Thinned Array Inspired Quasi-Uniform Leaky-Wave Antenna With Low Side-Lobe Level

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***Abstract*—In this letter, a new quasi-uniform leaky-wave antenna is proposed. The structure of antenna is based on an air-filled rectangular waveguide in which the radiation occurs through transverse slots on the broad wall of the waveguide. This antenna is designed using a systematic method based on the thinned array theory in order to achieve a low side-lobe level (SLL). The designed antenna radiates at center frequency of 10 GHz at $\theta = 60^\circ$ with the SLL of about –20 dB. The proposed antenna scans a part of forward quadrant with low SLL and high gain over the frequency band of 9.8–10.2 GHz. Simulated and measurement results of the antenna are investigated; there is a good consistency between measurement and simulation results.**

***Index Terms*—Leaky-wave antenna, side-lobe level (SLL), slotted waveguide, thinned array.**

I. Introduction

LEAKY-WAVE antenna is a guiding structure in which the radiation occurs due to the leakage of the traveling wave from a guiding structure to the free space [1]. Waveguide leaky-wave antennas are classified into three types: uniform, quasi-uniform, and periodic [1]–[4]. The uniform waveguide leaky-wave antenna contains a single long slot, and it can only scan the forward quadrant of space, i.e., from broadside to forward endfire [1]–[3]. The quasi-uniform waveguide leaky-wave antenna contains multiple closely spaced slots, so this antenna is similar to uniform waveguide leaky-wave antenna and can only scan the forward quadrant [1], [2]. The periodic waveguide leaky-wave antenna contains multiple slots that are separated from each other by greater distances. By selecting a proper distance between slots, in addition to forward quadrant, it can also scan the backward quadrant, i.e., from backward endfire to broadside [1]–[3].

Our main goal in this letter is to reduce the side-lobe level (SLL) of the quasi-uniform waveguide leaky-wave antenna with transverse slots. There are several ways to reduce the SLL of a waveguide leaky-wave antenna. Among them, amplitude tapering is one of the most common methods. In this method by changing the shape, length, or width of the slots, SLL of the antenna is reduced [5]–[8]. In [5] by changing the shape of the slot, SLL of a uniform substrate integrated waveguide (SIW) leaky-wave antenna was reduced to –29.3 dB. In [6], a quasi-uniform SIW leaky-wave antenna was designed by tapering slots length to have an endfire radiation with low SLL ($\sim$ –20 dB) and high gain. In [7], a butterfly configuration was applied to a quasi-uniform SIW leaky-wave antenna, which results in a reduction of SLL to about –14 dB. In [8] by changing the width of slots, the SLL of a quasi-uniform SIW leaky-wave antenna decreased to –15 dB.

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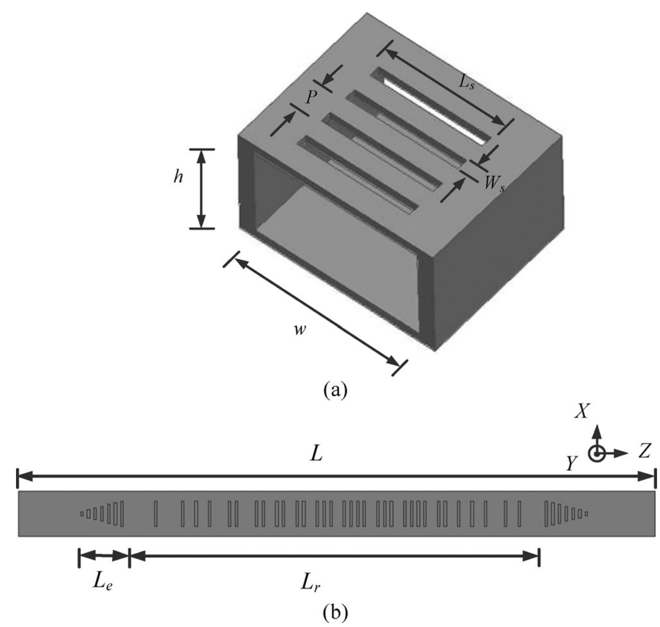

Fig. 1. Structure of the proposed antenna. (a) 3-D view of a section of the antenna. (b) Top view.

