Effect of Slow Wave Structures on Scan Angles in Microstrip Leaky-wave Antennas

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Abstract— This paper presents two miniaturized slow wave structures in microstrip leaky-wave antennas (MLWAs) which operate about 8 GHz. The effects of these structures on the scan angles have been compared in the paper. The designed interdigital capacitors and folded-back line have been investigated with ADS Momentum software. It has been shown that the interdigital capacitors (IDCs) yield to a broad scan angles from +53 to −74 degree, while the folded-back line inductor scans only the positive angles.

1. INTRODUCTION

Leaky-wave antennas (LWAs) are guided wave structures, which radiate electromagnetic waves by using travelling wave mechanism. Furthermore, LWAs are in classification of traveling-wave antennas [1–3]. The travelling wave mechanism consists of two structures, including fast travelling waves and slow travelling waves structures. In this type of antenna, the electromagnetic waves radiate continuously along its length, and hence the propagation wave number is complex, consisting of both a phase and an attenuation constant. Highly directive beam at an arbitrary specified angle can be achieved by this type of antenna, with a low side lobe level. In other words, beam scans with frequency inherently in LWAs. For scanning applications this is an essential advantage. Simple structure, no complicated feed network and cheap structures are the other benefits of LWAs. Moreover, they are popular in the microwave band and millimeter-wave band, because of their high directivity.

LWAs have been investigated since the 1940s, when an LWA consisting of a slotted rectangular waveguide was introduced. In [4] an LWA consisting of an inductive sheet spaced over a continuous conducting sheet, with a wave polarized in the plane of the antenna propagating between the two sheets has been represented.

LWAs can be divided into different categories depending upon the principle of operation; so uniform, quasi-uniform and periodic LWA is classification of them [1, 2]. A microstrip line that is periodically modulated in order to turn the non radiating microstrip mode into a radiating leaky mode has been reported in [2]. Recently, periodic slow wave structure has been nominated as appropriate media for LWAs. Substantially slow wave structures are special circuits that are used in microwave circuits to reduce and handle the wave velocity in certain direction. In other words, this structure controls the speed of the waves in LWAs in which non resonant periodic circuit or slow-wave structures are designed for producing large gain antennas [5].

In this paper, we present two slow-wave structures and their parameters for LWAs. Beam scanning is one of the most important parameters of LWAs and we report it here. We investigate the effect of these slow-wave structures on scan angles in periodic microstrip leaky-wave antennas (MLWAs).

2. ANTENNA DESIGN AND SIMULATION

2.1. LWA with Interdigital Capacitors

Folded-back line, zigzag line, corrugated waveguide, helical line and also interdigital capacitor, are structures that introduced as slow wave structures in [5]. Interdigital capacitors (IDCs) are widely used as lumped elements in the microwave integrated circuits (MIC), slow-wave devices, and integrated optical (IO) modulators [6]. Recently, IDCs has been utilized as slow wave structures in composite right/left handed leaky-wave antennas (CRLH LWAs) in order to control the speed of waves. CRLH LWA is another classification of LWAs that is part of the periodic LWAs. Metamaterials are usually known as periodic structures. However, there are several reports on metamaterial-inspired antennas [7, 8].

Although LWAs are cost-effective antennas in scanning the region over a large bandwidth, continuous backward to forward scanning is not reported for many of the structures [9, 10]. CRLH LWA introduces full-space continuous beam scanning, from backfire to endfire, including the broadside direction. Moreover, it can be fabricated in microstrip technology or in coplanar technology [1–4, 9–13].

Figure 1 illustrates a 16-cell LWAs with interdigital slow wave structures. This LWA is like another structure that reported in [14], but this paper compares the 16 cells of proposed LWA. This structure is a non resonant structure with the period IDCs. The existence of the IDCs makes the capacitors for CRLH in order to propagate forward and backward scanning through broadside.

As shown in Fig. 1, conventional IDC is utilized in CRLH LWA unit cell, and each unit cell is repeated periodically.

