

Microstrip Leaky-Wave Antenna for Radar Applications

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Abstract

The work in this article focuses on developing and improving the performance of new leaky-wave antenna configurations that can be adapted for use in radar systems. The study focused on the W-band, where we demonstrated the possibility of modifying resonant frequencies and reducing the number of patches required. The antenna was designed using HFSS, based on the finite element method. It we designed enabled us to observe the influence of the number of patches on the radiation pattern, and also to achieve low levels of minor's lobes. and good directivity at the operating frequency. These patches are arranged in the shape of an inverted T. The interest of this study is to meet the requirements of radar antennas dedicated to detection.

Keywords

Leaky-Wave Antenna, Microstrip, HFSS, Radar Applications

1. Introduction

In recent years, major technical innovations such as signal digitization and the introduction of fiber optics have had a major impact on the development of telecommunications. The modern high-speed telecommunications systems of today are in great demand in the microwave frequency band. At the same time, the millimeter band has become very attractive for the emergence of wireless applications [1] [2]. Recent advances in microwave circuit and device design mean that all these services can now be accessed on a single terminal, at the expense of increasingly drastic trade-offs between cost and complexity [1]-[4].

We are witnessing far-reaching changes in the field of telecommunications, whether in mobile telephony, wireless networks, satellite networks, satellite television, radar applications (civil or military), etc. This considerable expansion has created enormous needs and has led to very rapid development of the electronic systems associated with these applications.

In electronics systems, in addition to all the functions required for digital transmission and modulation, there are also antennas for transmitting and receiving these signals. In these systems, antennae are components that require special study. To adapt antennas to the latest applications, their performance must be constantly improved. The antenna must also meet the constraints of frequency band multiplication and integration into terminal architecture [3] [4].

These antennas are of various types, in terms of bandwidth, resonant frequency and power losses, to ensure smooth signal transmission [3]. Antennas are components in their own right in communication systems, requiring special design. As well as seeking to improve an antenna's performance, it must be adapted to the latest applications. They must also meet the constraints of frequency band multiplication, broadband and integration. Last but not least, the characteristics of antennas must not be easily influenced by the environment.

The fields of remote sensing and target location use circular antennas such as horn or parabolic dishes [4]. However, these antennas are widely criticized on the market for their weight, high power losses and very small coverage area [5]. In addition, these antennas are narrow-band antennas, with low efficiency and poor signal-to-noise ratio. Existing antennas in this field are therefore unable to provide transmission while guaranteeing good signal quality.

In view of these counter-performances, the antennas used in radars for remote sensing are the subject of a great deal of research [6]. The demand for high-precision radars for military applications (detection and location) has led to a significant need for less complex, high-performance, low-cost electronically scanned systems. These devices overcome the mechanical drawbacks of classic systems, which are expensive and have a scanning rate that is too slow for most applications.

The current trend is to have radar systems that can detect obstacles at a certain depth and in liquid media. New antenna prototypes are being envisaged to cover a wide range of frequencies with angular scanning [5]-[15].

Davide Comite *et al.* 2018 in [16] have proposed A low-cost compact planar leaky-wave antenna (LWA) offering directive broadside radiation over a significantly wide bandwidth. its design is based on an annular metallic strip grating (MSG) configuration, placed on top of a dual-layer grounded dielectric substrate. To design antenna, a method-of-moments dispersion analysis has been developed to characterize the relevant TM and TE modes of the perturbed guiding structure. this antenna is applied in radar and satellite communications at microwave and millimeter-wave frequencies as well as future 5G communication devices and wireless power transmission.

Jianfeng Chen *et al.* in 2020 [17] have proposed hybrid dispersion compensation method to design wideband fixed-beam leaky-wave antennas (LWAs), with the

tilting angle customizable in both forward and backward quadrants.

A triangular dispersive prism constituted by metallic pins was presented to compensate for the dispersion of traditional LWAs and achieve a squint-free radiation in a relative bandwidth of 20%. However, that design suffered from the drawbacks of large geometry and limited angular range. To overcome these limitations, here a broadband gradient metasurface based on geometric phase theory is loaded in front of the prism to customize the radiation angle and reduce the total prism size.