The other method for reducing the SLL of an antenna is the space tapering. This method is widely used in antenna arrays. However, it is rarely used for reducing the SLL of the quasi-uniform and periodic waveguide leaky-wave antenna. In this method by changing distances between slots of the antenna, SLL is reduced.

In this letter, a new quasi-uniform waveguide leaky-wave antenna with transverse slots is designed, simulated, and fabricated. This antenna, which is shown in Fig. 1, has lower SLL than similar antennas with uniform aperture distribution. To reduce SLL, a systematic design procedure that is based on thinned arrays is used. In a thinned or density tapered array, some of the elements are turned off in order to reduce SLL [9]. This leads to an unequally spaced array; hence, the operation of this array is based on the space tapering. In the proposed antenna, to turn off an element, we simply remove the slot from the structure.

Finding an optimized array with a large number of elements, without using an optimization algorithm, is not a simple task [9]–[12]. Therefore, we will use the genetic algorithm (GA) as a numerical optimization technique.

II. Design Procedure

In the design procedure, we consider center frequency, main lobe angle, and half-power beamwidth at the center frequency as the input parameters. The main lobe angle in a leaky-wave antenna is calculated by

$$\theta_0 = \cos^{-1}\left(\frac{\beta}{k_0}\right) \tag{1}$$

where θ_0, β, and k_0 are the main lobe angle from the forward endfire, the phase constant of the wave along the longitudinal axis of the structure, and the free space wave number, respectively [1], [2]. The half-power beamwidth in radians is approximately calculated by

$$\Delta\theta \cong \frac{\lambda_0}{L_r \sin\theta_0} \tag{2}$$

where L_r, $\Delta\theta$, and λ_0 are the radiation length, the half-power beamwidth, and the free space wavelength, respectively [2].

First, we find β from (1) and then we determine L_r from (2). In order to have a single beam scanning, we assume $p = \lambda_0/10$ [7]. With the aim of having control over the leakage rate, we consider $W_s/L_s \leq 0.1$ where L_s and W_s are the length and width of the slot, respectively. Furthermore, a proper value for the height of waveguide *(h)* is chosen.

Using slots on the waveguide as radiating elements of the antenna, causes that the propagation constant of the structure differs from that of a waveguide without slots. However, since the slots in this antenna are narrow, we first assume that β approximately equals to the phase constant of a rectangular waveguide without slots. Hence by considering that TE_{10} mode is excited, the width of an air-filled rectangular waveguide can be calculated by

$$w = \frac{c}{2\,f_c} = \frac{c}{2\,f\sqrt{1-\left(\frac{\beta}{k_0}\right)^2}} \tag{3}$$

where c, f_c, and w are the velocity of light in the free space, cut-off frequency, and the width of the rectangular waveguide, respectively [13]. Since we do not consider the effect of the slots in (3), the calculated w from (3) is only an initial guess.

Now in order to include the effect of slots on the propagation constant, we approximately consider this antenna as an infinite periodic structure in which each unit-cell has the length of p and contains one slot. Hence, we can simulate a unit-cell of the structure for different values of L_s and w in order to obtain the diagrams of phase constant and attenuation constant (α). Phase constant and attenuation constant of an infinite periodic structure with period of p are calculated by

$$\beta = \mathrm{Im}\left\{\frac{\cosh^{-1}\left(\frac{s_{12}s_{21}+((1+s_{11})(1-s_{22}))}{2s_{21}}\right)}{p}\right\} \tag{4}$$

$$\alpha = \mathrm{Re}\left\{\frac{\cosh^{-1}\left(\frac{s_{12}s_{21}+((1+s_{11})(1-s_{22}))}{2s_{21}}\right)}{p}\right\} \tag{5}$$

in which S_{ij} is the scattering parameter of a unit-cell of the periodic structure [13]. By using the obtained phase constant diagram from (4) and the calculated value of β from (1), the possible values of L_s and w are found. Moreover, the corresponding value of α is found from the attenuation constant diagram.

Finally, we use the idea of thinned arrays in order to reduce the SLL of the antenna. To do so, we write a MATLAB code that is based on the theory of the antenna arrays. Here, we consider that the proposed antenna is similar to the *N*-element array with inter element spacing of *p*. We assume that the phase difference between adjacent slots is βp. Moreover, we consider that by radiating from each slot, the amplitude of the propagating wave through the structure decreases with the coefficient of $e^{-\alpha p}$. If the amplitude of an element is 0, it must be removed from the array. As stated before, we use GA as an optimization algorithm. We define the maximum SLL of the array factor as the cost function of GA that must be minimized. Overall, by implying thinned array idea and GA, we determine the presence or absence of each element of the array for achieving the minimum SLL.

