Electronically Tunable Miniaturized Antennas on Magnetoelectric Substrates With Enhanced Performance

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Achieving relative permeability larger than 1 in antenna substrates can lead to antenna miniaturization, enhanced bandwidth, and tunable resonant frequency. Metallic magnetic films and self-biased ferrite films were introduced as a practical means to tune a patch antenna by loading a commercially available substrate in this paper. Novel antenna designs with metallic magnetic films and self-biased NiCo-ferrite films were investigated. Magnetic patch antennas were demonstrated at 2.1 GHz with a tuning resonant frequency range of 5–10 MHz (with the metallic magnetic films) and 7–23 MHz (with self-biased ferrite films). Three different cases of annular ring antennas with NiCo-ferrite films loading were also designed and analyzed. Antennas with self-biased magnetic films loading working at 1.7 GHz with a tuning range of 3–20 MHz were achieved.

***Index Terms*—Annular ring antennas, magnetic antennas, patch antennas, self-biased films.**

I. INTRODUCTION

ANTENNAS have been the critical components in radars, satellites, navigation systems, etc., which are crucial for the U.S. Navy, Department of Defense (DOD), as well as civilian applications. Compared with other components, antennas have been more resistant to orders-of-magnitude size reduction without drastic degradation in performance. Novel approaches are needed to improve the performance and reduce the size and signature of antennas with significantly enhanced bandwidth, high efficiency, and tunability for multifrequency and multiband operations. Microstrip antenna miniaturization can be achieved by printing a patch antenna over a high-permittivity substrate. However, the strong capacitive coupling between the antenna and the antenna's ground plane severely degrades its efficiency and bandwidth. To overcome this problem, antenna substrates with relative permeability > 1 need to be used [1], [2]. However, it has been challenging in achieving self-biased magnetic materials with a high permeability and low loss at radio frequency (RF) and microwave frequencies suitable for antenna applications. There has been no report on self-biased magnetic antennas at GHz range.

Bulk ferrite materials, composites of ferrite particles in polymer matrix, metamaterials with embedded metallic circuits, etc., have been used as antenna substrates for achieving $\mu_{\rm r} > 1$. However, these antenna substrate approaches are too lossy to be used at frequencies > 500 MHz; and large biasing magnetic fields are needed for ferrite materials in antenna substrate. In order to be practically feasible in miniature antenna applications, it is important for antenna substrates to be comprised of self-biased magnetic materials, in which no external bias field is applied.

Microwave magnetic thin films provide a unique opportunity for achieving self-biased magnetic patch antenna substrates with $\mu_{\rm r} > 1$ at GHz frequency range. The strong demagnetization field of magnetic films allows for high ferromagnetic resonance frequencies up to several GHz and self-biased magnetization as well, which are essential for microwave magnetic devices. We propose to use novel magnetoelectric composite substrates for antennas with low-loss magnetic film materials and low-loss high-permittivity dielectric materials.

Our research has led to new designs of electronically tunable self-biased patch antennas with metallic magnetic films and ferrite films. In the second section, we will introduce the self-biased antennas at 2.1 GHz with a CoFeB film showing large tunability [3]. In addition, we have achieved self-biased antennas at 1.7 GHz and at 2.1 GHz with high-quality self-biased ferrite films, which will be explained in the third section. This is the first demonstration of electronically tunable self-biased magnetic patch antennas with enhanced performance at GHz.

