Design and Analysis of a Slitted Waveguide Fed Mikaelian Lens Antenna

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***Abstract*—A near field focusing (NFF) planar gradient index (Mikaelian) lens antenna fed by a slitted waveguide is introduced. The structure is composed of a parallelepiped Mikaelian lens superstrate positioned on top of a one-dimensional continuous source provided by a rectangular waveguide leaky-wave antenna (LWA). The design of the lens superstrate by ray tracing is discussed and the focusing performance of the combined feed and lens is then verified by full-wave simulation.**

Keywords— Leaky-wave antennas (LWAs), slitted waveguide, gradient index lens antenna, near field focusing (NFF), additive manufacturing (AM), 3-D printing

I. Introduction

Owing to their compact form factor and capability of focusing in the near field by appropriate tapering of the phase constant (β) of the travelling wave propagating within them, rectangular waveguide LWAs capable of NFF have attracted a significant amount of research interest [1] - [7] and have found in applications in areas such as imaging [8], [9]. However, owing to the requirement of tapering β, a challenge posed by these structures from a design and fabrication complexity point of view is that the structure of the waveguide supporting the travelling wave needs to be mechanically modified in some way to accomplish the desired β taper. As such, this leads to potentially expensive and time-consuming fabrication pipelines.

To address this issue, the feed and the phase tapering structures are separated in the structure introduced in this work. This is accomplished by moving the β taper from the waveguide to a lens superstrate and in this manner, the fabrication complexity and cost is significantly reduced as the lens can be rapidly, sustainably and cheaply manufactured by 3D printing methods and easily changed should the application requirements change. This kind of flexibility is not available in the contemporary NFF LWA designs as the mechanical waveguide taper cannot be modified after fabrication and an entirely new structure needs to be fabricated if the focusing performance needs to be changed. The Mikaelian lens [10] is used as the superstrate because of its planar physical profile which allows easy integration with the slitted waveguide. The design of the antenna structure is discussed in Section II and verification by full-wave simulation is presented in Section III.

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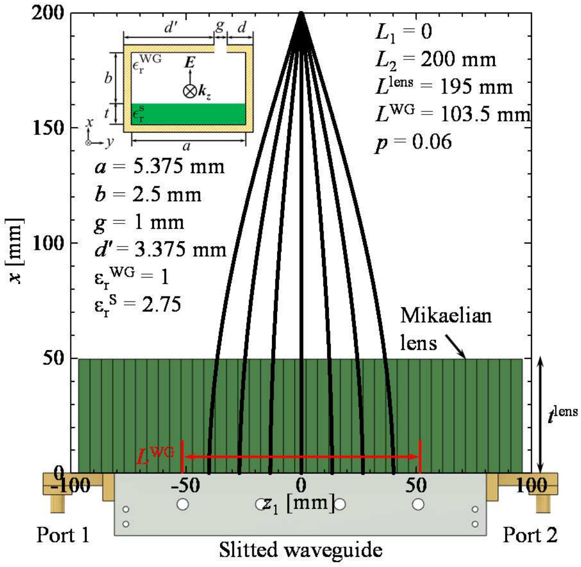

Fig. 1. Proposed lens antenna topology and ray trajectory through the non-generalized Mikaelian lens with t^{lens} = 50 mm. Inset shows the transverse geometry of the slitted waveguide.

II. Design of the Slitted Waveguide Fed Mikaelian Lens Antenna

The length of the longitudinal slit introduced to the broad wall of the slitted corrugated waveguide [11] used to feed the Mikaelian lens was first decided upon as L^{WG} = 103.5 mm for manufacturing convenience. Seeing as the slit is introduced to the broadwall of the waveguide, it is positioned at an offset from the center to allow radiation from the waveguide (See inset, Fig. 1) because at the center the electric current densities along the internal walls of the waveguide are nulled owing to the opposing symmetry of the current vectors at this position and therefore the silt would not be cutting across said densities which would mean no magnetic current is induced within the slit resulting in no radiation. This kind of waveguide was settled upon as it would allow radiation at broadside which is not typically possible from uniform leaky-wave antennas.

