Available online at www.sciencedirect.com

ScienceDirect

Journal of Electrical Systems and Information Technology 5 (2018) 263–270

www.elsevier.com/locate/jesit

Gain enhancement of patch antenna integrated with metamaterial inspired superstrate

M. Saravanan *, V. Beslin Geo, S.M. Umarani

Department of Electronics and Communication Engineering, Hindustan Institute of Technology and Science, Chennai, India

Received 26 October 2017; received in revised form 15 March 2018; accepted 9 April 2018
Available online 19 April 2018

Abstract

The paper investigates single band planar resonant antenna inspired by phi-shaped slotted metamaterial superstrate and a square patch antenna is used as a primary radiator. The antenna is modeled using finite difference time domain method and resonates at S band. The antenna comprises of single layer symmetrical metamaterial superstrate which is used to suppress surface waves based on μ-negative characteristics. The effective material parameters of the metamaterial structure are extracted from S-parameters using Nicholson–Ross–Weir method. The antenna achieves −28.64 dB reflection coefficient of 2.4 GHz and also maintains good radiation characteristics with a peak measured gain of 7.94 dB at its operating frequency. Due to its advantages, the antenna can be used for modern wireless communications.

Keywords: Patch antenna; Metamaterials; Nicholson–Ross–Weir method; Radiation pattern; Surface waves

1. Introduction

In last few decades the growth of photonic crystal plays a major role in the field of microwave circuits and antennas due to their enhanced propagation characteristics and to suppress harmonics frequencies and hence many researchers utilize photonic crystal substrate in microwave and antenna applications. Yablonovitch et al. (1989), experimentally demonstrates the propagation of electromagnetic waves in the photonic crystals like glass substrate and achieves a bandwidth of 2 GHz around 6.5 GHz operating frequency. Horii and Tsutsumi (1999) presented microstrip patch antenna having two-dimensional photonic bandgap (PBG) in the ground plane to suppress harmonic frequencies of the antenna. However these glass substrates have high permittivity and permeability compare to traditional substrates

* Corresponding author.
E-mail address: rs.sm0914@hindustanuniv.ac.in (S. M.).
Peer review under the responsibility of Electronics Research Institute (ERI).