As mentioned before, the phase and attenuation constants that were obtained in the previous step, are for an infinite periodic structure, while a thinned array is not periodic. Hence, there is an approximation in the presented design procedure. However, as it will be seen in the next section, this procedure leads to good results and by only tuning the value of *w*, the required characteristics can be achieved.

III. Geometry of the Structure

We consider $f_0 = 10\,\mathrm{GHz}$ as the center frequency, $\theta_0 = 60^\circ$, $\Delta\theta = 10^\circ$. Besides, we choose $p = \lambda_0/10 = 3\,\mathrm{mm}$, $W_s = 1\,\mathrm{mm}$, and $h = 10\,\mathrm{mm}$. Related to choosing the waveguide height, *h*, it should be noted that by decreasing the height, the waveguide conducting loss increases. Also by increasing the value of *h*, the cut-off frequency of the higher order modes is reduced, which limits the bandwidth of antenna. By using (2) and (3), L_r and initial guess for *w* are 198.5 and 17.3 mm, respectively. Initially, before thinning this antenna contains 66 slots.

Now, we simulate the unit-cell of the structure. It should be noted that by simulating multiple unit-cells we achieved the same results. It means that the mutual coupling between adjacent slots can be neglected in the design procedure. Phase constant and attenuation constant diagrams for different values of L_s and *w* are shown in Figs. 2. and 3, respectively. By using (1), β is about 104.7 rad/m. From Fig. 2. we select $L_s = 11.5\,\mathrm{mm}$ and $w = 16.5\,\mathrm{mm}$. Fig. 3. indicates that the corresponding α is about 7 Np/m.

Finally, we use the thinned array idea and binary GA to determine, which elements should be turned off to reduce the SLL. The main parameters of the applied GA are as follows. The length of chromosomes is 66, which is the number of slots before thinning. The value of each gene can be 0 or 1. Population size is 20. The selection type is stochastic universal sampling. The mutation type is uniform with rate of 0.01. The crossover type is uniform with mixing ratio of 0.5. As stated before, the maximum SLL of the array factor is defined as the cost function. Other parameters of the radiation pattern, i.e., required $\Delta\theta$ and θ_0 are also considered in the algorithm as constraints. The algorithm stops, if the average change in the cost function over 50 generations is less than 1e-6. After about 200 generations, which takes about 80 s for a system with 2.8 GHz CPU, the final

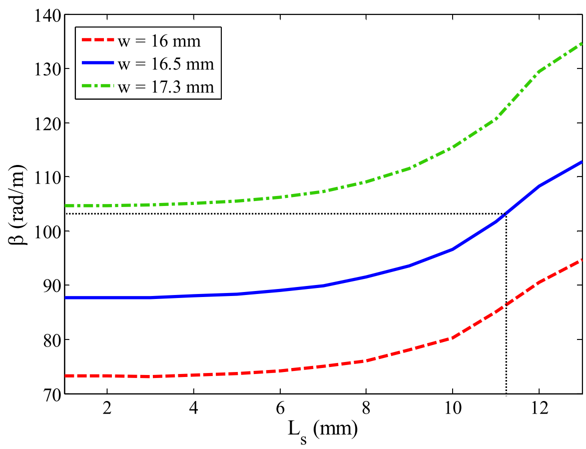

Fig. 2. Phase constant diagram of the infinite periodic structure for different values of L_s and w.

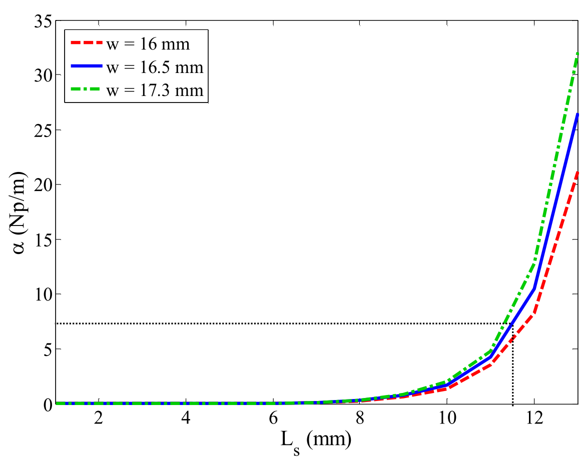

Fig. 3. Attenuation constant diagram of the infinite periodic structure for different values of L_s and w.

