2021 Photonics & Electromagnetics Research Symposium (PIERS) | 978-1-7281-7247-7/21/$31.00 ©2021 IEEE | DOI: 10.1109/PIERS53385.2021.9694822

A SIW Leaky-wave Antenna Featuring Wide Beam-scanning Range and Rapid Scanning Rate for 5G Applications

Qinwei Ji, Long Zhang, Jinfeng Zhang, Xianting Xie, Minqing Wang, and Yejun He
College of Electronics and Information Engineering, Shenzhen University, 518060, China

Abstract— In this paper, a substrate integrated waveguide (SIW) periodic leaky-wave antenna with both wide beam-scanning range and rapid scanning rate characteristics is proposed. By employing substrate with high dielectric constant and the longitudinal slot with impedance matching post, a wide beam-scanning angle through broadside is obtained. In addition, by adjusting the longitudinal slot and the dipole element in each unit cell, the slope of phase constant curve can be greatly increased, resulting in a relative high scanning rate more than four degrees per percentage bandwidth. The simulated results show that a continuous beam scanning from −46.12° to +33.76° within the operating band (24.4–30.4 GHz) is achieved. Moreover, a rapid scanning rate of 3.65° per percent bandwidth and stable gain are observed over the entire operating band.

1. INTRODUCTION

Leaky-wave antennas (LWAs) are a special class of traveling-wave radiating structures, which are attractive for various applications such as the 5G communication, automotive radar, and sensor [1]. According to the geometric structure and working principle, LWAs are divided into three categories: uniform, quasi-uniform and periodic LWAs [2, 3]. For the uniform and quasi-uniform LWAs, the radiation beam scan in the forward direction. However, the radiation beam of periodic LWAs can scan from the backward direction to the forward direction. Due to the existence of two in-phase oppositely directed spatial harmonics, no broadside radiation is obtained, which is known as the open stopband (OSB) problem. Obviously, to achieve wide beam-scanning range, the problem of OSB should be solved. In addition, a rapid scanning rate can effectively reduce the requirement of bandwidth, which is also necessary for the 5G applications.

Substrate integrated waveguide (SIW) provides several advantages such as low cost, easy fabrication, and integration with planar structures. Recently, SIW-based periodic LWAs have received considerable attention. For OSB suppression in SIW periodic LWAs, various reported efforts have been devoted. For instance, a SIW periodic LWA with both longitudinal and transverse slots was proposed to eliminate the OSB problem [4]. In [4], a wide beam-scanning range is achieved. However, the beam-scanning rate of the antenna is 1.7° per percent bandwidth and the antenna gain varies greatly (from 3 dBi to 12 dBi) within the operating frequency band. By combining the longitudinal slot and impedance matching posts, a SIW periodic LWA with wide beam-scanning range through broadside was obtained [5]. Unfortunately, the antenna also has the problems of large gain variation (from 7 dBi to 14.2 dBi) within operating frequency band and the scanning rate is only 2.2° per percent bandwidth. A magneto-electric dipole SIW periodic LWA consisting of a longitudinal slot and a patch dipole with two short circuit posts was presented to obtain a more stable radiation gain [6]. However, the beam-scanning range from +4° to +20° of the antenna is small and the scanning rate is 0.9° per percent bandwidth. Recently, by using the longitudinal slots, transverse slots and impedance matching posts simultaneously, a SIW periodic LWA with both wide scanning range and stable gain was achieved [7]. Nevertheless, the antenna beam-scanning rate is still not rapid. For designing LWAs with a rapid beam-scanning property, a transversely slotted SIW LWA featuring rapid beam-scanning was demonstrated in [8].

In this paper, a SIW periodic LWA with wide beam-scanning range, rapid scanning rate, and stable radiation gain is proposed. Firstly, the substrate with high dielectric constant is used to increase the beam-scanning range. Then, the OSB is suppressed by introducing the longitudinal slot and impedance matching post. Finally, by adding the dipole element in each unit cell, a rapid beam-scanning rate is obtained. By this means, the proposed antenna features a continuous beam scanning from −46.12° to +33.76° within a small operating band (24.4–30.4 GHz). Moreover, a rapid scanning rate of 3.65° per percent bandwidth and stable gain are also achieved.

2. ANTENNA CONFIGURATION AND OPERATING PRINCIPLE

2.1. Antenna Configuration

Figure 1 shows the configuration of the proposed antenna element. As shown in Fig. 1, a coupling longitudinal slot is etched on the top layer of Substrate 2, while a patch dipole element is placed above each coupling slot and etched on the top layer of Substrate 1. The Substrate 1 and 2 both use 0.635 mm-thin Rogers RO6010 substrate. As shown, the longitudinal slot is utilized to realize energy coupling between the patch dipole element and the SIW. An impedance matching post is added in Substrate 2 to suppressed the OSB problem.

