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空洞誘電体を用いた屈折率分布型レンズアンテナ

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あらまし　次世代無線通信の高周波化が進んでおり、高周波帯における高利得、低損失の大規模なアレーアンテナが求められている。一方、高周波帯における導体損失が大きいため、アンテナの高利得化、低損失化が重要な研究課題となっており、レンズアンテナをはじめとする誘電体アンテナはミリ波移動通信アンテナとして注目されている。本研究では、屈折率分布型レンズアンテナの設計法、及び 3D プリンタを用いた空洞誘電体レンズアンテナの製作法を検討し、移動通信用ビーム走査が可能な高利得アンテナ、及びミリ波イメージング用集光アンテナの特性を実験と電磁界シミュレーションにより示している。

キーワード　レンズアンテナ、誘電体アンテナ、ミリ波アンテナ、3D プリンタ

Gradient Index Lens Using Perforated Dielectric

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Abstract As the frequency of wireless communications of the next-generation becomes higher and higher, array antennas of high gain, low loss are required. However, because the conducting loss increases as the frequency becomes high, dielectric antennas such as the dielectric lens antennas become one of the potential candidates for the operation at millimeter wave band. In this research, a new design method for the gradient index lens is proposed, and the fabrication by using 3-D printers for the gradient index lens using perforated dielectric is introduced. The lens antennas are demonstrated for the application of beam scanning with high gain, as well as beam focusing at millimeter wave band.

Keywords Lens antennas, Dielectric antennas, Millimeter wave antennas, 3D printers.

New Lens Concept

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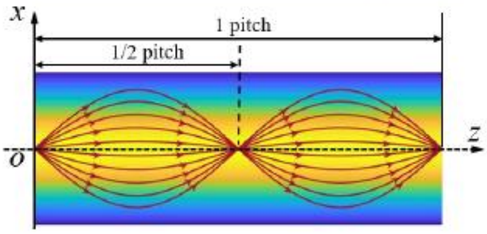
■ From Optical Lens Concept to Quasi-optical Lens Antenna

Intrinsic flat shape characteristic and structural extensibility

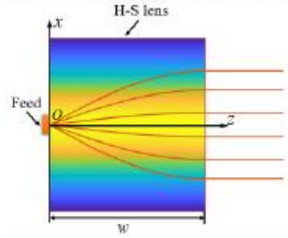


Key design equation

$$f = \frac{1}{n_0 \alpha}\cot(\alpha w) = \frac{w}{2\pi p n_0}\cot(2\pi p)$$

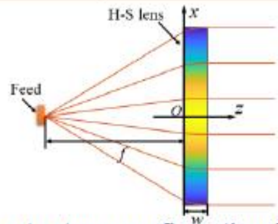
f, focal length of lens.
w, length of lens.
p, pitch of lens.
n_o, central refractive index

Integrated lens antenna



$p = 0.25$

Off-body fed lens antenna



$p \neq 0.25$

*Different antenna configurations by choose the suitable length and pitch of lens

[1] A. L.Mikaelian, *Prog. Opt.*, vol. XVII, pp. 283–346, 1980.

Full-dielectric Material

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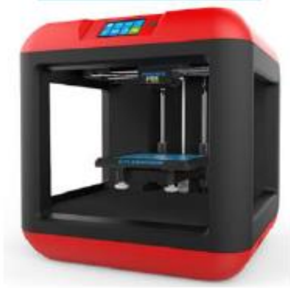
- Overcome the drawback of metamaterial with large loss and narrow bandwidth in traditional GRIN lens by using **full-dielectric material.**

Low-cost dielectric material[1]

Economic 3D printer



Summary of proposed lens concept

- **Intrinsic flat shape characteristic** of proposed new lens concept (Avoid using complex TO methods)
- **Not using metamaterials** (overcome the drawbacks of using inherently narrowband, lossy and dispersive metamaterial)
- **Cost-effectiveness, ease of fabrication** (easily accessible 3-D printing technique)

[1] J. Zechmeister et al., 2019 Conference on Microwave Techniques (COMITE), 2019, pp. 1-4.

