Lens Packaging of InP Feed using 2-D Antenna Simulation

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Abstract - **In this paper, an on-chip dual-slot antenna feed and its lens antenna packaging design are illustrated. H-band power detector circuit using the Teledyne 250 nm InP DHBT device is integrated to test the performance of the feed and lens antenna. Dimensions of dual-slot antenna and lens are meticulously designed with HFSS using a 2-D antenna pattern simulation method. The 2-D method can simplify the simulation with a low resource and provide reliable results on both E-plane and H-plane of the antenna. The goal of the feed antenna is to provide a circular beam pattern to the attached lens. With the HFSS 2-D method designed on-chip feed, both primary and secondary pattern showed an equal E-plane and H-plane beam width. The future purpose of this chip is matching the simulated results with pattern measurement and eventually calculating the packaging loss of the integrated circuit in the lens packaged system. Once the packaging loss is defined, alternate circuits such as oscillators or mixers could also be integrated using the same design.**

***Keywords*—Dual-slot Antenna, Hyper-hemispheric Lens, Lens Antenna, Radiation Pattern, Terahertz Antenna**

I. INTRODUCTION

Hardware with high data rate and wireless application is required for various 6G fields such as self-driving car or virtual augmented reality [1]. The Terahertz (THz) band is gaining high attention for 6G solution [2]. However, there are challenges in THz signal processing. The biggest issue is limited solid-state signal source with high power in the THz band due to the insufficient f_{max} and f_t characteristics in the present processes. Among the present processes the Teledyne 250 nm InP DHBT shows superior f_{max} of 580 GHz and f_t of 350 GHz which is feasible to produce high powered solid-state signal source in THz frequency [3].

After the chip fabrication, the solid-state power source needs to be packaged into a stable and standard form for various applications with other components. In Radio frequency (RF) bands this is usually made through waveguide packaging since both chip and waveguide size are big enough to handle. However, as the frequency surges from RF to THz the wavelength diminishes which makes the offsets in the waveguide unneglectable. In this condition lens antenna packaging is known to be a better solution for solid-state chip packaging rather than using waveguide packaging. Since the carving the waveguide mostly depends on Computerized Numerical Control (CNC), small dimensions are difficult to carve without offset and the conductor surface loss becomes significant [4]. On the other hand, an on-chip antenna design made by solid-state process shows a feasibility of designing much smaller dimensions and is free of surface loss. However, using an on-chip antenna alone suffers from substrate mode which occurs from chip-air interface. Since the cause of the substrate mode is mostly reflected beam from chip-air interface with incident angle larger than critical angle, spherical dielectric lens is attached to lower the incident angle of the beam to keep substrate mode from happening [5]. Additionally, lens antenna packaging is formed easily by stacking a planar antenna on top of a dielectric lens. This work presents H-band Silicon lens antenna packaging design with an InP on-chip antenna feed.

Sections are parted to describe each part of the packaged lens antenna in designing sequence. The shape of the overall lens antenna system and components are shown in Fig. 1. Section II describes the 2-D antenna pattern simulation method devised for simply designing the overall lens antenna. Section III addresses how the feed antenna and attached lens dimensions are designed with 2-D antenna method. Section IV The final circuit design with H-band detector integrated is presented for the future work of calculating package loss of the lens antenna packaging system.

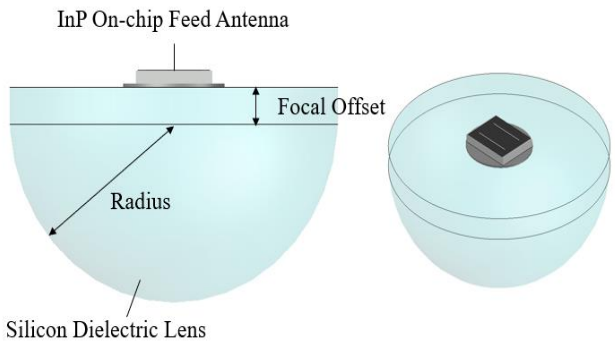

Fig. 1. The overall view of the on-chip antenna lens packaging which mainly consist of InP on-chip feed antenna and Si dielectric lens.

