A mmWave Leaky-Wave Antenna for Efficiency Enhanced Near-Field Wireless Power Transfer and Communication

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***Abstract*—A mmWave near-field-focused and beam steerable circularly polarized (CP) leaky-wave antenna (LWA) for wirelesses power transfer (WPT) with multiple users and communication is presented. The proposed design is achieved by etching uniform fan-shaped slots in a rectangular substrate integrated waveguide (SIW). The slots are elaborately designed and positioned for beam focusing at a desired focal distance of 0.5 m. Compared to the conventional LWA, the power density of the proposed design is enhanced by 1.4 dB. It allows a dual beam scanning propriety with a wide angular coverage of -43.18° and -33° in near field and far field, respectively. The proposed design benefits WPT systems by eliminating the beam forming network and offering wide power coverage. Moreover, it offers high realized gain no less than 12.62 dBi in the bandwidth of 22.5 GHz to 26 GHz. Hence, the LWA proposed is a promising transmitter candidate for integrated WPT and communication.**

***Index Terms*—Beam focusing, leaky-wave antenna (LWA), mmWave, near-field, substrate integrated waveguide(SIW), wireless power transfer (WPT).**

I. Introduction

In the future, the wireless power transfer (WPT) system would be required to serve multiple devices simultaneously [1]. Fig. 1 demonstrates a scenario of the future WPT system in daily life. These multiple user ends could be the mobile phones, laptops, watches, robot cleaners or other electronic devices commonly used in daily life. To fulfil the demands, the end to end efficiency of the WPT is required to be extremely high to deliver sufficient power to boost the multiple devices. This is a challenge for WPT with microwave band which suffers from the low power capacity. To overcome the limitation of power carrying, the WPT system in the millimeter-wave (mmWave) band has recently gained a lot of traction. Compared with the microwave band, mmWave band has the significant advantage of high EIRP limit of 75 dBm [2], which benefits the future WPT system. Moreover, as a crucial element of a WPT system, a transmitter antenna in the mmWave band is capable of offering higher directivity and higher aperture efficiency at a given aperture size [1][3]. It also allows a compact overall size. A drawback of the mmWave band is the high free-space path loss in high frequency. However, this could be compensated by the high gain achieved by the antenna. [1] has showcased an effective far-field mmWave band WPT which energizes multiple devices by properly designing the transmitter and receiver. Asides from the far-field mmWave WPT, [4] demonstrated a promising mmWave transmitter for a near-field WPT system.

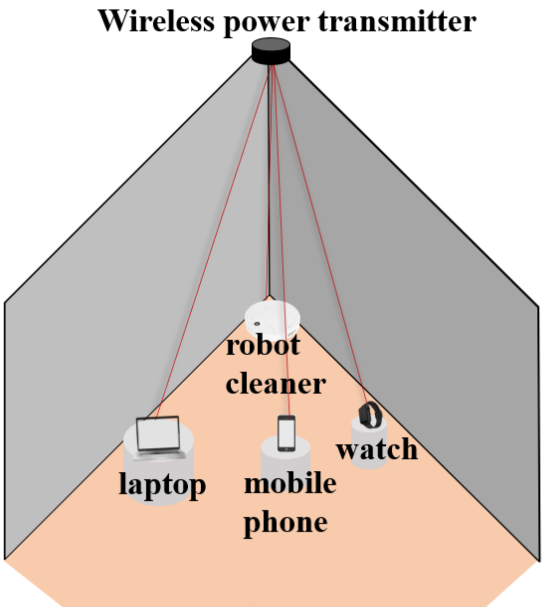

Fig. 1. The future WPT system with multiple users.

