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An Octave Bandwidth Metamaterials-based Hexagonal Patch Antenna

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***Abstract*—A broadband metamaterials (MTM)-based hexagonal patch antenna is designed and presented. A hexagonal shape of a top patch on a mushroom structure makes not only direct-current paths between two ends of the patch but also round-current path along the outside of the patch, thereby widening a resonance frequency of the mushroom MTM antenna. Moreover, input microstrip transmission line acted as a reflecting element for the surface wave, resulting in forward-directed end-fired radiation. The hexagonal patch was implemented by utilizing a composite right-and left-handed (CRLH) transmission line. The antenna operates from 15.9 GHz to 30.6 GHz covering the Ku- to Ka-band. The antenna gain is from 6 dBi to 9.3 dBi with small size compared to the conventional antennas. The application areas are in automotive radars and ground penetrating radar (GPR).**

***Index Terms*—Metamaterials antenna, broadband antennas, microstrip antennas, ground penetrating radar (GPR).**

I. INTRODUCTION

The Ground penetrating radar (GPR) is a well-known technology and has been found to be a special option for wide range applications, including archaeology, geophysical research, mine or buried object detection and so on [1].

Ultra-wideband antennas are one of the most critical parts of broadband GPR system. Most printed and planar antennas have gained interest due to their small size, low cost and low weight, ease of fabrication. But certain types have some disadvantage such as narrow frequency bandwidth and poor in robustness. Dispersive or non-dispersive antennas have been commonly used for GPR systems, such as dipole antenna, Bow-tie antenna, TEM horn antenna, Vivaldi or tapered slot antenna (TSA), and equiangular spiral antenna [2]. However, these are not compatible with high frequency microwave integrated circuits (MICs) because of their non-planar structure and electrically large size. Moreover, the input impedance of the conventional balanced antennas is more than 100 Ω, which is difficult in broadband impedance matching with 50 Ω feed line because of the frequency limitation of the transition or balun [3].

Recently, metamaterials (MTM) which simultaneously have negative permittivity (£) and permeability («) theoretically speculated in 1960s by the Russian physicist Viktor Veselago have received great attention due to negative refraction, reverse Cerenkov radiation, and slow light [4]–[6]. Due to these unique properties, MTM have been widely applied as microstrip patch antennas in military and commercial system applications [7]. MTM microstrip patch antennas have many attractive features such as anti-parallel phase velocity to group velocity and infinite wavelength at a certain frequency, as well as small size, low profile and integration with planar surfaces. However, they inherently have narrow frequency bandwidth, typically 1 %–5 %, limiting its many attractive features. Currently, mushroom structures have been demonstrated as an effective way to increase the bandwidth of MTM microstrip patch antennas with the techniques of the stacked top patches, inserting slits or slots in addition to increasing patch height and decreasing substrate permittivity [8], [9]. The stacked patches and the conventional techniques have solved the bandwidth problem with a relatively large antenna thickness. However, there is a practical limit on increasing the antenna thickness. Therefore, bandwidth extension technique of MTM antenna without increasing the volume or degrading the performance of low-profile is a critical approach.

In this paper, we present a mushroom-like MTM hexagonal patch antenna to improve the bandwidth and directivity. Conventional mushroom-like MTM antennas have narrow bandwidth. However, a hexagonal shape of a top patch on a mushroom structure makes not only direct-current paths between two ends of the patch but also round-current path along the outside of the patch, and hence it can widen a resonance frequency of the mushroom MTM antenna. Moreover, by using of open CRLH TL structure, a radiated leaky-wave (LW) mode is achieved where $= +k_0$ [10]. Therefore, broadside-to-endfire scanning capability was also provided. The proposed antenna was modeled by utilizing a composite right-and left-handed (CRLH) transmission line, and provided 6 dBi to 9.3 dBi of the antenna gain and a reduced small size compared to a conventional microstrip patch antenna. An octave bandwidth was achieved with VSWR less than 2:1.

