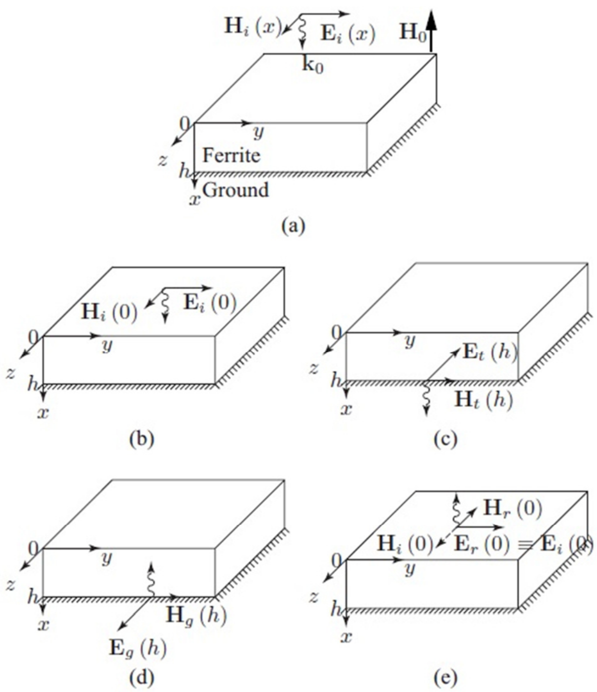

Fig. 1. (a to e) show the way that how a grounded ferrite can propose a PMC condition on its surface [11].

At this conceptual design of PMC surface, the effect of mismatch on ferrite-air surface is neglected. But it is mathematically shown in [11] that it has a negligible effect. At the continuation, we use this method to design a PMC substrate for patch and a ground for dipole antenna.

III. PATCH ANTENNA

Both the patch antenna and the dipole antenna are designed to operate at 3GHz. So, the grounded ferrite should satisfy the 90° Faraday rotation at 3GHz to realize a PMC substrate at the operating frequency. Now, we calculate the h (the thickness of ferrite substrate) using the following equations [12]:

$$\theta_{(\omega,y)} = -\left[\frac{\beta_{+(\omega)} - \beta_{-(\omega)}}{2}\right] y \quad (1)$$

$$\beta_{\pm(\omega)} = \omega\sqrt{\varepsilon\mu_0[\mu_\omega \pm k_\omega]} = \omega\sqrt{\varepsilon\mu_0}\sqrt{[\mu'_\omega - j\mu''_\omega] \pm [k'_\omega - jk''_\omega]} = \omega\sqrt{\varepsilon\mu_0\mu_{e\pm(\omega)}} \quad (2)$$

where $\beta +$ and $\beta +$ represent the right-handed circularly polarized (RHCP) and left-handed circularly polarized (LHCP) propagation constants, respectively. Because the ferrite is biased in the Y direction the permeability tensor is:

$$\bar{\bar{\mu}} = \begin{bmatrix} \mu & 0 & -jk \\ 0 & \mu_0 & 0 \\ jk & 0 & \mu \end{bmatrix} \quad (3)$$

$$\mu = \mu_0(1 + x) \quad (4)$$

$$k = -j\mu_0 \quad (5)$$

$$x = x' - jx'' \quad (6)$$

$$y = y'' + jy' \quad (7)$$

$$x' = \frac{[\omega_0\omega_m(\omega_0^2 - \omega^2) + \omega_0\omega_m\omega^2\alpha^2]}{T} \quad (8)$$

$$x'' = \frac{[\alpha\omega_0\omega_m(\omega_0^2 + \omega^2(1+\alpha^2))]}{T} \quad (9)$$

$$y' = \frac{[\omega\omega_m(\omega_0^2 - \omega^2(1+\alpha^2))]}{T} \quad (10)$$

$$y'' = \frac{2\alpha\omega_0\omega_m\omega^2}{T} \quad (11)$$

$$T = [\omega_0^2 - \omega^2(1+\alpha^2)]^2 + 4\omega_0^2\omega^2\alpha^2 \quad (12)$$

$$\alpha = \frac{\gamma\Delta H\mu_0}{2\omega} \quad (13)$$

$$\omega_0 = \mu_0\gamma H_0 \ \ and\ \ \omega_m = 4\pi\gamma M_s \quad (14)$$

The angular velocity ω_0 is often called the Larmor frequency and γ is the ratio of mass over the angular momentum of an electron which is $1.759 \times 10^{11}\ {}^{C}/_{Kg}$.

