Dispersion Engineered Metamaterial-Based Conformal Leaky-Wave Antennas

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Abstract — In this paper, novel dispersion engineered conformal metamaterial-based leaky-wave antennas (LWA) based on composite right/left-handed (CRLH) concept are being reviewed. As a planar CRLH LWA is conformed on a curved surface, the radiation characteristics of LWA is distorted. The effect of conformation on a CRLH LWA is investigated. A dispersion engineering method is presented to compensate for the conformation effect and obtain radiation characteristics comparable to the planar version for both convex and concave surfaces. Using the dispersion engineering technique an electronically controlled multifunctional CRLH transmission-line (TL)/LWA will be presented. The slow-wave and fast-wave characteristics of this CRLH device is electronically controlled by incorporating varactor diodes in the CRLH unit-cells. It will be shown that by using the developed dispersion engineering compensation technique along with applying the proper reverse-bias voltage to the varactor diodes of each unit-cells and tuning the capacitance of each unit-cell the effect of conformation is compensated. Furthermore, it will be shown that by having certain section of the CLRH device operating in the slow-wave mode and the remaining sections in the fast-wave mode, through applying the proper reverse-bias voltage to the varactor diodes, and by changing the location of the fast-wave section along the device a radiation aperture selective functionality is introduced. Thus, the radiation angle and the beamwidth of the LWA is electronically controlled at a fixed frequency.

Index Terms — Composite right/left-handed (CRLH), metamaterials, conformal antenna, electronically controlled, leaky-wave (LW).

I. INTRODUCTION

The concept of engineered artificial left-handed (LH) materials or negative refractive index materials, known to us today as Metamaterials, was initially speculated by Veselago in 1968 [1]. In his speculation Veselago theoretically showed that in order for such LH material to exist it must have simultaneous negative permittivity ($\varepsilon$) and negative permeability ($\mu$). Hence, electric field, magnetic and direction of wavevector will form a LH triad. Three decades later a group of researchers from UC San Diego led by D. R. Smith for the first time experimentally demonstrated metamaterial proof of concept [2]. In this demonstration D. R. Smith and his group used split ring resonators backed with thin metallic rods in a periodic arrangement to realized engineered artificial homogenous materials with simultaneous $-\mu$ and $-\varepsilon$. Ever since metamaterials and metasurfaces have been of great scientific interest and thus, subject of many studies in microwave [2]–[10], terahertz [11]–[20], and optical [21]–[30] spectral regions. This is due to their unprecedented characteristics and more importantly the fact that their spectral response can be controlled by their geometry and it is not limited by the characteristics of naturally existing materials.

One effective approach to realize metamaterials is through the use of resonant type of structures such as split ring resonators. However as a result of the resonant nature of these metamaterials, they are highly dispersive and somewhat lossy and they have narrow bandwidth. In contrary, transmission-line (TL) approach has been used to develop TL-based metamaterials known as composite right/left-handed (CRLH) metamaterials [31]. Unlike the conventional TL that can only support right handed (RH) slow-waves (guided-waves) under fundamental mode of operation, the CRLH TL has the ability to support both LH and RH slow-waves (SW) and fast-waves (FW, radiated-waves or leaky-waves) while operating in its fundamental mode. When a CRLH TL operates in the FW mode, it effectively behaves as a leaky-wave antenna (LWA) as the energy propagates along the structure [32]–[37]. In contrast to the conventional LWAs that only have the ability to support backward or forward radiation excluding broadside direction, the CRLH LWA has the ability to support backward, forward, and broadside radiation, while operating in the fundamental mode. Thus, the CRLH LWA has a very simple feeding mechanism, it has the ability for phase advance/delay, and it can perform continuous frequency beam scanning from back-fire to end-fire by sweeping the operation frequency. These features along with offering a high radiation gain, being low profile and very directive make a CRLH LWA an attractive candidate for conformal surface applications such as wearable device or to be mounted on curved and aerodynamic objects for radar and imaging application.

In this paper novel conformal CRLH LWAs are discussed. As a planar CRLH LWA is conformed on a curved surface the radiation characteristics of LWA is significantly affected. The effect of conformation on a CRLH LWA antenna is discussed in the paper. A dispersion engineering method is presented to compensate for the conformation effect and obtain radiation characteristics comparable to the planar version for both convex and concave surfaces. Using the dispersion engineering technique an electronically controlled multifunctional CRLH LWA is also demonstrated. The SW and FW characteristics of this CRLH device is electronically controlled by incorporating
varactor diodes in the CRLH unit-cells. It will be shown that by using the developed dispersion engineering compensation technique along with applying the proper reverse-bias voltage to the varactor diodes of each unit-cells, hence tuning the capacitance of each unit-cell, the effect of conformation is compensated. Furthermore, it will be shown that by having certain section of the CLRH device operating in the SW mode and the remaining sections in the FW mode through applying the proper reverse-bias voltage to the varactor diodes, and by changing the location of the FW section along the device a radiation aperture selective functionality is introduced. Thus, the radiation angle and the beamwidth of the LWA of the devices is electronically controlled at a fixed frequency.

