

# Electronically tunable magnetic patch antennas with metal magnetic films

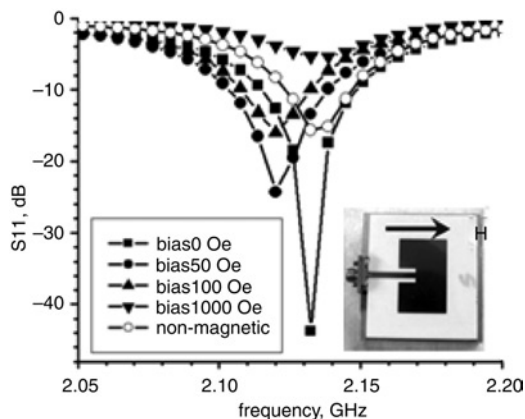
N.X. Sun, J.W. Wang, A. Daigle, C. Pettiford, H. Mosallaei and C. Vittoria

AS new type of electronically tunable magnetic patch antennas with metal magnetic films was designed, fabricated, and tested at 2.1 GHz. The magnetic patch antennas showed an enhanced bandwidth of 50% over the non-magnetic patch antennas, a significantly enhanced directivity, and a large tunability of the radiation intensity of 4.23 dB at a low applied magnetic field of  $\sim 20$  Oe.

**Introduction:** Patch antennas on ferrites substrates showed tunable radiation frequency, polarisation diversity, and beam steering [1]. In addition, it was recently demonstrated that patch antennas on a self-biased ferrite-dielectric composite substrate showed a miniaturisation factor of  $>5$ , a 600% enhanced bandwidth and a high efficiency at a resonance frequency of 277 MHz [2]. The introduction of magnetic materials into dielectric patch antenna substrates leads to enhanced substrate permeability, and an improved intrinsic impedance of the medium ( $\eta = \sqrt{\mu_0\mu_r/\epsilon_0\epsilon_r}$ ) that better matches that of free space. The better impedance match results in enhanced bandwidth and efficiency of the patch antennas.

Traditionally ferrites have been the default magnetic materials for antenna applications [1, 2]. However, the large loss tangents of the available self-biased ferrite materials (without applied magnetic bias field) severely limited their application frequencies to 500 MHz or less.

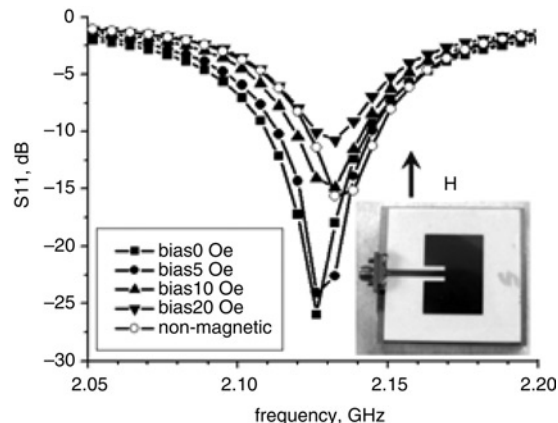
Metal magnetic films have high saturation magnetisation values of up to 24 kG and self-biased ferromagnetic resonances at several GHz [3, 4]. In addition, metal magnetic films with narrow ferromagnetic resonance linewidth comparable to those of ferrites, and high squareness (remnance ratio  $M_r/M_s$ ) of  $\sim 100\%$  [3, 4] were reported, making it possible to achieve self-biased magnetic patch antennas up to several GHz. Further, metal magnetic films and the associated fabrication technologies are low temperature processes compatible to MMIC technologies. In this Letter, we report a new type of electronically tunable magnetic patch antennas with metal magnetic films being designed, fabricated, and tested at 2.1 GHz, exhibiting enhanced performances.