Leaky-wave antenna (LWA), as its name indicates, leaks energy at the discontinuities (radiators) on the aperture while propagating in the guided structure [5] [6]. To match the phase of the guided wave and the wave radiated, the leaky wave propagates toward a frequency-dependent direction. At a given frequency, the polarization, radiation pattern and radiation direction are determined by the layout of the radiators, typically slots. To cater to the future WPT, the transmitter antenna is required to perform beam steering and beam focusing. The unique inherent beam steering property of LWA is attractive to the future WPT system by getting rid of the phase shifter and the feeding network associated, and thus reduce the cost and the system complexity. Various types of near-field focused LWA have been reported [7]-[11]. Among the various beam forming techniques utilized in WPT systems, the LWA with the SIW technology is a prospective candidate due to its capability in generating focused beams over near field or far field. In addition, LWA using SIW techology has the advantages of low profile, easy integration and low cost.

In this paper, a mmWave CP LWA antenna for the future WPT system integrated with communication will be present. First, a conventional CP mmWave LWA using rectangular SIW with periodical fan shaped slots will be designed and analyzed. Next, the beam focusing mechanism of the LWA will be introduced. Then, implementing the in-phase superposition theory and manipulating the slot positions, a near-field focused mmWave LWA with beam forming and a dual beam steering capabilities of in both near field and far field is proposed.

II. Antenna Design

A. Design of an Initial CP mmWave LWA Using SIW Technology for Far-Field Communication

In order to investigate the beam focusing effect, a conventional mmWave LWA using SIW technology is designed firstly. The initial design, to be capable of far-field communication, is required to be of high gain, wide beam steering and circularly polarized to eliminate the polarization loss. The SIW geometry size including the SIW width, via diameter and via spacing are determined by [12]. Roger RT5880, with a dielectric constant of 2.2 and a loss tangent of 0.0009, is used as the SIW substrate. Due to the capability of generating Ex and Ey components, a fan-shaped slot [13] is selected as the radiator element. It is properly designed in terms of the geometry and spacing in order to achieve circularly polarized waves and desired performance. Fig. 2 illustrates the structure of the initial SIW-based CP mmWave LWA. The proposed antenna contains 37 fan shaped slots and they are periodically placed on the aperture being separated at a distance of 7 mm. The SIW width including via walls is 6.615 mm, and the effective antenna length is 25.2 cm, which is approximately 20λ, where λ is the wavelength in free space at 24 GHz.

The analysis of the proposed design is conducted using CST MICROWAVE STUDIO. The S-parameters of the antenna element are shown in Fig. 3. The operation band of the element covers a wide range of 22.5 GHz to 26 GHz, where the reflection coefficient S11 is below -10 dB. As illustrated in Fig. 4, the total efficiency of the initial LWA is greater than 84% in the band of 23 GHz to 26 GHz. The AR performance is illustrated in Fig. 5. AR below 3 dB is obtained from 23 GHz and 26 GHz. A excellent AR of 0.5 dB is observed at the 24 GHz. Beam-steering is well inherited. As shown in Fig. 6, the radiation beam scans from $-58°$ to $-22°$ with high realised gain in between 17.08 dBi and 18.12 dBi when sweeping the frequency from 22.5 GHz to 26 GHz.

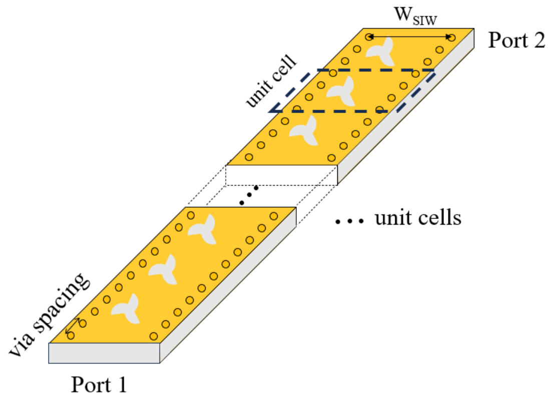

Fig. 2. The structure of the initial SIW-based CP LWA with fan-shaped slots

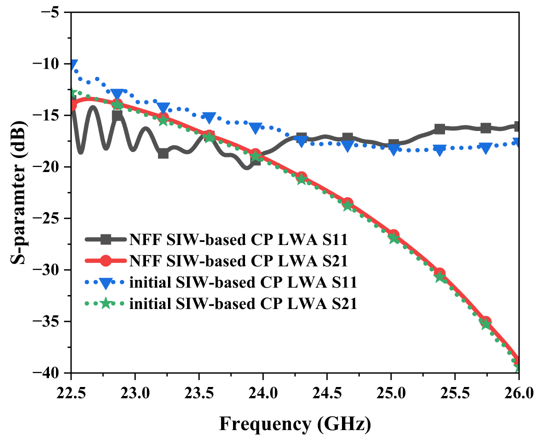

Fig. 3. The S-parameter of the proposed SIW-based CP LWA.

