Continuous Backward to Forward Scanning 1-D Slot Array Leaky-Wave Antenna with Improved Gain

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***Abstract*—A leaky-wave antenna (LWA) on a substrate integrated waveguide (SIW) with continuous beam scanning capabilities and improved gain is presented. A 1-D longitudinal slot array SIW antenna is used as the main radiating element. It was found that due to the capacitive effect of the slot, an open-stopband (OSB) restrains broadside radiation. Although a reduction of the bandgap can be achieved when the slots are closer to the center, the radiation performance of the LWA degrades around the broadside as the beam scans from backward to forward. Initially, the capacitive effect was mitigated, and hence the OSB was suppressed by introducing a group of three shorting vias at the opposite side of each longitudinal slot. However, the gain of the antenna drops significantly around its upper scan angles in the forward directions. To improve the radiation performance further, the centre via of each of the via group is replaced by a transverse slot. The new unit cell is then used to design a modified 1-D slot array LWA, and the antenna is analyzed, prototyped and measured to verify the concept.**

***Keywords*—Beam scanning, broadside, gain improvement, leaky-wave antenna (LWA), SIW, slot-array antenna.**

I. Introduction

Waveguide-based slot array antenna has a long history and used in various applications including radar and communication systems [1]. However, waveguides occupy a large volume, and are bulky and expensive [2]. The popularity of the antennas based on printed circuit boards (PCBs), e.g., substrate integrated waveguides (SIWs) are increasing rapidly because of their low-profile configuration, low cost and ease of integration with RF circuits [3]–[10]. Travelling-wave slot array antennas scan beam as the phase shift between the elements varies gradually with frequency [11]. A travelling-wave antenna (TWA) operating in the fast-wave region is also called a leaky-wave antenna (LWA) [12]–[15]. Various LWAs have been developed based on PCBs mostly on SIW structures, but the radiating beam of these antennas usually scans in the forward direction only [16]–[19]. Generally, uniform and periodic LWAs face difficulty when scanning the beam from backward to forward as an open-stopband (OSB) restricts radiation in broadside and hence the gain for the broadside beam drops significantly [20]–[22]. Different approaches have

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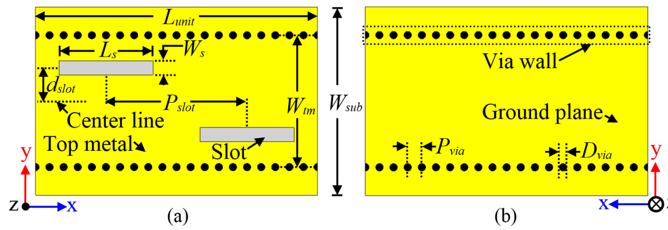


Fig. 1. Unit cell for initial study. (a) Top view. (b) Bottom view.

been reported to achieve a beam towards the broadside, such as feeding an LWA or array at the centre [23]–[25], using composite right/left-handed (CRLH) structures [26]–[29], and by exciting higher-order space harmonics of a periodic structure [30], [31]. In recent years, considerable effort has been made to achieve beam scanning continuously through broadside using a periodic structure [20], [32]–[36]. However, most of the reported LWAs are based on a transverse slot SIW structure and they usually suffer from significant gain variations.

On the other hand, longitudinal slot array antennas have excellent properties such as high gain, low cross-polarization and low sidelobe level [11], [37]. Waveguide based slot array antennas have been using for different applications. However, in most cases the beam points in a fixed direction, usually in the broadside. This type of antenna is called a standing-wave antenna where the antenna is fed from one end and the other end is closed by a wall. The separation between two adjacent slots is usually $\lambda_g/2$. When the structure is working as a TWA the other end needs to be terminated with a matched load, and the separation between the two slots is no longer $\lambda_g/2$, but can be spaced equally [37].

In this paper, a novel continuous beam scanning LWA on SIW is presented using both longitudinal and transverse slots together with shorting vias. The properties of a leaky wave longitudinal slot array antenna are studied in detail using unit cell dispersion analyses. Due to the capacitive effect of the slots, it is extremely difficult to eliminate the OSB by changing only the slot positions. Since the slots in a longitudinal slot array antenna are capacitive, a group of three shorting vias are used on the opposite side at the same offset. In this way the OSB was suppressed, but a significant gain drop was observed at higher frequencies. This is solved by replacing the centre via of each group with a transverse slot. The concept is verified through simulation and prototype measurement.

