Compact Meta-Material Antenna with A-shaped Topology for Ultra Wide Band Microwave Communications

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Abstract:
Modeling of MTM compact ultra wideband resonant (CUWBR) antenna with A-shaped left-handed structure has been proposed. The proposed MTM structure is modeled at a height of 0.8mm from the ground plane for 15.5GHz to 19.2GHz applications. The most interesting feature of the design is the ability of enhancing the gain and total efficiency of the antenna without negative effecting of the other important parameters like bandwidth. By using the A-formed MTM structure and printed planar technique, the bandwidth of the MTM compact antenna is significantly increased at a resonant frequency f=18 GHz and also a foot print area reduction of the antenna structure is provided. Antenna size is $17.66 \times 5.35 \times 0.8$ mm$^3$.

Keywords:
Metamaterial (MTM); A-shaped Structure; Wireless Communications; Compact Ultra Wideband Resonant (CUWBR) Antenna; Microwave Communications

1. INTRODUCTION

A printed patch antenna [1, 2] is a low-profile antenna consisting of a metal layer over a dielectric substrate [3, 4] and ground plane. Typically, a printed patch antenna is fed by input signal, but other feed lines such as coaxial and microstrip transmission line can be used. The advantages of printed patch antennas are that they radiate with moderately high gain in a direction perpendicular to the substrate and can be fabricated in a low cost PCB. The basic operating principle of a printed patch antenna is that the space between the patch and ground plane acts like a section of parallel plate waveguide. Neglecting radiation loss, the edge of the patch is an open circuit, so that energy reflects and remains below the patch. One disadvantage of a high-Q system is narrow bandwidth, so patch antennas have limited bandwidth, meaning that the input impedance of the antenna only remains near the desired value for a small range around the designed center frequency. To overcome this challenge we use MTM technology, in this paper, which as a result has been an extension of the bandwidth of antenna system.

MTMs represent a new paradigm in electromagnetic science and technology [5, 6]. Some of the applications of the MTM antennas are wireless communications, microwave communications, space communications, global positioning system (GPS), satellites, space vehicle navigation, and airplanes. They have already lead to many unprecedented microwave applications, which may be classified in three
categories: guided-wave, radiated-wave and refracted-wave applications [7]. Radiated-wave applications cover several types of novel antennas and reflectors, which may be 1D or 2D, passive or active, and static or dynamically tuned [7]. MTM antennas in 1D and 2D configurations may be of two types. The first type consists of conventional radiators (e.g. patches or dipoles) placed above artificial dielectrics [8], where the main benefits of the artificial dielectric MTMs are compactness [9] and slightly enhanced bandwidth in electromagnetically small antennas [10]. The second type consists in artificial transmission line (TL) MTM structures, which exhibit more diverse and original properties, such as for instance equivalent negative index of refraction or infinite wavelength propagation [5]. In this paper, we consider only the latter type. These TL MTMs generally exhibit a composite right/left-handed (CRLH) dispersive response [5], or related responses when the line integrates additional lumped elements in its unit cell (higher order TL) [11]. Although most CRLH antennas reported to date have been leaky-wave antennas (LWAs), much work has been recently done on CRLH resonant antennas (RAs) [7], since the introduction of the CRLH resonator in 2003 [12]. This paper presents an overview on CRLH RAs, including a brief theoretical recall and a description of the different properties, and also a new concept of design of the printed patch traveling-wave antenna based on CRLH-TLs.

2. TYPES OF MATERIALS AND BRIEF REVIEW OF METAMATERIALS

Materials may be categorized by their constitutive parameters $\varepsilon$ and $\mu$ according to the diagram shown in Figure 1. If both the permittivity and permeability have positive real parts as in the first quadrant of Figure 1, as most of the materials in nature do, they will be called double positive (DPS) media. In contrast, if both of these quantities are negative, as in the third quadrant of Figure 1, they will be called double-negative (DNG). The materials with one negative parameter, quadrants two and four, will be called single negative (SNG). If the permittivity is negative, as in the second quadrant, these SNG materials will be called epsilon negative (ENG). The ionospheric plasma layer exhibits this behavior at AM radio frequencies while natural plasmonic materials (noble metals and some dielectrics) do at optical frequencies. If the permeability is negative, as in the fourth quadrant, they will be called mu-negative (MNG). Ferromagnetic materials exhibit this behavior in the VHF and UHF regimes. If both $\varepsilon$ and $\mu$ are zero or very close to zero, the materials will be called zero index.

