一般社団法人　電子情報通信学会
THE INSTITUTE OF ELECTRONICS,
INFORMATION AND COMMUNICATION ENGINEERS

信学技報
IEICE Technical Report
A・P2024-217(2025-03)

[INVITED Talk (Young Researcher)] Study on Leaky-Wave Antennas for Imaging Applications

Kevin Kipruto MUTAI † and Qiang CHEN †

† Graduate School of Engineering, Tohoku University
Aramaki Aza Aoba 6-6-05, Aoba-ku, Sendai, 980-8579 Japan

E-mail: † {mutai.kevin.kipruto.s2@dc, qiang.chen.a5@}tohoku.ac.jp

Abstract In this study the high fabrication sensor related costs involved with contemporary imaging are addressed by a leaky-wave antenna (LWA) based system. By exploiting the inherent frequency scanning capability of the LWAs, the array of sensors required in traditional imaging paradigms are reduced to just a transmitting and receiving LWA pair. Various means of further reducing the fabrication costs and complexity whilst simultaneously increasing the scanning range of the near field focusing (NFF) LWAs required for imaging are investigated theoretically and validated experimentally.

Key words Leaky-wave antennas, millimeter-wave imaging, near field focusing

1. Introduction

Imaging at microwave and millimeter-wave frequencies continues to draw both industrial and academic interest. From a physical perspective, this interest is primarily driven by the fact that at these frequencies the photon energy carried by the electromagnetic wave incident upon a target body is not high enough to cause ionization leading to perceived harmful health effects as would be the case with alternative technologies such as X-ray [1]. The skin depth is also small enough such that the scattered field from both conductors and non-conductors is sufficient to allow the detection and subsequent imaging of both kinds of objects. From a commercial point of view, the development and operating costs of such systems are relatively modest compared to magnetic resonance imaging (MRI) thereby making millimeter-wave imaging an attractive prospect, especially in applications that do not require penetration into the skin.

To exploit the stated advantages of millimeter-wave imaging, several types of imaging systems have been developed that can be broadly divided into either passive or active. More recent research efforts on millimeter wave imaging have been aimed at minimizing sensor related costs by reducing the number of required sensors which is also the main overall target in this work. In the envisioned imaging system [2], the array of sensors used in contemporary imaging systems is reduced to just a single (for passive) or a transmitter-receiver pair (active) of LWAs where the inherent frequency scanning capability of the LWA is used to scan a spatial dimension of interest

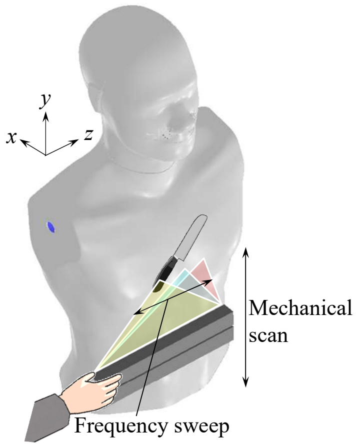

Fig. 1. Envisioned imaging scheme.

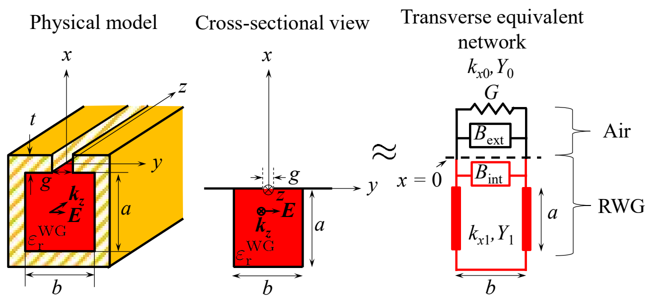

Fig. 2. Classical rectangular waveguide leaky-wave antenna (LWA).

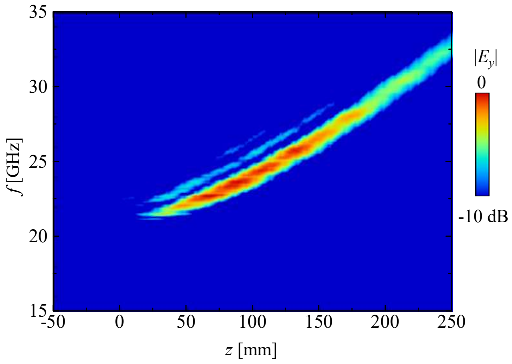

Fig. 3. Measured radiated $|E_y(z)|$ at $x = x_s = 195$ mm for the tapered a(z) NFF LWA.

as illustrated in Fig. 1.