Production and hosting by Elsevier

https://doi.org/10.1016/j.jesit.2018.04.002

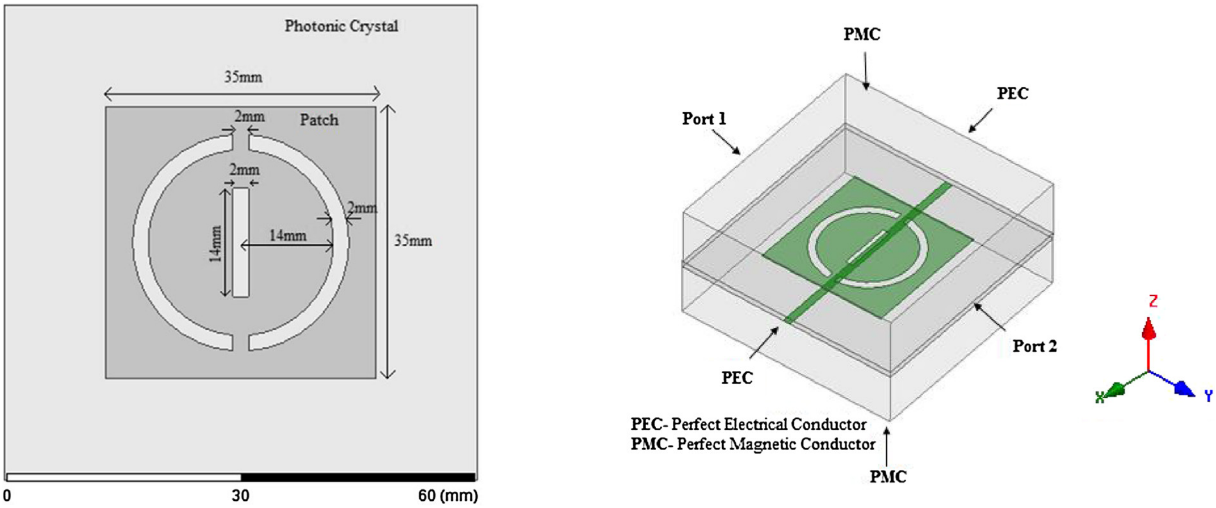
and makes the antenna less suitable at higher frequencies. This brings the use of metamaterial inspired glass substrates having negative material properties in antenna substrates. This was initially observed by Veselago (1968) and predicted that the EM wave in a medium flow directly opposite the direction of energy in the left handed materials having negative material properties. This principle was experimentally verified by Smith and Kroll (2000) by placing periodic structures of slip ring resonator in a negative refraction material. Nowadays these metamaterial substrates have been utilized by many researchers for improving performance of the antenna. Lubkoswski et al. (2009), show the advantages of using metamaterials in improving gain and directivity of the antenna and noted that directivity of antenna is improved for low dielectric materials especially at high frequencies. Song et al. (2011) proposed L-shaped left handed material for enhancing the gain of the patch antenna. The model uses periodic metamaterial structure around the patch in order to suppress the surface wave and thereby enhancing gain of the antenna. One more method of improving gain of the conventional antenna is by embedding metamaterial inspired 3D resonator structures in the Low Temperature Co-Fired Ceramic (LTCC) Substrate (Liu et al., 2013). This achieves a compact structure achieving narrow beamwidth and also it increases the fabrication complexity of the antenna. Gao et al. (2016) presented metamaterial inspired dual layer rectangular ring structure integrated around the periphery of patch antenna for improving gain and bandwidth of the antenna. Pires et al. (2013) presented a metamaterial inspired wired antenna instead of traditional planar structured metamaterials discussed above. However these antennas achieve poor gain in the operating frequency. Brown et al. (1998) fabricated bowtie antenna on photonic crystal substrate and measured the radiation properties (Brown and Parker, 1993). They observed that in planar antenna modeled on conventional silicon substrate, most of the power is radiated in to the substrate and hence reduces the gain and directivity of the antenna. The second characteristics is that the power radiated in to the substrate at an angle greater than $\theta_c = Sin^{-1}\varepsilon^{\frac{-1}{2}}$ will get total internally reflected in to substrate and gets trapped. However photonic crystal eliminates these problems due to its non-reactive impedance properties on homogeneous dielectric substrate. Hence the proposed metamaterial unit cell structure is modelled on photonic crystal substrate instead of conventional substrate.

This paper presents metamaterial inspired phi-shaped slot patch antenna operating at 2.4 GHz. The performance of the patch antenna is analyzed by finite difference time domain (FDTD) method using high frequency structure simulator. FDTD method is a numerical analysis method for modelling computational electromagnetics. The proposed geometry is modelled using Ansys High Frequency Structure Simulator (HFSS) which uses FDTD method of maxwell's equation and forms computational domain and grid materials and determines E and H fields at a point or series of points within computational domain. The metamaterial properties are extracted from S parameters using Nicolson–Ross–Weir method (NRW) (Ziolkowski, 2003). The metamaterial achieves simultaneous negative permittivity and permeability at 2.4 GHz and is incorporated with conventional patch antenna to improve its gain performance and reduce the reflection coefficient and hence the antenna finds application in modern wireless communications.