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II. 2-D ANTENNA PATTERN SIMULATION METHOD

Conventional lens antenna simulation is conducted by analyzing a whole 3-D structure. Short wavelength of the THz wave makes the lens component considerably bulky. Also, the curved surface of the lens surface raises complicity of the simulation. The issues introduced induces a wrong beam width and asymmetry in a bulky structure such as lens antenna.

Assigning a symmetric boundary to analyze only the half or quarter of the whole structure also exists and this method can assure the symmetry of the radiated pattern. However, there are no drastic mesh reduction in this symmetric method and beam width can still vary which depends on the mesh. Additionally, the reflective property of spherical lens itself induces superposition of fields from multiple angles and makes the field analysis complicated.

The radiation pattern could be anticipated by the two representative patterns of E-plane and H-plane of the antenna. Thus, only analyzing the E-plane and H-plane radiation pattern could improve accuracy and simplify the inner lens fields. The 2-D method devised could be the solution of the lens antenna radiation pattern analysis.

A. 2-D Antenna Pattern Simulation Configuration of Feed

Basic concept of the 2-D antenna pattern simulation is extracting only the principal plane antenna patterns among the whole antenna patterns. The simulation model is then limited to the 2-D sections overlapped with antenna E-plane and H-plane. In the case of lens feed antenna design, two different permittivity of air ($\varepsilon_{air} = 1$) and lens antenna system should be set to test the primary pattern into the dielectric lens. As the permittivity of InP feed substrate ($\varepsilon_{sub} = 12.5$) and the Si lens ($\varepsilon_{Si} = 11.9$) are considered similar, permittivity of 12 is selected for entire lens antenna system. The size of the lens is set to be infinite so that there is no reflected beam from lens-air interface which can affect the pattern beam width. The infinite lens condition could be set by making the lens dielectric extremely thick. However, as stated in the introduction the HFSS simulator has difficulty in analyzing a bulky lens structure even with a radius of few wavelengths.

As a solution the infinite substrate simulation is devised. The tomographic 2-D cross-section of the antenna is set as either PEC or PMC for H-plane and E-plane respectively. Since this boundary setting is assigned by the image theory the height of the structure does not affect the normalized radiated pattern. Lumped port is assigned to make the feed radiate to both air and substrate. As the region intersects with PEC or PMC boundary, Perfect Matched Layer (PML) could not be assigned. Instead, radiation boundary is assigned to the perimeter of the region. Since a rectangular radiation boundary could suffer from radiation boundary reflection when any structure contacts radiation boundary, the region is set to be circular. Lastly, the dielectric substrate and air condition could be relatively assigned. That is setting the substrate permittivity relatively to 1 and air to $1/\varepsilon_{substrate}$ with every dimension multiplied in $\sqrt{\varepsilon_{substrate}}$. As material outside the radiation boundary is considered air in HFSS, this method is used for alleviating the discontinuity of Si lens in and outside of circular radiation boundary.

In our work InP feed chip from Teledyne and Si lens from Tydex optics is used and the final setting of the 2-D simulation is shown in Fig. 2.

