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Periodic Leaky-Wave Antenna with Transverse Slots Based on Substrate Integrated Waveguide

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Abstract—**In this paper a new periodic leaky-wave antenna based on substrate integrated waveguide (SIW) is proposed and investigated. The proposed antenna uses multiple transverse slots in the upper plane of the SIW for radiation into the free space. This antenna operates in the first negative Floquet mode. Therefore, it scans the backward quadrant by a single beam over the frequency band of 14.6 to 20.2 GHz. The proposed antenna is simulated and the results are investigated.**

Keywords—Floquet modes; leaky-wave antenna; periodic structure; substrate integrated waveguide.

I. Introduction

Leaky-wave antenna is a kind of traveling wave antennas family [1]. This antenna is a guiding structure in which radiation occurs due to a traveling wave [2]. Leaky-wave antenna has an interesting ability to scan free space by changing the frequency [1]–[6]. Therefore, due to the scanning ability of leaky-wave antennas, they are very useful in the navigation systems.

One of the most common structures for realization of leaky-wave antennas is waveguide. Generally waveguide leaky-wave antennas are classified into three different types which are uniform, quasi uniform, and periodic waveguide leaky-wave antennas [1]–[6]. The uniform waveguide leaky-wave antenna only contains a long slot and it can only scan forward quadrant of space i.e., from broadside to forward endfire [1]–[5]. This antenna is the simplest one among all kinds of leaky-wave antennas. A systematic design procedure for the uniform waveguide leaky-wave antenna has been presented in [7]. The quasi uniform waveguide leaky-wave antenna contains multiple narrow slots which are too close to each other, so the behavior of this antenna is very similar to the uniform waveguide leaky-wave antenna [5], [6]. Since this antenna operates only in the fundamental Floquet mode, it can only scan forward quadrant [1], [2]. On the other hand, the periodic waveguide leaky-wave antenna contains multiple narrow slots that are separated from each other by greater distances. Depending on the operating frequency band and geometrical characteristics of this antenna, it can operate in different Floquet modes. By modifying the distances between slots, in addition to forward quadrant, this antenna can also scan the backward quadrant i.e., from backward endfire to broadside [1]–[5].

In the past, most of the waveguide leaky-wave antennas were realized based on rectangular waveguides and cylindrical waveguides [1], [2]. However waveguides are bulky and their fabrication is costly and time consuming [8], [9]. In recent years, after introducing SIW structures, many researches have been made in the field of SIW leaky-wave antennas [5]-[9]. SIWs have several advantages over ordinary waveguides due to their low cost of production, ease of fabrication, ease of integration, low mass, and compact size [8], [9]. Furthermore, frequency sensitivity of SIW is more than frequency sensitivity of an air-filled waveguide; therefore, SIW leaky-wave antenna is more useful for scanning applications.

In [8] a SIW quasi-uniform leaky-wave antenna with transverse slots was proposed that could scan the forward quadrant. In [9] by implementing a butterfly configuration in a SIW leaky-wave antenna, gain and side lobe level (SLL) were improved. In [10] by using a systematic method similar to [7], SLL was reduced; the proposed antenna in [10] radiates at near endfire with high gain. In [11] by using H shape slots in a SIW leaky-wave antenna, a circular polarization was achieved. In [12]-[15] waveguide leaky-wave antennas based on the composite right/left handed (CRLH) structures are proposed in order to have a continuous radiation from backward to forward including broadside.

In this paper a new periodic SIW leaky-wave antenna with transverse slots is designed and simulated results are provided. The organization of this paper is as follows. At first, the theory of leaky-wave antennas and Floquet's theorem will be investigated. Then the structure of the proposed antenna will be introduced and after that the simulated results will be presented and investigated.