II. ANTENNA DESIGN

The concept of composite right/left-hand (CRLH) MTM is introduced by Caloz *et al.* [11]. MTM are effective

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homogeneous structures that can be modeled by one-dimensional transmission lines (TLs) of CRLH structures under the condition that the average cell size be smaller than the guided wavelength. A general CRLH TL unit-cell consists of a series capacitance and a shunt inductance, as well as a series inductance and a shunt capacitance.

The CRLH TL model can be represented as a combination of a per-unit-length series inductance (L_R'), a per-unit-length shunt capacitance (C_R'), a times-unit-length shunt inductance (L_L'), and a per-unit-times length series capacitance (C_L'), as shown in Fig. 1. According to lossless transmission line theory, the propagation constant of a CRLH TL is given by $¥ = j \quad = \sqrt{Z'Y'}$, where Z′ and Y′ are the per-unit-length impedance and per-unit-length admittance, respectively. Z′ and Y′ are obtained as [11]:

$$Y'(\mu) = \frac{Y(\mu)}{\Delta z} = j\left(\mu C_R' - \frac{1}{\mu L_L'}\right), \quad (1)$$

$$Z'(\mu) = \frac{Z(\mu)}{\Delta z} = j\left(\mu L_R' - \frac{1}{\mu C_L'}\right). \quad (2)$$

The series resonance frequency and shunt resonance frequency are given as $\omega_{se} = 1/\sqrt{L_R' C_L'}$ and $\omega_{sh} = 1/\sqrt{L_R' C_L'}$, respectively.

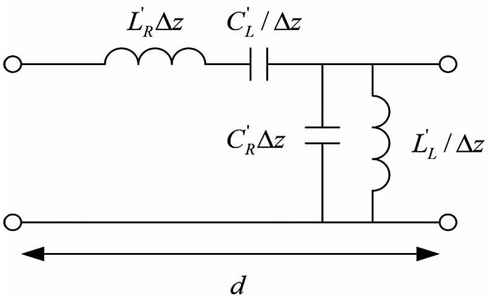


Fig. 1. Equivalent circuit model of composite right/left-handed (CRLH) MTMs TL.

For an open-ended CRLH TL, the resonant condition of $_mL = m®$ must be satisfied, where $m = 0, \pm 1, \pm 2, \pm 3, \ldots \pm (N-1)$ is the resonance mode. For a N-cell CRLH TL, the total length of the CRLH TL, $L = N \times d$, can be obtained, where d is the length of the unit cell; therefore,

$$\frac{m®}{N} = \cos^{-1}\left\{1 - \frac{1}{2}\left\{\frac{\mu^2}{\mu_{RH}^2} + \frac{\mu_{LH}^2}{\mu^2} - \left(\frac{1}{\mu_{sh}^2} + \frac{1}{\mu_{se}^2}\right)\mu_{LH}^2\right\}\right\}, \quad (3)$$

where $\omega_{RH} = 1/\sqrt{L_R' C_R'}$ and $\omega_{LH} = 1/\sqrt{L_L' C_L'}$.

As the resonance mode number (m) is zero, the CRLH TL supports zero propagation constant. Therefore, an infinite wavelength is obtained, and the length of the CRLH TL becomes independent of the resonance condition. In this case of the open-ended CRLH TL, the zeroth-mode frequency is determined by the inductance and the capacitance loaded in the CRLH TL. When a zeroth-order resonator is used for the antenna, it inherits independence of physical size, leading to one degree of freedom in designing an antenna smaller than a conventional patch antenna with a λ/2 field distribution.

On the other hand, any open CRLH TL structure can operate as a radiated leaky-wave (LW) mode since the CRLH dispersion curve always going into radiation region. From the μJ diagram, endfire radiated RH leaky mode is achieved where $\beta = +k_0$. Therefore, broadside-to-endfire capability can be provided by an open CRLH structure. Another advantage of the CRLH LW antenna feeding method is simple and broadband.

