Tunable Miniaturized Patch Antennas With Self-Biased Multilayer Magnetic Films

Guo-Min Yang, X. Xing, A. Daigle, M. Liu, O. Obi, S. Stoute, K. Naishadham, and Nian X. Sun

***Abstract*—Magneto-dielectric substrates with thin magnetic films show great potential in realizing electrically small tunable antennas with enhanced bandwidth, improved directivity, and high efficiency. This communication introduces self-biased NiCo-ferrite magnetic films as a practical mean to tune a patch antenna by loading single layer and multilayer self-biased ferrite films. The central resonant frequency of the unloaded patch antenna is measured at 2.1 GHz with a bandwidth of 18 MHz. However, with ferrite loading of the alumina substrate, this frequency is shown to be tunable within a range of 12 MHz–40 MHz, and the antenna efficiency is increased from 41% of the non-magnetic antenna to 56%, 65%, and 74% for the three magnetic antennas. The omnidirectional radiation pattern is significantly enhanced with the -5 dBic gain beamwidth increased from 140° to 155°, 156° and 160°, respectively for the three ferrite loaded antennas. In addition, the gains of the three magnetic antennas are enhanced by 0.32, 0.77, and 1.1 dB, respectively, over the unloaded antenna.**

***Index Terms*—Magnetic films, self-biased films, tunable magnetic antennas.**

I. Introduction

Achieving relative permeability larger than 1 ($\mu_{\rm r} > 1$) in antenna substrates can lead to antenna miniaturization, enhanced bandwidth, tunable center frequency, polarization diversity, and beam steering [1]–[3]. Bulk ferrite materials [4], 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 bulk ferrite materials or ferrite composites are too lossy to be used at $\rm frequencies\ > 500$ MHz under self-bias condition, i.e., no bias magnetic field is needed, and large biasing magnetic fields are needed for these magnetic antennas to operate at higher frequencies. In order to be practically feasible in miniature antenna applications, such as handheld wireless communication devices, it is important for antenna substrates to be comprised of self-biased magnetic materials. However, it has been challenging to achieve self-biased magnetic materials for antenna substrate applications at >500 MHz.

Magnetic thin films provide a unique opportunity for achieving self-biased magnetic patch antenna substrates with $\mu_{\rm r} > 1$ [5]–[7] and operating $\rm frequencies\ > 1$ GHz. The strong demagnetization field for magnetic thin films, $\rm H_{demag} = 4\pi M_s$, and large in-plane anisotropy field allow for a self-biased magnetization with high ferromagnetic resonance (FMR) frequencies up to several GHz, a necessary condition for operations in the cellular and WLAN bands.

Most recently, we have proposed to use novel magnetodielectric composite substrates for antennas with low-loss magnetic film materials and low-loss high permittivity dielectric materials. In our previous work, new designs of electronically tunable patch antennas with magnetic metallic magnetic films ($(\rm Fe_{60}Co_{40})_{85}B_{15}$) were investigated [5], which showed that the bandwidth was increased by 50% over the non-magnetic antennas. Most recently, new self-biased ferrite film of NiCo-ferrite films ($\rm Ni_{0.23}Co_{0.13}Fe_{2.64}O_4$) were investigated and adopted [6]–[8], these NiCo-ferrite films are magnetically isotropic in the film plane, which also have a low loss tangent under self-bias condition, i.e., no external bias field is needed for proper operation. We have demonstrated self-biased loop antennas at 1.7 GHz with a wide range of tunable resonant frequency with high quality self-biased ferrite films [7], which shows great potential in the applications of antenna miniaturization for mobile handheld wireless communication devices.

In this communication, we report on a patch antenna miniaturized using single layer and multilayer self-biased NiCo-ferrite thin films on alumina substrate, thus essentially creating a magneto-dielectric substrate for practical applications. Three different magnetic patch antennas are fabricated by loading the antenna with multilayer ferrite thin films adjacent to the patch. These antennas show enhanced bandwidth and significantly enhanced antenna efficiency. The -5 dBic gain beamwidth is increased from 140° to 155°, 156°, and 160°, for the three magnetic antennas, showing significantly improved omnidirectional performance.

