# A Butterfly Substrate Integrated Waveguide Leaky-Wave Antenna

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***Abstract*—A new leaky-wave antenna taking advantage of substrate integrated waveguide technology has been introduced. This antenna has a butterfly-like configuration consisting of eight wings, i.e., eight parts. By this configuration, better gain and side-lobe level for lower elevation angles (12°–45°) are obtained while in the uniform design, these angles were scanned with poor radiation performances. Besides, an effective matching part for good impedance matching has been employed. The simulated data have been compared with measurement results and showed good consistency.**

***Index Terms*—Butterfly design, elevation angle, leaky-wave antenna, substrate integrated waveguide (SIW).**

## I. Introduction

Leaky-wave antennas which are categorized as travelling-wave antennas are mostly known for their high gain and space-scanning capability. They have the potential to scan from near broadside to near end-fire [1]. First prototypes of these antennas were designed using ordinary waveguides [2]. They were taking advantage of different slots shapes. Rectangular slots have been employed in [2] while in [3] circular slots have been used. However, waveguide leaky-wave antenna suffers from cost of fabrication along with being bulky and heavy. After the introduction of microstrip structures, a lot of leaky-wave antennas were designed based on this technology [4]–[7]. Although microstrip leaky-wave antennas have favorable performance, leaky-wave antennas based on substrate integrated waveguide (SIW) technology are becoming popular. SIW technology impersonates a waveguide such that two wide strips are placed above and below the substrate, shorted with vias on side walls. Several examples of SIW architectures have been published in the past decade [1], [8], [9]. SIWs have different advantages such as low loss, ease of fabrication, low cost and being less bulky. One of their greatest advantages is ease of integration with other planar structures which makes them attractive for microwave and millimeter-wave technology. A sample of SIW leaky-wave antenna is shown in Fig. 1. Several SIW leaky-wave antennas have been proposed after the advent of the SIW technology. Reference [10] uses radiation from side walls which is obtained by large distances between the vias. Reference [11] considers a millimeter-wave leaky-wave antenna employing $\mathrm{TE}_{20}$ mode. In [12]–[14], total space scanning is obtained using composite right/left-hand (meta) materials. An SIW leaky-wave antenna based on uniform transverse rectangular slots has been proposed in [1] which has a high gain but also an undesired high side-lobe level. In this communication, a new SIW leaky-wave antenna has been proposed. The proposed architecture has a better performance over the entire elevation angle range (10°–80°) than the one proposed in [1]. It can also be implemented using thinner substrates, so the problem of cost which arises in thicker substrates is not of primary concern. The proposed antenna shown in Fig. 2 takes advantage of a butterfly configuration, through which, a stable behavior is obtained easily. This means that the antenna will scan the lower half of the angle interval with better performance. By the geometry used in [1], one third of the elevation angle range is not covered well, meaning, high side-lobe level and low gain are obtained. But in our design, this shortcoming has been removed such that the antenna is capable of scanning almost all the interval with prescribed specifications.

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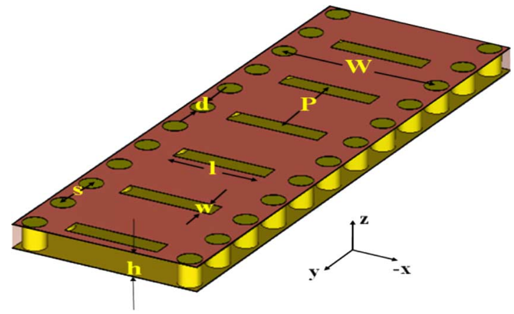



Fig. 1. Uniform leaky-wave antenna and its associated dimensions.

