



# Leaky-Wave Antennas for 5G/B5G Mobile Communication Systems: A Survey

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**Abstract:** Since leaky-wave antennas (LWAs) have the advantages of high directivity, low loss and structural simplicity, LWAs are very suitable for designing millimeter-wave (mmW) antennas. The purpose of this paper is to review the latest research progress of LWAs for 5G/B5G mobile communication systems. Firstly, 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 are summarized. Finally, the challenges and future research directions of LWAs for 5G/B5G mobile communication systems are presented.

**Keywords:** 5G/B5G; beam-scanning; frequency-fixed; fixed-beam; millimeter-wave (mmW); leaky-wave antenna (LWA)

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## 1 Introduction

Due to the rapid growth of mobile data services, the existing spectrum resources can no longer meet the requirements of mobile communication systems. In order to increase the data transmission rate, a higher carrier frequency must be used to provide greater bandwidth. Since the millimeter-wave (mmW) frequency band has rich spectrum resources which can provide greater bandwidth, mmW antennas can be used in 5G/B5G mobile communication systems.

tion systems.

Unlike traditional 4G antennas, mmW antennas must have the characteristics of low loss and high directivity to counteract the greater path loss of mmW propagation in free space. The dimensions of mmW antennas are in the level of millimeters, which poses a challenge to their process technology. Thus, the 5G/B5G mmW antennas should be designed as simply as possible. In addition, 5G/B5G mmW antennas should also have the characteristic of broadband to support 5G/B5G high data rate transmissions.

Generally, antenna arrays are used to generate highly directional beams. However, in mmW systems, the feeding network of an array antenna significantly increases the system complexity and brings additional loss to the system. Phased-array antennas have the characteristics of electrically controlled

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beam-scanning and high directivity<sup>[1]</sup>. In Ref. [2], the design considerations and solutions of mmW phased-array antennas applied to 5G smartphones are discussed in detail. Multi-beam antennas<sup>[3-4]</sup> can simultaneously generate multiple beams with the high directivity, where each beam covers a pre-determined angular range. In Ref. [5], the applicability of multi-beam antennas for 5G mobile communications and related challenges are introduced. However, phased-array antennas and multi-beam antennas have complex feeding networks, which is not conducive to massive production. Since leaky-wave antennas (LWAs) have the advantages of high directivity, low loss, and structural simplicity, they are expected to be an effective solution for 5G/B5G mmW antennas.

This paper is organized as follows. In Section 2, the classification and design methods of LWAs are introduced. Section 3 describes the latest research progress of LWAs for 5G/B5G mobile communication systems. Section 4 presents the challenges and future research directions of LWAs for 5G/B5G mobile communication systems. Finally, we draw the conclusions in Section 5.

## 2 Classification and Design Methods of LWAs

LWAs are based on guided wave structures and can continuously radiate along their guided wave structures. Since LWAs have a large radiation aperture and do not require a complicated feeding network, their structures are very simple and they have the characteristics of low loss and high directivity.

### 2.1 Classification of LWAs

Generally, LWAs can be categorized into three types, namely uniform LWAs, periodic LWAs and quasi-uniform LWAs<sup>[6]</sup>.

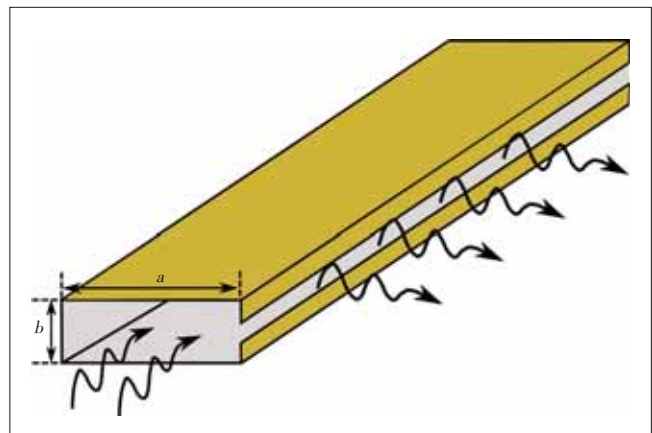
A uniform LWA has a constant cross section along its guided wave structure. Since its fundamental mode is a fast wave ( $\beta_0 < k_0$ ), it can radiate when its guided wave structure is open. When a uniform LWA is fed, its main beam scans from endfire direction to broadside direction as frequency increases. However, in most practical designs, the beam of a uniform LWA cannot scan to endfire or broadside direction. As shown in Fig. 1<sup>[7]</sup>, it is difficult for a slotted air-filled rectangular waveguide LWA to scan to broadside direction since the operating frequency corresponds to the cut-off frequency of the waveguide. It is also difficult for a slotted air-filled rectangular waveguide LWA to scan to endfire direction since the long slot of the rectangular waveguide is equivalent to a magnetic current source, and the endfire direction corresponds to the radiation zero point of the magnetic current source.

