The Periodic MLWA With Non-Uniform Aspect Ratios Based on Trapezoid DSPSL With Back-Firing to End-Firing Beam-Scanning Capacity

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ABSTRACT A periodic microstrip leaky wave antenna (MLWA) constructed of non-uniform aspect ratios microstrip patch periods is presented in this communication. Effective equations and simulations for the relevant antennas are used to obtain the propagation constants of the proposed antenna and design it. However, due to the presence of an open stop-band (OSB) in the broadside direction, double-side parallel-strip lines are then introduced in the antenna design. Truncating and interlacing the unit cells are developed to make them become impedance matched structures with the elimination of the OSB and the improvement of the radiation patterns. As a result, a new antenna configuration is created, and a prototype of the antenna is fabricated and measured. Continuous main beam scanning is observed from back-firing to end-firing with the operating frequency band of 4.8-18 GHz. Excellent agreements between the predicted and measured results are obtained. The measured peak gain of the prototype is 14 dBi, and the gain exceeds 6 dBi over the frequency band.

INDEX TERMS Periodic MLWA, non-uniform aspect ratios, end-firing, open stop-band.

I. INTRODUCTION

A S A CLASSICAL planar antenna, the microstrip leaky wave antenna (MLWA) has attracted extensive investigation attention since being introduced by W. Menzel in 1979 [1]. MLWA has played a significant role in microwave or millimeter-wave projects owing to its advantages of low profile, simple structure and easy to match [2]. The beam-scanning capacity in H-plane makes it a suitable choice for various fields [3]. Conventional uniform MLWA works in the first high-order mode, and the main beam scans in the forward quadrant only [4], [5]. Therefore, the backward-to-forward beam-scanning antennas would be preferred in more applications.

Various principles and techniques have been studied and reported in order to improve beam-scanning feature and expand applied range [6], [7]. One method to obtain this capability is to apply composite right/left-handed (CRLH) metamaterial in the antenna design [8] (e.g., leaky wave antenna (LWA) substrate-integrated waveguide (SIW)-based employing the transmission lines (TLs) with CRLH metamaterial [9], consistent-gain CRLH LWA with design flexibility [10], and 2-D CRLH LWA frequency scanning array with size reduction and beam steering control simplification [11]). Another approach to reduce the limitation of the scanning range is to apply periodic structure in the LWA [12], [13]. Different methods have been proposed to obtain the periodic perturbations in LWA, such as periodic longitudinal slots etched on broad wall of SIW LWA [14], periodically loading shunt radiation unit cells (UCs) along the host TL [15], periodic UCs composed of two microstrip step discontinuities and two via in a matched structure [16].

In a previous study of our laboratory, we proposed a back-fire-to-end-fire beam scanning periodic offset MLWA based on double-side parallel-strip lines (DSPSL) [17]; its scan range realize 180° but its operating frequency band exists two open stop-bands (OSBs), which is the most similar
previously reported antenna. Generally, a traditional periodic LWA has a uniform geometry of the UCs. In contrast, the antenna design in this communication focuses on non-uniform aspect ratios of the UCs. The proposed antenna is different from it in non-uniform geometry of UCs, the suppression of the OSB, and the working band.

In this paper, a periodic MLWA composed of non-uniform aspect ratios trapezoids based on DSPSL with back-firing to end-firing seamless beam-scanning capacity is presented. The proposed periodic MLWA, shown in Fig. 1, consists of a series of non-uniform aspect ratios offset DSPSL structures with triangular truncation and interleaving. In Section II, DSPSL is applied to the antenna design, and the UC is truncated by triangle and interlaced to match the input impedance of the UC to the characteristic impedance of the TL, consequently removing the OSB in the broadside direction and broadening the scan range. In Section III, a design of the proposed antenna based on the UC method and optimization is displayed and more details are given about it. In Section IV, the proposed antenna is fabricated and measured, showing good agreement with the simulated results.