II. Design of Patch Antennas

Microwave ferrite ceramics show relatively high permeability and high permittivity ($\varepsilon_{\rm r} \sim 15$), as well as low loss at RF/microwave frequencies. These characteristics are highly desirable for the miniaturization of many different RF/microwave devices, including antennas [9]. Two major loss mechanisms account for the limited operation frequency, the ferro/ferrimagnetic resonance (FMR) and domain wall motion. The operating frequencies of bulk microwave magnetic materials are limited to be $<$600 MHz due to the excessive magnetic loss tangents associated with various loss mechanisms, with FMR being the major loss mechanism. The FMR frequency is therefore the upper frequency limit for antenna substrates for achieving $\mu_{\rm r} > 1$. In other words, above the FMR frequency, prohibitive magnetic losses preclude the device operation.

For a uniformly magnetized sphere, the FMR frequency is linearly proportional to the net magnetic field $\rm H_{net}$, with the gyromagnetic constant, γ being close to 2.8 MHz/Oe. Large bias fields of the order of 1000 Oe are needed for the FMR frequency to reach GHz range, and allow device operation in that range. The relative permeability of the magnetic sphere can be described by

$$\mu_r = \frac{4\pi M_s}{H_{\rm net}} + 1 \tag{1}$$

which is inversely proportional to the net magnetic field $\rm H_{net}$. We can therefore readily reach the Snoek limit [10]

$$f_{\rm FMR} \cdot (\mu_r - 1) = \gamma \cdot 4\pi M_s \tag{2}$$

i.e., the product of the FMR frequency and the relative permeability is a constant that is determined by the saturation magnetization of the magnetic medium.

The permeability of the ferrite in the film plane is still $\mu_r = (4\pi M_s)/(H_{\rm net}) + 1$ with $H_{\rm net}$ being the net in-plane field; while the FMR frequency is increased to be

$$f_{\rm FMR} = \gamma\sqrt{H_{\rm net}\cdot(4\pi M_s + H_{\rm net})} = \gamma H_{\rm net}\sqrt{\mu_r}. \tag{3}$$

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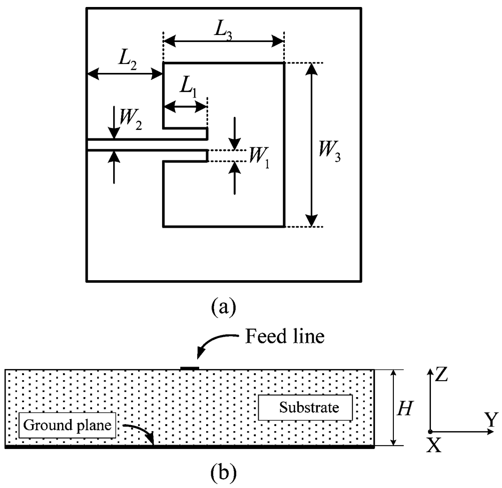

Fig. 1. Geometry of the designed rectangular patch antenna. (a) Top view, $L_1 = 8.0$ mm, $L_2 = 14.3$ mm, $L_3 = 22.2$ mm, $W_1 = 2.0$ mm, and $W_2 = 2.0$ mm, $W_3 = 30.0$ mm. (b) Side view, $H = 2.0$ mm.

The FMR frequency of magnetic films is therefore boosted to $\sqrt{\mu_r}$ times of that of magnetic spheres, allowing self-biased FMR frequency as well as the operation frequency of magnetic films in the GHz range. Similarly, the product

$$\mu_r \cdot f_{\mathrm{FMR}} = \gamma \cdot 4\pi M_s \cdot \sqrt{\mu_r} \tag{4}$$

is also boosted to $\sqrt{\mu_r}$ times of that of the magnetic spheres, indicating a significantly boosted Snoek Limit for magnetic films.