Compared with uniform LWAs, the fundamental mode of a periodic LWA is a slow wave. Thus, even if its guided wave structure is open, it cannot radiate. However, since a periodic LWA introduces periodic modulations along its guided wave structure, an infinite number of space harmonics<sup>[8-9]</sup> are generated in the guided wave structure of the periodic LWA, where

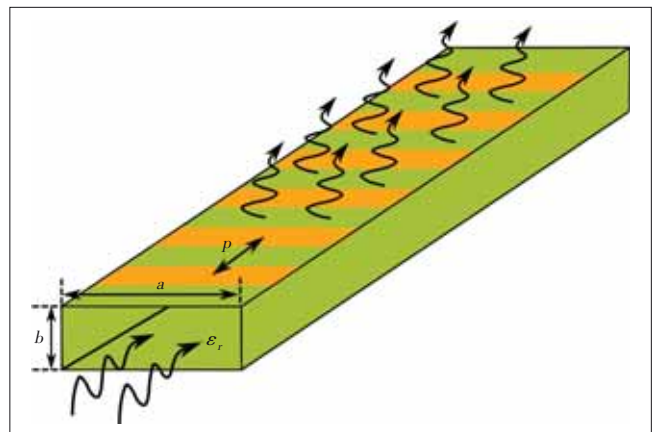
each space harmonic has a phase constant

$$\beta_n = \beta_0 + 2\pi n/p, \quad (1)$$

where  $\beta_0$  is the fundamental mode phase constant of the periodic LWA (slightly different from the fundamental mode phase constant when there is no periodic modulations),  $n$  is the harmonic order, and  $p$  is the period length. Although the fundamental mode of a periodic LWA is a slow wave, it is possible to obtain a space harmonic (usually the first space harmonic) that is a fast wave by designing a certain period length. As shown in Fig. 2, a rectangular dielectric rod with periodic metal strips is a classic example of periodic LWAs<sup>[10]</sup>. Compared with the uniform LWA, the main advantage of a periodic LWA is that its phase constant can be negative (for example,  $\beta_{-1} < k_0$ ), thus allowing its beam scan from backward to forward. However, due to the open stop band of periodic structures, the performance of a periodic LWA significantly deteriorates when its beam is scanned close to the broadside direction<sup>[8-9]</sup>. The reason is that the period length is equal to the fundamental mode guided wavelength of the periodic LWA at the frequency corresponding to the open stop band. Thus, the



▲ Figure 1. A slotted air-filled rectangular waveguide.



▲ Figure 2. A rectangular dielectric rod with periodic metal strips.

reflections from all periodic elements are superposed in phase so that most of the energy is reflected back to the input port of the periodic LWA. In recent years, many articles have proposed various methods to suppress the open stop band of periodic LWAs<sup>[11-16]</sup>.

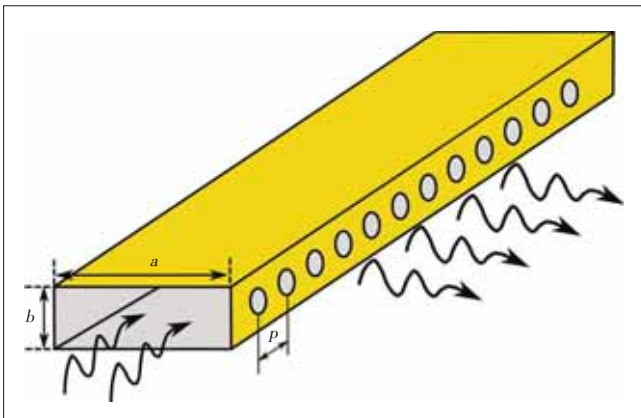
Similar to periodic LWAs, a quasi-uniform LWA also introduces periodic modulation along its guided wave structure. Thus, it can also generate infinite space harmonics. However, the fundamental mode of the quasi-uniform LWA is a fast wave like uniform LWAs, and its period length is selected to be small enough to ensure that radiation only comes from the fundamental mode. Thus, the period length of a uniform LWA does not directly determine the radiation mode. However, periodic modulations can be used to control the attenuation constant of leaky mode. A classic example of quasi-uniform LWAs is shown in Fig. 3, where it radiates by a series of closely spaced periodic holes which are on the side wall of an air-filled rectangular waveguide<sup>[17]</sup>. Compared with the slotted air-filled rectangular waveguide LWA<sup>[7]</sup>, this design can provide a smaller attenuation constant since periodic holes cannot completely cut the current lines on the side wall of the rectangular waveguides. However, the long slot of the side wall of the rectangular waveguides in Fig. 1 cuts the current lines.

