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INVESTIGATION OF METAMATERIAL UNIT CELLS BASED ON DISPERSION CHARACTERISTICS

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ABSTRACT

Metamaterials are artificial effectively-homogenous electromagnetic structures with properties that are not readily available in nature, they are periodic structures made up of unit cells. While the field of metamaterial is receiving much interest, not too many researches have been done to characterize the metamaterial. A few metamaterial unit cells are chosen to characterize and investigate the propagation of EM waves inside the metamaterial, eigenmode solver in Computer Simulation Technology Microwave studio (CST MWS) has been used to derive the dispersion diagram. We found that some unit cells produce pure left-hand (LH) propagation while the others produced composite right/left-handed (CRLH) propagation. It is also proposed for the unit cells that can be used for wireless applications.

Keywords: metamaterial, left hand material, composite right/left-handed transmission line.

INTRODUCTION

The concept of metamaterials, commonly known as left-handed materials (LHMS) was first examined by Veselago in 1968 [1]. These artificial materials that are not readily available in nature brought many unusual electromagnetic features such as the negative values for both permittivity and permeability. The negative values of permittivity and permeability brings backward wave propagation, such as group and phase velocity travel in opposite ways [2]. As the size of wireless devices is getting more compact, small size, low profile, light weight antennas became essential prerequisite, therefore LHMS has been suggested as a possible solution that can give to the size reduction of the antennas due to a the unusual and unique electromagnetic characteristics. Even though the LHMS are not found directly in the existing natural materials, it is artificially engineered in a way that it can have the features mentioned. There are two vital approaches for realizing the LHMS and they are classified as the resonant and non-resonant approach [3]. The resonant method synthesizes the LHM by inducing electric and magnetic dipole moments to obtain negative permittivity and permeability, respectively. The approach for transmission line (TL) towards the accomplishment of the backward wave, synthesis the LHM by reasonably loading a conventional TL. LHMS TL it can form non-resonant LHM and is commonly called CRLH TL model that has been taken into consideration by the parasitic elements that comes from wave propagation in conventional TL [4].

In this paper, an investigation of metamaterial unit cells is presented based on their dispersion characteristics. The dispersion graphs are being assigned by resonant frequencies and proposed for the cells that are suitable for wireless applications.

METAMATERIAL UNIT CELL MODELS

The transmission line structures consist of series capacitors C_L as (interdigital) and shunt inductors L_L as (stub) that are meant to deliver left-handedness mentioned in the above. However, as the wave passes through the structure, the related currents and voltages bring other natural effects like series inductance L_R and a shunt capacitanceC_R. As a result, a purely left hand structure does not exist, and this was the motivation behind by the introduction of CRLH.

The CRLH transmission line (TL) is a structure that can be realized by cascading unit cells. As it is depicted in Figure-1, a CRLH TL consists of series capacitance C_L and inductance L_R and as well a shunt capacitance C_R and inductance L_L.

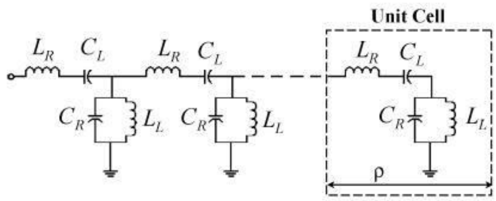

Figure-1. Composite right/left-handed transmission line model of cascaded unit cells [5].

CRLH structures can be transformed into resonators like conventional TL that is short-ended or open-ended. A CRLH TL that has N unit cells display a number of 2N-1 resonance frequencies [1]. These frequencies can be found by sampling the dispersion diagram as [2]:

$$\beta l = m\pi \tag{1}$$

Where:

m = resonance index: 0, ±1, ±2, ……

l= physical length of the unit cell

By increasing the number of unit cells we sample further resonance points from the dispersion diagram of the unit cell, and that results additional resonance

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frequencies. The metamaterial unit cells that are investigated based on their dispersion graphs are shown in Figure-3 (a), Figure-4 (a), Figure-5 (a), Figure-6 (a), Figure-7 (a), Figure-8 (a), Figure-9 (a) and Figure-10 (a).

