Design of Miniaturized Dominant Mode Leaky-Wave Antenna with Backfire-to-Endfire Scanning Capability by using Metamaterials

Dileep K. Upadhyay, Srikanta Pal

Abstract - **A new miniaturized dominant mode leaky-wave antenna is proposed. This antenna is a transmission line structure with radiating wavenumber increasing from negative to positive values, providing backward to forward scanning capability as frequency is increased. The antenna profile is designed based on microstrip technology using balanced composite right left handed transmission lines (CRLH TL) approach. The balanced CRLH TL is designed based on cascaded combination of inter digital capacitor (IDC) in series and vias to the ground plane at the bended stub ends in shunt. Bended stubs are used in each section for the purpose of miniaturization. Dispersion characteristics of CRLH TL shows the left handed region, right handed region and balanced design of composite right left handed metamaterial. The radiation pattern of the proposed antenna confirms the full scanability i.e. backfire-to-endfire scanning capability of the antenna. The characteristics and performances of the antenna are demonstrated by full-wave electromagnetic simulator based on method of moments and all characteristics and performances are verified by another full-wave electromagnetic simulator based on integrated equations.**

Keywords – **Left Handed Metamaterial, Composite Right Left Handed transmission Line, Dispersion curve, Leaky-Wave Antenna.**

I. INTRODUCTION

Unlike standard natural materials having positive values of permittivity and permeability, i.e., positive refractive index, metamaterials may exhibit both positive and negative values. Termed left-handed (LH) metamaterials, were first envisioned by Veselago in 1968 [1]. Metamaterials are called left-handed (LH) materials, according to the orientation of the vectors of the electric and magnetic field with a propagating vector of a traveling wave. The first experimental structure exhibiting backward-wave propagation characteristics, and therefore negative refractive index, was developed by Shelby et al in 2001 [2], using an array of split-ring resonators and thin wires. The unique properties (simultaneous negative values of the permittivity and permeability) of LHMs open huge opportunities for various applications [6]-[10].

Uniform transmission line leaky wave (TL-LW) antennas which are essentially travelling-wave frequency-scanning structures were discovered a few decades ago [3]-[4] and have been implemented in various designs. Owing to their high directivity and frequency scanning capability, LW antennas use a higher order mode with positive wave number ($\beta > 0$). As a consequence, they have the drawbacks of scanning only the half-space from broadside to endfire and requiring special feeding structures for suppression of dominant mode (DM).

Recently, a transmission line approach of LH materials was introduced and an artificial left- handed transmission line (LH-TL) with microstrip components including inter-digital capacitors and shorted stub inductors was proposed [5]-[6]. Such LH-TLs are essentially highpass filters with phase advance ($\beta < 0$), while conventional right-handed (RH) TLs and lowpass filters exhibit phase lag ($\beta > 0$). Combining structures with LH and RH contributions results in a composite RH-LH (CRLH) structure with LH and RH behaviours depending on frequency [6].

In this paper first design of LH metamaterial is done based on series interdigital capacitor (IDC) and shunt bended stubs for shunt inductor. Bended stubs are used in each section for the purpose of miniaturization as compared to straight stubs was used in [6, 9] without diminution of performances. Based on designed LH metamaterial a dominant mode leaky-wave antenna with backfire-to-endfire scanning capability is reported. Finally characteristics and performances of the antenna are demonstrated by full-wave electromagnetic simulator based on method of moments and all are verified by another full-wave electromagnetic simulator based on integrated equations.

II. FUNDAMENTALS

For a standard transmission line the series impedance is inductive and represents the stored energy of the magnetic field. The shunt admittance is capacitive and represents the stored energy of the electric field; such type of transmission line is known as right handed transmission line RH-TL. The propagation constant for a RH-TL with a unit-cell consisting of a series inductance (LR) and shunt capacitance (CR) is given

as $\beta_R(\omega) = -\omega\sqrt{L_R C_R})$, which yields phase velocity

$v_p = \left(\frac{\omega}{\beta}\right)$ equal to group velocity $v_g = \left(\frac{\partial\omega}{\partial\beta}\right)$ and it is

given as $-1/\sqrt{L_R C_R}$ [6,7,10], which shows that phase velocity is in same direction to that of group velocity[10]. In

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an artificial LH-TL with a unit-cell consisting of a series capacitance (C_L) and shunt induction (L_L) is presented [9].

propagation constant is $\beta_L(\omega) = -1/(\omega\sqrt{L_L C_L})$

and the phase velocity $v_p = -\omega^2 \sqrt{(L_L C_L)} < 0$

and group velocity $v_g = +\omega^2 \sqrt{(L_L C_L)} > 0$.