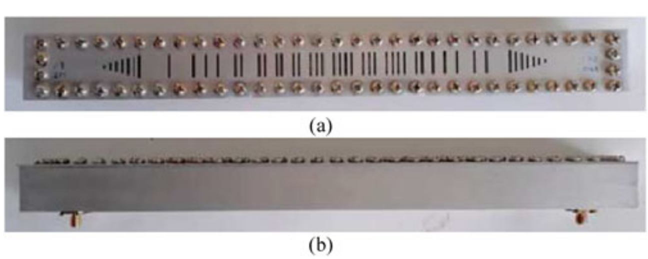

Fig. 4. Fabricated thinned array quasi-uniform leaky-wave antenna. (a) Top view. (b) Lateral view.

design can be obtained. Using this method leads to the removal of 31 elements from the structure at different positions.

Using approximations in the design procedure for calculation of the phase constant, leads to a little deviation of main beam angle from $\theta_0 = 60°$. Hence, we tune the value of w by doing multiple simulations in order to reach to the $\theta_0 = 60°$. The results shows that the best response is achieved by choosing $w = 16.8$ mm. By implying this design method, in MATLAB simulation, the maximum SLL reaches to –24.45 dB.

The fabricated antenna is shown in Fig. 4. The total length of antenna is $L = 310$ mm. We fabricated the antenna as a

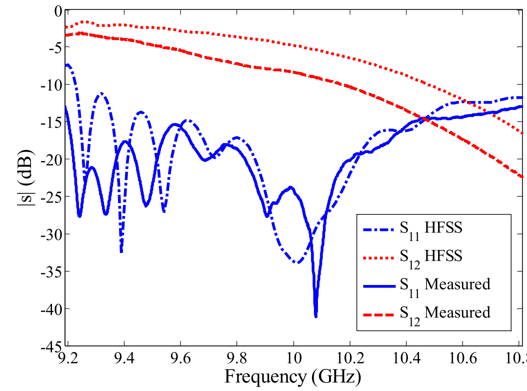

Fig. 5. Simulated and measured S -parameters of the proposed antenna.

