A Metamaterial Based Broadband Microstrip Antenna

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Abstract

In this paper, a broad bandwidth and high gain rectangular patch antenna using planar-patterned metamaterial concept is proposed. Top patch has seperated micro triangular patterns with periodic gaps while the ground plane etched with crossed strip-line gaps. The patterned metal patch and ground plane form a coupled capacitive-inductive circuit of negative index metamaterial. Extended bandwidth from a few hundred megahertz to a few gigahertz is demonstrated. In addition, experimental and theoretical power reception performances of metamaterial and patch antennas for different selected frequencies are compared.

1. Introduction

The demand for small, compact, low cost and broadband antennas has increased exceedingly over the past years, due to the need for reduced size and enhanced bandwidth antenna in both military and commercial applications. In that respect, compact size, lightweight, low profile, low cost and broadened bandwidth are now quite important challenges to be accomplished by the designers of wireless communication systems. It is a well-known fact that printed microstrip antennas present attractive features, such as a simple structure, small size, conformable to planar and nonplanar surfaces, inexpensive to manufacture and mechanically robust when mounted on rigid surfaces [1]. However, major disadvantage of microstrip antenna is narrow frequency bandwidth, which is typically about 5% bandwidth accordingly the center frequency [2]. Many techniques have been designed to overcome narrow bandwidth. These techniques are mainly increasing the thickness of the substrate, using different shaped slots or radiating patches [3], stacking different radiating elements of the loading of the antenna sideways [4, 5], utilizing magnetodielectric substrates [6], and engineering the ground plane as electromagnetic band gap metamaterials [7].

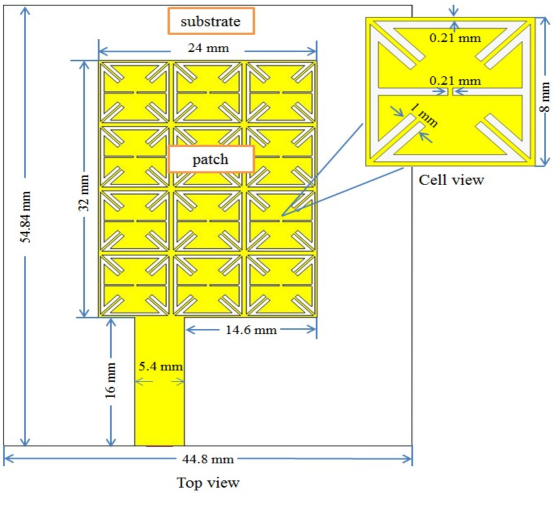
Since the artificial left-handed materials (LHMs) or metamaterials were theoretically and experimentally demonstrated [8, 9], scientists and engineers have tested varied ways to bring these artificial material into practical applications, especially in antennas [10-13].

In this paper, the purpose is to enhance the bandwidth of a patch antenna by applying the planar metamaterial patterned structures directly on the upper patch and bottom ground of the dielectric substrate (FR-4), which is different from similar previous study given in [10]. The proposed antenna, with a bandwidth from 2.89 to 5.31 GHz ($|S_{11}| < -10$ dB), is 44.8 × 54.87 × 1.6 mm^3.

2. Antenna Design

A microstrip patch antenna is mostly placed on a substrate and coated by a conducting ground plane. In the proposed study, a planar LHM pattern on the rectangular patch antenna placed on the substrate is designed to increase its horizontal radiation. Therefore, the conducting ground backed to the substrate is patterned to widen its bandwidth dissimilarly. On the upper patch, the periodic and parallel gaps are designed in the form of separeted micro triangular patterns, as shown in Fig. 1, while on the bottom ground plane, periodically distributed cross strip-line gaps are formed, as shown in Fig. 2.

Fig. 1. The top and cell geometry of the proposed metamaterial antenna.



The left-handed characteristics of these patterns were demonstrated in [14]. Physically, the top patch and ground plane are coupled to model a capacitive-inductive C-L equivalent circuit and thus can induce backward wave which travels along the plane of patch [15]. Therefore, the radiation along the patch direction is greatly enhanced.

