A New UWB Small Dimension MTM Antennas Based on CRLH Transmission Lines for Modern Wireless Communication Systems and Portable Devices

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Abstract

In this report, novel ultra wideband (UWB) small antennas based on the composite right/left-handed transmission lines structures are proposed and designed. The antennas are presented with best in size, bandwidth and radiation patterns. The physical size and the operational frequency of the antennas depend on the unit cell size and the equivalent transmission line model parameters of the CRLH-TL. To realize characteristics of first proposed antenna,

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Q-shaped gaps printed into rectangular radiation patches are used. The CRLH antenna is composed of two unit cells, each of which occupies only 10.8 mm x 8.6 mm. This antenna can be covers the bandwidth from 2.7 - 9.3 GHz for VSWR < 2. The antenna peak gain and radiation efficiency, respectively, are 5.78 dBi and 42.1% which happens at f = 9.3 GHz. Moreover, second antenna with same in size and enhancement bandwidth, gain and radiation efficiency than the first proposed antenna with similar design procedure is designed. This antenna is constructed of the printed Q-shaped four unit cells. The length, width and height of the later antenna are 21.6 mm, 8.6 mm and 1.6 mm, respectively, and this antenna can be covers bandwidth from 4.1 - 11.7 GHz for VSWR < 2, and also highest gain and radiation efficiency are 7.18 dBi and 92.69%, respectively at f = 4.1 GHz.

Keywords
Printed Q-shaped antennas, Ultra Wide Band (UWB) Antennas, Small Antennas, Composite Right/Left-handed Transmission lines (CRLH-TLs), Metamaterial (MTM), Modern Wireless Communication Systems, Portable Devices.

Introduction
Since their invention back in 1960s, microstrip patch antennas have found numerous applications for their simplicity in fabrication, compatibility with planar circuitry, low profile and planar structures, and unidirectional radiation capability. Despite many nice electrical and mechanical features of microstrip antennas, their use for a number of applications at low microwave frequencies has been limited due to their limited size and bandwidth.

The conventional approach for miniaturizing the antenna size is to print the radiator on a high dielectric substrate. However, because of the capacitive nature of the patch geometry and the existence of strong impedance contrast between the antenna substrate and the free space surrounding region, a large amount of electric energy is trapped inside the dielectric material resulting in a narrow antenna bandwidth and radiation loss. The metamaterials (MTMs) are very attractive for the design of small antennas and microwave devices [1, 2]. The composite right/left handed transmission lines (CRLH-TLs) provides a conceptual route for implementing small antennas. CRLH-based antennas can also be made very broadband to support today’s multi band communication.
and wireless applications requirements. The commercial uses of frequency band 3 GHz to 10.6 GHz for radar, location tracing, and data transmissions were approved by FCC in 2002 \[3\]. Recently, the Research and development of the UWB systems including antennas have been widely performed \[4, 5, 6\]. One of the main devices of the UWB system is an antenna. The low VSWR (VSWR < 2) over 3 - 10.6 GHz band is required. Two CRLH-based antennas designed in here, can supports all cellular frequency bands (from 2.7 GHz to 11.7 GHz), using single or multiple feed designs, which eliminates the need for antenna switches. Significant size reduction is also demanded to achieve the minimization of communication systems or devices. Ideally, the UWB antenna should be small, low cost, planar, and reliable. Compatibility and ease of integration with electronics for mobile communications also desirable. Furthermore, in order to satisfy the various demands for communication and wireless services, small antenna with wide bandwidth and good radiation characteristics are needed. We in report design two antennas based on CRLH-TLs which consist of small area, planar, low cost, ease in fabrication, very wideband and good radiation properties, therefore these antennas may be good candidate for modern communication systems.

Developments of wireless communications systems call for more compact and multi frequency antennas. In particular, next generation wireless devices will require multiple antennas to coexist in a small area, while maintaining their low coupling to support multipath channel decorrelation. Metamaterial structures have the ability to concentrate electromagnetic fields and currents near antenna structures, instead of spreading them along the antenna ground, causing higher coupling between antennas. This allows compact antenna arrays to be realized with minimal mutual coupling, to be able to decorrelate multipath channels in MIMO implementations \[7, 8\]. In this paper, we will focus on transmission lines (TL) based on composite right- and lefthand (CRLH) propagation \[9]-[24]. It is nearly impossible to implement a pure left-handed (LH) transmission line due to the right-handed (RH) propagation inherited by using lumped elements \[9\]. Such transmission lines make possible unprecedented improvements in air-interface integration, over the air (OTA) performance and miniaturization, while simultaneously reducing bill-of-materials (BOM) costs and specific absorption rate (SAR) values. Metamaterials enable physically small but electrically large air-interface components, with minimal coupling among closely spaced devices.