TABLE I. DIMENSIONS (IN MM) OF THE UNIT CELL IN FIG. 1.

L_{unit}	W_{sub}	L_s	W_s	d_{slot}	W_{tm}	P_{slot}	D_{via}	P_{via}
30	20	10	1.5	3.55	14	15	0.8	1.5

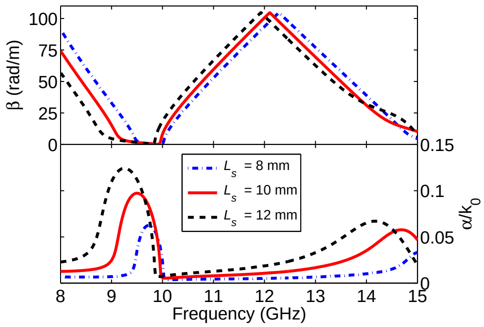


Fig. 2. Dispersion diagram for different slot length (L_s).

II. CONVENTIONAL SLOT ARRAY LWAS

Fig. 1 shows the top and bottom views of a conventional longitudinal slot array LWA unit cell in which the slots are etched above and below the centerline alternatively with respect to the centreline maintaining an offset d_{slot}. The unit cell is designed on a two-layer 1.57 mm thick copper-clad substrate (tanδ = 0.001 and ε_r = 2.2). Other dimensions of the unit cell in Fig. 1 are listed in Table I. As a 1-D periodic structure made out of cascaded unit cells, the convenient way to determine the properties is by analyzing its unit cell. From the unit cell analysis, we obtain the phase (β_n) and attenuation (α) constants which give us the beam scanning property of a periodic LWA made out of the same unit cell. The direction (θ) of the beam from broadside (0°) is given by $\sin^{-1}(\beta_n/k_0)$, where k_0 is free-space wavenumber [20], [31].

The dispersion characteristics, for the basic slot array unit cell in Fig. 1, are plotted for different slot length L_s and slot offset d_{slot} as shown in Figs. 2 and 3, respectively. The dispersion diagrams are obtained using the S-parameters from the unit cell simulation by the method discussed in [32]. Note that for each case of the parameter analysis the other parameters are fixed as in Table I. It is seen that the bandgap decreases significantly with the reduction of either slot length L_s or the offset d_{slot}. However, in both cases, the radiation performance of the structure degrades. The dispersion diagram for different (varied between 1 to 2 mm) slot width (W_s) was also studied and it was found that the width has negligible effect on the dispersion curves.

III. COMPLETE ANTENNA WITH ONLY SLOTS

In this section, the properties of an SIW based LWA consisting of only longitudinal slots on the top metal is verified through the simulation of a complete finite antenna structure. Fig. 4(a) shows the top view with details of the feed section (in the bottom inset) of the longitudinal slot array antenna for an initial study. A total of seven unit cells are utilized in the antenna design considering the leakage properties as seen from the dispersion diagrams. The antenna is fed (left side in Fig. 4) by a tapered line using an SMA connector through a matching pad. The tapered line and matching pad dimensions were optimized using a parameter analysis in CST Microwave Studio, and the optimum values for good impedance matching are chosen as l_1 = 4.5 mm, l_2 = 7.4 mm, w_1 = 4.9 mm, and w_2 = 9 mm. Note that the matching pad is designed 0.5 mm away from the edge of the substrate to ensure isolation between the SMA conductors (inner and outer) after soldering.

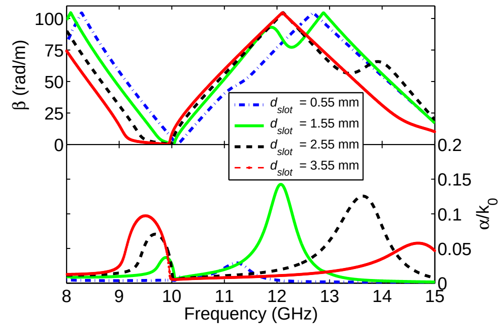


Fig. 3. Dispersion diagram for different slot offset (d_{slot}).

