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Research paper

A New Approach to Synthesis of a Quasi Non-Uniform Leaky Wave Antenna

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Abstract

Background and Objectives: In this paper, a closed-form mathematical formula has been presented using of the proposed periodic structure E-field distribution, that helps designers to calculate the width of the slots in Quasi Non-Uniform Leaky Wave Antenna (QNULWA).

Method: This method is based on two steps. In the first step, some important parameters for the proposed antenna design will be extracted using simulation. In the second step, by solving a discrete differential equation, a general relation will be obtained for these types of antennas. This method has been investigated in the case of slot LWA families.

Results: A Leaky wave antenna has been synthesized in the 15.5- 18 GHz frequency range for Gaussian radiation pattern. The results of simulation and antenna design will be very close to each other in 2.5 GHz Bandwidth (15.5 - 18 GHz), which shows the accuracy of this formula. Also, By changing the frequency range *2.5* GHz, the main lobe direction of the antenna will scan the space approximately *10* degrees (from 63 to 73 degree). The antenna has an SLL value of about *-25* dB and *13* dB Gain at whole band 15.5-18 GHz.

Conclusion: The obtained formula helps the antenna designers to calculate the dimensions this type of antenna for any pattern distribution.

Introduction

A leaky wave antenna is a type of antenna that radiates electromagnetic waves along its length rather than at its ends. It is called "leaky" because it allows some energy to leak out along the length of the antenna, resulting in radiation. Really, these antennas are designed to have a controlled radiation pattern along their length. This means that the direction and shape of the radiated beam can be adjusted by changing the properties of the antenna. By controlling the leakage of energy along the antenna, it is possible to steer the beam in a desired direction [1]-[5]. There are several types of leaky wave antennas, including:

1. Slotted Waveguide Antennas [6]-[8]: These antennas consist of a waveguide with slots cut into its walls. The slots allow energy to leak out and form a radiating wave along the length of the waveguide.
2. Dielectric Slab Leaky Wave Antennas [9]-[12]: These antennas use a dielectric slab placed on top of a ground plane. By varying the thickness and permittivity of the dielectric slab, the radiation pattern can be controlled.
3. Printed Leaky Wave Antennas: These antennas are made using printed circuit board technology. They consist of a microstrip transmission line with slots or periodic structures that allow energy to leak out and form a radiating wave.
4. Metamaterial Leaky Wave Antennas [13]-[17]: These antennas use metamaterials, which are artificially engineered materials with unique electromagnetic properties. By designing the metamaterial structure, it is possible to control the radiation pattern of the antenna.

Overall, leaky wave antennas offer flexibility in controlling the direction and shape of the radiated beam, making them suitable for various applications such as radar systems, wireless communication, and satellite communication.

No matter which category the leaky wave antenna is in, another category can be defined for it, which will be explained in more detail below.

A) A uniform leaky wave antenna is designed to have a consistent and constant radiation pattern along its length. It consists of a waveguide or transmission line with regularly spaced slots or apertures. The electromagnetic waves leak out gradually through these slots or apertures, resulting in a uniform radiation pattern without any significant variation in the radiation intensity along the antenna's length.
B) A non-uniform leaky wave antenna, on the other hand, is designed to have a varying radiation pattern along its length. It consists of a waveguide or transmission line with non-uniformly spaced slots or apertures. The non-uniform spacing of these slots or apertures causes the electromagnetic waves to leak out at different rates along the length of the antenna. As a result, the radiation pattern of the antenna varies along its length, allowing for controlled variation in the direction and intensity of the radiated waves.
C) A quasi-uniform leaky wave antenna is a combination of both uniform and non-uniform leaky wave antennas. It consists of a waveguide or transmission line with a combination of regularly spaced and non-uniformly spaced slots or apertures. This design allows for a partially uniform and partially non-uniform radiation pattern along the length of the antenna. The quasi-uniform leaky wave antenna provides some flexibility in directing and shaping the radiated waves while still maintaining a relatively consistent radiation pattern.
D) Lastly, a quasi-non-uniform leaky wave antenna is also a combination of uniform and non-uniform leaky wave antennas. It consists of a waveguide or transmission line with a combination of regularly spaced and non-uniformly spaced slots or apertures. However, in this design, the non-uniform spacing is more dominant, resulting in a radiation pattern that is mostly non-uniform with some elements of uniformity. The quasi-non-uniform leaky wave antenna offers a compromise between the constant radiation pattern of a uniform antenna and the variable radiation pattern of a non-uniform antenna, providing flexibility in directing and shaping the radiated waves.