Building on the main identified goal, some interesting technical challenges are identified and discussed in the succeeding sections. First, inexpensive metallized plastic NFF LWAs usable as imaging sensors are introduced in Section 2. NFF LWAs capable of supporting travelling waves with a negative constant and therefore capable of radiating toward both the backward and forward quadrant whilst using a single feed are introduced in Section 3. Imaging measurements to demonstrate the imaging capabilities of the proposed LWAs are also included herein. An extremely low-profile electronically reconfigurable LWA capable of mitigating the open-stopband issue encountered by traditional LWAs is presented in Section 4.

2. Portable and Inexpensive NFF LWAs

Owing to their relatively compact form factor, the classical uniform rectangular waveguide-based LWA [3] is used as a platform to develop the metallized plastic LWAs that are capable of NFF (See Fig. 2). To accomplish NFF, the phase constant along the longitudinal direction of the LWA, β_z, was first tapered by varying the broad wall height distribution $a(z)$ along the LWA [2].

In the design process, the complex wave number $k_z = \beta_z - j\alpha_z$ was extracted for different a by applying the transverse resonance method to an equivalent network of the LWA. The relationship between β_z and a was then obtained by fitting and a subsequently tapered such that

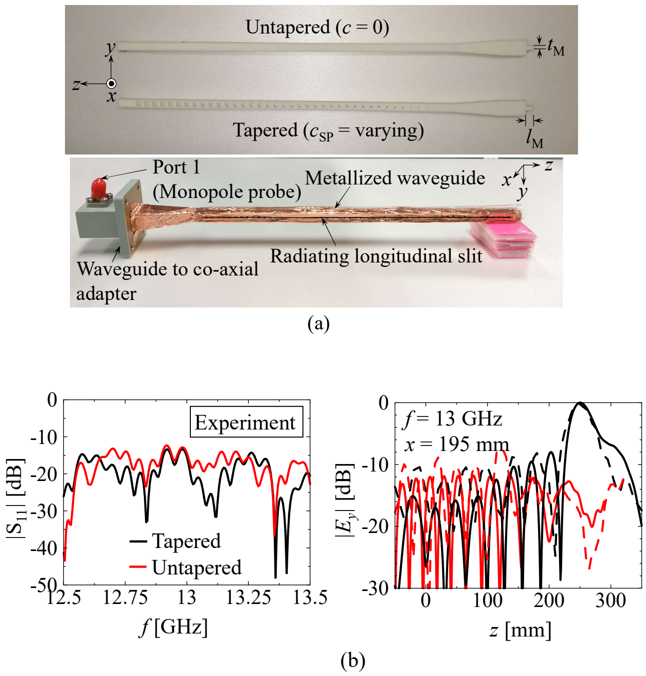

Fig. 4. (a) Fabricated tapered and untapered $\varepsilon_r^{WG}(z)$ prototypes before and after metallization. (b) Measured reflection coefficient and radiated $|E_y(z)|$ at $x = x_s = 195$ mm.

the field contributions from the LWA coincided at the designed focusing position of S(x_s = 195 mm, z_s = 250 mm) at 27 GHz.

A prototype was then fabricated using Acrylic and subsequently metallized and the focusing performance confirmed as indicated in Fig. 3. From the figure, it is apparent that the focusing spot at the designed S was obtained at 27 GHz. Additionally, the spot is scanned along the z direction when the frequency is changed which is a desired effect for imaging purposes.

To further reduce the fabrication costs, tapering the dielectric constant ε_r^{WG} of the material within the LWA instead of a was explored [4]. The same approach used to design $a(z)$ was followed to obtain $\varepsilon_r^{WG}(z)$ however because the physical dimensions of the LWA become prohibitively small at millimeter wave frequencies, the design frequency was set at 13 GHz. The key point in the proposed structure, however, is the relative ease with which the LWA can be fabricated by 3D printing and subsequent metallization by using adhesive copper tape.