Metamaterials (MTM) are man-made composite materials, engineered to produce desired electromagnetic propagation behaviour not found in natural me-
dia [9, 10]. The word metamaterial refers to many variations of these man-
made structures. Metamaterial antenna structures are copper, printed directly
on the dielectric substrate, and can be fabricated by using a conventional
Rogers_RT_Duroid5880 substrate or a flexible printed circuit (FPC) board.
Recently, novel antennas with these characteristics have been designed by
using composite right/left-handed transmission line (CRLH-TL) metamate-
rials [11, 12]. Unlike traditional right-handed (RH) transmission materials,
metamaterials based on left-handed (LH) transmission lines (TLs) have unique
features of anti parallel phase and group velocities ($v_p - |v_g|$) [11]-[13]. Pure
LH TLs cannot be implemented due to the existence of RH parasitic effects
that occur naturally in practical LH TLs. CRLH-TL structures have been
proposed, which also include RH effects. Several metamaterials-based antennas
have already been presented, such as backward-to-forward leaky-wave anten-
as [14]-[15], zeroth-order resonant antennas [16], and so on.

Metamaterials are broadly defined as effectively homogeneous artificial struc-
tures exhibiting unusual properties, such as, for instance, an index of refraction
that may be negative (left handedness), less than one, or modulated in a graded
manner. Such materials have spurred considerable interest and led to numerous
applications over the past decade [18, 19].

Metamaterials may be equivalently described in terms of media parameters
(electric/magnetic dipole moments, electric/ magnetic susceptibilities, permit-
tivity, permeability), or in terms of transmission-line (TL) parameters (induc-
tance/capacitance, impedance/ admittance, propagation constant/characteristic
impedance). The latter approach, introduced in [20, 21], has led to low-loss and
broadband metamaterials, due to the non-resonant nature of the structural
elements. This has been the foundation for the vast majority of the practical
applications reported to date. More particularly, the concept of composite
right/left-handed (CRLH) transmission-line metamaterials (introduced in [22]
and theorized in [23]), which describes in a simple and insightful manner the
fundamentally dual right-handed (RH)/left-handed (LH) nature of metamateri-
als, has been widely recognized as a powerful paradigm for the understanding
of metamaterial phenomena and the design of metamaterial devices.

The applications of metamaterials may be classified in three categories:

1. Guided-wave components (multi band, enhanced bandwidth, and miniatur-
ized components; tight broadband couplers; compact resonators; uniform
power combiners and splitters; UWB filters; agile distributed amplifiers;
2. Refracted-wave systems (focusing slabs, super-resolution imagers, reflectionless curved refractors, coordinate-transformation-based graded-index structures for electromagnetic manipulations); and

3. Radiated-wave devices (mono/multi band passive/active one dimensional/two dimensional printed planar antennas and reflectors).

This report is concerned with the third category. It presents a selected number of the most practical CRLH metamaterial printed planar antennas. Design and fabrication of these antennas is based on utilizing composite right/left-handed (CRLH) metamaterial (MTM) transmission lines (TLs) technology and printed planar methodology which caused to gap capacitance that act like series capacitance and this methodology with MTM technology using for foot print area reduction, also employing appropriate inductive elements, such as rectangular inductors and metallic via holes with their optimize structural values that provides shunt inductance accompanying suitable tuning distance between gap edges and using low loss materials for enhancement bandwidth and maximizes radiation characteristics. Design procedures of the antennas based on the above methods are discussed in the following sections.

This paper is organized as follows. Section 2 introduced antenna based on composite right/left-handed metamaterial transmission lines. This section, first establishes the fundamental of CRLH metamaterial transmission line structures (Section 2 A). It then presents CRLH Metamaterial technology in antenna design (Section 2 B). Next section recommends a new idea of the design UWB small CRLH MTM antennas as section 3 first proposed UWB and compact CRLH MTM printed two unit cells antenna (Section 3 A). It then presents improvement gain antenna with printed Q-shaped four unit cells structure (Section 3 B). In following simulation results and discussions of the proposed printed antennas arrangements in section 4. Afterwards in section 5, we have provided a brief talk about benefits of the presented CRLH based antennas. Finally, discussion and conclusion are raised.

Antennas based on Composite Right/Left-Handed Metamaterial Transmission Lines

Mohammad Alibakhshi-Kenari
Fundamentals of CRLH Metamaterial Transmission Line Structures

Figure 1 shows the equivalent circuit of periodic CRLH metamaterial transmission lines (MTM TLs) in general case (lossy case). It should be noted that periodicity is here a convenience but not a necessity, as long as the largest cell is much smaller than the guided wavelength \( p << \lambda_g \) for electromagnetic homogeneity. Another important note is that as long as the effective medium condition, \( p << \lambda_g \) is satisfied, there is no constraint on the minimum number of unit cells required for metamaterial operation. Even one single cell, when perfectly matched to the external world (i.e., presenting a bloch impedance equal to that of the external media or ports), behaves in a manner that cannot be distinguished from the behavior of a perfectly continuous medium of the same electrical size for the wave crossing it.

