

A Reconfigurable Leaky-Wave Antenna With High Horizontal Scanning Rate for mmWave Applications

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Abstract—This paper presents a novel substrate integrated waveguide (SIW)-based leaky-wave antenna (LWA) for millimeter-wave (mmWave) applications, featuring unidirectional horizontal radiation, high beam-scanning rate, and reconfigurable radiation pattern. The unidirectional horizontal radiation characteristic is achieved by integrating two pairs of offset symmetrical U-shaped slots on both the upper and lower metal layers of the SIW. Each unit cell of this proposed antenna comprises two pairs of longitudinally oriented capacitive slots and a pair of offset symmetrical inductive metallic vias, which collectively suppress the open stopband (OSB) effect and realizing high beam-scanning rate. Moreover, the radiation pattern reconfigurability is achieved by switching the excitation source, enhancing horizontal beam-scanning range. Simulation results demonstrate an operating bandwidth of 18.5%, a peak realized gain of 16.12 dBi, a beam-scanning rate of 2.4°/%, and a wide-angle beam-scanning range from -27° to 17° across the broadside direction. Owing to its radiation pattern reconfigurable and high horizontal scanning rate characteristics, the proposed LWA exhibits strong potential for modern various mmWave applications.

Keywords—*high beam-scanning rate, leaky-wave antenna, reconfigurable radiation pattern, substrate integrated waveguide, unidirectional horizontal radiation.*

I. INTRODUCTION

Leaky-wave antenna (LWA), with its simple structure, high gain, and the inherent characteristic of continuous frequency-dependent beam scanning, demonstrates great potential in radar, wireless communication, and imaging systems [1]. To achieve more flexible beam control, the research on reconfigurable leaky wave antennas with reconfigurable radiation patterns has become an important branch. Early studies achieved beam reconfiguration by modifying the physical structure of the antenna [1], while modern solutions mainly rely on active devices such as PIN diodes and varactor diodes [2, 3, 4]. [2] achieved electrically controllable adjustment of the equivalent width of the SIW by designing two additional rows of metallized vias that could be controlled by PIN diodes in the substrate integrated waveguide (SIW), thereby deflecting the beam from 46° to 68° at a fixed frequency of 5.2 GHz. [4] proposed a scheme based on multiple feed patch elements, by controlling multiple PIN diodes to select different feed paths, achieving a wide-angle fixed-frequency beam scanning from -62° to +60° at 5.3 GHz [4]. Additionally, the chemical potential tunability of graphene or the regulation of different modes of spoof surface plasmon polaritons (SSPP) units also enabled beam reconfiguration at a fixed frequency [3][5].

These works confirmed the feasibility of reconfigurable leaky wave antennas with radiation patterns. However, most of these schemes focus on achieving the reconfigurable function itself, and their scanning rates are generally low, making them limited in applications in scenarios with high spectral efficiency requirements such as millimeter waves.

High scanning rate is another key performance that frequency scanning leaky-wave antennas strive for. A high scanning rate means that the antenna can achieve a wider beam scanning range within a narrower operating bandwidth, which helps to save spectrum resources and improve the efficiency of the radio frequency system [6, 7, 8]. The core to achieving high scanning rate lies in introducing a strongly dispersive slow-wave structure to increase the slope of the propagation constant with frequency. [9] and [10] respectively based on the SSPP structure, using rectangular metal patch arrays and tree-shaped unit SSPP transmission lines, achieved high-performance frequency scanning with scanning rates of up to 7.35°/% and 11.24°/%. In addition, curved-line SIW [11], hybrid slow-wave waveguides [12], and other structures have also been used to further enhance the scanning rate. These high-scanning-rate antennas perform well in frequency scanning performance, but their beam scanning characteristics strictly depend on the operating frequency and lack the ability to flexibly reconstruct the beam at fixed operating frequency. In addition, these antennas are generally dual-beam radiation and beam scanning is performed in the vertical plane. There are few studies on the LWAs with horizontal single-beam scanning.

In this paper, a novel radiation-pattern-reconfigurable SIW LWA with unidirectional horizontal radiation and high scanning rate is proposed. Conventional LWAs typically feature beam-scanning radiation only on the vertical plane, which limits the radiation coverage. In contrast, the proposed antenna overcomes this limitation by symmetrically etching offset U-shaped slots on both the top and bottom metal layers of the SIW, enabling unidirectional horizontal radiation performance. Each unit cell consists of two pairs of offset slots symmetrically distributed on both sides of the SIW, along with a pair of offset symmetric metallic vias for open stopband (OSB) suppression. The U-shaped slot cuts off the surface current more effectively than a single longitudinal slot, enhancing the energy leakage rate and dispersion sensitivity. By adjusting the position and size of the slots and metallic vias, the OSB effect is successfully suppressed, resulting in high beam-scanning rate. The proposed antenna is implemented on a single-layer dielectric substrate with a thickness of only

1.524 mm, offering a compact, low-profile design. The proposed antenna has the advantages of unidirectional horizontal radiation, high beam-scanning rate, and reconfigurable radiation pattern, which makes it promising for applications in mmWave communication, radar, wireless communication and imaging.