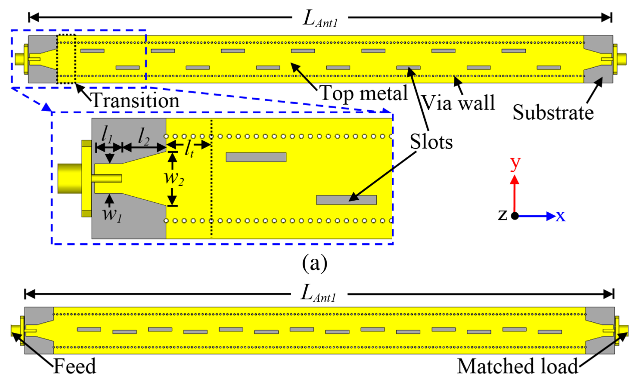


Fig. 4. Slot array LWA. (a) Top view with enlarged feed section. (b) Antenna with reduced offset (d_{slot} = 0.55 mm). L_{Ant1} = 249.8 mm; l_t = 7.5 mm.

As seen from Fig. 3 with the reduction of the slot offset (d_{slot}) the bandgap can be reduced significantly. To observe the radiation performance an antenna with d_{slot} = 0.55 mm is also studied. Fig. 4(b) shows the antenna with reduced d_{slot}. All other parameters of both of the antennas are the same. The simulated scattering parameters for both of the LWAs in Fig. 4 were analyzed. As expected, there is an open-stopband with a large bandgap between the forward and backward leaky regions in case of the antenna in Fig. 4(a) and the matching is comparatively better for the antenna in Fig. 4(b). The simulated radiation patterns (directivity) of the antennas are shown in Figs. 5 and 6. It is found that, the slot array antenna with larger offset (d_{slot}) [Fig. 4(a)] is unable to scan its beam efficiently through broadside. The radiation around broadside is improved with the reduction of d_{slot}. However, the overall radiation performance of the antenna degrades as the slots are very close to the center line and around this region the surface currents become weak. For the latter case, the beam scan range is very low, and the difference of the directivity between the forward and backward beams is also significant.

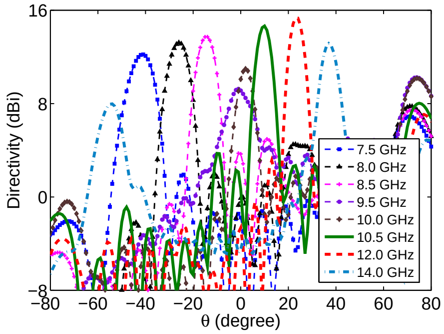


Fig. 5. Simulated directivity patterns of the antenna in Fig. 4(a).

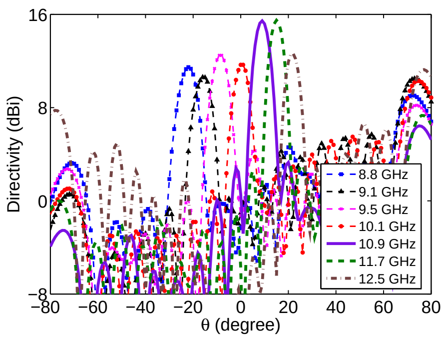


Fig. 6. Simulated directivity patterns of the antenna in Fig. 4(b).

IV. 1-D Backward to Forward Beam Scanning Modified Slot Array LWA

From the in-depth analysis of a conventional slot array antenna in the previous sections, we see that it is indeed difficult to simultaneously suppress the open-stopband and maintain good radiation performance of the scanning beam. In this section new antenna designs are discussed in which the open-stopband is suppressed and a continuous beam scan is achieved with better radiation performance. The gain of the initial design drops sharply at higher frequencies which is solved by developing a new antenna.

A. Unit Cell Design

The open-stopband behaviour of the conventional longitudinal slot array antenna is due the slots which are capacitive. Proper impedance matching can close the OSB. To improve the impedance matching we need to mitigate the capacitive effect which can be done by introducing additional inductive reactance in each unit cell. Since the slots are placed as an offset (d_{slot}) from the center line and two adjacent slots are placed alternatively (Fig. 1) the other half of the space is unused and can be utilized for impedance matching purpose. Since the slots are longitudinal, to mitigate the capacitive effect properly, a group of three shorting vias placed longitudinally are used to add distributed inductance in the unit cell as shown in Fig. 7(a). The radius of the vias and the distance between them is also optimized using parameter analyses in CST. In the final design, the diameter (d_{via}) of a shorting via is 0.7 mm and the center-to-center spacing (S_{via}) between them is 2.6 mm. Fig. 8 shows the dispersion characteristics of this unit cell. To

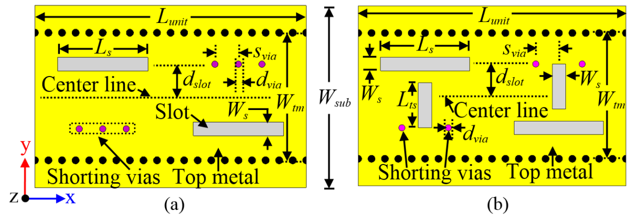


Fig. 7. Modified slot array LWA unit Cell. (a) Initial design. (b) Proposed.