The homogeneous models of a purely RH, purely LH, and CRLH lossless transmission lines are shown in figure 2 (A), (B) and (C) respectively [11]. For a purely RH lossless TL, its model is developed from conventional infinitesimal circuit model, where \( L_R \) is a series inductance and \( C_R \) is a shunt capacitance. The purely LH model is obtained by interchanging the inductance/capacitance and inverting the series/parallel arrangements in the equivalent circuit of the RH-TL, where \( C_L \) presents a series capacitance and \( L_L \) presents a shunt inductance. In effect, parasitic capacitance \( C_R \) due to development of voltage gradients and unavoidable parasitic inductance \( L_R \) due to current flow along the metallization will be added to LH TL and result in CRLH TL structure [11].

The quantities such as resistance \( R \) of the conductors, inductance \( L \) (due to...
the magnetic field around the patches, self inductance, etc), capacitance $C$ and conductance $G$ of the dielectric material separating the two conductors are known as the primary line constants, from which the secondary line constants, these being the propagation constant, attenuation constant and phase constant are derived. The propagation constant, symbol $\gamma$, for a given system is defined by the ratio of the amplitude at the source of the wave to the amplitude at some distance $x$ [28] expressed as:

$$\frac{A_0}{A_x} = e^{\gamma x}$$  \hspace{2cm} (1)

Since the propagation constant, is a complex quantity we can write:

$$\gamma = \alpha + j\beta$$  \hspace{2cm} (2)

where, $\alpha$, the real part, is called the attenuation constant, $\beta$, the imaginary part, is called the phase constant.

$$\gamma = \sqrt{ZY}$$  \hspace{2cm} (3)

For example in a copper transmission line, the propagation constant can be calculated from the primary line constants by means of the relationship: where $Z$ and $Y$ are, respectively, the impedance and admittance of the transmission line. In the special case of the CRLH TL, $Z$ and $Y$ are defined as [11]:

$$Z(\omega) = j\left(\omega L_R - \frac{1}{\omega C_L}\right)$$  \hspace{2cm} (4)
After calculation, the dispersion relation for a homogeneous CRLH TL is [11]:

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

(6)

where [11]

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

(7)

Figure 3 (a), (b), and (c) shows the \( \omega - \beta \) or dispersion diagram of a purely RH TL, purely LH TL, and CRLH TL, respectively. The group velocity or slope of the curve \( v_g = \frac{\delta \omega}{\delta \beta} \) and phase velocity or slope of the line segment from origin to curve \( v_p = \frac{\omega}{\beta} \) of these TLs can be inferred from the dispersion diagram. For a purely RH TL, it is shown that \( v_g \) and \( v_p \) are parallel \( (v_g || v_p \text{ and } v_g v_p > 0) \). However for a purely LH TL, the negative sign in \( \beta(\omega) \) indicates a negative phase velocity and therefore \( v_g \) and \( v_p \) are anti-parallel \( (v_p - || v_g \text{ and } v_p v_g < 0) \). In addition, the CRLH TL’s dispersion diagram shows that, it has both LH \( (v_p v_g < 0) \) and RH \( (v_p v_g > 0) \) region. Also note that the stop band occurs in the frequency range where \( K \) is purely real for a CRLH TL (in (2), where \( \beta = 0 \)). The group and phase velocities of the transmission line can be define as following:

\[ v_g = \left( \frac{\delta \beta}{\delta \omega} \right)^{-1} = s\omega^2 \sqrt{L_L C_L} \]

(8)

\[ v_p = \frac{\omega}{\beta} = s\omega^2 \sqrt{L_L C_L} \]

(9)

where, \( s \) is a handedness sign function defined as:

\[ s = \begin{cases} 
+1 & \text{if the purely RH TL} \\
-1 & \text{if the purely LH TL} 
\end{cases} \]

(10)

LH-TL is obviously of high-pass nature, in contrast to that of the RH-TL which is of low-pass nature, in result a CRLH-TL contributes LH property at
lower frequencies and RH at higher frequencies with a transition frequency \( \omega_0 \).

