Patch Antenna Miniaturization Using Artificial Magneto-Dielectric Metasubstrate

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1. Introduction

Effective antenna miniaturization is a challenging problem due to the inevitable trade-off between size and performance of the antenna. Increasing the effective medium parameters, permittivity and permeability, results in antenna size reduction. Note that the use of dielectric materials as the antenna substrate with high permittivity is to reduce size but at the same time the efficiency and the bandwidth are significantly reduced. Alternatively, therefore, one can use magneto-dielectric material (MDM) procuring an antenna size reducing with a sufficient bandwidth. MDMs are materials with both the permittivity and permeability greater than unity ($\varepsilon_{eff} > 1$, $\mu_{eff} > 1$). Recently, the use of MDM, whether real or meta, has been attracted a large amount of attentions. The real materials, magnetic nanoparticles, namely nickel and cobalt, require complex fabrication technology and hence are relatively expensive. Moreover, it is difficult to achieve low loss for these materials above a few GHz. Another possible way to design MDMs, involves using periodic structures composed of metallic and dielectric or magnetic materials. Nowadays, researchers devote to antenna miniaturization using artificial magneto-dielectric materials as a substrate, called artificial magneto-dielectric metasubstrate (AMDM). AMDMs are used as an antenna substrate of low profile antennas to reduce the size of antennas while maintaining good performance [1-2].

In this paper, artificial magneto-dielectric metamaterial is used as a substrate in design of miniaturized patch antenna. The new spiral loop resonator is a generic inclusion for design of AMDS with desired properties. The advantages of the AMDM, in comparison with dielectric and magnetic substrates, are reported.

2. Antenna Configuration

The geometries considered of the proposed artificial magneto-dielectric metasubstrate underneath the patch are shown Fig. 1 (a). As known, the patch antenna resonant frequency is usually determined by the patch length. The length (L) of patch is approximately equal to the half of the wavelength in the substrate; hence, $L = 0.5\lambda_0/\sqrt{\varepsilon_{eff}\mu_{eff}}$, where λ_0 is the wavelength of the radiation in the free space and ε_{eff} and μ_{eff} are the relative permittivity and permeability of the substrate, respectively. For the sake of simplicity, square patch dimensions are considered to be 40 $\times$ 40 mm^2 with 50-Ω coaxial probe feed arrangement. This patch is placed above the unit cell array of spiral loop. To obtain the effective properties of these composite substrates, a quasi-static mixing model can be employed when the unit cell is smaller than the wavelength in the medium. Since the size of the unit cell is much smaller than the wavelength near resonance, the volume occupied by the spiral array in the planar can be taken as an effective medium. The spiral loop array periodicity is 2.0 mm and 6.0 mm along the x and y directions, respectively. The structure of unit cell containing spiral loop embedded in a host dielectric material as shown in Fig. 1(b). The host dielectric is an inexpensive FR4 dielectric substrate with a dielectric constant $\varepsilon_r = 4.2$ and the thickness is equal to 0.8 mm. The unit cell has dimension of a = 10 mm and b = 10 mm. The dimension of the spiral loop is the major side width of 9.35 mm, the line width of 0.5 mm and the line gap of 0.5 mm. These effective medium parameters are obtained using full-wave simulations and the subsequent retrieved process [3]. Effective permeability (μ_{eff}) and permittivity (ε_{eff}) are extracted and shown in Fig. 2. The resonant frequency of this structure can be controlled by tuning the spiral and substrate dimensions. The resonant frequency declines by increasing the number of turns and line width or by increasing the spacing between adjacent turns. The unit cell resonates at frequency about 2.25 GHz. Since this slab was aligned so that the magnetic fields were perpendicular to the surface of the unit cells, which induce currents in the spirals. The induced currents generate magnetic dipole moments and can change the magnetic permeability of the medium. This phenomenon effectively creates an inductance within the host non-magnetic substrate material. This induced inductance along with the capacitance in the structures forms a resonant structure. The scale of spiral loop array is chosen as 4×6 arrays, corresponding to 40.0 mm×34.8 mm area undertaken patch. The array is located completely under the patch, given that the patch width is $L = 40$ mm. The physical parameters of the proposed antenna are given as follows: H = 10 mm, g = 6 mm and $X_p = 10$ mm.