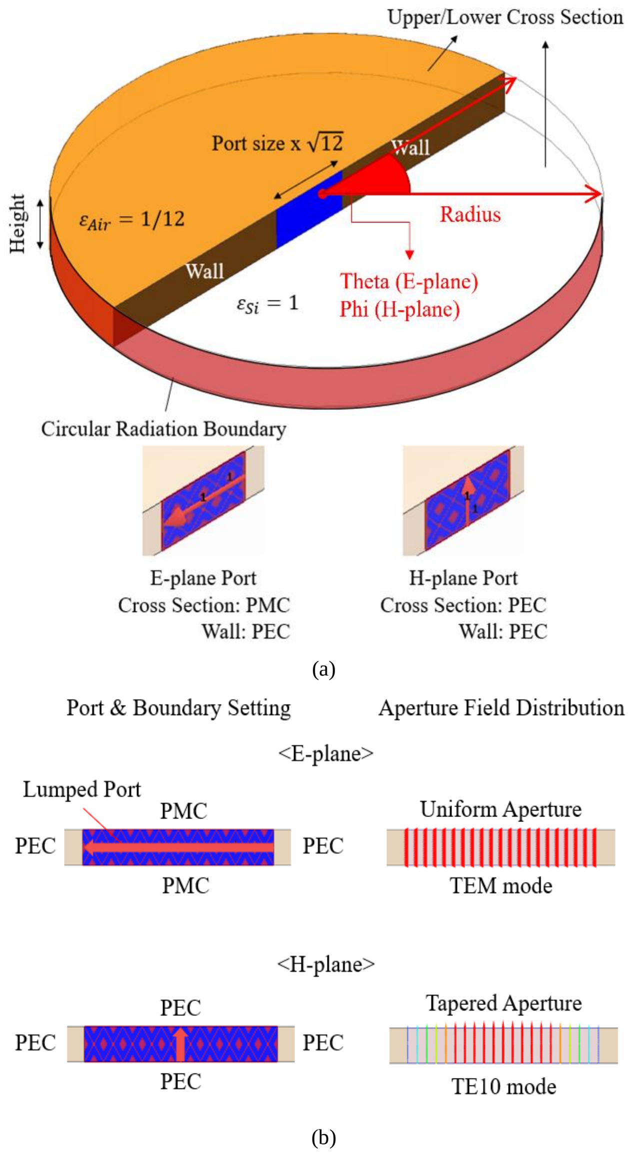


Fig. 2. (a) Simulation model of 2-D antenna pattern analysis for infinite substrate condition with a relatively set permittivity, (b) Port direction and Cross section boundary is assigned differently in each E/H-planes

B. 2-D Method and Theory Comparison

As the 2-D simulation model is set, the simulated pattern result is verified with the theory. Assuming an open waveguide-like aperture, uniform TEM mode aperture is set for E-plane and tapered TE10 mode aperture is set for H-plane. The term 'tapered' implies a cosine-wave shaped field distribution where the field is maximum at the middle and zero at the edge of the aperture. Since TE10 mode is dominant mode of waveguide aperture, it is appropriate to assume tapered field for H-plane field distribution. A theoretical formula of a uniform TEM mode aperture radiation pattern is known as

$$F_E(\theta) = \frac{\sin\left[\left(\frac{\beta L}{2}\right) sin\,\theta\right]}{\left(\frac{\beta L}{2}\right)\sin\theta} \tag{1}$$

where

F_E: Function of E-plane radiation pattern
θ: Angle variation at E-plane
βL: Electrical aperture length

which corresponds to the E-plane pattern.

Whereas the H-plane radiation pattern of a tapered TE10 mode aperture is known as

$$F_H(\phi) = \cos\phi \cdot \frac{\cos\left[\left(\frac{\beta L}{2}\right)\sin\phi\right]}{1-\left[\frac{2}{\pi}\cdot\left(\frac{\beta L}{2}\right)\sin\theta\phi\right]^2} \tag{2}$$

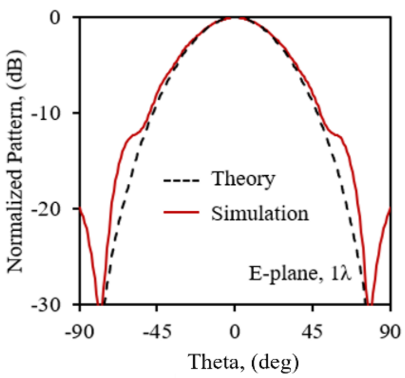
where

F_H: Function of H-plane radiation pattern
ϕ: Angle variation at H-plane
βL: Electrical aperture length

[6].