Overall, uniform/ non-uniform/ quasi-uniform/ quasi-non-uniform leaky wave antennas offer unique advantages depending on the specific application requirements. The choice between them depends on factors such as desired radiation pattern, beam-width, and scanning capabilities.

By examining the research done in this field, we can find valuable papers, some of which deal with the synthesis and others with the design of this type of antenna. Among others, we can mention the relationship presented by Oliner [18], which is of particular importance in the synthesis of the shape of the tapering slot in the leaky wave antenna [18]-[20]. The disadvantages of this design include the ability to scan the space in only the forward quadrant space of the antenna and the difficult implementation to create the exact tapering slot. To overcome these problems, the periodic LWAs were introduced by researchers. Indeed, periodic discrete slots are used instead of continuous slot. These antennas can scan the backward and forward quadrant space of the antenna [21]-[24].

Of course, in addition to the ability to scan one or two quarters of the sphere by the leaky wave antenna, increasing the scanning angle with low frequency changes, the stability of the radiation pattern with changing the scanning angle are also the challenges of this type of antenna design, which different designs have tried to overcome this challenge [25]-[27].

The following paper is a continuation and completion of a paper [28] in which the structure of the slots and design has changed. These changes lead to the creation of a new structure called QNU-LWA, where the width of the slots have been modified along antenna and this causes the distance between the slots to change and leads to QNU-LWA. Fig. 1 shows the difference between these two structures. In the structure of QU-LWA, the phase of the E-field distribution in each slot is fixed and their amplitude is changing, but in the structure of QNU-LWA in addition to the amplitude, the phase of the E-field distribution is changing in each slot.

In paper [28], considering that the distance between the slots were equal and only the length of the slots was different, a mathematical formula was presented to calculate the length of each slot according to the desired radiation pattern. While in this paper, the length of the slots is fixed and the width of the slots are different, which is the difference between these two structures. As a result, the main innovation of this paper is to present a mathematical formula for the distribution of the desired radiation pattern to calculate the slots width of the proposed structure. Finally, to confirm the obtained mathematical formula, an antenna sample with Gaussian radiation pattern was designed and constructed in the frequency range of 15.5 to 18 GHz.

This paper consists of the following sections: In Section II, the method of obtaining the important information required for the synthesis of these antennas will be mentioned. In Section III, the mathematical design method of the antenna will be explained. In Section IV, the simulation and construction results of this antenna will be compared. Finally, Section V concludes the paper.

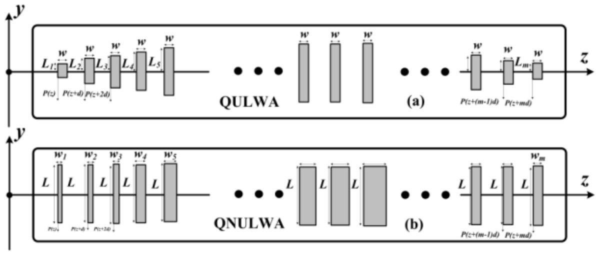

Fig. 1: (a) QU-LWA and (b) QNU-LWA model.