II. CRLH METAMATERIAL CONCEPT

The conventional TL can be model as a combination of a per unit length series inductor (\(L_R\)) and a per unit length shunt capacitor (\(C_R\)). On the other hand, a CRLH unit-cell is obtained by modifying this model by adding a series capacitor per unit length (\(C_L\)) and shunt inductor per unit length (\(L_L\)), as shown in Fig. 1(a). This equivalent circuit model can be then realized using microstrip implementation by using interdigital capacitors to realize \(C_L\) and shorted stub inductor for \(L_L\). The CRLH TL can be considered as a periodic structure which is obtained by cascading unit-cells with the discussed equivalent circuit model. The best way to understand and predict the behavior of the CRLH TL is through the use of dispersion diagram. To obtain the dispersion diagram, the propagation constant, \(\beta\), is calculated using the series impedance \(Z(\omega)\) and the shunt admittance \(Y(\omega)\) of the unit-cell as shown in (1). Where \(p\) is the period of the unit-cell, \(\omega\) is the angular frequency, and \(Z(\omega)\) and \(Y(\omega)\) are given by (2) and (3). A typical dispersion diagram of a CRLH unit-cell is shown in Fig. 1(b). The dispersion diagram of a CRLH unit-cell consists of two nonlinear branches: a LH branched where the group velocity (\(v_g = d\omega/d\beta\)) and phase velocity (\(v_p = \omega/\beta\)) are antiparallel (\(v_g \cdot v_p < 0\)) and a RH branch where the two velocities are parallel (\(v_g \cdot v_p > 0\)). In general these two branches are discontinued (\(\omega_{se} \neq \omega_{sh}\), \(\omega_0\) is called transition frequency) a
so-called balanced unit-cell is obtained which is shown by the red dashed curve in Fig 1(b).

In contrast to the conventional TL that only supports guided-wave under its fundamental mode of operation, the CRLH TL can support both guided-wave and radiating-wave while operating in its fundamental mode. Moreover, unlike the conventional LWA, that only supports backward or forward radiation excluding the broadside direction, the CRLH LWA can radiate in both the backward and forward direction and perform frequency beam scanning from back-fire to end-fire including broadside direction. If the operational frequency is located in LH SW region, regions (I), or RH SW region, regions (IV) of the dispersion diagram, as shown in Fig. 1(b), the wave is guided along the structure with a phase advance or phase delay, respectively. Instead if the operational frequency is located in LH FW region, region (II), or RH FW region, region (III), of the dispersion diagram, then leakage and radiation occurs in the backward or forward direction, respectively.

Broadside radiation can be achieved at a frequency corresponding to $\beta = 0$.

A CRLH LWA can be considered as a traveling wave phased array antenna with exponentially decaying excitation. In this case by using array factor approach shown in (4) the behavior of the CRLH LWA can be predicted. Furthermore, the radiation angle, $\theta_0$, of the structure is a function of propagation constant, $\beta$, and can be calculated from (7) for the zeroth order space harmonic index,

$$\vec{E} = \sum_{n=1}^{N} f_n(\theta, \phi) I_n \exp(jk_0(\vec{r} - \vec{r}_n) + j\zeta_n), \quad (4)$$

where $f_n(\theta, \phi)$ is the element pattern of the $n$-th unit-cell, and parameters $\zeta_n$ and $I_n$ are the phase and magnitude excitation functions which are given by (5) and (6), respectively. Parameter $k_0$ is the free space wavenumber, $N$ corresponds to the number of unit-cells in the structure, and at last, $\vec{r}$ and $\vec{r}_n$
I_n = I_0 \epsilon^{-\alpha(n-1)p}, \quad (5)
\xi_n = -(n-1)k_0p \sin \theta_0, \quad (6)
\theta_0(\omega) = \sin^{-1}\left((\beta(\omega))/k_0\right) \quad (7)
\hat{r} = \hat{x} \sin \theta \cos \phi + \hat{y} \sin \theta \sin \phi + \hat{z} \cos \theta, \quad (8)
\hat{r}_n = x_n \hat{x} + y_n \hat{y} + z_n \hat{z}, \quad (9)