HFSS 2-D simulated E and H-plane patterns are compared when the aperture is set as half and full wavelength (Fig. 3., Fig. 4.). To form a TEM mode aperture at the E-plane, horizontal lumped port adjacent to PMC cross section and PEC wall is set. Likewise, the H-plane TE10 mode aperture is formed by vertical lumped port adjacent to PEC cross section and wall (Fig. 2. (b)). Frequency of 300 GHz is chosen for a simple calculation of wavelength. The radius of circular radiation boundary set to 10 mm. The height of the structure does not affect the pattern result since the boundary conditions applied at upper and lower cross section acts as a mirror and forms infinite height according to the imaging theory. To save simulation resource, 0.1 mm is chosen for actual simulation height.

As the half wavelength line source sizes up to full wavelength, the tendency of beam widening of simulated pattern is similar as the theoretical case. The simulated pattern and theoretical pattern mostly overlap in the boresight angle of ± 45 degrees. The discrepancy above 45 degrees is assumed to be originated from the limited size of the radiation boundary.



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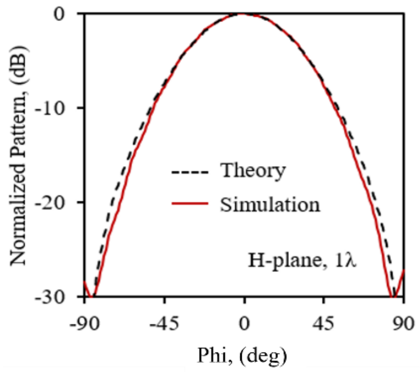

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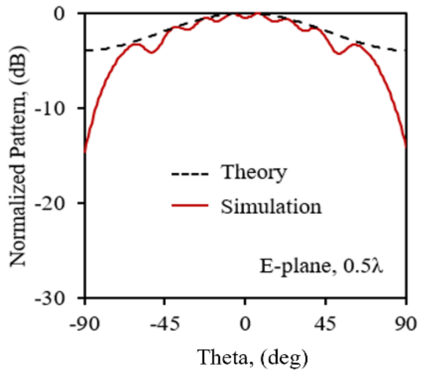
Fig. 3. Theoretical and Simulated patterns of full wavelength waveguide aperture; (a)E-plane (b)H-plane



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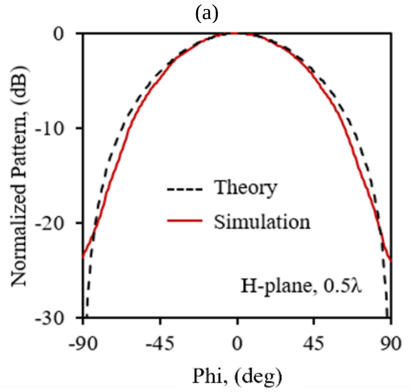

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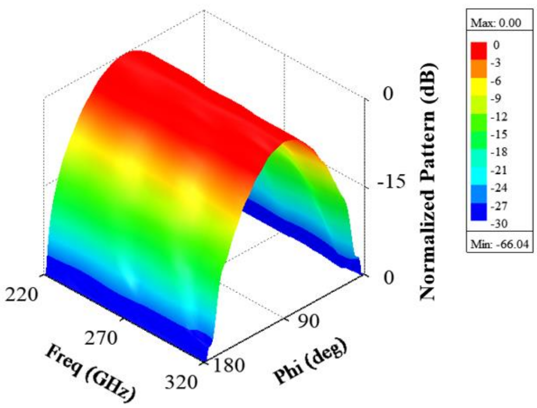
Fig. 4. Theoretical and Simulated patterns of half wavelength waveguide aperture; (a)E-plane, (b)H-plane