## 2.2 Design Methods of LWAs

LWAs can be designed by the microstrip line<sup>[18-23]</sup> and substrate integrated waveguide (SIW)<sup>[24-29]</sup>. Their radiation characteristics are determined by the phase constants and attenuation constants where the phase constants determine their beam directions and the attenuation constants determine their beam widths. The beam direction of an LWA can be approximated as

$$\theta = \arcsin(\beta/k_0), \quad (2)$$

where  $\theta$  is the angle measured from the broadside direction,  $\beta$  is the phase constant of the LWA, and  $k_0$  is the propagation



▲ Figure 3. An air-filled rectangular waveguide with closely spaced periodic holes.

constant of free space. The guided wave structure of an LWA is dispersive, which means that its phase constant does not change linearly with frequency, resulting in  $\beta/k_0$  to change with frequency. Thus, the beam of an LWA will be scanned with frequency. We can obtain the required beam-scanning range by controlling the phase constant of an LWA. The beam width  $\Delta\theta$  of an LWA can be approximated as

$$\Delta\theta = 2(\alpha/k_0)/\sin(\theta), \quad (3)$$

where  $\alpha$  is the attenuation constant. We can obtain a narrow beam by designing a small attenuation. The reason is that an LWA with small attenuation needs a long guided wave structure to fully radiate energy, and the long guided wave structure means that the effective radiation aperture is large.

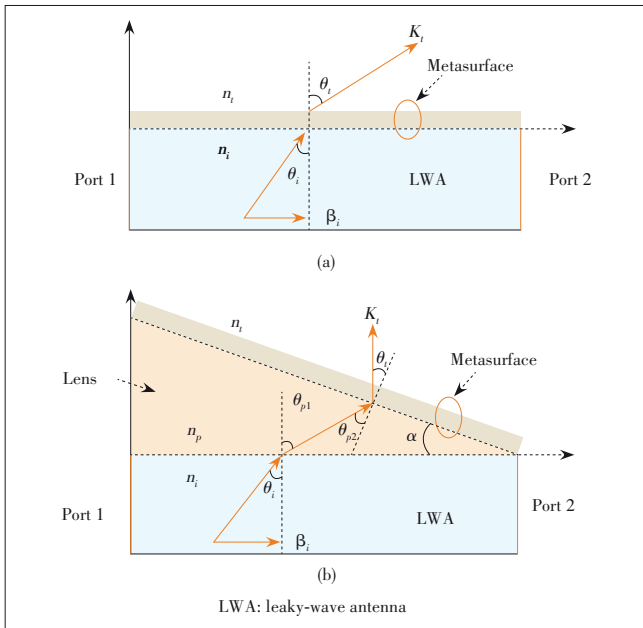
Uniform LWAs use their fundamental mode to radiate. When designing a uniform LWA, we must first determine which waveguide will be used. The required operating band and phase constant of a uniform LWA can be obtained by selecting the geometry and material of its waveguide. As shown in Fig. 1, the width and height of the rectangular are used to determine its operating band and phase constant. By adjusting the geometry of the slot, the attenuation constant can be controlled to obtain the required beam width. Quasi-uniform LWAs are similar to uniform LWAs, except that quasi-uniform LWAs introduce periodic disturbances such as the periodic holes. As shown in Fig. 3, the attenuation constant of the rectangular waveguide can be controlled by adjusting the geometry and spacing of the holes to obtain the required beam width.

