Compact Mikaelian Lens Design Using Metasurface Structure

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***Abstract* — Research on metasurfaces has been widespread recently because it can generate arbitrary permittivity and permeability which can be used to synthesize different types of flat surface-wave based lens for engineering applications such as nanofocusing, sensing, detection, and spectral imaging. In this paper, we use the periodic array of square metallic patches etched over a thin grounded dielectric sheet to synthesize a flat Mikaelian lens of rectangular shape that is narrower than contemporary circularly-shaped lens. The design is validated by simulation results, which demonstrate the effectiveness of the focusing.**

***Index Terms* —metasurface, Mikaelian lens, focusing, gradient index metamaterials**

1. Introduction

In recent years, there has been growing interest in the metasurface lens, which is constructed as a planar array of subwavelength-sized unit cells typically composed of thin dielectric substrates with metallic inclusions or etchings, the properties of which vary across the surface such that each localized region is exhibitive of a refractive index. Several different types of lenses can be synthesized in this manner, such as the Luneburg lens [1], Maxwell's fisheye lens [2], Eaton lens [3], among others. Albeit the different functions of spatial coordinates across the surface that define the various distributions of the refractive index, an often-shared feature amongst these lenses is the circular nature of their shapes. However, unlike these aforementioned lenses as well as most other types, the Mikaelian lens [4], [5] is instead rectangular in shape; and importantly, while one of its two opposite sides parallel with the impinging planar wavefront dictates the width across which the input power is prevalent, the other pair perpendicular to it is arbitrary and may be prescribed as any value at the fancy of the designer, thereby providing the possibility of squashing the lens along the direction perpendicular to the incident planar wavefront. As such, while the unnecessary space usage of conventional circularly-shaped lens along the direction perpendicular to the arriving planar wavefront is inevitable, this space wastage can be averted by the rectangular Mikaelian lens when designed with a high aspect ratio of the length to its breadth. The visual portrayal of the thinness of the Mikaelian metasurface lens as compared to its Luneburg counterpart is shown in Fig. 1. Due to this feature, not only can low-profiled planar flat surface-wave lenses be designed, those that are now narrow along one dimension in the plane of the lens surface can also be achieved by the Mikaelian lens.

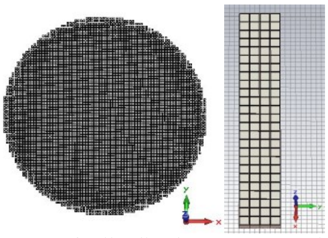


Fig. 1. Elongated nature of Mikaelian lens as compared to Luneburg lens

2. Characteristics of Mikaelian lens

In 1951 A. L Mikaelian devised a self-focusing cylindrical medium, thereafter known as Mikaelian lens. Such a lens comprises a dielectric waveguide whose refractive index decreases from the center to the rim as the inverse hyperbolic cosine according to the following equation (1) which was proposed in [6]

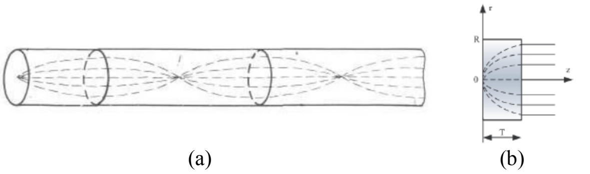
$$n(\mathrm{r}) = \frac{n(0)}{\cosh(\frac{1}{2}\pi \mathrm{r})} \tag{1}$$

where r is the radius of the cylinder and $n(0)$ is the refractive index along the cylinder axis. A section of a self-focusing waveguide is shown in Fig. 2(a).

In the pursuit of compact size, the two-dimensional Mikaelian lens was proposed in [7] as shown in Fig. 2(b), which depicts a rectangular lens of thickness T and radius R. Its refractive index varies with the radial distance r according to the following equation (2)

$$n(r) = \frac{n(0)}{\cosh(\frac{\pi}{2T}r)}, \quad 0 \le r \le R \tag{2}$$

where r is the radius of the lens and $n(0)$ is the refractive index along the cylinder axis.



(a) (b)

Fig. 2(a). Self-focusing cylindrical waveguide (Mikaelian lens)
Fig. 2(b). Mikaelian lens causes planar wavefront impingent on one side of lens to converge towards a point on opposite side, and vice-versa.