The period of structure is 4 mm and the capacitance of a single-layer IDC can be approximated as [5]:

$$C = (l/w)(?_r + 1)[(N - 3)A_1 + A_2] \tag{1}$$

where N = number of fingers. $A_1 = 0.089\,\text{pF/cm}$ is the contribution of the interior finger for $h > w$. $A_2 = 0.1$ pF/cm is the contribution of the two external fingers for $h > w$. l = finger length in cm. w = finger-base width in cm which has been demonstrated in Fig. 1(b).

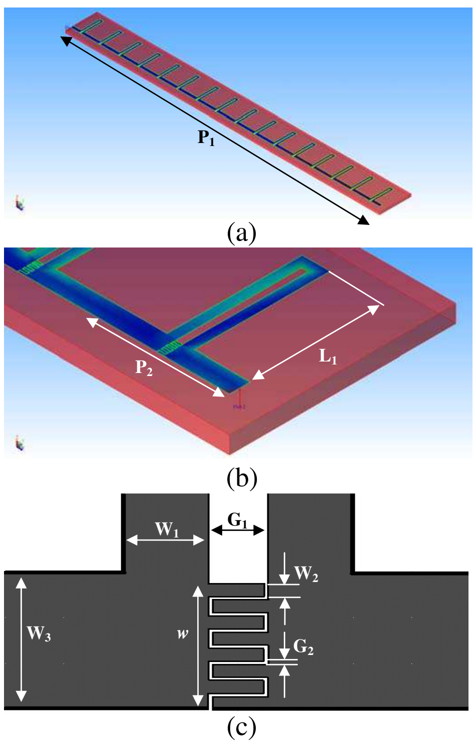

Figure 1: CRLH LWA with IDC. (a) 3D view of proposed LWA formed by 16 cells. The parameter value is: $P_1 = 64\,\text{mm}$. (b) 3D view of proposed LWA with periodic IDC as slow wave structure. The parameter values are: $P_2 = 4\,\text{mm}$, $L_1 = 3.9\,\text{mm}$. (c) Unit cell of IDC. The parameter values are: $w = 0.55\,\text{mm}$, $W_1 = 0.3\,\text{mm}$, $W_2 = 0.06\,\text{mm}$, $W_3 = 0.6\,\text{mm}$, $G_1 = 0.2\,\text{mm}$ and $G_2 = 0.01\,\text{mm}$.

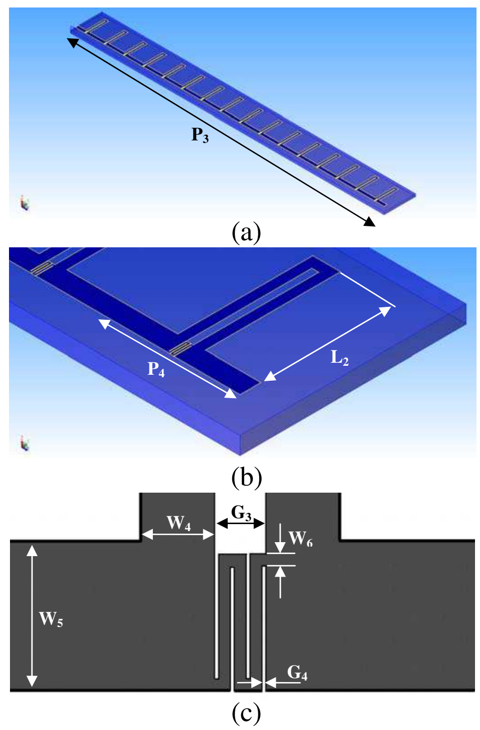

Figure 2: LWA with periodic folded-back line. (a) 3D view of proposed LWA formed by 16 cells. The parameter value is: $P_3 = 64\,\text{mm}$. (b) 3D view of proposed LWA with periodic folded-back line. The parameter values are: $P_4 = 4\,\text{mm}$, $L_2 = 3.9\,\text{mm}$. (c) Unit cell of folded-back line inductors. The parameter values are: $W_4 = 0.3\,\text{mm}$, $W_5 = 0.6\,\text{mm}$, $W_6 = 0.06\,\text{mm}$, $G_3 = 0.2\,\text{mm}$ and $G_4 = 0.01\,\text{mm}$.

