Circular Polarization GPS Patch Antennas with Self-biased Magnetic Films

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Abstract— Magneto-dielectric substrates with thin magnetic films show great potential in realizing electrically small tunable antennas with improved directivity and higher bandwidth than those realized on dielectric substrates. This paper introduces self-biased magnetic films as a practical means to tune a patch antenna by loading a commercially available dielectric substrate. Novel antenna designs with self-biased metallic magnetic films and ferrite films were investigated. These magnetic patch antennas have improved the axial ratio from 1.57 dB to 0.97 dB with respect to the central frequency ranging from 1.575 GHz to 1.562 GHz, a large radiation frequency tunability of about 40% to 80% of the −10 dB bandwidth, and a significantly enhanced directivity.

1. INTRODUCTION

In recent years, with the continuous growth of wireless communication technology, design and manufacturing low cost microwave components have become critical issues to the development of RF communications systems. As a very important passive component in a wireless communications system, miniaturized antennas with decent gain and bandwidth are receiving considerable attention in both industry and academia [1]. Planar antennas, because of their simple configuration, manufacturing advantages, as well as compactness, are highly desirable for these systems. The substrates of planar antennas play a very important role in antenna miniaturization. In particular, antenna substrates with larger relative permeability can lead to antenna miniaturization, enhanced bandwidth, tunable center frequency, polarization diversity, and beam steering [2–4].

Bulk ferrite materials, composites of ferrite particles in polymer matrix, metamaterials with embedded metallic circuits, etc., have been used as antenna substrates for achieving \( \mu_r > 1 \). However, these materials or composites are too lossy to be used at frequencies > 500 MHz under self-bias conditions, and large biasing magnetic fields are needed for ferrites to operate at higher frequencies. In order to be practically feasible in miniature circular polarizal vector (CP) antennas [5] for Global Positioning System (GPS) applications, it is important for antenna substrates to be comprised of self-biased magnetic materials, in which no external bias field is applied. However, it has been challenging to achieve self-biased magnetic materials for antenna substrate applications at > 500 MHz frequency range. Magnetic thin films, however, provide a unique opportunity for achieving self-biased magnetic patch antenna substrates with \( \mu_r > 1 \) at > 1 GHz frequencies [6]. The strong demagnetization field for magnetic thin films, \( H_{\text{demag}} = 4\pi M_s \), allows for a self-biased magnetization with high ferromagnetic resonance (FMR) frequencies up to several GHz, which are essential for microwave devices.

In this paper, a CP patch antenna miniaturized using self-biased ferrite thin films embedded in alumina substrate is presented, thus essentially creating a magneto-dielectric substrate for practical applications. These magnetic patch antennas showed a decrease in axial ratio from 1.57 dB to 0.97 dB with respect to the central frequency ranging from 1.575 GHz to 1.562 GHz, a large radiation frequency tunability of about 40% to 80% of the −10 dB bandwidth, and a significantly enhanced directivity. These magnetic antennas can be made conformably at a low cost near room temperature.

2. DESIGN OF CIRCULAR POLARIZATION PATCH ANTENNA

Figures 1(a) and (b) show the schematic top view and side view, respectively, of the circular polarization patch antenna. This antenna consists of a rectangular patch with seven fingers on each
side. Both the patch and the fingers are realized by patterned copper cladding on the top surface of the underlying dielectric substrate. A metallic side-wall is adopted to improve the antenna’s directivity, with the same height as the dielectric substrate. A circular ground plane with the radius of 101.6 mm is added at the back of the dielectric substrate. The feed point is located on the 45 degree diagonal, with a distance of 2.54 mm along the x-axis. This structure excites two degenerate orthogonal modes with equal amplitude and 90 degree phase difference, and right hand circular polarization (RHCP) radiation is obtained. The substrate has relative permittivity of 13 and a thickness of 1.52 mm. All the other parameters are listed in the caption of Fig. 1.

Figure 1: Geometry of the circularly-polarized rectangular patch antenna with fingers. (a) Top view, $W_1 = 2.54$ mm, $W_2 = 25.96$ mm, $L_1 = 25.76$ mm, $L_2 = 32.76$ mm and $R = 101.6$ mm, (b) side view, $H_1 = 1.52$ mm.

3. ANTENNAS WITH MAGNETIC FILMS AND SIMULATED RESULTS

In order to obviate biasing of magnetic substrates by an external field, we propose using self-biased ferrites films with a relatively high in-plane anisotropy. This large anisotropy enables a low loss tangent of the ferrite films at GHz frequencies. The ferrite films used have a relative permittivity of 13 and relative permeability of 10 with zero loss tangent.