HE Yejun *et al.* in 2020 [18] have examined latest research progress of LWAs for 5G/B5G mobile communication systems. They showed that, the conventional classification and design methods of LWAs are introduced and the effects of the phase constant and attenuation constant on the radiation characteristics are discussed. Then two types of new LWAs for 5G/B5G mobile communication systems including broadband fixed-beam LWAs and frequency fixed beam-scanning LWAs have been summarised. The challenges and future research directions of LWAs for 5G/B5G mobile communication systems were presented.

Utkarsh Pandey *et al.* in 2023 [19] have presented a new thin substrate-integrated waveguide with twisted integrated-digitated capacitor-based corrugations that offers a transmission loss <0.55 dB. The presented waveguide operates at TE₁₀ mode and is used to present a wideband beam-scanning leaky-wave antenna with an array of dumbbell-shaped slots. The antenna is shown to operate at a frequency band of 25 - 37 GHz and offers a gain >13 dBi throughout the frequency band. The proposed antenna being thin is extremely conformal and is suitable for applications in millimetre-wave off-body communication.

In this article, we propose a new microstrip leaky-wave antenna structure for radar systems. This antenna is designed using electromagnetic simulation software based on an integral formulation solved using the HFSS (High Frequency System Simulator) finite element method. Today, this finite element method (FEM) plays a fundamental role in the analysis of electromagnetic problems. The advantages of this method lie in its ability to adapt to structures with relatively complex geometrical shapes. Our structure's excitation source ensures a periodic distribution of the excitation field over the patches.

2. Theory Approach to the Analysis of an LWA

Let's consider a rectangular coordinate system (Ox, Oy, Oz), in which the (xOy) plane forms the separating surface between two media of different indices. Leaky-waves supported by this interface are characterised by the loss of energy by radiation as they propagate.

If the same wave can be guided along the 3 axes, in a medium where the wave number, in the case of free plane wave propagation, is K_0 . It can be demonstrated that we must have:

$$k_x^2 + k_y^2 + k_z^2 = k_o^2$$

where (k_x, k_y, k_z) are the propagation constants along the three respective directions (Ox, Oy, Oz). $k_o = \frac{2\pi}{\lambda_o}$ is the free-space wave number and λ_o the free-space

wavelength.

If the structure is infinite along (Ox) then $k_x = 0$ and suppose that propagation occurs along (Oy):

$$k_y = \beta_y - j\alpha_y$$

$$k_z = \beta_z - j\alpha_z$$

Let's now consider the propagating structure made of a rectangular waveguide with metal patches regularly distributed along the Oz axis on one of the faces, with a periodicity p shown in **Figure 1**. The phase constant of the structure is obtained by applying the Bloch-Floquet theorem [20]-[22].

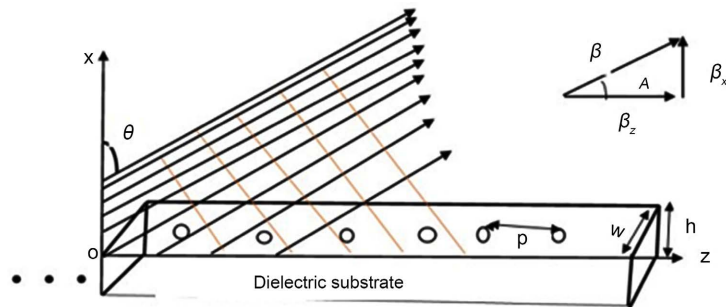


Figure 1. Radiation from a leaky-wave structure.

where k_{zn} is the wave number of n^{th} mode of Floquet is given by

$$k_{zn} = k_z + \frac{2\pi n}{p} = (\beta_z - j\alpha_z) + \frac{2\pi n}{p} = \beta_{zn} - j\alpha_z \tag{1}$$

With $\beta_{zn} = \beta_o + \frac{2\pi n}{p}$, is the phase constant of the n^{th} harmonic;

β_{zn} can take an infinity of values, β_o is the phase constant of the fundamental mode ($n = 0$); α_z is the attenuation constant in z direction, $\alpha_z \sim 0$, almost all values of k_{zn} are real. However, for some negative values of n , the term β_{zn} may be less than k_o so k_{zn} is real.