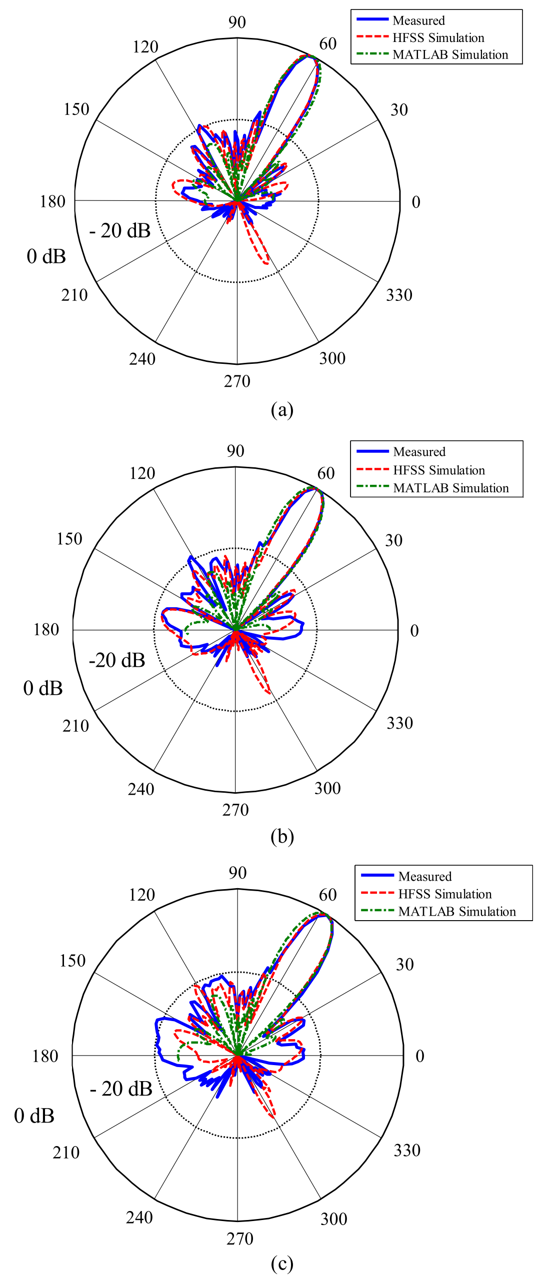

Fig. 6. MATLAB simulated array factor along with full-wave simulated, and measured radiation patterns at (a) 9.8 GHz, (b) 10 GHz, and (c) 10.2 GHz.

TABLE I
GEOMETRICAL PARAMETERS AND THE POSITION OF THE RADIATING SLOTS IN THE FINAL STRUCTURE

Parameter	W_s	L_s	p	h	w	L	L_e
Value (mm)	1	11.5	3	10	16.8	310	18

Position of radiating Slots (White rectangles are corresponding to the removed slots)

TABLE II
SIMULATED AND MEASURED GAIN OF THE PROPOSED ANTENNA

Frequency	Measured Gain	Simulated Gain
9.8 GHz	15.51 dB	13.47 dB
10 GHz	13.87 dB	14.30 dB
10.2 GHz	15.32 dB	14.84 dB

two-part structure and connected these parts with some screws. The first part is a hollow aluminum bar with “U” cross section that was fabricated using CNC machine. The second part is an aluminum plate in which, slots were embedded using wire-cut machine. The slots can perturb the TE_{10} mode of the waveguide; hence, in order to minimize unwanted end reflections [7], [8], [14], we use six additional slots at both ends of the structure and we taper the lengths of them linearly from 9.9 to 2 mm. The length of the tapered section at each end of the antenna is $L_e = 18\,\mathrm{mm}$.

The proposed antenna is connected to two similar waveguide to SMA adaptors at both ends that are united with the antenna. The distance of each SMA from the short end is 7 mm and the diameter and penetration height of the SMA core are 1.3 and 5 mm, respectively. One of the SMA connectors is terminated to a 50 Ω matched load and the other SMA connector is used for feeding the structure. In summary, Table I shows the geometrical parameters and the position of radiating slots in the final structure.

IV. RESULTS

In this section, we investigate the simulation and measurement results. All full-wave simulations are done by Ansoft HFSS 13 software.

Simulated and measured *S*-parameters are shown in Fig. 5. As seen in Fig. 5, in the frequency band of 9.2–10.8 GHz, S_{11} is approximately below –10 dB in both simulation and measurement. Hence, there is a good impedance matching at the input of the structure in this frequency band. The MATLAB simulated array factor along with full-wave simulated and measured normalized radiation patterns at three frequencies are shown in Fig. 6. It is observed that by increasing the frequency, the beam of the antenna scans part of the forward quadrant, i.e., from $\theta = 62^\circ$ to $\theta = 58^\circ$.

In addition in the frequency band of 9.8 to 10.2 GHz, the SLL is about –20 dB in both the measurement and the simulation results. It should be noted that the MATLAB simulated array factor is in the upper half-space region, i.e., from $\theta = 0^\circ$ to $\theta = 180^\circ$.

The simulated antenna efficiency at the center frequency is 68%. Simulated and measured gain values are shown in Table II. As it is seen, the proposed antenna radiates with high gain over the frequency band of 9.8–10.2 GHz.

V. CONCLUSION

In this letter, a new waveguide quasi-uniform leaky-wave antenna was designed. The proposed antenna has lower SLL than an antenna with uniform aperture distribution. To reduce SLL, we use a systematic design procedure which is based on the theory of the leaky-wave antenna, thinned arrays, and GA. The proposed antenna has been simulated, fabricated, and measured. It has a good impedance matching over the frequency band of 9.2–10.8 GHz and radiates with high gain over the frequency band of 9.8–10.2 GHz. At the center frequency, the measured and simulated main lobe angle, half power beamwidth, SLL, and gain of the proposed antenna are about 60°, 10°, –20 dB, and 14 dB, respectively. Moreover, the SLL of the proposed antenna is about –20 dB over the frequency band of 9.8–10.2 GHz.

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