To evaluate the performance of the proposed structure, a prototype was fabricated and compared against a version with an untapered constant $\varepsilon_r^{WG}(z) \approx 2.75$ (corresponding to the 3D printer material polylactic acid, PLA). Measurement results from both versions of the dielectric-filled rectangular waveguide LWA are presented in Fig. 4 where the focusing effect can be observed at the designed S in the LWA with a tapered $\varepsilon_r^{WG}(z)$.

3. Backward Quadrant Illumination

A limitation of the uniform LWAs studied in Section 2 is that they are incapable of radiating toward the backward quadrant ($\pi/2 \leq \theta_0 \leq \pi$ in Fig. 5(a)) as β_z can only assume a positive value thereby potentially limiting their applicability toward imaging. A possible solution to this challenge would be to employ a periodic approach whereby β_z can assume a negative value to allow illumination of both the forward ($0 \leq \theta_0 \leq \pi/2$) and backward quadrants. A challenge with contemporary periodic NFF LWAs, however, is that the scanning range is limited compared to uniform versions as the full-width at half-maximum (FWHM) deteriorates rapidly when the focusing spot is scanned away from the designed position owing to the large periodicities involved in tapering β_z. To address this challenge, a combined uniform and periodic NFF LWA approach is investigated [5].

The proposed structure is composed of a periodic LWA capable of supporting travelling waves with a negative β_z

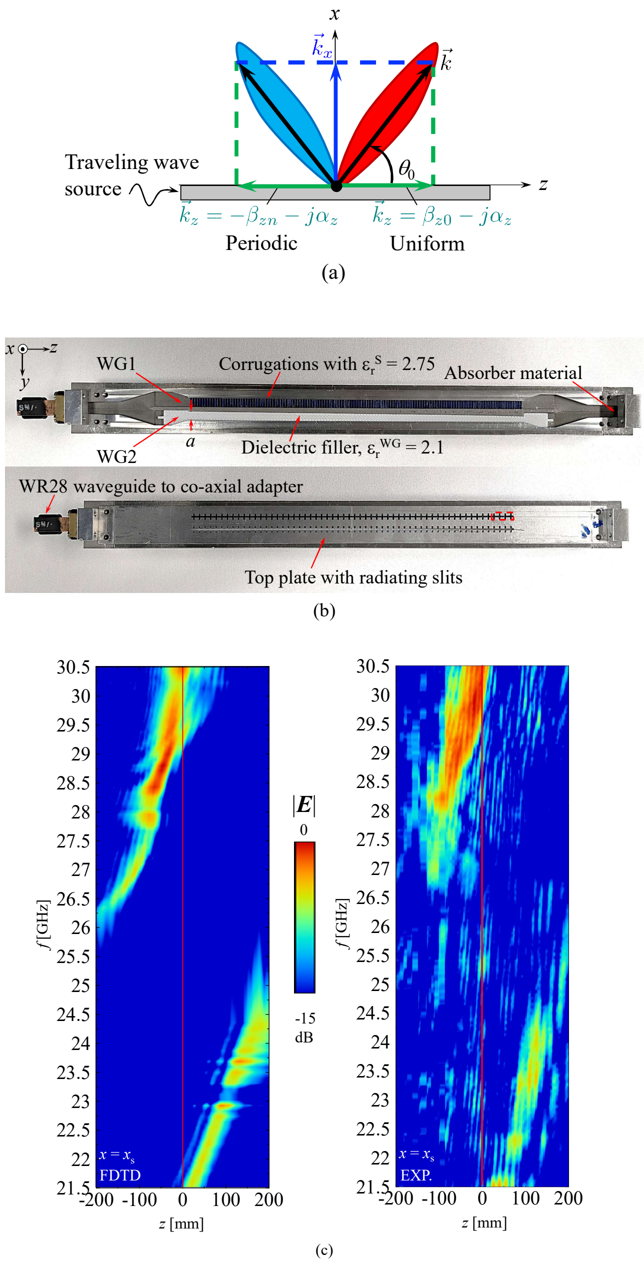

Fig. 5. Concept of the dual-waveguide approach to illuminate the backward quadrant. (b) Fabricated prototype. (c) Simulated and measured radiated $|E_y(z)|$ at $x = x_s = 195$ mm.