In this case, the total field is fast, except for $n = 0$, because the fundamental mode is slow according to Ghomi [8].

The excited modes in this case are Bloch-Floquet modes. The electric field of the wave is expressed using Bloch-Floquet theorem as an infinite sum of non-uniform plane waves [20] [21]:

$$E(x, y, z) = \sum a_n(x, y)e^{-jk_{zn}z} \tag{2}$$

In practice, to avoid spurious lobes, it is advisable to work with only one fast harmonic [4]; the $n = -1$ mode is then chosen to be the radiating mode.

The radiation harmonic $n = -1$ in the free space has an angle θ_{-1} who is given by:

$$\theta_{-1} = \sin^{-1} \left(\frac{\beta_{z-1}}{k_o} \right) \tag{3}$$

$k_o = \frac{2\pi}{\lambda_o}$ is the wave number and λ_o is the length of the wave in free space.

The sign θ_{-1} determines whether the resulting radiation is forward or backward. We can immediately see that the radiation condition is given by the following equation:

$$-1 < \frac{\beta_{zn}}{k_o} < 1 \quad (4)$$

Thus to design an LWA, the following formulas are used to determine the dimensions of the antenna [18] [19] [22] [23]:

$$\begin{cases} \frac{\lambda_o}{\frac{\beta}{k_o} + 1} \leq l \leq \frac{\lambda_o}{\frac{\beta}{k_o} - 1} & \text{if } \frac{\beta}{k_o} > 3 \\ \frac{\lambda_o}{\frac{\beta}{k_o} + 1} \leq l \leq \frac{2\lambda_o}{\frac{\beta}{k_o} + 1} & \text{if } \frac{\beta}{k_o} < 3 \end{cases} \quad (5)$$

$$0.2\lambda_o \leq l \leq 0.4\lambda_o \quad (6)$$

$$b < \frac{\lambda_o}{(\epsilon_{eff} - 1)^2} \quad (7)$$

3. Antenna Design

In this article, we have used software for an integral formulation solved using HFSS finite elements. Using a finite element calculation code. However, finite element codes have to convert partial differential equations into a system of linear equations whose coefficients depend on the type of problem and the media; an infinite space will lead to a system of infinite dimension whose numerical resolution will not be possible. This difficulty can be overcome by creating a problem approximated by an equivalent structure in a bounded volume, with boundary conditions chosen to approximate reality as closely as possible.

As an application, we propose to design an LWA meeting the following specifications:

- operating frequency: 80 GHz;
- levels of minor's lobes < -12 dB.

The LWA is a microstrip antenna with a perfectly conducting ground plane (Figure 2). on the top face of the substrate, metallic patches of inverted T shape were placed periodically with a period p to cause leakage wave radiation.

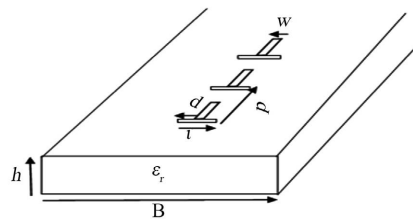
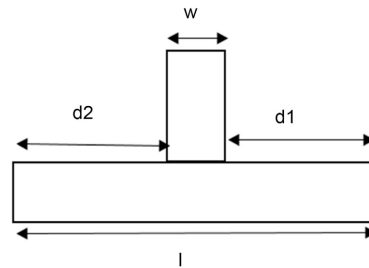


Figure 2. Leaky wave antenna with inverted T-pattern patches of length l .



The distance l is given by the following formula:

$$l = d_1 + d_2 + w \quad (8)$$

The antenna dimensions calculated from formulas 5, 6 and 7 at the operating frequency of 80 GHz are recorded in **Table 1** with $\epsilon_r = 2.46$.

Table 1. Dimensions of the antenna structure $\epsilon_r = 2.46$.

Designation	w	d	l	$d_1 + d_2$	p	B
Dimension	0.27 mm	1 mm	3 mm	2.73 mm	2.5 mm	30 mm

4. Simulations, Results and Discussions

We simulate the designed antenna using the HFSS software based on Equations (5)-(7) and the data reported in **Table 1** above.