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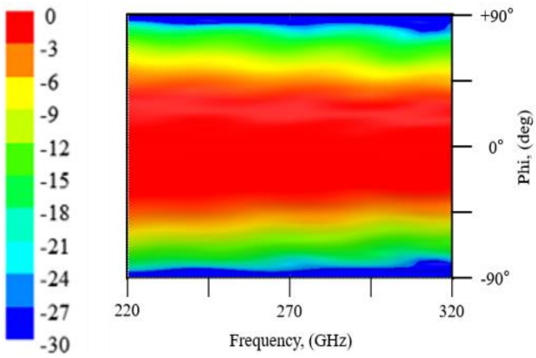


(b)

Fig. 5. 3-axis plot of H-plane TE10 aperture radiation pattern; (a)Isometric view with 3-axis, (b)Top view with Frequency and Phi axis

III. LENS ANTENNA DESIGN

Various planar antennas have been integrated to lens such as dipole, slot, dual-slot, bowtie, log-periodic or spiral antenna. Dipole antenna design is simple but when combined with THz circuit which requires overall ground with a signal line the radiation pattern could be distorted [8]. Thus, it is difficult to control the beam shape with a dipole structure. Bowtie, log-periodic or spiral antenna has a wide bandwidth but is big in size and multiple design variables need to be considered. Dual-slot antenna structure is selected which has the advantage of sufficient ground for the circuit combined and less design variables.

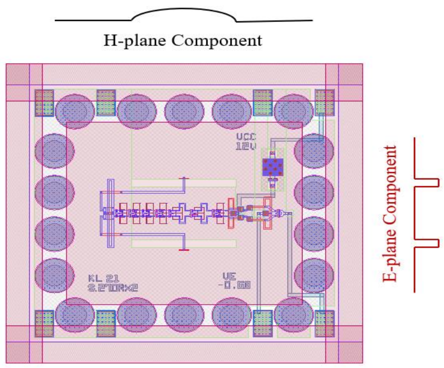
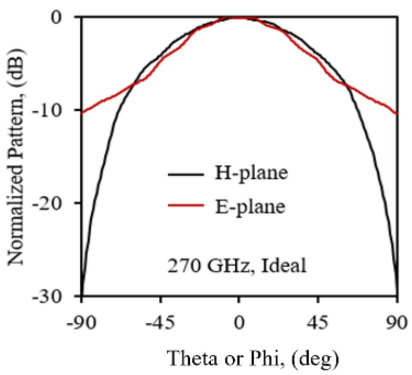


Fig. 6. Design of dual-slot feed antenna circuit. Slot length of 0.22 mm and separation of 0.146 mm is chosen for circular beam radiation.



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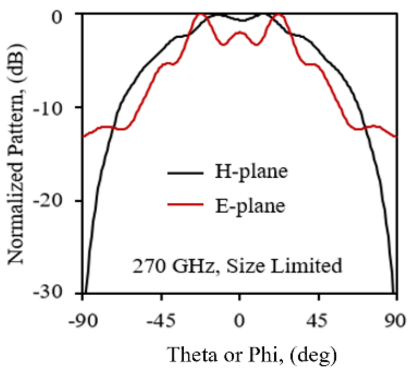

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Fig. 7. Change of principal plane far field radiation pattern; (a)Ideal feed, (b)Size limited feed

A. Dual-Slot Feed Antenna Circuit Design

Dual-slot antenna could be disintegrated in to two principal planes. On the E-plane side two slots with a separation gives two dirac delta functions of two TEM sources with a separation. On the other plane, dual-slot length gives a tapered field which can be implemented by a TE10 source. As the near field distribution and far field pattern has a relation of Fourier transform, the widening of the slot dimensions results narrow radiated beam width.

Since the feed antenna is placed between air and InP substrate, the wavelength λ_m of the feed antenna is known as (3) and (4) [7].