A CRLH TL MTM is an artificial TL structure composed of the periodic repetition of a CRLH unit cell, as shown in Figure 2. Such a TL exhibits in the lossless case the dispersion/attenuation relation [5]

$$
\cos[(\beta - j\alpha)p] = 1 + \frac{ZY}{2} = 1 - \frac{(\omega_e^2 - \omega_h^2)(\omega_R^2 - \omega_s^2)}{2\omega_R^2\omega_s^2}
$$

(1)

Where $\omega_e = \frac{1}{\sqrt{L_sC_s}}$, $\omega_h = \frac{1}{\sqrt{L_sC_L}}$ and $\omega_R = \frac{1}{\sqrt{L_sC_L}}$. Under the so-called balanced condition ($\omega_e = \omega_h = \omega_0$), the dispersion relation $\omega(\beta)$ can be explicitly derived from inversion of the general relation (1) as

$$
\omega(\beta) = \sqrt{\omega_0^2 + \omega_s^2\sin\left(\frac{\beta p}{2}\right)} + \omega_R\sin\left(\frac{\beta p}{2}\right)
$$

(2)

This dispersion curve is plotted in Figure 3.

In the MTM frequency range ($p \ll \lambda_g$), the artificial CRLH structure behaves as a uniform TL $[\beta(\omega) \rightarrow \frac{\omega}{\omega_0} \rightarrow \frac{\omega}{\omega_0}]$ where $\omega_L = \frac{1}{\sqrt{L_sC_L}}$, and may therefore be transformed, like any TL, into a TL resonator by using discontinuous (short/open) terminations. A difference with a uniform TL however is that, due to the CRLH pass-band characteristic, only 2N1 resonances, where N is the number of unit cells, can fit in the transmission band. These resonances naturally correspond to TL lengths $l = n\lambda_g/2$, and
therefore to propagation constants $\beta_n = \frac{n\pi}{l} = \frac{n\pi}{(Np)}$, with the CRLH particularity that $n$ can be both positive (RH range) and negative (LH range), and even zero (transition frequency). The Bloch (periodic structure) impedance is given in general by $Z_B = \sqrt{Z/\gamma} \sqrt{1+ZY/4}$ (see immittances in Figure 2), and reduces in the balanced case to [5, 7]:

$$Z_B(\omega) = Z_L \sqrt{1 + \frac{1}{4} \left[ \frac{\omega}{\omega_R} - \frac{\omega_R}{\omega} \right]^2 + \delta}$$  \hspace{1cm} (3)$$

Where $Z_L = \sqrt{\frac{L}{C}}$, and where $\delta = \delta(R, G)$ is a dissipative term, which is much smaller than the reactive terms. In the MTM range, this impedance may be assimilated to a TL characteristic impedance, which is frequency-independent ($Z_B \rightarrow Z_C = Z_L = Z_R$, where $Z_R = \sqrt{\frac{L}{C}}$).

In summary, a CRLH resonator supports 2N-1 resonance frequencies, N-1 in the LH band, N-1 in the
RH band, and 1 at the transition frequency $\omega_0$ (or $\omega_{se}$ or $\omega_{sh}$, depending on the terminations, if the CRLH structure is unbalanced, $\omega_{se} \neq \omega_{sh}$). These frequencies are obtained by sampling Eq. (1) at the points $\beta_n = n\pi/Np$ ($n=1,2,...,2N-1$)

$$\omega_n = \sqrt{\omega_0^2 + \omega_R^2 \sin^2\left(\frac{n\pi}{2}\right) + \omega_R \sin\left(\frac{n\pi}{2}\right)}$$

(4)

The Bloch impedance $Z_B$ given by Eq. (3) is the input impedance when the structure is infinitely periodic or terminated by a resistor of value $Z_B$. Since the terminations $Z_t$ of the CRLH resonator (Figure 2) are short or open circuits, the impedance at the input of the structure is naturally different from $Z_B$. However, as pointed out in the previous paragraph, $Z_B$ constitutes the equivalent TL characteristic impedance $Z_c$ in the MTM regime ($p/\lambda_g \to 0$), and is therefore essential for coupling energy into (i.e. matching) the resonant structure. The resistive elements $R$ and $G$ in Figure 2 represent in general the radiation resistance in the antenna, in addition to the conductor and dielectric losses, respectively.

3. PROPERTIES AND TYPES OF RAS

As all CRLH MTM structures, CRLH RAs may be implemented in different technologies [planar hybrid or MMIC, LTCC, hollow waveguide], in different waveguide or TL configurations [microstrip, coplanar waveguide (CPW), coplanar strip-line (CPS), coaxial, waveguide, etc.], and using different LC elements [printed or chip form; interdigital (ID) or metal-insulator-metal (MIM) capacitors; straight, spiral, meander inductors]. Some typical implementations are shown in Figure 4. The properties of the resulting antennas including polarization, radiation patterns, efficiency, directivity depend not only on the selection of the CRLH resonant mode, but also on the choice of the technology, configuration, and LC elements.