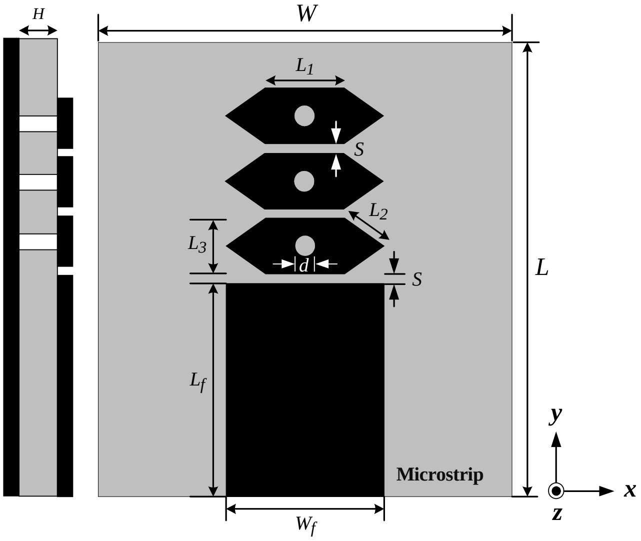


Fig. 2. Antenna geometry: $L_f = 10$, $W_f = 7.65$, $L_1 = 3.8$, $L_2 = 2.4$, $L_3 = 2.6$, $S = 0.44$, $d = 1$, $H = 2.37$, $W = 20$ and $L = 21$ (all dimensions are in millimeters).

Figure 2 shows the presented microstrip MTM mushroom-like antenna geometry with a hexagonal-shaped top patch. The mushroom structure is built with a hexagonal top patch and a metal via connecting the top patch to the ground. The gap between neighboring patches represents the left-handed series capacitance, and the vertical via of the top plate acts as the left-handed shunt inductance in the equivalent circuit model, while the shunt capacitance and series inductance, representing the right-handed TL, are due to parasitic effects caused by the microstrip geometry. The electrical length $L_3/2$ of the RH TL is ®/4 rad at 22.5 GHz. Using [12], the calculated RH-TL distributed series capacitance and inductance of the unit-cell hexagonal patch are 95 pF/m and 238 nH/m, respectively. The shunt inductance L is 0.78 nH. For impedance matching between 50 Ω input microstrip line and high input impedance of hexagon radiator, a simple coupling capacitor was utilized with gap (S) of 0.44 mm. The calculated coupling capacitance is about 49.8 fF. Input microstrip line serves as a reflector, endfire radiation characteristics are simply achieved and backward TE_0 surface wave mode is suppressed. The lengths of each side of the top hexagon patch are properly chosen 3.8 mm (L_1), 2.4 mm (L_2) and 2.6 mm (L_3), respectively; the via diameter (d) is 1 mm, and the height and relative permittivity (ε) of the substrate (RT/Duroid 5880) are 2.37 mm and 2.2, respectively.

III. EXPERIMENTAL RESULTS

In this paper, as a full-wave analysis method, ANSYS HFSS (FEM) is extensively used for simulations. High Frequency Structure Simulator (HFSS) is a complete solution for modelling arbitrarily-shaped, passive 3-D structures. It is a general purpose tool that can be used for a variety of electromagnetic (EM) modelling applications, including antenna design and analysis, machined-component design and analysis, circuit design and analysis and high-speed digital-circuit design and analysis. Moreover, cross check is also performed by using CST Microwave studio (FDTD). Figure 3 shows the S_{11} parameters of the presented antennas with a hexagonal top patch. The resonance mode of the parasitic patch was scaled to operate at 21 GHz, 26.4 GHz and 29.8 GHz. The 10-dB bandwidth of the presented antenna is 14.7 GHz between 15.9 GHz and 30.6 GHz, which corresponds to octave bandwidth. Figure 4 shows the maximum antenna gain and half-power beamwidth (HPBW). The maximum gain is 6 dBi to 9.3 dBi and the 3 dB HPBW varies from 42 degrees to 75 degrees. As can be seen, the radiation patterns are very similar and uniform over the whole operating frequencies.