The equivalent material parameters $\varepsilon(\omega) = -1/(\omega^2 L_L)$ and $\mu(\omega) = -1/(\omega^2 C_L)$ are simultaneously negative [6, 9], and therefore the equivalent refraction index, $n = \sqrt{\mu\varepsilon}$ (where, ε and μ are permittivity and permeability respectively), is also negative, indicating the LH nature of this TL [9]. Such a guiding wave structure supports backward wave propagation from which backward leaky radiation may be obtained.

Owing to their distributed dispersion RF nature, the microstrip components of the structure proposed above necessarily have RH behaviour at higher frequencies. The structure therefore belongs to the more general category of CRLH TL structure. The propagation constant becomes

$$\beta_c = \beta_L(\omega) + \beta_R(\omega) = (\omega^2 - \omega_{0R}\omega_{0L})/\omega^2\omega_{0R}$$

where $\omega_{0R} = 1/\sqrt{(L_R C_R)}$ and $\omega_{0L} = 1/\sqrt{(L_L C_L)}$

(C_R and L_R are unit-cell capacitance and inductance for RH-TLs) [9]. The CRLH structure changes from LH (β<0) to RH (β>0) at the transition frequency $\omega_0 = \sqrt{(\omega_{0R}\omega_{0L})}$, where β=0 [6, 9]. Fig. 1 shows the working principle of this DM-LW antenna. In region where $-k_0 < \beta < 0$ (k_0 is the free space wavenumber), the CRLH structure radiates backward as shown in Fig. 1a and in the region $0 < \beta < k_0$, it radiates forward as shown in Fig. 1b, respectively. The radiation angle is $\theta = a\cos(\beta/k_0)$ with respect to axis z. with frequency increases, β increases from negative to positive values and thus the LW-antenna operated in dominant mode can scan the whole space from backfire to endfire [9].

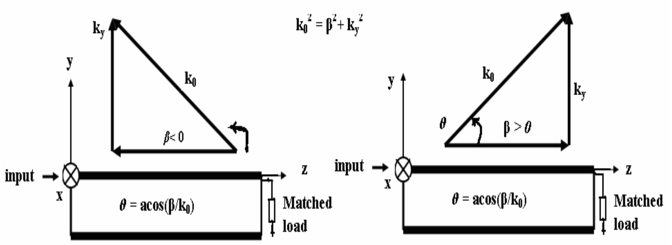


Fig. 1.(a): LH-backward radiation $-k_0 < \beta < 0$, (b): RH-forward radiation $0 < \beta < k_0$

III. Design of Balanced CRLH Metamaterial

The CRLH unit-cell used for realizing the leaky-wave antenna is shown in Fig. 3, and Fig. 2 shows levelling of all dimensions of Proposed one dimensional CRLH. This unit-cell is based on microstrip technology; the LH series capacitance (C_L) is provided by the interdigital capacitor, while the LH shunt inductance (L_L) is provided by the shorted bended stub. The bended stub is used to minimize the size of the conventional CRLH unit-cell based on shorted straight stub [6, 9]. The use of bended stub also enhances the performance of CRLH in terms of return loss and insertion loss. The RH series inductance (L_R) and shunt capacitance (C_R) are provided by the current and voltage gradient across the interdigital capacitor, respectively. The CRLH unit-cell of Fig. 3 is suited for applications that require a balanced unit-cell due to the following reasons: (1) Ability to achieve large or small values of series capacitance by adjusting interdigital capacitor (i.e. number of fingers pairs, width/length of fingers and spacing between fingers). (2) Shunt inductance can also be varied over a wide range.