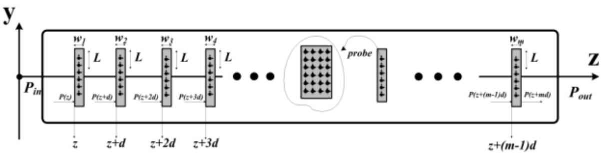

Fig. 2: Simulated antenna model to obtain the E-field distribution inside the slots.

Initial Step for Synthesizing QNU-LWA

To design this antenna, in the first step drew a QU-LWA structure in the CST software based on Fig. 2. The mentioned method in this section can be generalized to other types of LWA [28]. This structure is just an example and draws only to get the mathematical relations for the electric field inside the slots of this antenna. After the mathematical relation for antenna design is obtained in the next section, there is no need to do the first step in antenna design and can be ignored. A series of probes to measure the E-field inside these slots will then be placed on each slot. In this structure, w_m and L are the width and length of the slots and are considered constant. m is the number of antenna slots and is selected based on the $S_{21} = -10\ dB$ dispersion parameter. There are two ways to achieve $S_{21} = -10\ dB$. The first method is to increase the number of antenna slots. In this case, as shown as an example in Fig. 3, S_{21}will decrease by increasing the value of the parameter m. One of the problems with this method is the increased antenna length and the process of manufacturing and machining the antenna will be difficult. On the other hand, by increasing the length of the antenna, it will be easier to achieve a narrower 3 dB pattern. Fig. 3 shows the increase in the number of slots and the effects of this increase on the S_{21} parameter. As expected, by increases the number of slots, the value of S_{21} will decrease.

In the second method, the width of each slot w increases. As shown in Fig. 4, by increasing the w, the leakage field of each slot to the outside will increase and as a result, the parameter S_{21} will decrease.

One of the problems of this method is increasing the 3 dB beamwidth of the antenna. In antenna design, based on the need for gain and 3 dB beamwidth and antenna length limit, we select this parameter to access the appropriate S_21 value. By selecting the appropriate value for m, the distribution of the E-field inside the slot is drawn in Fig. 5. This figure shows an exponential function whose amplitude decreases along whit the antenna. This figure will change very little if the width of the slots or the number of slots changes. This figure will be the basis of antenna design in the next step.

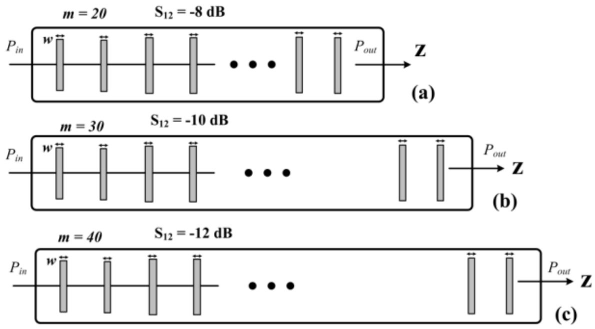

Fig. 3: Increase the number of slots and the effects of this increase on the S_{12} value.

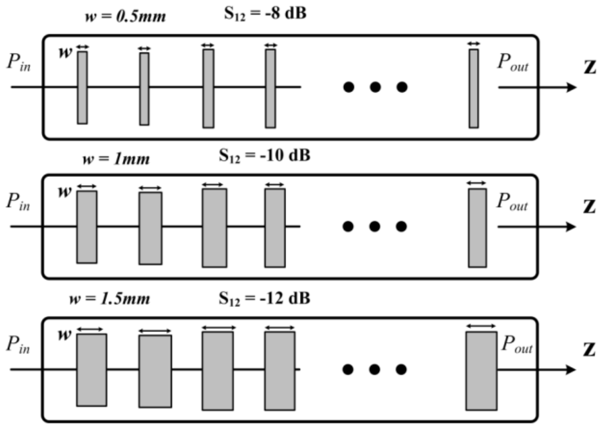

Fig. 4: Increase the width of each slots and the effects of this increase on the S_{12} value.