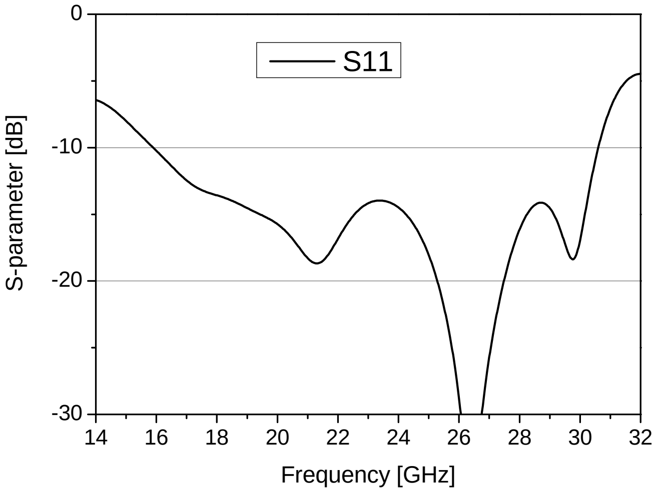


Fig. 3. Simulated S-parameter (S11).

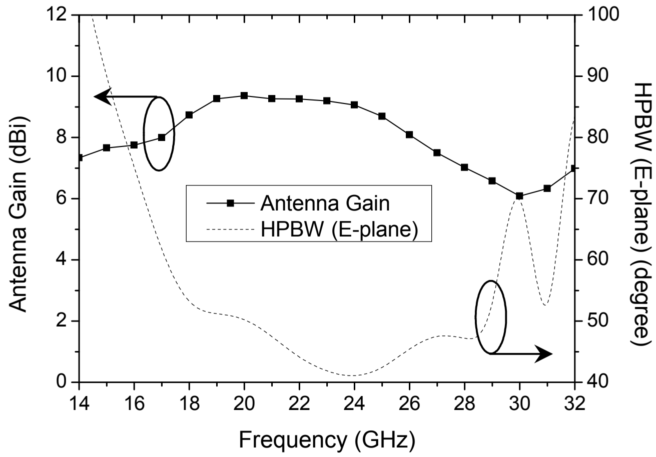
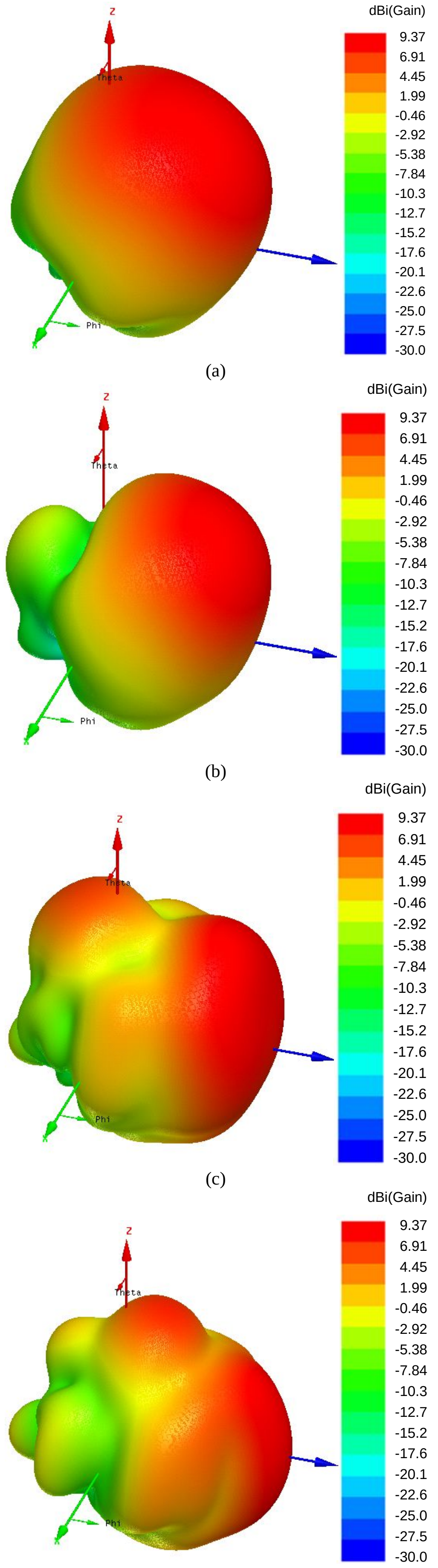


Fig. 4. Simulated maximum antenna gain and 3 dB HPBW of E-plane (x-y plane).