It has been developed that under balanced condition (11) or (12), when the series and shunt resonances (\( \omega_{se} \) and \( \omega_{sh} \)) are equal [11],

\[
\omega_{se} = \frac{1}{\sqrt{L_RC_L}} = \omega_{sh} = \frac{1}{\sqrt{L_LC_R}}
\]

or

\[
L_RC_L = L_LC_R
\]

in results the propagation constant in (6) reduces to the simpler expression [11]

\[
\beta = \beta_R + \beta_L = \omega\sqrt{L_RC_R} - \frac{1}{\omega\sqrt{L_LC_L}}
\]

where the phase constant distinctly splits up into the RH phase constant \( \beta_R \) and the LH phase constant \( \beta_L \). Thus, there is a seamless transition from LH to RH for the balanced case occurring at the transition frequency \( \omega_0[11] \):

\[
\omega_0^{unbalanced} = \frac{1}{\sqrt{L_RC_RL_LC_L}}
\]

and in the balanced case, \( \omega_0^{balanced} \) is equal:

\[
\omega_0^{balanced} = \frac{1}{\sqrt{L_RC_L}} = \frac{1}{L_LC_R}
\]
A balanced form of a CRLH TL is shown in figure 4. The simplified equivalent circuit model is the series combination of a RH and a LH TLs. Also, the balanced CRLH TL’s dispersion curve does not have a stop band. In addition, at $\omega_0$ the phase shift ($\phi = -\beta d$) for a TL of length $d$ is zero ($\beta = 0$). Phase advance ($\phi > 0$) occurs in the LH frequency range ($\omega < \omega_0$, $\beta < 0$), and phase delay ($\phi < 0$) occurs in the RH frequency range ($\omega > \omega_0$, $\beta > 0$)[11]. The characteristic impedance of a TL is given by $Z_0 = \sqrt{Z_\text{Y}}$. For the CRLH TL, in unbalanced case the characteristic impedance is [11]:

$$Z_0 = Z_L \sqrt{\frac{C_L L_R \omega^2 - 1}{C_R L_L \omega^2 - 1}}$$ \hspace{1cm} (16)

in the balanced case: $Z_0 = Z_L = Z_R$, with,

$$Z_L = \sqrt{\frac{L_L}{C_L}}$$ \hspace{1cm} (17)

$$Z_R = \sqrt{\frac{L_R}{C_R}}$$ \hspace{1cm} (18)

where $Z_L$ and $Z_R$ are the purely LH and RH impedances, respectively. According to (16) the characteristic impedance for the unbalanced case is frequency dependent, however, according to (17) and (18) for the balanced case is frequency independent and therefore, can be matched over a wide bandwidth.
The permeability and permittivity of a TL material have been related to the impedance and admittance of its equivalent TL model:

\[
\mu = \frac{Z}{j\omega} = L_R - \frac{1}{\omega^2 C_L}
\]

(19)

\[
\epsilon = \frac{Y}{j\omega} = C_R - \frac{1}{\omega^2 L_L}
\]

(20)

Equations (19) and (20) verified that for balanced case the permeability and permittivity are negative in LH region, where \( \omega < \omega_0 \).

The index of refraction \((n = \frac{c\beta}{\omega})\) for the balanced and unbalanced CRLH-TL is displayed in figure 5 [11]. This figure 5 shows that the CRLH-TL has a negative index of refraction in its LH range and a positive index of refraction in its RH range.

![Figure 5: Typical index of refraction plots for the balanced (green) and unbalanced (red) CRLH TL [11].](image)

**CRLH Metamaterial Technology in Antenna Design**

The antenna has become one of the most difficult challenges when designing wireless communication systems in portable devices. Due to the limited space available for the antenna, shrinking conventional antennas may lead to performance degradation and complicated mechanical assembly. Metamaterial technology provides an opportunity to design an antenna of a smaller size at lower cost with better radiation performance at both the antenna and system
levels. Various implementations of metamaterial structures have been reported and demonstrated [9, 10]. In this report, a transmission line type of realization CRLH-TL that possesses characteristics of low insertion loss, broad bandwidth, low profile and good radiation performances will be employed for the antennas design.

A metamaterial is usually a periodic structure with N identical unit cells cascading together, where each cell is much smaller than one wavelength at the operational frequency. The composition of one metamaterial unit cell is categorized as a series inductor ($L_R$), series capacitor ($C_L$), shunt inductor ($L_L$), and shunt capacitor ($C_R$). Shunt inductor ($L_L$) and series capacitor ($C_L$) determine the left-handed mode propagation properties, while series inductor ($L_R$) and shunt capacitor ($C_R$) govern the right-handed mode propagation properties. The behaviour of both left-handed and right-handed mode propagation at different frequencies can be easily addressed in a simple dispersion diagram, as shown in figure 6. The dispersion curve on the $\beta > 0$ side is the right-handed mode, while the dispersion curve on the $\beta < 0$ side is the left-handed mode [9]. The electrical size of a conventional transmission line is strongly related to its physical dimensions and thus reducing device size usually means increasing operational frequency. To the contrary, the dispersion curve of a metamaterial is determined by the four CRLH parameters. This property implies the following: if these four parameters are realized in a very compact form, the corresponding circuit size will be physically small but electrically large. This concept has been adopted successfully in small antenna designs [7]-[25].