III. DISPERSION ENGINEERING COMPENSATION TECHNIQUE

As mentioned, in the case of conventional transmission-lines the fundamental mode is in the SW region. In such structures, conformation will result in a negligible change in feeding, characteristic impedance, and reflection and transmission of the guided wave, as long as conformation does not damage the substrate and metallic traces [39]. This insignificant performance degradation can be seen by investigating the scattering parameters. Similar to the conventional TL when the CRLH TL is conformed it will experience insignificant performance change when operated in the SW region [39]. However this is not valid when the CRLH TL operates in the FW region. In the FW region as the wave propagates along the TL it starts to leak and radiate, thus the CRLH TL behaves as a CRLH LWA. When the CRLH LWA is conformed, the guided portion of the wave will have similar performance as to the...
planar version in terms of scattering parameters. But the resulting leaky-wave radiation characteristics such as pattern shape, beamwidth and directivity are significantly affected [39]. The change in the radiation characteristics is dependent on the amount of curvature. The amount of curvature that a CRLH LWA can tolerate depends on its physical length and its substrate.

The effects caused by bending a CRLH LWA are due to the fact that the unit-cells (radiating elements) no longer radiate in the same direction and their contribution will not add up in phase in the far-field, which degrades the antenna performance. Dispersion engineering technique can be used to solve this problem by taking advantage of the RH and LH nature of CRLH structures and the ability to operate in the RH and LH FW regions. The conformal LWA can be divided into multiple, identical sections with negligible curvature and similar Bloch impedances [31]. By obtaining the radiation pattern of each section using the array factor approach given in (4) and calculating the $\beta$-value corresponding to the rotation angle of the radiation pattern of each section we can modify the unit-cells in that section to compensate for its rotation. For example, if it is desired to have a broadside radiation for the conformal CRLH LWA, similar to its planar version, then the unit-cells in the sections that are radiating in the backward or negative direction are modified to operate in their RH FW region such that they are calibrated to radiate toward broadside direction. Similarly, the unit-cells of the sections that are radiating towards forward or positive direction are modified to operate in their LH FW region to radiate towards broadside direction. By applying this technique, the radiated beam gets refocused and recovered, the overall beamwidth becomes narrower, and the directivity increases. Thus the conformal antenna will have comparable performance as to its planar version. The proposed dispersion engineering procedure is illustrated in Fig. 2 [39].

IV. CONVEX CRLH LEAKY-WAVE ANTENNA [39]

A. Geometrical Layout

As a proof of concept a 25 unit-cell planar CRLH LWA is fabricated and conformed on a cylinder with a radius of 20.0 cm as shown in Fig 3(a). The CRLH LWA is fabricated on a Rogers RT/Duroid 5870 substrate with a dielectric constant $\varepsilon_r = 2.33$ and thickness of $h = 0.7874$ mm. Each unit-cell consists of five pairs of interdigital capacitors which are connected to a shorted stub inductor. The length and width of each interdigital capacitor finger is 6.3 mm and 0.15 mm, respectively. The gap between the fingers is 0.1 mm. The stub inductor is 8.0 mm by 1.0 mm in size, the ground via has a radius of 0.12 mm and the unit-cell period is 7.4 mm. Configuration of the designed unit-cell is shown in Fig. 3(b).

The dispersion diagram and the Bloch impedance of the designed unit-cell are shown in Fig. 4(a) and 4(b), respectively. From the dispersion diagram in Fig. 4(a) it is apparent that the designed unit-cell is balanced and has a transition frequency $f_0 = 3.67$ GHz. This CRLH structure is operating in a LH mode in the frequency region below 3.67 GHz, while at frequency region above 3.67 GHz it is operating in a RH mode. In addition, it operates in the LH SW mode in the frequency range 1.56 GHz $< f < 2.99$ GHz. Similarly the structure operates in the
RH SW mode in the frequency range above 5.6 GHz. In contrast, the CRLH structure is operating in a LH FW mode in the frequency range 2.99 GHz < f < 3.67 GHz, and it operates in RH FW mode in the frequency range of 3.67 GHz < f < 5.6 GHz. Also the designed unit-cell has an average Bloch impedance of 42 Ω. The jumps observed in the Bloch impedance curves are due to the resonant frequency of the interdigital capacitors. Furthermore, the negative sign associated with the resistance part of the Bloch impedance is to indicate that the corresponding resistance value belongs to the LH operating mode. However, the actual resistance value is the absolute value of which is being read from the figure. We focus our attention mainly on the frequency range of 2.99 GHz < f < 5.6 GHz, which corresponds to the FW region of this CRLH structure which behaves as LWA.

