Modeling and Analysis of Metalens Characteristics: Simulation Results

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***Abstract*—The paper presents the results of modeling linear metalenses based on split-ring resonators and double Möbius strips of different diameters using Ansys HFSS software. The study examined the distribution of the magnetic field (H-field) and analyzed the efficiency of the metalenses in different frequency ranges with variable focal distances. It was found that the investigated metalenses can act as either focusing or dispersing, depending on the radiation frequency and the distance to the lens surface. It was shown that at a frequency of 3.9 GHz, the Möbius strips provide a focal distance four times shorter (10 mm) compared to classical meta-elements in the form of split-ring resonators (40 mm). This effect can lead to a significant reduction in the size of microwave bridges and splitters. The obtained results demonstrate the promise of using the proposed metalens designs in the development of compact and highly efficient radio systems.**

Keywords—metalens, split-ring resonator, double Möbius strips, H-field

I. Introduction

The development of information and communication technologies requires the creation of increasingly compact and efficient radio systems. One of the promising directions in this field is the use of metamaterials, which allow the design of elements with unique electromagnetic properties. A characteristic example of this is metalenses, which represent the latest radio frequency elements that use metamaterials to control electromagnetic waves with high precision. Their unique properties enable the creation of compact radio frequency systems with the ability to control the phase, amplitude, and polarization of signals.

In particular, in work [1], a topology of magnetic metasurface lenses is proposed to improve the performance of Resonant Wireless Power Transfer (RWPT) systems. The authors optimized three subwavelength spiral meta-elements of different sizes to achieve negative magnetic permeability at a given frequency. Each of the three types of meta-elements provided a different refractive index. Next, the configuration of the elements for forming a circular metalens, which leads to the focusing of the magnetic field in a given direction, was determined. Simulation and experimental measurement results showed that the gradient of the refractive index created by the radial arrangement of the meta-elements leads to the manipulation of the magnetic field similar to optical lenses. When testing the performance of focusing and dispersing metalens topologies in the RWPT system, an improvement in the RWPT channel's performance in terms of efficiency and transmission range was demonstrated. The design method proposed in [1] can be generalized to various options of meta-elements and metalens configurations.

This paper, in contrast to [1], is devoted to the study of the properties of linear metalens based on ring-cut resonators and double Möbius strips. The simulation was carried out using Ansys HFSS software [2], which is one of the leading tools for the analysis of high-frequency electromagnetic fields. The purpose of the study was to determine the distribution of the magnetic field (H-field) and analyze the effectiveness of metal lenses in different frequency ranges with a variable focal length.

II. The Main Results of the Study

A. Metalens based on SRRs

The process of constructive synthesis of a new linear metalens based on split-ring resonators (SRR) relied on the selection of geometric dimensions of its meta-elements. The relationships for spiral elements proposed in [1] were taken as the basis. At the same time, similarly to the approach in [1], three split-ring resonators of different diameters were used. The key parameter was the outer diameter of the largest split-ring resonator, which we will designate as Circle SRR L1. This SRR determines the resonant frequency of the metalens. An example of its geometric relationships is shown in Fig. 1, where the following values of the corresponding dimensions were selected for modeling in Ansys HFSS: inner radius Ring_R = 4.435 mm, ring width Ring_W = 1.5 mm, gap between the rings Ring_D = 0.5 mm, and the width of the split in the rings Ring_G = 1 mm.

The general view of the set of specified SRRs as part of a linear metalens is shown in Fig. 2.

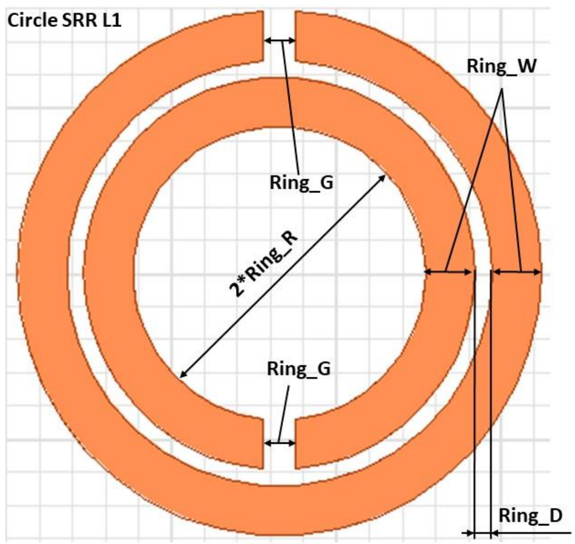

Fig. 1. Geometric relationships of the SRR L1.