Three CP patch antennas with ferrite films are designed as follows. Case I, a ferrite thin film of thickness 2 $\mu$m and surface dimensions $L_1 \times W_2$ introduced just below the rectangular patch, as indicated in Fig. 2(a).

For case II, a 2 $\mu$m thick ferrite film is added just above the ground plane, as shown in the schematic in Fig. 2(b). In this case, the ferrite film has the same size as the dielectric substrate. Combining the above two cases, we also design an antenna with two ferrite layers in case III. One film is just beneath the rectangular patch, and the other above the ground plane as shown in Fig. 2(c). All these three antenna designs with ferrite films can be readily fabricated.

In order to compare the results with the non-magnetic patch antenna, the return loss, the axial ratio and the radiation pattern of ferrite-loaded patch antenna are plotted and analyzed next. The return loss curves in Fig. 3 are from simulations under the condition that all the geometrical dimensions of the antenna are kept unchanged, and only the ferrite films are added at different layers. All the simulations, including the baseline non-magnetic patch antenna, were carried out with Ansoft’s HFSS software.

From Fig. 3 we can see that the central resonant frequency of the non-magnetic patch antenna is about 1.575 GHz, and the $-10$ dB bandwidth is 16 MHz. When a ferrite film is added below the patch in case I, the resonant frequency shifts down to 1.569 GHz with the magnitude of $-15.6$ dB. This indicates a tuning range of 6 MHz relative to the non-magnetic patch, or equivalent to approximately 40% of the bandwidth. The bandwidth remains unchanged with addition of the ferrite film. When a ferrite film is added just above the ground plane in case II, we observe that the resonant frequency is still equal to 1.569 GHz, but with a magnitude of $-18.4$ dB, indicating
that case II has better impedance matching than case I. In the third case, two ferrite films are added below the patch and above the ground plane at the same time, which moves the resonant frequency further down to 1.562 GHz, a shift about 80% of the antenna bandwidth relative to the non-magnetic patch antenna. In summary, we note that the patch antenna loaded with ferrite film can indeed miniaturize the geometrical dimensions effectively (as demonstrated by shifting down the resonance), while the bandwidth remains unaffected. We will show next that the antenna gain is also unaffected by the ferrite film, thus proving that the miniaturization does not compromise either gain or bandwidth.

Figure 3: Simulated return loss against frequency for the four different cases.

Figure 4: Simulated axial ratio against frequency of the four cases.

The axial ratios of the circular polarization are also computed and presented in Fig. 4, in which the CP bandwidth, determined from 3-dB axial ratio, is found to be about 4 MHz. The axial ratios of these four antennas are 1.57, 1.0, 1.1 and 0.97, respectively. The simulated radiation patterns at the corresponding central frequency are plotted in Fig. 5. Good right hand CP radiation is obtained, with the worst-case cross-polarization isolation at broadside equal to about −15 dB for case I. The isolation for cases II and III is slightly better, at about −17 dB. All the three cases have identical RHCP radiation pattern, with the antenna gain in the broadside direction about 2.8 dBi.

In order to evaluate omni-directionality in the xy-plane of the radiation pattern, the gain of the simulated RHCP radiation patterns for an elevation aspect of 80 degrees is plotted in Fig. 6 against the azimuth angle. The peak-to-peak variation in RHCP gain, a measure of the omni-directionality, is about 1.1 dB for the non-magnetic patch antenna, and 0.8 dB for case I. However, both case II
and case III demonstrate smaller peak-to-peak variation in the RHCP pattern, with values about 0.6 dB and 0.4 dB, respectively. Thus, to get the most omni-directional pattern, addition of ferrite films both below the patch and above the ground plane appears to be the best option. We note from Figs. 3 and 4, respectively, that case III also results in the lowest resonant frequency (or the smallest antenna) among the four options, and the lowest axial ratio.

4. CONCLUSIONS

Four circular polarization patch antennas with/without ferrite films are designed and analyzed in this paper. The designed magnetic patch antennas with self-biased ferrite magnetic films can realize a tuning range of 40 to 80% of the antenna bandwidth. The axial ratio can be improved from 1.57 dB to 0.97 dB with respect to the central frequency, which shifts from 1.575 GHz to 1.562 GHz, indicating modest miniaturization. Improvement of omni-directionality in the radiation pattern, without sacrificing peak gain, is also demonstrated with the addition of ferrite films adjacent to both the patch and the ground plane.

REFERENCES
