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Efficiency estimation in additive-manufactured geodesic lens antennas using a ray-tracing technique

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Summary

In this work, we use a generalized ray-tracing model to compute the radiation patterns of geodesic lens antennas with non-rotationally symmetric shapes. The radiation efficiency of these lenses can also be computed, which can be affected by the finite conductivity and surface roughness of the metallic plates. To evaluate this model, an elliptically compressed water-drop lens antenna is designed and manufactured in one piece using the laser powder-bed fusion technique.

Geodesic lens antennas have been shown to be a compelling solution for millimetre-wave applications [1]. They are highly efficient since dielectric materials are not used, very robust in manufacture, and can produce multiple beams with high directivity. Furthermore, if the lens is rotationally symmetric, the scan losses are very low, allowing for angular coverages above 120º [2]. Due to the large electrical size of these antennas, optimization of the lens profile can be costly in terms of computational resources and time. Consequently, in [2], a ray-tracing technique was proposed, although this model is limited to rotationally symmetric lenses. The use of a generalized geometrical optics tool was proposed later in [3] to overcome this problem. This tool makes it possible to compute the ray trajectories from the source to the target points (discretization of the lens aperture) in non-rotationally symmetric lenses. These ray trajectories, together with the amplitude distribution calculated with the help of ray tube theory, are used to compute the radiation pattern using Kirchhoff's diffraction formula [3].

In the design process of this type of lens antenna, efficiency is an important aspect. It can be affected by poor conductivity of the metallic plates or by high levels of surface roughness. In this work, we extend the ray-tracing model proposed in [3] to also allow us to estimate the losses in geodesic lenses due to these two factors. The efficiency $\mathrm{Eff}(\phi)$ is computed as the ratio of the electric field calculated without and with losses; that is, $\mathrm{Eff}(\phi) = |E_{\mathrm{tot}}(\phi)/E_{\mathrm{loss}}(\phi)|$. The electric field with losses is calculated as the sum of the contributions of each radiating element (target point) at the aperture of the lens [4]

$$E_{\mathrm{loss}}(\phi) \propto \sum_k E_k(\phi) A_k \frac{\mathrm{e}^{-\mathrm{j}k_0(r_k+\sigma_k)}}{r_k} \left[\hat{\mathbf{n}}_k \cdot \hat{\mathbf{s}}_k + \hat{\mathbf{n}}_k \cdot \hat{\mathbf{r}}_k\right] \mathrm{e}^{-\alpha\sigma_k} \mathrm{d}L_k \tag{1}$$

where $E_k(\phi)$ is the pattern of the element (to avoid back radiation), A_k is the amplitude of the k^{th} radiating element, $\mathbf{r_k} = r_k\hat{\mathbf{r}}_k$ is a vector from the target point to the observation point, σ_k is the length of the ray trajectory, $\hat{\mathbf{n}}_k$ is the normal to the lens edge, $\hat{\mathbf{s}}_k$ is the unit vector along the ray, and $\mathrm{d}L_k$ is the width of the ray tube at the aperture of the lens. E_{tot} is calculated with (1) dismissing the factor $\mathrm{e}^{-\alpha\sigma_k}$; that is, taking the attenuation constant $\alpha = 0$.

In the lossy case, the attenuation constant α is calculated as

$$\alpha = \frac{1}{h_{\mathrm{PPW}}} \sqrt{\frac{\omega\varepsilon_0}{2\sigma}} \left[1 + \frac{2}{\pi} \tan^{-1} 1.4 \left(\frac{\Delta}{\delta_s}\right)^2\right] \tag{2}$$

where h_{PPW} is the height of the parallel plate waveguide that makes up the geodesic lens channel, σ is the conductivity of the material, Δ is the RMS surface roughness, and δ_s is the skin depth [5, 6].

To demonstrate the potential of this technique, an elliptically-compressed water drop lens antenna is designed. The lens is compressed in the x direction with a ratio $a = 0.7$. Thirteen waveguide ports are added to the design to produce fixed beams in the angular range $\pm 60°$. The results of the RT model compare successfully with those of full-wave simulations. The efficiency of the lens can vary from -0.3 dB, with smooth and high-conductivity metallic plates, to -1 dB, with rough and low-conductivity ones. This lens is manufactured using the Laser Powder-Bed Fusion (LPBF) technique with two different metallic materials and roughness. With this technique, it is possible to manufacture an antenna in a single block, avoiding possible misalignment. However, this comes with a cost since the interior of the lens cannot be post-processed to reduce the surface roughness. Therefore, the estimation of losses is of great importance when this manufacturing technique is used. Furthermore, to reduce material waste and have a lightweight prototype, the metallic walls are conformal to the antenna with a thickness of 2 mm. Both prototypes are measured, and good agreement with simulations is achieved.

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