Since the fundamental mode of a periodic LWA is a slow wave, periodic modulation needs to be introduced to allow it to radiate. Periodic modulations will introduce infinite space harmonics and the phase constant of each space harmonic can be expressed as  $\beta_n = \beta_0 + 2\pi n/p$ . It can be seen that even if its fundamental mode is a slow wave, we can also obtain a space harmonic which is a fast wave. Usually the first space harmonic is used to radiate and its phase constant can be expressed as  $\beta_{-1} = \beta_0 - 2\pi/p$ . By properly selecting the period length, an operating band, where the first space harmonic wave is a fast wave and the rest of the harmonics waves are slow waves, can be obtained. Within this operating frequency band, controllable single beam radiation can be achieved. Fig. 2 shows a classic periodic LWA. Its guided wave structure is a rectangular dielectric rod. The width and height of the dielectric rod are  $a$  and  $b$ , respectively, and the dielectric constant is  $\epsilon_r$ , the fundamental mode phase constant  $\beta_0$  of the dielectric rod can be determined by these parameters. By properly selecting the period length of the periodic metal strips, a specified operating frequency band with the first harmonic being the fast wave and the remaining harmonics being the slow waves can be obtained, thereby obtaining the designated single beam-scanning range within the designated operating frequency band. By adjusting the geometry of the metal strip, the attenuation con-

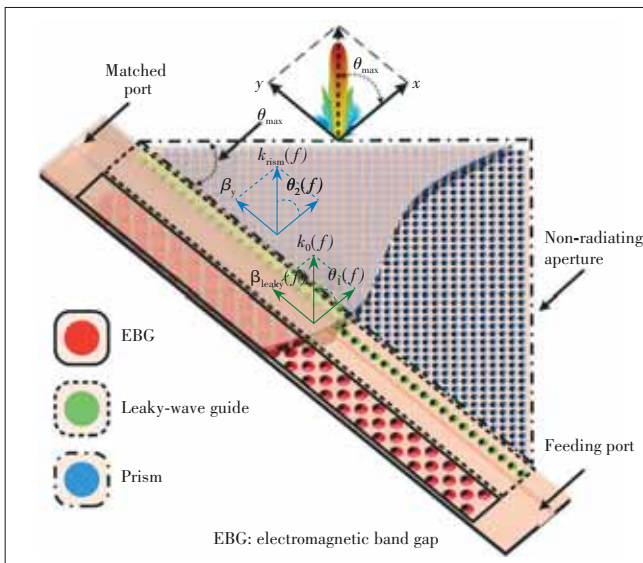


[32] and the beam direction can be customized.

In Ref. [35], a low-dispersion LWA operating in the 60 GHz band is proposed. Similar to Ref. [32], the frequency beam squint of the LWA is reduced by loading a lens with complementary dispersion characteristics on the radiation aperture of the LWA. The difference is that the electromagnetic band gap structure, leakage structure, and lens structure are all implemented with metal periodic round holes, as shown in **Fig. 8**. Thus, the solution in Ref. [35] has higher cost-efficiency and a more stable manufacturing process. Ref. [36] is based on the design ideas of Ref. [32]. Compared with Ref. [32], it discusses



▲ **Figure 7.** Operating principles of LWAs (a) loaded with metasurface and (b) loaded with both metasurface and compensation lens.



▲ **Figure 8.** Low-dispersion leaky-wave antenna (LWA) using fully holey groove gap waveguide technology<sup>[35]</sup>.

es how to simultaneously obtain low side lobes and low dispersion characteristics. In addition, it is confirmed that an LWA loaded with a complementary dispersion lens can simultaneously generate dual beams. In Ref. [36], two low-dispersion LWAs that operate in the 60 GHz band are designed. These two antennas use symmetric and asymmetric structures, respectively. The asymmetric structure can obtain the optimal side lobes and the symmetric structure can simultaneously obtain two stable beams. Both LWAs can obtain 20% bandwidth when the beam tilt angle is within  $\pm 0.5^\circ$ . In the operating frequency band, the gains obtained by the asymmetric and symmetric structures are stable at 17 dBi and 15 dBi, respectively. A comparison of the broadband fixed beam LWAs introduced above is given in **Table 1**.

### 3.2 Frequency-Fixed Beam-Scanning LWAs

5G mmW antennas should have high directivity to counteract the greater path loss of mmW propagation in free space. However, the disadvantage of a highly directional beam is that its beam width becomes narrower, resulting in a smaller coverage area. Using an LWA with frequency-fixed beam-scanning capability can improve beam coverage.