3. Results and Discussion

To validate the proposed concept, a prototype of the miniaturized patch antenna loaded with the AMDM was designed, fabricated and measured as shown in Fig. 3 (a). CST software is used to simulate antenna with and without AMDM filling. Effects of AMDM on antenna size reduction and antenna efficiency can be studied by comparing with simple patches on the air, dielectric and dispersion free-μ (magnetic) substrates. The antenna on air substrate, denoted as the reference antenna (Fig. 3 (b)), is studied and compared by simulation and fabrication for discussion. For comparison with the same resonance, we also design a patch with the dielectric-only and magnetic-only substrates whose relative permittivity and permeability are calculated to be $\varepsilon_r = \mu_r = 9.5$ with the same supporting material height, the same patch and ground plane sizes. However, we remark that the substrate permittivity and permeability of 9.5 are not available in the commercial PCB, hence the measured results for this antenna are not presented. The comparison of simulated and measured reflection coefficient between the AMDM, dielectric, magnetic, air-substrates are shown in Fig. 4. The S_{11} obtained from simulation and measurement of the proposed antenna with a very good agreement is shown in Fig. 4.The resonant frequency of the air substrate is 3.2 GHz, which shows that the resonant frequency is shifted to lower frequency by employing the AMDM for the same patch size. The radiation efficiency and directivity of air substrate, dielectric, magnetic and AMDM are tabulated in Table I. From the results, the miniaturization factor is $\sqrt{\varepsilon_{eff}\mu_{eff}} = 3.08$. For miniaturized patch antenna, it is observed that the best performance is magnetic type. However, the magnetic is not available for the antenna. AMDM is a good choice because the radiation efficiency and directivity are better dielectric. Therefore, utilizing the magneto-dielectric metasubstrate one can offer a miniaturized planar antenna with high efficiency. The result is found that the radiation efficiency and realized gain of AMDM are nearly magnetic substrate. Therefore, a miniaturization factor of 3.08 is achieved using the AMDM. A significant advantage of the proposed AMDM composed of spiral loop is that it can be used in design of miniaturized patch antenna. In fact, increasing the effective substrate parameters results in the antenna size reduction. Figure 4 shows the measured radiation patterns in the two principal planes (*x-z* plane and *y-z* plane) which are similarly the uni-directional at the resonant frequency 1.8 GHz.

4. Conclusion

For enhancement of the size reduction and radiation efficiency of a patch antenna, an artificial magneto-dielectric metasubstrate (AMDM) is preferred. Using the proposed AMDM, a square patch antenna is designed at the center frequency of 1.8 GHz. Moreover, experimental results indicate that by applying the AMDM, a total 65% size reduction can be obtained comparing with a half-wavelength patch antenna loaded without the AMDM. The designed antenna has radiation efficiency is 72% and directivity of this antenna is 6.24 dBi. Miniaturization factor of 3.08 is achieved using AMDM compared to a conventional air substrate.

Acknowledgments

The authors would like to acknowledge the Microwave and Wireless Communication laboratory at Rajamangala University of Technology Thanyaburi for supporting the measurement instruments.

References

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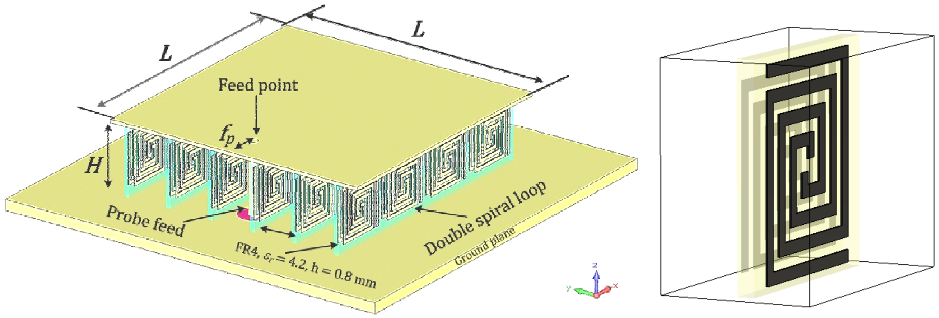


(a) (b)

Figure 1: (a) Configuration of the proposed antenna and (b) unit cell of the spiral loop resonator

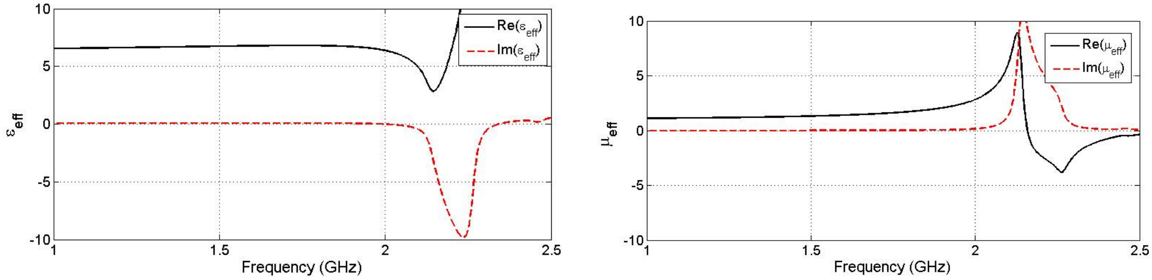
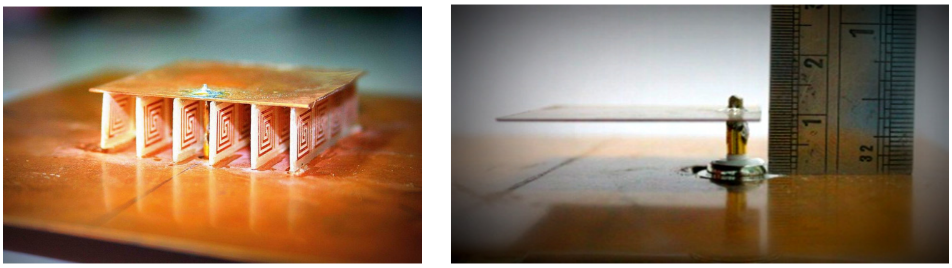