4.1. Reflection Coefficient

Figure 3 presents the variation of the reflection coefficient as a function of the antenna frequency with inverted T-shaped patches. We note that this antenna resonates at a frequency of 80.012 GHz, instead of 80 GHz with a reflection coefficient value equal to -24.96 dB. The level of adaptation is excellent.

The adaptation level is excellent, comparable to structures found in the literature [24] [25]. Furthermore, analysis of the same figure illustrates -24.96 dB as the reflection coefficient level for the proposed antenna configuration. This reflects good isolation and therefore a low level of coupling between the radiating elements making up the antenna structure. This value is well below -10 dB, which means that the radiation power is sufficient.

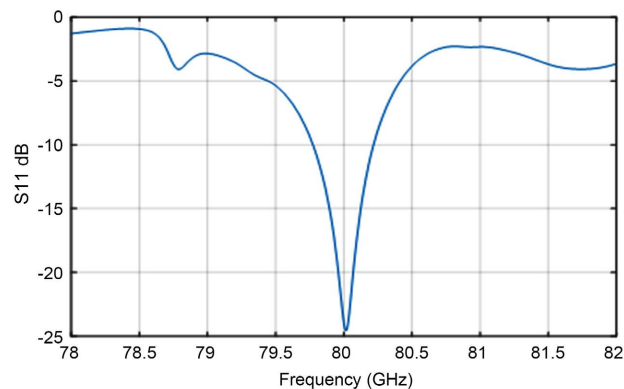


Figure 3. Reflection coefficient as a function of frequency.

4.2. Radiation Parameters

4.2.1. Radiation Patterns

To highlight the effect of physical and geometrical parameters on the behavior of the antenna.

We have represented the radiation patterns in polar and Cartesian coordinates for an LWA with inverted T-shaped patches for an antenna operating at 80 GHz.

In **Figure 4**, the radiation pattern of the antenna in the E-plane is represented in 3D for a number of patches $N = 11$. We note that all the energy radiated is concentrated at the main lobe limiting radiation losses.

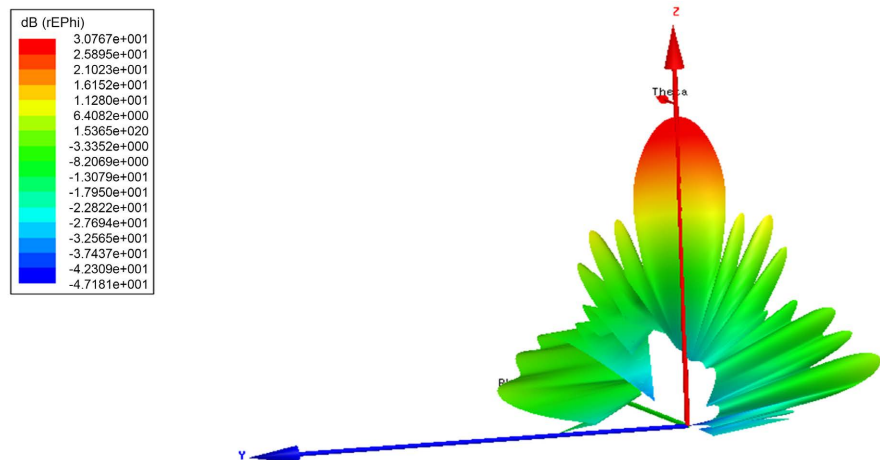


Figure 4. 3D representation of the radiation pattern in the E-plane: $F = 80$ GHz, $N = 11$, $\epsilon_r = 2.46$, $w = 0.3387\lambda_0$, $B = 8\lambda_0$.

The 3D view of the antenna's radiation pattern (**Figure 4**) provides some clues to understanding the performance shift. The minor's lobes at the ends also tend to point horizontally towards the side where the radiating elements are located. The main lobe is also subject to a slight inclination, which can modify the opening in the plane.

In **Figure 5**, the radiation pattern of the microstrip leaky wave antenna is presented for different values of the N .

