Scanning-Beam Antenna on Metamaterials Coplanar Structure for Wireless Applications

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ABSTRACT: A scanning-beam antenna on metamaterial coplanar structures is presented. The proposed antenna is, in essence, a composite of Right/Left-Handed (CRLH) coplanar waveguide (CPW) structure incorporating distributed periodic structures with L-C high-pass filter topology which support left-handed (LH) waves. The negative refractive index (NRI) properties of these structures are shown theoretically, numerically and validated by full-wave simulations. The supported LH wave is fully characterized and based on the composite right/left-handed transmission-line (CRLH-TL) theory; and the dispersion characteristics, refractive indexes and Bloch impedance are derived theoretically. In addition, formulas to extract equivalent-circuit parameters are given. Since the distance between adjacent cells of the array is small, $d \ll \lambda_0$ and the array becomes a uniform leaky-wave antenna (LWA) for a 10-cell operating near 10 GHz. Simulated radiation pattern, gain, and associated loss budget are presented. The results of LWA exhibit scanning-beam capability from backfire-to-endfire direction and accord well with the theoretical analysis. The antenna is printed on thin and flexible substrate ($h = 25 \, \mu m$). Furthermore, since the antenna is implemented with low-cost and CPW technology, it is a good candidate for integrated RF/microwave systems that can be used in digital wireless communications and radars.

Categories and Subject Descriptors
C.2.1 [Network Architecture and Design] Wireless communication
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1. Introduction

Over the past decade, Electromagnetic metamaterials have become an extremely active field of research in both wireless systems and engineering communities [1-6]. Since Oliner [7] first reported the leaky-wave structure, many microstrip LWA designs incorporating various modifications have been explored. Recently, Eleftheriads [8, 9], Caloz. [10, 11] have proposed a metamaterial-based backward radiating LWA on microstrip transmission line (TL).

This paper offers a fresh perspective on the operation of LH media that enables the modeling and the design of a scanning-beam antenna on CPW structure with negative refractive index. The main of this choice is explained by the advantages offered by CPW [12] over conventional microstrip line are: First, it reduces radiation loss; second, it facilitates easy shunt as well as series surface mounting of active and passive devices; third, it eliminates the need for wraparound and via holes, and fourth, it simplifies fabrication.

The proposed LWA is capable of continuously scanning the beam and contains 10-cell improved performance, such as wider scanning, high gain, and small unit cell (UC) size, and it offers several distinct advantages at X-band frequencies. The antenna is realized using flexible substrate material with dielectric constant $\varepsilon_r = 3.4$ and thickness $h = 25 \, \mu m$. The thin dielectric provides embedded planar capacitance capability, which represents one of the constituent elements of the CRLH antenna unit cell.

In addition, beamwidth can be changed, in general, by a phased array of antennas or by geometrical parameters [13, 14]. In this work, we present a new concept in which beamwidth is adjustable in a frequency change while keeping geometrical parameters unchanged and using a single antenna.

The obtained results show an improved type of a backfire-to-endfire LWA on coplanar structure. At low frequency ($f_l = 9 \, GHz$, $f_l < f_c$), this structure is LH (propagation constant $\beta < 0$) and therefore radiates backward. At high frequency ($f_h = 12 \, GHz$, $f_h > f_c$), it is RH ($\beta > 0$) and radiates forward. At the transition frequency ($f_{tr} = 10 \, GHz$, $\beta = 0$), it radiates broadside.

2. Circuit model of antenna unit cell

2.1 Approximation principle

In reality, a purely LH-Cell is unrealizable because the effect of the discrete periodic loading ($L_{dis}$-$C_{dis}$) of the host transmission-line medium (RH) cannot be neglected. Therefore, the topology of Figure 1(a) represents the most general form of a CRLH UC model to design a metamaterials structures with LH attributes, as shown in Figure 1(b). Practically, the length $\Delta u$ is less then $\lambda_0/5$ and the resulting structure is a high-pass filter mimicking the LH-TL in its pass-band.

We consider here only the lossless case, which can be straightforwardly extended to lossy case [15]; we consider also the balanced case that is defined by $L_{ur}C_{ur} = L_{ul}C_{ul}$ with the advantage of providing a more direct insight into the physical characteristics of the line.