2. Geometry of metamaterial unit cell and its performance characteristics

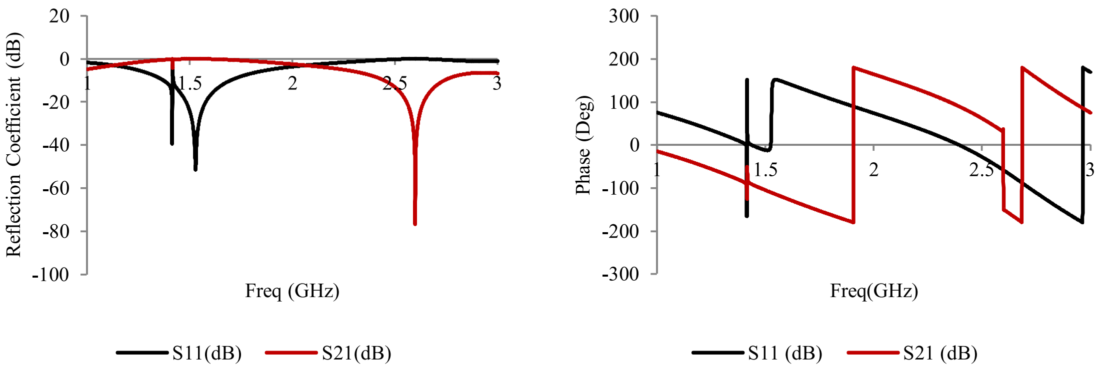
Fig. 1(a) shows the geometry of proposed metamaterial unit cell. The geometry consists of phi-shaped slot etched in square conductor having a dimension of 35 mm × 35 mm. Because of its geometry, the electrical length of the antenna is much larger than its actual physical size and hence introduce additional phase delays in the surface waves propagating over it and thereby stores and re-radiates energy. Thus metamaterials is used to improve antenna radiated power with increased directivity. The structure is modeled on photonic crystal substrate having a permittivity (ϵ) of 5.5 and permeability (μ) of 1. A thin line strip passes at bottom of the substrate for excitation of metamaterial structure. The boundary condition for the metamaterial unit cell is shown in Fig. 1(b). The boundary conditions are set in such way that the electric field components propagate normal to the photonic crystal substrate and magnetic field propagates parallel to the substrate. The performance of the metamaterial unit cell antenna structure is characterized using FDTD method and corresponding S parameters are obtained as shown in Fig. 2.

It is observed from Fig. 2(a) that S11 and S21 parameters crosses at 1.25 GHz and 2 GHz. This shows that the unit cell structure has a bandgap between 1.25 GHz–2 GHz where electromagnetic waves are reflected which makes the structure to have negative material properties. Hence the unit cell structure resonates at 1.5 GHz and has a bandgap between 1.25 GHz–2 GHz. Fig. 2(b) clearly shows electromagnetic waves propagates in opposite direction of excitation input port 1. The permittivity (ϵ) and permeability (μ) of the proposed metamaterial unit cell is extracted by using NRW method (Ziolkowski, 2003) as shown below.



(a) Unit Cell (b) Boundary Conditions

Fig. 1. Metamaterial geometry.



(a)Reflection Coefficient (b) Phase angle

Fig. 2. S Parameters for the metamaterial unit cell.

The transmission coefficient (T) and reflection coefficient (¥Ã) is given by

$$T = \frac{S_{11} + S_{22} - \Gamma}{1 - (S_{11} + S_{21)\Gamma}} \tag{1}$$

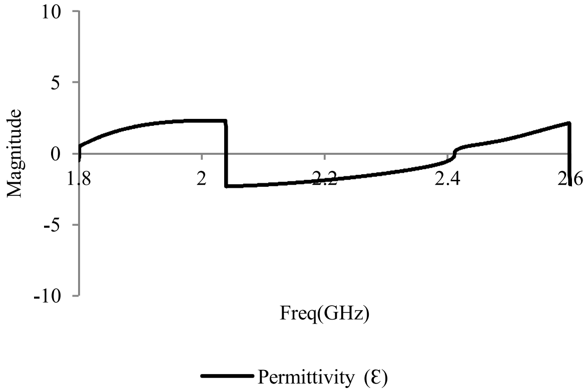
$$\Gamma = X \pm \sqrt{X^2 - 1} \tag{2}$$

$$\text{Where } X = \frac{{S_{11}}^2 - {S_{21}}^2 + 1}{2S_{11}} \tag{3}$$

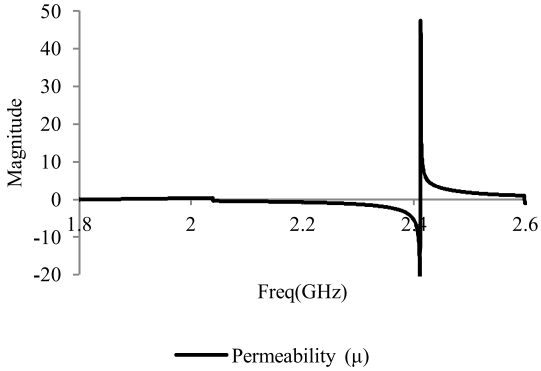
The permeability (μ) is given by

$$\mu = \frac{1 + \Gamma}{\Lambda\,(1 - \Gamma)\sqrt{\frac{1}{{\lambda_0}^2} - \frac{1}{{\lambda_c}^2}}} \tag{4}$$