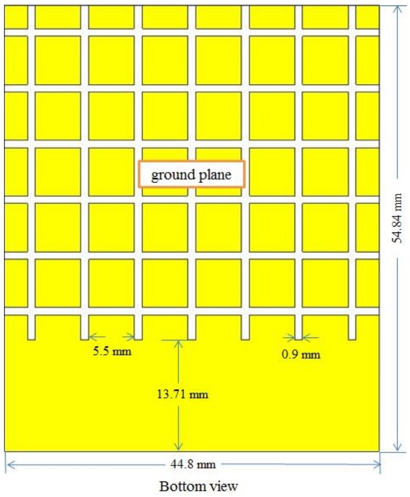


Fig. 2. The bottom geometry of the proposed metamaterial antenna.

A patch antenna of the same size is used as a reference for comparison and both the rectangular patch and the proposed patch antenna are fed by an off-centered microstrip line. The substrate used here is FR-4 with a relative permittivity of 4.3 and thickness of 1.6 mm. The area of the upper patch mounted is 24x32 mm^2.

The parameters of the antenna is analyzed by changing one at a time, while fixing the others. To fully understand the physical mechanisms of of the antenna's structure and to settle the optimum parameters, the antenna is analyzed using the CST Microwave Studio simulation software.

3. Results and discussion

The proposed LHM patch antenna was numerically simulated, physically fabricated, as shown in Fig. 3., practically measured, and comparatively studied with theoretical results. The computed S_{11} values of the proposed antenna and the reference patch antenna are shown in Fig. 4. As shown here, one of the working bandwidth of the patch antenna is 140 MHz between 3.71 and 3.86 GHz, which is typically very narrow as expected but serves as a comparison for the improved designs.

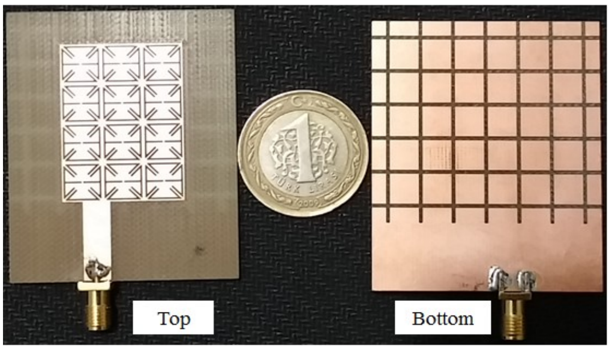


Fig. 3. Top and bottom views of a fabricated patch antenna.

The proposed antenna's -10 dB bandwidth which is standardly defined for engineering applications falls within 2.89 and 5.31 GHz, and it is 2.42 GHz in bandwidth. This is 17 times greater than the patch antenna.

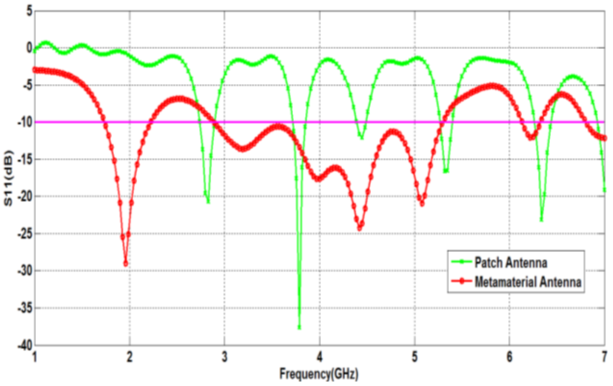


Fig. 4. Computed S_{11} values for metamaterial and patch antennas.

Experimental results of S_{11} values are compared with numerically predicted results in Fig. 5. The general variational trace of the experimental result follows nearly to that of the simulated S_{11} value. From the -10 dB level line, it is seen that a reasonably good agreement between the simulated working bandwidth and the measured bandwidth is found. In fact, the fabricated antenna has even wider bandwidth than of the modeled antenna.