For the unbalance and balance CRLH the transition frequency is given as [6]

$$\omega_0 \overset{\text{unbalanced}}{=} 1/\sqrt[4]{L_R C_R L_L C_L} \overset{\text{balanced}}{=} 1/\sqrt{LC}$$

Three unit-cell and five unit-cell CRLH metamaterials are realized by both, full-wave electromagnetic simulator based on method of moments and integrated equations using the substrate RT/Duroid 5880 with a relative dielectric constant $\varepsilon_r = 2.2$ and thickness $h = 1.57mm$ as shown in Fig. 5 and Fig. 6. The intet-digital capacitor for a unit cell includes 10 fingers each of which has Unit-cell period (p) 12.3 mm, Stub length 1 (ls1) of 7.0 mm, Stub length 2 (ls2) of 3.0 mm, Stub width (ws) of 1.00 mm, Interdigital finger length (lc) of 10.5 mm, Interdigital finger width (wc) of 0.30 mm, Spacing between fingers (S) are 0.20 mm and via radius (r) used in the stub is 0.12 mm. Two feed sections are required for the purpose of discontinuity/impedance matching, which have twice the capacitance value to that of interdigital capacitor used for the design of unit-cell CRLH metamaterial. Two edge ports are defined at the both ends of the structure by taking microstrip line of width 5mm which is corresponding to 50Ω impedance at the centre frequency of 2.5 GHz for the substrate RT/Duroid 5880.

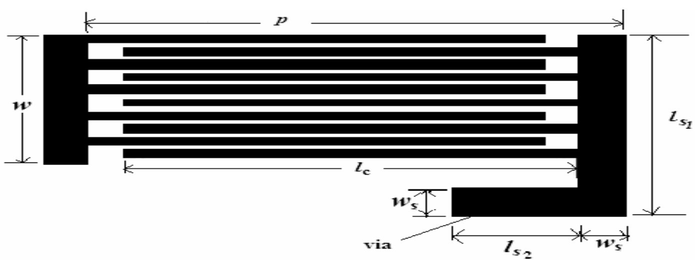


Fig. 2. Proposed one dimensional CRLH

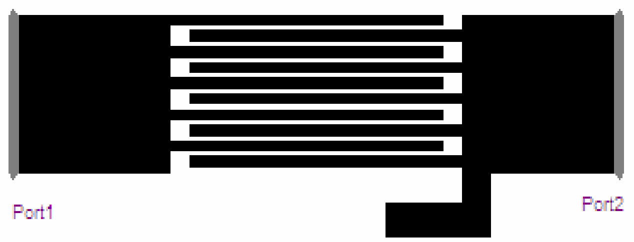


Fig.3. One-dimensional CRLH Unit cell unit cell with input and output

A dispersion diagram plots a structure's β versus frequency. Since three unit-cell and five unit-cell CRLH is a periodic structure, only the dispersion diagram for one unit-cell shown in Fig. 3 needs to characterize the entire structure. The dispersion diagram for a CRLH unit-cell is shown in Fig. 4, since series resonance and the shunt resonance are equal and no stop-band occurs between the transitions from LH to RH propagation, hence this is referred as balanced CRLH.

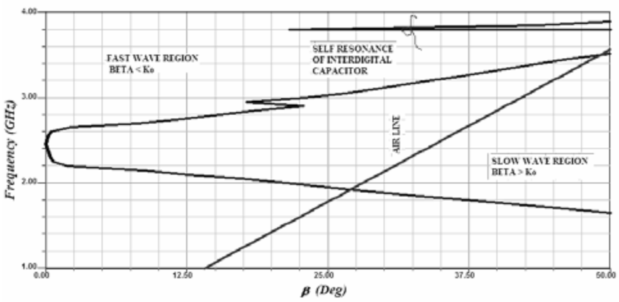


Fig. 4. Extracted dispersion diagram for the Proposed One-dimensional CRLH unit cell based on method of moment.

The resulted dispersion diagram shows that the predicted leaky wave frequency bands are backward leakage $1.90\,\text{GHz} < f_{LH} < 2.50\,\text{GHz}$, broadside leakage $f_0 = 2.50\,\text{GHz}$, and forward leakage $2.50\,\text{GHz} < f_{RH} < 3.50\,\text{GHz}$.

By using the same unit cell, three unit-cell and five unit-cell CRLH transmission line metamaterials are designed as shown in Fig. 5 and Fig. 6 respectively. The resulting return loss (S11) for three unit-cell and five unit-cell CRLH metamaterials, computed by using full -wave electromagnetic simulator based on method of moments and verified by full-wave electromagnetic simulator based on integrated equations are shown in Fig. 7 and Fig. 8 respectively, and corresponding insertion loss (S21) for three unit-cell and five unit-cell CRLH are shown in Fig. 9 and Fig. 10. From the plots it can be seen that, there are a good agreement in the results computed from method of moment and integrated equations also there is an improvement in return loss (S11) and insertion loss (S21) for five unit-cell CRLH metamaterial as compared to three unit-cell CRLH metamaterial.