B. Comparison Between Uniform Planar and Uniform Convex CRLH LWA

In order to investigate the effect of conformation on the presented CRLH LWA, three frequencies are chosen in the FW
regions and radiation patterns are obtained for these frequencies. The selected frequencies are 3.4 GHz (in LH region, $\beta < 0$), 3.7 GHz (near the transition frequency, $\beta \approx 0$), and 4.3 GHz (in the RH region, $\beta > 0$). The radiation pattern of these frequencies are shown in Fig. 5. These patterns confirm that both the planar and conformal CRLH LWA can achieve beam scanning. By sweeping the frequency from 3.4 GHz to 3.7 GHz to 4.3 GHz the main radiation beam is scanned from -22° to ~0° to 26° for both planar and uniform convex CRLH LWA. However, as can be seen from Fig. 5, by bending the CRLH LWA, the resulting radiation patterns are affected and the main beamwidth of the conformal antenna (red color curve) has become wider and the sidelobe levels have increased comparable to the planar antenna (blue color curve).

C. Modified Convex CRLH LWA

In order to compensate for the discussed conformation effect, the 25 unit-cell convex CRLH LWA was subdivide into three sections. Section 1, which is the left section, consists of eight unit-cells and radiates toward negative direction. Section 2, which is the middle section, consists of nine unit-cells and radiates toward broadside. Finally, section 3, which is the right section, radiates toward positive direction and consists of eight unit-cells. Next, the array factor approach was used to determine the radiation angle, $\theta_0$, of each individual section. The obtained radiation angle for section 1, 2 and 3 were -23.4°, -7.2°, and 29.6°, respectively. Next - $\theta_0$ value was used in (7) to obtain the $\beta$-value for each section that would correct the radiation angle for the corresponding section towards the desired angle, which for the proof of concept we have chosen to be broadside direction at $f = 3.7$ GHz. This is achieved by modifying the unit-cells in section 1 to operate in their RH region, and the unit-cells in section 3 to operate in their LH region, at 3.7 GHz. The calculated $\beta$-values are 30.28 rad/m, 9.44 rad/m and -38.74 rad/m for section 1, 2 and 3, respectively.

To achieve these $\beta$-values, the unit-cells for each section were modified independently. The modification for the unit-cells in section 1 was done by adding extra four pairs of interdigital capacitors to the original unit-cell; therefore, the section 1 modified unit-cell includes nine pairs of interdigital capacitors. This modification causes the transition frequency, $f_0$, to be shifted down on the frequency axis such that $f = 3.7$ GHz lies in the RH region of the modified unit-cell. For section 2 very small modification is applied by adding an extra pair of interdigital capacitors to the original unit-cell resulting in six pairs of interdigital capacitors. Finally, the original unit-cells in section 3 were modified by reducing the number of interdigital capacitor figures, from five pairs to three pairs, and also reducing the stub inductor length form 8.0 mm to 7.0 mm. As a result of this modification, the dispersion curve is shifted up on the frequency axis, thus $f = 3.7$ GHz will be placed in the LH region of the modified unit-cell. The Bloch impedance of the modified unit-cells for section 1, 2 and 3 are 26.63 $\Omega$, 36.6 $\Omega$, and 42.75 $\Omega$, respectively. To avoid mismatch at the feeding end a quarter-wave transformer was employed. The schematic diagram of the modified unit-cells and their dispersion diagrams are shown in Fig. 6.

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Fig. 13. Electronically control CRLH unit-cell: (a) equivalent circuit model, (b) schematic of the microstrip implementation, and (c) dispersion diagram. From [38] © IEEE.
The modified 25 unit-cell convex CRLH LWA was fabricated and Fig. 7 shows the image of the fabricated modified convex LWA. The radiation patterns of the modified convex LWA were measured at 3.4 GHz, 3.7 GHz and 4.3 GHz and the resulting radiation patterns are shown in Fig. 5 by the green color curves. As expected, all unit-cells perform broadside radiation at $f = 3.7$ GHz, which yield broadside radiation of all three sections. As a result, the main radiated beam is refocused and recovered, hence comparable results to the planar version are obtained. As it can be seen in Fig. 5, the modified CRLH LWA can also perform frequency beam scanning in the frequency range close to $f = 3.7$ GHz but not far from the designed frequency as the dispersion diagram of the unit-cells in the three section will start deviating from each other significantly.

