

Miniature CRLH-based ultra wideband antenna with gain enhancement for wireless communication applications[☆]

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Abstract

A novel miniaturized ultra wideband (UWB) antenna based on composite right/left-handed (CRLH) metamaterial unit cells for modern wireless communication applications is presented. The physical size of the small and compact antenna is $15 \times 7.87 \times 1.6 \text{ mm}^3$ or $0.15\lambda_o \times 0.07\lambda_o \times 0.01\lambda_o$ in terms of the free-space wavelength at 3 GHz. The proposed antenna covers an impedance bandwidth of 3–10.6 GHz, which is equivalent to a fractional bandwidth of 111%. The gain and efficiency of the antenna are greater than 2.89 dBi and 38.54%, respectively, with a peak gain of 9.41 dBi and a peak efficiency of 99.93%. The characteristics of the antenna were validated with measured results obtained from a fabricated prototype to establish the proof of concept.

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1. Introduction

The need for miniature ultra wideband (UWB) antennas is rapidly growing for applications in modern communication systems, as UWB technology offers the advantages of a high resolution and reliable transmission at a low transmission power, has a high immunity to multipath interference, and provides a high channel capacity. Although the commercial use of the frequency band of 3–10.6 GHz for radar, location tracing, and data transmission was approved by the FCC in 2002 [1], the research and development of UWB systems have recently accelerated owing to commercial demand [2–4]. One of the important elements in any wireless UWB system is the antenna, which needs

to have (i) a low VSWR (<2) over 3–10.6 GHz, (ii) a high radiation efficiency, (iii) good radiation characteristics, and (iv) compatibility for integration in electronics circuits. A significant size reduction is also required to minimize the wireless communication system. Furthermore, the UWB antenna needs to be highly compact, low cost, and reliable.

The usefulness of metamaterials (MTMs) has been amply demonstrated for designing compact antennas and microwave devices [5–11]. An MTM composite right/left-handed transmission line (CRLH-TL) provides a conceptual route for implementing small antennas. In this study, we have employed MTM technology to develop a more compact antenna while maintaining its performance in terms of the bandwidth, radiation efficiency, and radiation pattern. The proposed antenna has a length of 15 mm, a width of 7.87 mm, and a height of 1.6 mm, which are sufficiently small to fit inside most portable communication devices. The single antenna can support today's multiband wireless applications in the UWB band from 3 to 10.6 GHz, which eliminates the need for multiple antennas and a complex

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switching network. The antenna's characteristics were validated with measured results.

The rest of this paper is organized as follows. Section 2 provides a theoretical background on CRLH MTM antennas. The guidelines for UWB antenna design are discussed in Section 3. In Section 4, we elaborate upon the design procedure of the proposed antenna. Section 5 presents the antenna's measured performance, and the work is concluded in Section 6.

2. CRLH MTM antenna

The propagation of electromagnetic waves in most materials obeys the right-hand rule for the E , H , and β vector fields, where E is the electric field, H is the magnetic field, and β is the wave vector defined as follows:

$$\gamma = \alpha + j\beta = \sqrt{ZY} \quad (1)$$

with

$$\beta(\omega) = s(\omega) \sqrt{\omega^2 L_R C_R + \frac{1}{\omega^2 L_L C_L} - \left(\frac{L_R}{L_L} + \frac{C_R}{C_L} \right)} \quad (2)$$

where

$$s(\omega) = \begin{cases} -1 & \text{if } \omega < \omega_{se} = \min\left(\frac{1}{\sqrt{L_R C_L}}, \frac{1}{\sqrt{L_L C_R}}\right) \\ 0 & \text{if } \omega_{se} < \omega < \omega_{sh} \\ +1 & \text{if } \omega > \omega_{sh} = \max\left(\frac{1}{\sqrt{L_R C_L}}, \frac{1}{\sqrt{L_L C_R}}\right) \end{cases} \quad (3)$$

and

$$Z(\omega) = j \left(\omega L_R - \frac{1}{\omega C_L} \right) \quad (4)$$

$$Y(\omega) = j \left(\omega C_R - \frac{1}{\omega L_L} \right) \quad (5)$$

where $\beta(\omega)$, $s(\omega)$, $Z(\omega)$, and $Y(\omega)$ are functions of the frequency that represent the dispersion relation, sign function, impedance, and admittance of the antenna structure, respectively. The series and shunt resonance frequencies are respectively

$$\omega_{se} = \frac{1}{\sqrt{L_R C_L}} \quad (6)$$

$$\omega_{sh} = \frac{1}{\sqrt{L_L C_R}} \quad (7)$$

The phase velocity is in the same direction as the direction of the signal's energy propagation (group velocity), as indicated by the following relations:

$$v_p = \frac{\omega}{\beta} = \omega^2 \sqrt{L_L C_L} \quad (8)$$

$$v_g = \left(\frac{\partial \beta}{\partial \omega} \right)^{-1} = \omega^2 \sqrt{L_L C_L} \quad (9)$$