Magnetic patch antennas with self-biased NiCo-ferrite magnetic films were designed, fabricated and tested at 2.1 GHz. The geometry of the patch antenna, designed for operation at 2.1 GHz and the coordinate system are shown in Fig. 1(a) and (b). It is a conventional microstrip line-fed patch on a $2'' \times 2''$ alumina substrate ($\varepsilon_{\mathrm{r}} = 9.9$) with a thickness of 2 mm, and the loss tangent is about 0.001. This antenna is fed by an SMA connector mounted at the side of the substrate through a microstrip. The copper patch for this non-magnetic antenna has a length of $L_3 = 22.2$ mm, width $W_3 = 30$ mm and Cu conductor thickness of 3 μm. The width of the feed-line is 2.0 mm and the length is 22.3 mm.

NiCo-ferrite films with composition of $Ni_{0.23}Co_{0.13}Fe_{2.64}O_4$ are deposited onto thin transparency (with 15 μm thickness and low permittivity of 2.0). The thickness of ferrite film is about 2 μm by spin spray plating at a low temperature of 90°C. The magnetic hysteresis loops were measured with vibrating sample magnetometer (VSM) and shown in Fig. 2. The in-plane resistivity of the film is $5.6 \times 10^3\ \Omega\cdot$cm, and the coercivity is 165 Oe. The NiCo-ferrite film has a loss tangent of about 0.05 at 2 GHz. The governing equation for magnetodynamics is the well known Landau-Lifshitz-Gilbert (L-L-G) equation [11], [12]. And the in-plane susceptibility spectra of the magnetic films can be expressed by the following [13]:

$$\chi(\omega) = \frac{\omega_m(\omega_m + \omega_k + \omega_{\mathrm{appl}} + j\omega\alpha)}{-\omega^2 + j\omega\alpha\omega_m + \omega_m(\omega_k + \omega_{\mathrm{appl}})} \tag{5}$$

where α is the Gilbert damping factor, $\omega_{\mathrm{appl}} = \gamma\mu_0 H_{\mathrm{appl}}, \omega_k = \gamma\mu_0 H_k$ and $\omega_m = \gamma\mu_0 M_s$ (H_{appl} is the applied field, H_{k} is the in-plane anisotropy field, M_{s} is the saturation magnetization and γ is the gyromagnetic ratio). The permittivity of our ferromagnetic films can be considered as dispersion free in the frequency range of our interest, and can be supposed as a constant in our study. The relative

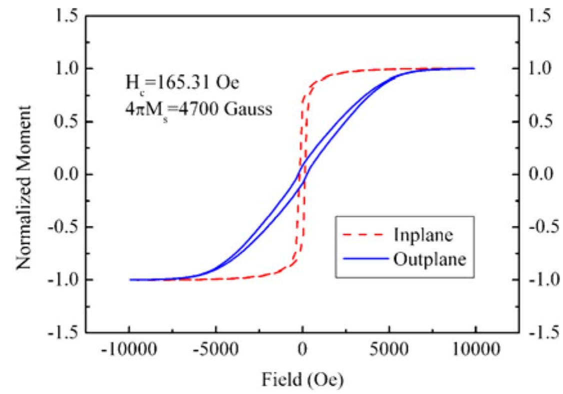

Fig. 2. Hysteresis loop of the NiCo-ferrite film.