At the selected value of L^{WG}, both the values d' = 3.375 mm and g = 1 mm were selected to ensure an attenuation constant

$$\alpha = \frac{-\ln(1-\eta_{rad})}{2L^{WG}} \tag{1}$$

that would allow a radiation efficiency η_{rad} = 0.9 at the frequency we wish to design the proposed structure at which in this case is 28 GHz. The values of these parameters were settled upon by full-wave simulations where α was extracted for different values of d' and g and was found to be

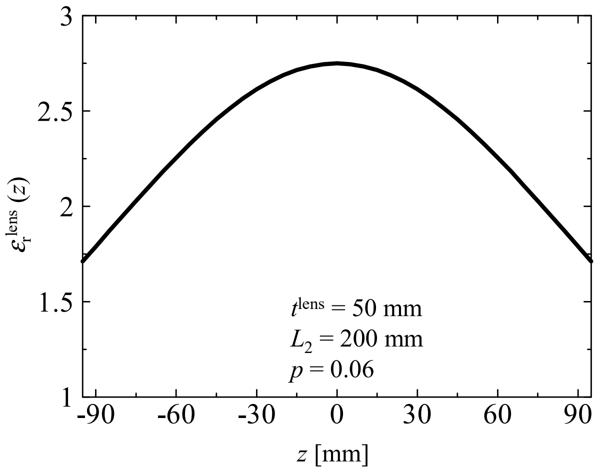

Fig. 2. Relative permittivity profile of the Mikaelian lens superstrate.

$\alpha = 11.1236$ Np/m at the set parameters which coincides with the result of (1). The dielectric material used to fill the corrugation $\varepsilon_r^S = 2.75$ along with the periodicity and width of the corrugations which were set as 1.5 mm and 1.175 mm were selected to enable broadside radiation from the slitted waveguide at 28 GHz.

With the slitted waveguide design completed, the next step was the design of the Mikaelian lens superstrate. As the slitted waveguide provides a continuous line source to the lens, it would present as a plane wave to the surface of the lens in contact with the waveguide. Further, we also wish to achieve focusing at some distance L_2 from the surface of the lens at the opposite end. As such, the lens parameters should be selected such that the ray trajectory through the lens exhibits these conditions. To rapidly perform the parametric study of the lens, the following ray matrix was used [12], [13]

$$\begin{bmatrix} z_2 \\ \theta_2 \end{bmatrix} = \begin{bmatrix} 1 & L_2 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ 0 & \dfrac{n_2(z_{\text{in}})}{n_1} \end{bmatrix} \begin{bmatrix} \cos gz & \dfrac{1}{n_1 g}\sin gz \\ -n_1 g \sin gz & \cos gz \end{bmatrix} \cdot \begin{bmatrix} 1 & 0 \\ 0 & \dfrac{n_1}{n_2(z_{\text{out}})} \end{bmatrix} \begin{bmatrix} 1 & L_1 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} z_1 \\ \theta_1 \end{bmatrix} \quad (2)$$

in which $g = 2\pi p/t^{\text{lens}}$, $n_2(z_{\text{in}})$ and $n_2(z_{\text{out}})$ are the refractive indices at the interface with the slitted waveguide and at the opposite end respectively and $n_1 = 1$. The pitch of the lens is represented by p, θ_1 is angle of incidence of the ray to the lens, θ_2 is the exit angle from the lens, L_1 is the distance from the source to the lens.

To satisfy the conditions imposed on the desired ray trajectory through the lens with $L_2 = 200$ mm and $L_1 = 0$ (lens sits directly on top of the slitted waveguide), the lens design parameters were set as $p = 0.06$ and $t^{\text{lens}} = 50$ mm. With these parameters and the refractive index profile of the Mikaelian lens given as [1]

$$n_2(z) = \frac{n_2(0)}{\cosh \dfrac{2\pi pz}{t^{\text{lens}}}}, \quad (3)$$

the ray trajectory through the lens was calculated and is presented in Fig. 1 for a lens with length $L^{\text{lens}} = 195$ mm. The

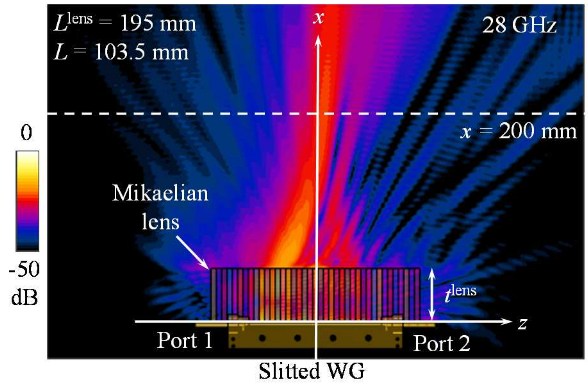

Fig. 3. Simulated 2-D electric field distribution at 28 GHz.