II. PATCH ANTENNA WITH MAGNETIC METALLIC FILMS

A conventional (nonmagnetic) patch antenna operating at 2.1 GHz was designed on a $2'' \times 2''$ square alumina substrate with a thickness of 2 mm [4], [5]. The dimension of the Cu patch size is 22.2 mm by 30 mm, and a thickness of the copper is 3 μm. A new magnetic antenna was designed and fabricated with the alumina substrate and Cu patch dimensions as those of the nonmagnetic antenna, except that there was one 1-μm-thick metallic magnetic film between the Cu patch and the alumina substrate. The shape of the magnetic layer was controlled to be the same as that of the Cu patch (excluding the feed line), as shown in Fig. 1. This magnetic film shape was finalized as a result of two considerations. First, we would like to have a strong coupling between the magnetic film and the microwave magnetic drive fields, which are concentrated beneath the patch. Second, we would like to minimize the unwanted loss on the feed line, so no magnetic film was put beneath the Cu feed line. Metallic magnetic films used for magnetic patch antennas have an atomic composition of $(\mathrm{Fe}_{60}\mathrm{Co}_{40})_{85}\mathrm{B}_{15}$, which were amorphous with a saturation magnetization of 16 kG, a coercivity of < 0.3 Oe, and a high resistivity of 100 $\mu\Omega\cdot$ cm. The FeCoB film

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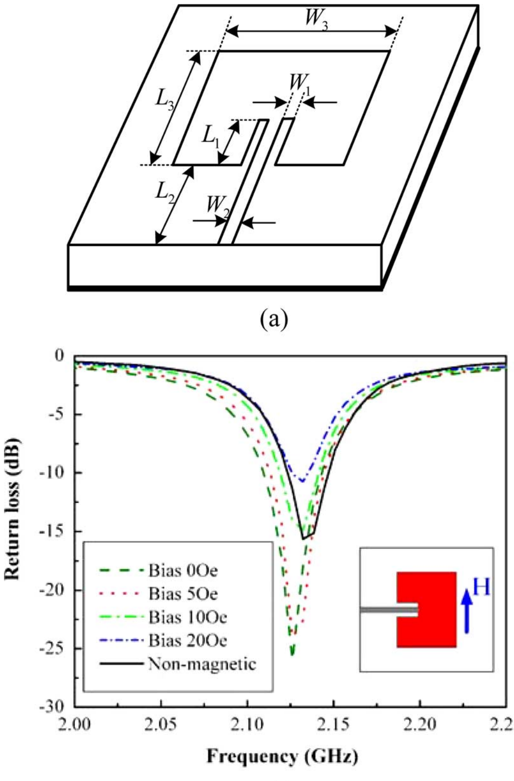

(a)

(b)

Fig. 1. Geometry of the rectangular patch antenna. (a) Top view, $L_1 = 8.0$ mm, $L_2 = 14.3$ mm, $L_3 = 22.2$ mm, $W_1 = 2.0$ mm, and $W_2 = 2.0$ mm, $W_3 = 30.0$ mm. (b) Measured return loss of the magnetized patch antenna with various bias fields applied perpendicular to the feed line.

was 1 μm thick, deposited by sputtering with an *in situ* magnetic field to preset the magnetization direction, thus achieving anisotropic in-plane permeability. The magnetic antennas were made with magnetization of the FeCoB magnetic film preset to be perpendicular to the feed line. Photolithography and wet etching were used for patterning the Cu and magnetic layers.

Return loss of the nonmagnetic antenna on alumina substrate was measured and shown in Fig. 1(b). The nonmagnetic antenna shows a measured resonance frequency of 2136 MHz and the -10 dB bandwidth is 24± 3 MHz (or 1.1% of resonance frequency). The results for this nonmagnetic antenna will be used as a control for comparison with the antennas on magnetoelectric substrates. The return loss of the magnetic patch antennas was measured under magnetic bias field perpendicular to the feed line. When the bias field is 0 Oe, the resonant frequency of the magnetic patch antenna shifts down to 2.126 GHz, indicating a tuning range of 10 MHz relative to the nonmagnetic antenna. The bandwidth is 34 MHz, which shows an increase of 42% in contrast to nonmagnetic antenna. When the magnetic fields are applied perpendicular to the feed line, the magnetic antenna shows an upward shift of the resonance frequency. The frequency shifts are about 8 MHz and 7 MHz at a low bias field of 5 and 10 Oe, respectively, relative to the nonmagnetic antenna. Therefore, with a small applied field of < 20 Oe, a tunable resonant frequency range of 5–10 MHz can be achieved.