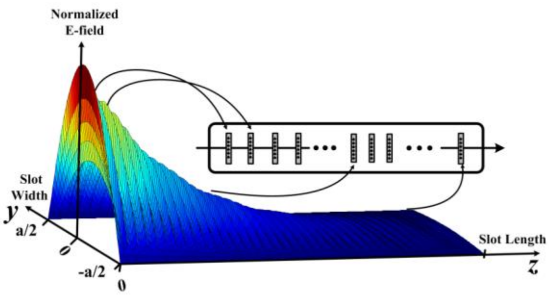

Fig. 5: The E-field distribution inside each slot.

Method of Extraction of the Mathematical Formula

According to distribution of the E-field drawn in Fig. 5, it can be written for the E-field inside the antenna slot as follows [29]-[30]:

$$E_y = \sum_{n=-\infty}^{n=\infty} E_0 cos\left(\frac{\pi}{a}y\right) exp(-\alpha z) exp\left(-j\left(\beta + \frac{2n\pi}{d}\right)z\right) \quad (1)$$

where n th Floquet mode or also referred to as space harmonic. d indicates the fixed period of each slot and a is waveguide width. α and β are leakage and phase constant of the waveguide respectively. The value of E_x and E_z is very small compared to E_y component and can be neglected. Based on the Floquet's theorem and the 3D distribution of the E-field in Fig. 5, it is expected that the E-field and the radiation power are periodic. In Fig. 5, function $exp\left(-j\left(\beta + \frac{2n\pi}{d}\right)z\right)$ decreases with the exponential function $exp(-\alpha z)$ during the antenna length. First, it is supposed that P_{in} is the input power applied to the antenna, some input power is radiated by each slot and the remained power at the antenna end is absorbed by the match load. w_1, w_2, ..., w_i and L are the width and length of the slots of each segment. In the QU-LWA antenna design, the amount of w is constant and L is changed in each slot, while in QNU-LWA, L is constant and w changes in each slot. Based on the periodic structure in Fig. 5 and Floquet's theorem, geometric periodicity forces the field to be periodic. So, it can be defined as a periodic function for the radiation power of each segment $P(z)$ as [13]:

$$\begin{aligned} &P(z+d) = CP(z) \\ &P(z+2d) = CP(z+d) \\ &P(z+3d) = CP(z+2d) \\ &\vdots \\ &P(z+id) = CP(z+(i-1)d), i = 1,2,\dots,m \end{aligned} \quad (2)$$

where C^i is the form of:

$$C^i = \sum_{n=-\infty}^{n=\infty} \exp(-2\alpha i d) \exp\left(-2j\left(\beta + \frac{2n\pi}{d}\right)id\right)$$
$$i = 1,2,\dots,m \quad (3)$$

where m is the number of slots in the antenna. In (3), $P(z)$ is the applied power to the antenna. Part of the power will be propagated to the outside of the antenna and $P(z+id)$ is applied power to the i th slot, where $i = 1,2,\dots,m$. The radiation power in each slot is proportional to the input power, size of the slot, and $|E_y|^2$ coefficient. So, for total radiation in each slot, it can be written based on [29] as follows:

$$P_{rad} = \frac{P_{in} - P_{in}}{P_{out}} = cos^2(\pi/_a L_i)A \times L \sum_{i=1}^{m} w_i C^i = \sum_{i=1}^{m} P_{r,i} \quad (4)$$

A is a coefficient of $^1/_{meter^2}$ that will be calculated in the future. $P_{in} = P(z)$ is input power, $P_{out} = P(z+id)$ is output power and $y = L$. While P_{rad} is the total radiation power of the antenna and $P_{r,i}$ is the radiation power in each slot. In order to implement a mathematical distribution function, the radiation power must follow the amplitude distribution such as Gaussian. Suppose that the desired aperture distribution or slot radiation is T_i, $i = 1,2,\dots,m$, so:

$$cos^2(\pi/_a L)A \times L \times w_i C^{i-1} = BT_i^2 \quad (5)$$

where B is a constant coefficient. Finally, gives w_i the form of (6):

$$\mathrm{w_i} = \frac{\mathrm{BT_i^2}}{\mathrm{A \times L \times cos^2(\pi/_a L) C^{i-1}}} \quad (6)$$