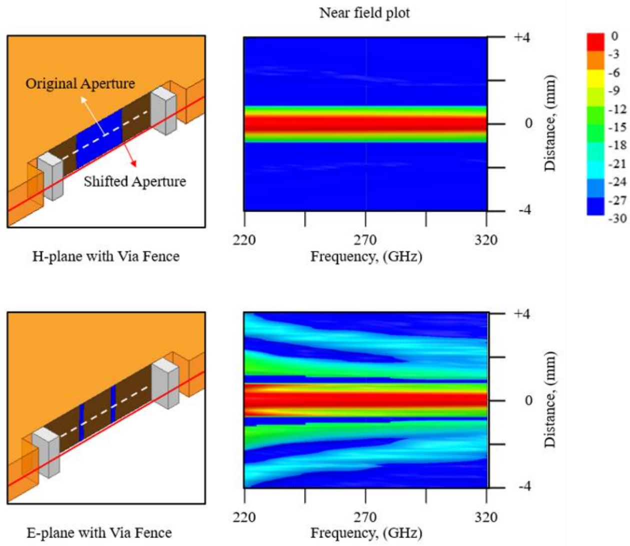
$$\lambda_m = \lambda_0/\sqrt{\varepsilon_m} \tag{3}$$

$$\varepsilon_m = (1 + \varepsilon_{subs}) \tag{4}$$

where

λ_m: wavelength in the material
λ_0: wavelength in the air
ε_m: overall permittivity of the material
ε_{subs}: permittivity of the substrate only

The main design frequency is 270 GHz and calculated wavelength of the feed dimension is 0.44 mm. Slot separation and length size is meticulously set as 0.146 mm (0.34 λ_m) and 0.22 mm (0.5 λ_m). This antenna size is expected to give circular beam of 65~70° half power beam width (HPBW) to the substrate direction in ideal case. However, the limited ground pattern of 0.5 mm x 0.54 mm and the antenna chip size of approximately 0.72 mm x 0.76 mm make the radiated pattern suffer from distortion as Fig. 7 (b) [9,10]. This distortion could affect patterns at all frequencies and therefore abnormal tendency of beam width could occur. Especially the chip size of the feed is decided by manual dicing which is difficult to be controlled. Instead of leaving the unpredictably diced substrate edge to directly affect the pattern, conductor via fence is integrated through the InP substrate vertically along the chip perimeter. The diameter of single cylindrical via fence diameter is 50 μm and minimum separation from adjacent via fence is 100 μm. On the bottom of the substrate a conductor rim of 50 μm width is added. Since the via fence confines the aperture the radiating aperture from dual slot to conductor rim should be considered at the bottom of the substrate. Since 2-D infinite substrate model does not consider an aperture shift, a free space 2-D antenna model is devised (Fig. 8. (b)). By attaching a quarter wavelength radially Anti-Reflection (AR) coated [11] hemispheric lens to the feed the primary pattern of the shifted aperture can be simulated. The simulated result shows a circular beam of 45~55° HPBW. The size of the feed antenna aperture is assumed to be same as the conductor rim size which is 0.54 mm x 0.6 mm.



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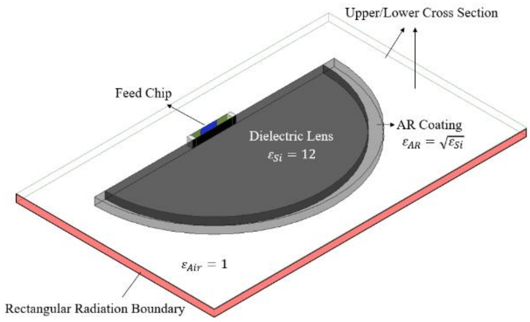

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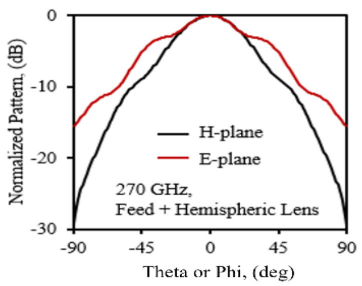