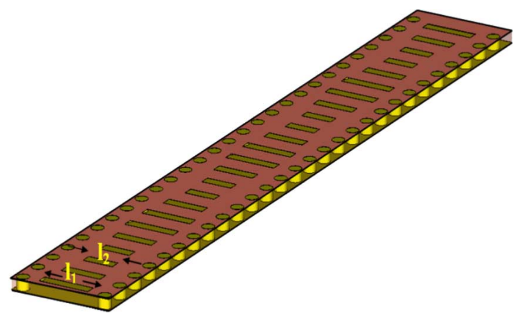



Fig. 2. Proposed butterfly configuration containing 8 similar tapered parts.

The communication is organized as follows. First, in Section II, uniform leaky-wave antennas with slot length rather than the ordinary length are investigated. Thereafter, the proposed butterfly structure is fully described. Section III investigates the characteristics of the proposed structure along with the measurement results and Section IV concludes the communication.

## II. Design Procedure

In a leaky-wave antenna radiating from broad wall, leakage is obtained by periodic slots mounted on the top wall of the structure. The slot length is

$$l = \frac{\lambda_0}{4\sqrt{\varepsilon_r}} \tag{1}$$

where $\lambda_0$ is usually chosen as the wavelength at the center frequency of operation. The slot width is better to be chosen such that $w/l \ll 1$. The periodicity of the structure, p, is normally chosen about 1/10 of the guided wavelength to avoid multi-beam operation. Moreover, $W$ is obtained by the method explained in [15]. The length of the non-tapered part of the antenna leading to 90% radiation is calculated by the formula introduced in [16]. Here, a value of 0.022 has been chosen for $\alpha/k_0$ to agree well with [1]. This value leads to a length of 220 mm at the center frequency of operation (11 GHz).

### *A. Uniform SIW Leaky-Wave Antenna*

Firstly, an SIW leaky-wave antenna with uniform slots like the one in [1] is designed. The design procedure is the same as [1], but in order

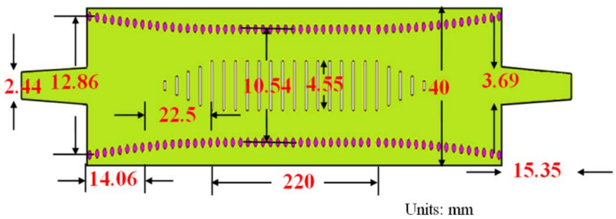



Fig. 3. Uniform SIW leaky-wave antenna.

to have a view of the experimental data, all the simulations have been done considering the exact SMA port. The simulations have been verified by Ansoft HFSS. Substrate is RT/Duroid 5880, the same as [1], but a height of 0.787 mm is chosen instead. However, no significant change in the design dimensions is made except for the matching section. A slight reduction in antenna's gain is observed which is caused by an increase in conductor loss. An increase in conductor attenuation would cause the radiation efficiency [1] to drop a little, but no considerable change could be observed overall. The dimensions of the antenna are shown in Fig. 3. It is worth mentioning that the number of non-tapered slots is 89 and the tapered length is 22.5 mm, the same as [1].