II. PERIODIC MLWA WITH TRUNCATION AND INTERLEAVING DSPSL-BASED

A. COMPLEX PROPAGATION CONSTANTS

The radiation characteristics of the periodic MLWA are decided by the complex propagation constant $k_{zn}$. According to Bloch-Floquet theorem, $k_{zn}$ can be described as follows [12]:

$$k_{zn} = k_z + \frac{2n\pi}{kp}, n = \pm1, \pm2, \pm3, \ldots,$$  \hspace{1cm} (1)

$$k_{zn} = \beta_{zn} - \alpha_z,$$ \hspace{1cm} (2)

where $\beta_{zn}$ is the phase constant, $\alpha$ is the attenuation constant that is identical for all space harmonics in the periodic structure, and $n$ is the order of the space harmonics; $k_z = \beta_z - j\alpha_z$ is the wave number of the fundamental mode in the UC [18], [19] and $p$ is the period.

$|\beta_{zn}| < k_0$ indicates that the periodic antenna operates in the fast-wave radiating region and energy leaks from the periodic structure into the free space. Usually, one space harmonic is sufficient to responsible for the leaky wave radiation and the order is $n=1$. Then the normalized phase constant $\beta_{zn}/k_0$ and attenuation constant $\alpha/k_0$ of the antenna are characterized as follows [3], [20]:

$$\frac{\beta_{zn}}{k_0} = \frac{\beta_z}{k_0} + \frac{2n\pi}{kp} = \frac{\beta_z}{k_0} - \frac{\lambda_0}{p},$$ \hspace{1cm} (3)

$$\frac{\beta_{zn}}{k_0} = \sin\left(\frac{\pi}{2} - \theta\right),$$ \hspace{1cm} \hspace{1cm} (4)

$$\frac{\alpha_z}{k_0} = 0.18\theta_{HPBW} \cos\left(\frac{\pi}{2} - \theta\right),$$ \hspace{1cm} (5)

where $k_0 = 2\pi/\lambda_0$ is the wave number in the free space; $\theta$ and $\theta_{HPBW}$ denote the direction angle and half-power beam-width of the main lobe.

Theoretically, a periodic MLWA should consist of UCs with same propagation constants, and the UCs of the traditional periodic MLWA have the same structure. According to the equation (1), there can be derived to an equivalent relation of $k_{zn}/p_m$ as follows:

$$k_{z1} + \frac{2n\pi}{p_1} = k_{z2} + \frac{2n\pi}{p_2} = k_{z3} + \frac{2n\pi}{p_3} = \cdots = k_{zm} + \frac{2n\pi}{p_m},$$ \hspace{1cm} (6)

$$k_{zn1} = k_{zn2} = k_{zn3} = \cdots = k_{znm},$$ \hspace{1cm} (7)

By adjusting the periodic or wave number of UCs in the fundamental mode, these UCs have different geometries, but they still have the same or similar propagation constants. This is the key of the proposed antenna design in this paper. Therefore, we propose a periodic MLWA composed of the UCs with different geometries but uniform propagation constants, then we will provide several kinds of these UCs to validate this design concept.

According to [21], the propagation constant $k_{zn}$ of the proposed periodic structure can be obtained by the unit cell method as follows:

$$\cosh(jkzp) = \frac{A + D}{2},$$ \hspace{1cm} (8)

where $p$ is the period, $A$ and $D$ are the transmission parameters of the $ABCD$ matrix in the UC, which are calculated by $S$-parameters with the classical conversion formulas.
B. THE PERIODIC MLWA BASED ON DSPSL

DSPSL is a transmission that is easy to adjust structural impedance, thus it is introduced in the antenna structure to realize the impedance matching and suppress the OSB. The four calculated normalized propagation constants are similar in (6), which satisfies the design principle, then they also form a rectangular-interlaced periodic MLWA DSPSL-based, shown in Fig. 2. As an example, by applying the unit cell method, we also provide four UCs DSPSL-based of different aspect ratios with similar propagation constants as follows:

Model 1: \( W_1 = 16.4 \) mm, \( p_1 = 32.6 \) mm
Model 2: \( W_2 = 20 \) mm, \( p_2 = 30.4 \) mm
Model 3: \( W_3 = 22 \) mm, \( p_3 = 30.2 \) mm
Model 4: \( W_4 = 24 \) mm, \( p_4 = 30 \) mm

The calculated normalized propagation constants of the UCs with four different aspect ratios are shown in Fig. 3, which are calculated by the unit cell method. The OSB is represented by the bump of the normalized attenuation constant over broadside direction (red dotted circle), shown in Fig. 3. The presence of the OSB will seriously affect the continuous scanning of main beam.