**Ultra Wide Band and Small CRLH MTM Proposed Antennas Design**

**UWB and Compact CRLH MTM Printed Q-Shaped Two Unit Cells Antenna**

The design of equivalent circuit model of the proposed MTM antenna is based on the CRLH-TL structure shown in figure 7. The proposed planar antenna is fabricated on an Rogers_RT_Duroid5880 substrate, with a dielectric constant of 2.2, and a thickness of 1.6 mm. This mushroom type unit cell consisted of a 10.8 mm x 8.6 mm top patch, printed on top of the substrate and a rectangular inductor attending a metallic via hole. Each unit cell was coupled to its adjacent unit cell and the vertical via was connected between the rectangular inductor and the ground on the back of the substrate. This antenna was excited by external port
Figure 6: Dispersion diagrams (in unbalanced case) for a CRLH TL. The labels RH and LH indicate the RH and LH frequency branches, respectively.

Comparison of the CRLH, PLH ($\beta_{PLH}$) and PRH ($\beta_{PRH}$) TLs for energy propagation along the $+z$ direction ($v_g > 0$).

as input signal, as shown in figure 8. The shape and dimensions of the antenna structure were optimized for matching purposes, reducing the occupy area, enhancement bandwidth and providing good radiation properties of the antenna.

The antenna is based on two simplified planar mushroom structure unit cells. The unit cell is composed of a host transmission line with two printed Q-shaped gaps into rectangular radiation patches and a rectangular inductor connected to ground plane through a metallic via. The Q-shaped gaps printed within patches operates as series capacitance ($C_L$) and the rectangular inductor accompanying vertical metallic via hole connected to ground plane performs a shunt inductance ($L_L$). A purely left-handed transmission line cannot exist physically because, even if we intentionally provide only series capacitance ($C_L$) and shunt inductance ($L_L$), parasitic series inductance ($L_R$) and shunt capacitance ($C_R$) effects, increasing with increasing frequency, will unavoidably occur due to currents flowing in the metallization and voltage gradients developing between the metal patterns of the trace and the ground plane, which indicates that these inductance and capacitance cannot be ignored. Thus, the CRLH model represents the most general MTM structure possible. This antenna structure is excited by external port (i.e.; port 1) as input signal and port 2
Figure 7: The equivalent circuit model of the proposed printed Q-shaped antenna composed of two unit cells. A) For one unit cell, B) For whole structure.

is matched to 50Ω load impedance of the SMD1206 components connected to ground plane through a metallic via hole. Configuration of the recommended printed Q-shaped two unit cells antenna is displaying in figure 8.

In this design procedure of the antenna, we employed MTM technology and used printed planar technique, which results to downsizing of the proposed antenna, therefore, proposed antenna size is very compact in comparison to conventional antennas size. Presented antenna is formed of the two simplified planar mushroom structure Q-shaped unit cells, each of which occupies only 10.8 mm x 8.6 mm or 0.18\(\lambda_0\) x 0.15\(\lambda_0\) in terms of the free space wavelength at the resonance frequency \(f = 5.2\) GHz, therefore, the physical length, width and height of this antenna are 21.6 mm, 8.6 mm and 1.6 mm, respectively, or, 0.37\(\lambda_0\) x 0.15\(\lambda_0\) x 0.02\(\lambda_0\).

One important issue many conventional metamaterial antennas confront is
a lack of bandwidth [26, 27]. Although many research articles have demonstrated the ability to design small antennas by using metamaterial technology, very little work has been done to address the bandwidth issue.

The transmission coefficient of the antenna system is an important frequency domain indicator of the time domain performance of an UWB antenna [29]. In this paper, we proposed several efficient method to extend the bandwidth of the MTM antennas with a fixed antenna size. The points summarize in below,
are guidelines for the UWB antenna design.

1. Travelling wave antennas or antennas having low Q can be very broad
   band.

2. Antennas incorporating tapers or rounded edges tend to give broad band-
   widths because surface currents have a smooth path to follow [30].

3. Linearly polarized transmit and receive antennas are the simplest to
   implement in a compact planar package.

4. Minimizing the thickness of the substrate and using low loss materials
   maximizes radiation efficiency.

5. Using of the printed planar methodology into radiation patches for antenna
   design with minimizing acceptable distance between gap edges results to
   extended the bandwidth of the antenna.