Antenna's gain, directivity, and absolute value of side-lobe level are shown in Fig. 4. It is important to note that in Fig. 4(b), the values used for gain are not the realized gain values since matching has not been taken into account. The values of realized gain are about 1 dB lower than the gain values. As could be inferred from Fig. 4, the antenna is not operating well for angles less than 45°. This means that the antenna has a lower gain and higher SLL compared to angles more than 45°. This defect stems from two facts; first, the antenna's radiation efficiency is low at lower frequencies which is tantamount to scan angles less than 45°, and second, the antenna's slot length has been chosen a quarter of the guided wavelength at the center frequency of operation which is 11 GHz. Henceforth, their length at 10 GHz is less than $\lambda_g/4$ and so good radiation could not be achieved. The first idea which comes to mind is that it might be useful to increase the slots lengths so that good radiation could be achieved. To realize this, three different values between $\lambda g/4$ and $\lambda g/2$ have been chosen. Antenna's directivity, gain and absolute value of side-lobe level for these three values along with $\lambda g/4$ and $\lambda g/2$ have been plotted in Fig. 4. Information about the frequency at which the leaky mode loses its significance [1] for each slot length is shown in Table I. It is clear from Table I that as the lengths of the slots increase, the antenna's response in frequency domain becomes fast. This means that the leaky mode loses its significance at lower frequencies compared to the normal design [1]. Also it could easily be inferred from Fig. 4 that as the slot length increases, the antenna's range of scanning decreases. However, the associated values for gain, directivity and absolute value of side-lobe level (AVSLL) for $\mathrm{l} = 9.1$ mm and $\mathrm{l} = 8$ mm are not really good especially the ones related to AVSLL. Note that SLL is negative, but in order to plot SLL and gain in one graph easily, we have defined AVSLL which is a positive value. Higher AVSLL is tantamount to lower SLL which is desired. Zero AVSLL indicates the fact that the antenna's beam is very fat, so discerning the scan angle is not possible; henceforth the leaky-wave antenna does not exhibit a good performance. As a matter of fact, $\mathrm{l} = 7$ mm and $\mathrm{l} = 6$ mm exhibit better performances compared to $\mathrm{l} = 4.55$ mm state, although their associated SLL and gain are not still acceptable.

### B. Butterfly Leaky-Wave Antenna

In order to improve the antenna's performance, mild tapering can be useful. As a first try, we taper the non-tapered part like a butterfly as shown in Fig. 5. The first slot has a length of 6 mm and the last slot in the right part of the left wing has a length of 4.55 mm. After that, the left wing is mirrored with respect to its axis of symmetry. The length of the butterfly-tapered part is chosen 220 mm, the same as the ordinary design and other parameters of Fig. 3 remain unchanged. It is worthy to mention that $\mathrm{l} = 6$ mm demonstrates better performance characteristics than $\mathrm{l} = 7$ mm as is clear from Fig. 4. So, we have chosen this value for our design along with $\mathrm{l} = 4.55$ mm. The antenna's performance is plotted in Fig. 6 . As could be observed from Fig. 6, the antenna's gain is very good but its AVSLL is poor for angles less than 60°. Although its AVSLL becomes very good in the (60°–80°) interval, poor AVSLL for most of the scanning range, caused the structure to be