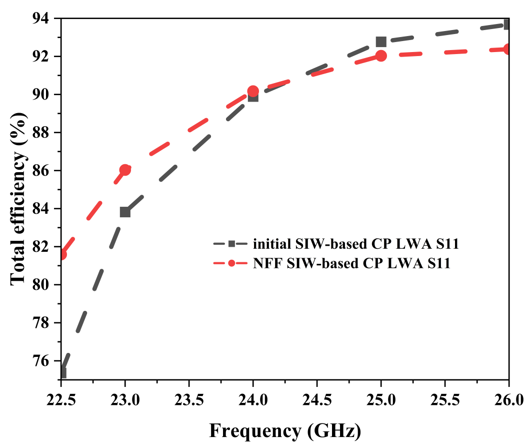

Fig. 4. The total efficiency of the proposed SIW-based CP LWA.

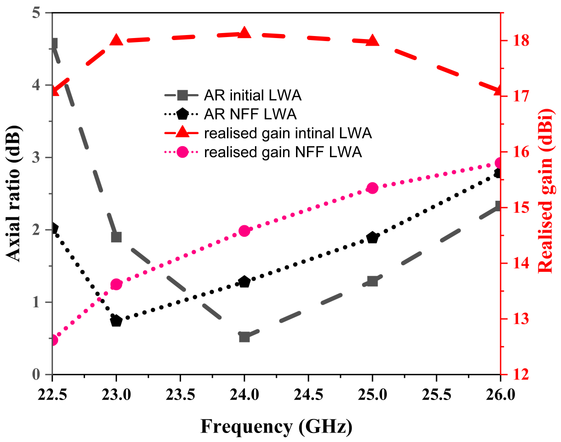

Fig. 5. The axial ratio and the realised gain of the proposed SIW-based CP LWA.

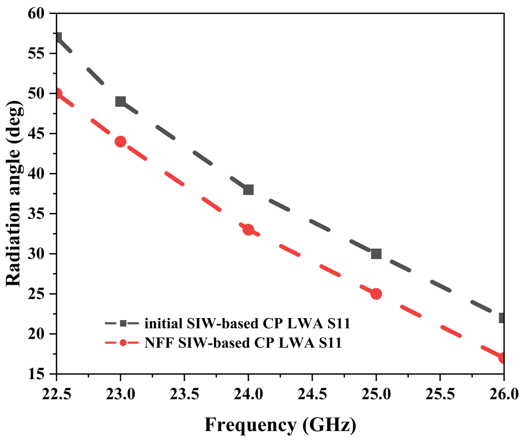

Fig. 6. The radiation angle of the proposed SIW-based CP LWA.

B. Near-Field Focusing Principle

The principle of the near field focusing LWA relies on the in-phase superposition of the leaky waves radiating from the fan shaped slots at the point of interest. The scheme of aperture illumination is illustrated in Fig. 7. In the SIW structure, the guided wave propagates along the SIW in longitude direction with a phase constant of β_0. Here, for the TE_{10} mode, β_0 represents the propagation constant of the propagating wave in the SIW and it could be calculated by [12]:

$$\beta_0 = \sqrt{{k_0}^2 \varepsilon_r - \pi^2 {W_{eff}}^{-2}}, \tag{1}$$

where k_0 is the wave number in free space, ε_r is the relative dielectric constant of the substrate, and W_{eff} is the effective width of the SIW, which is expressed as [12]:

$$W_{\text{eff}} = W_{SIW} - 1.08 d^2 s^{-1} + 0.1 d^2 {W_{SIW}}^{-1}. \tag{2}$$

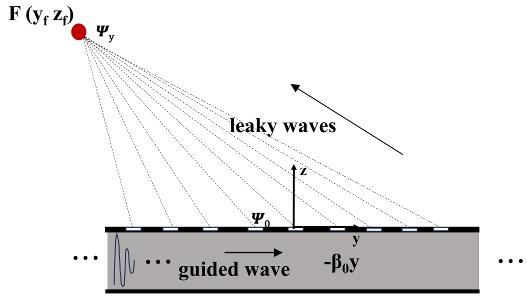

Fig. 7. NFF principle.