If the refractive index is positive, then the material is referred to as "right-handed" (RH). Unlike RH materials, an MTM

can exhibit a negative refractive index, with the permittivity (ϵ) and permeability (μ) being simultaneously negative. These parameters are defined by

$$\mu = \frac{Z}{j\omega} = L_R - \frac{1}{\omega^2 C_L} \quad (10)$$

$$\epsilon = \frac{Y}{j\omega} = C_R - \frac{1}{\omega^2 L_L} \quad (11)$$

The direction of their phase velocity is opposite to the direction of the signal's energy propagation, where the relative directions of the E , H , and β vector fields follow the left-hand rule. Thus, MTMs are also referred to as "left-handed" (LH) materials. Since no MTM exists naturally, it can only be formed by an artificial structure.

In reality, MTMs exhibit LH and RH behavior and are thus referred to as composite right and left-handed (CRLH) MTMs. A CRLH MTM can behave like an LH MTM in the low-frequency range and an RH material in the high-frequency range [5–11]. CRLH MTMs can be structured and engineered to exhibit electromagnetic properties that are tailored to specific applications and can be used in applications where it may be difficult, impractical, or infeasible to use other solutions. The realization of small antennas is an important application of CRLH MTMs. It has been shown that an electrically large but physically small antenna can be designed by using a CRLH MTM while maintaining the same or better performance than conventional UWB antennas [12–15].

3. Guidelines for UWB antenna design

The transmission coefficient of the antenna system is an important frequency-domain indicator of the time-domain performance of a UWB antenna [16]. The guidelines for UWB antenna design are summarized as follows:

- ✓ Traveling-wave antennas having a low Q can be very broadband.
- ✓ Antennas incorporating tapers or rounded edges tend to give broad bandwidth performance because their surface currents have a smooth path to follow [17].
- ✓ Linearly polarized transmit and receive antennas are the simplest to implement in a compact planar package.
- ✓ Minimization of the thickness of the substrate and the use of low-loss materials maximize the radiation efficiency.
- ✓ Antennas with printed planar patches will have a gap capacitance. A smaller gap capacitance can result in broad bandwidth performance.

4. Antenna configuration

A CRLH MTM unit cell comprises a series capacitance and shunted inductance. The series capacitance can be achieved by printing a gap on the patch, and the shunt inductance can be achieved by constructing a thin microstrip line that is grounded through a metal via hole.

In this study, we have used an electromagnetic band gap (EBG) unit cell as the radiating unit, which is the simplest

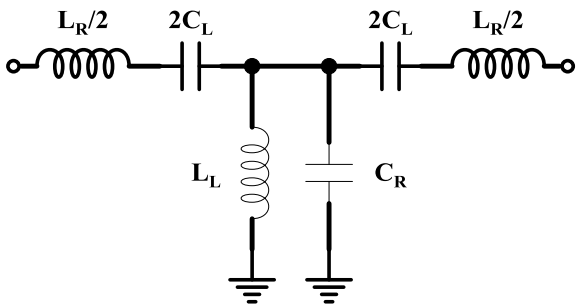


Fig. 1. Equivalent circuit model for the CRLH MTM antenna unit cell.

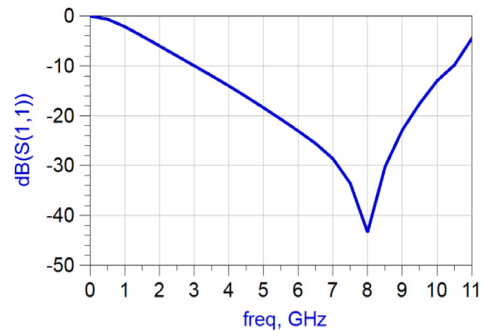


Fig. 3. Return loss parameter.