Figure-3 (a) demonstrates a CRLH unit cell. The unit cell is formed from a four split-ring resonator (SRR) that has got hexagonal strips [6]. The cavities between the neighbouring patches on the unit cell forms capacitance, C and the hexagonal strips bring an inductance, L that permits for regulating the resonant characteristic of the structure.

The dimensions of the unit cell structure are as follows: a=13.5 mm, b= 12.5 mm, c=d=0.5mm and e=1.5 mm.

Figure-4 (a) depicts the layout of CRLH TL unit cell 2 that was used for reduction size purposes [7]. The effects of left handedness is responsible by the shunt inductor and as well the series inter digital capacitors where by the length of the unit cell capacitance and inductance of the host coplanar-waveguide (CPW) contributes for the propagation at higher frequencies in the right-handed region. Dimensions of the structure are as follows

L_{unit} =8.6mm, $W_{unit} = 5.1mm$,
$L_f = 3.15mm$ $W_f = 0.20mm$, $W_s = 0.15mm$.

Figure-5 (a) is a usual CRLH microstrip unit cell topology and its circuit model [8]. The inter-digital capacitance acts as series capacitance and the shunt inductance is applied as a short-circuited stub. The settings that is used in the structure is as follows, substrate Rogers RO 4003 with h= 1.52 mm, $\in_r$=3.38 and tan δ= 2.7*10^{-3} .

Figure-6 (a) shows Left-handed mushroom structure [9], the metallic patch is joined to the ground plane by using a vias through a dielectric slab. The parameters of the cell that is used are P= 5mm, g=0.2 mm, h=1.57 mm, t= 0.5 mm, vias radius = 0.1 mm.

Figure-7 (a) this unit cell suggested by the authors in [10] and they have utilized to load it in monopole antenna. The structure is an adjusted form of a unit cell suggested in [11]. The interdigital capacitor is being used as to contribute the series capacitance and on the shunt short-circuited stub to give the parallel inductance. The dimension of the parameters as follows: $S_s = 0.3\ mm$, $W_s = 0.7\ mm$, $W_3 = 0.5\ mm$,$W_4 = 0.3\ mm$ $L_s = 5.5\ mm$, W_5 =1.625mm ,$W_c = 0.4\ mm$, $S_c = 0.6\ mm$, $L_3 = 2.6\ mm$.

Figure-8 (a) is left handed metamaterial (LHM) unit cell [12] it comprises of a mixture of rectangular split ring resonator (SRR) and thin wire (TW). The SRR and TW are printed on the same side of FR4 substrate. The parameters values are ,FR4 substrate is = 4.4 , h = 1.6 mm. length of the outer SRR = L1=7.3 mm, and the inner SRR is L2= 5.4 mm, W1=0.5mm, the gap between the outer and inner is W2=0.5mm, the cut on both rings is G1=1.6mm and L3 is the protrusion of the Tw which connect to the patch.

Figure-9 (a) is a unit cell that v has been used for dual mode CRLH TL metamaterial antenna [13]. Both the interdigital capacitor and shut strip inductor of Length = L_{LSC}. Length of the cell = 5 mm.

Figure-10 (a) shows a microstrip employment of the convention CRLH unit cell [14]. For this structure the inter digital fingers relate to C_L and short stub is used as L_L.Both the C_R and L_R are the outcomes of the parasitic effects.

These are some of the equivalent circuit models for the unit cells mentioned in the above literature.