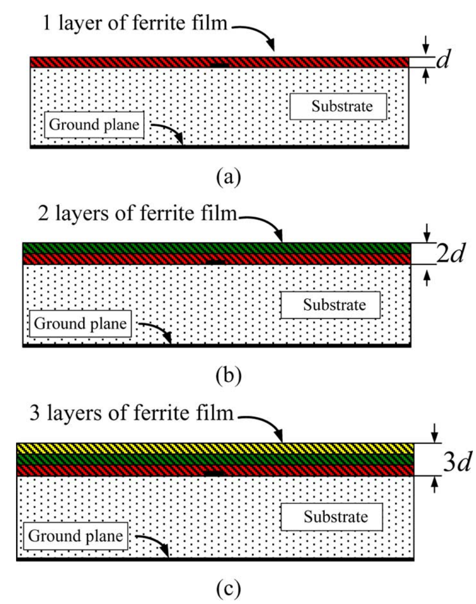

Fig. 3. Side view of rectangular patch antenna with ferrite films. (a) One layer of ferrite film above the patch. (b) Two layers of ferrite film above the patch. (c) Three layers of ferrite film above the patch. $d = 0.002$ mm.

permittivity of the NiCo-ferrite film is about 13 and the relative permeability is about 10 at the frequency of 2 GHz, similar to what was reported in [14].

III. Tunable Antennas With Self-Biased Ferrite Films

Multiple superstrates loading is one of effective gain enhancement methods for microstrip antennas [15]. Self-biased NiCo-ferrite films with a relatively high in-plane anisotropy field were used for magnetic loading of the patch antenna. This large anisotropy field enables a low loss tangent of the ferrite films at several GHz frequencies. Three antennas with single layer and multilayer ferrite films are designed as follows. First, as can be seen from Fig. 3(a), a ferrite thin film of thickness 2 μm is introduced above the non-magnetic rectangular patch.

The other two magnetic patch antennas employ either two or three 2 μm ferrite multilayer above the patch, as shown in Fig. 3(b) and (c), respectively. All the four antennas shown in Figs. 1 and 3 were fabricated and tested.

The measured reflection coefficient for these three antennas with ferrite films is plotted in Fig. 4, along with that of the non-magnetic patch

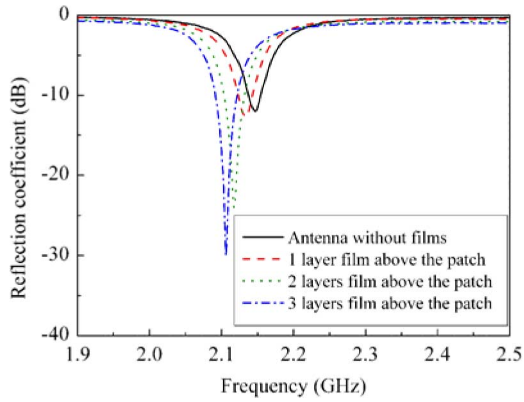

Fig. 4. Measured reflection coefficient of the patch antennas with/without ferrite films loading.

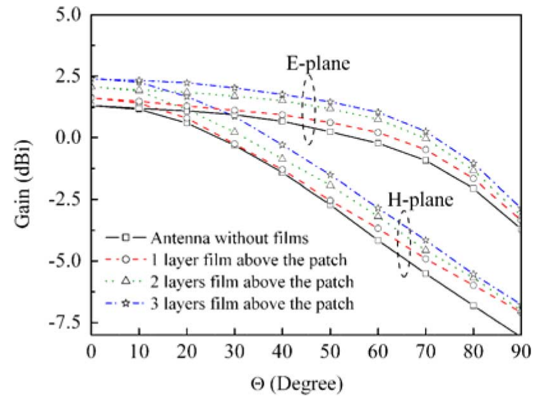

Fig. 5. The gains of four patch antennas at different elevation angles.

TABLE I
THE MEASURED PARAMETERS OF THE FOUR ANTENNAS

	without films	1 layer film	2 layers film	3 layers film
Central Freq. (GHz)	2.146	2.134	2.117	2.106
Bandwidth (MHz)	18	21	28	29
Gain (dBi)	1.31	1.63	2.08	2.41
Efficiency	41%	56%	65%	74%
-5dB Beamwidth (H-plane)	140°	155°	156°	160°

for comparison. All the measured resonant frequencies and the bandwidth of these four antennas are listed in Table I.