H-S Lens with Perforation Structure

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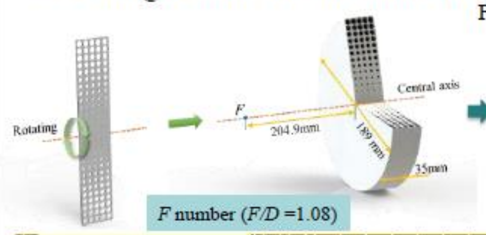
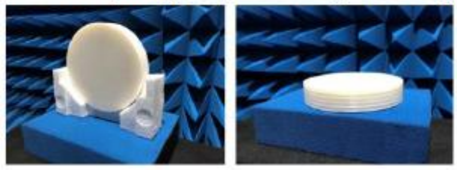
■ Design of H-S Lens Structure



F number (*F/D* =1.08)

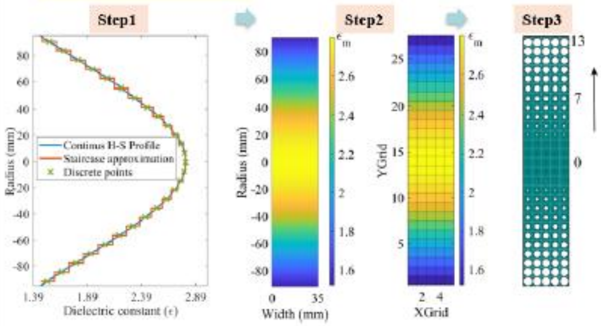
Fabricated lens prototype at10GHz using FDM 3-D printer



Intrinsic flat shape

Design Procedure

Unit-cell(mm): 7 × 7< λ/4 = 7.5 mm (Frequency = 10Ghz)



Step 1: Staircase approximation of H-S lens permittivity profile

Step 2: Grid discretization

- Grid size: 5 × 27

Step 3: Perforation structure

- Minimum hole size(mm): 0.32
- Maximum hole size(mm): 6.6

*Diameter

Can be fabricated

Measurement Results

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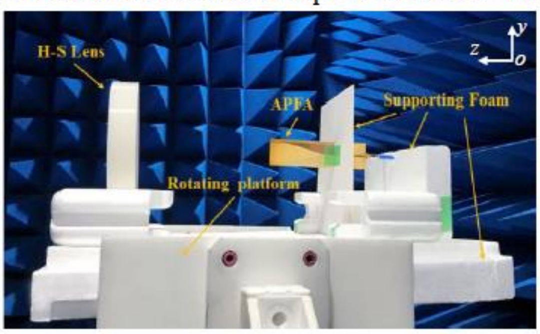
■ Measured Radiation Performance

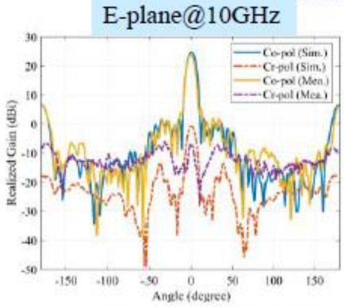
Foam-based Measurement setup in anechoic chamber



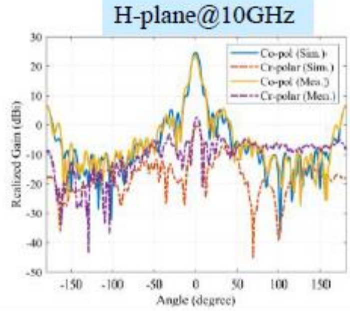
The simulation results are almost consistent with the measurement results.

*E- and H-plane patterns of lens feeding antenna (APFA)are not symmetric.