2.2. LWA with Folded-back Line Inductor

Folded-back line inductors are another of structures that introduced as slow wave structure in [5]. They are similar to meander-line structures.

As declared above, beam scanning is one of the most important parameters of LWAs. As reported in [15], producing maximum radiation in the range $0? < \theta < 90?$ For slow-wave structures appears more challenging at first, but as we investigated and analyzed in X-band, this folded-back line structure is one of the slow-wave structures that produces a maximum gain in the positive range of theta.

Figure 2 shows a folded-back line inductor LWA with 16 cells. The period of the structure is as same as the LWA with IDC.

Actually in this paper capacitor substitutes with an inductor. This substitution effects on beam scanning and on scan angles.

3. COMPARISON AND SIMULATION RESULTS

As demonstrated above, the proposed MLWAs are located on the Rogers 5880 commercial substrate. For both proposed antennas, the thickness on the substrate should be chosen 0.508 mm with $?_r =$ 10.2 and finite structure formed by 16 cells. The commercial ADS Momentum software is adopted for the simulations, and the results are presented below. Fig. 3 illustrates S-parameter of proposed MLWAs. These antennas operate around X-band.

Figure 3: Magnitudes of S-parameters in proposed MLWAs.

In the designed LWA with interdigital capacitors, the main beam scans from $\theta_1 = +53$ degree to $\theta_2 = -74$ degree with increasing the frequency from 8 GHz to 10.363 GHz. This scanning investigated in $\varphi = 0?$ plane. Furthermore, the gain of the antenna not changes greatly in this range which is appropriate parameter in antenna design. Also this parameter is critical for scanning applications. This is obvious from the Fig. 4 that the antenna radiates in negative values of theta with increasing the frequency. Maximum gain occurs at 9.285 GHz and it is about 17.647 dB when the scan angle is $\theta = -18$ degree.

The LWA with folded-back line scans from $\theta_1 = +3$ degree to $\theta_2 = +54$ degree with increasing the frequency from 8 GHz to 8.714 GHz. But in the broadside region, we have gain reduction. See the radiation pattern in the Fig. 5. In the other word, the folded-back line LWA only scans in the positive range of theta. It's clear that maximum gain occurs in $\theta_2 = +54$ degree too.

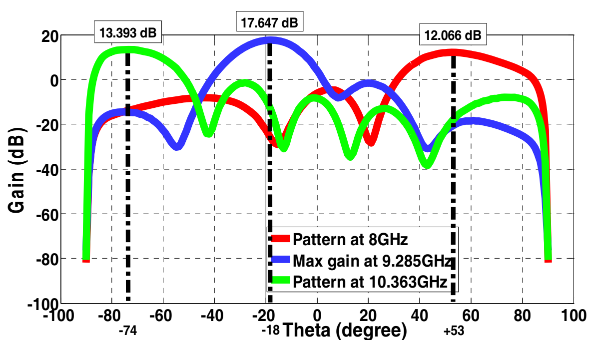

Figure 4: Radiation pattern of MLWA with IDC and scanning interval with maximum gain about 17.647 dB.

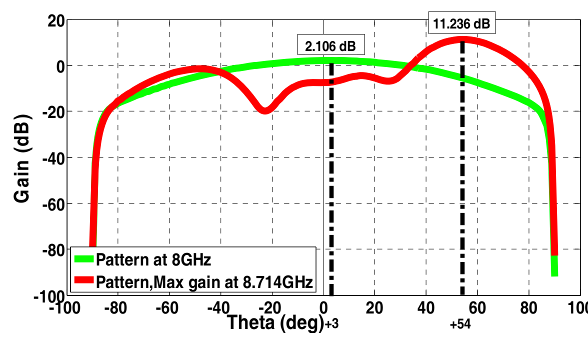

Figure 5: Radiation pattern of MLWA with folded-back line inductor and scanning interval with maximum gain about 11.236 dB.