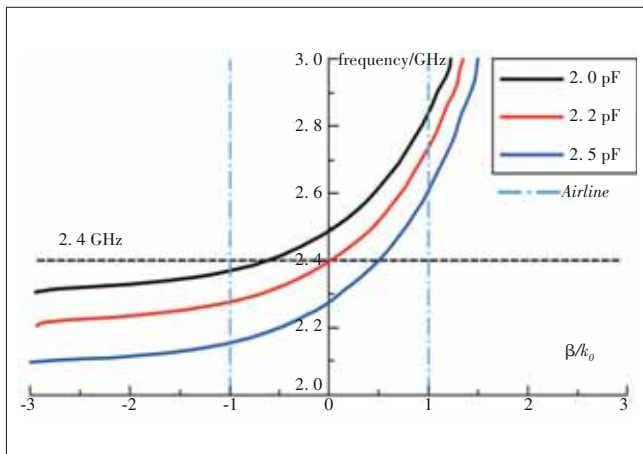
In Ref. [37], a frequency-fixed circularly polarized beam-scanning LWA is proposed. The unit cells of the LWA are composed of a varactor diode and a subwavelength square patch. As shown in **Fig. 9**, changing the capacitance of the varactor diode can control the dispersion behavior of the LWA. By adding different bias voltages, the capacitance of the varactor diode can be changed, thereby realizing electronically controlled frequency-fixed beam-scanning. In Ref. [38], an LWA composed of corrugated microstrip lines with triangular modulation surface impedance is proposed (**Fig. 10**). Due to the periodic modulation of the surface impedance, the guided waves propagating on the microstrip line can be effectively converted into leaky waves. By adding different bias voltages, the capacitance of the varactor diode can be changed, thereby controlling the surface impedance of the corrugated microstrip line. Different surface impedances correspond to different dispersion behaviors, thus, the electronically controlled beam-scanning of the LWA can be achieved by changing the bias voltage. This LWA can reach a beam-scanning range of  $45^\circ$  at each frequency from 5.5 to 5.8 GHz.

In Ref. [39], a frequency-fixed beam-scanning LWA based on a corrugated substrate integrated waveguide is proposed. **Fig. 11** shows its structure. The unit cells of the LWA consist of a rectangular ring slot and a metallic via connected to the ground. The rectangular ring slot is loaded by four varactor diodes. By adjusting the direct current (DC) bias voltage, the series and shunt capacitance of the varactor diodes can be controlled. Thus, the dispersion behaviors of the LWA can be controlled by the DC bias voltages to obtain electronically controlled frequency-fixed beam-scanning. In Ref. [40], a composite right/left-hand (CRLH) microstrip LWA enabling frequen-

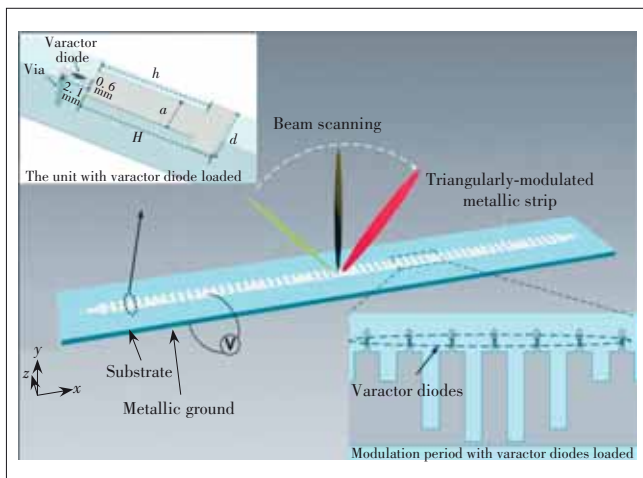
▼Table 1. Comparison of the broadband fixed beam LWAs