and a uniform LWA with a positive β_z . In both waveguides, β_z is tapered using a to allow NFF in the forward and backward quadrants. To separate the operation of the two waveguides and allow switching between them by changing the frequency like more traditional LWAs, the uniform LWA is filled with dielectric material to lower its cutoff frequency. An additional advantage of including dielectric material within the

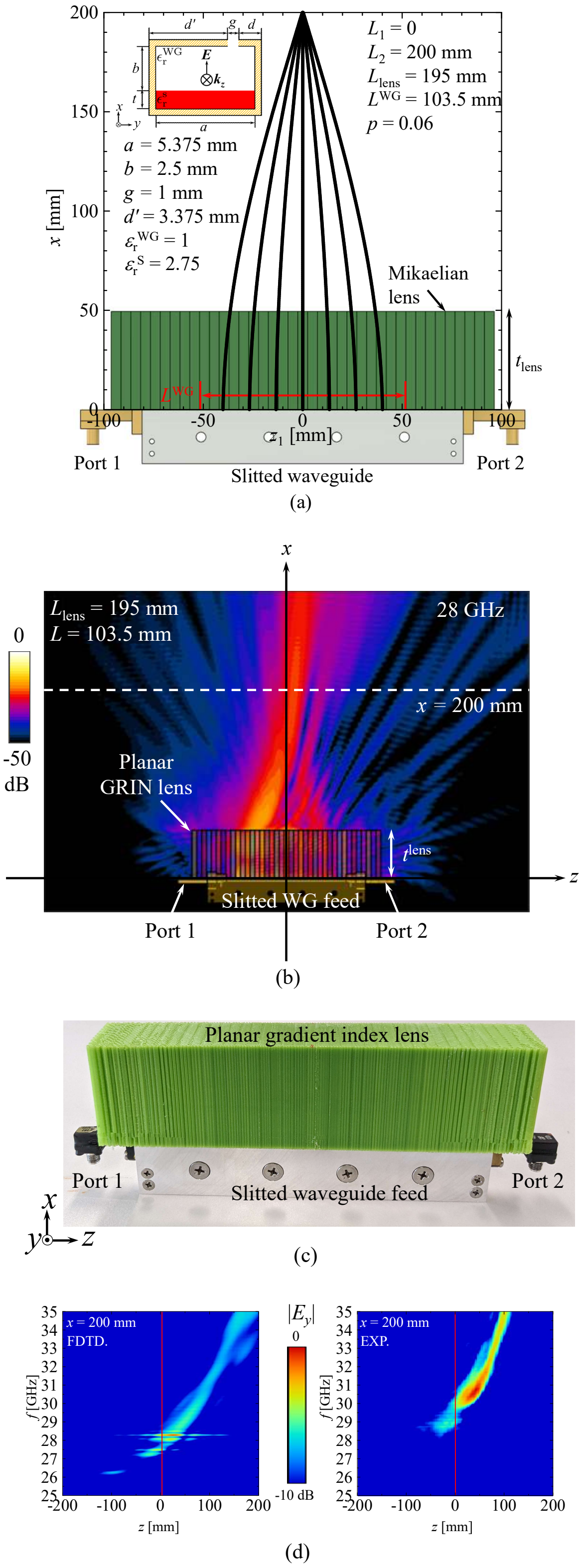

Fig. 6. (a) Ray-tracing model of the LWA fed lens. (b) Simulated |E| distribution in the near field. (c) Fabricated prototype. (d) Simulated and measured $|E_y(z)|$ at $x = 200$ mm.

uniform LWA is that it allows the LWA to support non-radiating surface waves when the frequency is increased. Therefore, the radiated field from the uniform LWA would not interfere with that from the periodic LWA when the frequency is increased whereas when the frequency is lowered the periodic LWA would be in the cutoff region and therefore would not interfere with the radiated field from the uniform LWA.