In this report, we using of the second, fourth and last proposed approaches
for increasing the bandwidth and radiation characteristics of the proposed
antennas. By using a smaller value of the loaded series capacitance (CL) on
the CRLH-TL, broadband performance can obtain. A smaller value of the
loaded series capacitance will be realized by implementation of the Q-shaped
gaps with closely space edges printed into rectangular patches of the radiation
patches. We used of this method to increase the bandwidth of the our antenna,
as providing a ultra wideband (UWB) antenna with 6.6 GHz workable band-
width (from 2.7 GHz to 9.3 GHz) for VSWR < 2, which corresponding to 110%
bandwidth and also with employing uniform excitation mechanism by utilizing
two port as first port is fed with input signal and second port is matched
to a 50 ohm load impedance of the SMD1206 resistance components which
through a vertical metallic via is connected to ground, the aperture efficiency
of the antenna can extend, thus, the antenna gain and radiation efficiency are
increased. The antenna gain and radiation efficiency at resonance frequency
$f_r = 5.2$ GHz are equal to 4.71 dBi and 41.82%, respectively. The simulated
reflection coefficient ($S_{11} < -10 dB$) of the presented antenna and too radi-
ation gain pattern at $f_r = 5.2$ GHz are plotted in figures ?? and ??, respectively.

For the exhibition of this MTM antenna with reduced size and extended
bandwidth, useful MTM antenna based on two simplified planar mushroom
structure unit cells is designed. The configuration of this small UWB CRLH
MTM antenna employing the proposed methods is shown in figure 8. The
performances of the presented methods and CRLH MTM antenna structure

Mohammad Alibakhshii-Kenari

A New UWB Small Dimension MTM Antennas Based on CRLH Transmission
are verified using Agilent ADS full-wave simulator. As an advantage of the proposed ways, (i.e.; employing MTM technology, printed planar patches, using low loss materials maximizes radiation efficiency and suitable inductive parameter consist of rectangular inductors and metallic via holes accompanying their optimize values and optimized distance between gap edges), those are very easy to implement small UWB MTM antennas by properly introducing the CRLH-TL unit cells. The proposed printed Q-shaped antenna has much
smaller size and wider bandwidth than conventional antennas. This antenna can support all cellular frequency bands from 2.7 GHz to 9.3 GHz, using single or multiple feed designs, which eliminates the need for antenna switches. All of these attributes make the fabricated Q-shaped two unit cells antenna well suitable for the modern communication units [7, 26].

Proposed Improvement Gain Antenna with Printed Q-Shaped Four Unit Cells Structure

In this section, we present the printed Q-shaped antenna structure that constructed of four unit cells with enhancement bandwidth, radiation gain and efficiency in comparison to printed Q-shaped antenna structure proposed in previous section. The design procedure of the proposed antenna in this part is completely same with design procedure of the presented Q-shaped antenna in prior section, but equivalent circuit model and geometry of the later antenna structure is different with first antenna structure prototype. This proposed difference caused which later antenna providing enhancement bandwidth and improvement radiation characteristics than first antenna designed. Presented antenna in this section is designed as one rectangular inductor attending a metallic via are considered for each gap area which become one constructing one unit cell, in results this antenna composed of four unit cells as display in figure 12, in opposite, proposed antenna in previous section was designed as one rectangular inductor accompanying a vertical via considered for two gap area which together constructing one unit cell as first antenna consists of two unit cells and exhibited in figure 8. Equivalent circuit model for proposed antenna in this section and previous section are shown in figures 7 and 11, respectively. As obvious recent structure composed of four unit cells as each unit cell consist of a series capacitance \((C_L)\) which created by printed Q-shaped gap capacitance, a shunt inductance \((L_L)\) that caused with a rectangular inductor connected to ground plane through a metallic via hole as these capacitor an inductor plays left-handed roles, also a series inductance \((L_R)\) which established by unavoidable current flow on the patches and a shunt capacitance \((C_R)\) that performed with gap capacitor between patches and ground plane, as later inductor and capacitor cannot be ignored and portrays right-handed function.

This typical CRLH antenna structure consists of a feed line that is electromagnetically coupled to metallic patches, rectangular inductors, metallic via holes that connects the rectangular inductor to the ground plane. This feed line through a small gap excites the CRLH unit cells. Typically, the antenna is matched to a port with 50 ohm load impedance. The resonant frequencies,
Figure 11: The equivalent circuit model of the proposed printed Q-shaped antenna constructed of four unit cells. A) For one unit cell, B) For whole structure.

The matching of multiple right-handed and left-handed modes, and associated efficiencies can be controlled by changing and tuning the size of the cell patch, the width of the via line, the length of the feed line, the distance between the antenna elements and the ground, optimizing the rectangular inductor and various other dimensions and layouts [7]-[17]. The gap capacitor and the rectangular inductor accompanying a metallic via hole could be viewed as series capacitance $C_L$ and shunt inductance $L_L$, while the top patch possessed the series inductance $L_R$ and the shunt capacitance $C_R$ to the ground. Therefore, a left-handed resonance could be obtained at the desired frequency by properly designing the gap capacitor and the rectangular inductor that connected to ground plane through a vertical metallic via hole. Formation of the recommended antenna with enhancement bandwidth and improvement radiation properties is exhibit in figure 12.