II. Theory

A. *Theory of Leaky-Wave Antenna*

Leaky-wave antenna must operate in the fast-wave region to radiate to the free space [1]–[3]. In the fast-wave region, the phase velocity is greater than the velocity of light in the free

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space; therefore, in leaky-wave antenna the primary condition of the radiation is

$$-k_0 \le \beta \le k_0 \tag{1}$$

where β is the phase constant of the wave along the longitudinal axis of the structure and k_0 is the free space wavenumber [2]. The main lobe angle in a leaky-wave antenna is calculated by

$$\cos\theta_0 = \beta_n / k_0 \tag{2}$$

where θ_0 is the main lobe beam angle from forward endfire and β_n is the phase constant of nth space harmonic [2]. Moreover, the beamwidth is calculated by

$$\Delta\theta \cong \frac{\lambda_0}{L_r \sin\theta_0} \tag{3}$$

where L_r is the radiation length and λ_0 is the free space wavelength [1].

B. Floquet's theorem

Floquet modes or space harmonics are based on Floquet's theory [1]-[3]. They have been widely used in the analysis and design of periodic structures. They are also useful in the design and analysis of the periodic leaky-wave antenna. Using Floquet's theorem and dispersion diagram, we can find the regions in which periodic leaky-wave antennas can radiate.

Because the SIW is fundamentally equivalent to rectangular waveguide, the theory of the SIW leaky-wave antenna is similar to the theory of the rectangular waveguide leaky-wave antenna which is presented in [16]. In a periodic waveguide leaky-wave antenna the dispersion diagram is obtained by

$$\beta_n = \beta_0 + \frac{2\pi n}{p} \tag{4}$$

$$\beta_0 \cong k_0\sqrt{\varepsilon_r}\sqrt{1-\left(\frac{f_c}{f}\right)^2} \tag{5}$$

where β_0, n, p, ε_r and f_c are phase constant of the fundamental space harmonic, which is approximately equal to the phase constant of the waveguide dominant mode, number of space harmonic, period, relative permittivity and cutoff frequency of the waveguide, respectively [1], [2].

Based on (2) and (4), space harmonics with $n \ge 0$ can only scan the forward quadrant, but space harmonics $n < 0$ can scan both backward and forward quadrants. However, the appearance of multiple space harmonics and waveguide modes limits the range of the single beam scanning in SIW periodic leaky-wave antennas [1].

III. Geometry of the Proposed Antenna

We consider the center frequency, main beam angle, and beamwidth at the center frequency as the inputs of the design procedure. Based on (1), (4), and (5) we choose the appropriate values for ε_r, f_c, and p such that in the desired frequency band the radiation occurs only due to the n = -1 space harmonic. This leads to a single beam scanning in the backward quadrant. By using (3) we find L_r and by knowing the values of L_r and p we determine the number of slots.

In the proposed antenna which is shown in Fig. 1, Rogers RT/Duroid 5880 substrate with ε_r = 2.2 is used. The thickness and the width of dielectric layer are 0.79 mm and 30 mm, respectively. Length of the structure is L = 317 mm.

In this structure twenty-two slots as radiating elements are used. The length and the width of each slot are L_s = 4.5 mm and w_s = 0.5 mm, respectively. The period of the structure is p = 10 mm and the radiation length of the antenna is L_r = 227 mm. Also to improve the impedance matching, three additional slots at both ends of the structure are used and the lengths of them are changed from 4.5 mm to 1.5 mm. The length of this tapered section at each end of the antenna is L_e = 30 mm.

For feeding this structure, two microstrip lines with the length of L_m = 15 mm are used. Furthermore, for making a better impedance matching at the input and the output, we taper each microstrip line, so the width of each microstrip line changes from 3.1 mm to 4.7 mm continuously. The antenna is fed by a coaxial cable via SMA connector. Furthermore, the proposed antenna is terminated to a 50 Ω matched load.

