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Generation of Non-Diffractive Bessel Beams for Near-Field Links Applications using Meta-Axicons

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Abstract—This contribution explores the generation of a linearly-polarized Bessel-Gauss beam generated by a fully dielectric metasurface axicon (meta-axicon) illuminated with a Gaussian beam. It is shown that this Bessel launcher generates a beam with similar characteristics as compared to the one that would be radiated by an ideal aperture. A theoretical model is presented, which allows to estimate the wireless power transfer efficiency (WPTE) of a system composed of two identical such launchers. We investigate the radiated fields, both in the direct and spectral domains obtained with the model and full-wave simulations.

Index Terms—Bessel beams, axicon, focusing, wireless transfer efficiency.

I. INTRODUCTION

Bessel beams [1] are a particular type of beam that does not undergo diffraction while propagating and possesses a property known as self-healing [2]. In practical applications, these beams conserve their non-diffractive characteristics in a limited region of the near-field [3], because they are generated using finite apertures and power.

In the optical regime, Bessel beams find many applications such as material processing, optical trapping, and optical coherence tomography [4]. In the microwave regime, they appear as an interesting solution to overcome the free-space path loss [5], as it is mainly caused by electromagnetic spreading of the fields.

Our objective is to investigate Bessel beams generated by a launcher based on an optical component known as an axicon [6], that also finds applications in other frequency ranges [7]. When a beam passes through an axicon, it undergoes a linear phase change with respect to the transverse radial coordinate, creating a focal line along the propagation axis where we observe a Bessel beam. As described in [8], this Bessel beam can be understood as the interference of conical waves generated by the axicon.

To replicate the properties of the axicon, we have chosen a quasi-periodic all-dielectric metasurface comprising pillar structures [9]. The required phase profile of the transmitted fields is achieved by structuring the material at a sub-wavelength scale (radius of the pillar). We identify this system as meta-axicon. The idea is to obtain a low profile, efficient and versatile Bessel beam launcher.

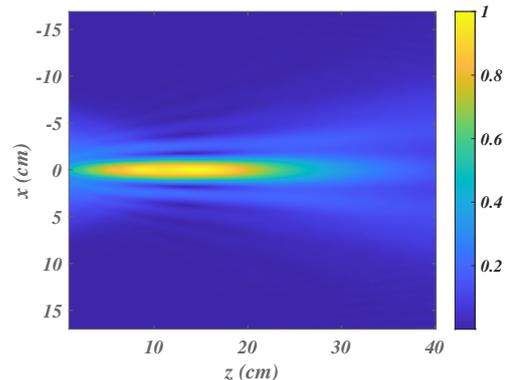


Fig. 1. Normalized $|E_x|$ radiated by the meta-axicon launcher. The aperture radius is 7.5 cm, $\alpha = 13^\circ$ and the system operates at 30 GHz.

In this contribution, we compare an analytical model with the results obtained using the commercial full-wave software CST Studio Suite for the meta-axicon, comparing the radiated fields. In order to analyze the meta-axicon, an ideal Gaussian beam illumination is used in this work. Furthermore, we calculate the wireless power transfer efficiency (WPTE) of two identical meta-axicons.

II. THEORETICAL DEVELOPMENT

In our theoretical model, a linearly polarized Bessel beam is generated by imposing a tangential field distribution over an aperture. This field distribution is characterized by a Gaussian amplitude profile with a linear phase and a polarization along \hat{x} , as described in Eq. 1,

$$\vec{E}_t(x, y, z = 0) = A e^{-((x^2+y^2)/w_0^2)} e^{-j\phi} \hat{x} \quad (1)$$

$$\phi(\rho) = k_0 \rho \sin \alpha \quad (2)$$

where A represents the amplitude factor, $\rho = \sqrt{x^2 + y^2}$, w_0 is the Gaussian waist, k_0 is the operating wavenumber, α is the axicon angle, and the linear phase profile is represented by $\phi(\rho)$.

