

A Broadband High-Gain Omnidirectional SIW-Based Leaky-Wave Antenna 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 wideband operation, high gain, and omnidirectional radiation. The omnidirectional radiation characteristic is achieved by integrating a pair of symmetrical parabolic-shaped slots on both the upper and lower metal layers of the SIW structure. Each unit cell of this proposed antenna comprises a pair of longitudinally oriented capacitive parabolic slots and a pair of inductive metallic vias positioned opposite to the centerline, which collectively suppress the open stopband (OSB) effect. Notably, the proposed LWA is designed on a single-layer dielectric substrate with a thickness of only 0.813 mm, enabling a low-profile configuration. Simulation results demonstrate an operating bandwidth of 40.7%, a peak realized gain of 13.8 dBi, and wide-angle beam-scanning range from -56 degrees to 25.5 degrees across the broadside direction. Owing to its broad bandwidth and high-gain omnidirectional radiation characteristics, the proposed LWA exhibits strong potential for various mmWave applications.

Index Terms—broadband, high-gain omnidirectional radiation, leaky-wave antenna, substrate integrated waveguide.

I. INTRODUCTION

In wireless communication systems, omnidirectional antennas are of significant value due to their capability to provide uniform 360° coverage. Early research established the foundation for omnidirectional antenna design by employing dielectric rods loaded with metallic gratings to achieve millimeter-wave (mmWave) omnidirectional radiation, utilizing TE₀₁/TM₀₁ mode excitation and periodic perturbation to generate leaky waves [1]. In recent years,

a variety of technical approaches have been proposed to enhance the performance of omnidirectional antenna. For instance, a slender Fabry-Perot cavity combined with a partially reflective strip has been utilized to realize high-gain omnidirectional radiation [2], while periodic modulation of a coplanar waveguide with exponentially tapered open-end slots enables a steerable conical omnidirectional beam [3]. A half-mode substrate integrated waveguide (SIW)-based antenna achieves broadband omnidirectional radiation by gradually varying its width to modulate the cutoff frequency [4]. Furthermore, employing dual long slots on the broad wall or arranging slot arrays on both sides of a waveguide can produce omnidirectional radiation with a tilted beam or high pattern uniformity in the E-plane [5], [6]. To further combine high gain, wide bandwidth, and low loss, hollow-waveguide structures has been introduced [7]. However, existing designs face limitations in bandwidth, gain, structural complexity, and omnidirectional beam scanning range.

In this paper, a novel broadband high-gain omnidirectional leaky-wave antenna (LWA) based on SIW is proposed. Conventional leaky-wave antennas typically feature slots etched only on the upper surface, which limits the radiation direction and hinders the achievement of full omnidirectional coverage. In contrast, the proposed antenna overcomes this limitation by symmetrically etching parabolic-shaped slots on both the top and bottom metal layers of the SIW, enabling omnidirectional radiation performance. Each unit cell consists of a pair of slots symmetrically distributed on both sides of the SIW, along with a

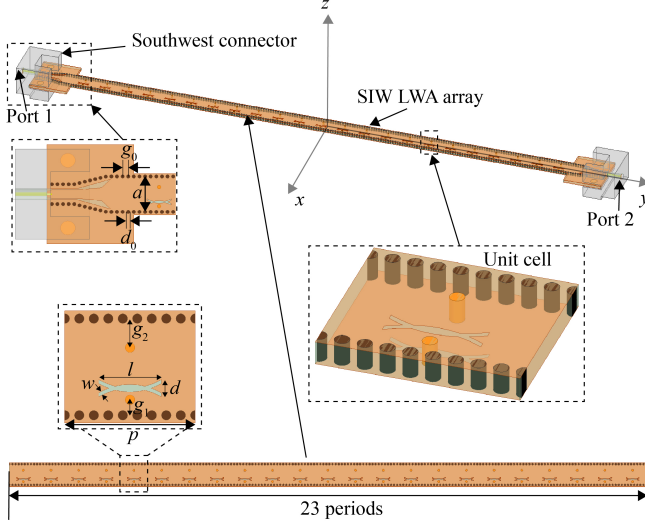


Fig. 1. Geometry of the proposed omnidirectional LWA. (All units are in mm: $g_0 = 0.75$, $d_0 = 0.5$, $a = 5$, $p = 6.75$, $w = 0.2$, $l = 4$, $d = 0.68$, $g_1 = 0.8$, $g_2 = 1.5$)

pair of metallic vias for open stopband (OSB) suppression. This configuration effectively tailors the electromagnetic field distribution and enhances radiation efficiency. Notably, through the strategic placement of metallic vias, the OSB effect is successfully suppressed, resulting in stable high-gain omnidirectional beam scanning over a broad frequency band. The proposed antenna is implemented on a single-layer dielectric substrate with a thickness of only 0.813 mm, offering a compact, low-profile design while maintaining favorable impedance matching and omnidirectional radiation characteristic. Owing to its combined advantages of wide bandwidth, high gain, and uniform omnidirectional coverage, the proposed antenna demonstrates promising application prospects in mmWave communications, indoor wireless coverage, mobile terminals, and similar scenarios.