The 3-dimensional radiation patterns of the hexagonal-shaped top plates are plotted in Fig. 5 at 16 GHz, 20 GHz, 24 GHz and 28 GHz. From 16 GHz to 28 GHz, we can see the broadside-to-endfire scanning capability of the proposed antenna. The E-field distributions at 16 GHz, 20 GHz, 24 GHz and 28 GHz on the surface of the antenna were investigated as shown in Fig. 6.



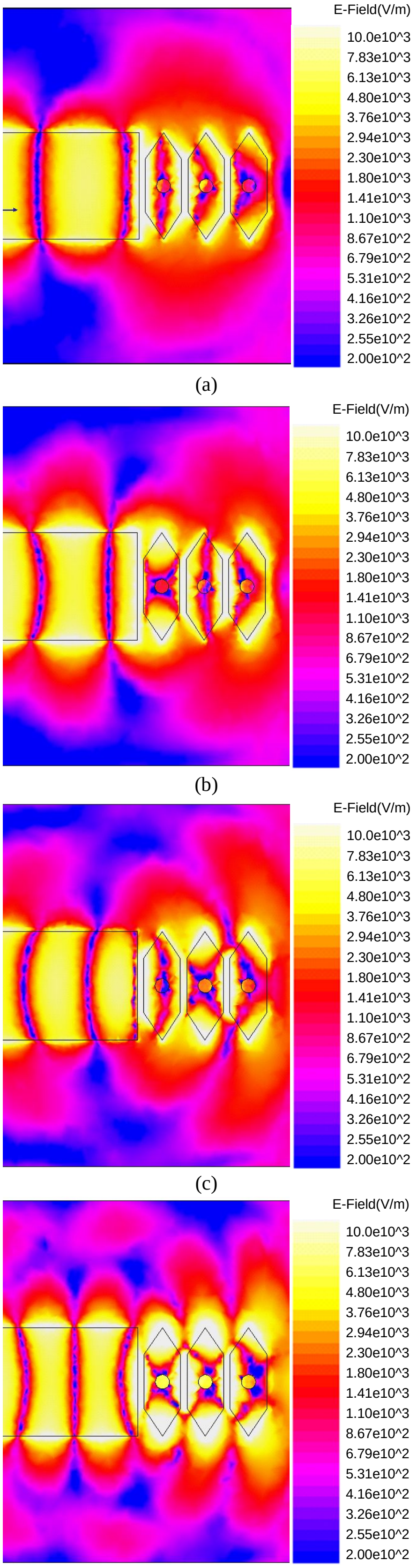
(a)

(b)

(c)

(d)

Fig. 5. Simulated 3D radiation patterns at (a) 16 GHz, (b) 20 GHz, (c) 24 GHz, (d) 28 GHz.



(a)

(b)

(c)

(d)

Fig. 6. E-field distributions at (a) 16 GHz, (b) 20 GHz, (c) 24 GHz, (d) 28 GHz (x-y plane).

As it can be seen, at high-band frequencies, end-fired travelling wave are gradually generated and propagated to forward direction (+y) of radiator. On the other hand, backward wave seem to be more suppressed by input feed line. The front-to-back (F/B) ratio is the ratio of the maximum forward directivity to that of the backward direction. Simulated F/B ratio ranges from 10 dB to 20 dB.

IV. CONCLUSIONS

In this paper, we present an octave band hexagonal-shaped patch antenna with mushroom-structured MTM. Owing to the effect of lengthening current paths on the hexagon patch and open CRLH TL structure, the proposed antenna demonstrates an octave (2:1) frequency bandwidth from 15.9 GHz to 30.6 GHz with the nominal radiation efficiency of 90 %. The simulated gain is from 6 dBi to 9.3 dBi and front-to-back ratio is more than 10 dB. The overall antenna size with input feed line is 20 mm × 21 mm. The application areas are in broadband automotive radar and sensor applications.

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