The radiation patterns of the magnetic antennas were tested and plotted in Fig. 2 at different applied magnetic fields perpendicular to feed line. All the H-plane patterns were measured at the frequencies of minimum return loss in each case, and normalized with respective to the maximum detected power. The detected power of magnetic antenna with bias 0 Oe at the broadside is about 1.5 dB less than the maximum power. It is interesting to note that with increasing the applied magnetic field, i.e., 5, 10, 20 Oe in this paper, the maximum power increases to -0.7 dB, -0.03 dB, and -0.1 dB, respectively, which is very low loss for patch antennas with magnetic substrates operating at GHz.

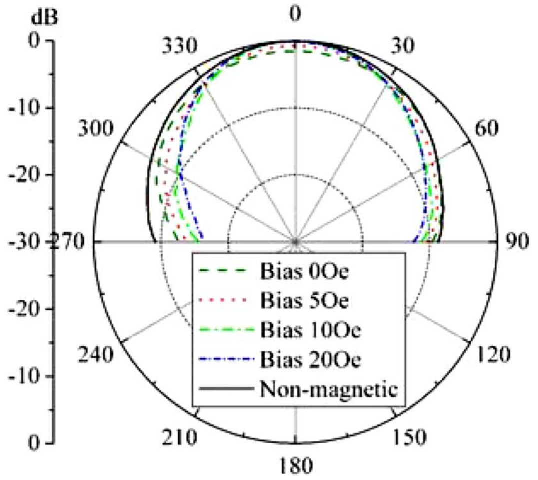

Fig. 2. The H-plane of magnetic antennas with different magnetic fields applied perpendicular to the feed line. All the patterns were measured at the frequencies of minimum return loss in each case.

III. ANTENNA WITH FERRITE FILMS

A. Patch Antennas

In order to obviate biasing of magnetic substrates by an external field, we propose using self-biased NiCo-ferrite films with a relatively high in-plane anisotropy field. This large anisotropy field enables a low-loss tangent of the ferrite films at GHz frequencies. Three antennas with NiCo-ferrite magnetic films are designed as follows. First, a ferrite thin film of thickness 2 μm is introduced just below the nonmagnetic patch with dimensions indicated in Fig. 1. As in the case of metallic magnetic films, there is no ferrite beneath the feed line. Besides antennas with a ferrite film below the patch, we also consider the second antenna designs with a 2-μm-thick ferrite film just above the whole surface of the alumina substrate, as shown in the schematic in Fig. 3(b). The third antenna design is realized by adding 1 layer of film above the ground plane, as shown in Fig. 3(c). All these three antenna designs with ferrite films have been fabricated and tested.

The nonmagnetic patch shows a resonant frequency of 2.147 GHz, bandwidth of 18 MHz, When the ferrite film is added beneath the patch, the resonance shifts down to 2.136 GHz, indicating a tuning range of 11 MHz relative to the nonmagnetic substrate. The bandwidth is 21 MHz, which shows an increase of 16% in contrast to that of nonmagnetic antenna.

Addition of the ferrite film just above the whole surface of the alumina substrate tunes the resonance down to 2.124 GHz,

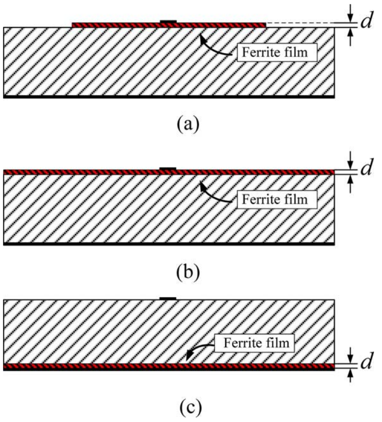

Fig. 3. (a) Antenna with film under the patch. (b) Antenna with film on the whole surface. (c) Antenna with film above the ground plane, $d = 2\mu$m.

which is 23 MHz central frequency shift compared with the nonmagnetic antenna, or equivalent to approximately 127% of the bandwidth. Also, the -10 dB bandwidth is 37 MHz in this case. Adding the ferrite film just above the ground shifts the resonance down to 2.140 GHz with the minimum return loss of -38 dB, which indicates a good impedance matching is achieved, combined with an improved bandwidth of 30 MHz. From the above analysis, we can see that the low resistivity of the ferrite films used in the antennas shown in Fig. 3 could be responsible for the enhanced bandwidth and the frequency downshift.