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Fig. 8. The effect of via fence structure; (a)Near field at the shifted aperture, (b)free space 2-D antenna model, (c)Far field pattern of the shifted aperture

B. Lens Design

Silicon is chosen as a lens dielectric by the similarity of permittivity with InP. Among the various forms of lenses Hyper-hemispheric lens is chosen for its easy accessibility and characteristic of resembling the curve of elliptic lens which is known to have a maximum aperture area. The ratio of focal offset and radius of 1:3 is chosen which is reported as an optimal ratio for high directivity and similarity to gaussian beam [12]. Note that the focal offset excludes the InP thickness since the aperture is shifted to the edge of the substrate by implementing via fence structure.

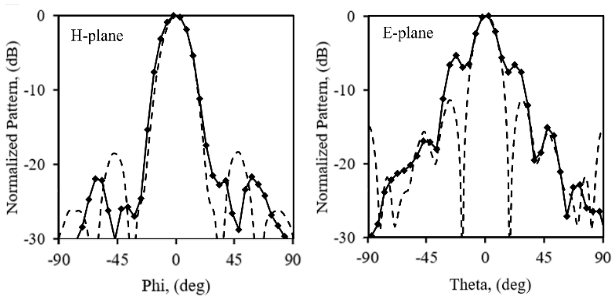
To make beam easily analyzable and measurable, bulky lens forming a pencil beam with only 1~2° is refrained. Lens with 3 mm diameter is chosen with a reasonable beam width of approximately 16~17° at 270 GHz. This gives an anticipated directivity of 20 dB by using directivity approximation for uniform circular apertures [13].

$$D_{u_{cir}} = \frac{33{,}709 \text{ deg}^2}{HP_{E^\circ} HP_{H^\circ}} \quad (5)$$

where

$D_{u_{cir}}$: Linear Directivity of a uniformly circular apertured antenna
HP_{E°: Half-power beamwidth of E-plane pattern in degrees
HP_{H°: Half-power beamwidth of H-plane pattern in degrees

Since the aperture is fixed to the via fence rim, a predictable tendency of beam width is expected as well as shown in Fig. 9. Measured pattern of InP Feed assembled lens antenna module at 270 GHz shows a good match with the simulated pattern which proves the simulation result is appropriate. Further frequency sweep overall 220-320 GHz (Fig. 9 (c)) shows the designed system functioning without abnormal radiation pattern.



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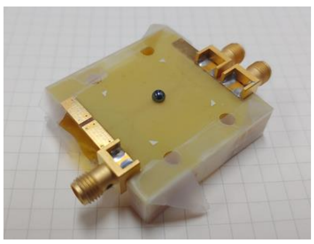

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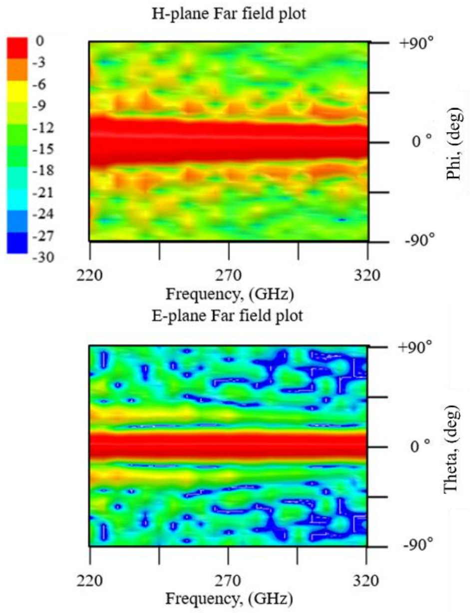

(c)

Fig. 9. Far field pattern of hyper-hemispheric lens system; (a) Comparison of measured (dot with solid line) and simulated (dash line) radiation pattern, (b) Assembled lens antenna module for measurement, (c) simulated single main-lobed pattern in H/E plane.