3. Design method

The dispersion diagram is a convenient portal through which the surface wavenumber may be conveyed graphically. Here, the square-shaped unit cell is chosen to be made up of a likewise square metallic patch printed over the surface of a metal-grounded dielectric substrate, as shown in Fig. 3. The dispersion diagram in Fig. 4 is obtained by adjusting different patch sizes *a*, the surface wavenumber can be modulated to suit the range of refractive index values required in the synthesis of the Mikaelian lens.

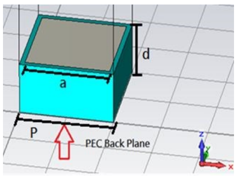


Fig. 3. Square patch structure

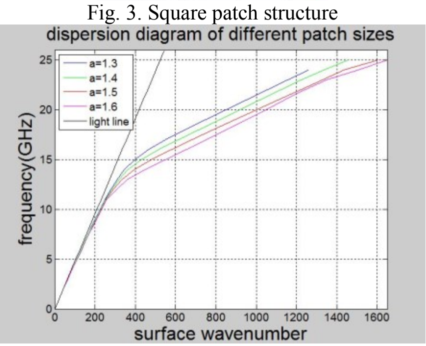


Fig. 4. Dispersion diagram of array of square metallic patches printed on grounded substrate for different patch sizes

In order to achieve thin lens, we have to increase the ratio between the length and width, i.e. the aspect ratio. For convenience, we define the aspect ratio by a parameter S and stated by:

$$S = \frac{\text{length of lens}}{\text{width of lens}} \quad .$$

The lens of S = 1.6 with dimensions 80 × 128 mm^2 is designed, as shown in Fig. 5. As seen, the continuous distribution over *r* of the refractive index is discretized into 17 different refractive indices, each of which is synthesized by adjusting the square patch.

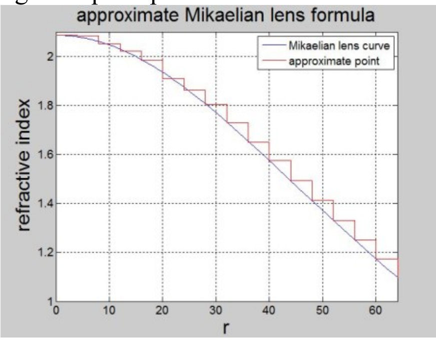


Fig. 5. 17 different refractive indexes in each lens

4. Simulation results

The thin lens is synthesized for focusing at a prescribed frequency of 13.9 GHz. The simulation results are shown in Figs. 6(a), which presents the *z*-component of the electric field at z = 1.01. The incident wave is a plane wave which enters from the left side of the lens. The bending of the energy flow traces and the resultant focusing onto the midpoint on the output side of the lens are evident. In addition, the side view of the distribution of the E_z component above the lens surface as given in Fig. 6(b) shows that the energy of the surface wave is well-confined to the surface and that the field is indeed strong at the focal point on the right output side of the lens. To sum up, all simulation results display the good focusing effect and compressibility of the Mikaelian lens.

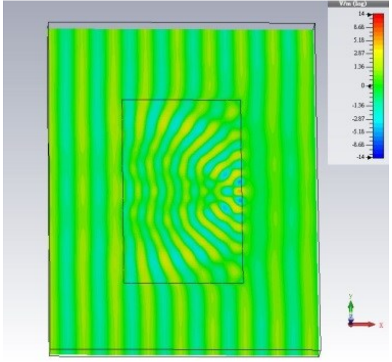


Fig. 6(a) E_z on surface at z = 1.01 and

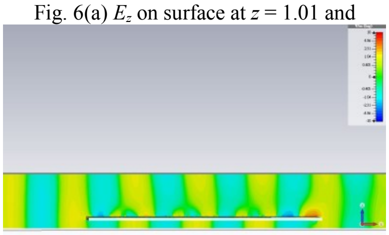


Fig. 6(b) side view of E_z component above lens surface; at y = 0.

5. Conclusion

In this paper, the Mikaelian lens is synthesized by a periodic array of square patches etched on a grounded substrate. The surface-wave dispersion diagrams dictate the sets of parameters that pertain to various refractive indices, which are then used to discretely sample the governing formula for the Mikaelian lens. In addition, the dispersion diagram allows one to select design parameters that correspond to points that are deep in the slow wave region so as to attain strong surface confinement. A high value of the parameter S, defined as the ratio of the length to width of the lens, has been designed to achieve a lens that is vertically thin as well as laterally narrow.

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