W_{SIW} is the physical width of the SIW, d is the diameter of the vias, and s the spacing of vias. The phase of the guided wave propagating in the SIW can be calculated by:

$$\Psi_{\text{SIW}}\,(\text{rad}) = -\beta_0 y. \tag{3}$$

y_{n} is the distance of the n_{th} slot along the longitude direction of the antenna aperture.

To simplify the case, in this paper, the focal point is assumed at the yoz plane with a coordinate of F (y_{f}, z_{f}). Hence, the travel distance of the leaky wave to the focal point could be written as $\sqrt{(y_f - y)^2 + z_f^2}$. Therefore, the phase of the leaky wave at the focal point could be calculated by

$$\Psi_F(y) = \Psi_0(y) + k_0 \sqrt{(y_f - y)^2 + z_f^2}. \tag{4}$$

Here, $\Psi_0(y)$ represents the initial phase of the leaky wave at the aperture. To achieve the focused beam at the focal point, the phase differences of the leaky wave and the guided wave should satisfy the following equation:

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

where n is an integer. In this approach, beam forming could be achieved by elaborately manipulating the slots positions.

C. Design of a Near-Field Focused CP LWA

In this paper, a focal distance of 0.5 m with respect to the center of the aperture is selected as an example.The corresponding focal height and longitudinal length are 0.3875 m and -0.325 m, respectively.

Applying the aforementioned near-field focusing technology, the positions of 37 fan shaped slots could be determined by solving the equation (1) to (5). Here, the location of the first slot is assumed as $p_0 = 0$, and the calculated positions of the rest 36 slots are given in TABLE. I.

As shown in Fig. 3, Fig. 4 and Fig. 5, respectively, in the operation band of 22.5 GHz to 26 GHz, S11 is below -10 dB parameter, and the radiation efficient is above 82%. AR below 3 dB is well maintained. The realised gain increases with the frequency and it remains between 12.62 dBi and 15.9 dBi in the operation band.

TABLE I
SLOT POSITION ON THE NFF LWA

p_1	p_2	p_3	p_4	p_5	p_6
$7.8mm$	$15.5mm$	$23.2mm$	$30.8mm$	$38.3mm$	$45.8mm$
p_7	p_8	p_9	p_{10}	p_{11}	p_{12}
$53.2mm$	$60.6mm$	$67.9mm$	$75.2mm$	$82.5mm$	$89.7mm$
p_{13}	p_{14}	p_{15}	p_{16}	p_{17}	p_{18}
$96.8mm$	$104mm$	$111.1mm$	$118.1mm$	$125.1mm$	$132.1mm$
p_{19}	p_{20}	p_{21}	p_{22}	p_{23}	p_{24}
$139.1mm$	$146mm$	$152.9mm$	$159.8mm$	$166.7mm$	$173.5mm$
p_{25}	p_{26}	p_{27}	p_{28}	p_{29}	p_{30}
$180.3mm$	$187mm$	$193.8mm$	$200.5mm$	$207.2mm$	$213.9mm$
p_{31}	p_{32}	p_{33}	p_{34}	p_{35}	p_{36}
$220.6mm$	$227.2mm$	$233.9mm$	$240.5mm$	$247.1mm$	$253.7mm$

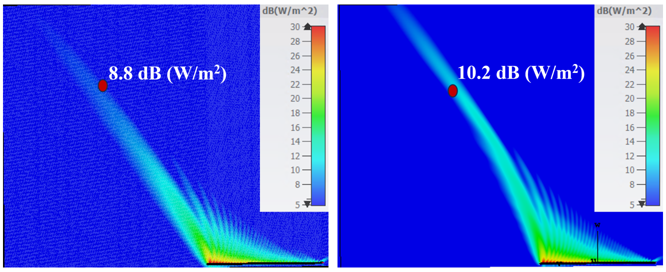

Fig. 8. Power density distribution in the near field at 24 GHz: (a) the initial LWA and (b) NFF LWA.