For the parameters: f= 3GHz, 4πMs = 0.101 T, ΔH = 20 Oe, ε_r = 13.2, $\mu_0 H_0$= 0.124 T, the required 90° Faraday rotation angle will be achieved by putting h = 4 mm. So, a grounded slab ferrite with the aforementioned parameter can realize a PMC surface.

The patch antenna on the new substrate is shown in Fig. 2. The patch antenna is supported by a dielectric layer with ε_r= 2.35 (blue section in Fig. 2). The dimensions of this dielectric layer are 38.4mm×38.3mm and the thickness of this supporter dielectric is 1.14 mm. This supporter dielectric is surrounded by the designed ferrite with the dimensions 103mm×103mm and its thickness is 4mm (the yellow section in Fig. 2). This ferrite substrate is backed by a PEC ground to form a grounded ferrite. This grounded ferrite can be biased by a slab magnet at the back of the PEC. This magnet provides $\mu_0 H_0$= 0.124 T. The dimensions of the rectangular patch are 32 mm×32 mm, this patch on the substrate with ε_r= 2.35 and the dimensions of 38.4mm×38.3mm can resonate at 3 GHz. The patch is fed by a pin which is 8 mm away from the center point of the patch along with the z-axis. The S_{11} is plotted in Fig. 3. CST Microwave Studio 2009 is used for simulation.

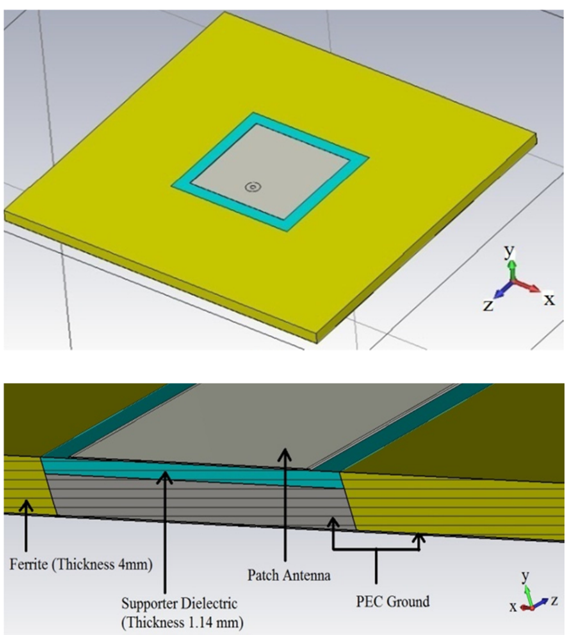

Fig. 2. The perspective view and side cut view of patch antenna on the ferrite substrate.

The operating frequency of the patch antenna shifts to 3.03 GHz in the presence of the ferrite. The directivity of a conventional patch antenna is almost 7 dBi but as it can be seen in Fig. 4 the directivity of the proposed patch antenna backed by new biased grounded ferrite substrate is 10.7 dBi at the 3.03 GHz.

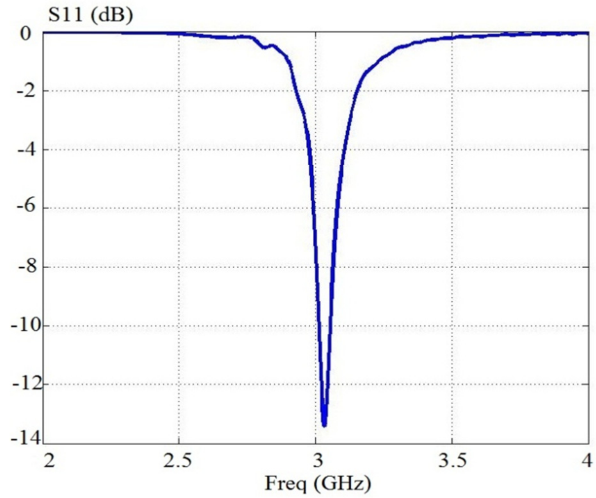

Fig. 3. S11 for patch antenna above the biased ferrite substrate.