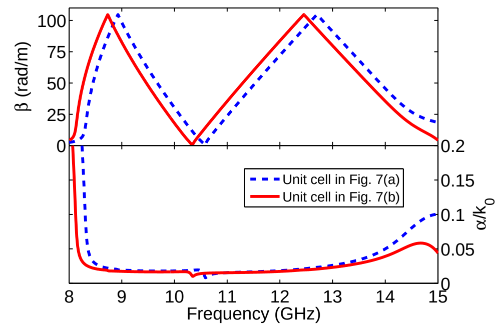
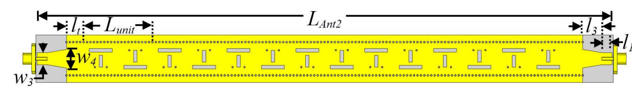
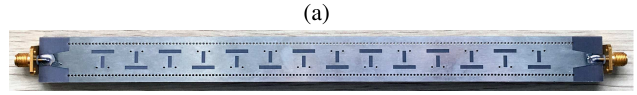


Fig. 8. Dispersion diagram for the modified slot array unit cells in Fig. 7.



(a)



(b)

Fig. 9. Modified slot array LWA. (a) Top view of the simulation model. (b) Top view of the fabricated prototype. The dimensions (in mm) are: L_{Ant2} = 251.6, l_1 = 4.5, l_3 = 8.3, w_3 = 5.4, w_4 = 7.8.

suppress the OSB, a smooth transition, i.e., without a bandgap, is required between the forward and backward phase constant curves. Furthermore, there should not be a rapid change of the attenuation constant, and its value must remain non-zero around the transition point [30], [38]. It is seen from Fig. 8 that both the conditions are satisfied, and the OSB is removed completely. However, a sharp increase of the leakage rate at higher frequencies is observed which may cause considerable gain variation around those frequencies. To solve this issue the centre via is replaced by a transverse slot and a new unit cell is designed as shown in Fig. 7(b). It is seen that the leakage rate curve is also flat over a wide frequency range compared to the unit cell in Fig. 7(a). The flat leakage rate indeed indicates a stable radiation performance of the antenna made out of this unit cell compared to the previous one.

B. Antenna Configuration

The final modified slot array SIW LWA simulation model, using the unit cell in Fig. 7(b), is shown in Fig. 9(a). Similar to the previous antenna a total of seven unit cells are utilized in the design. The antenna is fabricated and measured for verification of the study. A photograph of the modified longitudinal slot-array SIW LWA prototype is shown in Fig. 9(b).

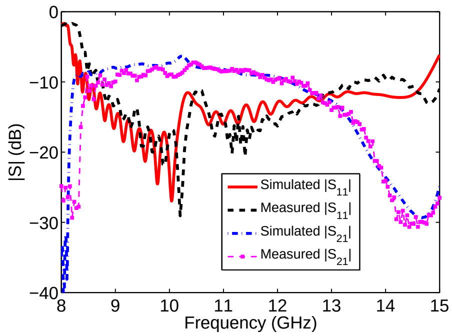


Fig. 10. Measured and simulated S-parameters of the proposed LWA in Fig. 9.

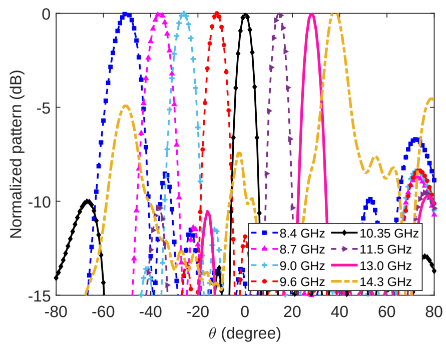


Fig. 11. Simulated x-z plane normalized radiation patterns (co-pol) of the modified slot array LWA in Fig. 9 at various frequencies.