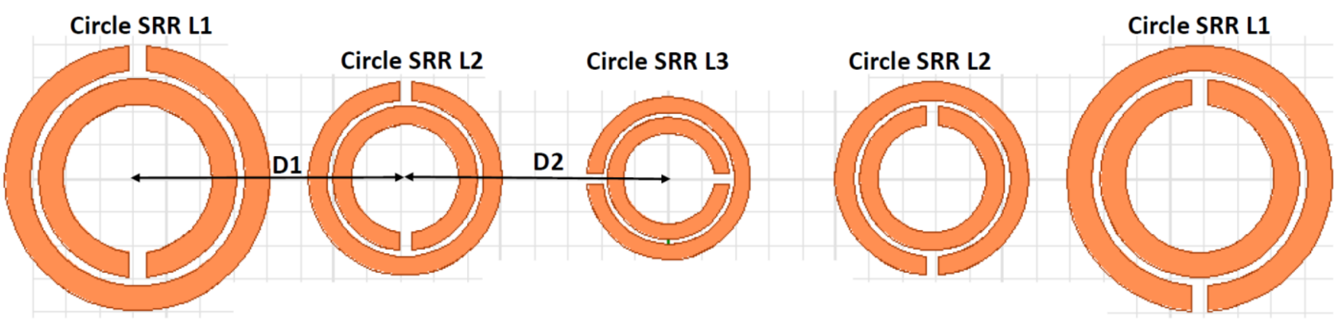

Fig. 2. The topology of a metalens.

The dimensions of the two other SRRs (SRR L2, SRR L3) of the proposed metalens were determined according to the formulas Size SRR L2 = 0.72904852 · Size SRR L1, Size SRR L3 = 0.6131065 · Size SRR L1.

The Fig. 2 illustrates one of the investigated options for the orientation of the cuts in SRR, while the distances D1 and D2 between the centers of the rings have the following values: D1 = 15.9952 mm, D2 = 15.74 mm. The studies were conducted for the simplest case, when all SRRs are located in the air, and any elements fixing them are absent.

In addition to the specified geometric relationships for modeling in HFSS, the size of the air box and the distance from the top surface of the metalens to the wave port play an important role. In the case under consideration, the distance from the feed port to the surface of the metalens was 80 mm, while the central axis of symmetry of the metalens was 120 mm away from the lower edge of the air box.

At the first stage, the frequency dependence of the refractive index n of the metalens was analyzed to determine the frequency ranges in which its negative value occurs. The calculation method used at the Ansys HFSS macros level, as presented in [3 - 5], was employed for this purpose:

$$n = \frac{1}{k_0 d} \arccos\left[\frac{1}{2S_{21}}\left(1 - S_{11}^2 - S_{21}^2\right)\right] \quad , \tag{1}$$

$$z = \sqrt{\frac{\left(1 + S_{11}\right)^2 - S_{21}^2}{\left(1 - S_{11}\right)^2 - S_{21}^2}} \quad , \tag{2}$$

where $k_0 = 2\pi f/c$, c is the speed of light, f is the frequency, d is the linear size of the metamaterial unit cell, S_{xy} are the S-parameters of the dispersion matrix.

The obtained values of the refractive index n and wave impedance z were further used to calculate the frequency dependencies of the dielectric permittivity ε_r and magnetic permeability μ of the metalens. The corresponding dependencies are presented in the graphs in Fig. 3:

$$\varepsilon_r = n / z \text{ и } \mu = n \cdot z. \tag{3}$$

The frequency intervals where the real components of both these parameters take on negative values ($\mathrm{Re}(\varepsilon_r) < 0$ and $\mathrm{Re}(\mu) < 0$) correspond to the zones where the metalens exhibits double-negative (DNG) metamaterial properties [6, 7].

As can be seen in Fig. 3, the widest zone of DNG properties for the metalens occurs at frequencies from 0.55 to 1.25 GHz.