E-plane@10GHz



H-plane@10GHz



Measurement Results

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- Radiation Pattern Characteristic at 10GHz

		SIMULATED	MEASURED
Realized Gain (dBi)		24.7	**23.8**
3-dB Beamwidth (°)	E-plane	9.2	9
	H-plane	8.7	9
Cr-pol Levels (dB)	E-plane	-25.5	-29.7
	H-plane	-25.1	-21.0
Side Lobe Levels (dB)	E-plane	-18.1	**-17.4**
	H-plane	-18.0	**-16.7**

High Gain

Low SLLs

Aperture efficiency

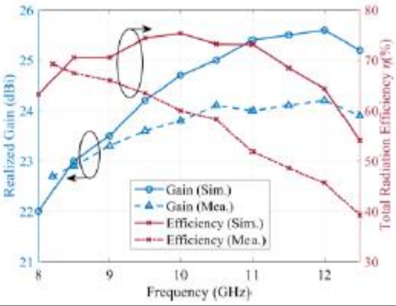
$$\eta_{ape} = D_a \lambda^2/(4\pi A)$$

D_a, directivity of antenna
A, physical aperture area of lens
λ, wavelength

Total radiation efficiency

$$\eta = G_e \lambda^2/(4\pi A)$$

G_e, measured gain



Broadband response

The total radiation efficiency is above ~40% across all tested frequencies (X-band)

2-D Beam-scanning by Feed Movement

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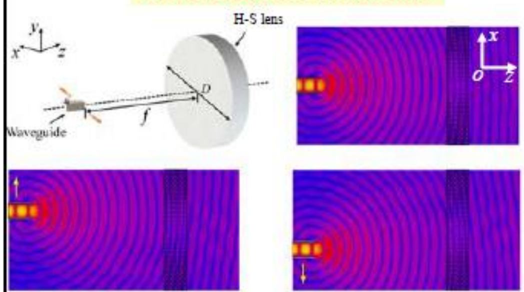
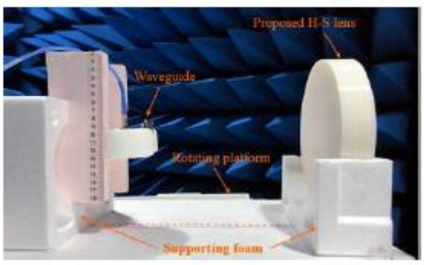
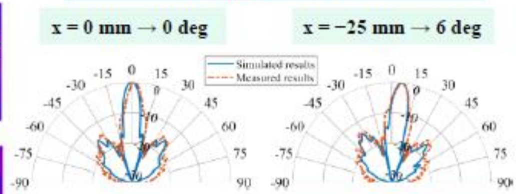
- Beam-scanning in H-plane (xoz plane)

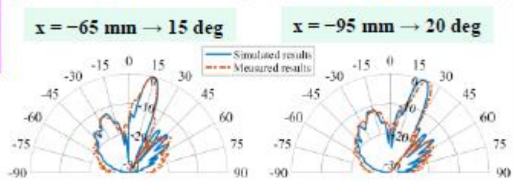
Move waveguide along x-axis





Explore the functionality of beam scanning for H-S lens





The waveguide placed at off-center position of lens leads to a steered beam

2-D Beam-scanning by Feed Movement

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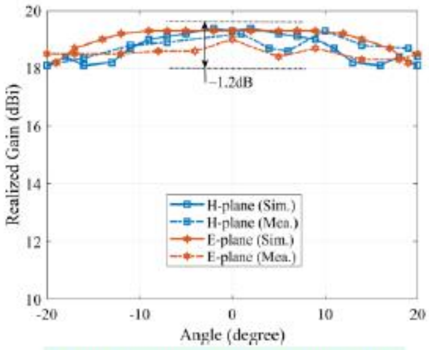
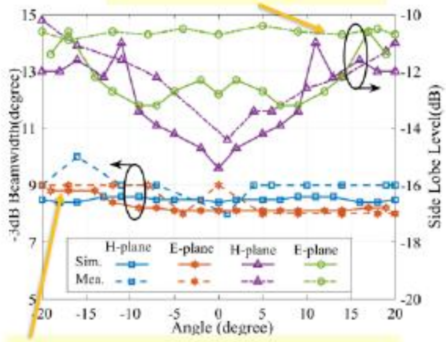
■ Gain, Bandwidth and SLLs Versus Scanning Angle

less than -10dB SLLs





Good gain stability of lens with **less than 1.2dB variation**

Very narrow beamwidth ~9deg

The functionality of beam scanning for proposed H-S lens by **mechanically moving the feed antenna** can be achieved with good gain stability and low side lobe levels.