A prototype to validate the proposed concept was fabricated and measured with the results being included in Fig. 5. The focusing spot in both the uniform and periodic NFF LWAs was set at S1(x_s = 195 mm, z_s = 150 mm) and S2(x_s = 195 mm, z_s = -150 mm) respectively. From the results, the focusing effect can be observed in both the forward and backward quadrants in the simulated data. However, in the measured data, the focusing performance in the forward quadrant is patchy and the focusing spot is deviated from the designed positions. These discrepancies are attributed to errors encountered in the fabrication of the prototype owing to the somewhat complicated tapering of $a(z)$ required to achieve NFF.

To reduce the fabrication complexity and minimize the probability of errors occurring, the NFF function was moved from the LWA waveguide to a lens superstrate in the approach illustrated in Fig. 6(a) [6]. In this structure, a mechanically untapered waveguide can then be used to provide the feed to the lens thereby providing an extra degree of freedom in the fabrication process as both the lens and LWA can be separately optimized upon. Furthermore, should application needs change in the future, then only the cheaply manufactured lens would need to be changed instead of refabricating the entire antenna structure as would be the case in more traditional NFF LWAs potentially reducing the costs and time involved in design and fabrication.

The lens superstrate in this latter structure is a planar gradient index (GRIN) lens easily fabricated by 3D printing. The pitch, thickness and length of the lens were designed to enable focusing at $x = 200$ mm above the

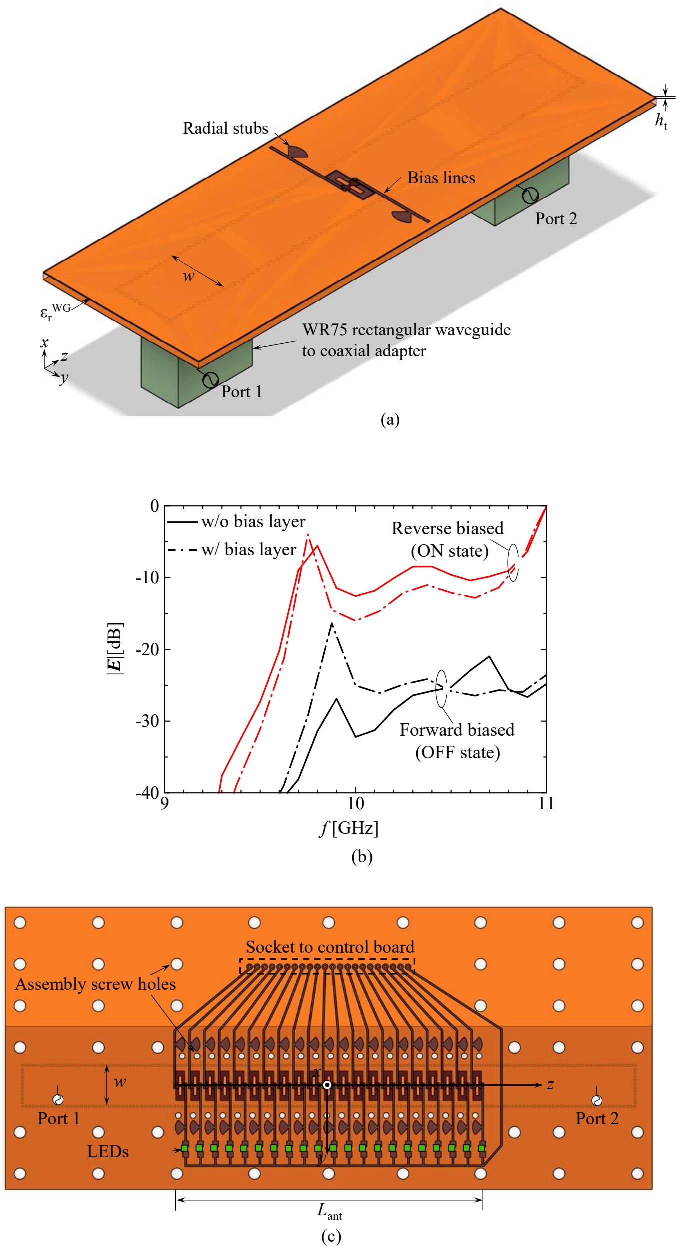

Fig. 7. (a) Unit cell of the proposed electronically reconfigurable LWA. (b) Measured $|E|$ in the ON and OFF states. (c) Full-sized 21-element array.

longitudinal radiating slit of the LWA. The LWA used to feed the lens is the periodic version with dielectric-filled corrugations at the bottom that was used earlier as this waveguide can support $\pm\beta_z$ to enable radiation toward both the forward and backward quadrants.