C. Results and Discussion

The simulated S-parameters of the proposed LWA is shown in Fig. 10, which has a -10 dB reflection coefficient bandwidth of 8.48 - 14.73 GHz. The transmission coefficient ($|S_{21}|$) of the antenna is very low throughout the operating band means that the LWA has very good radiation performance. The measured S-parameter curves are also shown in Fig. 10 and a good agreement is seen between the measured and simulated results. It is noted that the measured results shifted slightly in higher frequencies; these discrepancies may happen due to minor fabrication error.

The simulated radiation patterns of the modified slot array antenna are shown in Fig. 11. The main beam scans continuously from $-50°$ (8.4 GHz) to $+38°$ (14.3 GHz) with a broadside beam at 10.35 GHz. The simulated radiation efficiency of the LWA is $> 76\%$ within the beam scan range, and over 84% between 8.6 to 14.4 GHz. As mentioned earlier another antenna was designed using the initial unit cell in Fig. 7(a). The simulated directivity and gain of both of the antennas are shown in Fig. 12 together with the measured gain of the proposed antenna. The initial antenna with the unit cell in Fig. 7(a) can scan beam from $-51°$ (8.55 GHz) to $+36°$ (14.3 GHz) with a gain variation between 15.05 and 9.97 dBi. It can be seen from Fig. 12 that the gain drops sharply at higher frequencies. As expected from the dispersion analysis, at higher frequencies the gain of the proposed antenna is significantly greater than the initial antenna design. For example, the gain of the proposed antenna at 14.3 GHz is 11.14 dBi and the variation of antenna gain within the beam scan range is between 10.96 to 15 dBi. Moreover, the gain is > 12.2 dBi between 8.55 and 14 GHz. Note that an antenna proposed in [35] uses a single via opposite to the slot and can scan beam in a comparatively wider range in the forward direction, but the variation of gain is over 7 dB.

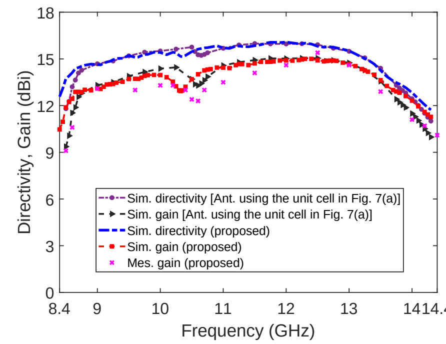


Fig. 12. Simulated directivity and gain of the initial antenna [unit cell in Fig. 7(a)] and the proposed LWA in Fig. 9 and measured gain of the prototype.

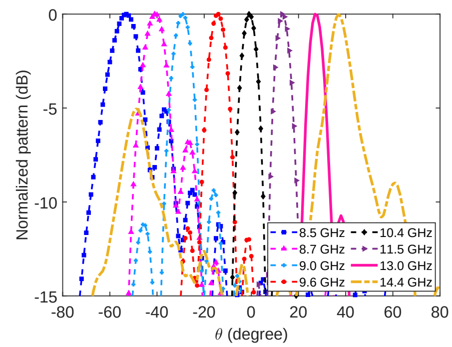


Fig. 13. Measured x-z plane normalized radiation patterns of the modified slot array LWA prototype at various frequencies.

The measured normalized radiation patterns are shown in Fig. 13. The main beam of the antenna prototype scans continuously from $-53°$ (8.5 GHz) to $+37°$ (14.4 GHz). The measured antenna gain is shown in Fig. 12. A good agreement is seen between the measured and simulated results except for some minor discrepancies between them. For example, as seen from Figs. 11 and 13, for a particular beam direction the corresponding frequencies are slightly different in simulated and measured results. Similarly, for only a few frequency points, the measured gain is slightly different than the simulated ones. As mentioned before, these discrepancies may happen due to minor fabrication errors.

V. Conclusion

A modified 1-D slot array LWA with continuous beam scanning ability is presented. Initially, the OSB was suppressed using a group of vias with an appropriate diameter at the opposite side of each slot. The antenna can scan beam from backward to forward, but suffers from a sharp gain drop at higher frequencies. This issue was solved by replacing the middle via with a transverse slot. The concept was verified through unit cell dispersion analyses and full-wave simulation of the antennas. The proposed LWA was also fabricated and tested and it was found that the measured and simulated results agree well with each other.

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