One of the unknown parameter of (6) is A. To calculate A according to $i = 1$ in the (5), $BT_1^2 = A \times L \times cos^2(\pi/_a L)w_1$, it can be written as:

$$\mathrm{A} = \frac{\mathrm{BT_1^2}}{\mathrm{w_1 \times L \times cos^2(\pi/_a L)}} \quad (7)$$

Since, in (6), the amplitude distribution is calculated for a slot on the antenna, the value of C^i should be an absolute value and therefore used $|C^i|$ instead of C^i. Combining (6) and (7), it can be concluded that w_i as:

$$w_i = \frac{w_1}{|C^{i-1}|}\left(\frac{T_i}{T_1}\right)^2, w_i < d, \quad i = 1,2,\dots,m \quad (8)$$

Equation (8) is a very simple relation that shows, to calculate the width of the slots, only needed the width of the initial slot w_1, C^i and distribution coefficients T^i. To get the initial conditions w_1 consideration the $T_m^2 = T_1^2$ for distribution coefficients, so $w_1 < |C^{m-1}|d$ and as a result, the allowable range for w_1 is shown with dashed line in Fig. 6.

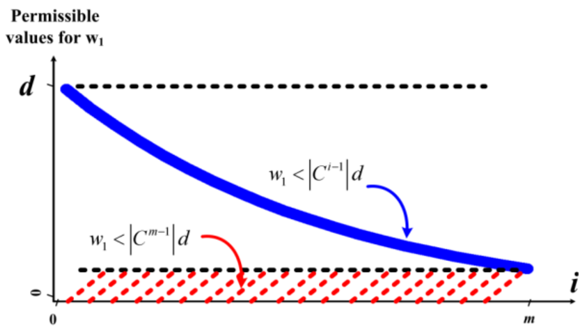

Fig. 6: Allowable range for selection $\mathrm{w_1}$ parameter.

By selecting a suitable interval for w_1 and using (8), the w_i coefficients can be obtained as Table 1. In this case, Gaussian distribution coefficients are used. Other distribution coefficients such as ChebyChef, Taylor, and ... can also be used and the different properties of these distributions can be implemented on the antenna. In this structure, the distance between the two slots d is fixed, and the width of the slot w_1 is changing based on Table 1. By selecting the Gaussian distribution and using (8), the slot shape on the antenna wall can be designed. Fig. 7 shows how the use of a Gaussian distribution leads to the creation of a series of slot structures on the antenna wall.

Table 1: The value of calculated w_i

i	w_i	i	w_i	i	w_i	i	w_i
1	0.5745	11	1.8366	21	3.4211	31	3.8431
2	0.6649	12	1.9960	22	3.5539	32	3.7151
3	0.7640	13	2.1583	23	3.6750	33	3.5494
4	0.8719	14	2.3223	24	3.7817	34	3.3493
5	0.9882	15	2.4870	25	3.8711	35	3.1203
6	1.1128	16	2.6512	26	3.9398	36	2.8696
7	1.2450	17	2.8138	27	3.9841	37	2.6056
8	1.3842	18	2.9735	28	4.0000	38	2.3367
9	1.5298	19	3.1290	29	3.9839	39	2.0707
10	1.6809	20	3.2788	30	3.9324	40	1.8145

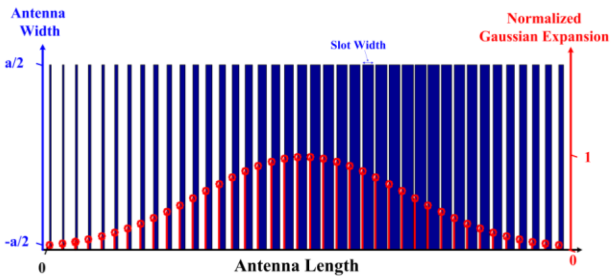

Fig. 7: The Width of the slots designed based on (8) and the Gaussian coefficients to be created on the antenna wall.

