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# Near-Field Focusing mmWave Leaky Wave Antenna for Enhanced Wireless Power Transfer

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***Abstract*-A near-field focusing millimeter-wave (mmWave) leaky wave antenna (LWA) using non-periodic rectangular slots for wireless power transfer application is presented in this paper. The proposed design is based on a rectangular substrate integrated waveguide and fed by two coaxial probes. The phase distribution in the near field and slot positioning are derived by a theoretical approach. By skillfully manipulating the slot positions, the uniform slot elements facilitate an in-phase superposition within the desired near-field region, resulting in a significant focusing effect. To explore the performance of the antenna, the focusing effect is examined at a 2D focal distance of (10λ, 10λ). Here, λ represents the free space wavelength at 28 GHz. While maintaining a beam steering from 27.5 GHz to 30.5 GHz, an impressive 69% enhancement compared to the traditional far-field LWAs is obtained at 28 GHz. This breakthrough design not only offers a substantial enhancement in focusing capability but also opens the door to an emerging transmitting system with a notably high beam efficiency for wireless power transfer (WPT).**

## I. Introduction

Wireless power transfer (WPT) within millimeter-wave (mmWave) bands has gained significant attention in recent years [1-2]. This surge in interest is fueled by emerging demands, such as the transfer of solar power collected in space to terrestrial locations. Among the array of beamforming techniques employed in WPT systems, leaky wave antennas (LWAs) built upon the substrate integrated waveguide (SIW) architecture stand out as promising choices for generating focused beams over short or long distances [1-3]. LWAs are well known for their simple feeding networks as well as the inherent property of beam steering with frequencies [4], and thus they avoid complicated beamforming systems and are suitable for mmWave applications. LWAs on SIW have further advantages of low profile and easy component integration catering for mmWave WPT systems [5]. In addition, based on the relation between leaky wave elements and the near-fields, non-uniform leaky wave elements with modulated width, length and periodicity have been used to synthesize focused beams in the near field [6]. In this paper, an approach of the near-field focusing beam on a leaky wave antenna with –45° polarization is presented as an example, which balances both the reflection coefficient and radiation efficiency.

## II. Leaky Wave Antenna Design

### *A. Conventional Far-field Focusing Leaky Wave Antenna Design*

Fig. 1 (a) shows the structure of a far-field focusing LWA for 28 GHz operation with periodically placed rectangular slots

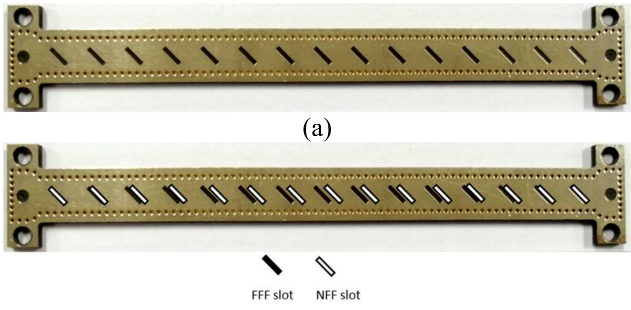


Figure 1. Structures of the leaky wave antennas. (a) is the traditional far-field focusing LWA, whereas (b) is the comparison on the slot positions between the far-field and near-field focusing scenarios.

reported in [7]. Rogers RT5880 is used as the substrate with a thickness of 1.575 mm. The dielectric constant and loss tangent are 2.2 and 0.0009, respectively. There are 15 slots placed with a uniform spacing of 5.9 mm. The total physical length of the antenna is 100 mm, and the effective antenna length is 82.6 mm which is 7.7λ, where λ is the free space wavelength at 28 GHz. The far-filed radiation beam is pointing along –45° with a realized gain of 15.2 dBi at 28 GHz.