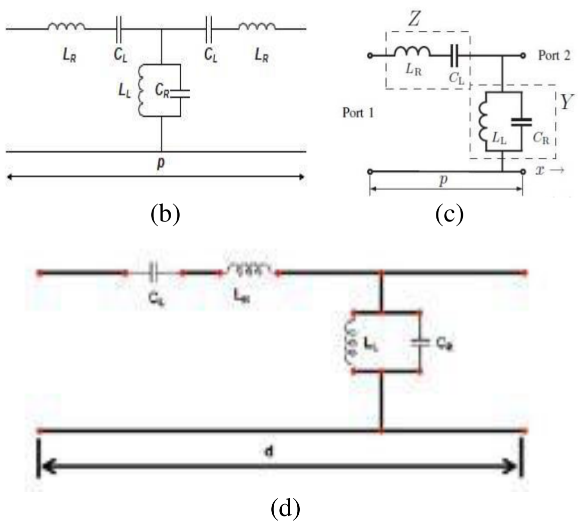

Figure 2. Equivalent circuit models for the unit cells (b) unit cell 2 (c) unit cell 3 (d) unit cell 4.

SIMULATION: RESULTS AND ANALYSIS

The following CRLH unit cells are investigated for its dispersion characteristics, by using its dispersion diagram and it is modelled and simulated by using the Eigenmode solver in Computer Simulation Technology Microwave studio (CST MWS). Settings are done as follows for studying the unit cell. Perfect magnetic boundary condition (PMC) is being placed in the z-direction, while periodic boundary condition (PBC) in both y and x-direction. The following figures depict the dispersion diagram along with the unit cell structures.

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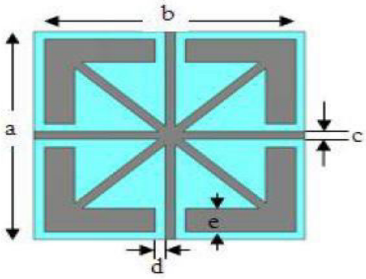
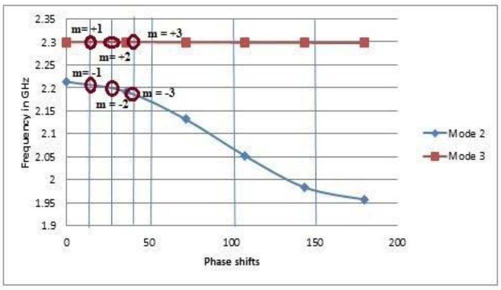
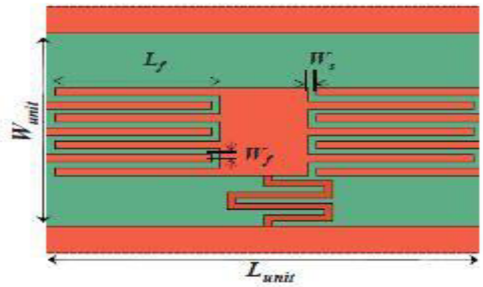


(a)



(b)

Figure-3. (a) Unit cell 1 (b) Dispersion diagram.



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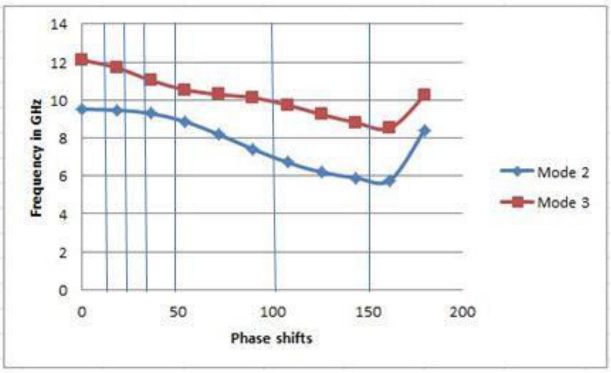
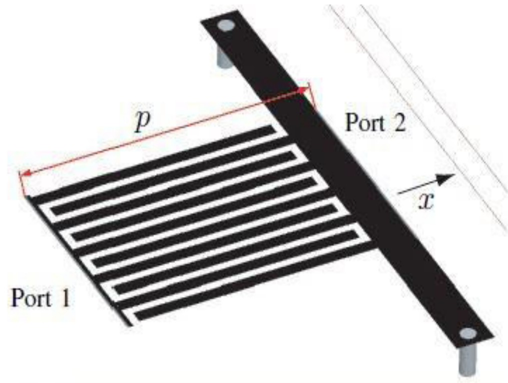


(b)

Figure-4. (a) Unit cell 2 (b) Dispersion diagram.