II. ANTENNA DESIGN

A. Antenna Geometry

The geometric structure of the proposed antenna is shown in Fig. 1. This antenna is fabricated using a Rogers RO4003C dielectric substrate with a thickness of 1.524 mm. Its structure mainly consists of two southwest connectors, two sections of impedance matching structures, and a slot array with 15 periodic units.

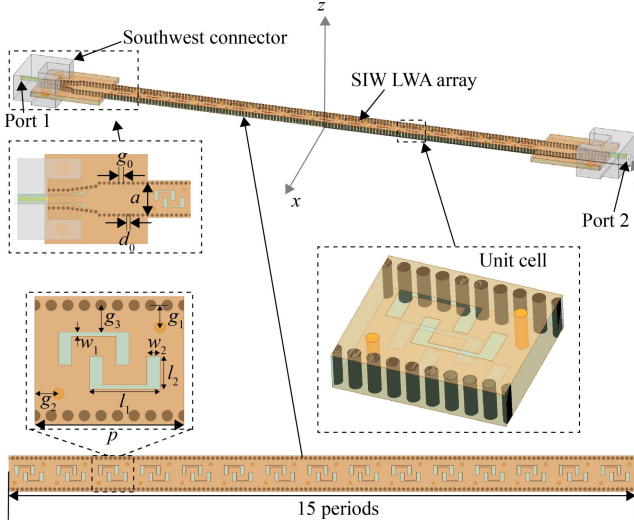


Fig. 1. Geometry of the proposed LWA. ($p = 6.75$ mm, $a = 5$ mm, $g_0 = 0.75$ mm, $d_0 = 0.5$ mm, $g_1 = 1$ mm, $g_2 = 1.075$ mm, $g_3 = 1.2$ mm, $l_1 = 3.2$ mm, $w_1 = 0.2$ mm, $l_2 = 1.5$ mm, $w_2 = 0.6$ mm)

To achieve a unidirectional horizontal radiation characteristic, two rows of offset U-shaped slots arranged symmetrically on the upper and lower metal layers of the substrate-integrated waveguide (SIW) are etched, thereby forming a SIW-based slot array. At the same time, two rows of offset metallized vias are arranged on both sides of the center line of the SIW to achieve impedance matching and suppress the OSB. The design of the slots and vias effectively enhance the energy leakage and dispersion characteristics, thereby improving the beam-scanning rate of the antenna. The feeding network includes two sections of ground coplanar waveguide (GCPW) and the corresponding GCPW-to-SIW transition structure, which are symmetrically distributed on both sides of the slot array to realized reconfigurable radiation pattern. In the simulation settings, when Port 1 is set as the excitation input port and Port 2 is connected to the matching load.

B. Analysis of Antenna Unit Cell

As shown in Fig. 1, this unit cell consists of two pairs of offset symmetrical U-shaped slots on the top and bottom metal

layers of SIW, as well as a pair of symmetrically configured metallic vias. The dispersion characteristics of the unit cell are analyzed by the following expressions.

$$\beta_{eff} = \frac{1}{p} \cdot \text{Im} \left[\cosh^{-1} \left(\frac{1 - S_{11}S_{22} + S_{12}S_{21}}{2S_{21}} \right) \right] \quad (1)$$

$$\alpha_{eff} = \frac{1}{p} \cdot \text{Re} \left[\cosh^{-1} \left(\frac{1 - S_{11}S_{22} + S_{12}S_{21}}{2S_{21}} \right) \right] \quad (2)$$

Based on (1) and (2), the corresponding normalized propagation constants are depicted in Fig. 2. As shown, the OSB can be suppressed completely and the beam-scanning rate is high.

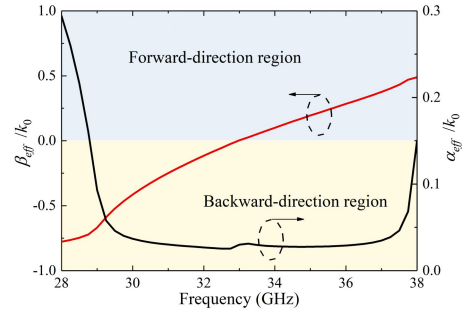


Fig. 2. Dispersion characteristics of the proposed unit cell.