Simulations and Results

For a detailed study of the mathematical relationship expressed in (8), compared in this section simulations results with practical measurement results. The photograph of the construction antenna is shown in Fig. 8. The antenna consists of two parts that are connected with screws. The lower part is made of aluminum and the upper part is made of stainless steel to be able to withstand machining stresses. Due to the need for high accuracy in the manufacturing process, the CNC machine with micron precision has been used. Making the first slots $(i = 1 - 2, w_1 = 0.5645,\ w_2 = 0.6649)$ were complicated because they were so thin and it is with some errors.

The manufacturing antenna parameter is shown in Table 2. The simulation and measure test results pattern of the antenna are shown in Fig. 9. The antenna at 2.5 GHz bandwidth shows very acceptable results compares to the simulation. By changing the frequency range 2.5 GHz, the main lobe direction of the antenna will scan the space approximately 10 degrees (from 63 to 73 degree). The antenna has an SLL value of about -25 dB and 13 dB Gain. By the theory of Gaussian expansion coefficients with coefficient number 40 and $\sigma = 1.7$, we should reach SLL about -27 dB. Therefore, the results of simulation and antenna design are very close to the theoretical results. Fig. 10 shows S_{11} and S_{21} in both simulation and measure test. The results of the simulation and measure tests are very similar. An important point is that initially the antenna was designed for $S_{21} = -10$ dB, but in Fig. 10 it has reached about $S_{21} = -40$ dB. The reason for this difference is that we initially chose the width of the slots as fixed, but changed the width of the slots using (8), These changes have improved the antenna radiation to the outside space and the value of S_{21} has been somewhat improved.

Table 2: Antenna physical parameter

a	b	L_{slot}	L_{total}	t	d	m	f_0	BW
10.1 mm	5 mm	175 mm	235 mm	1 mm	3.8 mm	40	16.75 GHz	2.5 GHz

Fig. 8: The photograph of the fabricated antenna.

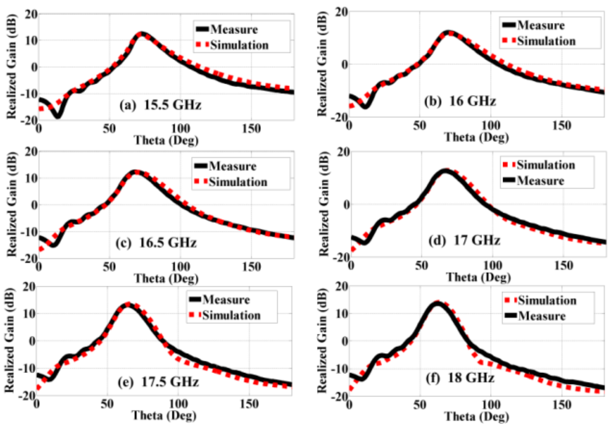

Fig. 9: Theoretical and measured patterns for the QNULWAs. (a) 15.5 GHz. (b) 16 GHz. (c) 16.5 GHz. (d) 17 GHz. (e) 17.5 GHz. (f) 18 GHz. based on (8) and The value of calculated w_i (Table 1).

Variations of the beam angle and α/k_0 based on the variation of frequency are shown in Fig. 11. The antenna main beam scans with frequency changes; in fact, it moves from 64 to 72 degree as the frequency decrease from 18 to 15.5 GHz. Through analyzing the changes in α/k_0 and β/k_0, caused by frequency variations, the possible radiation frequency range can be found. In other words, the dimensions for the structure, which make the desired radiation pattern possible within the operating frequency range, are selected.

