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High Gain Printed Radial Leaky Wave Antenna for Millimeter-Wave Applications

Abduladeem Beltayib [1]*, Allafi Omran [2], Yahya Entiefa Mansour [3]
[1,2,3] Electrical Engineering Department College of Technical Sciences Bani Walid, Libya

*Corresponding author: adeem81@gmail.com

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Abstract:
This paper proposes a two-dimensional (2D) radial printed periodic leaky-wave antenna (LWA). The proposed LWA is designed using substrate-integrated waveguide (SIW) technology. A radial substrate-integrated waveguide (SIW) with rectangular SIW is designed, and then two-dimension slots on the top of the proposed structure are etched. The wave propagation inside the guide is leaked out through periodic slots, the distribution of these slots results in a low side lobe level (SLL), and a high gain. As a result of the geometry of the proposed antenna and slot distribution, the radiation pattern gained a promised properties such as a high gain, a low side lobe level (SLL), and low cross-polarization. The simulated gain of the antenna is 20 dBi with SLL less than -21 dB and cross-polarization less the -35 dB. The antenna is proposed in order to work with millimeter-wave (mm-wave) applications. The resulting proposed antenna is simulated through a well-known full wave simulator CST STUDIO package.

Keywords: Leaky-wave antenna (LWA), High Gain Antenna, Millimeter-wave,

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الملخص
تقترح هذه الورقة تصميم هوائي ثناءي الابعاد (2D)للموجة المتسربة دوريا والمطبوع على شكل نصف قطري. تم تصميم الهوائي المقترح باستخدام تقنية الدليل الموجي المدمج في الركيزة (SIW). تم تصميم دليل موجي نصف قطري متكامل مع الركيزة (SIW) مع SIW مستطيل، ثم بعدها تم حفر فتحات ثنائية الأبعاد في الجزء العلوي من الهيكل المقترح. في هذا التصميم يتم تسريب انتشار الموجة داخل الدليل من خلال فتحات دورية، وينتج عن توزيع هذه الفتحات مستوى فص جانبي منخفض(SLL) ، وكسب مرتفع. ونتيجة للشكل الهندسي للهوائي المقترح وتوزيع الفتحات، تحصلنا على نتائج جيدة تتمثل في الكسب العالي، ومستوى الفص الجانبي المنخفض(SLL) ، والاستقطاب المتقاطع المنخفض. حيث يبلغ الكسب المحاكي للهوائي 20 ديسيبل مع مستوى SLL أقل من -21 ديسيبل واستقطاب متقاطع أقل من -35 ديسيبل. تم اقتراح الهوائي للعمل مع تطبيقات الموجات الملليمترية (موجة ملم). تمت محاكاة الهوائي المقترح الناتج من خلال حزمة CST STUDIO المعروفة لمحاكاة الموجة الكاملة.

الكلمات المفتاحية: هوائي الموجه المتسربة، هوائي عالي الكسب، الموجه الملليمترية.

Introduction

In this era of emergent wireless communication networks such as 5G and 6G networks, the growth of the number of multi-applications in existing or emergent networks, mobile users expect unlimited capacity anytime and everywhere, at an affordable cost, millimeter wave frequencies, which offers huge bandwidth, has been considered as a solution. Unfortunately, the air molecules resonantly interact negatively with electromagnetic waves at mm-wave frequencies, causing characteristic of the antenna results. The wave attenuation is brought on by this resonance, and it worsens in the presence of rain and hail. In addition to the basic difficulty of wave transmission in the mm-wave spectrum, interferences, and multi-path waves significantly attenuate the signal [1].

Due to all of the issues that restrict wave propagation in mm-wave spectrum, high-gain antennas with beam-developing characteristics need to be developed to compensate for both natural and artificial hindrances. Since the last fifth decades, traveling wave antennas, including leaky wave antennas, have been introduced for use in mm-wave applications. Leaky-wave antennas (LWAs) are a unique category of travelling-wave radiating structures that have been an area of interest and inspiration for mm-wave and microwave applications, including wireless communication systems, automobile radar, and sensors, for decades. Its many attractive characteristics, such as its low profile, easy to use feeding mechanism, strong directivity, narrow beam, and frequency beam-scanning capabilities, are responsible for this. The leaky wave antennas are commonly classified into two main categories, which are principally uniform and periodic forms [2]. Uniform LWAs feature a fast wave dominant mode ($\beta < k_0$) that leaks at discontinuities, radiates in the forward quadrant, and scans from broadside to end fire. In other words, periodic LWAs radiate in both the forward and backward quadrants. This kind of scannable antenna have the ability to scan from the backward end to the forward quadrant's partial area [3].