As obvious, according to figure 12, we using four rectangular inductor which each through a metallic via connected to ground plane, that results to changing
configuration of the unit cells and therefore changing configuration of this antenna structure than antenna designed in figure 8. This varies, i.e.; increase number of rectangular inductor from two to four, decrease number of turns of the rectangular inductor from two to one turn and too reduce width of the rectangular inductor than first case, results to changes frequency range and hence extend the bandwidth of this antenna, also, this varies caused to improvement and increase of the radiation properties. Printed Q-shaped antenna which is designed on Rogers_RT_Duroid5880 substrate with dielectric constant $\varepsilon_r = 2.2$ and thickness $h = 1.6$ mm has wider bandwidth and better...
radiation performances than prior antenna. Presented antenna is formed of the four simplified planar mushroom structure Q-shaped unit cells, each of which occupies only 5.4 mm x 8.6 mm or 0.1λ₀ x 0.16λ₀ at the resonance frequency \( f_r = 5.65 \) GHz, where \( \lambda_0 \) is free space wavelength, therefore, overall size of the Q-shaped antenna is 21.6 x 8.6 x 1.6 mm³ (0.4λ₀ x 0.16λ₀ x 0.03λ₀). This antenna has 7.6 GHz applicable bandwidth from 4.1 GHz to 11.7 GHz for VSWR < 2, which corresponds to 96.2% practical bandwidth, in addition at resonance frequency \( f_r = 5.65 \) GHz the antenna gain and radiation efficiency are 6.52 dBi and 60.47%, respectively. The simulated return loss bandwidth (\( S_{11} \) parameter) of the antenna and radiation gain pattern at \( f_r = 5.65 \) GHz are plotted in figures 13 and 14, respectively. The results shown that latter antenna has same physical size, broader bandwidth and superior radiation performances in comparison to first antenna prototype. Both proposed antenna have smaller size and wider bandwidth attending higher radiation properties than conventional antennas.

Entire equivalent circuit model and configuration of the both Q-shaped antennas, as first is constructed of two unit cells and second is composed of four unit cells, are illustrated in figures 7 and 11, and figures 8 and 12, respectively, as shown two proposed antenna have identical design procedures but different equivalent circuit models and different layout structures. Two designed UWB small antennas based on CRLH MTM-TLs are suitable and useful for microwave and portable devises and wireless communication applications.

![Figure 13: Simulated return loss (S₁₁ parameter).](image)
Simulation Results and Discussions of the Proposed Printed Antennas

The antennas were designed on Rogers RT Duroid5880 substrates with $\epsilon_r = 2.2$ and thickness $h = 1.6$ mm. Each unit cell of the first and second proposed antenna respectively occupies only 10.8 mm x 8.6 mm and 5.4 mm x 8.6 mm and overall size of the proposed antennas are equal to 21.6 mm x 8.6 mm x 1.6 mm and 21.6 mm x 8.6 mm x 1.6 mm, respectively. As obvious two antennas have identical overall size, but because both antennas composed of not equal number of unit cells as first antenna constructed of two unit cells, however second antenna build of four unit cells, therefore, each unit cell dimension of each antennas are unequal. Figure 9 and figure 13, respectively shows the simulated return losses ($S_{11}$ parameters) of the printed Q-shaped antenna assembled of two unit cells and printed Q-shaped antenna organized of four unit cells. The simulated results were obtained using Agilent ADS full-wave simulator. As illustrated in figure 9 the simulated return losses bandwidth ($S_{11} < -10 dB$) of the first presented antenna is 6.6 GHz (from 2.7 GHz to 9.3 GHz), this corresponds to 110% practical impedance bandwidth, which is more than conventional antennas. The simulated return losses bandwidth ($S_{11} < -10 dB$) of the second proposed antenna that shown in figure 13 is 7.6 GHz (from 4.1 GHz to 11.7 GHz), which corresponds to 96.2% practical impedance bandwidth, which is more than conventional antennas. The simulated two dimensional (2-D)
radiation gain patterns of the recommended antennas at different frequency are plotted in figures 15 and 16, respectively. For first antenna, radiation gains are 2.8 dBi and 5.78 dBi, respectively, at 2.7 GHz and 9.3 GHz. Also, radiation efficiencies of this antenna are 37.23% and 42.1% at same frequencies, respectively. For second antenna, at 4.1 GHz, 9.6 GHz and 11.7 GHz, gain and efficiency are equal to 7.18 dBi and 92.69%, 5.83 dBi and 34.89%, and 5.42 dBi and 54.19%, respectively.