For a quantitative assessment of the width of this zone for metalenses and to compare it with other similar DNG regions, the concept of relative DNG bandwidth can be used. For the boundary frequencies f_1 and f_2, within which the condition $\mathrm{Re}(\varepsilon r) < 0$ and $\mathrm{Re}(\mu) < 0$ is satisfied, the relative bandwidth is calculated using the well-known expression [8]:

$$\delta f_{DNG} = \frac{2|\Delta f|}{f_1 + f_2} \quad , \tag{4}$$

where $\Delta f = f_2 - f_1$.

Accordingly, for the frequency interval of 0.55–1.25 GHz, the specified relative bandwidth δf_{DNG} amounts to 77.78 %.

Among other DNG frequency bands of interest within the scope of the study, a relatively narrow frequency interval of 3.76–3.94 GHz should be noted, for which $\delta f_{DNG} = 4.68$ %.

After determining the frequency intervals within which the metalens functions as a DNG metamaterial, an analysis of the magnetic field (H Field) distribution within the metalens structure and at various distances from its surface was conducted. The main focus was on identifying spatial zones where the metalens operates as a focusing element.

A frequency of 1 GHz, which lies within the first of the mentioned DNG frequency intervals, was chosen as the operating frequency for the feed port. Fig. 4 presents one of the many results of modeling in the Ansys HFSS environment, showing the distribution of the magnetic component (H Field) of the electromagnetic field [9] after it passes through a metalens composed of several SRRs.

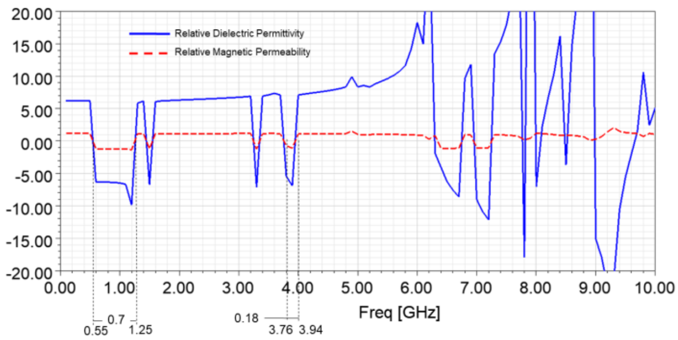

Fig. 3. The frequency dependencies of $\mathrm{Re}(\varepsilon_r)$ and $\mathrm{Re}(\mu)$ of the investigated metalens.

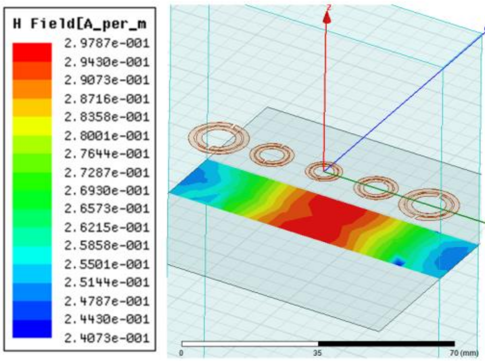

Fig. 4. The distribution of the magnetic field magnitude parallel to the surface of the metalens at a distance of 15 mm.

The Fig. 4 shows the distribution of the magnetic field magnitude parallel to the surface of the metalens at a distance of 15 mm from its center, which is illustrated by a color scale, where different colors correspond to different field levels.

According to the modeling, the magnetic field is concentrated in the central area of the horizontal projection of the ruler formed by these rings, creating characteristic zones of high and low field intensity. This indicates effective control of the wave fronts of electromagnetic radiation passing through the metalens. Overall, the obtained results suggest that such a structure is capable of effectively focusing electromagnetic waves, which could be useful for applications in microwave technologies and other fields where precise control of the distribution of electromagnetic fields is required.

Notably, as the distance from the metalens increases, the focusing mode with a maximum field in the central area of its projection changes to a scattering mode, where the central area corresponds to a zone of minimal field magnitude. An illustration of one such case is shown in Fig. 5. In this case, the distance from the lens surface was 80 mm.

Based on the modeling results of the metalens formed using SRR at a radiation frequency of 1 GHz, the following intermediate conclusions can be made:

1. The focusing mode of the considered metalens is provided in the frequency range of 550–1250 MHz. This range corresponds to the DNG region obtained during the investigation of the frequency dependencies of dielectric permittivity and magnetic permeability.