In recent years, many types of LWA have been proposed and designed in the mm-wave band [4-7]. In [4], a 4 2x2 and 4x4 MIMO SIW antenna is designed. This design provides a maximum gain of 7.3 dBi and 8.1 dBi in the K band (18 GHz–27 GHz) region. In [5], the authors presented a design of leaky wave antenna for 5G application based on a partially reflective surface (PRS) and high impedance surface (HIS). The design fed by a printed dipole antenna and used a piezoelectric actuator (PEAs) as phase shifting. The antenna offers about 13.7dBi with a beam scanning angle of 43^o over the entire frequency band (50-60) GHz.

Other high leaky wave antennas are studied in detail in [8,9]. A two-dimensional (2D) periodic leaky-wave antenna (LWA) is studied and designed. The authors in [8] used a dielectric-filled wedge-like waveguide as a medium for wave propagation. Quasi-TEM wave inside this structure is leaked out through periodic rings of narrow slots, resulting in a high gain frequency-dependent beam. In [9], using the same technique which uses lossy dielectric material in order to excite leaky wave mode, resulting in high gain of around 20dBi. Although both designs offer good performance, they are relatively bulky.

In [10,11], a variety of leaky wave structure antennas working at mm-wave spectrum have been introduced. The goal of these designs is to achieve beam scanning and high gain, where the highest obtained gain was at 18 dBi, while the lowest gain was 10.8 dBi. Even though [10] has acceptable bandwidth, it suffers from high SLL (−5 dB). In [11], the maximum gain is approximately 18dBi, Although the mentioned antenna has a narrow bandwidth.

In this paper, the beam scanning technique using printed radial slot leaky wave antenna, where the slots are etched and arranged period arcs to provide a beam scanning with high gain, low side lobe level, and a low cross-polarization of over the interested bandwidth. The radiation pattern and all the simulation results were done using CST.

Antenna Design and Theory

A. The Concept of the LWA

For designing an LWA radiating in the broadside free space, it is essential to operate in the fast-wave region space [12], in which the primary condition for designing an LWA is

$$-k_o \leq \beta \leq k_o \quad \ldots\ldots\ 1$$

Where k_o is the free space wavenumber and β is phase constant of the wave along the guide structure. Based on selecting appropriate values for dielectric constant and slot distribution, radiation occurs only due to the space harmonic, which leads to beam scanning of the radiation pattern in the backward quadrant.

The angle of the main lobe radiation pattern (θ_n) can be determined by

$$sin(\theta_n) = \frac{\beta_n}{k_0} \qquad \ldots\ldots 2$$

where β_n is the phase constant of nth space harmonic, in which the space harmonic based on the Floquet’s theory. Based on the radial waveguide that introduced in [8] and Floquet’s theorem, the dispersion diagram can be obtained by

$$\beta_n = \beta_0 + \frac{2\pi n}{p} \qquad ......3$$

Where, p is the period, the number of the space harmonic in the radial waveguide. Because the thickness of the radial waveguide allows Q-TEM mode wave to propagate inside the guide while suppressing the other modes.

B. SIW fundamental mode

The substrate-integrated waveguide is a line between two rows of vias that act as a perfect electric conductor (PEC) surrounding boundaries. This structure confines the field between vias rows and makes it evenest at the PEC boundaries. The propagation mode behavior of SIW is similar to the field distribution of the metallic conventional rectangular waveguide (WG). The fundamental mode in both SIW and conventional WG is TE10 mode.

From this point, similar to rectangular waveguide, the fundamental mode of full-mode SIW is TE10 mode and its field distribution can be expressed as

$$E_z = -j\frac{\omega\mu a}{\pi} A_{10} sin\frac{ny}{a} e^{-j\beta x} \qquad ......4$$

$$H_x = A_{10} cos\frac{nz}{a} e^{-j\beta x} \qquad ......5$$

Where A_{10} is an arbitrary amplitude of fundamental mode.

Based on equation (4), the Electric field distribution of the first mode in the SIW along the x-axis can be estimated and plotted by using CST. The electric field distribution of the first mode of a SIW is shown in Fig. 1. It is clear that the fundamental mode (TE10) has even symmetry.