In Fig. 1, we depict the amplitude of the tangential electric field radiated by the meta-axicon. The radiating aperture is positioned at the origin of the coordinate system, in the plane $z = 0$. It is evident that the field exhibits greater intensity in

the range from $z = 5$ cm to $z = 25$ cm, corresponding to our focal line, where we observe a Bessel-like field pattern.

To calculate the WPTE between two meta-axicons we resort to the concept of electromagnetic reaction [10] between them. The electromagnetic reaction is calculated using the equivalent magnetic distribution over the radiating surfaces, which is derived by applying the equivalence theorem [11] on the tangential electric field over the apertures. The WPTE is then expressed as Eq. 3 [12]:

$$\Gamma = \frac{|\langle a, b \rangle|^2}{16P_a P_b}, \quad (3)$$

where $\langle a, b \rangle$ is the electromagnetic reaction between sources a and b , and $P_{a(b)}$ is the total power radiated by aperture $a(b)$ when $a(b)$ is acting as the emitter. Note that Eq. (3) assumes a simultaneous conjugate matching condition [12]. Furthermore, in this study, the electromagnetic reaction is obtained by considering that the fields radiated by one aperture are computed under the assumption that the physical structure of the other antenna has been removed [13].

III. NUMERICAL ANALYSIS

The simulations were performed for a system operating at 30 GHz, $\lambda = 1$ cm, with an aperture radius of 7.5λ , and an axicon angle $\alpha = 13^\circ$. Schematics of the designed meta-axicon are presented in Fig. 2 and 3, where we show its top and lateral views respectively. The unit-cell of the meta-axicon is a pillar of 15.5 mm height arranged in a square grid of 2.6 mm pitch. Thanks to the use of a high permittivity material ($\epsilon_r = 8.5$), the required aperture phase distribution can be implemented without phase wrappings while keeping a relatively low-profile design. It is worth noting that such phase wrappings would be detrimental to the beam generation as it would locally break the quasi-periodicity of the meta-axicon. Finally, the meta-axicon is illuminated by a gaussian beam whose waist is located on its lower interface, providing a tapered amplitude profile with 10 dB field intensity drop on the edge. The meta-axicon was simulated using a commercial full-wave software, and the results are presented in Figs. 4, 5 and 6.

The amplitude of tangential radiated fields along the z axis, ($x = y = 0$), is shown in Fig. 4. We observe a good agreement between the field generated by the ideal aperture and the one obtained with the meta-axicon. The observed differences are due to the slight imperfections of the meta-axicon aperture field, resulting mainly from its discretized character. Also, we can notice that the field amplitude is maximum at $z = 15$ cm and it reaches 50% of this value at $z = 25$ cm.

The normalized spectrum of the tangential field over the radiating aperture is presented in Fig. 5. Both the theoretical and simulated results exhibit peaks around $k_x/k_0 = 0.20$, and there is a strong agreement between them. At $k_x = 0$, the peak of the simulated field is 8% higher than the theoretical one. Additionally, we observe that the intensity of the ripples in the region $|k_x/k_0| < 0.5$ is higher in the simulated results