For example, in [10] a slotted substrate integrated waveguide (SIW) LWA is proposed that has the advantages of both rectangular waveguide with transverse slots and SIW. Furthermore, this SIW LWA can only scan in the positive range of theta. As declared above, the main beam of LWAs scans the space when the frequency changes. In other words, beam scans with frequency inherently in LWAs and it's apparent from Fig. 6.

Degradation of gain in LWAs is another meaningful parameter that is examined in such a this paper. Also we have been investigated here. Notice the Fig. 7.

It is clear that, the average gain for each structure is not same and so the LWA with folded-back line inductor has less gain than LWA with interdigital capacitor. Also scanning bandwidth of LWA with folded-back line inductor is about 0.714 GHz.

As shown in Fig. 8, the average percentage of efficiency in LWA with a folded-backline inductor is less than LWA with IDC. This examinations show that LWA with a folded-backline inductor spoils the efficiency in the scanning interval because it has unbalanced unit cell. Also this reason justifies defection of gain in LWA with the folded-backline inductor.

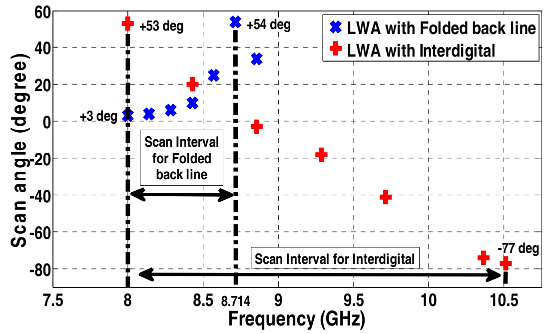

Figure 6: Details of scan angles in both proposed LWAs when frequency changes.

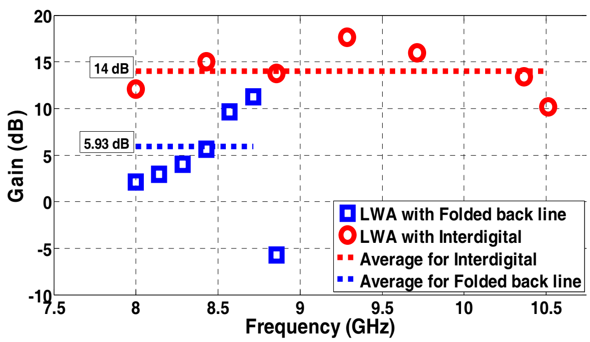

Figure 7: Details of magnitude of the gain in both proposed LWAs when frequency changes and the average of gains in interval of scan.

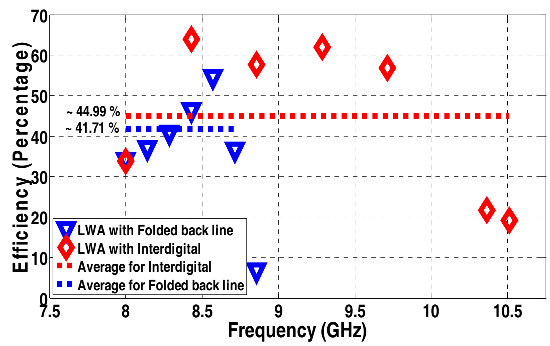

Figure 8: Details of efficiency when frequency changes and the average of gains in interval of scan.

4. CONCLUSION

This paper presented two miniaturized microstrip slow wave structures in periodic MLWAs. The effects of these structures on the scan angles have been compared. Interdigital capacitor is one of the slow wave structures and folded-back line inductor is another structure that has been investigated here. Actually in this paper a capacitor substitutes with an inductor. This substitution affects on beam scanning and on scan angles. It has been shown that IDCs yield to a broad scan angles from +53 to −74 degree, while the folded-back line inductors scan only the positive angles. This examinations show that LWA with folded-back line inductor spoils the efficiency and flat gain in the scanning interval because it has unbalanced unit cell.

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