III. SIMULATION RESULTS

The proposed antenna is constructed and optimized using the HFSS software. Figs. 3 and 4 respectively show the S parameters and antenna gain of the antenna. As shown in the Fig. 3, the proposed SIW LWA has a bandwidth of 18.5% in the range of 29.5 to 35.5 GHz. Moreover, when the proposed antenna operates at 33 GHz, its gain can reach 16.12 dBi.

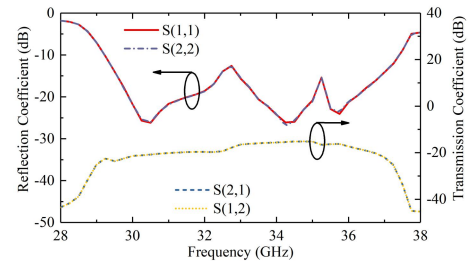


Fig. 3. S-parameters of the proposed LWA.

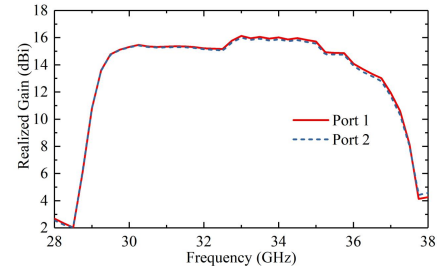


Fig. 4. Realized gain of the proposed LWA.

Fig. 5 shows the three-dimensional radiation pattern of the proposed antenna. From Fig. 5(a), it can be seen that when Port 1 is excited and Port 2 acts as a matching load, the radiation beam scans over the upper horizontal plane of the antenna. Fig. 5(b) shows the radiation scanning over the lower horizontal plane of the antenna. At this time, Port 1 is a matching load and Port 2 is excited. Based on this approach, the radiation pattern reconfigurable feature is achieved, and the coverage range of the antenna can be further increased.

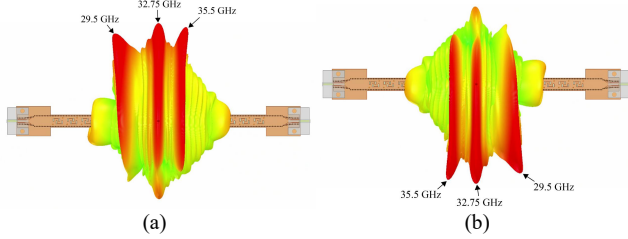


Fig. 5. Simulated 3-D beam-scanning characteristics of the proposed antenna. (a) Only Port 1 is excited. (b) Only Port 2 is excited.

Fig. 6 shows the two-dimensional radiation performance of the antenna in the xoy plane. As shown in the Fig. 6, when the frequency increases between 29.5 and 35.5 GHz, the radiation beam scans from 207° to 163° and 27° to -17° , thereby forming a wide horizontal scanning range. Additionally, through calculation, the antenna scanning rate can be determined to be $2.4^\circ/\%$.

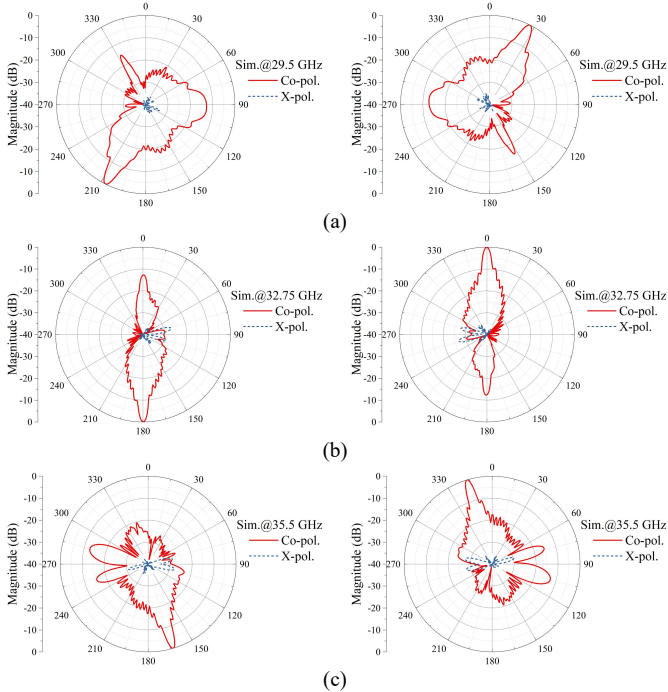


Fig. 6. 2-D radiation patterns of the LWA (xoy plane). (a) 29.5 GHz, (b) 32.75 GHz, and (c) 35.5 GHz. (On the left is the radiation pattern generated when Port 1 is excited, and on the right is the radiation pattern produced when Port 2 is excited.)