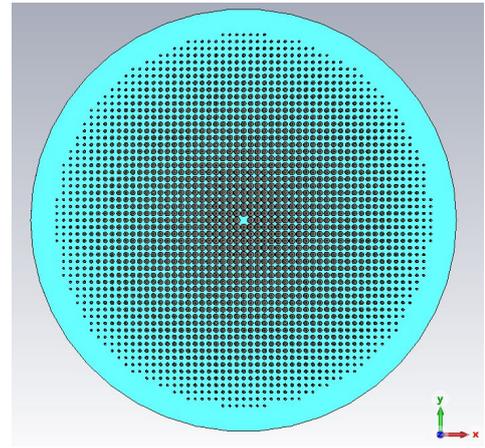


Fig. 2. Top view of the meta-axicon

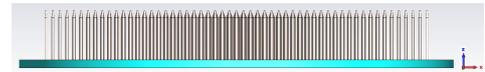


Fig. 3. Lateral view of the meta-axicon

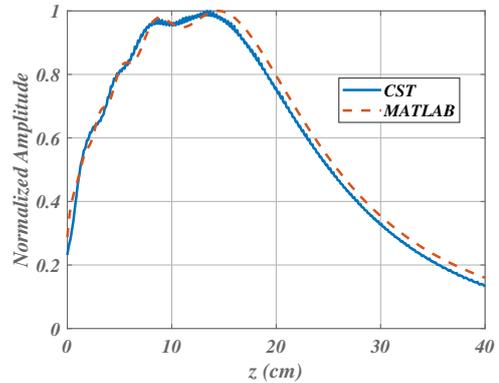


Fig. 4. Normalized amplitude of the x component of the field radiated by the meta-axicon along the z -axis ($x = y = 0$). The aperture radius is 7.5 cm, $\alpha = 13^\circ$ and the system operates at 30 GHz.

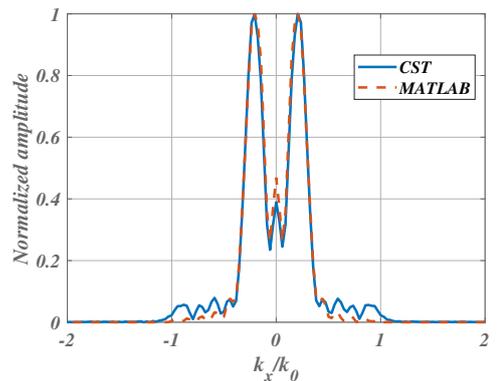


Fig. 5. Normalized spectral component of the tangential electric field over the radiating aperture. The aperture radius is 7.5 cm, $\alpha = 13^\circ$ and the system operates at 30 GHz.

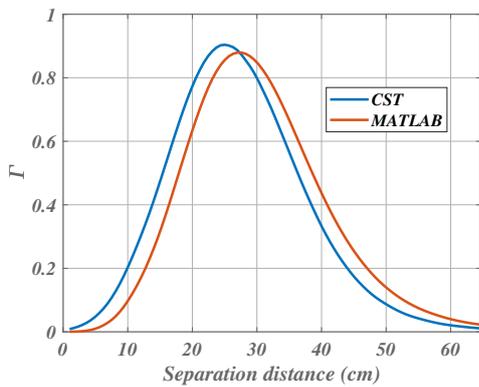


Fig. 6. Wireless power transfer efficiency between two identical meta-axicons. The aperture radius is 7.5 cm, $\alpha = 13^\circ$ and the system operates at 30 GHz.

compared to the theoretical results (maximum difference of 5%).

In Fig. 6, the WLTE which would characterize a link between two meta-axicons facing each other is depicted. This efficiency is computed under the assumption of two identical and axially aligned apertures, referred to as emitter and receiver. To obtain the WLTE of the meta-axicon simulated using full-wave software, the tangential electric fields over the apertures were extracted from the commercial full-wave software, and a MATLAB routine was developed. Again, the theoretical and simulated results demonstrate a strong concordance, and the offset observed between them is due to the slight aperture field differences between the two. We notice a focusing behavior on the WLTE, with a maximum of 90% at $z = 25$ cm for the simulated results, and 88% at $z = 27$ cm for the theoretical results. Furthermore, we observe that the efficiency remains higher than 50% in the region $15 \text{ cm} \leq z \leq 36 \text{ cm}$, which represents 30% of the maximum separation distance considered.

IV. CONCLUSION

In this contribution, a Bessel beam launcher using a fully dielectric metasurface that replicates the properties of an axicon was presented. We compared a theoretical model using an ideal aperture distribution with full-wave simulations of the meta-axicon, investigating the radiated fields and the power transfer efficiency. The agreement between the two shows that the proposed meta-axicon is a good candidate to generate the Bessel beam. Furthermore, we observed a focusing behavior in the power transfer efficiency, reaching a maximum of 90% at $z = 25$ cm, which corresponds to a distance of 25 wavelengths at the operating frequency of 30 GHz.

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