	Antenna Type	Guided Wave Structure	Advantage	Operating Frequencies/GHz	Max Gain/dBi	Beam Squinting/°
[30]	LWA loaded with metasurface	Coplanar waveguide	• Simple structure	9.5 – 10.45	5	12
[31]	LWA loaded with prism	Substrate integrated waveguide	• Lightweight • Easy to integrate with other circuits	35 – 40	8.5	1
[32]	LWA loaded with prism	Groove gap waveguide	• Low loss	11.5 – 13	16.5	0.6
[34]	LWA loaded with prism and metasurface	Ridged gap waveguide	• Custom beam direction • Minituriazation	9.3 – 11.3 (Radiating at an angle of 38.3°)	15.7	1.5
				9.5 – 11.3 (Radiating at an angle of -0.4°)	15.2	1.2
[35]	LWA loaded with prism	Groove gap waveguide	• Low side lobe level • High cost-efficiency • Stable manufacturing process	54.81 – 61.19 (Glide-symmetric)	16.5	3.4
				54.81 – 61.19 (Mirror-symmetric)	17.5	1.8
[36]	LWA loaded with prism	Groove gap waveguide	• Low side lobe level • Dual beam radiation	54 – 66 (Asymmetric)	17	1
				54 – 66 (Symmetric)	15	1

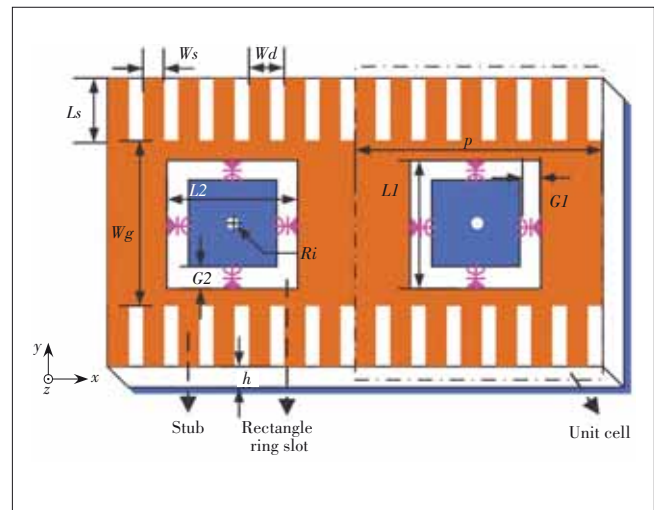
LWA: leaky-wave antenna



▲ Figure 9. Dispersion curves corresponding to different capacitances of the varactor diodes<sup>[37]</sup>.



▲ Figure 10. Corrugated microstrip leaky-wave antenna (LWA) loaded with varactor diodes<sup>[38]</sup>.



▲ Figure 11. Structure of the corrugated substrate integrated waveguide leaky-wave antenna (LWA)<sup>[39]</sup>.

cy-fixed electronically controlled beam-scanning in the frequency band of 4.75 GHz to 5.25 GHz is designed. **Fig. 12** shows its structure. By loading two sets of varactor diodes, the circuit parameters of the CRLH microstrip LWA can be controlled to change its dispersion behavior. Thus, by adding different amplitudes bias voltages to change the capacitance of the varactor diodes, the electronically controlled frequency-fixed beam-scanning can be achieved. The measured results show that it can achieve beam-scanning from  $-37^\circ$  to  $32^\circ$  at 5 GHz and from  $-15^\circ$  to  $34^\circ$  at 5.25 GHz.

In Ref. [41], a method is proposed to achieve frequency-fixed beam-scanning by controlling the period lengths of periodic LWAs. The designed antenna consists of a substrate integrated waveguide with an H-shaped slot and two rows of patch