**Fig. 1** Return loss of first magnetic patch antenna with different applied magnetic fields along feedline direction

**Designs and fabrication:** A conventional (non-magnetic) patch antenna operating at 2.13 GHz was designed on a  $2'' \times 2''$  square alumina substrate with a thickness of 2 mm. The Cu patch size for this non-magnetic antenna is  $L = 22.2$  mm,  $W = 30$  mm and thickness of 3  $\mu\text{m}$ . Two new magnetic antennas were designed and fabricated with the same alumina substrate and Cu patch dimensions as those of the non-magnetic antenna, except that there was one 1  $\mu\text{m}$ -thick metal 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 feedline), as shown in Figs. 1 and 2. This magnetic film shape was finalised as a result of two considerations. First, we wish to have a strong coupling between the magnetic film and the microwave magnetic drive fields, which are concentrated beneath the patch. Secondly, we wish to minimise the unwanted loss

on the feedline, so no magnetic film was put beneath the Cu feedline. Metal magnetic films used for magnetic patch antennas have an atomic composition of  $(\text{Fe}_{60}\text{Co}_{40})_{85}\text{B}_{15}$ , and were amorphous with a saturation magnetisation of 16 kG, a coercivity of  $<0.3$  Oe, and a high resistivity of  $100 \mu\Omega \cdot \text{cm}$ . All FeCoB films were 1  $\mu\text{m}$  thick, deposited by sputtering with an in-situ magnetic field to preset the magnetisation direction, thus achieving anisotropic in-plane permeability. Two magnetic antennas were made with magnetisation of the FeCoB magnetic film preset to be either parallel (1st) or perpendicular (2nd) to the feedline, as shown in Figs. 1 and 2. Photolithography and wet etching were used for patterning the Cu and magnetic layers.

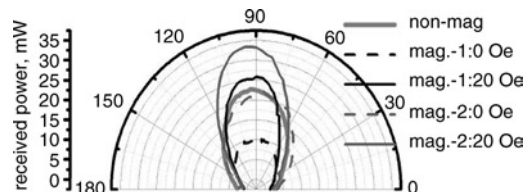


**Fig. 2** Return loss of first magnetic patch antenna with different applied magnetic fields perpendicular to feedline direction

**Test results:** Return loss of the conventional antenna (non-magnetic antenna) on alumina substrate, and the two magnetic antennas was measured and is shown in Figs. 1 and 2. The non-magnetic antenna shows a measured resonance frequency of 2135 MHz and the  $-10$  dB bandwidth (BW) is  $24 \pm 3$  MHz (or 1.1% of resonance frequency), very close to the HFSS simulated BW of 28 MHz. The results for this non-magnetic antenna will be used as a control for comparison with the antennas on magnetolectric substrates.

The return loss of the two magnetic patch antennas was measured under different magnetic bias fields parallel or perpendicular to the feedline. The return loss of the first magnetic patch antenna with magnetisation preset to be parallel to the feedline is shown in Fig. 1 with bias magnetic fields // feedline, and in Fig. 2 with bias magnetic fields  $\perp$  feedline.

It is clear that magnetic bias fields have a strong effect on the return loss of the first magnetic antenna. At zero bias field, the first magnetic patch antenna shows a resonance frequency of  $2132 \pm 3$  MHz and a  $-10$  dB bandwidth of  $37 \pm 3$  MHz. This bandwidth of 37 MHz is 50% higher than that of the conventional patch antenna (non-magnetic antenna) with the same dimension. With a small bias magnetic field of 20–50 Oe along the feedline direction, the resonance frequency is shifted from 2132 MHz down to 2120 MHz, while the bandwidth of 37 MHz is maintained. It is notable that at bias field of 1000 Oe applied // feedline, the resonance frequency is 2132 MHz, the same as the case when no magnetic field is applied.



**Fig. 3** Comparison of H-plane received power for all three antennas (non-magnetic, first magnetic antenna, second magnetic antenna) at different magnetic fields applied perpendicular to feedline

When the magnetic fields are applied perpendicular to the feedline, the first magnetic antenna shows an upward shift of the resonance frequency, opposite to the case when magnetic field is applied parallel to the feedline. The shift is about 7 MHz at a low bias field of 10 Oe. Therefore, with a small applied field of  $<50$  Oe, a total resonance

frequency shift of 19 MHz can be achieved, which is  $\sim 50\%$  of the  $-10$  dB bandwidth of the magnetic antenna.