The proposed artificial CRLH TL can be virtually realized in any technology. However, it can be artificially released in the form of a lumped-element distributed network. The CRLH TL is ideal in the sense that it transmits energy from dc to $\infty$, and does not exist in nature, particularly because of its LH range. One possibility consists in periodically repeating an electrically small lumped unit cell, shown in Fig. 1, into an artificial line.

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where \( \theta = kd \) and \( d \) is the period of the unit cell. In general, the effect of the discrete distributed elements of the host transmission-line medium cannot be neglected. In the full dispersion relation given by (3), it is clear that \( \beta \) can become periodically complex, choosing the circuit parameters as aforementioned, the dispersion diagram of (3), for a balanced case \((L_R C_L = L_C R_C,\ \text{represented by solid line})\) and unbalanced case \([15]\) \((L_R C_L \neq L_C R_C,\ \text{dashed line})\) LC-based, is depicted in Fig. 2.

Figure 2. Dispersion diagram for a balanced (solid) and unbalanced (dashed) 1-D CRLH TL

As shown, the LHM and RHM can be identified and the passbands are observed, separated by a finite stopband (indicated by the band-gap in the unbalanced case). The lowest cutoff frequency (Bragg) associated with this dispersion curve (indicated in Fig. 2 by \( f_{CL} \)) is approximately determined by (1) to be equal to 3.18 GHz. The CRLH circuit exhibits two eigen-frequencies that are expressed as follows:

\[
\begin{align*}
\hat{f}_{cL} &= \frac{1}{2\pi\sqrt{L_C C_L}} \\
\hat{f}_{cR} &= \frac{1}{2\pi\sqrt{L_R C_R}}
\end{align*}
\]

(4)

In this work, having the matching mode (balanced case), both frequencies in (4) are equal to 10 GHz and correspond to the resonant frequencies of the series resonant branch \( (L_R, C_L) \) and parallel antiresonant branch \( (L_C, C_R) \), respectively. Based on this mode, these branches cross at a unique point on the axis \( \beta = 0 \). This point corresponds to transition frequency \( f_{cT} \), equals 10 GHz. Whereas, if these frequencies are different, (or unbalanced case), a band-gap appears between the LHI and RH branches, limited by \( f_{c1} \) and \( f_{c2} \) as shown in dispersion diagram of Fig. 2.

2.2 Results for Antenna cells using lumped elements

The simulation results for LC-based CRLH TL, using the extracted parameters \((L_R = 1\ \text{nH}, C_R = 0.1\ \text{pF})\) and \((L_L = 2.5\ \text{nH}, C_L = 0.25\ \text{pF})\) in a ten-cell coplanar waveguide CRLH TL are shown in Fig. 3. The S-parameters results for different number of unit-cells \((N = 1, 3, 10)\) are depicted in Fig. 3(a,b). Consequently, according to the return loss \( (S_{11}) \) and insertion loss \( (S_{21}) \), the cutoff frequency \( f_{cT} \) of the resulting high-pass filter decreases when \( N \) increases. Excellent agreement can be observed, which shows that the circuit model with extract parameters (at \( f_{cT} = 10\ \text{GHz} \)) is accurate and can be potentially used in the more complicated problem of the antenna, which will be described in the following sections. Fig. 3(b) and equation (1) provide an exact approximation of cutoff frequency for \( N > 3 \). It can be seen that if the bandwidth is to be increased (toward lower frequencies), larger values of capacitance and inductance

\[
\cos(\beta d) = \cos(\theta) + \frac{\nu}{2} \cos^2 \left(\frac{\theta}{2}\right) + \frac{1}{2} \left(\frac{\nu}{\eta} + \frac{\eta}{\nu}\right) \sin(\theta)
\]

(3)
are required due to the larger number of unit-cells to keep the characteristics of the CRLH transmission line unchanged.