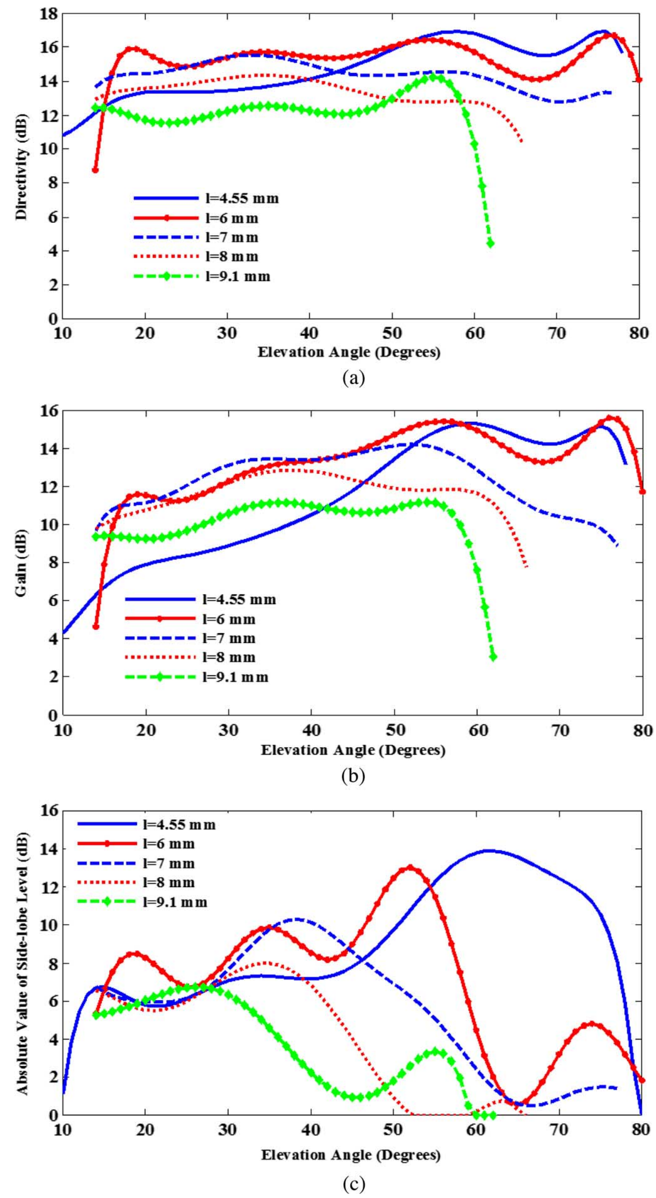



Fig. 4. Radiation characteristics of leaky-wave antenna for different variations of slot length. (a) Directivity. (b) Gain. (c) Absolute value of side-lobe level.

TABLE I
CHARACTERISTICS OF DIFFERENT VARIATIONS OF SLOT LENGTH

| Slot length (mm) | Stop frequency (GHz) | Stop angle (Degrees) |
|---|---|---|
| 4.55 | 12.2 | 80 |
| 6 | 11.4 | 80 |
| 7 | 11.1 | 77 |
| 8 | 10.55 | 66 |
| 9.1 | 10.45 | 62 |

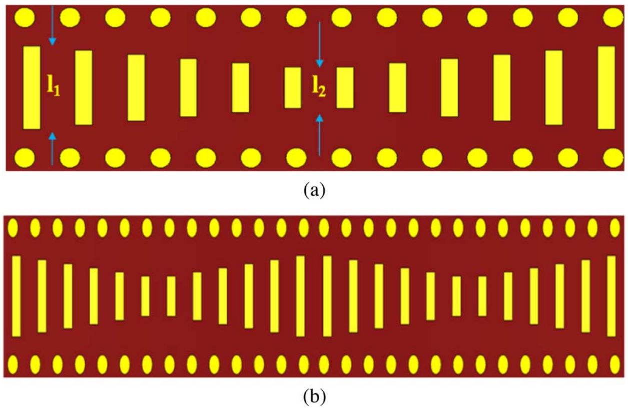



Fig. 5. Butterfly configurations. (a) 2-winged configuration. (b) 4-winged configuration.

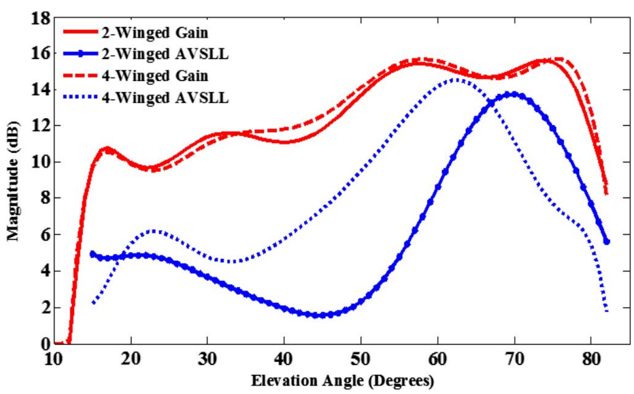



Fig. 6. Radiation characteristics of the 2-and 4-winged butterfly structures.