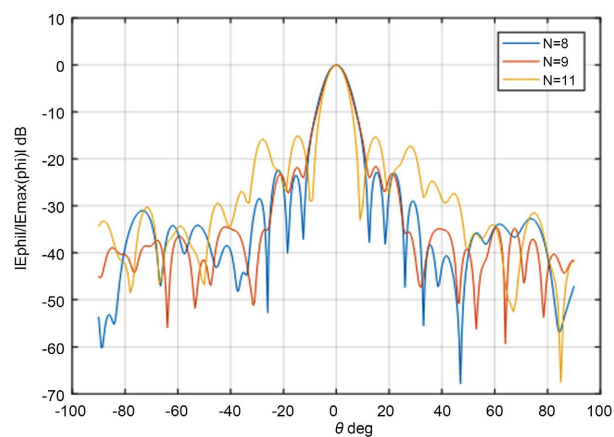


Figure 5. Radiation patterns of the E-plane at $F = 80$ GHz, for $l = 3$ mm, $d_1 = d_2 = 1.365$ mm, $\epsilon_r = 2.46$, $w = 0.3387$, $B = 8\lambda_0$.

We note that the levels of minor's lobes increase with N . The number of patches has an effect on the beamwidth. The beamwidth decreases as the number of patches increases. The maximum of the radiated field is concentrated in the main lobes.

Figure 6 illustrates the radiation pattern in the E-plane for different frequencies values. We note a clear narrowing of the main beams as the frequency decreases. The levels of minor's lobes increase when the frequency decreases. We also observe an influence of the frequency on the beamwidth.

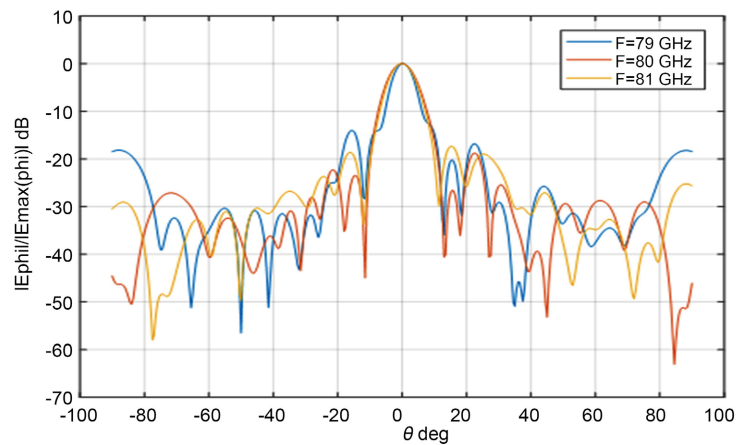


Figure 6. Variation of the antenna radiation pattern as a function of frequency in plane E, for $l = 3$ mm, $d_1 = d_2 = 1.365$ mm, $\epsilon_r = 2.46$; $w = 0.3387$, $B = 8\lambda_0$, $N = 11$.

Figure 7 shows the radiation patterns of LWA for different values of d_1 . We note that d_1 has no effect on beamwidth and the scanning angle, but the level of minor's lobes is lower when as d_1 decreases.