V. CONCAVE CRLH LEAKY-WAVE ANTENNA [40], [41]

A. Comparison Between Uniform Planar and Uniform Concave CRLH LWA

In this section we investigate the effect of conforming a CRLH LWA on a concave surface. Furthermore, by using the developed dispersion engineering technique, the structure is modified such that it can produce comparable radiation characteristics to the planar version by refocusing the main radiation beam. For this reason the uniform 25 unit-cell planar CRLH LWA that was discussed in section IV-A is chosen and mounted to the inside of a cylindrical object with a radius of 20 cm to obtain a concave CRLH LWA with a curvature radius of 20 cm. The obtained uniform 25 unit-cell concave CRLH LWA is shown in Fig. 8.

In order to investigate the effect of conforming the uniform 25 unit-cell planar CRLH LWA on the concave surface radiation pattern for three chosen frequencies are measured. The chosen frequency are 3.4 GHz ($\beta < 0$), 3.7 GHz ($\beta \approx 0$), and 4.3 GHz ($\beta > 0$) which are the same frequencies what were chosen in the case of convex CRLH LWA. The measured radiation patterns for the uniform concave CRLH LWA and the planar version are shown in Fig. 9 by red and blue color curves, respectively. These radiation patterns confirm that both the uniform planar and the uniform concave CRLH LWA can achieve frequency beam scanning from backward to forward direction. However, by bending the CRLH LWA, the resulting radiation pattern is affected and the radiation beamwidth increases similar to the convex case [40]. In order to compare the effect of conforming the uniform planar CRLH LWA to a concave surface to that of a convex surface the measured radiation patterns of the uniform concave and the convex CRLH LWA are plotted in Fig. 9 for the three chosen frequencies. As suspected conforming the planar CRLH LWA
to a convex surface will result in more severe changes in the radiation characteristics, more specifically radiation beamwidth, compared to concave surface conformation [40]. This is due to the fact that, unlike the convex case, in the concave case, the unit-cells radiate inward toward the inside of the curved surface, hence, the radiation patterns will converge at some point in near-field and then diverge.

B. Modified Concave CRLH LWA

In order to compensate for the conformation effect, the discussed dispersion engineering modification technique, which was introduced in section III, can be applied. Similar to the convex CRLH LWA, this can be achieved by subdividing the structure into multiple sections and obtaining the radiation pattern and radiation angle for each section. Using the radiation angle of each section in (7) the $\beta$-value required to correct the rotation of the radiation pattern of each section at a desired frequency is calculated. As an example let us assume again broadside radiation is desirable, and let us subdivide the structure into three sections similar to what was shown in Fig. 2 and was discussed in section II for convex CRLH LWA [40]. However, unlike the convex case, in the concave case, the first section radiates in the forward direction, so the unit-cells in this section are required to be modified to operate in their LH FW mode to compensate for the rotation of the radiation pattern of this section caused by conformation. Hence, the radiation pattern of first section will be redirected towards the broadside. For the second section no significant change in the unit-cells is required as this section is already radiating towards broadside. However, the third section radiates in the backward direction and the unit-cells in this section need to be modified to operate in their RH FW mode to perform broadside radiation.

The discussed modification method is a general and useful technique when designing a concave CRLH LWA with similar performance as to a planar CRLH LWA. However, the similarity in the modification process of the concave and convex structures has been the inspiration for the possibility of using one modified CRLH LWA for both convex and concave surface application. In fact this is possible by first modifying the uniform convex structure to obtain similar results as to the uniform planar version. A modified concave CRLH LWA with the same radius of curvature as to the convex one can then be obtained by reshaping the convex CRLH LWA to a concave surface and excite the CRLH LWA from the opposite port that was terminated previously and terminating the other port. To understand this idea let us consider the modified convex CRLH LWA that was mounted to outside of a cylindrical object and was subdivided into three sections which now provides a radiation pattern comparable to that of the original uniform planar CRLH LWA. In this case the unit-cells in the section closest to the excitation port are modified to operate in the RH FW mode, while the unit-cells in the last section are modified to operate in the LH FW mode and unit-cells in the mid-section remain unchanged to operate near transition frequency. As a result all three sections radiate in the same direction towards broadside. If we unfold this convex CRLH LWA into a planar antenna the three sections radiate in the forward, broadside and backward direction consecutively, rather than all radiating towards broadside. The key point is to remember that the CRLH LWA can be considered as a two port travelling wave antenna with one port being excited and the other port being terminated.
with 50Ω. Now by switching the excitation port and the terminated port of the unfolded modified CRLH LWA the first section radiates towards the backward direction, the mid-section at the broadside direction and the last section radiates towards the forward direction. By conforming this CRLH LWA to inside of the cylindrical object rather than the outside of the same object, the three sections of the modified LWA radiate towards the same direction meaning broadside. As a result the main radiating beam is refocused and a concave CRLH LWA can be realized. This concave LWA can provide comparable radiation characteristics as to the original uniform planar CRLH LWA as well as the modified convex CRLH LWA. Thus this CRLH LWA can be used for both convex and concave applications. This process is shown in Fig. 10 [41].