C. TRIANGULAR TRUNCATION IN UC

According to the paper [17], the surface currents in the non-truncated structure consist of two regimes: the longitudinal transmission (i.e., the overlap region of the top patch and bottom patch) and the lateral transmission. In order to realize impedance matching of the UCs, triangular truncations are introduced in UCs. Compared to the original case, shown in Fig. 4 (\( f = 10 \) GHz), the transverse current disappears and the overall surface current flows in the longitudinal direction.

From Fig. 5, we observe that the OSB around broadside direction is suppressed by triangular truncation, and the operating bandwidth of the antenna becomes wider. But due to the impedance mismatching between different aspect ratios UCs, the bump of the normalized attenuation curve still exists.

D. THE LEFT AND RIGHT INTERLEAVINGS IN UC

The suppression of OSB around broadside direction has been discussed in above section, but the ideal propagation curve was not reached because of the impedance mismatching. In this section, the impedance matching of the overall antenna is analyzed by setting the left and right interleaving in UCs.

Firstly, we select the Model 1 to compose a periodic MLWA based on offset DSPSL and analyze the effect of interleaving width \( t \) and depth \( q \) on propagation characteristics of the antenna. The interleaving between left one and right one in the truncated UC is shown in Fig. 6. Secondly, choosing three kinds of the interleaving sizes (\( q = 14.2 \) mm, \( t = 0 \) mm; \( q = 14.2 \) mm, \( t = 0.6 \) mm; \( q = 7.1 \) mm, \( t = 0.6 \) mm) to observe the changing trends of the normalized propagation constants simulated in Ansoft HFSS, as depicted in Fig. 7.

From Fig. 7, the propagation curve tends to be smooth as the interleaving width \( t \) increases, and the bump of
the attenuation curve gradually disappears. However, the beam scanning range becomes smaller accordingly. Likewise, the peak propagation becomes more gradual and scanning range becomes wider with the interleaving depth \( q \) increasing, which indicates that the radiation characteristics of the antenna tend to be optimal.

Fig. 8 shows the input impedance against frequency of the antenna with different interleaving widths and depths. The imaginary part close to zero and the real part in the vicinity of 50 \( \Omega \) as the propagation curve tends to be smooth and the scanning range becomes wider at the same time. The results indicate that the antenna nearly achieves impedance matching, which resulting in the elimination of the OSB.

Finally, joint the analytic situations of the two influential factors and get the appropriate interleaving width, interleaving depth and truncation length corresponding to each UC through numerous simulated data in Ansoft HFSS. A periodic MLWA with non-uniform aspect ratios based on trapezoid DSPSL is obtained after analysis and optimization. Fig. 9 shows the calculated propagation curve of the antenna, the normalized phase constant is linear; and the normalized attenuation has a small swing, but is basically constant around the broadside direction. OSB suppression around the broadside direction has been achieved of the resulting antenna, and can expand the impedance bandwidth and beam scanning range.