2. The focusing distance of the field depends on the frequency. A higher frequency corresponds to a shorter focal distance.

3. At certain radiation frequencies, such as 1 GHz, the same lens can be both converging and diverging depending on the distance from the lens surface.

4. On the other hand, at a fixed distance from the layer of rings, to switch the lens from focusing mode to scattering mode, it is necessary to vary the radiation frequency.

With the increase in radiation frequency from 1 GHz to 3.9 GHz, corresponding to another DNG property zone of the metalens, a transformation from a single-focus lens to a dual-focus lens was observed. Fig. 6 illustrates the corresponding situation, which occurred at a distance of 40 mm from the center of the metalens.

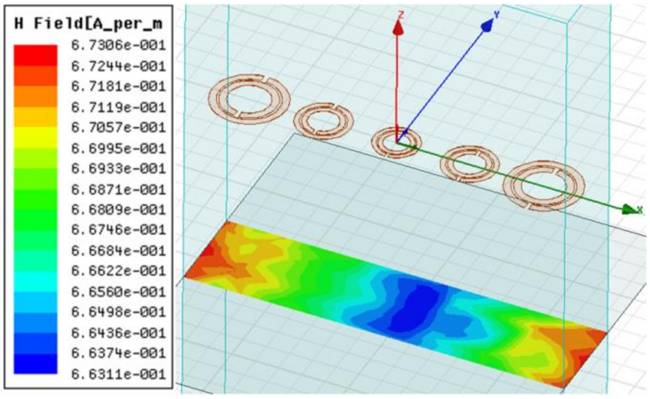

Fig. 5. The distribution of the magnetic field magnitude parallel to the surface of the metalens at a distance of 80 mm.

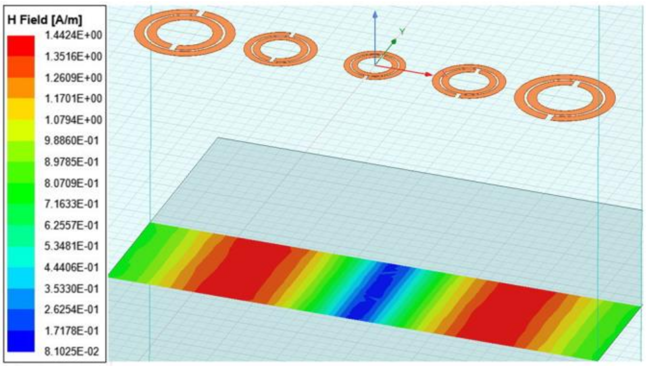

Fig. 6. The distribution of the magnetic field magnitude parallel to the surface of the metalens at a distance of 40 mm for 3.9 GHz.

This effect indicates the potential for developing compact microwave bridges and splitters based on the studied metalens design.

B. Metalens based on double Meobius strip

In addition to the research on the metalens based on SRR-elements, a new design of the metalens based on meta-elements in the form of double Möbius strips with local cuts (Fig. 7) was also analyzed. This version of the meta-elements was described in detail in [10].

To maintain continuity with the metalens based on SRR elements, the sizes of the radii of the outer cylinders, into which the double Möbius strips are inscribed, were chosen to be consistent with their geometric parameters. In particular, the radius of the described cylinder for the largest Möbius strip is 7.935 mm, for the medium one is 5.785 mm, and for the smallest one is 4.865 mm. At the same time, the distances D1, D2 between the centers of the Möbius strips (Fig. 7) were kept the same as for the metalens with SRRs.

It should be noted that, due to the more efficient interaction of the double Möbius strip with the magnetic component of the electromagnetic field, the new metalens forms a higher quality pattern of its distribution. In particular, at a frequency of 800 MHz, the Möbius metalens demonstrates a magnetic field focusing effect at a distance of 18 mm (Fig. 8).

Just like with the SRR-metalens, the Möbius strip also shows the ability to concentrate or disperse the magnetic field, depending on the radiation frequency. Fig. 9 presents the dispersing effect at a frequency of 1.2 GHz at a distance of 11 mm from the center of the lens.