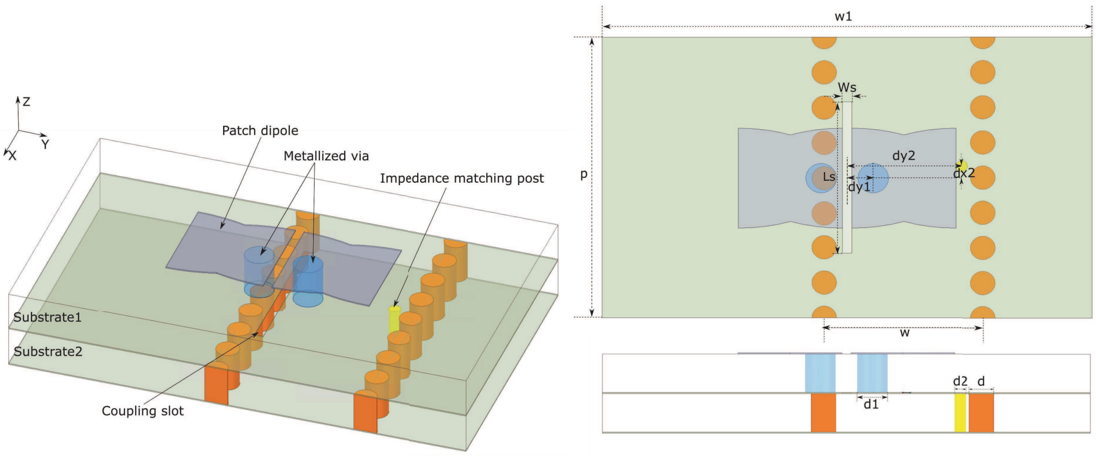
Figure 2 shows the structure of the proposed antenna array. The proposed antenna is constituted by ten elements which are constructed on two Rogers RO6010 substrates. According to the design principles of LWA, the phase constand (β) and the attenuation constant (α) can be calculated by,

$$\beta = \mathrm{Im}\left[\operatorname{arccos} h\left(\frac{1 - S_{11}S_{22} + S_{21}S_{12}}{2S_{21}}\right)/p\right] \tag{1}$$

$$\alpha = \mathrm{Re}\left[\operatorname{arccos} h\left(\frac{1 - S_{11}S_{22} + S_{21}S_{12}}{2S_{21}}\right)/p\right] \tag{2}$$

And the required antenna length is calculated by

$$L/\lambda_0 = \frac{0.18}{\alpha/k_0} \tag{3}$$



(a)

(b)

Figure 1: The configuration of the proposed antenna element. (a) Perspective view, (b) top view and side view.

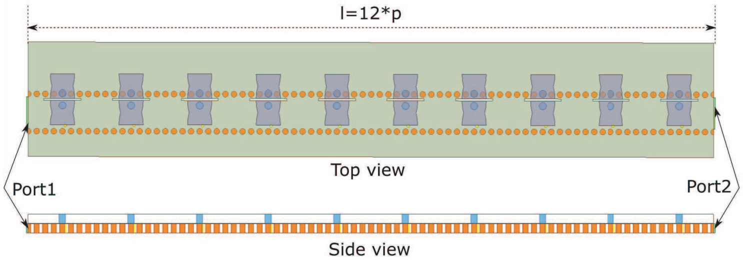


Figure 2: Geometrical configuration of the proposed antenna arrray.

2.2. Operating Principle

To illustrate the operating principle of the proposed antenna, the unit cell performance is studied. Firstly, by increasing the dielectric constant of the substrate, the scanning angle of the proposed antenna can be significantly increased, which has been illustrated in detail in [8]. Therefore, the Rogers RO6010 substrate with $\varepsilon_r = 10.2$ is utilized as the antenna substrate. As shown in Fig. 3, the slope of the normalized phase constant at backward direction is greatly improved by adding a dipole element. This phenomenon allows for a narrower frequency range at the same scanning angle, resulting in a higher scan rate.

Moreover, as shown in Fig. 4, by changing the dimensions of the longitudinal slot, the slope of the normalized phase constant at forward direction is also effectively enhanced. Obviously, by choosing suitable dimension of the longitudinal slot and the dipole element, the slope of phase constant curve can be greatly increased. The problem of OSB is eliminated by introducing impedance matching post as introduced in [9]. As shown in Fig. 5, the smooth transition between the normalized phase constant curve and the normalized attenuation constant curve means that the problem of the antenna's OSB is eliminated. With these measures, a ten-element periodic LWA is designed.