undesirable. One reason for poor AVSLL at most of the interval is very long tapering. As the tapering length becomes longer, the versatility of the slots decreases, meaning, slots of nearly equal lengths increase quantitatively. The less versatile the slots, the more versatile their associated beams. Note that each slot has an associated beam based on Fig. 4 and Table I. Now, suppose there are 44 slots starting from 6 mm and ending to 4.55 mm, so 5.275 mm would be the median. Therefore, 22 slots can be grouped in the (4.55 mm, 5.275 mm) interval and the remaining 22 slots fall in the (5.275 mm, 6 mm) interval. The former group, has performance characteristics like the uniform design with $\mathrm{l} = 4.55\ \mathrm{mm}$ while the latter is similar to $\mathrm{l} = 6\ \mathrm{mm}$ design. Henceforth, when we have two wings, the number of similar slots in each group is 44. This number is half the total number of slots used in a uniform leaky-wave antenna. As a result, each group acts as a leaky-wave antenna having its associated beam at a certain frequency of operation. Therefore, having high SLL at lower frequencies tantamount to angles less than $60^\circ$ is something that should be expected. This is because the antenna has two different beams pointing toward different angles with nearly the same magnitude. This causes the design to have SLL as high as $-1$ dB.

As the frequency increases, based on Fig. 4, slots longer than 4.55 mm lose their significance. This means that they stop radiation, so the antenna's SLL becomes unbelievably low at angles more than $60^\circ$. In order to improve the antenna's performance, tapering should be perturbed in a way that the slots lengths become more different from one another such that when they become grouped, number of similar slots in the groups becomes less considerable than the aforementioned state.

To remedy this, a configuration which consists of 4 wings as shown in Fig. 5(b) has been tested. As shown in Fig. 6, the antenna still suffers from unacceptable SLL. Henceforth, in order to solve this, the number

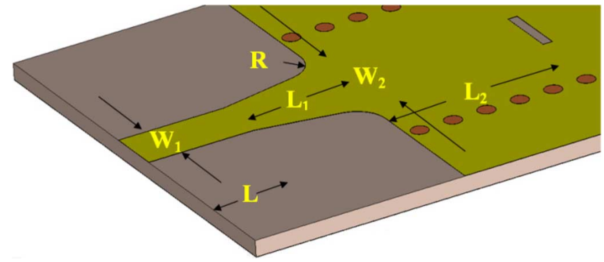



Fig. 7. Proposed matching scheme.

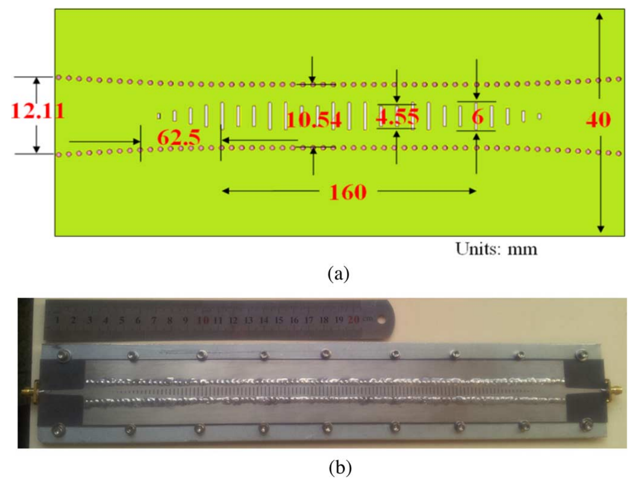



Fig. 8. Geometry of the proposed structure. (a) Dimensions of the SIW part of the leaky-wave antenna (Not to scale). (b) Fabricated antenna.

of the wings (or equivalently the parts) should be increased so that the slots become more versatile. As a third guess, a design with eight parts has been tested which showed very good radiation characteristics. This design has been fully described in the next section. One might think of using 10, 12, 14, 16 or more parts for designing the butterfly antenna in order to improve the radiation characteristics. This has been examined by the authors and showed no significant improvement over the 8-winged design.