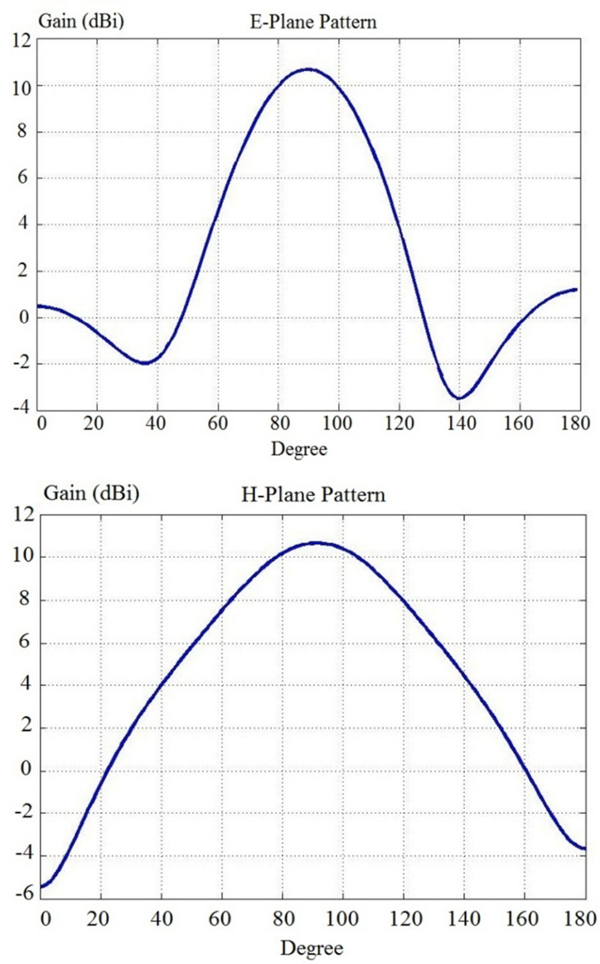

Fig. 4. Directivity of improved patch, E-plane and H-plane at f_0= 3.03GHz.

The main reason for low directivity of the conventional patch antenna is the surface waves in TE, TM or hybrid modes excited by the patch into the dielectric slab. But by the biased grounded ferrite substrate, the surface of the substrate will change into PMC at operating frequency and the tangential component of the magnetic fields will vanish and therefore eliminates the TM modes. As a result, the amount of coupled power into the substrate will reduce and it causes an increase in the directivity and the gain.

IV. DIPOLE ANTENNA

The dipole antenna above the new ferrite ground is shown in Fig. 5.

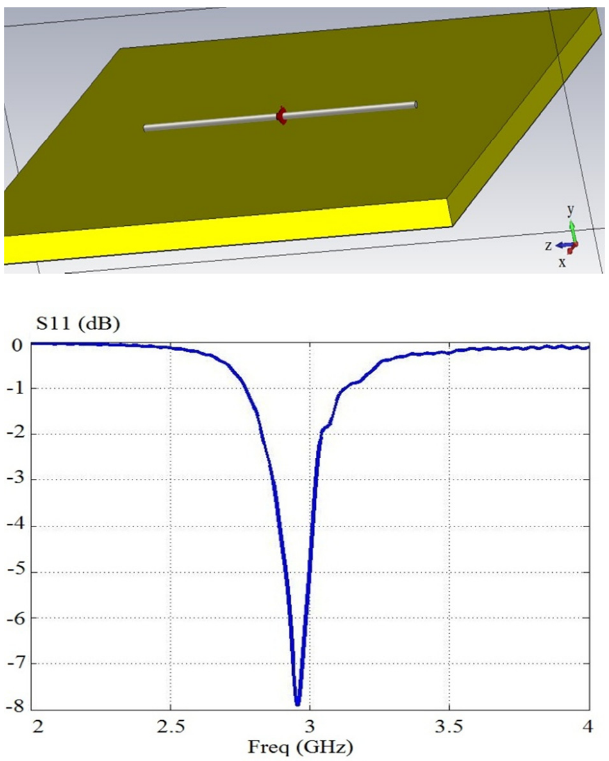

Fig. 5. The upper figure is the schematic of dipole antenna above the grounded biased ferrite substrate and the lower figure is the S11 of the antenna.