The parameters of SIW are calculated based on formulas which were introduced in [17]. Diameters of vias are 0.8 mm, distance between vias is 1.6 mm, and w = 10.5 mm. Moreover, for improving impedance matching of the structure, at both ends of the structure we change the distance between vias along x-axis from w = 10.5 mm to w_1 = 12.9 mm.

The dispersion diagram of the proposed antenna is presented in Fig. 2. This diagram is based on this assumption that by introducing slots in the structure, phase constant remains the same as phase constant of the structure without slots. According to Fig. 2, proposed antenna can radiate with a

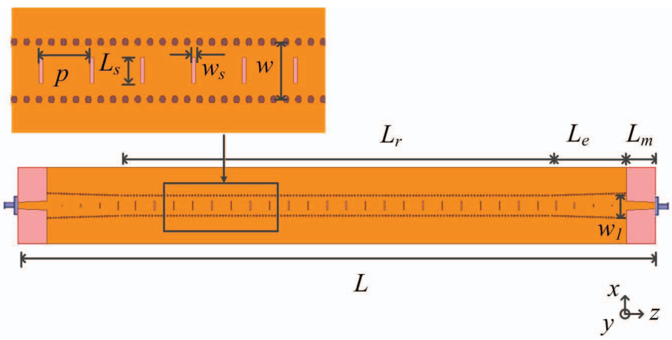


Fig. 1. The structure of the proposed antenna.

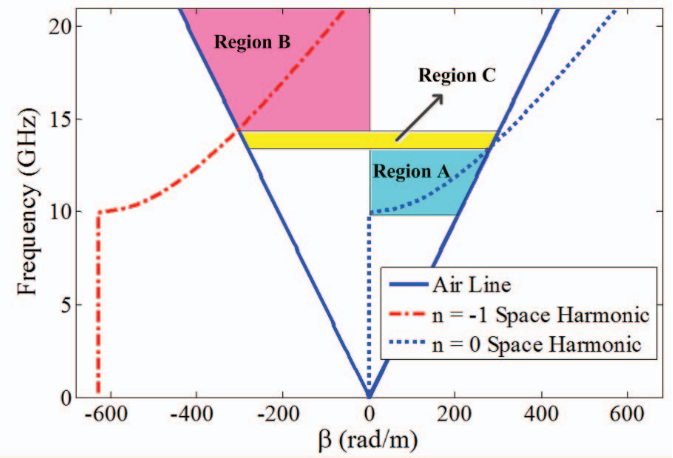


Fig. 2. Dispersion diagram of the proposed antenna.

single beam, only in two radiation regions which are labeled as region A and region B. In the region A, radiation with a single beam occurs in the forward quadrant due to the $n = 0$ space harmonic and the frequency band of this region is from 10 to 13.8 GHz. In the region B, radiation with a single beam occurs in the backward quadrant due to the $n = -1$ space harmonic in the frequency band of 14.6 to 20.2 GHz. However, when the frequency is about 20 GHz, the beam of the antenna enters the broadside region and radiation characteristics of the antenna degrade, since at broadside the open stopband occurs [1]-[6]. Moreover, Fig. 2 shows that in the frequency band of 13.8 to 14.6 GHz, which is labeled as region C, no radiation occurs. The reason of this fact is that in this particular region no space harmonic is in the fast-wave region, so no leakage occurs.

Since the radiation efficiency in the case of forward radiation is low, the proposed antenna cannot scan forward quadrant with high gain. In fact periodic leaky-wave antenna is not useful for forward radiation applications [1], [2]. Therefore, periodic leaky-wave antenna is more useful for scanning the backward quadrant [1]-[6].

IV. SIMULATED RESULTS

In this section we investigate simulated results for the case of backward radiation. In this case the radiation occurs due to $n = -1$ space harmonic which is the first negative Floquet mode. All simulations are done by Ansoft HFSS 13.

S-parameters are shown in Fig. 3. As observed in Fig. 3, in the frequency band of 15.8 to 19.4 GHz, S_{11} is approximately below −10 dB, which indicates that a good impedance matching occurs at the input of the structure.