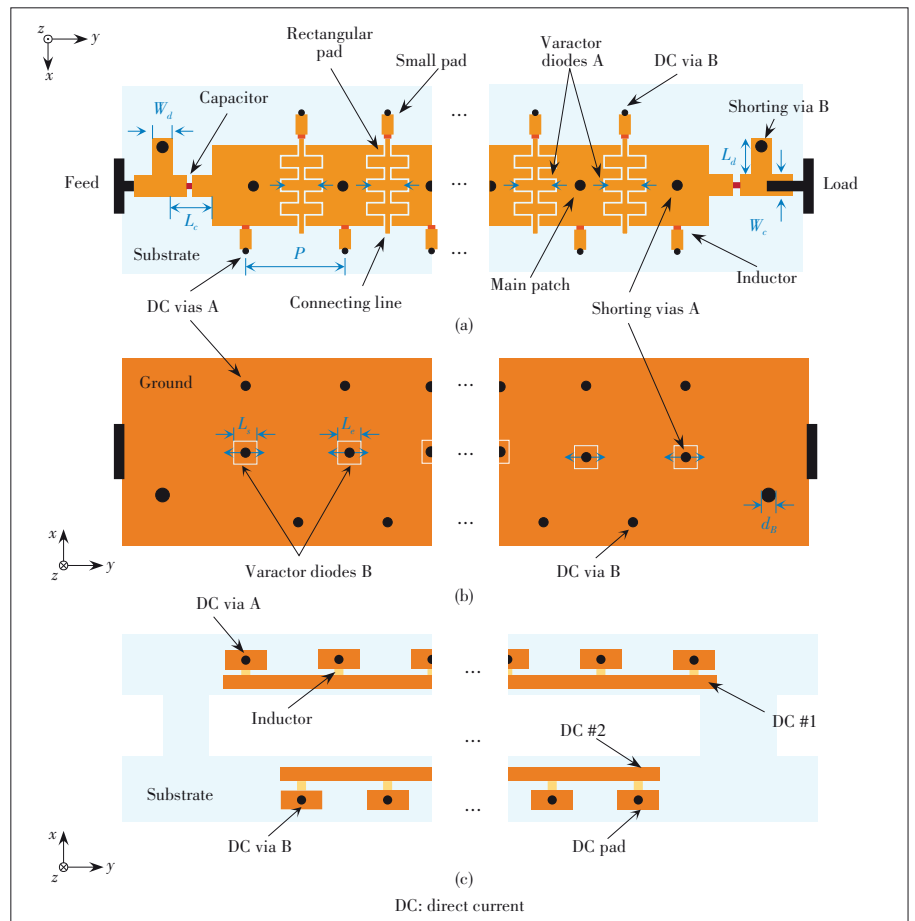
elements. Two symmetrical dumbbell-shaped slots are etched on the element. **Fig. 13** shows the structure and equivalent circuit of the element. By controlling the operating state of each patch element through the diode on the parasitic strip, the LWA can obtain different effective period lengths at a frequency-fixed; thus, the frequency-fixed electronically controlled beam-scanning capability can be obtained. The measured results show that the antenna can achieve  $125^\circ$  beam-scanning range and the peak gain can reach 11.8 dBi. A comparison of the frequency-fixed beam-scanning LWAs introduced above is given in **Table 2**.

#### 4 Challenges and Future Research Directions of LWAs

Leaky-wave antennas play a very important role in 5G/B5G mmW mobile communication systems, especially affecting the performance of the entire mobile communication systems. A high-performance transceiver antenna can significantly improve the communication quality. In order to obtain a high gain beam to counteract the greater path loss of mmW propagation in free space, 5G/B5G mmW antennas should have the characteristics of high directivity and low loss. In addition, in order to improve the data transmission rate, 5G/B5G mmW antennas should also have a larger bandwidth. Based on these requirements, both fixed-beam and frequency-fixed beam-scanning LWAs are still facing the challenges of low loss, simple structure and broadband.

Since LWAs have the characteristics of high directivity, low loss and structural simplicity, they are very suitable for designing mmW antennas. However, due to the dispersion characteristics of LWAs, their beams scan

with frequency. Thus, the 3 dB pattern bandwidths of LWAs are very narrow, which is not conducive to high data rate transmission for 5G/B5G mobile communication systems. How to increase the pattern bandwidth of LWAs is a major challenge. Some recent articles have proposed several methods of using complementary metasurfaces or lenses to cancel the dispersion characteristics of LWAs. Although these methods effectively improve the pattern bandwidth of LWAs, they make the antenna structure larger and increase the complexity and losses of LWAs. In addition, more complex structures are not con-