## III. Final Structure

Based on what was described in the last section, we designed an 8-winged butterfly SIW leaky-wave antenna with superior features over its uniform counterpart. Fig. 7 shows the antenna's matching network. The scheme is similar to [1] but with some manipulations. The edges, where the matching network connects the structure, i.e., the beginning of the SIW, have been blended like a quarter of a circle of radius R to obtain better matching. Also the length $\mathrm{L}_2$ which denotes the free distance (No slots included) from the beginning of the SIW structure to the center of the first slot has been employed to control mainly the reactance of the line [13]. Length L has the duty of suppressing multi-mode behavior caused by the connection of SMA to the microstrip line. $\mathrm{W}_1 = 2.44\ \mathrm{mm}$ has been chosen based on the standard 50 $\Omega$ impedance. An optimization process has been done and values of $\mathrm{W}_2 = 3.95\ \mathrm{mm}$, $\mathrm{L}_1 = 18.03\ \mathrm{mm}$, $\mathrm{R} = 2\ \mathrm{mm}$, $\mathrm{L}_2 = 15.33\ \mathrm{mm}$ and $\mathrm{L} = 10\ \mathrm{mm}$ have been chosen for this design. The SIW structure would be the same as Fig. 2 with 8 wings. Each wing has 8 slots. By placing a single slot of length 6 mm at the center of the antenna, a total number of 65 slots is achieved. Other dimensions of the antenna are depicted in Fig. 8(a). The period of the slots and vias and the diameter of vias are the same as the uniform design [1]. We simulated the antenna using Ansoft HFSS and compared the results with those obtained through measurement of the fabricated sample.

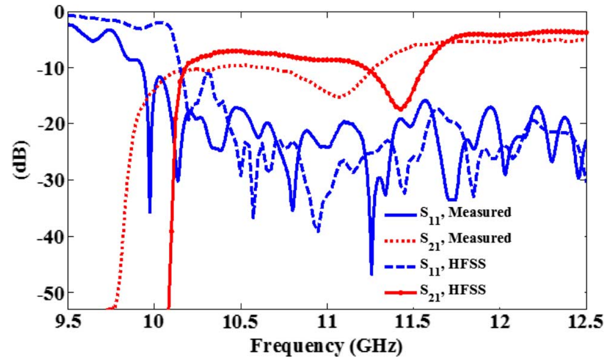



Fig. 9. Scattering parameters of the proposed design.

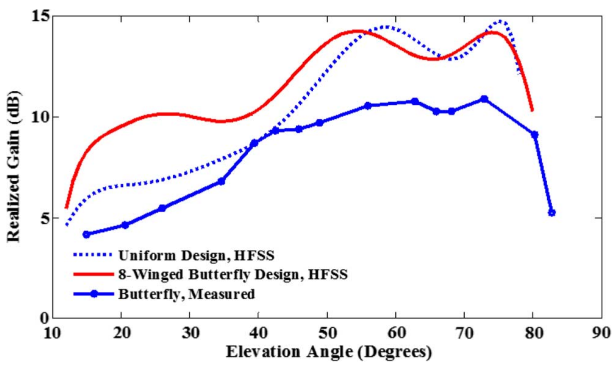



Fig. 10. Values of realized gain for the uniform design and the 8-winged butterfly design.

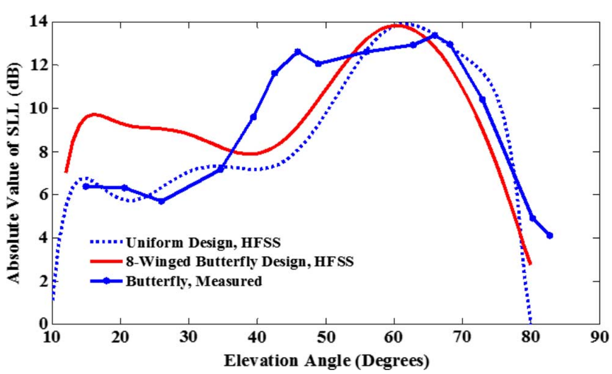



Fig. 11. Values of AVSLL.