II. ANTENNA DESIGN AND OPERATING PRINCIPLE

A. Antenna Topology

The geometric structure of the proposed antenna is depicted in Fig. 1. The design is implemented on a Rogers RO4003C dielectric substrate with a thickness of 0.813 mm. Fig. 1 shows that the proposed antenna consists of two southwest connectors, two tapered impedance-matching sections, and a slot array of 23 unit cells. To enable efficient omnidirectional radiation, two rows of periodically arranged symmetrical parabolic slots are etched on both the top and bottom metal layers of the SIW, forming a SIW-based slot array. Additionally, two rows of metallic vias are positioned on either side of the SIW centerline, serving to provide impedance matching and suppress the OSB effect. At each end of the antenna,

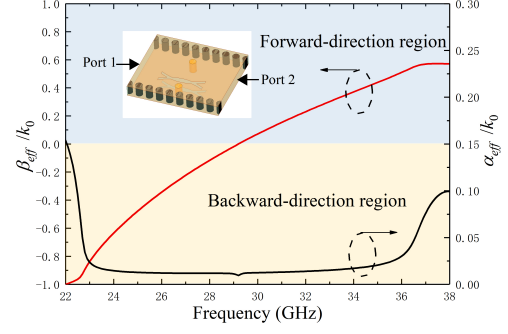


Fig. 2. Normalized phase and attenuation constants of the proposed unit cell.

a southwest connector is installed to facilitate a detachable, low-loss interface. The feeding network includes two ground coplanar waveguide (GCPW) sections and corresponding GCPW-to-SIW transitions, symmetrically arranged on both sides of the slot array to ensure balanced excitation, low-loss transmission, and effective mode conversion. In the simulated configuration, Port 1 is excited as the input port, while Port 2 is terminated with a matched load.

B. Analysis of Antenna Unit Cell

As illustrated in Fig. 1, the unit cell comprises a pair of symmetrical parabolic-shaped slots etched on the top and bottom metal layers of the SIW, together with a pair of metallic vias. The profile of the parabolic slot is defined by the equation

$$y^2 = 4fx \quad (1)$$

where f denotes the geometric focal length of the parabolic slot, which is set to 1.5 mm in this design. The dispersion characteristics of the unit cell are analyzed using the following expressions

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

$$\alpha_{eff} = \frac{1}{p} \text{Re} \left[\cosh^{-1} \left(\frac{1 - S_{11}S_{22} + S_{12}S_{21}}{2S_{21}} \right) \right] \quad (3)$$

Based on (2) and (3), The normalized phase constant (β_{eff}/k_0) and attenuation constant (α_{eff}/k_0) of the unit cell are derived, with the corresponding results illustrated in Fig. 2.

As shown in Fig. 2, the dispersion curves of the unit cell indicate that the operating frequency band covers 22-29.2 GHz in the backward-direction region, and 29.2-38 GHz in the forward-direction region, with the broadside radiation occurring at 29.2 GHz. It can be observed from Fig. 2 that near 29.2 GHz, the attenuation constants exhibit no abrupt variation, while the propagation constants change approximately linearly. This behavior confirms the effective mitigation of the OSB. The underlying mechanism

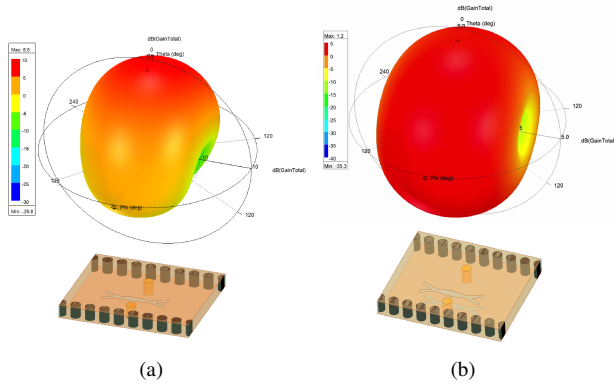


Fig. 3. Three-dimensional radiation patterns of the unit cell with slots etched on (a) only the upper layer, and (b) both the upper and lower layers of the SIW.

is attributed to the complementary reactance provided by the inductive pair of metallic vias and the capacitive effect introduced by the longitudinal parabolic slots, which together counteract each other and suppress the OSB. This contributes to achieving wideband operation and high-gain performance in the proposed antenna.