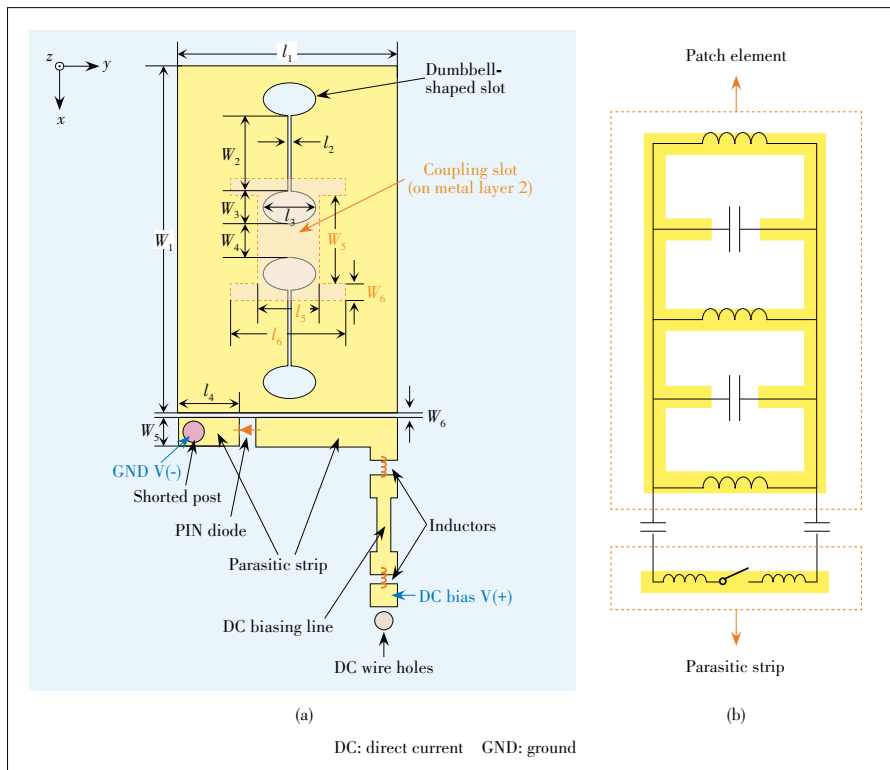


▲ **Figure 12.** Composite right/left-hand (CRLH) leaky-wave antenna (LWA) configuration<sup>[40]</sup>: (a) top view of the patch layer; (b) bottom view of the ground layer; (c) bottom view of the biasing layer.

▼ **Table 2.** Comparison of the frequency-fixed beam-scanning LWAs

	Antenna Type	Operating Principle	Operating Frequencies/GHz	Max Gain/dBi	Beam Scanning Range/deg
[37]	CRLH	Manipulation on dispersion characteristic	2.4	6.15	40 to -17
[38]	Corrugated microstrip line	Modulation on surface impedance	5.5 - 5.8	8	-16 to 27 (at 5.8 GHz)
[39]	Corrugated SIW	Manipulation on dispersion characteristic	4.5	7.5	-40.66 to 31.32
[40]	Microstrip CRLH	Manipulation on dispersion characteristic	5 5.25	5.7 6.4	-37 to 32 -15 to 34
[41]	Slotted SIW	Reconfiguration of period length	5	11.8	-60 to 65

CRLH: composite right/left-hand LWA: leaky-wave antenna SIW: substrate integrated waveguide



▲ Figure 13. Configuration and equivalent circuit of the patch element proposed in [41]: (a) element structure; (b) equivalent circuit model.

ductive to cost efficiency. Thus, how to obtain a larger pattern bandwidth without significantly increasing the complexity of LWAs is an important research direction of LWAs.

The 5G/B5G mmW mobile communication system requires an antenna with high directivity that also means a smaller coverage area. Using LWA with frequency-fixed beam-scanning capability can improve beam coverage. Recent articles have introduced various methods to achieve frequency-fixed beam-scanning, most of which use active circuits to control the dispersion characteristics of LWAs to achieve frequency-fixed electronically controlled beam-scanning. Due to the introduction of active circuits, the loss will increase and the structures become more complicated. How to overcome these problems is another important research direction of LWAs. In addition, most frequency-fixed beam-scanning LWAs can only be implemented at one frequency or a narrow band. How to achieve frequency-fixed beam-scanning in a broadband range is also a major challenge for LWAs.

## 5 Conclusions

This paper reviews the recent research on LWAs for 5G/B5G mobile communication systems. The structural characteristics and radiation characteristics of uniform LWAs, quasi-uniform LWAs and periodic LWAs are first introduced in detail. The latest studies on broadband fixed-beam LWAs and

frequency-fixed beam-scanning LWAs are then presented. The operating principles and applicability to 5G/B5G mobile communication systems of the broadband fixed-beam LWAs and frequency-fixed beam-scanning LWAs are discussed. Future research directions on LWAs for 5G/B5G mobile communication systems should be how to obtain a larger pattern bandwidth without significantly increasing the complexity of LWAs and how to achieve frequency-fixed beam-scanning in a broadband range.

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➔ To Page 41

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