### A. Scattering Parameters

The scattering parameters of the antenna are depicted in Fig. 9. It is clear that $S_{11}$ is well below $-10$ dB for the frequency range of interest, illuminating the fact that the matching part is well designed. Besides, measured $S_{21}$ curve is close to the simulated one. A small discrepancy is observed between the measured and simulated curves of $S_{21}$ which might be due to increased conductor loss [1]. A small frequency shift of about 300 MHz is observed, which is a common consequence of fabrication errors (such as an increase in $W$ in Fig. 1). This frequency shift does not deteriorate the scattering parameters but degrades the antenna's performance at lower frequencies tantamount to small angles. This is discussed in the next section.

### B. Gain and SLL

The antenna's radiation characteristics have been shown in Figs. 10 and 11. Fig. 10 shows the realized gain of the designed antenna along with uniform design and those obtained through measurements. It is clear that the realized gain of the 8-winged butterfly design is higher

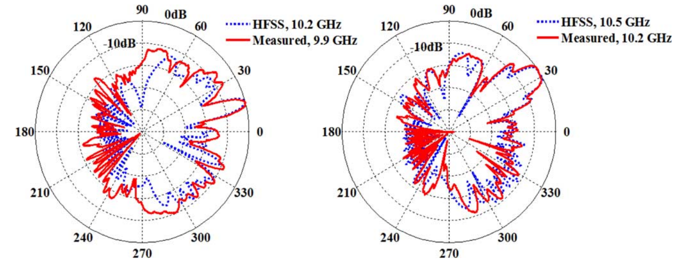



Fig. 12. Measured and simulated radiation patterns at elevation angles of 16° and 30°.

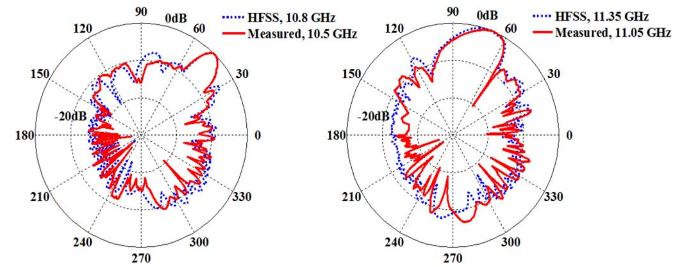
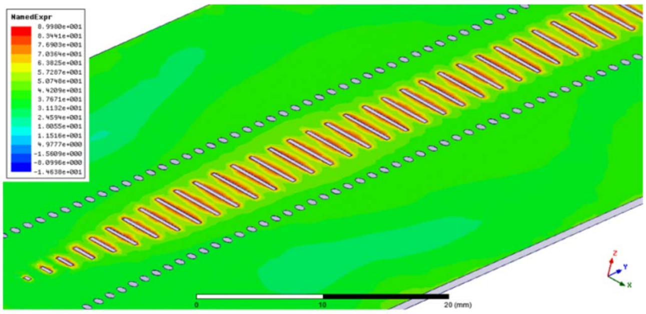


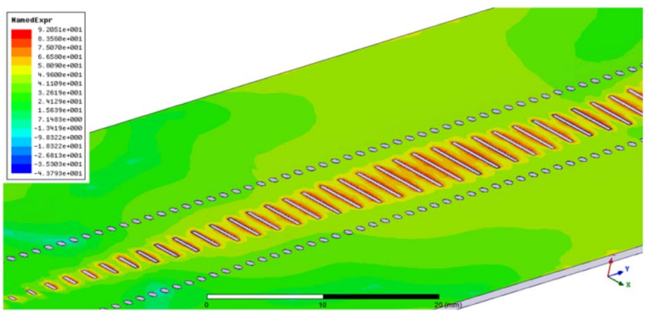

Fig. 13. Measured and simulated radiation patterns at elevation angles of 50° and 69°.