4. DESIGN METHODOLOGY AND SIMULATION OF THE PROPOSED CUWBR ANTENNA

Several MTM structures like SRR, Spiral, Rod, Omega, S, Symmetric Rings etc. have already been
This paper introduces a new and distinct MTM structure named printed A-formed antenna as shown in Figure 5. The proposed antenna is constructed from two A-shaped unit cells. Each of unit cells consists of A-formed gaps which these gaps are printed on rectangular radiation patches and acts like series capacitance (CL), spiral inductors with two turn accompanying metallic via holes that are connected to the ground plane and implementing shunt inductors (LL). The structural parameters of rectangular printed patch antenna are \( L = 17.66 \text{mm}, W = 5.35 \text{mm} \) and \( h = 0.8 \text{mm} \) shown in Figure 5 (b). This antenna is designed on Rogers_RO4003 (Lossy) substrate with \( \varepsilon_r = 3.38 \) and height from the ground plane of \( h = 0.8 \text{mm} \). Two waveguide ports were defined at the left and right of the x-axis in order to calculate the S11 and S21 parameters as shown in Figure 5 (a). Port 1 is excited by input signal and port 2 is matched to 20 ohm load impedance of the SMD components.

As obvious for implementation of the minimized antenna, we used MTM technology and printed planar technique, as printed gaps acts like left-handed capacitors (CL) and lead to foot print area reduction. Overall size of the proposed antenna is \( 17.66 \times 5.35 \times 0.8 \text{mm}^3 \) or \( 0.91\lambda_0 \times 0.27\lambda_0 \times 0.04\lambda_0 \), where \( \lambda_0 \) is free space wavelength at 15.5GHz. Equivalent circuit model of the A-formed antenna is displayed in Figure 6.

Shunt capacitance (CR) and series inductance (LR) are right-handed parasitic effects which unavoidably are produced by exist gaps between patches and ground plane and current flows on the patches. Losses of the structure are modeled by RR, GR, RL and GL. RR and GR are right-handed losses and RL and GL...
are left-handed losses.

In this paper, for realization of the ultra wide band antenna (UWBA) we employed of a new concept based on smaller value of the loaded series capacitance. For implementation of the smaller value of the loaded series capacitance, here, utilized of the A-formed gap capacitances with close spaces of the edges of the gaps, as a result reduce of the printed gaps area and in agreement with it the bandwidth of the antenna has been extension. Proposed antenna can be cover impedance bandwidth ($S_{11} < -10\text{dB}$) from 15.5GHz-19.2GHz, equal to 3.7GHz bandwidth and correspond to 21.32% practical bandwidth. The reflection coefficient ($S_{11} < -10\text{dB}$) of the proposed antenna is exhibited in Figure 7.

Other important issue in design of the antenna systems is radiation performances. Therefore, acceptable radiation characteristics will be necessary properties of the antenna systems. In this framework, we suggested a new idea for providing good radiation performances, beside the designed antenna has small size and wide bandwidth. For obtaining suitable radiation properties, we employed of the uniform excitation mechanism by utilizing two ports, as port 1 is excited by input signal and port 2 is matched to 20 ohm load impedance. Furthermore, in procedure design of the proposed antenna for obtaining appropriate radiation performances, used of inductive and capacitive elements with optimized values.
as a result aperture efficiency is increased which lead to enhancement of radiation characteristics. The radiation gain and efficiency of the CUWBR antenna at 18GHz are 3.28 dBi and 29.62%, respectively. The radiation gain patterns of this antenna at 18GHz are plotted in Figure 8.

Plainly, radiation patterns of the proposed antenna have unidirectional characteristics. Therefore, suggested antenna is include advantages of small size as has general dimension equal to 17.66mm × 5.35mm × 0.8mm or 0.91λ0 × 0.27λ0 × 0.04λ0, ultra wideband with 3.7GHz bandwidth from 15.5GHz to 19.2GHz, which correspond to 21.32% practical bandwidth and excellent radiation performances with 3.28dBi gain and 29.62% radiation efficiency at resonant frequency f=18 GHz. The simulation is done using ADS (advance design system) software.

According to obtained results the proposed compact ultra wideband resonant (CUWBR) antenna based on CRLH MTM-TLs can be appropriate nominee for wireless and microwave communications.

5. CONCLUSION

Here, we presented new concepts of design of the compact ultra wide band resonant (CUWBR) antenna based on MTM technology, printed patch technique and smaller value of the loaded series capacitance.

The A-shaped MTM structure with rectangular patch antenna has been proposed in this paper. Overall size of this antenna structure is very compact in comparison conventional antennas. On making A-shaped structure by double negative left-handed MTMs, antenna parameters like gain, efficiency, and bandwidth can be improved up to a desired limit but practical limitations should be taken care of while fabricating the structure with ADS software. The proposed antenna have benefits of low cost, ease of implementation, unidirectional radiation patterns, high gain and efficiency, broader bandwidth than conventional wideband antennas and smaller size than conventional compact antennas and this antenna can be fabricated in a low cost and low-profile printed circuit board (PCB) using standard PCB manufacturing techniques.
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References