To examine the proposed idea, the fabricated modified 25 unit-cells convex CRLH LWA shown in Fig. 7 is reshaped and mounted to the inside of the same cylinder with the radius of 20 cm to obtain a modified 25 unit-cell concave CRLH LWA. The obtained modified 25 unit-cells concave CRLH LWA is shown in Fig. 11. Radiation patterns for the original uniform planar, uniform concave and modified 25 unit-cells concave CRLH LWA are measured at 3.4GHz, 3.7GHz and 4.3GHz and plotted along with the predicted pattern for the uniform concave antenna using the array factor approach, in Fig. 12. As expected, all unit-cells perform broadside radiation at \( f = 3.7 \) GHz yielding broadside radiation of all three sections for the modified concave antenna. As a result, the main radiation beam of the modified concave CRLH LWA is refocused and recovered, thus comparable radiation pattern to the uniform planar CRLH LWA is achieved. In addition the modified concave CRLH LWA can perform beam scanning in the frequency range close to \( f = 3.7 \) GHz.

VI. ELECTRONICALLY CONTROLLED CONVEX CRLH LEAKY-WAVE ANTENNA [38]

A. Electronically Controlled CRLH Concept

In the previous sections the effect of conforming a CRLH LWA on a convex and a concave surface was investigated. A dispersion engineering compensation technique was also introduced. As a proof of concept and to show the effectiveness of the introduced compensation technique new device was fabricated with different unit-cell geometrical configurations for a fixed operation frequency; thus it has limited applications. However, what would really be attractive and desirable is to fabricate a single CRLH LWA that can be able to electronically control its radiation performance and dynamically compensate for the conformation effect. For this reason we closely consider the dispersion relationship given in (1). According to (1), (2) and (3), the \( \beta \) parameter of a CRLH unit-cell is not only a function of operation frequency \( \omega \) but it is also a function of the equivalent circuit model parameter values, \( C_R, L_R, C_L, \) and \( L_L \). Thus the propagation characteristics of a CRLH structure can be controlled by changing its dispersion relation through changing the operation frequency or by changing the series impedance or shunt admittance, effectively by controlling the value for \( C_R, L_R, C_L, \) or \( L_L \). One way to achieve this goal is to use varactor diodes as electronically tunable capacitors [38].

In order to obtain an electronically controlled CRLH LWA the equivalent circuit model of the unit-cell, shown in Fig. 1(a), is modified. This modification is done by introducing three varactor diodes into the unit-cell’s equivalent circuit model as shown in Fig. 13(a). The schematic of the microstrip
By introducing the varactors into the unit-cell, the capacitance of the unit-cell becomes dependent on the reverse biasing voltage applied to the varactors. As a result the series impedance and shunt admittance of the unit-cell becomes dependent on the biasing voltage. Hence, $\beta$ also becomes a function of the biasing voltage and can be controlled electronically. Thus, the dispersion curve can be shifted up or down on the frequency axis by changing the biasing voltage as illustrated in Fig. 13 (c). From (1) it can be seen that the radiation angle, $\theta_0$, is now a function of both frequency and biasing voltage. By using varactor diodes as tunable capacitors, an extra degree of freedom is introduced to control the behavior and propagation characteristics of the CRLH structure.

