3D-Printed Fresnel Zone Plate Lens

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***Abstract* - 3D-printing has been used for rapidly prototyping a low-cost and light-weight dielectric zone plate Fresnel lens (FL). This lens was comprised of four dielectric zones and they were fabricated in one process with the tailored permittivities. Measurements show that this lens provides 7.3 to 12.8 dB gain enhancement over the frequency band from 8 to 12 GHz.**

***Index Terms* — Fresnel lens, zone plate, 3D-printing, additive manufacturing**

1. Introduction

Fresnel lenses (FL) are relatively thin and flat, they usually have smaller volumes and weighs compared with conventional shaped lenses. They can be fabricated by using inexpensive dielectric materials, which makes them suitable for consumer applications [1]–[4]. The traditional fabrication approaches are dominated by using mechanical machining [5], [6]. However, the precisely machining is involved in which increases manufacturing complexity. Furthermore, the machining technique removes or shapes parts of the raw materials which generates material waste.

The 3D-printing technology constructs objects as successive layers. It is one-step process and able to generate complex internal structures. It significantly simplifies the manufacture process and reduces material waste. Furthermore, 3D-printing can create perforated structures that are difficult to be realised by machining due to the mechanical strength of material. The dielectric materials can be custom-made by using 3D-printing [7].

This paper presents a novel dielectric FL that is fabricated by using 3D-printing. In this work, an acrylonitrile butadiene styrene (ABS) based 3D-printing filament PREPERM® TP20280 was used. The dielectric constant of this 3D-filament is 4.4 and loss tangent is 0.004. A fused deposition modelling (FDM) Makerbot® Replicator™ 2X 3D-printer was used to fabricate the FL. The extrusion temperature was 230°C with the 110°C heated platform. The dielectric zones in the lens were tailor-fabricated in one-step process.

2. Lens design and 3D-printing

The design of the FL was carried out at 10 GHz and the lens had a uniform thickness. The radii (Ri) for each dielectric zone can be determined using:

$$R_i = \sqrt{2Fi\left(\frac{\lambda_o}{P}\right) + (i\frac{\lambda_o}{P})^2} \qquad i = 2, 3, \ldots, P \quad (1)$$

where P is the phase correcting index, λo is the design wavelength and F is focal length. In this work the lens was designed for quarter wave phase correction. An $F/D = 0.3$ was chosen, to obtain a short focal length. The focal length F was 30 mm.

The thickness of the lens t is related to the dielectric constants of two adjacent Fresnel zones and it can be obtained using:

$$t = \frac{\lambda_o}{P(\sqrt{\varepsilon_i}-\sqrt{\varepsilon_{i-1}})} \qquad i = 2, 3, \ldots, P \quad (2)$$

In this design, the highest dielectric constant value was 4.4. This was equal to the 3D material. In order to reduce the thickness and the weight, the centre ring with the minimum dielectric constant was equal to 1 which was air. Therefore, the lens was made of three dielectric rings and one air ring per full-wave zone. By substituting $P = 4$, $t = 20.5$ mm, $\varepsilon_{rmax} = 4.4$, $\varepsilon_{rmin} = 1$ and $\lambda o = 30$ mm into (2), the dielectric constant values for each rings could be obtained. . It is worth noting that the FL has the lowest permittivity at the first Fresnel zone from the centre and the maximum at the second Fresnel zone. The other dielectric constant values then were decreased from the inner to the outermost. Therefore, the permittivites of the FL zones in this case had $\varepsilon_{r2} > \varepsilon_{r3} > \varepsilon_{r4} > \varepsilon_{r1}$

The tightly fitted concentric dielectric zones in the FL were entirely 3D-printed using one single 3D-printing material. The dielectric rings were printed as non-solid which leads air voids into the lens. By altering the volume fractions of the air voids in the 3D-printed dielectrics, the dielectric constants were tailored to the desired values. The required volume fraction f of a non-solid 3D-printed dielectric was obtained by using equation (3), which showed the relation between the relative permittivity of the 3D-printing material ε_{ro} and the expected relative effective permittivity of the non-solid structure ε_{reff}:

$$f = \frac{\varepsilon_{reff}-1}{\varepsilon_{ro}-1} \quad (3)$$

The values with the corresponding infill percentages for the Fresnel zone radii are given in Table I. And the final 3D-printed dielectric FL is shown in Fig. 1. The whole lens was 3D-printed in a single process.

TABLE I FRESNEL ZONE RADII AND CORRESPOIND DIELECTRIC CONSTANTS

i	ε_i	R_i in mm	Infill percentage in %
1	1.0	22.5	0
2	4.4	33.5	100
3	3.0	43.1	58.8
4	1.9	52.0	25.6

