Continuous Beam Scanning Novel Leaky-Wave Antennas Using 1-D Mushroom Structure

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Abstract **- Continuous backward-to-forward beam-scanning novel leaky-wave antennas (LWAs) are designed using 1-D mushroom structure. An effective method is proposed to suppress the bandgap of a 1-D mushroom structure. The study starts from an equivalent circuit of a mushroom unit cell and is verified through simulation and measurement. The 1-D LWAs designed using this method realize a smooth transition between the backward and forward leaky-wave regions and hence supports continuous beam scan. The measured results confirm that a continuous beam scanning of 126°, starting from −60°, is possible with a gain variation of less than 3 dB. Moreover, the measured 3dB gain bandwidth is greater than 58%.**

Index Terms **— Backward, continuous beam scanning, forward, leaky-wave antenna (LWA), mushroom structure.**

1. Introduction

Leaky-wave antennas (LWAs) inherited with beam scanning capability can be used to reduce system complexity [1]. Continuous backward-to-forward beam scanning of an LWA remained one of the major limitations for a long time. Composite right/left-handed (CRLH) transmission line structure is an efficient solution for this limitation. It has both left-handed (LH) and right-handed (RH) properties and supports continuous backward to forward beam scanning when a balanced condition is achieved [2], [3]. However, most of the reported CRLH LWA structures are very complex.

On the other hand, the mushroom structure is very simple; each unit cell consists of a metallic patch and a center shorting via between the patch and the ground plane [4]. Owing to its exceptional properties, mushroom structures have been used for various applications. Usually, they are used to improve the antenna performance by loading around the driven element. Very limited research has been conducted to use the mushroom structure as a main radiating element as it has a bandgap between two radiating leaky modes. Furthermore, the edge coupling between the patches of two conjugative mushroom unit cell is very week. To achieve a balanced condition of a mushroom structure, as discussed in [5], additional metal patches are used within the substrate, resultant in a multilayered structure.

This paper presents a mushroom-based unit cell suppressing the bandgap by maintaining the structure single layer. The 1-D LWAs consisting of such unit cells are able to scan the beam continuously from backward to forward direction over a wide angular range. The study is verified through equivalent circuit model of the unit cell, simulation of the physical unit cell, full-wave simulation of the complete structures, and measurement.

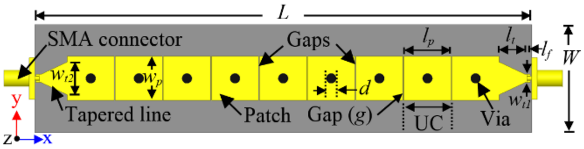


Fig. 1. Top view of the new CRLH LWA.

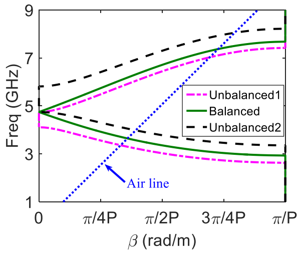


Fig. 2. Dispersion diagram for unit cell equivalent circuit.

2. Theory

Based on the physical structure of the mushroom unit cell (UC in Fig. 1) a simplified equivalent circuit for a 1-D periodic structure can be developed which is similar to a CRLH transmission line equivalent circuit model. In our design, L_v, L_p, C_p, and C_g are the inductance of the via, the inductance of half of the patch, the capacitance between the patch and the ground plane, and the capacitance which form in half of the gap between two adjacent patches, respectively. The balanced condition is achieved when $L_p/L_v = C_p/C_v$.

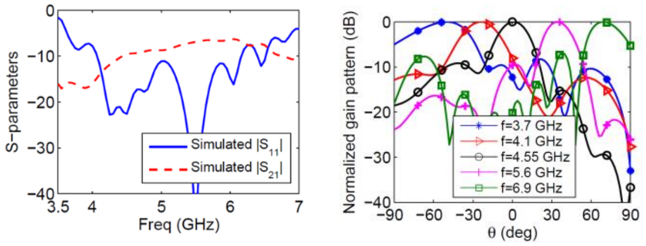
The phase constant (β) of a unit cell can be determined from the transmission matrix of the equivalent circuit model using the following standard formula [5]:

$$\beta = \frac{1}{P}\cos^{-1}\left(\frac{A+D}{2}\right), \tag{1}$$

where the transmission matrix coefficients A and D can be obtained using the element matrices given below:

$$A = D = 1 - \left(\omega^2 L_p C_p + \frac{1}{\omega^2 C_g L_v} - \frac{C_p}{C_g} - \frac{L_p}{L_v}\right). \tag{2}$$