C. Omnidirectional Radiation

The omnidirectional radiation characteristic of the proposed antenna originates from its core slot array design. At the same point on the broad wall of the SIW, the current directions on the upper and lower surfaces are opposite. Therefore, the pair of symmetrical parabolic-shaped slots proposed in this work radiate complementary beams, which together form an omnidirectional radiation pattern. Furthermore, each unit cell incorporates a pair of precisely positioned metallic vias to achieve broadband high-gain performance. To demonstrate the operating principle of omnidirectional radiation, Fig. 3 illustrates the three-dimensional radiation patterns of the unit cell. As observed in Fig. 3(a), when slots are etched solely on the upper layer of the SIW, radiation is confined to the upper half-space. In contrast, Fig. 3(b) demonstrates that by introducing a pair of symmetrical slots on both the upper and lower layers of the SIW, full omnidirectional radiation is achieved. Extending this configuration into an array arrangement ultimately enables the realization of an omnidirectional LWA array.

III. PARAMETER STUDY

To further investigate the antenna performance, a detailed parametric study was conducted in this section. Fig. 4 illustrates the dispersion characteristics of the antenna without metalized vias. It is evident from Fig. 4 that the antenna without metalized vias exhibits a pronounced open stopband phenomenon. In contrast, the incorporation of metalized vias effectively suppresses this issue.

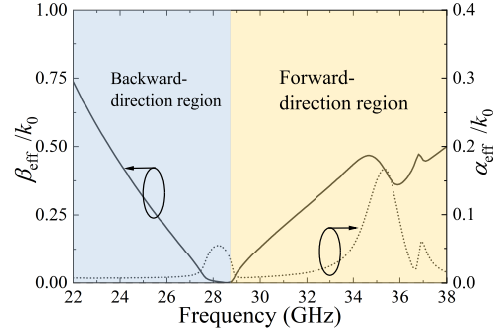


Fig. 4. Normalized phase and attenuation constants of the proposed unit cell without metalized vias.

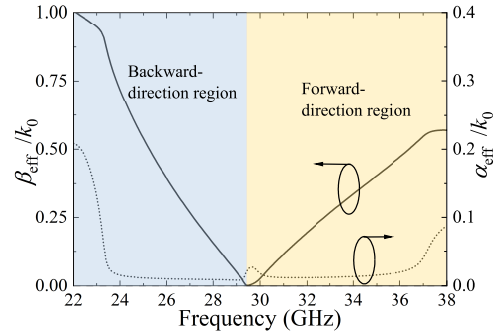


Fig. 5. Normalized phase and attenuation constants of the proposed unit cell with rectangular slots.

Fig. 5 depicts the dispersion curves of the antenna loaded with rectangular slots. As observed in Fig. 5, the antenna with rectangular slots displays a distinct open stopband, accompanied by significant fluctuations in phase and attenuation characteristics. Conversely, the antenna with parabolic slots exhibits a dispersion curve devoid of open stopband issues and maintains a stable attenuation constant. This favorable dispersion characteristic enables continuous beam scanning from backward to forward directions, providing a solid foundation for high-gain wideband leaky-wave antennas.

Furthermore, Fig. 6 presents a gain comparison between the antenna loaded with parabolic slots and the one with rectangular slots. The results demonstrate that the antenna with parabolic slots achieves higher gain while maintaining low circularity.

IV. RESULTS AND DISCUSSIONS

The proposed antenna was simulated using HFSS, and its S-parameters are presented in Fig. 7. As shown in Fig. 7, the reflection coefficients remain below -10 dB across the frequency range of 23-34.75 GHz, corresponding to a relative bandwidth of 40.7%. This broadband performance makes the antenna well-suited for high-frequency communication and radar systems operating in the K/Ka bands.

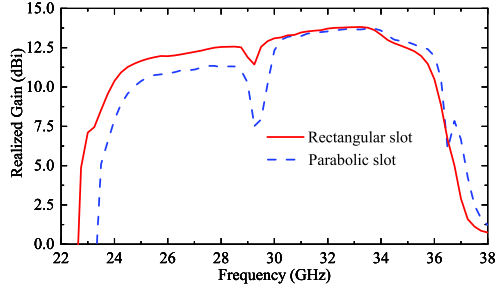


Fig. 6. Simulated realized gain of the proposed antenna loaded with parabolic slots and the one with rectangular slots.

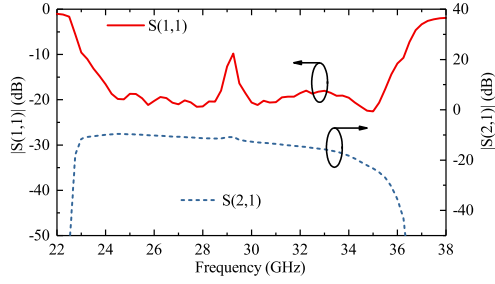


Fig. 7. Simulated S-parameters of the proposed LWA.