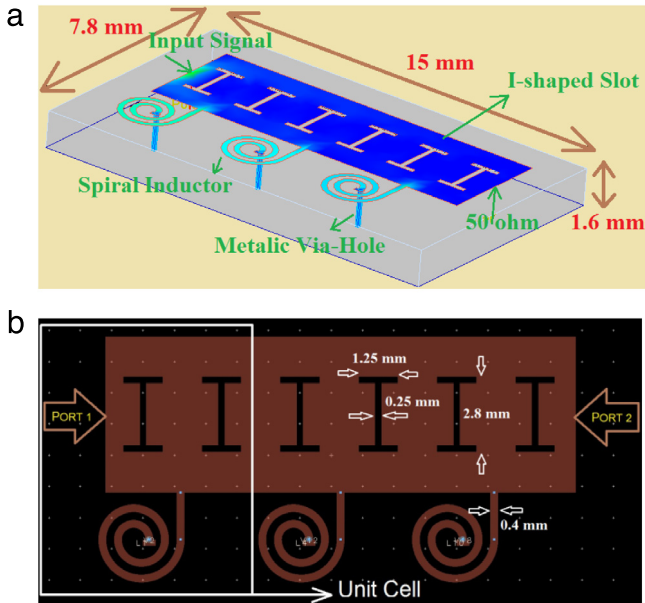


Fig. 2. Configuration of the proposed miniature UWB MTM antenna, which consists of three unit cells based on a CRLH-TL. (a) Isometric and (b) top views with detailed dimensions.

way to achieve a series capacitance and shunt inductance. The antenna structure presented in Fig. 2 consists of three unit cells comprising two closely spaced I-shaped slots etched in a rectangular patch and a spiral inductor that is grounded through a via hole. The equivalent circuit model of this structure is shown in Fig. 1. In each unit cell, the I-shaped gaps printed into the rectangular patch serve as the series capacitance (C_L), and the spiral inductor accompanying the metallic via acts as a shunt inductance (L_L). The transmission line possesses the RH parasitic effect that can be interpreted as a shunt capacitance (C_R) and series inductance (L_R). The shunt capacitance mostly originates from the gap capacitance between the patch and the ground, and an unavoidable current flows on the patch and establishes a series inductance, thus indicating that this capacitance and inductance cannot be ignored. In this structure, port 1 is excited with the input signal, and port 2 is matched to a 50-Ω load impedance. The proposed antenna has a small footprint area ($15 \times 7.87 \times 1.6 \text{ mm}^3$) and a wide operational bandwidth from 3 to 10.6 GHz for $S_{11} \leq -10 \text{ dB}$, as shown in Fig. 3. This configuration makes it possible to combine the antenna with integrated RF electronics.

Table 1

Comparison of the proposed antenna with other reported antennas.

Reference	Dimensions (mm^3)	Bandwidth (GHz)	Gain (dBi)
[18]	$12 \times 12 \times 3.33$	2.34–2.54	1
[19]	$20 \times 25 \times 0.8$	3.45–3.75	2
[20]	$60 \times 5 \times 5$	0.82–2.48	0.4
Proposed antenna	$15 \times 7.87 \times 1.6$	3–10.6	9.4

The series capacitance can be adjusted by varying the distance between the edges of the printed I-shaped gaps. This feature provides other important parameters that can be used to vary the performance of the antenna. We have used the printed planar approach to produce the gap capacitance. This allowed us to select the appropriate capacitance gaps printed into the rectangular patch so that the antenna could be miniaturized, and its impedance bandwidth could be enhanced.