An apparent paradox of the LHMs is that its guided wavelength $\lambda_g$ is frequency dependent, whereas in a RH-TL, $\lambda_g = \frac{2\pi}{\beta}$. The frequency dependence (1) of $\lambda_g$ is clearly seen in the distribution of peaks of $S_{11}$, which become more and more distant when $\omega$ increases, the highest frequency peak corresponding to an electrical length of the line of $\delta_e = \frac{\lambda_g}{4}$. Fig. 3(c) shows the phase of the $S$-parameters in the LHMs is

$$\lambda_{g,\text{LHM}}(\omega) = \frac{2\pi}{\omega} = \frac{2\pi\omega}{\sqrt{L_C C_L}} < \omega$$

The frequency dependence (1) of $\lambda_{g,\text{LHM}}(\omega)$ is clearly seen in the distribution of peaks of $S_{11}$, which become more and more distant when $\omega$ increases, the highest frequency peak corresponding to an electrical length of the line of $\delta_e = \frac{\lambda_g}{4}$. Fig. 3(c) shows the phase of the $S$-parameters in the ideal CRLH transmission line. The phase $\varphi[S_{21}] = 0$ as $\omega \rightarrow \infty$ (at open circuit), and it progressively accumulates as frequency decreases so that eventually at $\varphi[S_{21}] = \infty$ as $\omega \rightarrow 0$, as it can be revealed by unwrapping the phase curve. Finally, Fig. 3(d) demonstrates the dispersion diagram obtained by the unwrapped phase of $S_{21}$ as follows:

$$\beta_d = -\varphi[S_{21}]$$

The dispersion curves of the ideal LH unit cell with lumped elements can also be seen to be in excellent agreement with the theoretical curve (3) of the fictitious line (Fig.3), specifically at the transition frequency $f_0 = 10$ GHz.

3. Antenna Implementation Using Cpw

3.1 Antenna unit cell design

In general, distributed-element implementations, with nondispersive L/C components, will naturally provide the best results. Any physical implementation of these structures at RF/microwave frequencies must be a periodic one and must, therefore, possess a certain infinitesimal size. However, the needed dimensionality perturbs slightly the homogeneity of the distributed system. In this work, we consider a practical planar design that periodically loads a host CPW network with discrete reactive elements. Every CPW unit cell (CPW-LH) can generate the required inductances ($L_R$ and $L_L$) and capacitances ($C_R$ and $C_L$). The motivation of this choice is twofold: first, coplanar waveguide does not need via-hole; second, a distributed structure such as a CPW topology will potentially provide better performances at high frequencies. The proposed CPW LH unit cell of antenna consists of a capacitor obtained using a gap on the CPW center conductor and symmetrical shorted-stub meander inductances as shown in Fig. 4. The component capacitance/inductance used is strongly dispersive, which will necessarily introduce some discrepancy with respect to the ideal case.
3.2 Antenna unit cell results

The dimensions of the unit cell are given to fabricate the designed antenna at 10 GHz, on 25 µm substrate of ε_r = 3.4. The commercial method of moments software ADS (Advanced Design System) has been used in designing the prototype of the UC. To obtain the characteristically desired values of the LHM (L_L = 2.5 nH and C_L = 0.25 pF), gaps in the CPW center conductor (feed line, RFIN) with bottom metal plaques are served as series capacitors; and to keep the symmetry of the coplanar structure, two short meander inductors are used as shown in Fig. 4.

The antenna unit cell is optimized, at the transition frequency f_0 = 10 GHz, to provide low insertion loss (S21 < 5 dB) which is still reasonable in comparison with the huge losses (S21 < 30 dB) reported in [16]. Fig. 5(a) and 5(b) show UC performances, obtained by full-wave simulation, such as return loss and insertion loss. Very good agreement can be observed with the L-C circuit model, from dc to 20 GHz. This agreement has been also verified for phase where ϕ(S11, S21) changes the sign at f_0 = 10 GHz, as shown in Fig. 5(b).

3.3 Antenna implementation and results

A 10-UC of Fig. 4 is used to realize the desired antenna as shown in Fig. 7. A realizable antenna structure would, however, include small CPW-length between adjacent series capacitors and shunt inductors. The proposed antenna is designed using flexible substrate material, Kapton-E, a registered trademark of El Dupont de Nemours and Company.