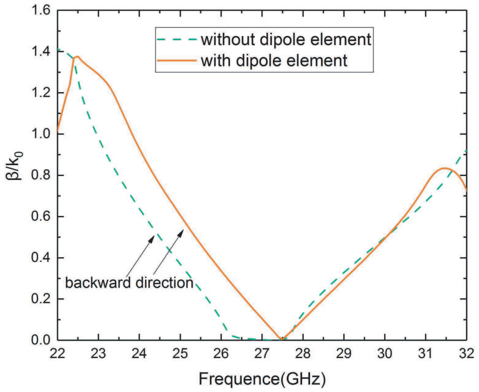


Figure 3: Comparison of the normalized phase constant of the antenna with and without diople elements.

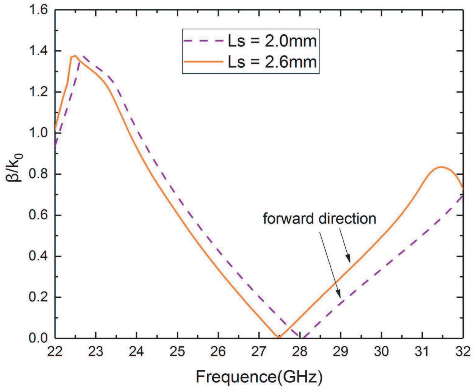


Figure 4: Comparison of the normalized phase constant with different Ls.

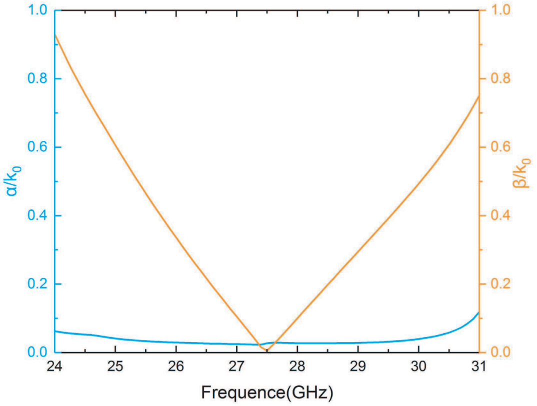


Figure 5: The normalized phase constant and the attenuation constant.

3. SIMULATION RESULTS

Figure 6 shows the simulated S-parameters of the proposed antenna. As shown, the $|S_{11}|$ is less than $-10\,\mathrm{dB}$ within the bandwidth of 24.4–30.4 GHz, which means that the antenna is well matched in this band. Moreover, it is noticed that the OSB is also effectively suppressed. The $|S_{21}|$ is basically less than $-7.5\,\mathrm{dB}$ within the operating frequency band, which means that a large part of energy is radiated out, and only a small part of energy is absorbed by the terminal matching port.

Figure 7 shows the two-dimensional radiation patterns of the proposed antenna at different frequencies. As can be seen from Fig. 7, within the bandwidth of 24.4–30.4 GHz, the antenna radiation beam can be scanned from −46.12° to +33.76°, with a scanning rate of 3.65° per percent bandwidth. With the increase of frequency, the radiation beam can be scanned continuously from backward to forward direction, and good radiation is also achieved in the broadside direction.

Figure 8 shows the three-dimensional radiation patterns of the proposed antenna at 24.4, 27.4 and 30.4 GHz, respectively. As shown, the antenna has a fan-shaped radiation beam, which scans from backward to forward direction with the increasing of frequency.

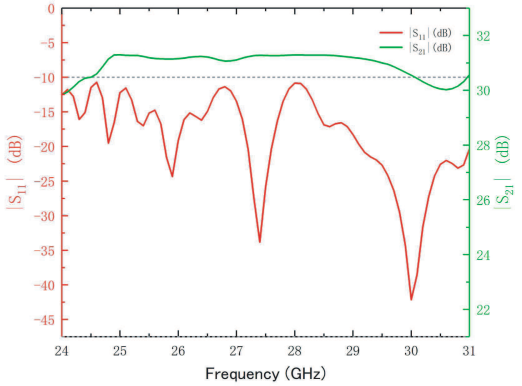


Figure 6: The simulated $|S_{11}|$ and $|S_{21}|$ of the proposed antenna.