IV. CONCLUSION

In this work, a lens antenna feed circuit is designed with a newly devised 2-D pattern simulation method. Primary of the feed antenna and lens antenna is observed, and abnormal behavior of a limited size feed chip is brought to an issue. By introducing the via fence structure of 0.54 mm x 0.6 mm size, the aperture of the feed chip is not affected by the size limit of the chip. When packaged with a focal lens of 1.5 mm radius and 0.5 mm extension, the packaged system is expected to have high directivity of 20 dB. Packaged lens antenna pattern at a single frequency showed a good match with the 2-D method pattern result. In the future work, packaged lens antenna pattern, directivity and packaging loss will be measured at overall frequency band with integrated power detector circuit.

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REFERENCES

[1] M.W. Akhtar, S.A. Hassan, R. Ghaffar, H. Jung, S. Garg, and M.S. Hossain, "The shift to 6G communications: vision and requirements." *Human-centric Computing and Information Sciences*, vol. 10, no. 1, pp. 1-27, Dec. 21, 2020.

[2] J. Happich, “What’s next after 5G? 6G at THz frequencies”, eeNews EUROPE, Nov. 6, 2019.

[3] Z. Griffith, M. Urteaga, P. Rowell, R. Pierson, and M. Field, “Multifinger 250 nm InP HBTs for 220 GHz mm-wave power,” *Proc. Int. Conf. Indium Phosphide and Related Materials*, p. 204-207, 2012.

[4] V. Desmaris, D. Meledin, D. Dochev, A. Pavolotsky and V. Belitsky, “Terahertz Components Packaging Using Integrated Waveguide Technology”, *IEEE MTT-S Int. Microw. Symp. Dig.*, pp. 81-84, 2011.

[5] D.B. Rutledge, “Substrate-lens coupled antennas for millimeter and submillimeter waves,” *IEEE Antennas Propag. Soc. Newsl*., vol. 27, no. 4, pp. 4-8, 1985.

[6] W.L. Stutzman and G. A. Thiele, *Antenna Theory and Design, WILEY*, pp. 290, 2007.

[7] M. Kominami, D.M. Pozar, and D. H. Schaubert, “Dipole and slot elements and arrays on semi-infinite substrates,” *IEEE Trans, Antennas Propagat.*, vol. AP-33, pp. 600-607, 1985.

[8] J. Murdock, E. Ben-Dor, F. Gutierrez, and T.S. Rappaport, “Challenges and approaches to on-chip millimeter wave antenna pattern measurements,” *Proc. IEEE Int. Microwave Symp*., pp. 1-4, 2011.

[9] J.X. Yun and R.G. Vaughan, “Open slot antenna in a small ground plane”, *IET Microw. Antennas Propag.*, vol. 5, issue 2, pp. 200-213, Jan. 31, 2011.

[10] J. D. Kraus and R. J. Marhefka, *Antennas for All Applications*, McGrawHill, pp. 307-311, 2001.

[11] A.J. Gatesman, J. Waldman, M. Ji, C. Musante, and S. Yngvesson, “An Anti-Reflection Coating for Silicon Optics at Terahertz Frequencies,” *IEEE Microw. Guid. Wav Lett.* vol. 10, issue 7, pp. 264-266, 2000.

[12] D.F. Filipovic, S.S. Gearhart, and G.M. Rebeiz, “Double slot on extended hemispherical and elliptical silicon dielectric lenses”, *IEEE Trans. Microwave Theory Techniques*, vol. 41, no. 10, pp. 1738-1749, 1993.

[13] W.L. Stutzman, “Estimating directivity and gain of antennas”, *IEEE Antenn. Propag. M*, vol. 40, issue 4, pp. 7-11, 1998.

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