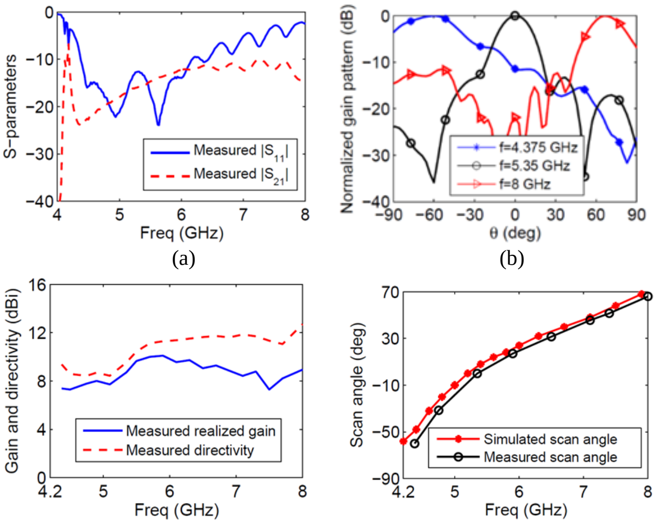
Fig. 2 shows the dispersion diagram obtained using (1) in MATLAB for three different values of the via inductance (L_v = 1, 0.75, and 0.5 nH for Unbalanced1, Balanced, and Unbalanced2, respectively) with all other circuit parameters are fixed to L_p = 1.5 nH, C_p = 1.5 pF, and C_g = 0.75 pF. It can be seen from Fig. 2 that the bandgap suppresses completely for an appropriate value of L_v when other parameters fixed. In the case of a metallic via, the inductance reduces with the increase of its diameter when the other parameters remain unchanged. Therefore, the desired value of via inductance can be achieved by changing the diameter. The direction of the beam (θ) of an LWA can be determined, using β from the dispersion diagram in Fig. 2, by $\theta(f) = \sin^{-1}[\beta(f)/k_0(f)]$, where k_0 is the wavenumber for free space and θ is the angle between the broadside and main beam direction [1].



(a) (b)

Fig. 3. Simulated (a) S-parameters and (b) radiation patterns of the LWA in Fig. 1.

Fig. 4. Top view of a prototype with three vias in a unit cell.



(a) (b)

(c) (d)

Fig. 5. (a) Measured S-parameters, (b) measured radiation patterns, (c) measured directivity and gain, and (d) a comparison between simulated and measured beam directions.

3. Antenna Design Using Single Via

Initially, a novel mushroom-based LWA using one via in each unit cell is designed on a substrate with dielectric constant (ε_r) and loss tangent (tanδ) of 2.2 and 0.001, respectively. It is fed from one side (left) using a tapered feed line, and another side (right) is terminated with a 50 Ω load to suppress reflected wave. The dimensions (indicated in Fig. 1) are l_f = 1.6 mm, w_{t1} = 2.5 mm, w_{t2} = 10 mm, l_t = 8 mm, d = 3 mm, l_p = 14.8 mm, w_p = 13.5 mm, and W = 33 mm. The total length (L) of the complete structure is 2.319λ_0, where λ_0 is the free-space wavelength at 4.55 GHz.

The simulated S-parameters and the radiation patters of the LWA (in Fig. 1) are shown in Fig. 3(a) and (b), respectively. As seen the antenna has a wide impedance bandwidth. The simulated normalized x-z-plane radiation patterns of the 1-D LWA (in Fig. 1) are shown in Fig. 3(b). At 3.7 GHz the beam points at −50° and scans closer to the broadside with an increase of frequency. At 4.55 GHz the main beam points at the broadside (0°) direction. With further increase of frequency, the beam moves away from the broadside direction and points closer to the endfire direction. For example, at 5.6 and 6.9 GHz, the beam points at +34° and +70°, respectively. The antenna has a maximum gain of 10.77 dBi, and the gain variation within the scan range is 3.47 dB.

4. Antenna Design Using Distributed Vias

From our study in previous sections, we see that a via diameter d of 3 mm is required to achieve a balanced condition for the LWA in Fig. 1, which is indeed large. To ensure design flexibility, multiple vias placed closely to each other, with a suitable diameter, can be used. The diameter of the vias will reduce with an increase in the number of vias. This is because the vias are in parallel and the resultant inductance of multiple vias is low. An antenna prototype with three vias in each unit cell is shown in Fig. 4. The diameter of each via is now 1.3 mm, which is much smaller than the previous design.

As shown in Fig. 5(a), the prototype has a measured -10 dB reflection bandwidth from 4.38 to 6.18 GHz. Frequency beyond 6.18 GHz, the reflection coefficient increases with frequency, but the transmission coefficient remains below -10 dB throughout the beam scan range indicating good radiation characteristics. The measured radiation patterns and the gain and directivity of the prototype (Fig. 4) are shown in Figs. 5(b) and (c), respectively. The antenna can scan the main beam from −60° to +66° with a maximum measured gain of 10.1 dBi and gain variation of only 2.9 dB. Finally, a comparison between the measured and simulated beam directions at different frequencies are shown in Fig. 5(d). An excellent agreement is observed between them.

5. Conclusion

A mushroom-type unit cell has been investigated in this paper to utilize in 1-D beam-scanning antennas. An effective method is proposed to achieve the balanced condition. By changing the inductance of the metallic via, the bandgap was suppressed, and a smooth transition between two leaky modes is achieved. Complete mushroom structure based LWAs with a single via and distributed vias in each unit cell are developed to realize such continuous beam scan. The measured results confirmed that the antenna is able to scan the main beam continuously from −60° to +66° with a low gain variation.

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