### B. Electronically Controlled CRLH LWA Geometrical Layout

A 25 unit-cell electronically controlled planar CRLH LWA is fabricated on a RT/Duriod 5580 substrate with a dielectric constant of $\varepsilon_r = 2.2$ and thickness of $h = 1.5748$ mm. An image of the fabricated prototype of this electronically controlled CRLH LWA is shown in Fig. 14(a). Each unit-cell has two six-pairs of interdigital capacitors connected to two stub inductors $L_{L1}$ and $L_{L2}$. The stub inductor $L_{L1}$ is connected in series with a varactor diode, modeled as a series tunable capacitor in series with a fix inductor, then shorted to the GND by a via. The stub inductor $L_{L2}$ is connected to the interdigital capacitors and parallel varactor diodes at one end and to the GND plane through a via at the other end. This provides the required current flow path to the GND to bias the parallel varactors diodes. This configuration is shown by the zoomed image of a single unit-cell in Fig. 14(a). Each interdigital capacitor finger has a length of 4.216 mm and a width of 0.07874 mm. The small inductive stubs, $L_{L1}$, are 9.95 mm by 0.4724 mm in size. The large inductive stubs, $L_{L2}$, has dimensions of 15.748 mm by 3.048 mm. The gap between the fingers is 0.215 mm. The overall size of the unit-cell is 12.73 mm by 30.201 mm. Three varactor diodes are used in each unit-cell for wider scanning range and also maintaining fairly constant characteristic impedance. Two varactors are in series and one is shunted. All the cathode electrodes of the varactors are connected to the same node to have a single biasing circuitry. The varactors in use are Metelics MSV 34060-E28X Si. A Murata chip inductor with an inductance 4.7 nH is used for DC biasing. This electronically controlled planar CRLH LWA exhibits continuous beam scanning range of 55° to -45° when the biasing voltage is tuned form 0V to 25 V at 3.24 GHz. The biasing voltage of 3.5 V provides broadside radiation at 3.24 GHz. To evaluate the performance of this electronically controlled planar CRLH LWA and its electronic beam scanning capability from backward direction to forward direction, its radiation pattern was measured for three uniform biasing voltages of 18 V, 3.5 V, and 0.5 V at $f = 3.24$ GHz. The measured radiation patterns and those obtained using array factor approach from (4) are shown in Fig. 15. The radiation angle for these three uniform biasing voltages are, $-43^\circ$ ($\beta < 0$), $-6^\circ$ ($\beta \approx 0$), and $30^\circ$ ($\beta > 0$), respectively. A good agreement can be observed between the radiation patterns obtained from the array factor approach and the corresponding measurement in terms of radiation angle and beamwidth.
In order to obtain an electronically controlled convex CRLH LWA, the discussed electronically controlled 25 unit-cell planar CRLH LWA was conformed on a cylindrical object with a radius of 25 cm. An image of this electronically controlled 25 unit-cell convex CRLH LWA is shown in Fig. 14(b).

C. Electronic Radiation Beam Recovery Functionality

As discussed earlier, when the planar CRLH LWA is conformed, its unit-cells no longer radiate in the same direction and their contributions no longer add up in phase at the far-field distance. As a result, radiation pattern of the conformal antenna is distorted and beamwidth becomes wider. In order to compensate for the effect of conformation and to refocus the main radiation beam, the conformal CRLH LWA can be subdivided into multiple sections. Then using the array factor approach the radiation angle of each section is obtained and the corresponding $\beta$-values required to correct the radiation beam of each section is obtained from (1) as discussed in details in section III. However, in the case of electronically controlled CRLH LWA by adjusting the biasing voltage of each section the dispersion curves of the unit-cells in that section can be manipulated to be shifted up or down on the frequency axis of the dispersion diagram to generate the desirable $\beta$-value electronically. As a result all the sections radiate in the same direction and their contribution adds up in phase at far-field in a desirable direction, thus the radiation main beam will be recovered.

To demonstrated the proposed electronic radiation beam recovery functionality, the radiation patterns of the 25 unit-cell convex CRLH LWA is compared to the planar version while they are operating at 3.24 GHz with a uniform biasing voltage of 3.5 V being applied. This comparison can be seen in Fig. 16(b). It is apparent in Fig. 16(b) that as the CLRH LWA is conformed its radiation pattern gets affected and its beamwidth becomes wider. To electronically compensate for the conformation effect at 3.24 GHz, corresponding to the broadside radiation of the planar CRLH LWA, the conformal structure is subdivided into five sections and using the array factor approach the radiation angle of each section is found. These radiation angles are $-23^\circ$, $-9^\circ$, $6^\circ$, $22^\circ$ and $32^\circ$ for sections 1 to 5, respectively, starting from the excitation port. Using (1) and the negative value of the obtained radiation angles, the $\beta$-values required to compensate for the conformation effect are found to be 26.6 rad/s, 10.6 rad/s, -7.1 rad/s, -25.5 rad/s and -36.07 rad/s corresponding to sections 1 to section 5, respectively. These $\beta$-values can be obtained by applying biasing voltages of 1 V, 2 V, 4.5 V, 9 V and 12 V, based on their dispersion diagram shown in Fig. 16(a), respectively. The measured radiation pattern of the electronically modified convex CRLH LWA is shown in Fig. 16(b). It is evident that from Fig. 16(b) that the radiation pattern of the electronically modified conformal CRLH LWA is recovered and its main radiation beam is refocused in comparison to the uniformly biased CRLH LWA by applying the proper biasing voltage to each section.