5. Antenna performance

The CRLH MTM antenna was constructed on a Rogers RT/Duroid 5880 substrate with a height of 1.6 mm, a dielectric constant of 2.2, and $\tan \delta = 0.0001$. The physical size of the antenna in Fig. 2 is $15 \times 7.87 \times 1.6 \text{ mm}^3$ ($0.15\lambda_o \times 0.07\lambda_o \times 0.01\lambda_o$, where λ_o is the free-space wavelength at 3 GHz). The results were obtained using Agilent Advanced Design System (ADS), which is a full-wave EM software. The return loss (S_{11}) in Fig. 3 shows that the proposed antenna has a UWB operational bandwidth from 3 to 10.6 GHz for $S_{11} \leq -10 \text{ dB}$, which corresponds to a fractional bandwidth of 111%. The radiation gain patterns of the desired antenna at 5, 8, and 10.5 GHz are plotted in Fig. 4. The antenna radiates over the entirety of one plane. The gain at the spot frequencies of 5, 8, 10.5 GHz are 6.30, 8.56, and 9.41 dBi, respectively. Moreover, the radiation efficiency is 75.40% at 5 GHz, 94% at 8 GHz, and 99.93% at 10.5 GHz. The antenna gain and efficiency are generally above 2.89 dBi and 38.54% with a peak of 9.41 dBi and 99.93%, respectively. The antenna is compared with several other UWB antennas in terms of the dimensions and radiation characteristics, as summarized in Table 1. These results confirm that the proposed antenna is suitable for modern wireless communication systems and, in particular, UWB applications.

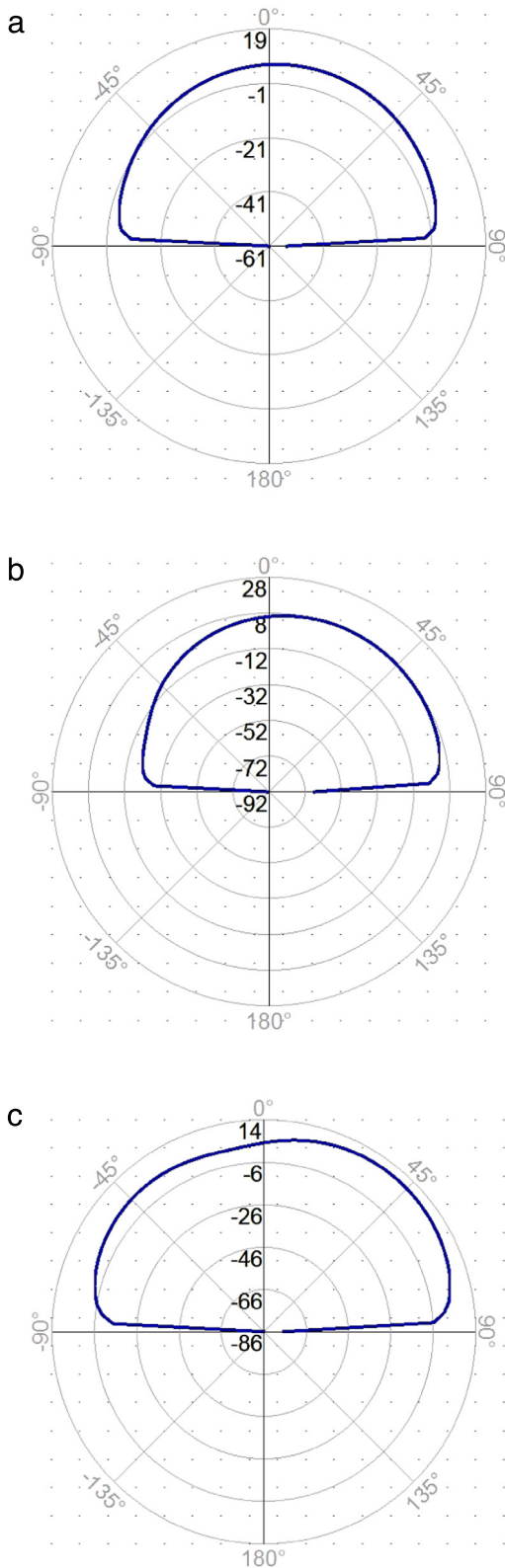


Fig. 4. Radiation patterns of the proposed antenna in the elevation plane at (a) 5, (b) 8, and (c) 10.5 GHz.

6. Conclusions

A miniature UWB antenna based on a CRLH MTM is demonstrated to be viable for modern wireless communication

systems and UWB applications. The antenna consists of three CRLH MTM unit cells, where each unit cell is realized by embedding two I-shaped slots close to each other inside a radiating patch that is terminated to ground through an inductive spiral, which is grounded using a metal via hole. The antenna operates over a frequency span of 7.6 GHz from 3 to 10.6 GHz for $S_{11} \leq -10$ dB. The compact antenna has dimensions of $15 \times 7.87 \times 1.6$ mm³ ($0.15\lambda_o \times 0.07\lambda_o \times 0.01\lambda_o$, where λ_o is the free space wavelength at 3 GHz).

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