The non-magnetic (conventional) patch antenna and magnetic antennas (first and second) were tested in the anechoic chamber with the same input power to the antenna. The far-field H-plane radiation pattern of the non-magnetic antenna is shown in Fig. 3, exhibiting a broad beam pattern typical of conventional patch antennas.

The first magnetic antenna was tested and its H-plane radiation pattern is shown in Fig. 3 at different applied magnetic fields perpendicular to feedline. The directivity is enhanced from 5.58 to 6.73 dB compared to that of the non-magnetic antenna. The beam pattern of the first magnetic antenna shows strong bias field dependence, which is consistent with the return loss results shown in Figs. 1 and 2. At a low bias field of 20 Oe perpendicular to feedline, the maximum detected power shows a 4.23 dB enhancement at  $\theta = 90^\circ$  with enhanced directivity, indicating a strong low-field tunability of the beam pattern. The H-plane beam pattern for the second magnetic antenna which has its magnetisation preset to be perpendicular to the feedline is shown in Fig. 3. Again, the directivity is enhanced at a bias field of 20 Oe, showing a 2.5 dB enhancement of the maximum radiated power at  $\theta = 90^\circ$ , similar to that observed for the first magnetic antenna.

At a bias field of 20 Oe perpendicular to feedline, the maximum radiated power of the first magnetic antenna is significantly enhanced compared to that at zero field, even slightly higher than that of the non-magnetic antenna. The beam pattern of the second magnetic antenna, of which the magnetisation is preset to be perpendicular to feedline, is comparable to that of the non-magnetic antenna at zero bias fields. This indicates that the second magnetic antenna is a self-biased magnetic antenna. At an applied field of 20 Oe perpendicular to feedline, the maximum radiation power of the second magnetic antenna is significantly enhanced to be about two times that of the non-magnetic antenna with a narrow beam, indicating an enhanced directivity over the non-magnetic antenna.

*Discussion:* The resonance frequency of a patch antenna can be described by:  $f_{TM_{010}} = 1/2L\sqrt{\mu_{eff}\epsilon_{eff}}$ , with  $L$  being the length of the patch,  $\mu_{eff}$  and  $\epsilon_{eff}$  being the effective permeability and permittivity of the patch antenna substrate, respectively. The effective permittivity is expected to be nearly independent of the bias magnetic field. In contrast, the permeability of the magneto-dielectric composite substrate of magnetic metal film and alumina substrate can be readily changed by bias fields, which can be expressed as  $\mu_{eff} = \mu_0 \cdot \epsilon_{dielectric} + \mu_0\mu_r \cdot \epsilon_{mag}/\epsilon_{dielectric} + \epsilon_{mag} \approx \mu_0 + \mu_r \cdot \epsilon_{mag}/\epsilon_{dielectric}$  for the two magnetic antennas with  $\epsilon_{dielectric} = 2 \text{ mm} \gg \epsilon_{mag} = 1 \text{ }\mu\text{m}$ .

The relative permeability of the magnetic film,  $\mu_r$ , can be negative, zero, or positive at the antenna resonance frequency, leading to the resonance frequency shift as shown in Figs. 1 and 2. For example, at zero bias field, the relative permeability  $\mu_r$  of the magnetic film patch for the first magnetic antenna has a negative relative permeability along

the width direction as the ferromagnetic resonance frequency of the magnetic film is below the antenna resonance frequency (2132 MHz). At an applied field of 50 Oe along the feedline, the FMR frequency of the magnetic patch is above the antenna resonance frequency, leading to a positive relative permeability  $\mu_r$  and a down-shifted resonance frequency of 2120 MHz. At an applied field of 1000 Oe along the feedline direction, the relative permeability of the magnetic film patch is close to 1, leading to reduced permeability and an up-shift of the resonance frequency back to 2132 MHz.

*Conclusion:* Metal 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 miniaturised patch antennas on magnetoelectric substrate with significantly enhanced bandwidth, improved directivity, and high efficiency when multilayers of metal magnetic films are introduced into antenna substrates. In addition, these magnetic antennas can be made conformably at a low cost with the low-temperature physical vapour deposition method, making these patch antennas with metal magnetic films very promising for real applications.

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