Soret lens-antenna based on the fishnet metamaterial

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Soret Lens-Antenna based on the Fishnet Metamaterial

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***Abstract*— In this work we present the design, numerical and experimental results for an ultrathin Soret fishnet metamaterial lens working at f_{exp} = 96.45 GHz. The fishnet metamaterial with effective refractive index close to zero (*n* = -0.06) is introduced on the back side of the classical Soret lens in order to improve its efficiency. The experimental results are in good agreement with simulation results and demonstrate half-wavelength focal length and spot size. In a lens antenna configuration a high gain of 10.64 dB was measured at the operation frequency. The presented lens has a low-cost compact design, and may find applications in integrated lens antenna systems.**

***Index Terms*—antenna, metamaterial, propagation, Fresnel zone.**

I. INTRODUCTION

A Soret lens, like any member of Fresnel zone plate lenses, consists of alternating concentric opaque and transparent zones [1]. Opaque zones block the part of the incident wave that otherwise would interfere destructively at the focal point. Unfortunately, the efficiency of this lens is low because half of the power is blocked [2], [3]. A possible solution to increase the efficiency is to replace opaque areas by dielectric, which provides an additional phase shift of π to the transmitted wave. In such design a constructive interference between all zones occurs at the focal point. However, such technique increases the thickness of lenses and complicates the manufacturing process [2]–[4].

A smarter solution could be to use metamaterials [5] in the lens design, replacing the conventional dielectrics. Given the possibility of manipulating the values of permittivity and permeability independently, metamaterials provide more possibilities for control of electromagnetic waves [6]. One of the most promising metamaterials for the millimeter range is the fishnet structure (stacked subwavelength hole arrays), which has low losses in this range [7], [8]. The fishnet metamaterial has been successfully used to design lenses for the millimeter range [9]–[12]. Surface currents, excited on the surface of the plates of the fishnet improve the adaptation of the lens and its illumination efficiency [13], [14]. Moreover, designing the fishnet metamaterial to behave as a medium with index of refraction close to zero provides a quasi-plane-wave front on its surface [15], [16], improving the gain and sidelobe levels of an Soret metalens antenna.

In this work a Soret lens based on a fishnet metamaterial is designed, fabricated and measured [17]. The experimental focus is placed at 1.973 mm ($0.6\lambda_0$) in good agreement with the numerical results. The metalens-antenna shows an experimental gain of 10.64 dB at the frequency f_{exp} = 96.45 GHz.

II. LENS DESIGN

A. Fishnet metamaterial

The unit cell of a fishnet metamaterial implemented in the Soret lens consists of a metal plate (aluminum of thickness 0.017 mm) embedded between two dielectric plates (Rogers RO5880™ with thickness 0.19 mm) of permittivity ε_r = 2.2 and loss tangent $\tan\delta = 9 \times 10^{-4}$. Therefore, the dimensions of the unit cell are: d_x = 1.26 mm, d_y = 2.1 mm, d_z = 0.398 mm, hole diameter $a = d_y/4$ = 0.525 mm; see Fig. 1(a). For these parameters, the cut-off frequency of the hole fundamental TE_{11} mode is 112 GHz. The effective refractive index is evaluated from the dispersion diagram computed with the eigen-mode solver of CST Microwave Studio™. At the design frequency *f* = 95 GHz, the fishnet metamaterial behaves as a medium with *n* = -0.06.

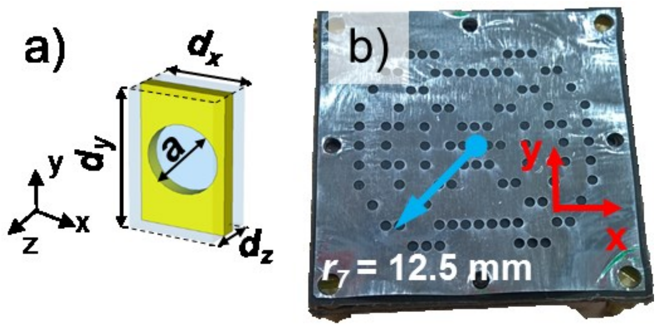

Fig.1. (a) Fishnet metamaterial unit cell. (b) Photograph of the fabricated metalens (without first protective layer)

B. Fresnel zones

Fresnel zone plate lens consists of circular zones whose radii are calculated by the following equation [2], [3]:

$$r_i = \sqrt{\frac{2FL \cdot \lambda_0 \cdot i}{p} + \left(\frac{i \cdot \lambda_0}{p}\right)^2} \qquad (1)$$

where λ_0 is the wavelength at the working frequency, FL is the focal length, i is the number of Fresnel zones and p is the number of phase quantization levels. In the designed lens $i = 7$ is used, with outer radius $r_7 = 12.5$ mm. The other parameters are: $FL = 1.58$ mm ($0.5\lambda_0$), $p = 2$. The fabricated prototype with these design parameters is shown in Fig. 1(b). The overall dimensions are 32 mm × 32 mm × 1.973 mm.