The dipole is designed to operate at 3GHz. The length of the dipole is 50mm and it is located $0.005\lambda_{3GHz}$ above the surface of the grounded biased ferrite. The ferrite should realize a PMC surface at 3GHz so we have used a ferrite which its characteristics are same as the ferrite which mentioned in the previous section. The grounded ferrite dimensions are 90mm×70mm× 4mm. The operating frequency of the dipole antenna shifts to 2.95 GHz in the presence of the ferrite substrate. The S_{11} is shown in the Fig. 5.

The E-Plane and the H-Plane directivity of this system are obtained and they are shown in Fig. 6. The directivity of the dipole antenna is surprisingly increased to 10.4 dBi.

In wireless applications, Dipole antennas do not function effectively when positioned very close and parallel above a PEC ground plane because of the reverse image currents, which reduces the antenna radiation efficiency [10] but in our case a positive image current is created by biased grounded ferrite. This is the main reason for increasing the directivity.

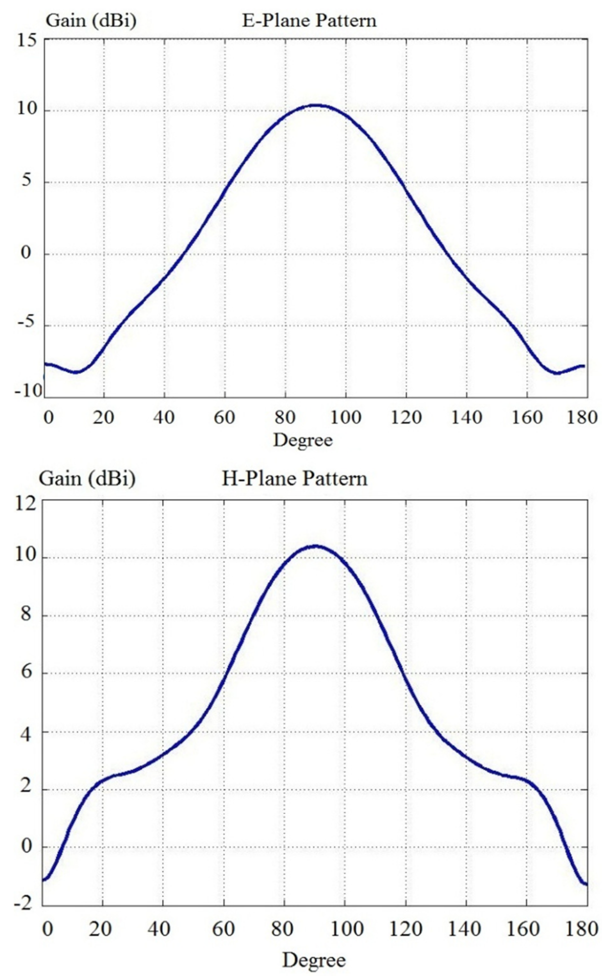

Fig. 6. The directivity of the improved dipole, E-plane and H-plane at f_0= 2.95GHz.

In conventional dipole antenna which operates in wireless communication, for solving the problem of reverse image and directivity reduction, the dipoles are positioned at the height of 0.25λ or higher from the ground plane which is not practical for the wireless communication systems [10]. But in our proposed structure, with this new PMC ground the height is decreased to $0.005\boldsymbol{\lambda}$.

V. MAGNETIC LOSS

As it is evident in Eq. (2), the right hand circularly polarization and left hand circularly polarization have different permeability. They are $\mu + k$ and $\mu - k$ for RHCP and LHCP respectively. The magnetic loss of the ferrite substrate can be taken into consideration by calculating the imaginary part of the permeability for different polarizations separately. The real and the imaginary parts of the $\mu + k$ and $\mu - k$ for right and left hand circularly polarizations are calculated and compared in Fig. 7.