Directivity and radiation efficiency diagrams are shown in Fig. 4 and Fig. 5, respectively. The obtained radiation efficiency contains dielectric and conductor loss as well. Fig. 4 and Fig. 5 indicate that by increasing the frequency, directivity and radiation efficiency increase. However, when the beam of the antenna enters broadside region, since open stopband occurs, directivity and radiation efficiency decrease.

The radiation patterns in φ = 90° plane for three typical frequencies are shown in Fig. 6. Since the corresponding cross-polar patterns are too small in compared to the co-polar patterns, they are not shown in Fig. 6. As observed in Fig. 6,

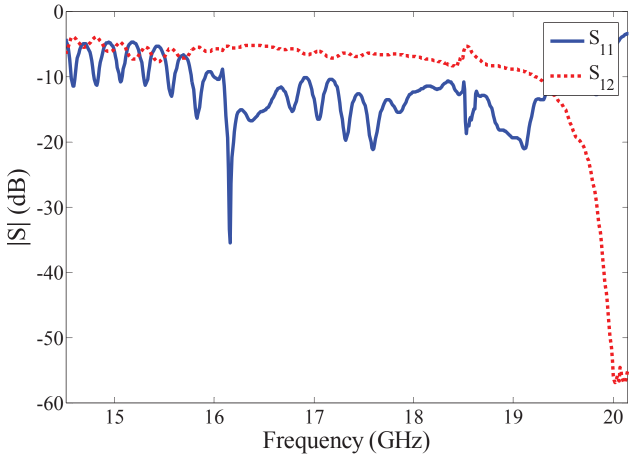


Fig. 3. Simulated *S*-parameters of the proposed antenna.

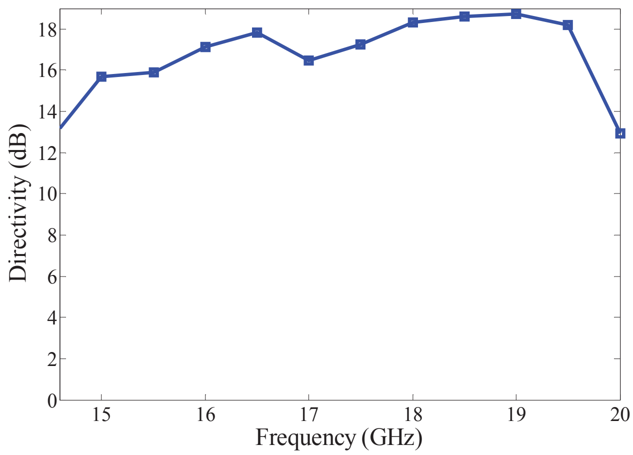


Fig. 4. Simulated directivity of the proposed structure.