III. Results

First, the designed lens was numerically analyzed using the transient solver of CST Microwave Studio™. In order to reduce the computation time, and considering the symmetry of the problem, magnetic and electrical symmetries were imposed on the *yz*- and *xz*-planes, respectively; see coordinate axis in Fig. 1. A vertically polarized wave (E_y) was used to illuminate the lens from its flat side. In Fig. 2 (a, b) you can see numerical results for the field distribution in (a) the *xz*-plane and (b) the *yz*-plane at slightly different from the design frequency f_{sim} = 98 GHz, where the maximum power at the focal spot is detected. This shift can be explained by an additional protective layer in the final prototype which was not taken into account in the design. The characteristics of the focus in each of the planes are: focal length $FL = 1.94$ mm ($0.64\lambda_0$), depth of focus $DF = 1.97$ mm ($0.65\lambda_0$), and $FWHM_1 = 1.39$ mm ($0.46\lambda_0$) and $FWHM_2 = 1.58$ mm ($0.52\lambda_0$) for *xz*- and *yz*-planes, respectively.

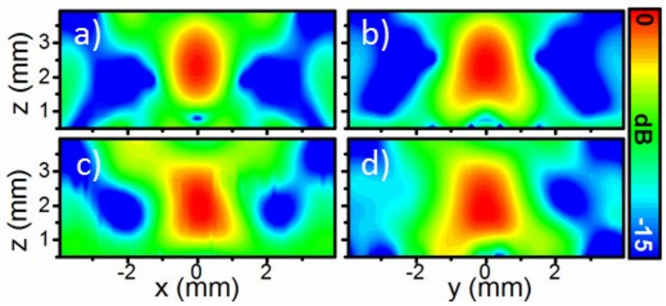

Fig.2. Normalized field distribution in *xz*-plane (a,c) and *yz*-plane (b,d) for numerical (top) and experimental (below) results.

Next, the lens was experimentally analyzed using the vector network analyzer ABmm VNA [18]. The distribution of the experimental electric field amplitude at frequency f_{exp} = 96.45 GHz (where the maximum focus was detected) can be seen in Fig. 2 (c, d), where (c) shows the *xz*-plane and (d) the *yz*-plane. The parameters of focus are: focal length $FL = 1.9$ mm ($0.64\lambda_0$), depth of focus $DF = 2$ mm ($0.64\lambda_0$) and $FWHM_1$ = 1.44 mm ($0.46\lambda_0$) and $FWHM_2 = 1.73$ mm ($0.56\lambda_0$) for *xz*- and *yz*-plane respectively. It is obvious that the numerical and experimental results are in good agreement.

Finally, the performance of the lens at the working frequency was analyzed, for the case when the lens is used to improve the radiation pattern of a low directional antenna. To this end, at the focal point of the metalens a waveguide probe (an open rectangular waveguide with chamfered edges to avoid reflections) was placed, acting as a transmitter. The radiation pattern of metalens-antenna system was captured by a high gain horn antenna. The numerical and experimental radiation patterns are shown in Fig. 3 (a, b) for *E*- (a) and *H*-plane (b) respectively. The disagreement between simulation and experiment for the *E*-plane is noticeable and can be explained by several factors. First, the errors in the measurements, such as displacement of the waveguide probe, can significantly widen the beam. Moreover, since the numerical and experimental focal maxima appear at different frequencies therefore the experimental and simulation radiation patterns are also obtained for different frequencies f_{sim} and f_{exp}, which results in the wider beamwidth [17].

High gain of 10.64 dB was measured at frequency f_{exp} = 96.45 GHz while the gain predicted by the simulation was 14.6 dB. The disagreement may be explained by dielectric losses and air gap between the dielectric plates.