The measured radiation patterns of the patch antenna for the same three cases of ferrite films loading are plotted in Fig. 4(b), along with the radiation pattern of the baseline nonmagnetic patch for reference. The maximum power at the broadside is about -0.2 dB for the nonmagnetic patch. While with the three magnetic antennas, the maximum powers are -0.4 dB, -0.2 dB, and 0 dB, respectively. It should be noted that the third magnetic antenna gain at the elevation angle of 80° is 1.2 dB higher than the nonmagnetic antenna, which shows improved omnidirectional performance with ferrite films loading.

B. Annular Ring Antennas

Annular ring antennas have smaller circumference compared with those circular patch antennas. And they can radiate a linearly polarized wave in the far-field zone or a circularly polarized wave by disturbing the symmetry of the ring [6]–[8]. All these advantages show that annular ring antennas have great potential in the mobile wireless communication. Fig. 5(a) and (b) show the schematic top view and side view, respectively, of the annular ring antenna. This antenna consists of a microstrip ring and a tuning stub. The feed point is located on the junction of the tuning stub and the microstrip ring with a distance of 0.5 mm to the outer edge of the ring. The radius of the outer ring is 12.4 mm, and the inner ring is 11.4 mm, the length of the tuning stub is 6.22 mm with the width of 1 mm. We adopted Rogers RT/duroid 6010 as the substrate in both simulations and fabrications, which has a relative permittivity of 10.2 and a thickness of 1.27 mm. Three annular ring antennas with ferrite films are fabricated as follows. First, a ferrite thin film of thickness 2 μm is introduced just above the microstrip ring. Second, a 2-μm-thick ferrite film is added just under the ground plane. In this case, the ferrite film has the same size as the ground plane. Combining the above two cases, we also design an antenna with two layers of ferrite film, in which one layer is just above the ring, and the other under the ground plane. In order to compare the results with the nonmagnetic antenna, the measured return loss of four antennas are plotted and analyzed. The return loss curves in Fig. 6 are measured under the condition that all the

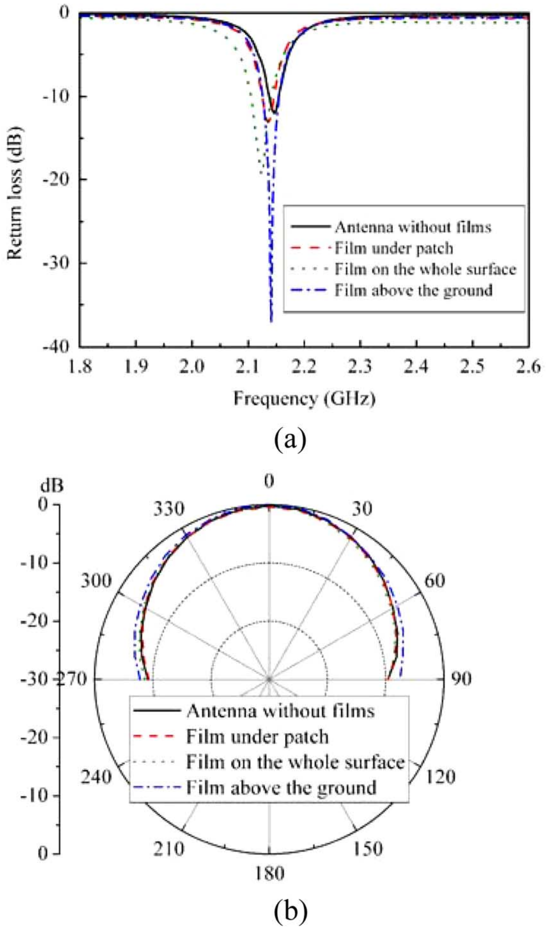

Fig. 4. (a) Measured return loss of the magnetized patch antenna with different ferrite films loading. (b) The H-plane of patch antennas with different ferrite films loading. All the patterns were measured at the frequencies of minimum return loss in each case, and normalized with respective to the maximum detected power.