The non-magnetic patch shows a resonant frequency of 2.146 GHz, and 2:1 VSWR bandwidth of 18 MHz. When one layer of ferrite film is added above the patch; the resonance shifts down to 2.134 GHz, which indicates a tuning range of 12 MHz relative to the non-magnetic substrate. The bandwidth is 21 MHz with addition of the ferrite film, an increase of 3 MHz compared to non-magnetic antenna. As shown in Fig. 4, the reflection coefficient is also improved with the thickness of the ferrite film. Clearly the ferrite film loading leads to enhanced bandwidth and improved matching.

The addition of two layers of the ferrite film above the patch tunes the resonance down to 2.117 GHz with the minimum reflection coefficient of about -24 dB. The resonant frequency shift is 29 MHz compared with the non-magnetic antenna. Adding three layers of ferrite film above the patch shifts the resonance down to 2.106 GHz, with the best reflection coefficient of -30 dB. We observe a central frequency shift about 40 MHz relative to the baseline non-magnetic patch, and an improved bandwidth of 29 MHz.

As summarized in Table I, we can see that the antenna efficiency is increased from 41% of the non-magnetic antenna to 56%, 65%, and 74% for the latter three antennas. As mentioned above that superstrate loading is one of effective gain enhancement methods for microstrip antennas. The superstrate loading of ferrite films combined with the improved impedance matching are the main reasons for the improved efficiency. And the films are so thin that 2 μm for each layer in our antennas, the energy loss associated with the loss tangent is not a significant issue in such antennas with an alumina substrate thickness of 2 mm. The antenna gain is enhanced by 0.32, 0.77, and 1.1 dB, respectively, over the non-magnetic antennas. In order to evaluate the antenna gain at the different elevation angles, the gains of the patch antennas with/without ferrite films are plotted in Fig. 5. From this figure we can see that the gains at the elevation angle of 80 degree are improved by 1.01, 1.03, and 1.36 dB in the H-plane, and 0.4, 0.74 , and 1.0 dB in the E-plane relative to the unloaded patch, respectively, for the three antennas with ferrite films. The -5 dBic gain beamwidth is increased from 140° to 155°, 156° and 160°, for the three magnetic antennas, showing significantly improved omnidirectional performance.

IV. CONCLUSION

Single layer and multilayer self-biased ferrite magnetic films have been introduced as a practical means to tune a patch antenna operating at 2.1 GHz by loading a commercially available substrate. Measurements on magnetic patch antennas demonstrate that the central resonant frequency can be shifted downward over a tuning range of 12–40 MHz, which indicates the self-biased magnetic films do lead to minimized antenna by shifting down the resonance frequency. The antenna bandwidth of the magnetic antennas is enhanced by 3 MHz–11 MHz over the non-magnetic antenna. In addition, the antenna efficiency was increased from 41% to 56%–74% with multilayer ferrite films added onto the antenna. In summary, spin spray deposited self-biased ferrite films provide a unique way of achieving self-biased magnetic antennas operating at GHz frequency range with significantly enhanced performance.

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Performance of Hemielliptic Dielectric Lens Antennas With Optimal Edge Illumination

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***Abstract*—The role of edge illumination in the performance of compact-size dielectric lens antennas (DLAs) is studied in accurate manner using a highly efficient algorithm based on the combination of the Muller's boundary integral equations and the method of analytical regularization. The analysis accounts for the finite size of the lens and directive nature of the primary feed placed close to the center of the lens base. The problem is solved in a two-dimensional (2-D) formulation for both E- and H-polarizations. It is found that away from internal resonances that spoil the radiation characteristics of DLAs made of dense materials, the edge illumination has primary importance. The proper choice of this parameter helps maximize DLA directivity, and its optimal value depends on the lens material and feed polarization.**