than the uniform counterpart at lower elevation angles; therefore, our design is capable of scanning the elevation angle domain with a much higher gain compared to the uniform design. An improvement of about 4 dB at small angles has been observed. The realized gain is not much perturbed at higher angles due to the elegant design of 8-winged butterfly which employs a series of slots with good versatility such that they are capable of scanning lower angles with higher gain while not altering the gain at higher angles. The measured gain curve is the same as the simulated one but is below what was obtained by simulation. Several reasons have been reported in previous works [1], [12] and [17] for the measured gain values being lower than the simulated ones. Two of them are of great importance. First, this antenna is electrically large, so in order to measure the antenna's radiation characteristics, a large anechoic chamber is required. As the frequency increases, the problem gets worse since $\lambda$ decreases. As a result, based on the $2D^2/\lambda$ criterion which denotes the far-field for an antenna, a larger anechoic chamber is required. Second, the conductor loss is higher in the fabricated antenna than the simulated one, causing a slight drop in gain [1]. There is another factor especially in our structure which degrades the antenna's gain. Because of a frequency shift of 300 MHz, the slots lengths become electrically smaller. The reason why this happens is that the slots have been designed based on 11 GHz, while now, the center frequency has been changed to 10.7 GHz. So the slots lengths should be modified. To remedy this, the slots lengths are scaled by the correction factor (11/10.7). An improvement of about 1 dB for realized gain values at angles less than 35° was observed.

Note that the antenna's measured realized gain values at the lower elevation angle domain are close to the simulated results for the uniform design. This is another indication that the antenna's realized gain has been improved at smaller angles; because values of about 3 dB for 25° and 7 dB for 45° have been reported in [1], while our measured data are 5 dB and 9 dB respectively. As could be easily inferred from Fig. 11, the antenna has a favorable AVSLL in the elevation angle domain which prevails its uniform counterpart. The measured values are close to the simulated ones with a slight difference. The main reason for this discrepancy in measurement results is the aforementioned frequency shift which causes the slots to become electrically smaller. By correcting the slots lengths as stated earlier, an improvement of about



(a)



(b)

Fig. 14. Magnitude of electric field (dB) for elevation angle of 26°. (a) Uniform design. (b) 8-winged butterfly design.

1.5 dB was seen for angles less than 35°. Beyond 35°, the AVSLL starts to increase as expected.

### C. Radiation Patterns

Figs. 12 and 13 show the antenna's radiation patterns. As was stated earlier in the text, a frequency shift of 300 MHz was observed between the simulated and measured data. As a consequence, we sketched the patterns at the same elevation angles. It could easily be seen that the 300 MHz frequency shift is present in Figs. 12 and 13. On the other side, very good consistency between the measured and simulated radiation patterns could be observed at the same elevation angles. It is worthwhile to mention that the antenna's frequency range of operation is (10.2 GHz, 11.8 GHz) based on the simulation data and (9.9 GHz, 11.5 GHz) based on measurement results.

### D. Field Analysis

Fig. 14 shows the magnitude of electric field (dB) for both uniform and 8-winged structures at a specified elevation angle of 26°. Comparing Fig. 14(a) with Fig. 14(b) explains why the 8-winged structure has better performance characteristics than the uniform design. It is clear that the electric field intensity between adjacent slots in the uniform design, depicted by green, is less than that in the 8-winged design, depicted by orange and even red. Thus, the more intense the electric field, the better the radiation would be. However, the field intensity of the uniform design at higher elevation angles, tantamount to better radiation performances, is similar to Fig. 14(b). This indicates the fact that by using butterfly design, we have been able to improve antenna's radiation at lower elevation angles.

## IV. Conclusion

In this communication a new SIW leaky-wave antenna was introduced. First, a uniform design was investigated which suffers mainly from high SLL and low gain for elevation angles less than 45°. Afterwards, in order to achieve better radiation specifications, an 8-winged butterfly configuration has been introduced. The structure has lower SLL and an improved gain for smaller scan angles compared to the uniform design. The antenna was fabricated and good consistency was observed between the measured and simulated results.

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