Spatial Resolution Imaging Experiment

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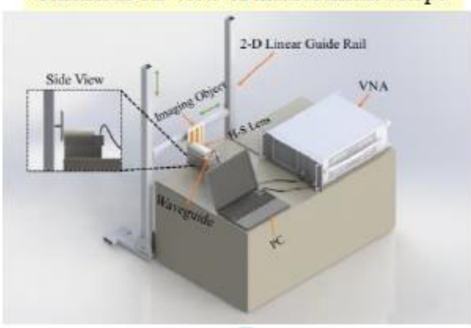
■Micro-/millimeter-wave Imaging Measurement Setups

Schematic 3D view of measurement setups

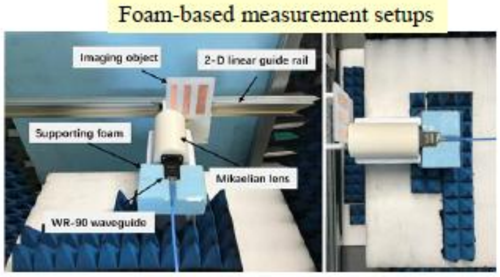


Four main parts

- Designed H-S lens
- Standard waveguide
- Vector network analyzers (VNA)
- 2-D linear guide rail

***Time domain measurement**

Foam-based measurement setups



Key point in measurement :

- The **distance** between the imaging target and the lens is required to **be kept as small as possible**, while **not blocking the movement** of the 2-D linear guide rail.

Spatial Resolution Imaging Experiment

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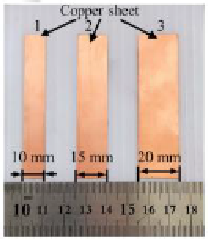
■Microwave Imaging at X-band

Imaging object

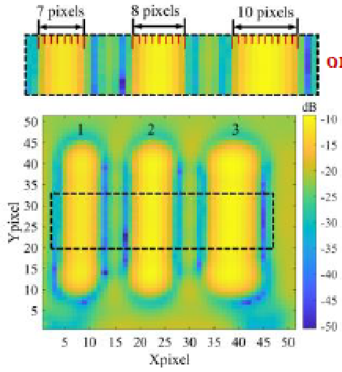
- plastic bottom plate
- three copper sheets with different physical widths of 10mm, 15mm and 20mm



2-D linear guide rail:

- The entire scanning area:102mm×102 mm.
- Distance of each movement (called **one pixel**) is set to **2mm**.

Magnitude of the reflection coefficient @ 10GHz



one pixel → 2mm

A spatial imaging **resolution of ~0.5λ (~15mm)** is achievable with this measurement setup.

Related Publications

Chen-Konno Lab.

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1. W. Shao, H. Sato, X. Li, K.K. Mutai, and Q. Chen, "Perforated extensible 3-D hyperbolic secant lens antenna for directive antenna applications using additive manufacturing," Optics Express, vol. 29, no. 12, pp. 18932-18949, 2021/06/07 2021. DOI: 10.1364/OE.426824.

2. W. Shao and Q. Chen, "Performance analysis of an all-dielectric planar Mikaelian lens antenna for 1-D beam-steering application," Optics Express, vol. 29, no. 18, pp. 29202-29214, 2021/08/30 2021. DOI: 10.1364/OE.438182.

3. W. Shao and Q. Chen, "2-D Beam-Steerable Generalized Mikaelian Lens With Unique Flat-Shape Characteristic," IEEE Antennas and Wireless Propagation Letters, vol. 20, no. 10, pp. 2033-2037, 2021. DOI: 10.1109/LAWP.2021.3102316.