$$\text{Where } \frac{1}{\Lambda^2} = \left(\frac{\varepsilon_r * \mu_r}{{\lambda_0}^2} - \frac{1}{{\lambda_c}^2}\right) = -\left(\frac{1}{2\pi L} ln\left(\frac{1}{T}\right)\right)^2 \tag{5}$$



(a) Permittivity (Ɛ)



(b) Permeability (μ)

Fig. 3. Metamaterial material properties.

The permittivity (ϵ) is given by

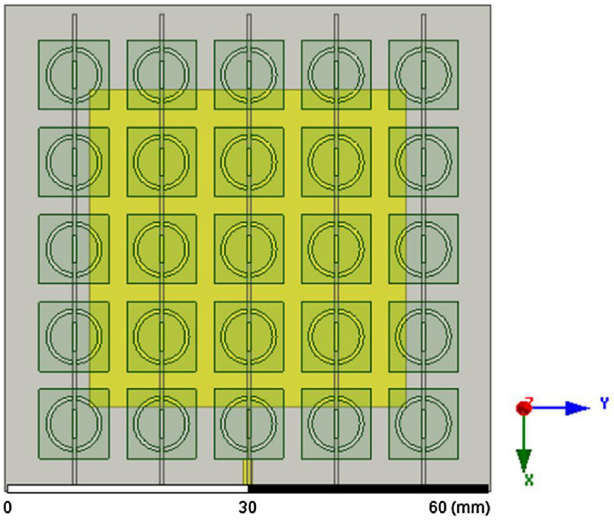
$$\varepsilon = \frac{\lambda_0{}^2}{\mu_r}\left(\frac{1}{\lambda_c{}^2} - \left(\frac{1}{2\pi L} ln\left(\frac{1}{T}\right)\right)^2\right) \tag{6}$$

Fig. 3 shows the negative permittivity (ϵ) and permeability (μ) of the given metamaterial structure extracted from S parameters using NRW method.

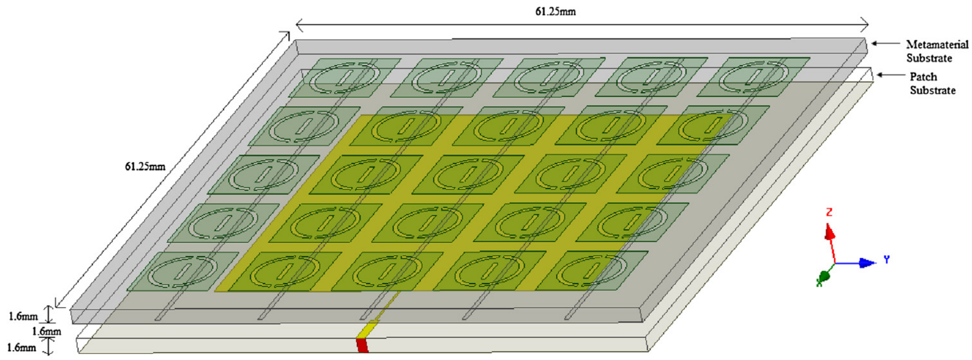
3. Geometry of proposed patch antenna and its performance characteristics

Fig. 4 shows the geometry of the proposed antenna integrated with metamaterial inspired superstrate. The proposed antenna is modeled using ansys high frequency structure simulator using FDTD method. The photonic crystal is used as a superstrate which has a thickness of 1.6 mm and size of 61.25 mm × 61.25 mm and is placed at 1.6 mm above the patch antenna model. An array of 5 × 5 metamaterial unit cells is etched on superstrate in order to enhance the performance of the patch antenna.