As it is apparent the imaginary part of permeability for both polarizations is negligible in comparison with corresponding real parts. Therefore, we can conclude that the magnetic loss in this structure is not the main problem and we can neglect it. Also, it is apparent that the imaginary part is negative, which is expected for passive medium.

Now, we shortly discuss about the effects of the operating frequency on the performance for this proposed material specially, magnetic loss. There are two methods for realization of PMC surface by using a biased grounded ferrite with assumption of a fixed thickness. As it was mentioned above, to realize a PMC surface by biased grounded ferrites for a specific thickness, the ferrite should be able to rotate the electromagnetic wave 90 degrees. If we suppose a fixed thickness for the ferrite and a constant static magnetic field for biasing the ferrite, the speed of Faraday rotation will be increased by increasing the magnetic saturation of the ferrite. As a result of this phenomenon, the 90 degrees Faraday rotation will occur at lower frequencies but we should notice that by increasing the magnetic saturation the magnetic loss will also increase. Therefore, a trade-off should be considered between the loss and lowering the operating frequency. Another solution for the lowering the operating frequency for a fixed thickness can be found by decreasing the magnetic resonance of the ferrite which means decreasing the amount of the applied static magnetic field. Decreasing the magnetic resonance of the ferrite seems better idea comparing with increasing the magnetic saturation because, by decreasing the amount of the applied static field the magnetic loss decreases.

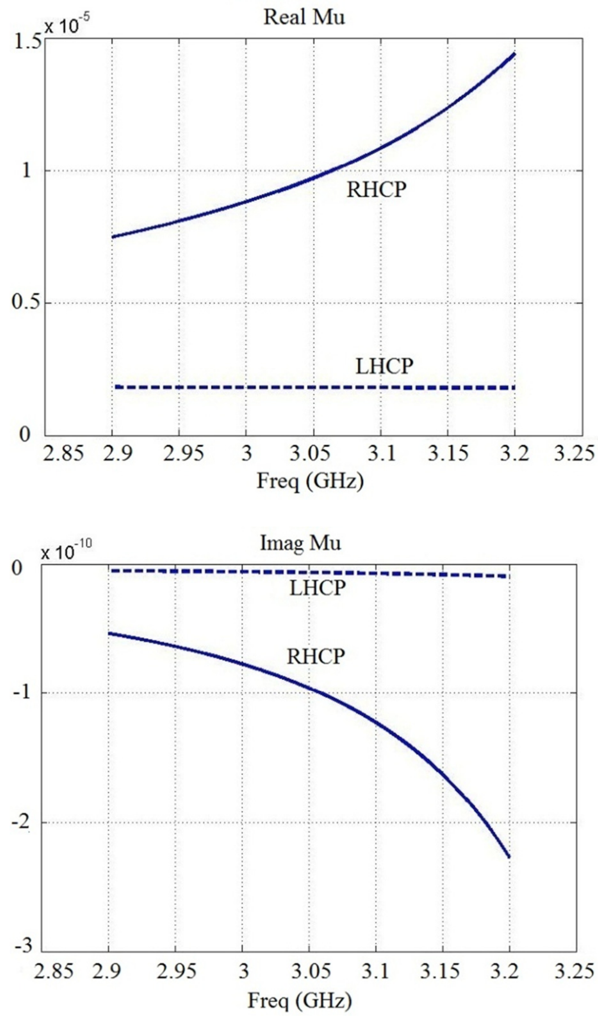

Fig. 7. Real and imaginary parts of effective permeability for RHCP and LHCP.

As a result of the aforementioned discussion the concept of PMC by using biased grounded ferrite is applicable for low frequency bands utilizing above mentioned ideas.

VI. CONCLUSION

A new substrate for patch antenna and a new ground for dipole antenna have been designed. The directivity and the magnetic loss are calculated. The results show that, the directivity for patch and dipole is improved meaningfully. This new substrate can increase the directivity of the patch antenna up to 10.7 dBi and the directivity of the dipole antenna up to 10.4 dBi. And moreover the height of the dipole antenna was decreased from $0.25\lambda_{\text{free space}}$ to $0.005\lambda_{\text{free space}}$, which is very suitable for wireless communications. Since this substrate is made by ferrite, the magnetic loss is calculated and it is presented that this loss is negligible for this structure.

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