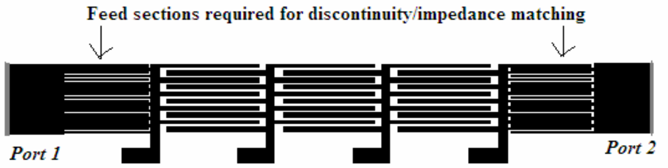


Fig. 5. Completed Three unit-cell CRLH transmission line metamaterial for the design of leaky wave antenna.

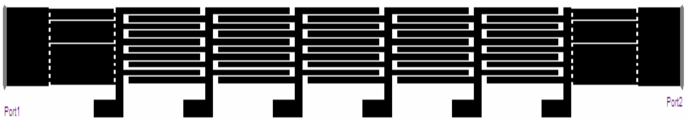


Fig. 6. Completed five unit-cell CRLH transmission line metamaterial for the design of leaky wave antenna.

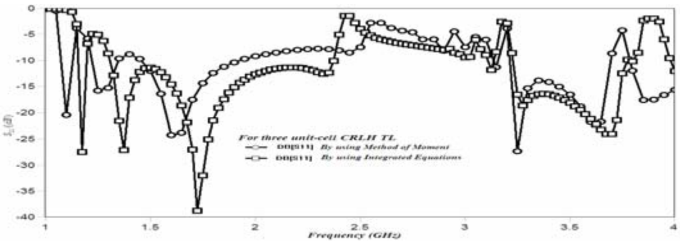


Fig. 7. Return loss S11 (dB) corresponding to three unit-cell CRLH metamaterials.

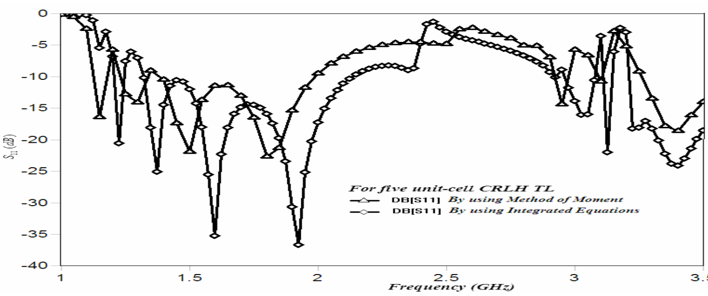


Fig. 8. Return loss S11 (dB) corresponding to five unit-cell CRLH metamaterials.

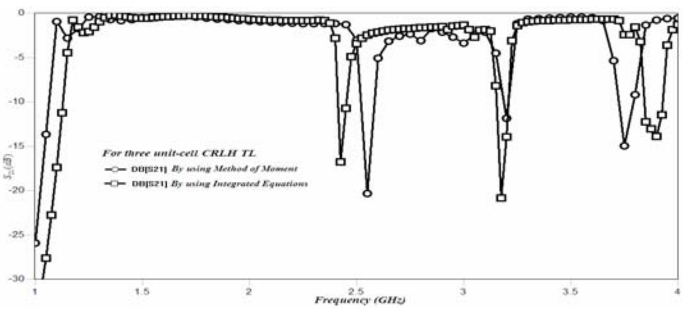


Fig. 9. Insertion loss S21 (dB) corresponding to three unit-cell CRLH metamaterials

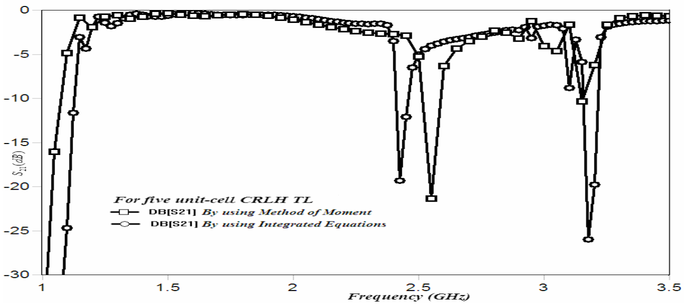


Fig. 10 Insertion loss S21 (dB) corresponding to five unit-cell CRLH metamaterials