Figure 2: Effective constitutive parameters of the spiral loop unit cell (a) ε_{eff} and (b) μ_{eff}



(a) (b)

Figure 3: Photograph of the prototype patch antennas (a) above the artificial magneto-dielectric metasubstrate and (b) air substrate as reference antenna.

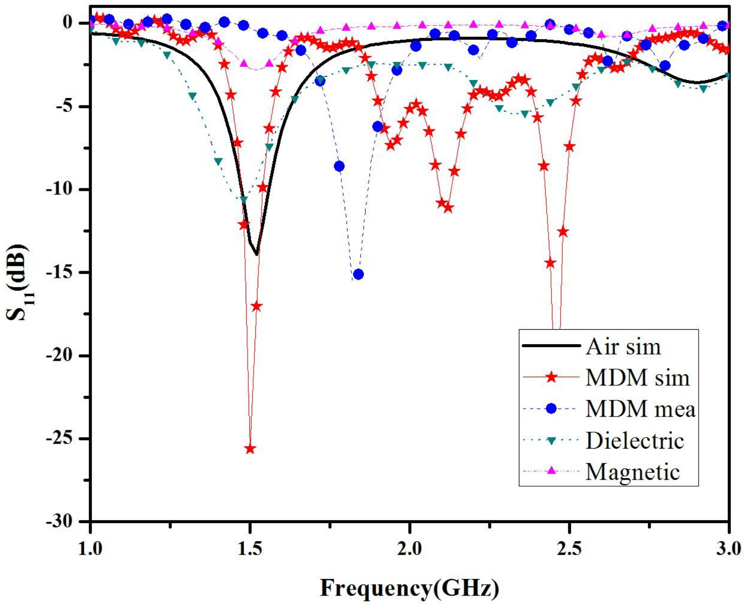
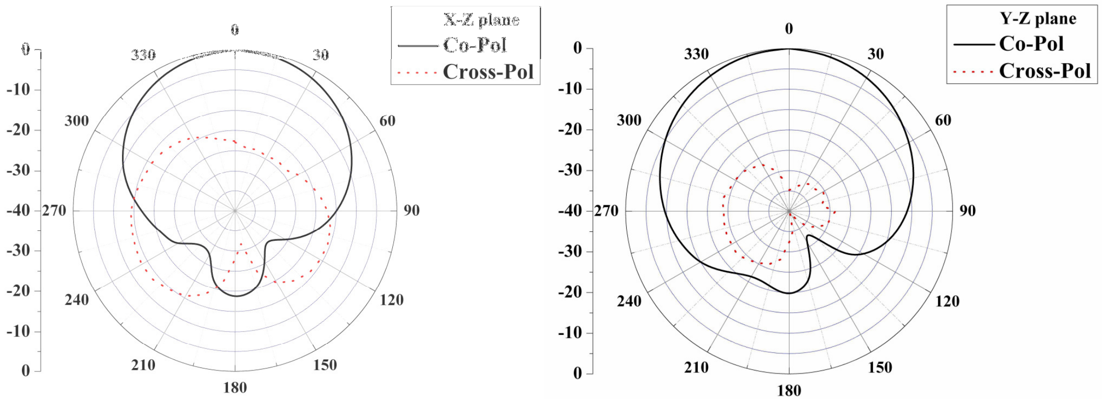


Figure 4: Comparison of S_{11} for three patch antennas with different substrates.



(a) (b)

Fig. 4 Measured radiation patterns of the proposed antenna at 1.8 GHz (a) *x-z* plane and (b) *y-z* plane.

Table I Performances of the patch antenna above different four substrates with the same resonant frequency at 1.8 GHz.

Parameters/Substrate (H= 10 mm)	Air-Filled	Dielectric $\varepsilon_r = 9.5$, $\mu_r = 1$	Magnetic $\varepsilon_r = 1$, $\mu_r = 9.5$	Magneto-Dielectric $\varepsilon_r = 6.8$, $\mu_r = 1.4$
Dimension	92x92 mm^2	40x40 mm^2	40x40 mm^2	40x40 mm^2
Miniaturized Factor	1.0	3.08	3.08	3.08
Radiation Efficiency	98%	51.5%	94%	72%
BW($S_{11} \leq$-10dB)	1472-1558 MHz	1437-1525	1460-1520	1470-1540 MHz
Directivity (dBi)	9.76	6.19	7.75	6.241