3-D Printed Multifunctional Dielectric Lens Antennas Based on Gradient-index Fiber Concept for Beam-steering and Imaging Applications

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***Abstract*— In this paper, based on gradient-index (GRIN) fiber concept, two types of dielectric lens antenna for beam-steering and imaging application were introduced respectively. The properties of beam-steering and high-resolution imaging for proposed lens antennas were analyzed based on ray tracing method and full-wave simulation. The prototype of proposed lenses can be fabricated by 3-D printing technique in a low-cost. Besides, the flexible beam-steering capability with switched-beam and subwavelength imaging resolution were measured and validated.**

Keywords—3-D printing, beam steering, gradient-index, subwavelength imaging, lens antenna

I. Introduction

3D printed gradient-index (GRIN) lens [1], represented by Luneburg lens and Maxwell Fish-eye lens, exhibits broadband, high-directivity, and flexible beam-scanning with minimal power consumption for the potential applications of beyond 5G and 6G wireless communication, which has become the focus of intense research in recent years. However, the advantages and capabilities of GRIN lens are far more than that. The unique sub-diffraction focusing characteristic of GRIN lens in the near field also provides a potential way to achieve excellent performance in super-resolution millimeter-wave imaging.

Inspired by GRIN optical fiber concept, a self-focusing cylindrical GRIN lens called Mikaelian lens [2]-[3] or hyperbolic secant lens [4] has a unique flat shape characteristic, which has attracted great interest in the application field antenna in recent years. The light oscillates along the central axis inside lens, as shown in Fig.1. The oscillation period of the light is defined as Pitch (P). When the suitable lens width and pitch of lens is selected, various interesting phenomena such as beam collimation and surface focusing can be observed.

In this paper, we introduce two types of GRIN lens structure with different widths and pitches for beam-steering and imaging application, respectively. The capability of beam-steering and high-resolution imaging for proposed lenses were explored based on ray tracing method and full-wave simulation. The proposed lenses were fabricated by 3-D printing technique in a low-cost.

II. Multifunctional GRIN Lens Antenna Design

A. Beam-steering Lens Antenna Design

The transverse permittivity profile or hyperbolic secant (H-S) profile of proposed GRIN lens is defined by the following equation [5].

$$\varepsilon(r) = [n(r)]^2 = \varepsilon_0 sech^2(\alpha r) \qquad (1)$$

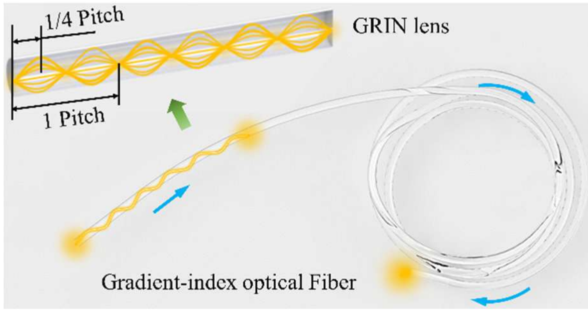

Fig. 1. Self-focusing cylindrical GRIN lens structure based on optical fiber concept. The light oscillates along the central axis inside lens.

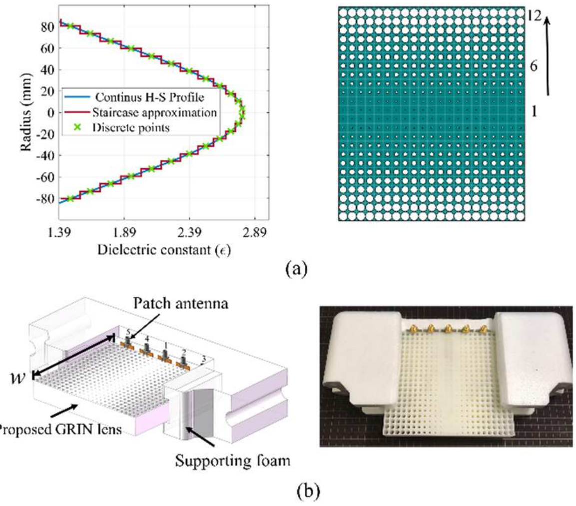

Fig. 2. (a) The implemented design procedure of proposed GRIN lens operating at 10 GHz. (b) Fabricated beam-steering GRIN lens antenna prototype excited by five rectangular microstrip patch antennas [5].

where ε_0 is the material permittivity. $\alpha = 2\pi P/w$ is the gradient parameter. w and P is the width and pitch of lens.

Based on staircase approximation, the continuous permittivity profile of lens is discretized into 24 layers, as shown in Fig.2(a). Then different sizes of air-hole are utilized to achieve the corresponding discrete permittivity values. The perforated GRIN lens structure is fabricated by 3-D printing technique as shown in Fig.2(b). The pitch, length, width and thickness of proposed lens is 0.25, 168mm, 147mm and 25mm ,respectively. The beam-steering capability of proposed lens is verified by using ray tracing method and full wave analysis, Fig.3 shows three examples of ray tracing and corresponding electric field distribution inside lens at different lunching positions of focal plane ($r = 25mm, 0mm, -25mm$). Five rectangular microstrip patch antennas utilized as feeding sources are placed at the focal plane or lens surface. Each

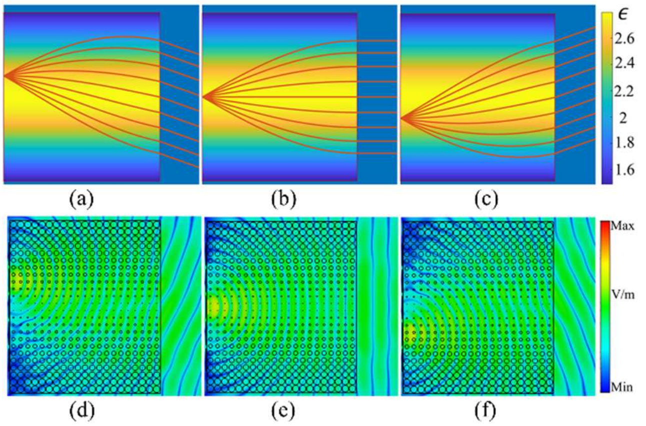

Fig. 3. Ray tracing and full wave analysis of proposed GRIN lens.