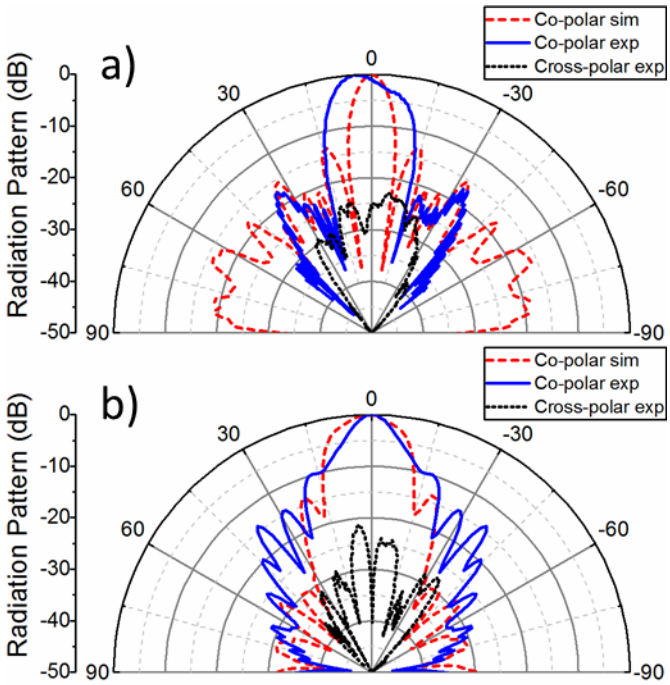

Fig. 3. Normalized radiation pattern for *E*-plane (a) and *H*-plane (b), measured with waveguide probe.

Additional measurements were performed for the radiation patterns in order to confirm the performance of the metalens-antenna. To this end the waveguide probe at the focal position was replaced by a high gain horn antenna. Due to the changes in the setup the focal position with maximum power has shifted slightly from $FL_{probe} = 1.9$ mm ($0.64\lambda_0$) to $FL_{horn} = 2.3$ mm ($0.64\lambda_0$) with the frequency f_{horn} = 98.6 GHz, which is closer to the f_{sim}. The normalized numerical and experimental radiation patterns for this setup are shown in Fig. 4(a,b) for *E*-(a) and *H*-plane (b) respectively. The results (measurement vs. simulation) are in better agreement than for the case when the waveguide probe is used. We believe that this is because the configuration is significantly more robust to misalignment and we are investigating this issue under this assumption.

Analogously to the case with the waveguide probe, the high gain of 18.2 dB was measured at frequency f_{horn} = 98.6 GHz. The higher gain can be explained by closer frequencies and the higher illumination efficiency when the horn antenna is used as source.

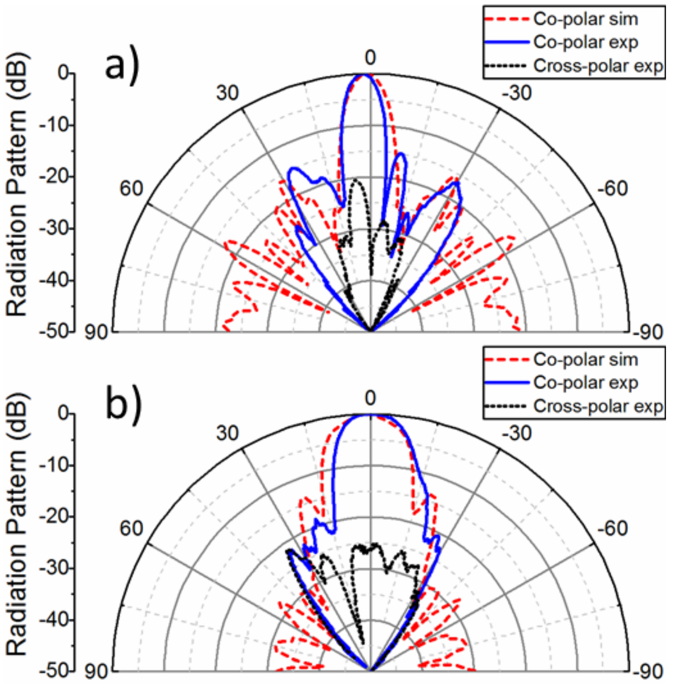

Fig. 4. Normalized radiation pattern for *E*-plane (a) and *H*-plane (b), measured with horn antenna.

IV. CONCLUSIONS

In conclusion, the Soret lens based on a fishnet metamaterial and working in millimeter waves has been designed, fabricated and measured. A good agreement between the simulation and experimental results has been shown. The proposed design, which is low-profile, relatively inexpensive and easy to manufacture, demonstrates a solution to improve the radiation characteristics of a Soret fishnet metalens-antenna. Such compact devices may find applications in wireless or radar systems.

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