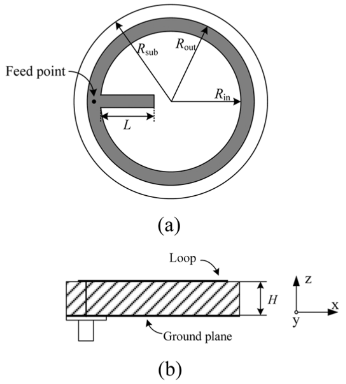

Fig. 5. Geometry of the proposed annular ring antenna. (a) Top view: $R_{\rm sub} =$ 14 mm, $R_{\rm out} = 12.4$ mm, $R_{\rm in} = 11.4$ mm, and $L = 6.22$ mm. (b) Side view: $H = 1.27$ mm.

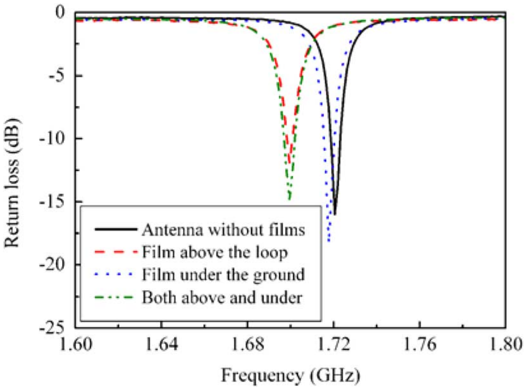

Fig. 6. Measured return loss against frequency for the four different cases.

geometrical dimensions of the antenna are kept unchanged, and only the ferrite films are added at different position.

From Fig. 6, we can see that the central resonant frequency of the nonmagnetic antenna is about 1.72 GHz, and the -10 dB bandwidth is 5 MHz. When a ferrite film is added above the annular ring antenna, the resonant frequency shifts down to 1.70 GHz. This indicates a tuning range of 20 MHz relative to the nonmagnetic antenna, or equivalent to approximately 1.2% of the resonant frequency. When a ferrite film is added just under the ground plane, we observe that the resonant frequency is 1.717 GHz, with a slightly enhanced S_{11} peak magnitude of -18.2 dB, indicating a better impedance matching. When two ferrite films are added above the microstrip ring and under the ground plane at the same time, which moves the resonant frequency further down to 1.70 GHz again with a S_{11} peak magnitude of -15 dB. Clearly, the antenna loaded with ferrite film can indeed miniaturize the geometrical dimensions effectively as demonstrated by shifting down the resonance.

IV. CONCLUSION

Magnetic films are successfully introduced into antenna substrates, leading to electronically tunable magnetic patch antennas with enhanced performance at 2.1 GHz. These magnetic antennas show great promise for achieving self-biased miniaturized patch antennas on magnetoelectric substrate with significantly enhanced bandwidth, improved directivity, and high efficiency. In addition, these magnetic antennas can be made conformably at a low cost with low-temperature physical vapor deposition method, making these patch antennas with metallic magnetic films very promising for real applications. Annular ring antennas with/without self-biased ferrite films are fabricated and analyzed in this paper. The fabricated magnetic antennas with self-biased magnetic films can realize a tuning range of 3–20 MHz, which shifts from 1.72 to 1.717 GHz and 1.70 GHz, respectively, indicating the self-biased magnetic films do lead to minimized antenna by shifting down the resonant frequency.

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