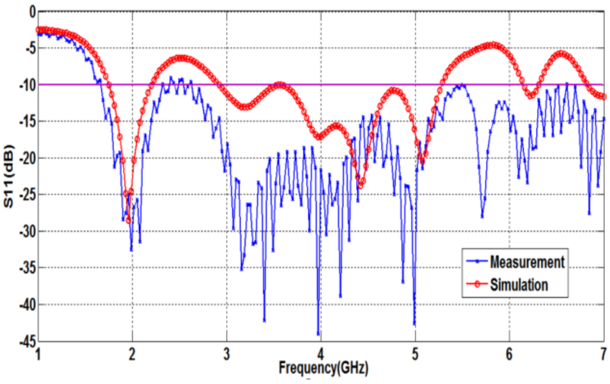


Fig. 5. Measured and computed S_{11} values for metamaterial antenna.

Antenna gains are measured within the entire frequency band as shown in Fig. 6(a). The antenna gain is generally above 3.4 dB with the peak of 5.56 dB. The voltage standing wave ratio (VSWR) value serves as a good measure to check if the system is working efficiently. In the present work, the simulated VSWR value is well below 2 which provides a good reference value for most of the engineering applications within the frequency band as shown in Fig. 6(b). Table 1 compares the proposed antenna and existing antennas.

Table 1. Comparisons between the proposed antenna and existing antennas.

Antennas	**BW GHz (-10dB)**	**Dimension (mm³)**	**Gain dB**
[2]	4.43 - 15.78	31.8 × 27.7 × 0.78	3 - 7.17
[10]	5.3 - 8.5	32 × 28 × 0.79	4 - 7.2
[11]	4.08 - 7.83	27.8 × 31.9 × 0.79	2 - 6
[16]	3.93 - 5.89	32 × 28 × 0.78	5 - 6.8
[17]	1.61 - 2.52	80 × 90 × 1.5	max. 5.46
[18]	3.4 - 13 14.5 - 17.7	28 × 44 × 0.8	4 - 7.8
[19]	3.84 - 22.77	27.6 × 31.8 × 0.79	max. 8.8
Proposed	2.89 - 5.31	44.8 × 54.87 × 1.6	3.4 - 5.56

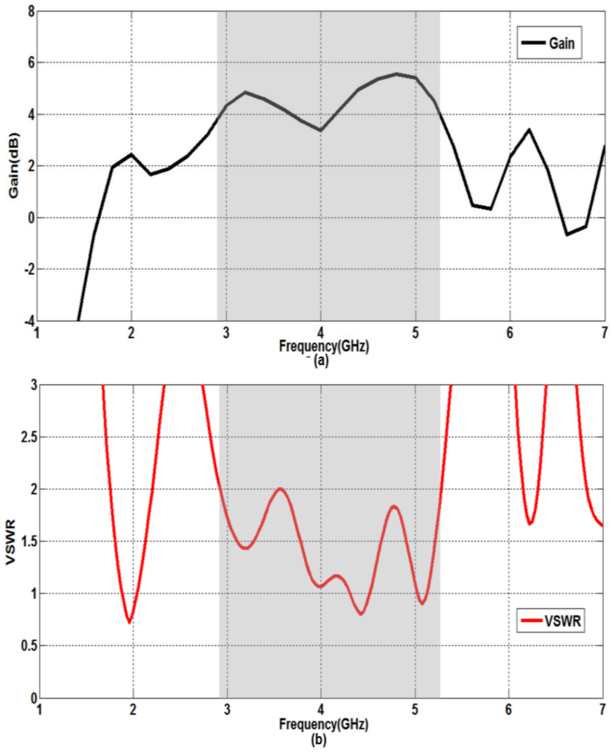


Fig. 6. (a) Simulated gain and (b) VSWR of metamaterial antenna.

The metamaterial (MMA) and patch (PA) antennas received powers are calculated by Friis Transmission Equation [1]

$$P_r = P_t\, G_t\, G_r \left(\frac{c}{4\pi f R}\right)^2 (W). \qquad (1)$$

where P_r is received power of antenna, P_t is output power of transmitter, G_t is gain of transmitter, G_r is gain of antenna, c is speed of the electromagnetic wave in vacuum, f is frequency, R is distance between transmitter and antenna. If the gain and power have units of dB, dBm respectively, the equation is modified to

$$P_r = P_t + G_t + G_r + 20\log_{10}\left(\frac{c}{4\pi f R}\right) (dBm). \qquad (2)$$

In the experimental setup, as shown in Fig 7, a spectrum analyzer (Rohde&Schwarz, 9 KHz-7 GHz), a transmitter (Software defined radio (SDR), 400 MHz-4.4 GHz) and antennas (MMA and PA) are used. R is set 50 cm. The antennas (MMA and PA) are connected to spectrum analyzer respectively in order to measure received powers. Five sample frequencies, which are in working bandwidth of MMA, are generated by SDR.