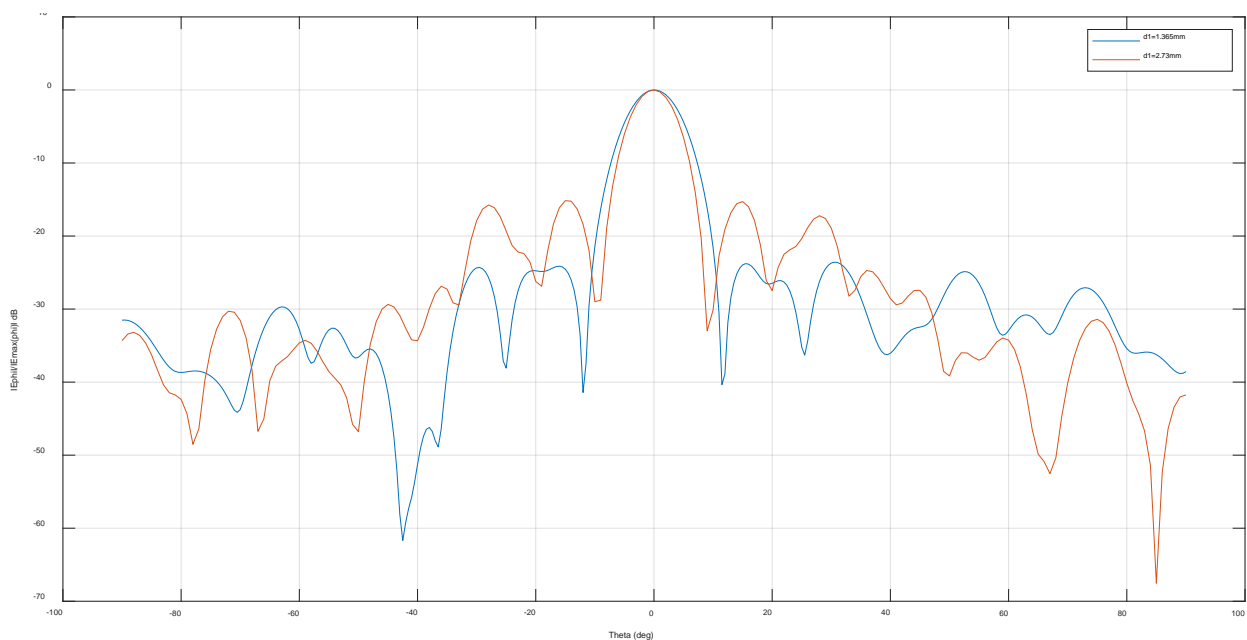


Figure 7. Radiation patterns of the E-plane at $F = 80$ GHz.

The levels of the first minor's lobes are -24.1756 dB and -15.23 dB respectively for $d_1 = 1.365$ mm and $d_1 = 2.73$ mm. This diagram shows a much lower aperture as d_1 increases. This diagram is symmetrical on either side of the pointing. This diagram shows a much smaller opening due to the constant number of patches.

4.2.2. Directivity

Figure 8, we represent the antenna directivity variation versus frequency for different values of d_1 and for $b = 0.8$, $w = 0.3387$, $B = 8$ mm. At the operating frequency, we observe that the distance d_1 has a considerable influence on the directivity. It decreases as the directivity increases. It is equal to -15.4901 dB for $d_1 = 1.365$ mm and -9.35734 dB for $d_1 = 2.73$ mm at the operating frequency. This means that the antenna is of good quality antenna in this frequency band. Finally, a very good directivity stability can be around the operating frequency for $d_1 = 1.365$ mm.

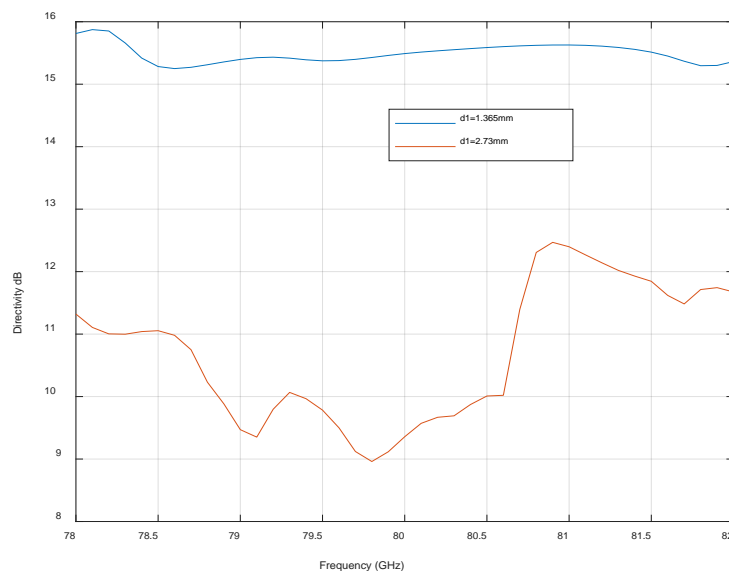


Figure 8. Directivity of the microstrip leaky-wave antenna.

5. Conclusion

The work in this article focuses on developing and improving the performance of new leaky-wave antenna configurations that can be adapted for use in radar systems. The study focused on the W-band, where we demonstrated the possibility of modifying resonant frequencies and reducing the number of patches required. The antenna we designed enabled us to observe the influence of the number of patches on the radiation pattern, and also to achieve low levels of minor's lobes and good directivity at the operating frequency.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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