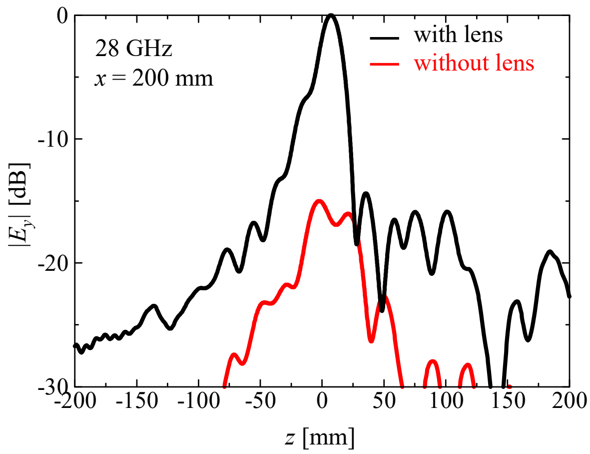

Fig. 4. Normalized electric field distribution extracted at $x = 200$ mm.

lens was designed to be longer than the slitted waveguide feed to allow it to be easily attached to the waveguide and to also prevent illumination of the ends of the lens by the longitudinal slit which may negatively impact the focusing performance of the combined structure. The relative permittivity profile of the lens $\varepsilon_r^{\text{lens}}(z)$ was then derived from (3) and is presented in Fig. 2 with the step size $\Delta z = 5$ mm.

A phenomenon observed from Fig. 1 is that the predicted L_2 from (2) is at 200 mm instead of the expected 250 mm. This is theorized to be caused by the L^{lens} being longer than L^{WG} which means that not the entire length of the lens is illuminated by the slitted waveguide. A quarter wave matching layer was also included at the bottom of the dielectric lens (the section in contact with the slitted waveguide) with a thickness of $\lambda_g/4 \approx 1.6$ mm designed at 28 GHz using $\varepsilon_r^{\text{lens}}$ $(z = 0) = 2.75$ to minimize reflections between the dielectric lens superstrate and the air-filled region within the waveguide and consequently optimize upon the radiation efficiency of the combined structure.

III. Simulation Results and Discussion

The slitted waveguide and lens superstrate with the design parameters finalized in Section II were modelled in full-wave simulation software (FDTD) and calculated at 28 GHz to confirm the result predicted in Fig. 1. The 2D distribution of the y-component of the electric field in the xz-plane was extracted and is plotted in Fig. 3.

From the figure, it can be observed that the radiated field from the slitted waveguide does indeed appear as a plane wave to the lens superstrate. Further, the focusing effect at x = 200 mm predicted by the ray trajectory in Fig. 1 can be observed. To further clarify upon the performance of the structure, the 1D electric field distribution was extracted at x = 200 mm and is compared with the slitted waveguide without the lens superstrate in Fig. 4. From the figure, it is readily apparent that the addition of a lens superstrate has the effect of both increasing the magnitude (by about 15 dB) of the electric field at the focusing position and reducing the full-width at half maximum (FWHM) in addition to significantly suppressing the side lobes compared to the case without the lens, as expected thereby validating the NFF capabilities of the proposed topology.

IV. Conclusion

In this work a NFF focusing antenna structure composed of a slitted waveguide feed and a Mikaelian lens superstrate is introduced. The design of the lens superstrate by ray tracing is discussed and focusing performance of the combined slitted waveguide and lens superstrate was evaluated by full-wave simulation where the focusing effect predicted by ray tracing was observed. Following the promising results achieved, next steps in this work would focus on further clarifying the frequency scanning of the focusing spot in addition to the experimental verification of the concept introduced here.

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