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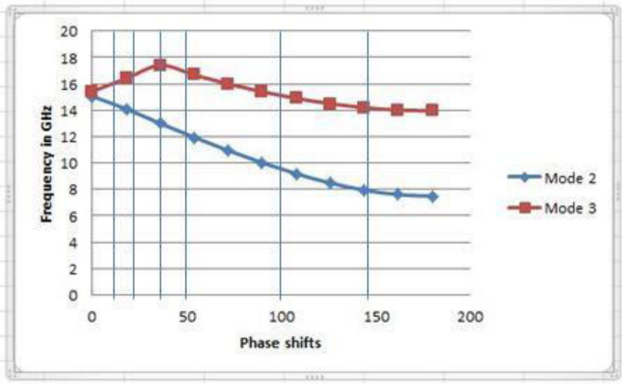
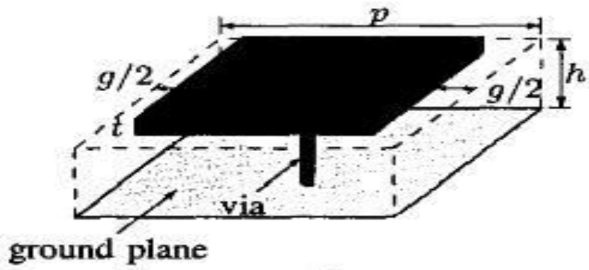


(b)

Figure-5. (a) Unit cell 3 (b) Dispersion diagram.



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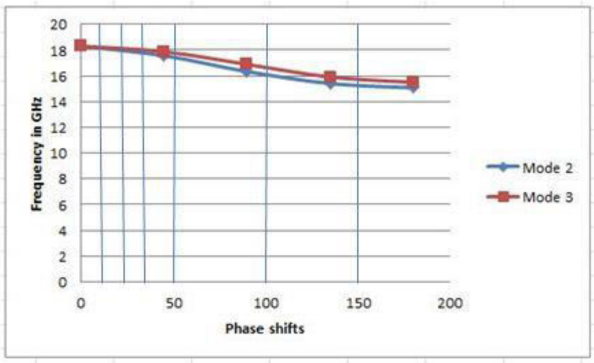

(b)

Figure 6: (a) Unit cell 4 (b) Dispersion diagram

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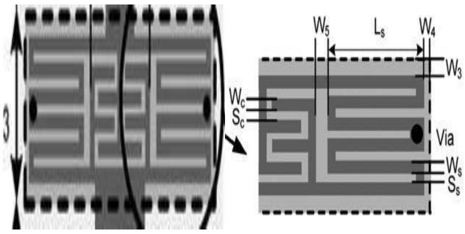

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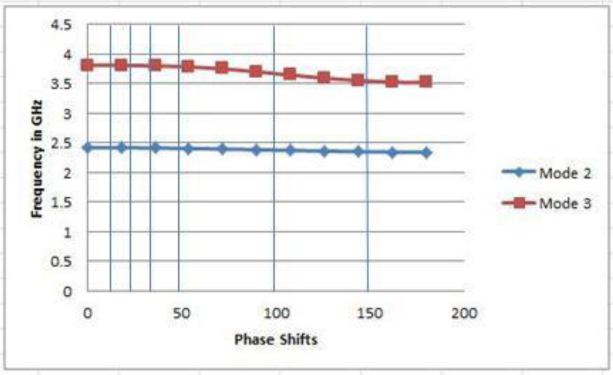
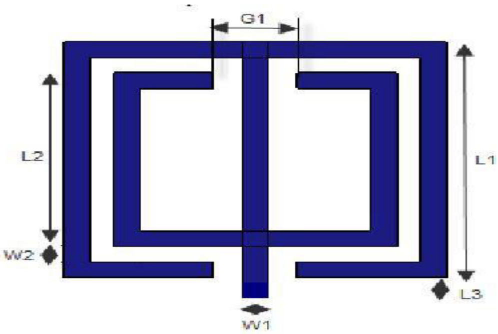
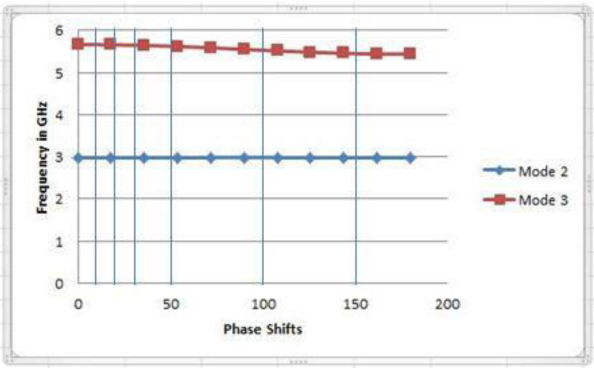