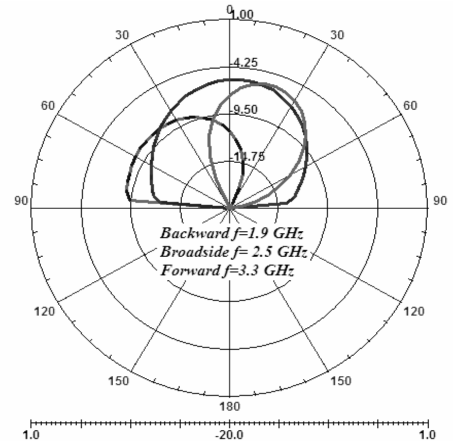
Table 1 shows comparative results of three unit-cell and five unit-cell CRLH TL by using method of moment and integrated equations. Since for both, three unit-cell and five unit-cell CRLH transmission line metamaterials the insertion loss is very less $(\cong -20dB)$ at stopband centre frequency f_0, and hence these can be used to design the backfire-to-endfire leaky-wave antenna by terminating port2 with 50Ω impedance matching microstrip line.

TABLE 1

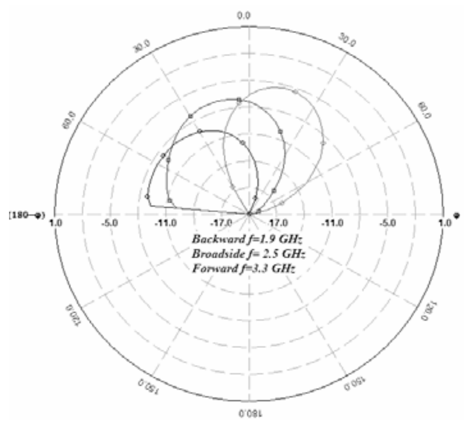
CRLH Metamaterials	Method of Moment			Integrated Equations		
	f_0, (GHz)	S_{11} (dB) at f_0	S_{21} (dB) at f_0	f_0, (GHz)	S_{11} (dB) at f_0	S_{21} (dB) at f_0
Three unit-cell	2.55	-2.777	-20.307	2.425	-1.465	-16.780
Five unit-cell	2.55	-2.449	-21.353	2.425	-1.677	-19.281

IV. ANTENNA DESIGN AND DESCRIPTION

The balanced CRLH TLs of Fig. 5 and Fig. 6 can be used as an efficient, frequency-scanned leaky-wave (LW) antenna when optimally matched to the air impedance. A CRLH LW antenna has two distinct advantages over conventional LW antennas. First, a CRLH LW antenna can operate at its fundamental mode, because this mode contains a radiation (or fast-wave) region ($|\beta| < k_0$ where k_0 is the free-space propagation constant) in addition to a guided (or slow-wave) region ($|\beta| > k_0$) as shown in Fig. 4. In contrast, RH structures have to be operated at higher order modes in order to radiate and, consequently, require a more complex and less-efficient feeding structure, because the fundamental mode of RH structures are always guided ($\beta > k_0$). Second, a CRLH LW antenna is capable of continuous scanning from backward (backfire) to forward (endfire) angles, unlike conventional LW antennas. As shown in Fig.1, 'θ' can take on values from -90° (backfire), 0° (broadside) to $+90^\circ$ (endfire). Referring to the dispersion diagram which is shown in Fig. 4 antenna is able to radiate backward (backfire) in the frequency region $1.90\,\text{GHz} < f_{LH} < 2.50\,\text{GHz}$ known as left handed (LH) region, broadside $f_0 = 2.50\,\text{GHz}$ because $v_g = 0$ at $\beta = 0$ for the balanced CRLH TL and forward (endfire) in the frequency region $2.50\,\text{GHz} < f_{RH} < 3.50\,\text{GHz}$ known as right handed (RH) region. In contrast, a conventional nonperiodic LW antenna can only scan from broadside to endfire, since β is always positive. In addition, a conventional nonperiodic LW antenna cannot radiate at broadside because $v_g = 0$ (standing wave) at $\beta = 0$ for a RH structure.