A square shaped patch antenna of size 40 mm × 40 mm is used as a primary radiator. The patch is engraved on FR_4 substrate having a thickness of 1.6 mm and a size of 61.25 mm × 61.25 mm. In order to validate the performance of the proposed model, the antenna fabricated and are analyzed using agilent network analyzer (N9925A) and antenna test systems. Fig. 5(a) shows fabricated model in which metamaterial structure is etched in conventional FR_4 superstrate placed over rectangular patch radiator. Fig. 5(b) shows proposed fabricated model in which metamaterial structure is



(a) Front View



(b) Side View

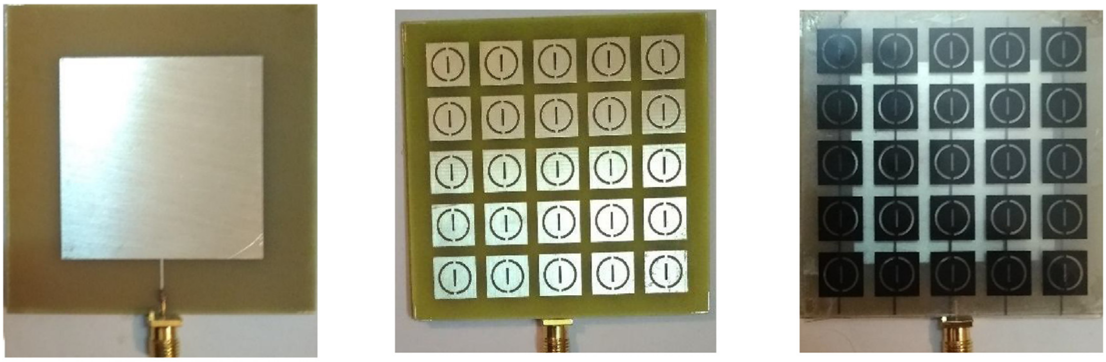
Fig. 4. Geometry of patch antenna with metamaterial inspired superstrate.

etched in photo crystal superstrate placed over rectangular patch radiator. Both the fabricated model are analyzed using agilent network analyzer (N9925A) and antenna test systems and the results are compared with conventional patch antenna.

Fig. 6 depicts the reflection coefficient (S11 (dB)) curve as a function of operating frequency obtained using FDTD method. The reflection coefficient curve compare proposed model with standard patch without metamaterial superstrate and metamaterial with FR_4 superstrate structure operating at same frequency. It is observed that the proposed antenna model integrated with metamaterial photonic crystal superstrate reduces reflection coefficient significantly in the operating frequency when compared with other models.

Radiation characteristics of the proposed antenna model are compared with standard patch antenna and are given in Fig. 7. It is observed that the proposed model improves the gain of the antenna compared with conventional antenna. It is due to the fact that additions of metamaterial superstrate suppress the surface waves due to its negative μ characteristics and hence results in significant improvement in gain as shown in Fig. 7.

The antenna gives a simulated gain of around 6.96 dB for conventional patch antenna and 7.92 dB for FR_4 superstrate model and 9.67 dB for photonic crystal superstrate model. The measured gain is calculated using two antenna method. A standard pyramidal horn antenna having a gain of 9 dB is used as a reference antenna. The distance between two antennas (R) is measured and the gain is calculated using Friis transmission equation given below



(a) Conventional Patch antenna

(b) Metamaterial etched on FR_4 Superstrate

(c) Proposed model with Metamaterial etched on Photonic crystal Superstrate

Fig. 5. Fabricated prototype model.