IV. CONCLUSION

This paper presents a novel reconfigurable LWA. By setting two pairs of offset symmetrical U-shaped slots on the upper

and lower layers of the SIW, a single-directional horizontal radiation is achieved. The combination of the slots and the metallic vias effectively suppress the OSB and achieve a high scanning rate. Finally, by switching the excitation source, the reconfigurable characteristics of the radiation pattern is realized. Due to its low profile, high gain, high scanning rate and radiation-pattern-reconfigurable characteristics, the proposed antenna is very suitable for modern millimeter-wave applications.

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REFERENCES

- [1] Shaoqiu Xiao, Zhenhai Shao, M. Fujise and Bing-Zhong Wang, "Pattern reconfigurable leaky-wave antenna design by FDTD method and Floquet's Theorem," *IEEE Transactions on Antennas and Propagation*, vol. 53, no. 5, pp. 1845-1848, May 2005.
- [2] Y. Geng, J. Wang, Y. Li, Z. Li, M. Chen and Z. Zhang, "Radiation pattern-reconfigurable leaky-wave antenna for fixed-frequency beam steering based on substrate-integrated waveguide," *IEEE Antennas and Wireless Propagation Letters*, vol. 18, no. 2, pp. 387-391, Feb. 2019.
- [3] J. Li, M. He, C. Wu and C. Zhang, "Radiation-pattern-reconfigurable graphene leaky-wave antenna at Terahertz band based on dielectric grating structure," *IEEE Antennas and Wireless Propagation Letters*, vol. 16, pp. 1771-1775, 2017.
- [4] X. Li et al., "A novel reconfigurable leaky wave antenna with beam scanning ability at fixed frequency," *IEEE Transactions on Antennas and Propagation*, vol. 74, no. 1, pp. 1132-1137, Jan. 2026.
- [5] M. Wang, Q. Yao, J. R. Chen, Z. W. Cheng and H. F. Ma, "A highly reconfigurable leaky-wave antenna based on multimode spoof surface plasmon polaritons," *IEEE Antennas and Wireless Propagation Letters*, vol. 24, no. 7, pp. 2084-2088, July 2025.
- [6] D. Zhang, B. Wu, W. -H. Li, H. -R. Zu, X. -Z. Song and T. Su, "Full-space-scanning substrate integrated waveguide antenna with enhanced scanning rate and efficiency," *IEEE Antennas and Wireless Propagation Letters*, vol. 22, no. 10, pp. 2517-2521, Oct. 2023.
- [7] H. -H. Zhang et al., "High-scanning-rate and wide-scanning-angle leaky-wave antenna based on double-layer slow-wave structure," *IEEE Antennas and Wireless Propagation Letters*, vol. 22, no. 9, pp. 2145-2149, Sept. 2023.
- [8] H. -H. Zhang et al., "A backfire-to-endfire leaky-wave antenna using corrugated offset parallel stripline with improved scanning rate and sidelobe," *IEEE Antennas and Wireless Propagation Letters*, vol. 23, no. 10, pp. 2954-2958, Oct. 2024.
- [9] Z. Wu, J. Wang, L. Zhao and Z. Shen, "Full-space and high-scanning rate leaky-wave antenna based on spoof surface plasmon polaritons," *IEEE Antennas and Wireless Propagation Letters*, vol. 23, no. 2, pp. 693-697, Feb. 2024.
- [10] P. Kang, Q. Wang and J. Qi, "Dual-beam high-scanning rate leaky-wave antenna based on a tree-shaped strong dispersion spoof surface plasmon polariton," *IEEE Antennas and Wireless Propagation Letters*, vol. 24, no. 8, pp. 2212-2216, Aug. 2025.
- [11] S. Lei, G. Wei, T. Qiu and M. Wang, "High-scanning-rate leaky-wave antenna with simple structure and low profile," *IEEE Antennas and Wireless Propagation Letters*, vol. 24, no. 4, pp. 868-872, April 2025.
- [12] J. -Y. Yin, P. -Y. Li, F. Li and J. -Y. Deng, "High-scanning-rate dual-beam leaky-wave antenna based on hybrid slow-wave waveguide," *IEEE Antennas and Wireless Propagation Letters*, vol. 23, no. 12, pp. 4233-4237, Dec. 2024.