The focusing performance of the proposed structure was evaluated by using a ray-tracing model [7], [8] and the results in Fig. 6(a) and then by full-wave simulations as

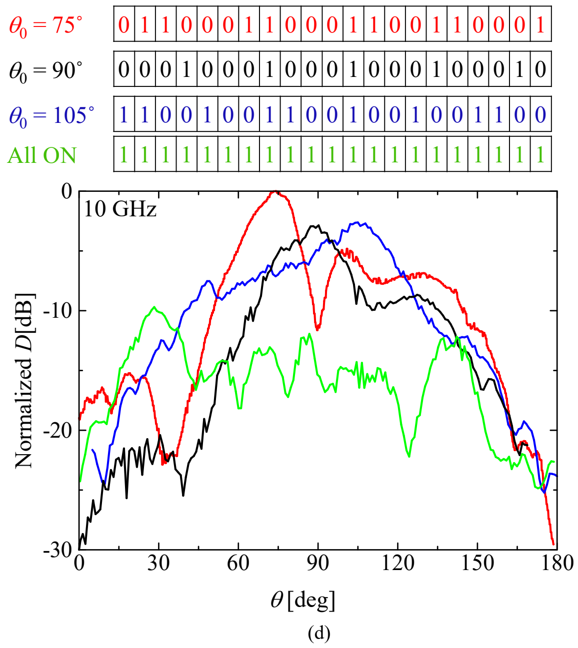

Fig. 8. Measured radiation patterns for $\theta_0 = 75^\circ$, 90° and 105°.

indicated in Fig. 6(b) where good correspondence between the two results was observed. The position of the focused spot was, however, shifted in the fabricated prototype compared to the calculated versions with this deviation being attributed to minor fabrication errors in the 3D printed dielectric fillings used within the corrugations. The magnitude of the radiated field in the backward quadrant was also observed to be lower compared to the forward quadrant owing to the increased α_z in this direction because of the uniform waveguide region above the corrugations being within the cutoff region. Despite these remaining issues, NFF by using a 3D printed GRIN lens approach was demonstrated.

4. Dynamic Beam Control

Evidently, from Fig. 5 and Fig. 6, the magnitude of the radiated electric field in the broadside direction of the LWAs ($\theta_0 = \pi/2$) is much lower than at other directions as at this point $\beta_z = 0$ within the open-stopband of the LWAs. To avoid this situation, a possible solution would be to employ an electronic means of reconfiguring β_z that is independent of the frequency and would allow radiation toward $\theta_0 = \pi/2$ as well as toward both the forward and backward quadrants. Several types of electronic LWAs have been investigated to realize this goal but a remaining challenge in most contemporary versions is their relatively large physical profiles in addition to the difficulty of integrating the control circuitry with the antenna structure. To address this challenge, an extremely low-profile electronically reconfigurable LWA based on 1-bit switching is proposed [9].

The unit cell of the antenna is presented in Fig. 7(a) and is based on a slot dipole antenna etched onto a substrate integrated waveguide (SIW). The radiating state of the slot is controlled by a PIN diode soldered across the center of the slot such that when the diode is forward biased the resonant frequency of the dipole is doubled and it is effectively off at the design frequency whereas when the diode is reverse biased the dipole operates as usual. A biasing layer with the control circuity used to deliver the biasing signals to the antenna elements is included above the SIW layer with the slot dipoles.

To accomplish reconfigurability, the phase required to radiate in a desired direction is compared to the phase of the travelling wave at the position of each element. If the difference between the two values is within 70° (selected as s compromise between beam scanning accuracy and the side lobe levels), the antenna element at the given position is turned ON (state '1' with the PIN diode reverse biased) otherwise it is turned OFF (state '0'). The magnitudes of the electric field in the far field of the slot dipole elements were calculated and extracted for both the ON and OFF states from full-wave calculations and are compared in Fig. 7(b). From the figure, upon addition of the biasing layer the magnitude difference between the states drops from 20 dB to 10 dB which is still sufficient to accomplish reconfigurability though it would impact the directivity of the antenna.