According to figures 15 and 16 radiation patterns are unidirectional character-

![Figure 15: The simulated two dimensional (2-D) radiation gain patterns of the Q-shaped antenna constructed of two unit cells in elevation plane ($\phi = 0^\circ$). A) at 2.7 GHz, B) at 9.3 GHz.](image)

istics. The peak gain and radiation efficiency of the first and second antennas occurs at 9.3 GHz and 4.1 GHz, respectively, and are equal to 5.78 dBi and 42.1%, and 7.18 dBi and 92.69%, respectively. The simulated three dimensional (3-D) radiation gain patterns of the presented antennas at different frequencies are plotted in figures 17 and 18, respectively. To validate the design procedures the proposed antennas were compared with several compact and UWB antennas and their radiation characteristics and their dimensions were summarized in Table 1 and Table 2, respectively.
Figure 16: The simulated two dimensional (2-D) radiation gain patterns of the latter antenna in elevation plane ($\phi = 0^\circ$). A) at 4.1 GHz, B) at 9.6 GHz, C) at 11.7 GHz.

Table 1: Radiation characteristics of two compact antennas in comparison to the proposed small antennas.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Design in [26]</th>
<th>Design in [31]</th>
<th>Proposed 1st Antenna</th>
<th>Proposed 2nd Antenna</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gain (dBi)</td>
<td>0.6</td>
<td>0.45</td>
<td>5.78</td>
<td>7.18</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>1-2 GHz</td>
<td>0.8-2.5 GHz</td>
<td>2.7-9.3 GHz</td>
<td>4.1-11.7 GHz</td>
</tr>
<tr>
<td>Efficiency</td>
<td>26%</td>
<td>53.6%</td>
<td>42.1%</td>
<td>92.69%</td>
</tr>
</tbody>
</table>

Recommended CRLH-Based Antennas Benefits

Proposed CRLH-based antennas are ultra wideband (UWB), low profile and ultra compact in size, smaller than 50 mm by 10 mm in area on a printed circuit board, and consist of superior radiation performances. In fact, the proposed CRLH-based antennas are typically five times smaller than conventional antennas, or 1/10th of the signal’s wavelength, while offering equal or better performances. Furthermore, unlike conventional three-dimensional (3D) antennas - which must be designed, tooled and fabricated as a complex metal-and-plastic assembly- the proposed antennas shown in figures 8 and 12 are a simple three-dimensional (3D) design, tool and fabricate. Copper artwork is printed directly on a printed circuit board using standard printed-circuit board manufacturing techniques. This offers manufacturers faster time to market and
Figure 17: The simulated three dimensional (3-D) radiation gain patterns of the first antenna in elevation plane ($\phi = 0^\circ$). A) at 2.7 GHz, B) at 9.3 GHz.

Figure 18: The simulated three dimensional (3-D) radiation gain patterns of the Q-shaped antenna composed of four unit cells in elevation plane ($\phi = 0^\circ$). A) at 4.1 GHz, B) at 9.6 GHz, C) at 11.7 GHz.

reduced bills-of-materials due to the simplified design. It also offers a greatly
reduced need for fabrication and assembly of antenna components.

In addition, the CRLH-based antenna’s ability to concentrate electromagnetic fields and currents near their antenna structures results in achieving better performance.

<table>
<thead>
<tr>
<th>Some of the UWB Monopole Antennas</th>
<th>Size of Antenna</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slotted planar binomial monopole antenna [32]</td>
<td>30 x 27.4 x 1 mm³</td>
</tr>
<tr>
<td>Slotted circular monopole antenna [33]</td>
<td>26 x 27 x 1 mm³</td>
</tr>
<tr>
<td>Slotted rectangular monopole antenna [34]</td>
<td>18 x 20 x 1 mm³</td>
</tr>
<tr>
<td>Fork shaped antenna [35]</td>
<td>35 x 30 x 0.769 mm³</td>
</tr>
<tr>
<td>Slotted arc-shaped edge rectangular antenna [36]</td>
<td>24 x 35 x 0.8 mm³</td>
</tr>
<tr>
<td>Both proposed UWB antennas in this article</td>
<td>21.6 x 8.6 x 1.6 mm³</td>
</tr>
</tbody>
</table>

**Conclusion**

CRLH transmission line metamaterials represent a paradigm shift in electromagnetics engineering and, in particular, for antennas. They exhibit exceptional properties, resulting from their rich dispersion and their fundamental left/right-hand duality. They offer simple and deep insight into metamaterial phenomena, and provide efficient tools for the practical design of components and antennas.

In this paper, we introduced a new concept of antenna size reduction based on metamaterial design technology and printed planar methodology, and also presented a novel idea of antenna bandwidth enhancement and radiation’s properties improvement based on employing appropriate inductive elements accompanying their optimize values and using low loss materials maximizes radiation efficiency. All simulated results demonstrated that the proposed CRLH-based antennas have superior performances and smaller size compared to other conventional antennas designs. These antennas have the advantages of small size, UWB, lightweight, high gain and efficiency, unidirectional radiation patterns, simple implementation and low cost. The simulated results exhibit that the proposed antennas should be potential candidates to use in the modern wireless systems.
wireless communication systems and portable devices.

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