***Index Terms*—Beam collimation, dielectric lens antenna, directivity, edge illumination, edge taper.**

I. Introduction

Similarly to parabolic dish reflectors, elliptical dielectric lenses have the ability to collect rays propagating parallel to their axis of symmetry into their focus, e.g., [1], [2]. Reciprocally, in emitting mode, this shape is expected to provide a locally plane wave in the radiating aperture of the hemielliptic DLA. Note that while the whole reflector surface is involved into the beam forming, it is only the frontal part of elliptical lens surface that plays similar role; the rear part of lens, behind the central cross-section, has no importance (as suggested by the geometrical optics). A truly plane wave can emerge only for an infinite reflector or lens and omnidirectional source. For realistic feeds and antennas, however, the spillover and illumination losses are inherently present: the former are associated with the power that misses reflector or lens whereas the latter are due to a nonuniform illumination of the reflector or the lens front part, as schematically shown in Fig. 1. In reflector antenna theory it is usually stated that a -10 dB edge taper provides reasonable compromise for these losses and enables one to use the reflector in the most efficient way (see, e.g., [1, Fig. 4-4] and discussion thereafter).

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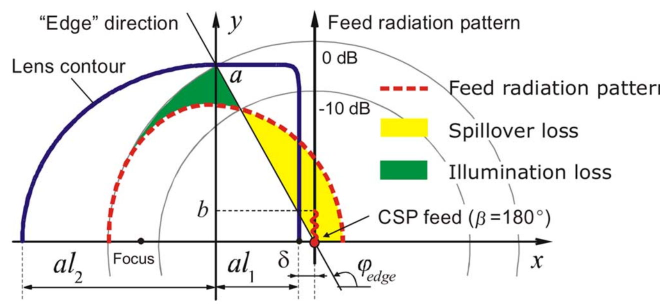

Fig. 1. Geometry and notations for the 2D model of a hemielliptic DLA (due to the symmetry only upper half is drawn). Curved line indicates the branch-cut appearing in the real space due to the CSP modeling the aperture feed. A schematic diagram for the CSP radiation pattern is given to interpret the losses associated with a nonuniform illumination of the lens front part.

In the case of DLAs, there is apparently no such analysis in open textbooks or research papers. Although there is a number of papers describing the performance of DLAs with variable lens extensions (e.g., see [3]–[5]), the role of edge illumination seems to have escaped a clear physical interpretation. Several obvious circumstances make a similar design advice for DLAs far from obvious. First, both the electrical size and the focal distance of elliptical DLAs are usually much smaller than that of reflectors [3], and thus the feed is never far away from the lens (as it is common for reflectors). Second, unlike a gently curved metal reflector, any dielectric lens is, in fact, an open dielectric resonator which is capable of supporting resonant modes. The quality factors of such modes depend on the lens parameters (shape, size, and permittivity) and can achieve rather high values for lenses made of dense materials such as silicon. If excited, internal resonances strongly affect the performance of DLAs [6], [7]. Finally, for DLAs, the focal distance and thus the favorable feed location depend on the lens material. This happens because, in geometrical optics approximation, the eccentricity of elliptical lens is determined by its material permittivity [2], [4]. These essential distinctions between reflector antennas and DLAs make the -10 dB optimal edge taper a questionable recommendation and call for additional study aimed at clarification of the role of edge illumination.

To handle this problem, we study numerically the 2-D model of a compact-size hemielliptic DLA typically used in millimeter (mm) and sub-mm wave applications [3]. The lens is fed by an aperture source simulated using the complex source point (CSP) beam [8]. The analysis is performed using a highly-efficient algorithm based on the Muller boundary integral equations (MBIE) combined with the method of analytical regularization and Galerkin projection on the set of trigonometric polynomials [9]. It fully accounts for the resonance properties of the lens and guarantees uniqueness of the solution as well as fast convergence and controllable accuracy of the numerical algorithm. Details about this technique and its numerical implementation have been already given in [6], [7] and therefore are not presented here. Comparing to [10] where performance of a hemielliptic silicon lens with varying