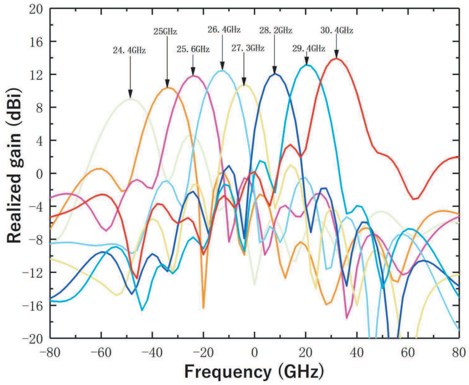
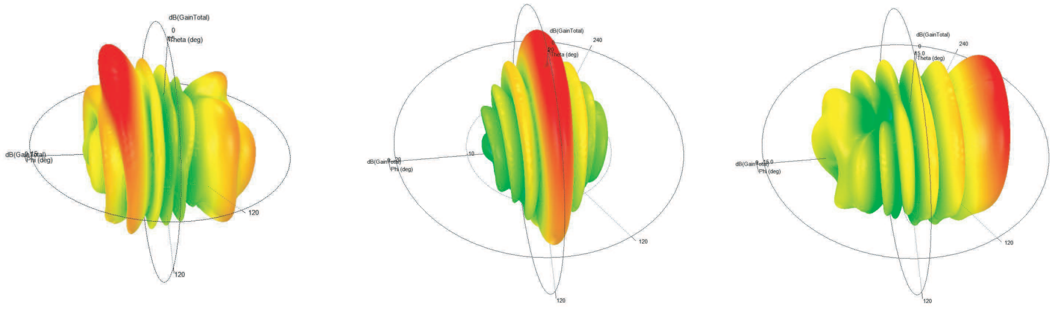


Figure 7: The gain pattern of the antenna at different frequencies.



(a)

(b)

(c)

Figure 8: The three-dimensional radiation pattern of the antenna. (a) 24.4 GHz, (b) 27.4 GHz, (c) 30.4 GHz.

4. CONCLUSION

In this paper, a SIW periodic leaky-wave antenna with both wide beam-scanning range and rapid scanning rate is proposed. A wide beam-scanning angle through broadside is obtained by employing high dielectric constant substrate and longitudinal slot with impedance matching post. In addition, by adjusting the longitudinal slot and dipole element in each unit cell, a rapid beam-scanning rate is also achieved. Simulated results indicate that the proposed antenna scans from −46.12° to +33.76° within a small operating band (24.4–30.4 GHz), which resulting a rapid scanning rate of 3.65° per percent bandwidth. These attractive properties of the proposed antenna make it appealing for 5G applications.

ACKNOWLEDGMENT

This work was supported in part by National Natural Science Foundation of China under Grant 61801299, and in part by the Natural Science Foundation of Guangdong Province under Grant 2020A1515011037.

REFERENCES

1. He, Y., J. Jiang, L. Zhang, W. Li, S.-W. Wong, W. Deng, and B. Chi, "Leaky-wave antennas for 5G/B5G mobile communication systems: A survey," *ZTE Communications*, Vol. 18, No. 3, 3-11+41, 2020.
2. Oliner, A. A. and D. R. Jackson, *Antenna Engineering Handbook*, 4th Edition, Chap. 11, McGraw-Hill, New York, 2007.
3. Balanis, C. A., ed., *Modern Antenna Handbook*, 325–368, Hoboken, Wiley, 2008.
4. Lyu, Y.-L., et al., "Leaky-wave antennas based on noncutoff substrate integrated waveguide supporting beam scanning from backward to forward," *IEEE Transactions on Antennas and Propagation*, Vol. 64, No. 6, 2155–2164, 2016.
5. Ranjan, R. and J. Ghosh, "SIW-based leaky-wave antenna supporting wide range of beam scanning through broadside," *IEEE Antennas and Wireless Propagation Letters*, Vol. 18, No. 4, 606–610, 2019.
6. Mak, K.-M., K.-K. So, H.-W. Lai, and K.-M. Luk, "A magnetoelectric dipole leaky-wave antenna for millimeter-wave application," *IEEE Transactions on Antennas and Propagation*, Vol. 65, No. 12, 6395–6402, 2017.
7. Karmokar, D. K., S. Chen, D. Thalakotuna, P. Qin, T. S. Bird, and Y. J. Guo, "Continuous backward-to-forward scanning 1-D slot-array leaky-wave antenna with improved gain," *IEEE Antennas and Wireless Propagation Letters*, Vol. 19, No. 1, 89–93, 2020.
8. Zheng, D., Y.-L. Lyu, and K. Wu, "Transversely slotted SIW leaky-wave antenna featuring rapid beam-scanning for millimeter-wave applications," *IEEE Transactions on Antennas and Propagation*, Vol. 68, No. 6, 4172–4185, 2020.
9. Zheng, D. and K. Wu, "Leaky-wave antenna featuring stable radiation based on multimode resonator (MMR) concept," *IEEE Transactions on Antennas and Propagation*, Vol. 68, No. 3, 2016–2030, 2020.