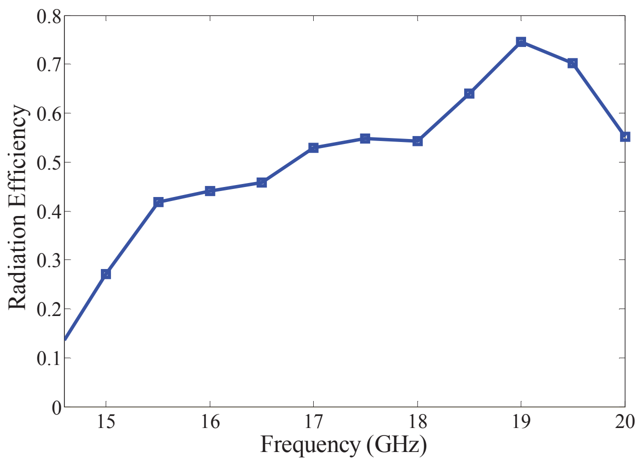
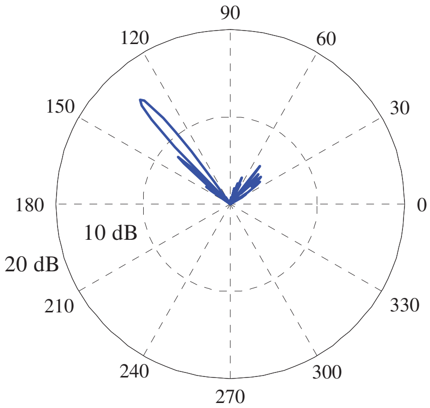
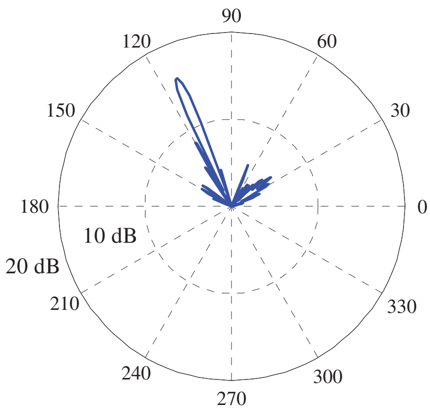


Fig. 5. Simulated radiation efficiency of the proposed antenna.

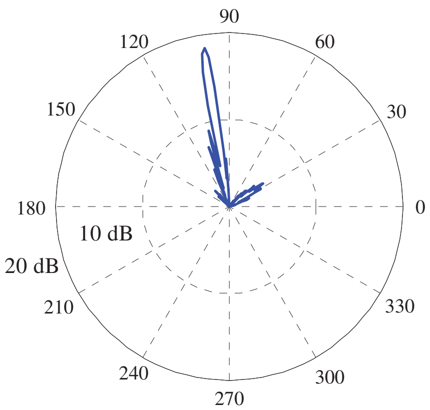
by changing the frequency from 16 to 19 GHz, the beam of the antenna scans part of the backward quadrant i.e., from $\theta = 131°$ to $\theta = 99°$. Furthermore, Fig. 6 shows that by increasing frequency, the beamwidth decreases. These facts are confirmed by (2) and (3). The co-polar and cross-polar radiation patterns in $\theta = 113°$ plane at 17.5 GHz are shown in Fig. 7 as well. Backward radiation results indicate that the proposed antenna can scan backward quadrant with high gain and directivity.



(a)



(b)



(c)

Fig. 6. Simulated radiation pattern in $\varphi = 90°$ plane at (a) 16 GHz, (b) 17.5 GHz, and (c) 19 GHz.

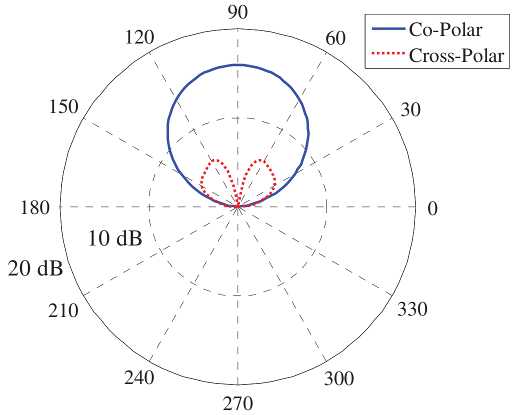


Fig. 7. Simulated radiation pattern in $\theta = 113°$ plane at 17.5 GHz.

V. CONCLUSION

A new SIW leaky-wave antenna was designed based on the theory of leaky-wave antenna, Floquet's theorem, and dispersion diagram. Since SIW is more compact and has more frequency sensitivity than an air-filled waveguide, the proposed antenna is more useful for scanning applications. Moreover, the proposed antenna has the ability to scan the backward quadrant with high gain. The proposed antenna has been simulated and some of the antenna parameters such as *S*-parameters, directivity, radiation efficiency, and scanning capability of the antenna were separately investigated.

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