(a)



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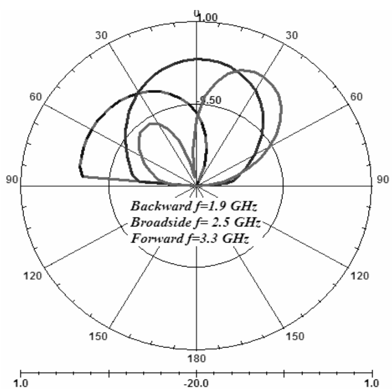

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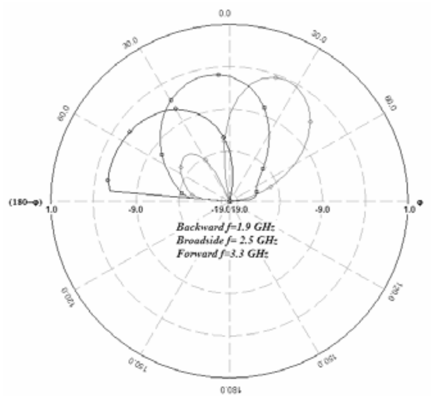
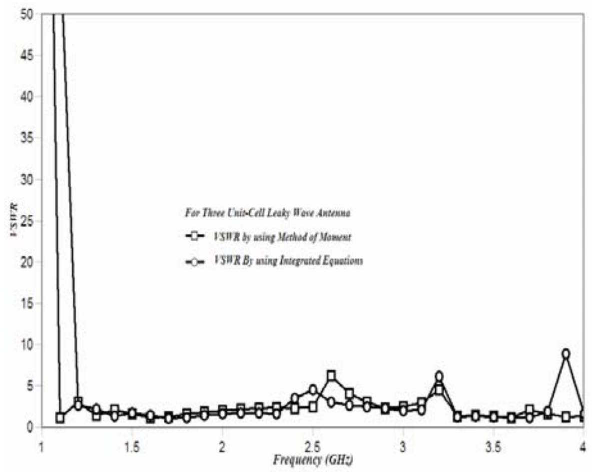
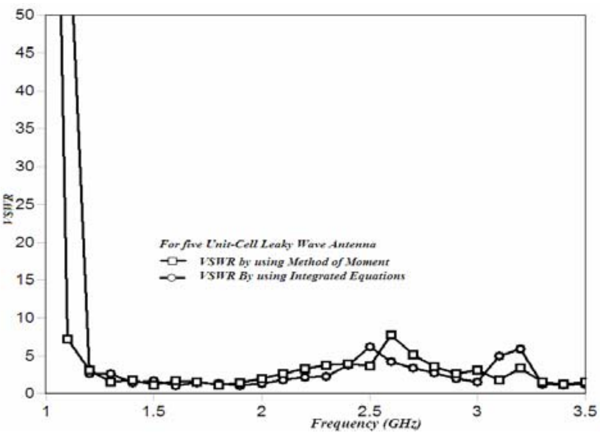


(d)

Fig. 11. (a) Radiation patterns of LW antenna for three unit-cell CRLH TL by method of moment, (b) Radiation patterns of LW antenna for three unit-cell CRLH TL by integrated equations, (c) Radiation patterns of LW antenna for five unit-cell CRLH TL by method of moment, (d) Radiation patterns of LW antenna for five unit-cell CRLH TL by integrated equations



(a)



(b)

Fig. 12. Comparative plot for VSWR of LW antenna for (a) three unit-cell CRLH TL by method of moment and Integrated equations (b) five unit-cell CRLH TL by method of moment and Integrated equations

To radiate efficiently, the TL of Fig. 5 and Fig. 6 are terminated with a matched load to eliminate reflections which would otherwise produce spurious beams. Continuous backfire-to-endfire scanning was achieved from 1.9 to 3.5 GHz. Simulated radiation patterns of LW antenna for three unit-cell CRLH TL and five unit-cell CRLH TL by method of moment and integrated equations demonstrating backward, broadside, and forward scanning are shown in Fig.11, which shows that as number of unit-cell increases in CRLH TL the gain of antenna increases. The plots of VSWR are given in Fig. 12 which shows the antenna performance.

V. Conclusion

In this article, the fundamental properties of LHMs were discussed. LHMs are designed based on the principles of microstrip transmission line. Based on the designed LHMs, a new miniaturized dominant mode leaky-wave antenna with backfire-to-endfire scanning capability is introduced. Compared to the conventional higher order mode LW antennas, this LW antenna is operated in the dominant mode and does not required any special feeding structure which therefore reduces the size of the antenna.

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