(b)

Figure-7. (a) Unit cell 5 (b) Dispersion diagram.

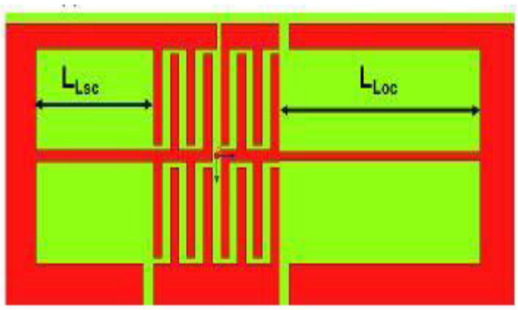


(a)



(b)

Figure-8. (a) Unit cell 6 (b) Dispersion diagram.



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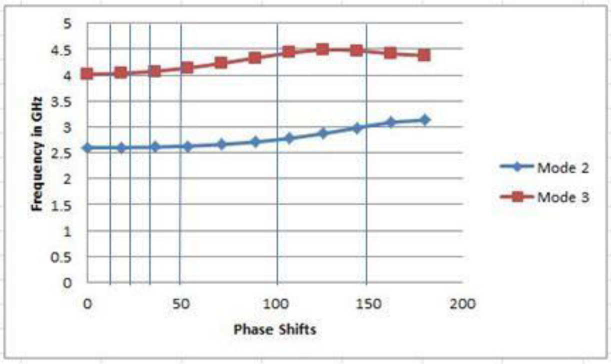
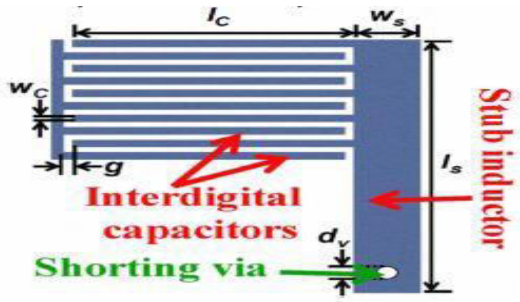
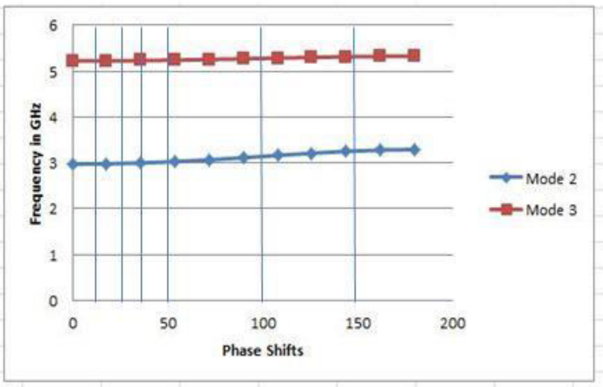


(b)

Figure-9. (a) Unit cell 7 (b) Dispersion diagram.



(a)



(b)

Figure-10. (a) Unit cell 8 (b) Dispersion diagram.

Table 1. Resonance frequencies at each mode index, *m* obtained from sampling the dispersion diagram of Figure-3 (b).