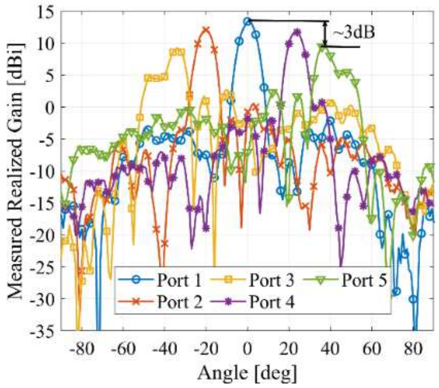

Fig. 4. Measured radiation patterns at 10 GHz for each port at horizontal plane [5].

patch antenna corresponds to the radiation in one defined direction, which allows for wide-angle beam-steering in the horizontal plane. The measured radiation patterns for five different ports at horizontal plane is shown in Fig. 4.

B. Imaging Lens Antenna Design

The pitch, diameter, and length of designed imaging lens operating at X-band is 0.5, 70mm, and 133mm respectively. Fig.5 (a)-(b) shows the design steps of lens operating at center frequency of 10 GHz. As before, The 2-D continuous permittivity distribution of lens is discretized into19×10 grids. After discretizing, the different sizes of air-hole is utilized to achieve the intended discrete permittivity distribution. As shown in Fig.5(c)-(d), the proposed GRIN lens design at X-band can be a good phase transformer to convert a diverging spherical wave into a converging spherical wave, which provides a way to map objects points to image points.

In our case [6], the X-band standard waveguide as receiving antenna is placed on the lens surface. In order to verify the imaging performance of proposed imaging lens, two single-sided copper clad laminates engraved the Japanese romaji word "TOHOKU" are utilized as shown in Fig.6 (a)-(b). The linewidth of each letter is less than 15 mm. By using the time domain measurement method, the measured echoed signal for each of the reflecting points (or pixels) at the imaging object can be recorded by VNA, which form the scanning image of "TOHOKU" as shown Fig.6(c)-(d). Owing to the limited spatial resolution of ~0.5λ (~15mm) for the proposed imaging lens, there are some distortions in the scanning image. This problem can be solved by expanding the functionality of this GRIN lens to higher frequency bands.

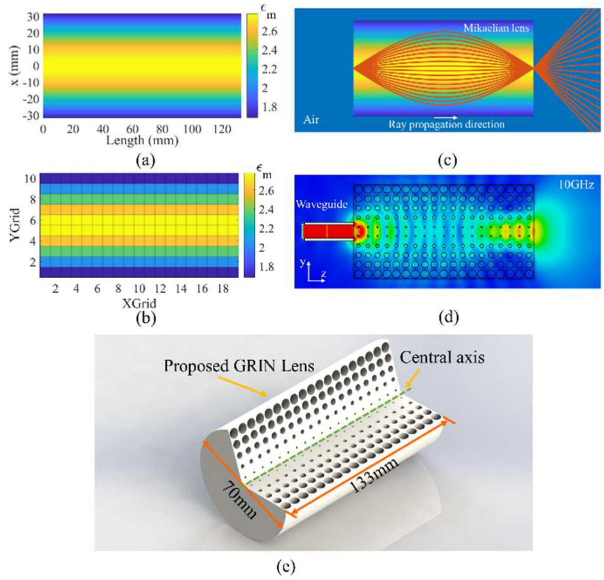

Fig. 5. Measured H-plane radiation patterns at 10 GHz for each port.

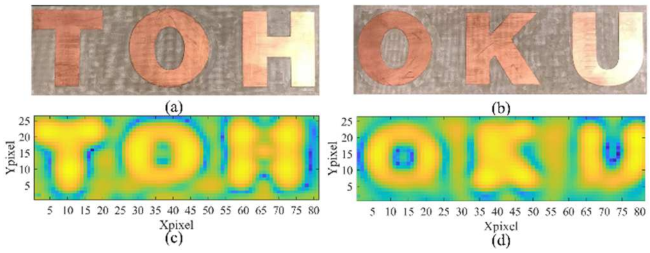

Fig. 6. The scanning image for the word "TOHOKU" at 10GHz by using proposed GRIN imaging lens [6].

III. Conclusion

Inspired by GRIN optical fiber concept, two types of GRIN lens structure for multiple applications was presented in this paper. The different lens structure can be easily obtained by selecting different widths and pitches of lens. Then, benefiting from 3-D printing techniques. The designed GRIN lens structure with different sizes of air-hole was fabricated. Besides, the function of beam-steering and high imaging resolution was analyzed and verified by ray tracing and full wave simulation. The experiment results indicates the proposed structure could be a potential lens type for wireless communication and imaging applications.

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