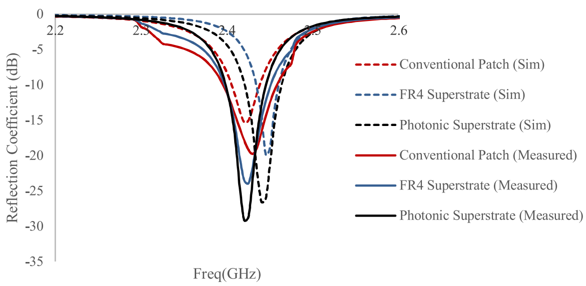


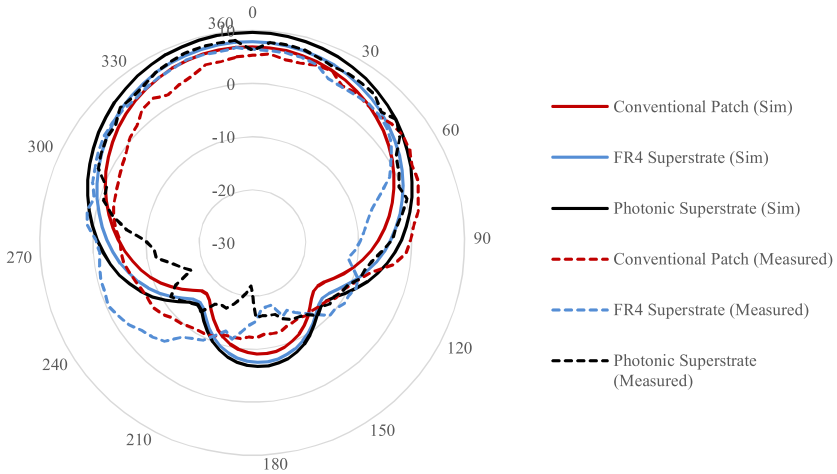
Fig. 6. Reflection coefficient (dB).

Table 1
Performance comparison of proposed model with conventional antenna.

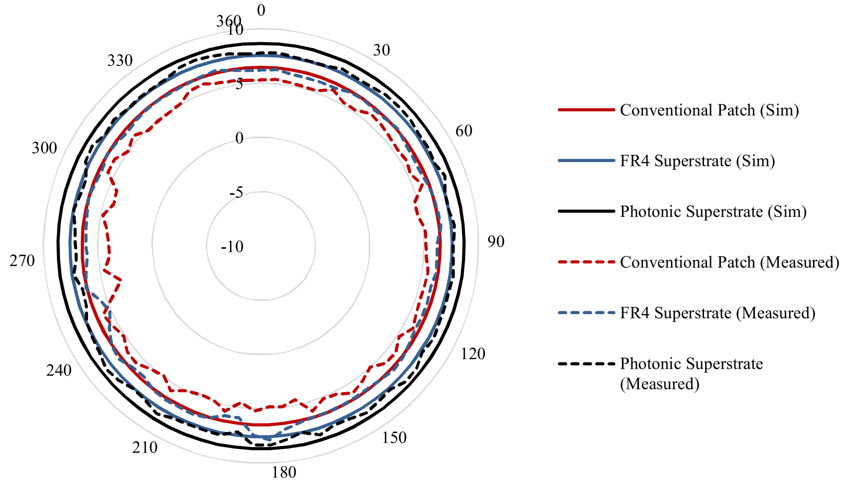
Antenna Geometry	Parameter					
	Reflection coefficient (dB)		Bandwidth (S11 = −10 dB)		Gain (dB)	
	Simulated	Measured	Simulated	Measured	Simulated	Measured
Conventional Patch Antenna	−15.27 dB	−20.15 dB	52 MHz	65 MHz	6.96 dB	5.41 dB
FR_4 Superstrate	−19.80 dB	−24.74 dB	43 MHz	55 MHz	7.92 dB	6.56 dB
Photonics Superstrate	−27.43 dB	−28.64 dB	48 MHz	55 MHz	9.67 dB	7.94 dB

$$\frac{P_r}{P_t} = \left(\frac{\lambda}{4\pi R}\right)^2 G_t G_r \tag{7}$$

From Fig. 7, it is observed that the antenna gives symmetrical radiation pattern and achieved a measured gain of 5.41 dB for conventional patch antenna and 6.56 dB for FR_4 superstrate model and 7.94 dB for photonic crystal superstrate model. Table 1 gives performance comparison of proposed antenna structure with conventional antenna structure. It is observed that the proposed model with photonic superstrate structure gives better reflection coefficients when compared to conventional and FR_4 superstrate structures. In order to improve the gain characteristics of the antenna, a metamaterial superstrate is placed over the radiating antenna element which improves directivity (Bait-Suwailam et al., 2010) and reducing mutual coupling effect (Yang et al., 2012). However the presence of superstrate over the radiating element in the proposed structure has negative effect over operating bandwidth due to its narrowband characteristics (Gao et al., 2016) and hence restricts the bandwidth which is observed from Table 1. Though the



(a) E-Plane



(b) H-Plane

Fig. 7. Radiation Pattern.

proposed antenna has narrowband characteristics, the antenna better gain performance and lesser reflection coefficient over operating band when compared to conventional antenna and hence suitable for narrowband high gain applications like radar altimeter and other modern wireless communication.