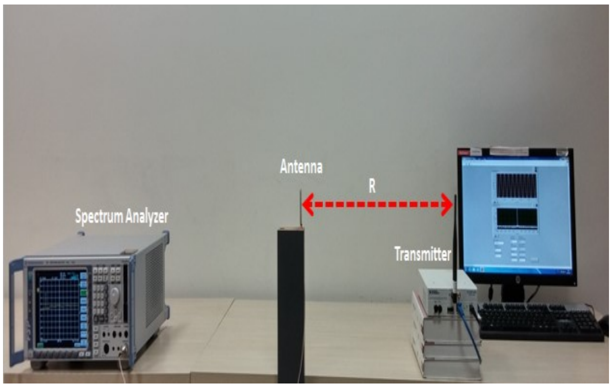


Fig. 7. Experimental setup to measure received powers of MMA and PA.

The calculated and measured results are shown that the metamaterial antenna has better performence in the received power with respect to the patch antenna, as shown in Fig. 8.

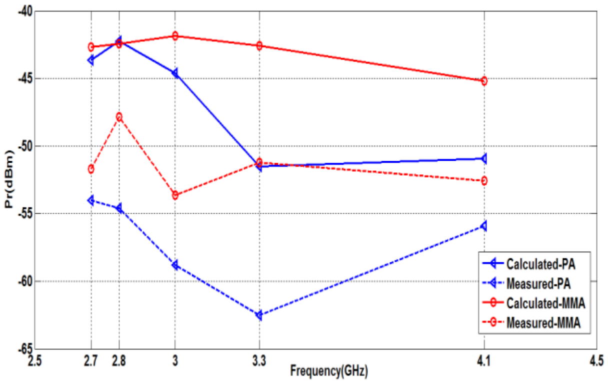


Fig. 8. Received powers of MMA and PA at R= 50 cm.

The wave propagation along the metamaterial antenna induces the strongest radiation in horizontal direction instead of the vertical direction of the patch antenna. To further confirm this, 3.2 and 5 GHz frequencies, which are both in the working bandwidth, are chosen to characterize radiation of the antenna. According to the computed results, the three dimensional (3D) radiation patterns at these frequencies are shown in Fig. 9. It is obvious that energy radiates to the horizontal (y-x axis) directions.

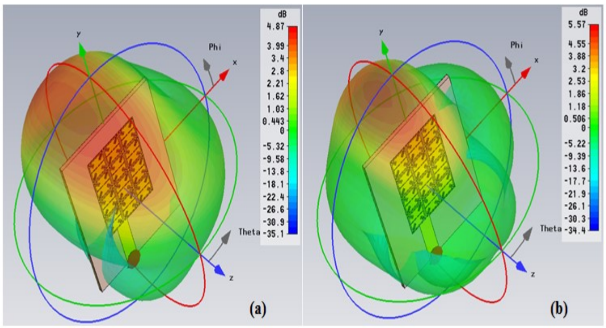


Fig. 9. 3D radiation patterns at (a) 3.2 GHz and (b) 5 GHz.

4. Conclusions

In this paper, a broad-bandwidth patch antenna is designed and fabricated using the metamaterial concept via the pattern-etched top patch and bottom ground plane. The working frequency bandwidth of the rectangular patch antenna is significantly broadened from about 140 MHz to approximately 2.4 GHz, which corresponds to about 17 times. Also, the designed metamaterial antenna has high gain, low VSWR and better received power performance.

5. Acknowledgement

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6. References

[1] C. A. Balanis, "Antenna theory analysis and design", John Wiley & Sons, Inc., Hoboken, New Jersey, 2005.