### *B. Proposed Near-field Focusing Leaky Wave Antenna Design*

An approach for the near field focusing at a 2D focal point F is discussed based on the traditional LWA (Fig. 1(a)) in this section. Fig. 2 illustrates the scheme of aperture illumination of the near field focusing LWA. The desired focal point is assumed at F ($y_f$, $z_f$), where $y_f$ and $z_f$ are the focal distances measured from the center of the antenna aperture. The distance of the focal point to an arbitrary point on the surface of the antenna (y, 0) is expressed as $\sqrt{(y_f - y)^2 + {z_f}^2}$.

The phase of the propagating wave in the SIW is given as

$$\Psi_{SIW}(rad) = -\beta_0 y, \tag{1}$$

where $\beta_0$ denotes the propagation constant of the propagating wave in the SIW and is expressed by

$$\beta_0 = \sqrt{{k_0}^2\varepsilon_r - \pi^2 {W_{eff}}^{-2}}, \tag{2}$$

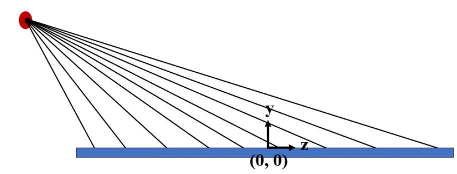


Figure 2. Illustration of the near-filed focused leaky wave antenna.

where $W_{eff}$ *is* the effective width of the SIW, $k_0$ is the wave number, $\varepsilon_r$ is the relative dielectric constant of the substrate. The $W_{eff}$ is given as [8]:

$$W_{eff} = W_{SIW} - 1.08d^2s^{-1} + 0.1d^2{W_{SIW}}^{-1}, \quad (3)$$

where $W_{SIW}$ is the physical width of the SIW, $d$ is the via diameter and $s$ is the via spacing.

The phase at the focal point F is calculated by

$$\Psi_F(y) = k_0\sqrt{(y_f - y)^2 + {z_f}^2}\ . \quad (4)$$

In order to achieve a focusing effect at the focal point, the phase of leaky wave at the focal point and the phase of the propagating wave in SIW at the point (y, 0) should satisfy the following condition:

$$\Psi_{SIW}(rad) = \Psi_F(y) + 2n\pi, \quad (5)$$

where $n$ is an integer.

The slot position can thus be derived by solving the equations (1) - (5). In this paper, as an example a focal distance of 10λ is selected, i.e., F ($y = -10\lambda$, $z = 10\lambda$).

## III. Results and Analysis

Fig. 3 depicts the simulated phase distributions in the near field of the antenna. The red lines represent the phase observed at the focal point F (y = –10λ, z =10λ). The blue lines denote the phase of the propagating wave in the SIW. The intersection points correspond to the slot positions, which are summarized in Table I.

The structure of the proposed near-field focused LWA is shown in Fig. 1(b). CST Microwave Studio is used to simulate and analyze the proposed design. The power density distortion in the near field is demonstrated in Fig. 4. As shown in Fig 4(a), the power density at the desired focal point obtained by the traditional far-field focusing antenna is 49.53 W/m$^2$, whereas a stronger power density at the same focal point, which is 83.85 W/m$^2$, is observed in the proposed design, as shown in Fig. 4(b). A 69% power enhancement has been achieved by the proposed design, validating the significant beam focusing effect.

## IV. Conclusion

This paper introduces a near-field focusing millimeter-wave (mmWave) leaky wave antenna (LWA) designed for wireless

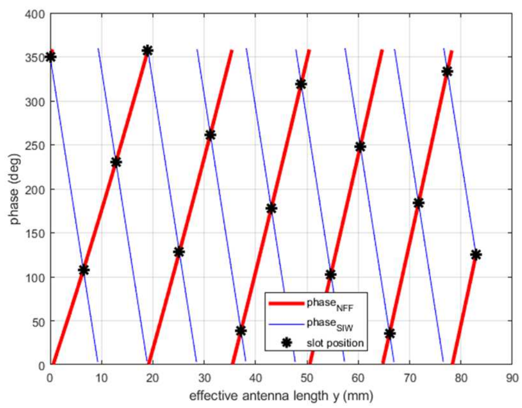
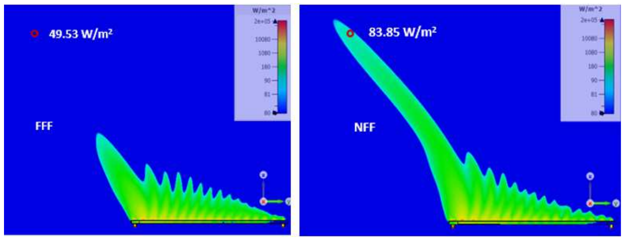


Figure 3. Phase distribution in the near field.