4. Conclusion

In this manuscript metamaterial inspired patch antenna is presented. The proposed model is integrated with metamaterial superstrate in order to improve the gain and reduce the reflection coefficient. The model is characterized using FDTD method and its material parameters are extracted by NRW method using Matlab tool. It is observed that the proposed metamaterial structure achieves negative permeability and permittivity and its integration with conventional patch antenna significantly improves gain and also reduces the reflection coefficient. The antenna achieves −28.64 dB reflection coefficient of 2.4 GHz and also maintains good radiation characteristics with a peak measured gain of 7.94 dB at its operating frequency. Therefore the proposed antenna model is more suitable for modern wireless communications.

References

Bait-Suwailam, M.M., Boybay, M.S., Ramahi, O.M., 2010. Electromagnetic coupling reduction in high-profile monopole antennas using single-negative magnetic metamaterials for MIMO applications. IEEE Trans. Antenn. Propag. 58, 2894–2902.

Brown, E.R., Parker, C.D., 1993. Radiation properties of a planar antenna on a photonic-crystal substrate. J. Opt. Soc. Am. B 10 (2), 404–407.

Brown, Elliott R., McMahon, Oliver B., Parker, Christopher D., 1998. Photonic-crystal antenna substrates. Linc. Lab. J. 11 (2), 159–174.

Gao, Xiang-Jun, Cai, Tong, Zhu, Li, 2016. Enhancement of gain and directivity for microstrip antenna using negative permeability metamaterial. Int. J. Electron. Commun. (AEÜ) 70, 880–885.

Horii, Yasushi, Tsutsumi, Makoto, 1999. Harmonic control photonic bandgap on microstrip patch antenna. IEEE Microw. Guided Wave Lett. 9 (1), 13–15.

Liu, Zhenzhe, Wang, Peng, Zeng, Zhiyi, 2013. Enhancement of the gain for microstrip antennas using negative permeability metamaterial on Low Temperature Co-Fired Ceramic (LTCC) substrate. IEEE Antennas Wirel. Propag. Lett. 12, 429–432.

Lubkoswski, G., Bandlow, B., Schumann, R., Weiland, T., 2009. Effective modeling of double negative metamaterial macrostructures. IEEE Trans. Microw. Theory Tech. 57 (5), 1136–1146.

Pires, E.S., Fontgalland, G., Melo, M.A.B., Valle, R.R.M.S., Barbin, E., 2013. Metamaterial-inspired wire antennas. IEEE Trans. Magn. 49 (5), 1893–1896.

Smith, D.R., Kroll, N., 2000. Negative refraction index in left handed materials. Phys. Rev. Lett. 85 (14), 2933–2936.

Song, Xue-Hua, Wu, Wen-Yun, Shen, Ting-Gen, Zhou, Yue-Qun, 2011. Investigation of a patch antenna based on I-shaped left-handed material. Optik, 1426–1429.

Veselago, V.G., 1968. The electrodynamics of substances with simultaneously negative values of ε and μ. Sov. Phys. Usp. 10, 509–514.

Yablonovitch, E., Kapon, E., Gmitter, T.J., Yun, C.P., Bhat, R., 1989. Double heterostructure GaAs/AlGaAs thin film diode lasers on glass substrates. IEEE Trans. Photonics Technol. Lett., 41–42.

Yang, X.M., Liu, X.G., Zhou, X.Y., Cui, T.J., 2012. Reduction of mutual coupling between closely packed patch antennas using waveguided metamaterials. IEEE Antennas Wirel. Propag. Lett. 11, 389–391.

Ziolkowski, Richard W., 2003. Design, fabrication, and testing of double negative negative refraction materials. IEEE Trans. Antennas Propag. 51 (7), 1516–1528.