	Resonant frequencies, GHz								
Mode of indices	m=-3	m=-2	m=-1	m = 0	m=+1	m=+2	m=+3	Number of replicating the unit cell	The physical length of the unit cell
Unit cell in figure 3(a)	2.01	2.2	2.21	2.21	2.3	2.3	2.3	4 times	13.5 mm

Table 2. Resonance frequencies for eight different unit cells.

	Resonant frequencies, GHz								
Mode of indexes	m = -3	m = -2	m = -1	m = 0	m = +1	m = +2	m = +3	Number of replicating the unit cell	The physical length of the unit cell
Unit Cell 1	2.01	2.2	2.21	2.21	2.3	2.3	2.3	4	13.5 mm
Unit Cell 2	9	9.7	9.8	9.8	11.9	11.7	11	4	8.6 mm
Unit Cell 3	13.1	13.9	14.1	15.9	16	17	17.9	4	19.7 mm
Unit Cell 4	17.8	17.9	18	18	18.02	18.01	18.01	4	5 mm
Unit Cell 5	2.45	2.45	2.45	2.45	3.8	3.7	3.7	4	27.7 mm
Unit Cell 6	3	3	3	3	5.7	5.7	5.7	4	7.3 mm
Unit Cell 7	2.62	2.62	2.5	2.5	4	4	4.12	4	5mm
Unit Cell 8	3.25	3.25	3	3	5.25	5.25	5.25	4	7.4 mm

The dispersion diagrams of metamaterial unit cells are shown in Figure-3 (b), 4 (b), 5 (b) , 6 (b) , 7 (b) , 8 (b), 9 (b) , and 10 (b).

All figure show left-handed material except Figure-3(b) that approved the composite right/left-handed behaviour of the unit cell by presenting the negative (left-handed, LH) and positive slope (right-handed, RH) traces. It can be also realized from the dispersion curve that LH modes occur at the lower frequencies, and the RH modes at the higher frequencies. Moreover, the dispersion diagram depicted one of the two cases of the composite right/left –handed transmission line (CRLH-TL) which is unbalanced case by displaying a gap between the transition of left hand (LH) and right hand (RH) ranges. The dispersion diagram of Figure-3(b) can also be used to assign the resonant frequencies of the CRLH TL antenna that will be designed by repeating the unit-cells in Figure-3(a) as follows.

The CRLH TL antenna that will be achieved by repeating the CRLH unit cell in figure 3 (a) by four times, in the y-direction, it means that, the number of unit cells, N, used in creating the CRLH TL antenna is four unit cells. By using the equation, number of resonances = 2N-1=2(4)-1=7, the number of resonance points that can be gained from the CRLH TL antenna structure is seven, and that corresponds to mode indices of m = 0,±1,±2, ±3 by using equation (1) and taking the physical length of the unit cell 13.5 mm, the dispersion diagram can be sampled as follows, (1) Zeroth-order mode, m = 0 , β = 0, (2) the two first-order modes m = -1 and m = +1 at β = $+13.3^0$ and β = -13.3^0 respectively (3) the two second order-modes m = -2 and m = +2 at β = -26.6^0 and $\beta = +26.6^0$,(4) the two third order-modes m= *-3* and m= *+3* at $\beta = -40^0$ and $\beta = +40^0$ All the anticipated resonance frequencies are listed in Table-1. From the resonance frequencies of the metamaterial unit cell, unit cells in Figure-3 (a), 8 (a), 9 (a), and 10 (a) can be used for wireless application due to the resonances occurred at 2-5 GHz as it shown in table 2 while the cells in Figure-4(a), 5 (a), and 6 (a) cannot be used for wireless application based on their resonances occurred at 7-18GHz as it depicted in Table-2

CONCLUSIONS

Eight metamaterial unit cells are investigated using computer simulation technology (CST) microwave studio simulator. Based on their dispersion diagrams, it has been found that seven of them are left handed material while the other one is CRLH unit cell. It is recommended that unit cell 1, unit cell 6, unit cell 7 and unit cell 8 can be used for wireless applications while the unit cell 2, unit cell 3 and unit cell 4 cannot be used for wireless application purposes.

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