[2] S. Lamari, R. Kubacki, M. Czyzewski, "Frequency range widening of the microstrip antenna with the sierpinski fractal patterned metamaterial structure", in Microwaves, Radar and Wireless Communication Conference, Gdansk, 2014, pp. 1-3.

[3] J. Lao, R. Jin, J. Geng, Q. Wu, "An ultra-wideband microstrip elliptical slot antenna excited by a circular patch", Microw. Opt. Technol. Lett., vol. 50, no. 4, pp. 845–846, 2008.

[4] B.L. Ooi, S. Qin, M.S. Leong, "Novel design of broad-band stacked patch antenna", IEEE Trans. Antennas Propag, vol. 50, no. 10, pp. 1391–1395, Oct., 2002.

[5] M. A. Matin, B. S. Sharif, and C. C. Tsimenidis, "Probe fed stacked patch antenna for wideband applications", IEEE Trans. Antennas Propag., vol. 55, no. 8, pp. 2385–2388, Aug., 2007.

[6] F. Namin , T. G. Spence , D. H. Werner and E. Semouchkina "Broadband, miniaturized stacked-patch antenna for L-band operation based on magneto-dielectric substrates", IEEE Trans. Antennas Propag., vol. 58, no. 9, pp. 2817 -2822, Sept., 2010.

[7] N. Engheta, R.W. Ziolkowski, "Metamaterials: physics and engineering explorations", John Wiley & Sons, Inc., Hoboken, New Jersey, 2006.

[8] V. G. Veselago, "The electrodynamics of substances with simultaneously negative values of ε and μ, " Sov. Phys. Usp., vol. 10, no. 4, pp. 509-514 , Jan., 1968.

[9] J. B. Pendry, "Negative refraction makes a perfect lens", Phys. Rev. Lett.,vol.85, no.18, pp. 3966-3969, Oct., 2000.

[10] L.W. Li, Y.N. Li, T.S. Yeo, J.R. Mosig, O.J.F. Martin, "A broadband and high-gain metamaterial microstrip antenna", Appl. Phys. Lett., vol. 96, no. 16, pp. 164101, Apr., 2010.

[11] H. Xiong, J. S. Hong, M. T. Tan, B. Li, "Compact microstrip antenna with metamaterial for wideband applications", Turk. J. Elec. Eng & Comp Sci., vol. 21, pp. 2233 – 2238, Nov., 2013.

[12] L. Tang, Z. Zhang, "Ultrawide bandwidth rectangular patch antenna over artificial magnetic conductor", in International Conference on Microwave and Millimeter Wave Technology, Shenzhen, 2012, pp. 1-3.

[13] G. K. Pandey, H. S. Singh, P. K. Bharti, M. K. Meshram, "Metamaterial-based UWB antenna",Electron. Lett., vol. 50, no. 18, pp. 1266-1268, Aug., 2014.

[14] N. Matsunaga, A. Sanada, H. Kubo, "Novel two dimensional planar negative refractive index structure", IEICE Transactions on Electronics, vol. E89C,no. 9, pp. 1276-1282, Sep.,2006.

[15] C. Caloz, T. Itoh, "Electromagnetic metamaterials: transmission line theory and microwave applications", John Wiley & Sons, Inc., Hoboken, New Jersey, 2006.

[16] Tao Liu, Xiang-Yu Cao, Jun Gao, Qun Yang, and Wen-Qiang Li, "Design of Miniaturized Broadband and High Gain Metamaterial Patch Antenna", Microw. Opt. Technol. Lett., vol. 53, no. 12, pp. 2858–2861, 2011.

[17] Y. Gou, J. Hua, Q. Wu, H. Wang, "Broadband Microstrip Antennas Using Complementary Metamaterials Structure", in Cross Strait Quad-Regional Radio Science and Wireless Technology Conference, China, 2011, pp. 530-533.

[18] L. Wang, J.W. Li "A novel metamaterial microstrip antenna of broadband and high-gain", in Antennas and Propagation International Symposium, Nagoys, 2012, pp. 806-809.

[19] H. Xiong, J.S. Hong, Q.Y. Zhu, D.L. Jin "Compact Ultra-wideband Microstrip Antenna with Metamaterials", Chin. Phys. Lett., vol. 29, no. 11, pp. 114102, 2012.