The LWA was fed by an air-filled WR-75 rectangular waveguide to coaxial adapter through a longitudinal slit cut at an offset from the center as indicated in Fig. 7(c). This feed mechanism was selected for ease of fabrication purposes with the wideband performance of the LWA being sacrificed in the process and is an area to be further studied in the future. The radiation patterns in three cases of $\theta_0 = 75^{\circ}$, $\theta_0 = 90^{\circ}$ and $\theta_0 = 105^{\circ}$ were measured and are presented in Fig. 8 for 10 GHz which is the design frequency of the LWA. From the radiation pattern results, the LWA was shown to be capable of radiating toward both the backward and forward quadrants in addition to the broadside direction without encountering the open stopband in an extremely low-profile structure of $0.05\lambda_0$ thickness.

5. Conclusions

In this study, a relatively inexpensive imaging scheme based on LWA sensors was proposed. The research efforts presented herein focused on:

1. Accomplishing NFF in relatively inexpensive, lightweight and simple to fabricate metallized plastic LWAs to address the sensor related costs in existing imaging systems.
2. Significantly expanding the scanning range in NFF LWAs by leveraging a combined uniform and periodic approach.
3. Increase the design flexibility in NFF LWAs by separating the feed and phase tuning mechanisms.
4. Mitigate on the open stopband issue to allow smooth scanning through the broadside in an extremely low-profile electronically reconfigurable LWA.

Future work would therefore build on these accomplishments to overcome the remaining challenges of realizing 3D printed NFF LWA in millimeter wave, patchy scanning of the focusing spot in the dual-waveguide LWA, reduced magnitude of the radiated field toward the backward quadrant in LWA fed lens antenna and low gain performance of the electronic LWA.

6. References

[1] D. J. Griffiths, "Electrodynamics and Relativity," *Introduction to Electrodynamics*, 3rd ed. Upper Saddle River, NJ, USA: Prentice-Hall, 1999, ch. 12, sec. 2, pp. 511-516.

[2] K. K. Mutai, H. Sato and Q. Chen, "Active Millimeter Imaging using Leaky-Wave Focusing Antennas", *IEEE Trans. Antennas and Propag.*, vol. 70, no. 5, pp. 3789-3798, May 2022.

[3] L. Goldstone and A. Oliner, "Leaky-Wave Antennas I: Rectangular Waveguides", *IRE Trans. Antennas and Propag.*, vol. 7, no. 4, pp. 307-319, Oct. 1959.

[4] K. K. Mutai, H. Sato and Q. Chen, "Near-Field Leaky-Wave Focusing Antenna with Tapered Dielectric Constant Distribution", *IEEE Antennas Wireless Propag. Lett.*, vol. 22, no. 5, pp. 1209-1213, May 2023.

[5] K. K. Mutai and Q. Chen, "Frequency Scanning Leaky-Wave Array Antenna with Extended Scanning Range for Millimeter Wave Imaging", *IEEE Antennas Wireless Propag. Lett.*, vol. 22, no. 8, pp. 1977-1981, Aug. 2023.

[6] K. K. Mutai and Q. Chen, "Compact Leaky Wave Fed Frequency Scanning Gradient Index Lens Antenna for Near-Field Focusing Applications", *IEEE Trans. Antennas and Propag.*, vol. 72, no. 3, pp. 2314-2322, Mar. 2024.

[7] A. Mikaelian and A. Prokhorov, "V: Self-Focusing Media with Variable Index of Refraction," *Progress in Optics*, vol. 17, pp. 279–345, 1980.

[8] K. Nishizawa, "Principle and Application of Gradient Index Optical Imaging," *Rev. Laser Eng.*, vol. 8, no. 5, pp. 748–758, 1980.

[9] K. K. Mutai and Q. Chen, "An Extremely Low-Profile Electronically Reconfigurable 1-D Leaky-Wave Antenna", *IET Microw. Antennas Propag.* (Under review).