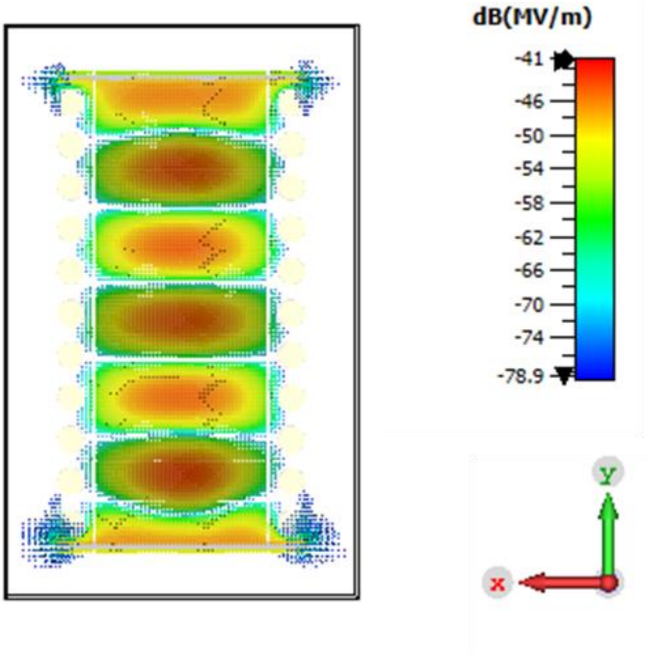


Figure 1. Electric field distribution of the fundamental mode (TE10).

C. Antenna Configuration

A two-dimensional (2D) periodic leaky-wave antenna (LWA) is built on RT/Duroid 5880 substrate, which has a dielectric constant 2.2 and loss tangent of 0.0009 with a thickness of 1.575 mm. As shown in Fig.2, the proposed structure consists of the feeding guide and the radiation part (Radial Waveguide). The radial waveguide and excitation guide are built using substrate-integrated waveguide (SIW) technology. As shown in Fig. 2, the walls built by via metallic. All the dimensions of the antenna are indicated in Table 1.

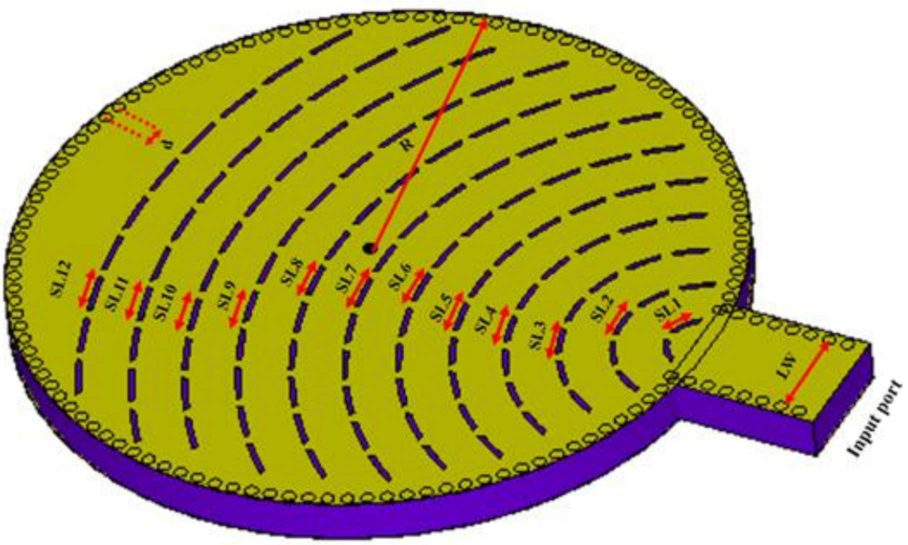


Figure 2 The geometry of the proposed Radil Leaky Wave Antenna structure.

Both the radial waveguide and excitation guide are filled with the dielectric constant of 2.2. The dielectric-filled rectangular waveguide has dimensions of w =7.51 mm and h = 1.575 mm.

Table 1

parameter	SL1	SL2	SL3	SL4	SL5	SL6
Value(mm)	2.61	2.622	2.7	2.8	2.91	3.002
parameter	SL7	SL8	SL9	SL10	SL11	SL12
Value(mm)	3.13	3.24	3.35	3.46	3.57	3.68
parameter	R					
Value(mm)	25.35					

The challenge in this type of antenna is providing beam scanning, high gain, and low side lobe level simultaneously. In order to meet all these requirements, narrow slots with the same width and tarped length, are etched on the top plate. The slots are distributed over 12 rings.

Results and discussion

Fig. 3 shows plots of both simulated S-parameters and simulated realized gains. In the target frequency band, the simulated realized gains are roughly 20 dBi with a variation of less than 3 dBi. in contrast to the steady gain throughout the entire relevant frequency range (38 to 46 GHz). The reason for this is that deteriorated losses from materials (conductors and dielectrics) happen as the frequency decreases and approaches the SIW cut-off. The results show the reflection coefficient is below −10dB from 38 GHz to 46 GHz.

