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B. Orazbayev[1], V. Pacheco-Peña[1], V. Torres[1], M. Beruete[1], M. Navarro-Cía[2]
[1] TERALAB (MmW—THz—IR & Plasmonics Laboratory), Universidad Pública de Navarra, Campus Arrosadía, 31006 Pamplona, Spain. miguel.beruete@unavarra.es
[2] Optical and Semiconductor Devices Group, Department of Electrical and Electronic Engineering, Imperial College London, London SW7 2BT, UK; Centre for Plasmonics and Metamaterials, Imperial College London, London SW7 2AZ, UK; and Centre for Terahertz Science and Engineering, Imperial College London, London SW7 2AZ, UK. m.navarro@imperial.ac.uk

***Abstract*—Here we present numerical and experimental results of a zoned fishnet metamaterial lens with dual-band response. Good performance is demonstrated at frequencies 54 GHz and 55.5 GHz at which the fishnet metamaterial behaves as a medium with refractive indexes n_1 = -0.78 and n_2 = -0.43, respectively. Experimental focal lengths are FL_1=8.4λ_1 and FL_2=9.4λ_2. The dual-band response of zoned fishnet metamaterial lens shows potential for application in non-mechanical zoom millimeter-wave imaging system.**

***Index Terms*—fishnet metamaterial, millimiter waves, metallic lenses.**

I. Introduction

Since the dawn of civilization the possibility of controlling transmission of light has been of great interest for researchers. The best-known devices, the conventional dielectric lenses have been successfully used for this purpose even before Maxwell´s equations were reported. However, such lenses are limited to the electromagnetic parameters of natural materials. By introducing metallic lenses [1] Kock demonstrated new possibilities of lens design based on artificial dielectrics. A further advance has been recently witnessed with the appearance of metamaterials, which allow manipulation both permittivity (ε) and permeability (μ), and have made possible perfect lenses, superlenses, hyperbolic lenses, chiral lenses, ε-near-zero (ENZ) lenses, etc. [2]–[7].

The fishnet metamaterial has shown good performance for higher frequencies, because of its lower losses and frequency-robust magnetic response. Hence, lenses based on the fishnet metamaterial have also shown good performance [8]–[10], although they are still relatively bulky to be integrated in compact systems. The time-honored zoning technique can help to solve this problem. Although such a technique reduces even more the frequency range of the fishnet metamaterial lens [11], [12]. Therefore an optimization of the zoned lens profile is required, in order to have a dual regime.

In this work we present simulation and experimental results for the dual-band zoned fishnet metamaterial lens [13].

II. Lens design

The design procedure of the zoned fishnet metamaterial lens with dual band response consists of two steps: first, an application of the zoning technique in order to obtain a slim profile, and second, finding the optimal profile of the lens supporting the dual regime.

A. Zoning technique

In order to obtain a slim profile for the fishnet lens the zoning technique is applied, whereby redundant material is removed each time one wavelength phase shift is reached. The limit of the thickness t depends on the free-space wavelength λ_0 and the index of refraction of the medium n [1]:

$$t = \frac{\lambda_0}{1-n}, \tag{1}$$

From the general equation of an ellipse [10] we obtain the design equation of the lens profile [11]:

$$z = \mathrm{mod}\left(\frac{FL(1-n_{lens}) - \sqrt{FL^2(1-n_{lens})^2 - x^2(1-n_{lens}^2)}}{1-n_{lens}^2}, t \right), \tag{2}$$

where n_{lens} is the effective refractive index of the structure, FL is the focal length, and m is an integer (m = 0, 1, 2, 3) that represents the successive steps for the zoned lens profile.

B. Final design

The unit cell of the fishnet metamaterial, used in this work, has the following parameters: d_x = 2.5 mm, d_y = 5, d_z= 1.5 mm and w = 0.5 mm (Fig. 1(a)). The effective index of refraction of the fishnet metamaterial evaluated from the dispersion diagram, using the Eigenmode solver of CST Microwave Studio™ [14], is shown in Fig. 1(a). For the chosen working frequencies f_1 = 54 GHz and f_2 = 55.5 GHz the effective refractive indices are n_{lens1} = -0.78 and n_{lens2} = -0.43 respectively. Due to the discretization imposed by d_x and d_z, the zoned profile is approximated by a staircase profile, which is outlined in Fig. 1(b) (black solid line), where also the curves for both frequencies defined by (2) for four successive steps (m = 0, 1, 2, 3) are plotted (dashed blue and red lines, respectively). The zoned fishnet metamaterial lens is optimized to work in the dual band regime by a minimization of the root-mean-square-error between (2) and the staircase approximation. As a result a slim dual-band zoned fishnet metamaterial lens with two focal lengths

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FL_1=48.7 mm (8.8λ_1) and FL_2 = 55 mm (10.2λ_2) is synthetized.