(a) (b)

Figure 4. Power density distribution in the near field. (a) is the traditional far-field focusing LWA, whereas (b) is the proposed near-field focusing LWA.

TABLE I. Slot position (P) for the proposed near-field focusing antenna.

| Slot | Position (mm) | Slot | Position (mm) | Slot | Position (mm) |
|---|---|---|---|---|---|
| 1 | 0 | 6 | 31.2 | 11 | 60.4 |
| 2 | 6.5 | 7 | 37.2 | 12 | 66.1 |
| 3 | 12.8 | 8 | 41.3 | 13 | 71.7 |
| 4 | 19 | 9 | 48.9 | 14 | 77.3 |
| 5 | 25.2 | 10 | 54.7 | 15 | 82.9 |

power transfer (WPT) applications. The effectiveness of the focusing effect is showcased through a comparison with the conventional far-field focusing LWA. Moreover, the focused beam scanns from 30 to 80 degrees when the frequency vaires from 27.5 to 30.5 GHz, offering wide coverage and position flexibility from the user ends. This contribution presents a promising avenue for future WPT systems, specifically as transmitters. Further substantiating this paper, experimental data will be presented during the conference.

## References


[1] C. Song *et al*., "Wideband mm Wave Wireless Power Transfer: Theory, Design and Experiments," *2023 17th European Conference on Antennas and Propagation (EuCAP)*, Florence, Italy, 2023, pp. 1-5.

[2] C. Song *et al*., "Novel mmWave Wireless Power Transfer Systems Using Broadband Circularly Polarized Rectennas and Leaky Wave Transmitters," *2023 IEEE International Symposium on Antennas and Propagation and USNC-URSI Radio Science Meeting*, Portland, USA, 2023, pp. 1-2.

[3] Y. F. Wu and Y. J. Cheng, "Two-Dimensional Near-Field Focusing Folded Reversely Fed Leaky-Wave Antenna Array with High Radiation Efficiency," in *IEEE Transactions on Antennas and Propagation*, vol. 67, no. 7, pp. 4560-4569, July 2019.

[4] C. A. Balanis, *Leaky-Wave Antennas*, 1st ed. John Wiley & Sons, Ltd, 2008.

[5] M. Poveda-García, J. Oliva-Sánchez, R. Sanchez-Iborra, D. Cañete-Rebenaque and J. L. Gomez-Tornero, "Dynamic Wireless Power Transfer for Cost-Effective Wireless Sensor Networks Using Frequency-Scanned Beaming," in *IEEE Access*, vol. 7, pp. 8081-8094, 2019.

[6] J. L. Gómez-Tornero, A. J. Martínez-Ros and J. Monzó-Cabrera, "Demonstration of Simple Electronic Near-Field Beamforming Using Multitone Microwave Signals with a Leaky-Wave Focused Applicator," in *IEEE Antennas and Wireless Propagation Letters*, vol. 14, pp. 143-146, 2015.

[7] X. Li, L. Wang, J. Wang and G. Goussetis, "Conformal High Gain Aperture Antenna Based on Leaky-Wave Array for CubeSat Communication," *2020 International Symposium on Antennas and Propagation (ISAP)*, Osaka, Japan, 2021, pp. 499-500.

[8] F. Xu and K. Wu, "Guided-wave and leakage characteristics of substrate integrated waveguide," in *IEEE Transactions on Microwave Theory and Techniques*, vol. 53, no. 11, pp. 66-73, Jan. 2005.