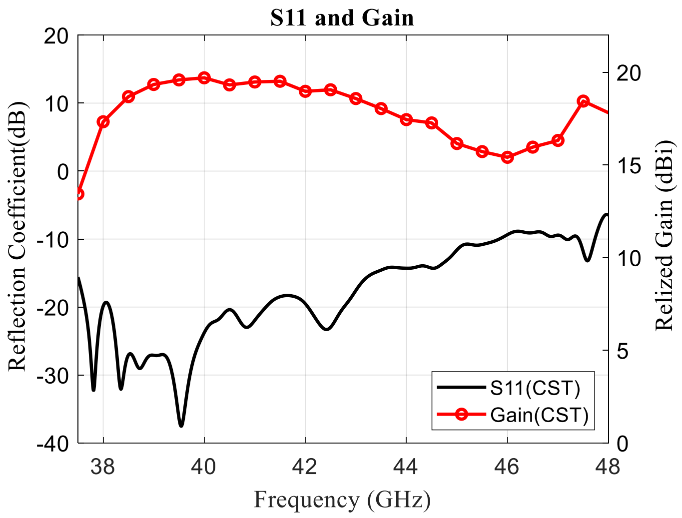
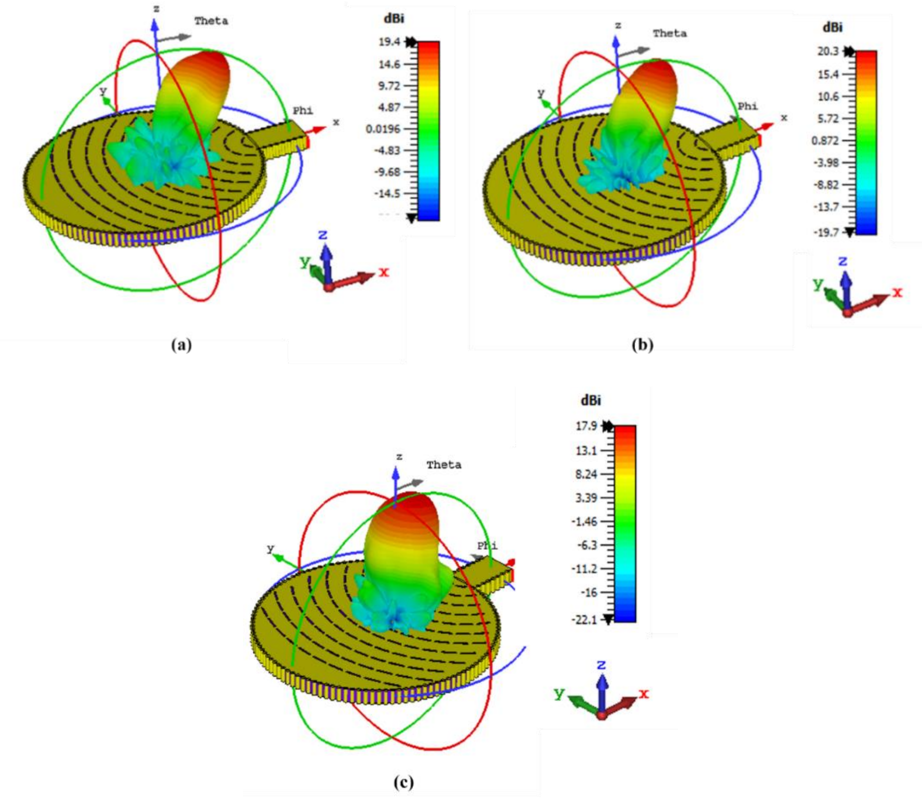


Figure 3 Reflection-coefficient and Realized Gain of the proposed Radil Leaky Wave Antenna structure.

Diagrams of the proposed 3-D radiation patterns are simulated and presented in Fig.4. The realization of an omnidirectional radiation beam in the azimuth plane is demonstrated, and it is shown that the omnidirectional beam's scan improves with frequency. The energy flows upward and the scanning beam increases with frequency from the direction perpendicular to the axis because the design is fed from the side of the radial proposed structure.

Fig.5 shows the radiation pattern and cross-polarization of the proposed antenna for frequencies 38.5,39.5,40.5,41.5,42.5,43.5,45.5 and 46.5 GHz in E-plane. From the figures, the radiation pattern has good properties such as a high gain, a low side lobe level (SLL), and low cross-polarization.