Fig. 6 shows the dispersion curve obtained by full-wave simulation with the extracted circuit parameters (L_R = 1 nH, C_R = 0.1 pF, L_L = 2.5 nH and C_L = 0.25 pF). Depending on the operating frequency, the CRLH leaky-wave antenna exhibits left-handed or right-handed behavior.
dielectric provides embedded planar capacitance capability, which represents one of the constituent elements of the CRLH metamaterials antenna unit cells. The LH capacitance/inductance are $C_L = 0.25 \text{ pF}$ and $L_L = 2.5 \text{ nH}$, which yields the cutoff frequency $f_{CL} = 3.18 \text{ GHz}$. The length of the unit cell is $2.7 \text{ mm}$, the unit cell repeated periodically and the length of the entire antenna is around $27 \text{ mm}$.

The electromagnetic field, over each unit cell of the antenna, has been explored by ADS simulator. It is in fact the capacitive gaps that radiate in this structure while the inductive meander lines are non-radiating due to the anti-parallel currents flowing on each pair of inductive meander lines. This odd symmetry causes cancellation in the far-field and to low cross-polarization levels.

It is demonstrated that CRLH structure is applicable to a frequency-dependent backfire-to-endfire leaky-wave antenna. Fig. 8 shows the measured radiation pattern of the proposed antenna. The obtained results show an improved type of a backfire-to-endfire LWA on coplanar structure.

At low frequency ($f_{CL} = 9 \text{ GHz}$, $f_{CL} < f < f_0$), this structure is LH ($\beta < 0$) and therefore radiates backward. At high frequency ($f_{CR} = 12 \text{ GHz}$, $f_0 < f < f_{CR}$), it is RH ($\beta > 0$) and radiates forward. At the transition frequency ($f_t = 10 \text{ GHz}$, $\beta = 0$), it radiates broadside as virtually depicted in Fig. 9. Excellent agreement can be observed between measurement and theoretical predictions based on dispersion diagram approach. Finally, a flow design of proposed structure is shown in Fig. 10. These processes can be generalized to design other microwave devices using CRLH metamaterials.

![Figure 7. Prototype view of the proposed scanning-beam antenna with electromagnetic field distribution along each cell. The E-field polarization is along the z-direction](image)

![Figure 8. Radiation patterns of the backfire-to-endfire CRLH LWA at 9 GHz, 10 GHz, and 12 GHz](image)

![Figure 9. A backfire-to-endfire scanning-beam operation, where $f_{CL}$, $f_0$, and $f_{CR}$ are equal to 9 GHz, 10 GHz, and 12 GHz, respectively](image)

![Figure 10. Flow design of the proposed antenna](image)
4. Conclusion

A technique has been demonstrated for implementing novel electronically-controlled scanning-beam antenna on metamaterial coplanar structures. A CRLH transmission-line model has been introduced and discussed in detail to understand the operation of the new scanning-beam antenna and facilitate its design. Based on this model and refinements through method of moments electromagnetic simulations, the proposed CRLH leaky-wave antenna has been characterized and designed at 10 GHz, with CPW configuration on a thin and flexible substrate which exhibits all functions and performances superior to the prior state of the art. The equations to extract the equivalent-circuit parameters $L_p$, $C_p$, $L_i$, $C_i$, and cutoff-frequencies from the dispersion characteristics and Bloch impedance have been successively provided and validated by full-wave simulation. It has been confirmed that with ideal components, left-handedness can be achieved without losses over an unlimited bandwidth, starting from the cutoff of the resulting high-pass filter and extending to infinity. It has also been shown that an excellent agreement with the theoretical $\omega - \beta$ diagram is obtained. The characterization of the antenna unit cell has been carried out based on the CRLH-circuit theory which has been successfully obtained by full-wave simulation with a good level of accuracy.

Finally, the entire antenna implementation, which supports backward-wave using series capacitors and short stub-inductors without needing the via-holes, has been clearly investigated. It has been demonstrated that the capacitive gaps represent the radiated elements while the inductive meander lines are non-radiating due to the anti-parallel currents flowing on each pair of inductive meander lines. A scanning-beam from backfire-to-endfire direction has been successfully obtained. A technique has been demonstrated for implementing microstrip arrays using diodes, Proc. IEEE AP-S Int. Symp. Dig., In: IEEE Antennas and Wireless Propagat. Lett., 14 (4,) 183-185.


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