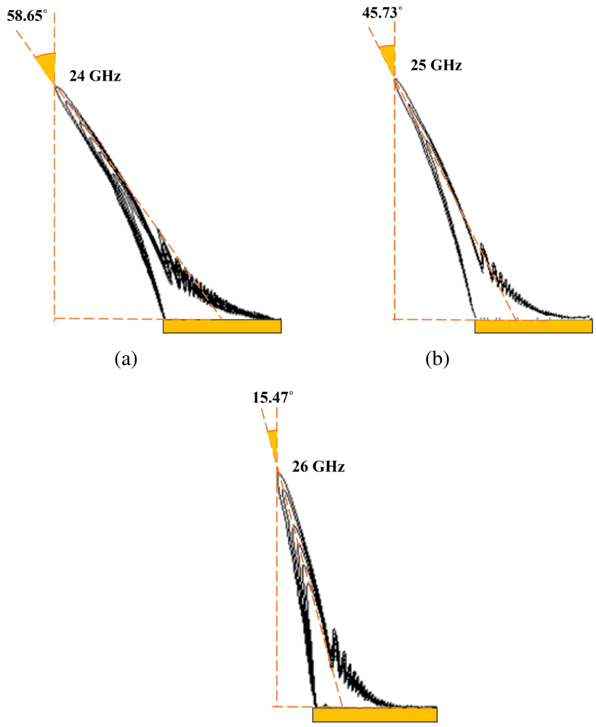

Fig. 9. Power density distribution(in contour lines) of the NFF SIW-based CP LWA in the near field: (a) at 24 GHz, (b) at 25 GHz, and (c) at 26 GHz.

III. PERFORMANCE ANALYSIS

Fig. 6 shows the beam steerable property of the proposed design in the far field. The radiation beam scans from $-50°$ to $-17°$ with high realised gain no less than 12.62 dBi while sweeping the frequency from 22.5 GHz to 26 GHz. It offers wide coverage and is favoured by the radar or satellite communication applications. The power density at the designed focal is shown in Fig. 8. Compared to the initial design (Fig. 8 (a)), the power density at the focal point in the NFF design (Fig. 8 (b)) is increased from 8.8 dB(W/m^2) to 10.2 dB(W/m^2), which is a significant enhancement. Moreover, the near-field beam-steering is demonstrated in Fig. 9. At 24 GHz, the focused radiation beam points along $-58.65°$ with respective to the broadside. Adjust the frequency to 25 GHz and 26 GHz, the angular direction changes to $-45.73°$ and $-15.47°$, respectively. It offers a wide angular coverage of 43.18° in a bandwidth of 3 GHz.

IV. CONCLUSION

This paper presents a mmWave near-field-focused circularly CP LWA for WPT with multiple users and communication. The concepts of beam scanning and beam forming rely on the natural beam steering of LWA and the in-phase superposition of the leaky waves, respectively. The high efficiency near-field focused CP mmWave LWA works in a wide high frequency band of 22.5 GHz to 26 GHz. It allows dual beam-scanning capabilities in both near-field power beams and far-field communication beams.

In the near filed, a 1.4 dB enhancement in power density is achieved by the near-field focusing approach. The focused beam covers from $-58.65°$ to $-15.47°$ with a band of 24 GHz to 26 GHz. It validates the approach is an efficacious strategy. Meanwhile, the beam scanning coverage from $-50°$ to $-17°$ is obtained in the far field. The realised gain is great than 12.62 dBi in the operation band range. Hence, the proposed antenna is promising for the future beam-steering WPT system with multiple users and communication. More experimental results will be presented at the conference.

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