III. ANTENNA DESIGN AND FABRICATION

A prototype of the periodic MLWA based on trapezoid DSPSL with back-firing to end-firing beam-scanning capacity is fabricated using the WangLing Teflon woven glass fabric substrate with relative dielectric constant of \( \varepsilon_r = 2.65 \), dielectric loss tangent of \( \tan \delta = 0.005 \) and thickness of \( h = 0.8 \) mm. A photograph of the fabricated antenna is shown in Fig. 10. As described above, the antenna consists of four nonuniform aspect ratios UCs with triangular truncation and interleaving. \( W_1 = 16.4 \) mm, \( W_2 = 20 \) mm, \( W_3 = 22 \) mm, \( W_4 = 24 \) mm are the widths of the Model 1, 2, 3, 4, and \( p_1 = 32.6 \) mm, \( p_2 = 30.4 \) mm, \( p_3 = 30.2 \) mm, \( p_4 = 30 \) mm are the periods respectively, the side length of truncation in which are \( c_1 = 7 \) mm, \( c_2 = 8 \) mm, \( c_3 = 9 \) mm, \( c_4 = 10 \) mm in turn. Table 1 shows the other parameters of the proposed antenna.

| Parameter | Size (mm) | Parameter | Size (mm) |
|-----------|-----------|-----------|-----------|
| \( s \)   | 2.7       | \( m \)   | 2.2       |
| \( l \)   | 17        | \( q_1 \) | 14.2      |
| \( a \)   | 2.8       | \( q_2 \) | 17.8      |
| \( b \)   | 12        | \( q_3 \) | 19.8      |
| \( t \)   | 0.6       | \( q_4 \) | 21.8      |

IV. EXPERIMENTAL VERIFICATION

The simulated and measured H-plane radiation patterns of the proposed periodic antenna are depicted in Fig. 11 and
Fig. 11, respectively. In Fig. 12(a), the operating frequencies are 4.8 GHz, 5.3 GHz, and 6 GHz, and the main beam directs at $\theta = 180^\circ$, $\theta = 110^\circ$ and $\theta = 96^\circ$, respectively; the main lobe steers in the backward direction. In Fig. 12(b), the main beam points at $\theta = 87^\circ$, $\theta = 45^\circ$ and $\theta = 0^\circ$ at respective operating frequencies of 6.4 GHz, 11.6 GHz and 18 GHz; the main beam steers in the forward direction. The experimental results show that the main beam continuously steers from $180^\circ$ to $0^\circ$ in the y-z plane with omnidirectional scanning range when the operating frequency increases from 4.8 GHz to 18 GHz. The measured and simulated results are in good agreement.

The simulated and measured normalized phase constant $\beta_{zn}/k_0$ and attenuation constant $\alpha/k_0$ are depicted in Fig. 13, which illustrate that measured results agree well with the simulations without the OSB region. The desired results further verify the feasibility of the proposed design concept.

The measured $S$-parameter ($S_{11}$) of the proposed periodic MLWA is displayed in Fig. 14. It is observed that the reflection coefficient is below $-10$ dB in all operating bands, which indicates that it has overcome the OSB in the broadside. The peak gain of the proposed antenna is also shown in Fig. 14. The gain curve has a gentle rise or fall trend without the declining steeply region. Measurements show that the peak gain level is 14 dBi and its gain over the frequency band is better than 6 dBi in the direction of maximum radiation.

A complete comparison between the characteristics of the proposed periodic MLWA and some of the recent antennas are listed in Table 2. From Table 2, the advantage of the wider beam scanning range is obvious compared to most antennas. And the advantage of continuous beam scanning around broadside direction is highlighted.

V. CONCLUSION

In this paper, a triangle-truncated and interlaced periodic MLWA based on DSPSL with back-firing to end-firing beam-scanning capacity is proposed and studied. The antenna is composed of non-uniform aspect ratios of the UCs. The unit cell method is used to analyze the propagation characteristics, which provides us with an effectively and quickly
method to find different aspect ratios UCs with a uniform propagation constant. DSPSL is introduced to adjust structural impedance. Then the suppression of the OSB is studied at truncated length, interleaving width and depth for the improvement of the radiation characteristics. The design method is validated by experimental prototype fabrication and measurements, which demonstrates a good agreement with theoretical predictions. Seamless beam scanning from back-firing to end-firing is achieved from the antenna measurements. Since the antenna is low cost and easy to fabricate, it can be redesigned to apply in some other beam-scanning systems bands.

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