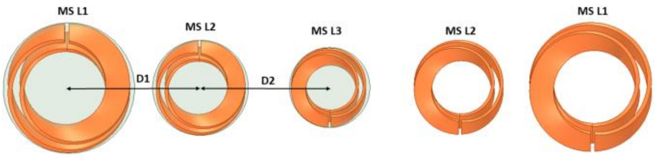

Fig. 7. Geometric relationships for the Möbius strip-based metalens.

When transitioning to the radiation frequency of 3.9 GHz, the metalens with Möbius strips without cuts also provides two separate foci, with the focusing zone observed at distances from 10 mm to 55 mm (Fig. 10). With further distance from the lens, up to 62–90 mm, a dispersing mode occurs.

Thus, when modeling a flat bifocal lens in the form of a line of meta-elements, it was found that at a frequency of 3.9 GHz, Möbius strips provide a focal length that is 4 times shorter (10 mm) compared to classical meta-elements in the form of split-ring resonators (40 mm). This potentially allows for a fourfold reduction in the size of microwave bridges and couplers based on them.

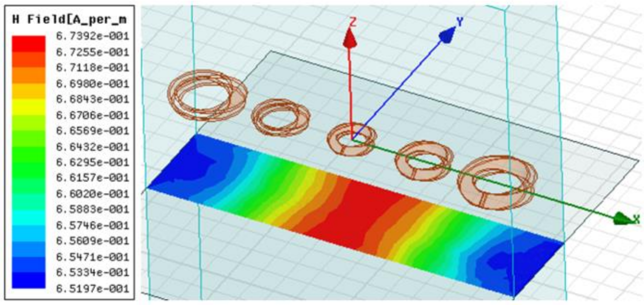

Fig. 8. The distribution of the magnetic field magnitude parallel to the surface of the Möbius metalens at a distance of 18 mm for 800 MHz.

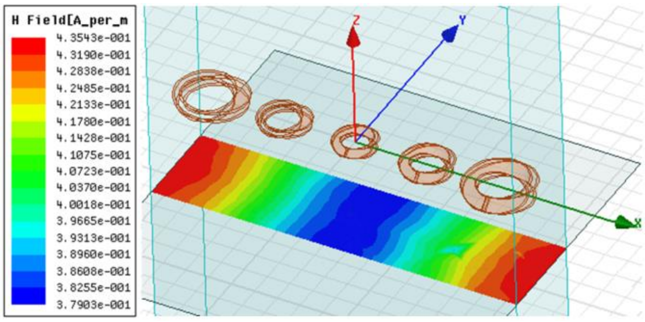

Fig. 9. The distribution of the magnetic field magnitude parallel to the surface of the Möbius metalens at a distance of 11 mm for 1.2 GHz.

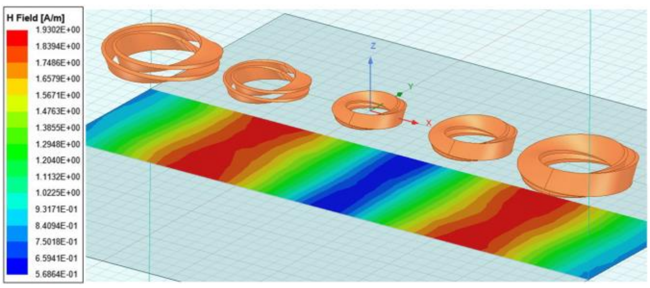

Fig. 10. The distribution of the magnetic field magnitude parallel to the surface of the metalens at a distance of 10 mm for 3.9 GHz.

III. CONCLUSION

During the conducted modeling and analysis of the characteristics of metalenses based on split-ring resonators (SRR) and double Möbius strips, their features regarding the focusing and scattering of electromagnetic waves were identified. In particular, the frequency ranges in which the metalenses exhibit the properties of double-negative metamaterials were studied, as well as the conditions for the transition from focusing to scattering mode were determined. The obtained results confirm the feasibility of using such metalenses to create compact, highly efficient radio-frequency systems capable of controlling the amplitude, phase, and polarization of signals. This opens up new opportunities for the development of microwave bridges, dividers, and other radio-electronic components, including intelligent reflective surfaces [11]. Of particular interest is the possibility of reducing the size of devices based on metalenses with double Möbius strips compared to classical solutions. The achieved gain in reducing the focal length creates prerequisites for further research to maximize it with the goal of implementing metalens technologies in practice.

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