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Wood zone plate lens based on fishnet metamaterial

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Abstract- A study of a low-profile hybrid Wood zone plate fishnet metamaterial lens working at f = 99 GHz is presented. The use of fishnet metamaterial with effective refractive index close to zero (n = 0.51) as a medium for Fresnel zones allows to reduce the reflections from the metalens and increase the overall efficiency, while maintaining low profile, low cost and ease of manufacturing. The performance of metalens was analyzed numerically and confirmed experimentally, demonstrating a good agreement.

The Fresnel zone plate lenses possess high reflections from the opaque rings (the even or odd zones), which deteriorate the focusing efficiency. In the Wood zone plate lens (WZPL) this disadvantage is overcome by replacing the opaque rings with dielectric rings that produce fields with a π phase difference with respect to the original transparent ring zones. When the refractive indices of the materials used for the even and odd zones are similar, the lens becomes thick and heavy. On the other hand, high index contrasts enable thinner lenses but at the expense of impedance mismatch with free-space, which causes a focusing efficiency reduction. [1], [2].

To tackle this problem, here we propose a hybrid half-wavelength WZPL based on a fishnet metamaterial. The fishnet metamaterial, which consists of closely-packed subwavelength hole arrays working under extraordinary optical transmission [3] [see Fig. 1(a)], can have a refractive index less than unity (for the design reported here, n = 0.51) and therefore enable faster π phase difference between odd and even zones. Moreover, the fishnet metamaterial has the potential to minimize reflection, increasing the overall efficiency of the lens. In our metalens' design four periods of fishnet metamaterial (plus one dielectric layer as a protection cover) are used, which provide a good trade-off between total thickness and electromagnetic performance in terms of insertion loss. Therefore, the total thickness of the metalens is $w = 4d_z+t_d$ = 1.97 mm (~$0.62\lambda_0$) (where d_z = 0.4 mm is the period of the fishnet metamaterial, t_d = 0.38 mm is the thickness of dielectric layer). The required refractive index n_f = 0.51 was derived from the equation of the thickness of the WZPL: $w = \lambda_0/(\sqrt{\varepsilon_r}-\sqrt{\varepsilon_f})$ (where ε_r, ε_f is the permittivity of the dielectric and fishnet metamaterial respectively). The value of the refractive index of the fishnet metamaterial can be adjusted by varying the diameter of the holes a, which at the design frequency f = 99 GHz (λ_0 ~ 3.03 mm) was found to be a = 1.08 mm.

Figs. 2 (c, d) show the numerically-computed electric field distribution in the xz-plane (c) and the yz-plane (d). The focal length is FL = 22.5 mm ($7.4\lambda_0$) and $FWHM_1 = FWHM_2$ = 2 mm ($0.66\lambda_0$) for xz- and yz-planes, respectively. The measurement can be seen in Fig. 2 (e, f) for the xz-plane and the yz-plane, respectively. The focal length is FL = 23 mm ($7.6\lambda_0$) and $FWHM_1 = FWHM_2$ = 2.1 mm ($0.69\lambda_0$) for xz- and yz-plane respectively. Thus, the numerical and experimental results are in good agreement.

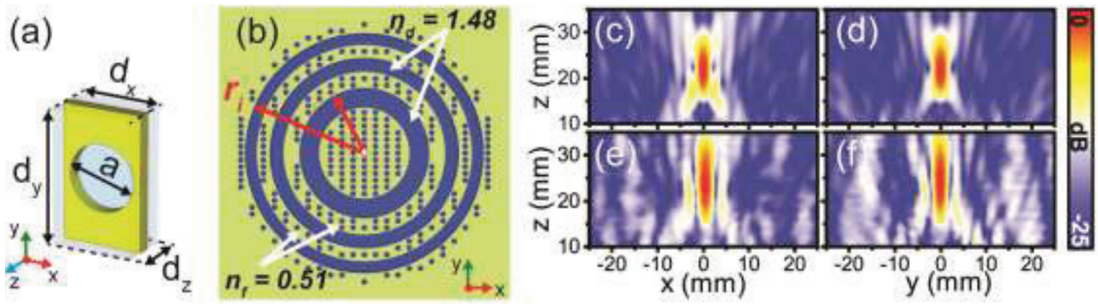

Fig.1. (a) Fishnet metamaterial unit cell. (b) Fabricated WZP fishnet metamaterial lens. Normalized electric field distribution in *xz*-plane (c,e) and *yz*-plane (d,f) for numerical (top) and experimental (below) results.

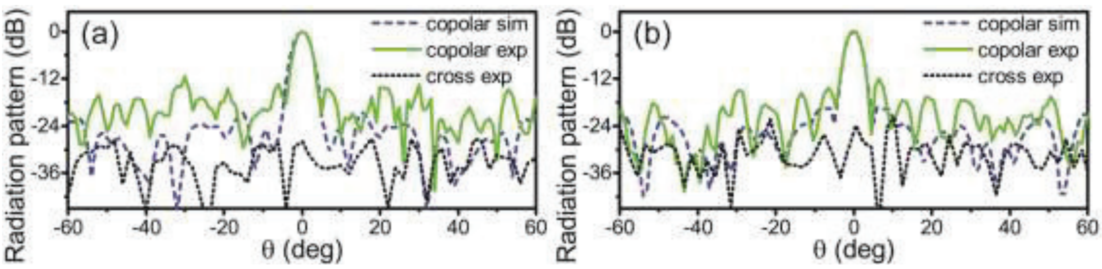

Fig. 2. Normalized radiation pattern for *E*-plane (a) and *H*-plane (b) (simulation and experimental).

The performance of the fishnet WZPL in lens-antenna configuration was also analyzed. The normalized numerical and experimental radiation patterns are shown in Fig. 2 (a, b) for *E*- (a) and *H*-plane (b) respectively. It is obvious that the radiation patterns for the main lobes are in good agreement, however the side lobes are higher in the experiment. This can be explained by the higher ratio main/sidelobe in numerical results, which results in lower lobes in the normalized radiation pattern.

Finally, a relatively high gain of 16.6 dB was measured at the design frequency f = 99 GHz while the numerical gain is 24.3 dB. This disagreement may be explained by experimental errors (misalignment, accuracy of distance measurement) and by defects in the fabrication (non-perfect contact between dielectric and metallic plates, errors in the radius of the holes) and effective substrate losses higher than nominal values.

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