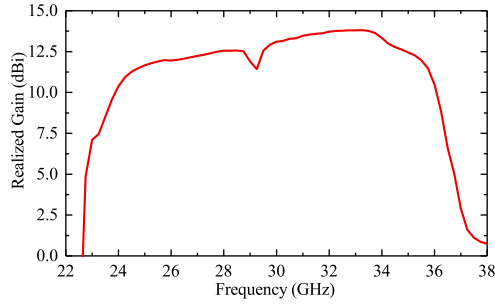


Fig. 8. Simulated realized gain of the proposed LWA.

Fig. 8 plots the realized gain of the antenna within the frequency range of 22-38 GHz. The antenna peak gain is 13.81 dBi at 33.25 GHz. Throughout most of the operating band, the antenna gain exceeds 10 dBi, indicating that the antenna exhibits high-gain omnidirectional radiation characteristics. Fig. 9 illustrates the omnidirectional radiation pattern of the antenna in the xoz -plane at 29.20 GHz with a maximum non-circularity being approximately 2 dB.

Fig. 10 illustrates the radiation patterns of the proposed LWA at four frequencies: 23.00 GHz, 24.75 GHz, 29.20 GHz, and 34.75 GHz. As the frequency increases from 23 GHz to 34.75 GHz, the main beam direction scans continuously from approximately -56° to $+25.5^\circ$, covering a total scanning range of over 80° , which demonstrates the wide-angle frequency-scanning capability of the proposed antenna. Moreover, the cross-polarization level remains consistently low, indicating good polarization purity and

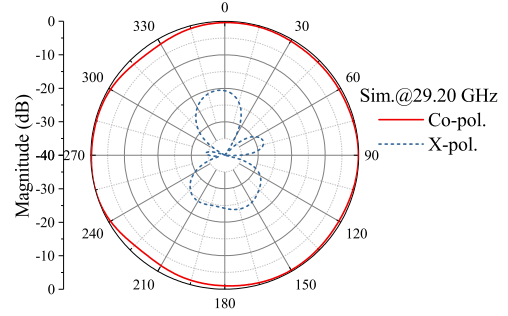


Fig. 9. Radiation pattern of the antenna in the xoz -plane at 29.20 GHz.

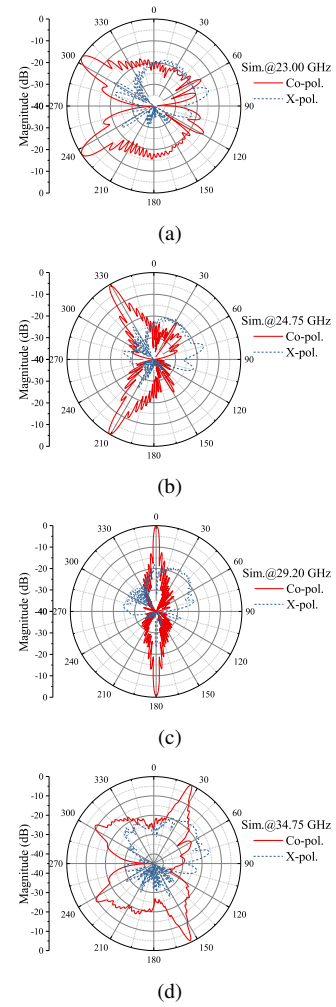


Fig. 10. Simulated radiation patterns of the proposed LWA at four different frequencies (yoz plane). (a) 23 GHz, (b) 24.75 GHz, (c) 29.2 GHz, and (d) 34.75 GHz.

high radiation efficiency.

V. CONCLUSION

This paper presents a novel broadband, high-gain omnidirectional LWA based on SIW. By symmetrically etching

parabolic-shaped slots on both the upper and lower metal layers of the SIW and incorporating metallic vias, the OSB effect is effectively suppressed, which enables broadband impedance matching and stable omnidirectional radiation. The antenna operates over the 22-38 GHz frequency band, achieving a fractional bandwidth of 40.7%, a peak gain of 13.81 dBi, and omnidirectional beam-scanning capability. It also exhibits wide-angle beam-scanning performance and high polarization purity. Owing to its compact, low-profile structure and high performance, the proposed antenna is well-suited for next-generation mmWave communication systems requiring wideband high-gain omnidirectional coverage.

ACKNOWLEDGMENT

This work was supported in part by the National Key Research and Development Program of China under Grant 2023YFE0107900, in part by the Program for Scientific Research Startup Funds of Guangdong Ocean University under Grant 060302112504, in part by the National Natural Science Foundation of China (NSFC) under Grant U2541208, in part by the Key Program of Shenzhen Natural Science Foundation under Grant JCYJ20241202124219023, and in part by the Program of Shenzhen Key Laboratory Evaluation under Grant SYSPG20241211173908022.

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