D. Electronic Beam Steering Through Selective Radiation Aperture Functionality

In the case of CRLH LWA, as discussed beam steering can be achieved by a different approach such as frequency scanning or electronic scanning by adjusting the $\beta$-value. Furthermore, as emphasized, in the conformal case each unit-cell radiates in a different direction. By taking advantage of this fact and the curved nature of the structure and dividing the conformal CRLH LWA into multiple sections it is possible to electronically select the radiating aperture, both in terms of location along the CRLH structure also in terms of aperture size. This is achieved by biasing certain sections of the CRLH structure to operate in the guided-wave mode and apply different biasing voltage to the remaining sections to operate in the radiation mode. Thus, if the location of the radiating section of the CRLH structure is changed through applying the same biasing voltage configuration to different sections of the CRLH structure, with the same number of unit-cells, the radiation beam will be steered due to the rotation caused by the surface curvature of the structure. The schematic representation of this electronic beam scanning functionality through selective radiation aperture is shown in Fig. 17 [38]. On the other hand, if the same biasing voltages are applied to different number of unit-cells, the size of the radiation aperture will change and the beamwidth can be tuned.

In order to demonstrate the electronic selective radiation aperture and beam steering functionality of the presented convex CRLH LWA, the structure was subdivided into five sections. Each section has five unit-cells. Two voltages of 1 V and 18 V are chosen for biasing purposes as their dispersion curves are far enough apart on the frequency axis. When 18 V is used for biasing, the biased unit-cells have LH FW region $3.145 \text{GHz} < f < 3.715 \text{GHz}$ and RH FW region $3.715 \text{GHz} < f < 4.78 \text{GHz}$. On the other hand, when varactors are biased with 1 V, the biased unit-cells have LH FW region $2.485 \text{GHz} < f < 2.725 \text{GHz}$ and RH FW region $2.725 \text{GHz} < f < 3.445 \text{GHz}$, as shown in Fig. 18(a). The operational frequency is chosen to be 2.86 GHz such that the sections that are biased with 1 V operate in their LH FW region and contribute towards radiation. On the other hand, the remaining sections are biased with 18 V, as a result, at 2.86 GHz they will operate in their LH SW region and they behave as a guided-wave structure without participation in radiation. Three cases are considered for illustration purposes, case 1 is when 1 V is used to bias the first ten unit-cells (first two sections) and 18 V for the three remaining sections. Case 2, corresponds to applying 1 V to unit-cells 5 to 15 (sections 3 and 4), and 18V to the other sections. Finally case 3, is when the last ten unit-cells (last two sections) are biased with 1 V,
and remaining sections are biased with 18 V. The count of unit-cells starts from the excitation port side according to Fig. 14(b). As can be seen in Fig. 18(b), in case 1, 2 and 3 the convex CRLH LWA has a radiation angle of -45°, -40° and -32°, respectively [38]. Clearly the beam has been steered electronically by selecting different radiation sections along the CRLH structure and 13° of beam scanning is achieved through the demonstrated electronic selective radiation aperture functionality [38].

VII. SUMMARY

In this article the effect of conforming a CRLH LW-TL on a convex and concave surface was investigated. In particular, a 25 unit-cell CRLH LW-TL was conformed on inside and outside of a cylindrical object with radius of 20.0 cm. The measurement showed that conforming the structure significantly affects its performance when it is operating in the fast-wave mode, as it effectively behaves as a LWA, in terms of radiation characteristics. In order to compensate for the conformation effect, a novel dispersion engineering technique was introduced. Consequently, a modified conformal CRLH LWA was obtained with the ability to produce comparable radiation characteristics as to the original planar CRLH LWA. As a proof of concept the modification was done through changing the geometrical configuration of the unit-cells of the CRLH LWA. It was shown that the modified CRLH LWA can be used for both convex and concave surface applications with a same radius of curvature. This was done by interchanging the excitation port and terminated port in the case of convex CRLH LWA to obtain the concave CRLH LWA. Thus, a modified 25 unit-cell CRLH LWA suitable for both convex and concave surface applications was attained. To obtain a more practical device for conformal applications, a multifunctional 25 unit-cell electronically controlled CRLH LWA was introduced by using varactor diodes. It was shown that by applying different biasing voltage to different sections of this structure, it can be manipulated to operate partially in the guided-wave mode and partially in the radiation mode. By applying the same biasing voltage configuration but to different section of the CRLH structure the radiation aperture becomes selective and the radiation angle can be steered. Furthermore, the effect of the conformation can be compensated by applying proper biasing voltage to different sections along the CRLH LWA using the presented dispersion engineering technique. By doing so the main radiation beam was refocused and a comparable result as to the original planar uniformly biased CRLH LWA was demonstrated.

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