The fabricated lens is demonstrated in Fig. 1(c). The final design has overall dimensions 111 mm × 135 mm × 8 mm (19.8λ1 × 24.1λ1 × 1.4λ1).

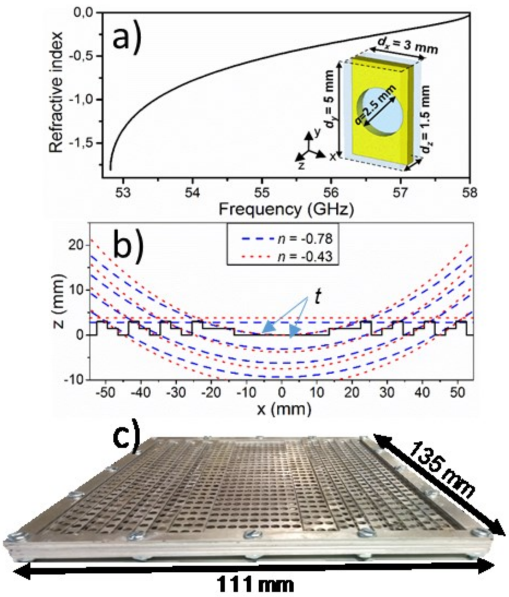

Fig. 1. a) Effective refractive index of an infinite fishnet metamaterial. (Bottom-right inset). The unit cell dimensions: d_x = 3mm, d_y = 5mm, d_z = 1.5mm, metal thickness w = 0.5 mm and hole diameter a = 2.5 mm. b) Lens profiles and curves of the successive steps for: f_1 = 54 GHz (dashed blue curve) and for f_2 = 55.5 GHz (dotted red curve), the thickness limits, t_1 and t_2 (blue and red horizontal curves, respectively). c) Fabricated zoned fishnet metamaterial lens.

III. Results

First, the zoned fishnet metamaterial lens is simulated with the transient solver of CST Microwave Studio^{TM}. In order to reduce the computational effort, magnetic and electric symmetries are used at *yz*- and *xz*-planes respectively. A vertical polarized (E_y) plane-wave has been used as a source exiting the structures from their planar face.

In Fig. 2(a, c) the numerical results for the field distribution on the *xz*-plane are plotted for the design frequencies f_1 = 54 GHz and f_2 = 55.5 GHz respectively. The focal length FL = 44.2 mm (7.9λ_1) and 50.3 mm (9.3λ_2), the depth of focus DF= 10 mm (1.8 λ_1) and 10.7 mm (2λ_2), and the FWHM along x is 2.8 mm (0.5 λ_1) and 2.8 mm (0.5λ_2) for f_1 and f_2 respectively.

Finally, in Fig. 2(b, d) experimental results for spatial power distribution in *xz*-plane are shown for f_1 and f_2 respectively. Agreement between simulation and experimental results is evident. The focal length FL = 47 mm (8.4λ_1) and 51 mm (9.4λ_2), the depth of focus DF= 13.7 mm (2.5 λ_1) and 14.2 mm (2.6λ_2), and the FWHM along x is 3.3 mm (0.6 λ_1) and 3.4 mm (0.6λ_2) for f_1 and f_2 respectively. The numerical and experimental values of the focal lengths coincide with the design values.

IV. Conclusions

The dual-band zoned fishnet metamaterial lens has been designed, fabricated and measured at the V-band of millimeter-waves. Experimental and simulation results are in good agreement. The low-profile and weight of the zoned lens with millimeter-wave dual-band response demonstrates a possibility to work in integrated systems with good competition to other conventional diffractive optical devices.

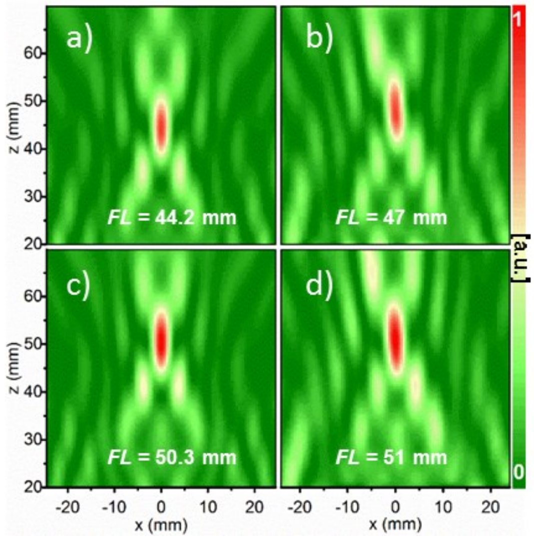

Fig. 2. The spatial power distribution on the xz-plane for f_1 = 54GHz (a, b) numerical and measured respectively, and for f_2 = 55.5 GHz (c, d) numerical and measured respectively.

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