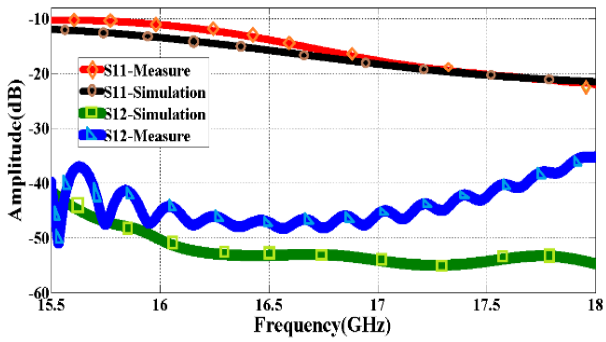

Fig. 10: Theoretical and measurement S_{11} and S_{12}.

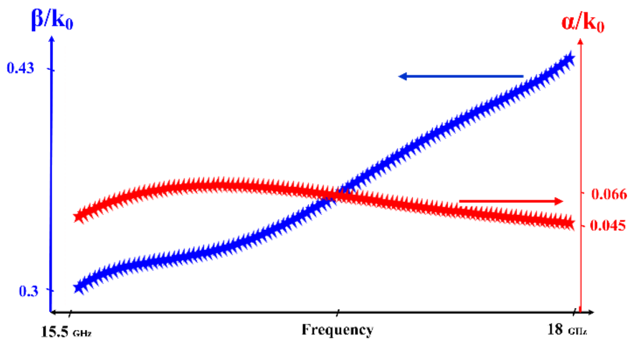

Fig. 11: Leaky-mode propagation constant α/k_0 and β/k_0.

As mentioned in the introduction, the main goal of this paper is to derive the mathematical formula for QNU-LWA antenna synthesis. Then, an antenna sample was designed to confirm the formula. Finally, Table 3 compares the design antenna specifications with some other references reported in recent years.

Table 3: Compare of the design antenna specifications with some other references

Reference no.	Frequency range (GHz)	Scanning range (Degree)	Gain (dB)	Side-Lob level (dB)	Antenna Type
[22]	11.7 to 19.6	-61 to +34	14.1	-12	A symmetrical SIW
[23]	9.5-13.7	+5 to +81	15.7	-15	SIW with Dumbbell-shaped slots
[24]	9.3 to 9.93	-65 to +65	NA	NA	Composite right/left-handed
[25]	6 to 16	-68 to +23	16.86	NA	Hole array spoof surface plasmon polaritons
[26]	9.2 to 10.8	58 to 62	14.5	-20	Quasi-uniform leaky-wave antenna
This work	15.5 to 18	63 to 73	13	-25	Quasi-Non-Uniform leaky-wave antenna

Results and Discussion

In this paper, a mathematical formula to synthesis the QNU-LWA was presented. Using a method based on simulation and obtaining the distribution E-field inside the slots and solving a differential equation, it was possible to calculate the width of slots in the QNU-LWA.

To verify the obtained formula, an antenna with Gaussian distribution for the radiation pattern was synthesized and constructed. The simulation results confirm the correctness of the formula. Also, the simulation and construction results of this antenna are exactly the same.

Author Contributions

A. Kiani and F. Geran conceived the idea, analyzed the theoretical feasibility, and wrote the manuscript. S.M. Hashemi carried out the full-wave simulations and performed the measurements.

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Conflict of Interest

The author declares that there is no conflict of interest regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy have been completely observed by the authors.

Conflict of Interest

The authors declare no potential conflict of interest regarding the publication of this work. In addition, the ethical issues including plagiarism, informed consent, misconduct, data fabrication and, or falsification, double publication and, or submission, and redundancy have been completely witnessed by the authors.

Abbreviations

QU-LWA	Quasi Uniform Leaky Wave Antenna
QNU-LWA	Quasi non-uniform leaky wave antenna

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