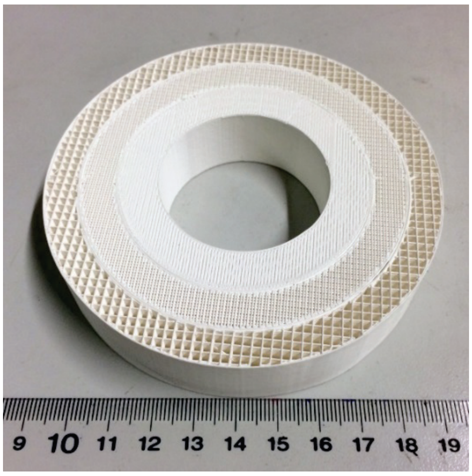

Fig. 1. Photo of 3D printed FL

3. Far-field measurement results

The measured normalised gain of the FL at the frequency band from 8 to 12 GHz is shown in Fig. 2. The gain value is the received power at boresight (theta = 0°) with the lens normalised to the received power without the lens. This result indicates the gain enhancement of the 3D-printed FL. The simulated results using CST Microwave Studio is included in Fig. 2 for a comparison. The measured results agree well with the simulated results, and show that the 3D-printed FL increases the received power level by 7.3 to 12.8 dB over the entire 8 to 12 GHz range. The measured far-field radiation patterns of the FL at 8, 10 and 12 GHz are shown in Fig. 3, and compared with the simulated patterns. The radiation patterns are normalised to the maximum received power at boresight at each individual frequency. Fig. 3 shows a good agreement between measured and simulated patterns.

4. Conclusion

A low-profile, light-weight and wideband dielectric zone plate FL has been successfully rapidly prototyped using 3D-printing. The entire lens was 3D-printed in a single-step process without machining or assembling, which significantly simplified the manufacturing process. These tightly fitted dielectric rings with the bespoke permittivities were 3D-printed as non-solid internal structures with specific material infill percentages. This 3D-printed dielectric FL offered 7.3 to 12.8 dB gain over the frequency range from 8 to 12 GHz, when fed by an X-band waveguide source that was located at the focal point of the lens.

Acknowledgment

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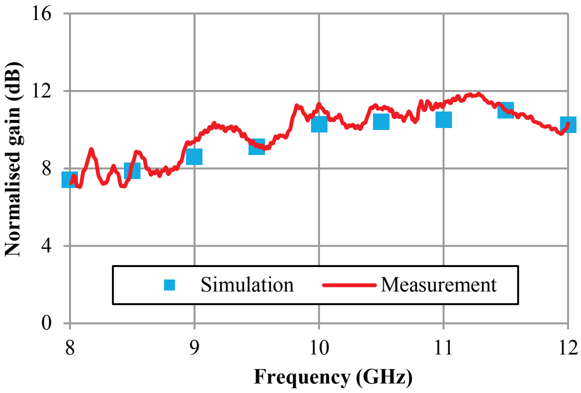

Fig. 2. Normalized gain of the 3D-printed FL

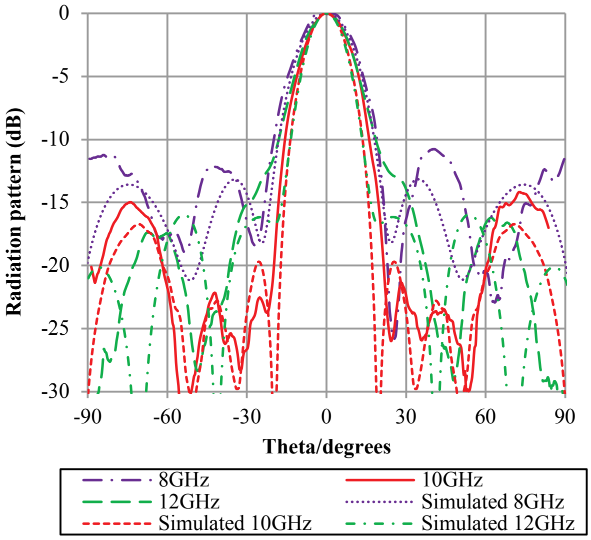

Fig. 3. Far-field radiation patterns of the 3D-printed FL in H-plane at different frequencies

References

[1] D. N. Black and J. C. Wiltse, “Millimeter-Wave Characteristics of Phase-Correcting Fresnel Zone Plates,” Microwave Theory and Techniques, IEEE Transactions on, vol. 35, no. 12, pp. 1122–1129, 1987.

[2] H. D. Hristov and M. H. A. J. Herben, “Millimeter-wave Fresnel-zone plate lens and antenna,” IEEE Transactions on Microwave Theory and Techniques, vol. 43, no. 12, pp. 2779–2785, 1995.

[3] H. D. Hristov and J. M. Rodriguez, “Design Equation for Multidielectric Fresnel Zone Plate Lens,” IEEE Microwave and Wireless Components Letters, vol. 22, no. 11, pp. 574–576, Nov. 2012.

[4] L. P. Kamburov, J. M. Rodriguez, J. R. Urumov, and H. D. Hristov, “Millimeter-Wave Conical Fresnel Zone Lens of Flat Dielectric Rings,” IEEE Transactions on Antennas and Propagation, vol. 62, no. 4, pp. 2140–2148, Apr. 2014.

[5] A. Petosa and A. Ittipiboon, “Design and performance of a perforated dielectric Fresnel lens,” IEE Proceedings - Microwaves, Antennas and Propagation, vol. 150, no. 5, p. 309, 2003.

[6] A. Petosa, A. Ittipiboon, and S. Thirakoune, “Investigation on arrays of perforated dielectric Fresnel lenses,” IEE Proceedings - Microwaves, Antennas and Propagation, vol. 153, no. 3, p. 270, 2006.

[7] S. Zhang, C. C. Njoku, W. G. Whittow, and J. C. Vardaxoglou, “Novel 3D printed synthetic dielectric substrates,” Microwave and Optical Technology Letters, vol. 57, no. 10, pp. 2344–2346, Oct. 2015.