(a) (b) (c)

Figure 4 3D radiation pattern at 38.5,41.5,44.5GHz

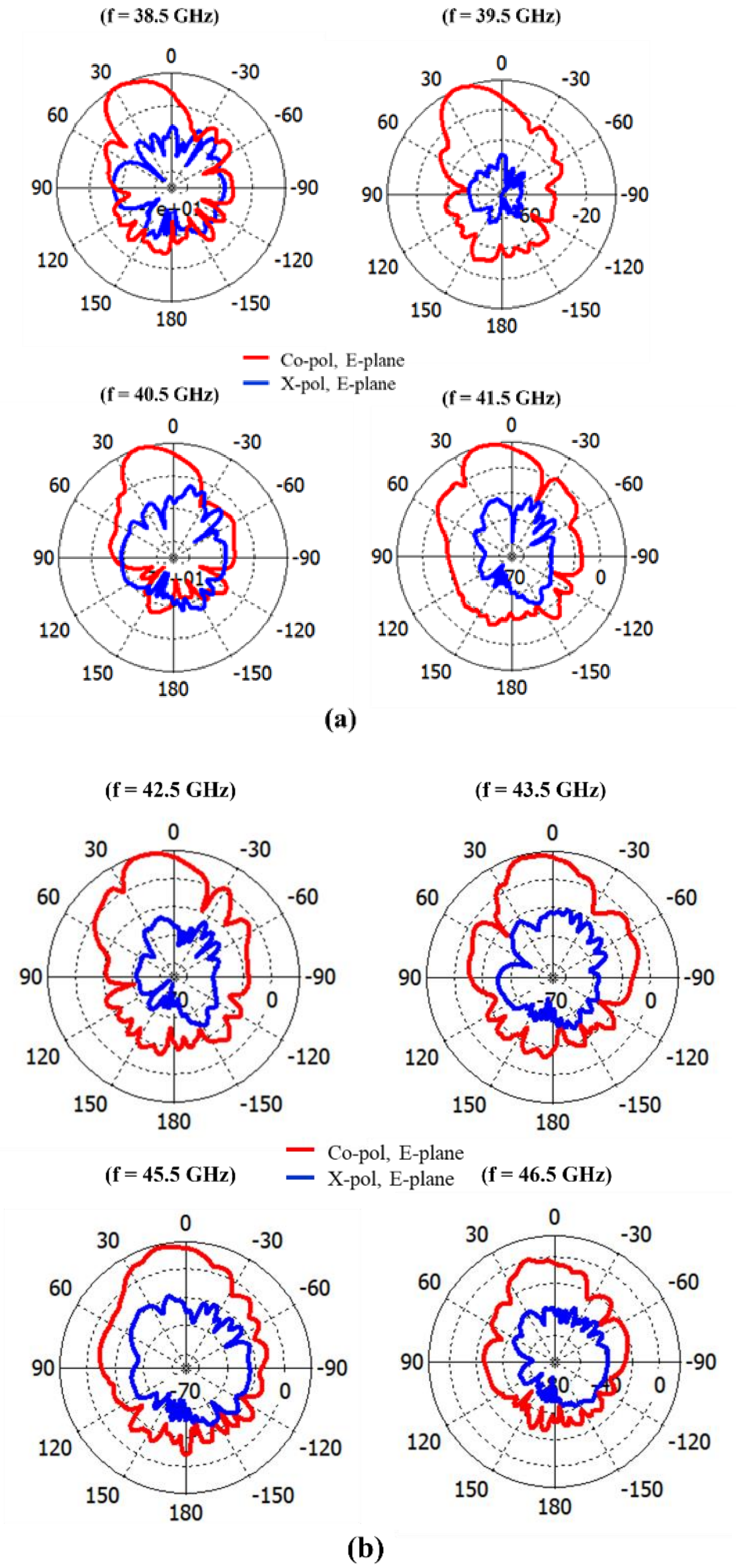


Figure 5 Simulated radiation patterns for frequencies 38.5,39.5,40.5,41.5,42.5,43.5,45.5 and 46.5 GHz.

Conclusion

This work presented a new design of a high gain printed radial leaky wave antenna for emergent millimeter-wave applications. At this point, the particular shape only serves as a clear and practical example of the idea behind how the radial shape can improve a LWA's performance. The proposed design offers 8GHz of bandwidth around 42.5GHz and a peak realized gain of 20.3 dBi. The radiation efficiency of this design is more than 75% over the operating band. The average SLL is -18 dB over the entire bandwidth with cross-polarization less than -35dB. This paper proposes a printed radial leaky wave antenna with considerable potential applications in 5G communication due to its wide impedance bandwidth, high gain, and ease of fabrication.

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