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Self-Healing Analysis of Distorted Weakly-Diffracting Vector Beams

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Abstract—A study of the self-healing property of weakly-diffractive vector beams radiated by a finite circular radiating aperture on an infinite ground plane is presented. The obstacle is a circular metallic disk, which is axially aligned and placed at a certain distance over the radiating aperture. Three different field distributions are considered as excitation for the aperture: the non-diffractive Bessel beam (BB), the Bessel-Gauss beam (BG), and the transverse electromagnetic mode (TEM) of a coaxial cable. The analysis is performed resorting to a spectral Green approach and to a Physical Optics (PO) framework. In all cases, a radially polarized beam is assumed. The results confirm the self-healing property of the non-diffracting beams. They also show the impact on the amplitude of the regenerated field due to the obstacle radius. The chosen approach is validated using a full-wave commercial software.

Index Terms—Bessel, Bessel-Gauss, non-diffractive beams, self-healing, spectral Green's functions.

I. INTRODUCTION

The scalar Bessel beams are exact solutions to the scalar Helmholtz equation [1] described by Bessel functions. These beams do not exhibit diffractive spreading while propagating in free space. Moreover, they also have the ability to self-reconstruct (regenerate) their initial intensity profile after an obstruction [2]. The scalar solution of [1] can be extended to the vectorial case as shown in [3].

However, in practice, the ideal non-diffracting beams are not realizable since they would require infinite power and an unlimited radiating aperture [4] to be able to operate in an infinite range. As an alternative, we can use finite apertures to create weakly-diffracting beams that do not undergo diffraction over a limited range known as non-diffractive range (NDR) [4]. The self-healing propriety is also observed over the NDR. In [5], the researchers have experimentally validated the theory previously developed in [4] using finite radiating apertures to produce weakly-diffracting vector Bessel beams.

The goal of this work is to analyze the self-reconstruction of weakly-diffracting vector Bessel Beams. For this purpose, we study the electromagnetic scattering by a circular disk, composed of a perfect electric conductor (PEC). The fields radiated by the circular aperture are radially polarized and transverse magnetic with respect to the z coordinate (TM _{z}) [7].

Considering the cylindrical coordinate system (ρ, ϕ, z) , the TM _{z} tangential component of the electric field can have the form [4]:

$$E_\rho = A(\rho)J_1(k_\rho\rho)e^{-jk_zz} \quad (1)$$

where $A(\rho)$ is a tapering function to control the amplitude of the transverse field distribution, $k_0^2 = k_\rho^2 + k_z^2$, and k_0 is the free-space propagation constant.

The circular radiating aperture is located over an infinite ground plane, and it is excited with three different radially polarized field distributions: Bessel (BB) and Bessel-Gauss (BG) beams, which are non-diffractive, and the transverse electromagnetic mode (TEM) of a coaxial cable [8]. For the analysis, an equivalent magnetic current distribution is assumed over the radiating aperture [7]. To derive the radiated fields we use a spectral Green function approach [9].

The paper is organized as follows. In section II, the scattering problem is modeled. In section III, we present the simulated results for three obstacles of different sizes. In the last section, we conclude the paper and propose future directions for this work.

II. METHODOLOGY

The system aperture-obstacle is modeled as a scattering problem [7]. In this formulation, the fields are divided in incident, scattered and total fields. The incident fields, \vec{E}^{in} and \vec{H}^{in} , are defined as the fields of the radiating source with the obstacle absent, while the scattered fields, \vec{E}^s and \vec{H}^s , are the fields due to the electric current on the surface of the obstacle with the aperture absent. Finally, the total fields are the ones considering both the obstacle and the radiating aperture: $\vec{E}(\vec{H})^{tot} = \vec{E}(\vec{H})^{in} + \vec{E}(\vec{H})^s$.

To derive the current over the obstacle surface we use a Physical Optics (PO) approach [7]. As presented in [10] the PO delivers good results only when the effects of multiple scattering in the system are negligible and the radius of curvature of the obstacle is sufficiently greater than the wavelength of operation. In this approximation, the surface electric current exists only over the surface which is illuminated by the source, and is calculated as $\vec{J} \approx 2\hat{n} \times \vec{H}^{in}$, where \hat{n} is the normal to the surface of the obstacle.

To propagate the fields, we use the a spectral free space Green function approach based on [9]. The BB, BG and TEM

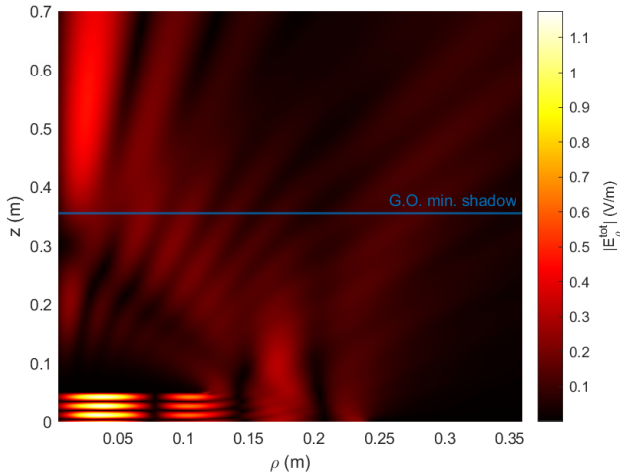


Fig. 1. Evolution of the amplitude of the distorted $E_{\rho}^{tot}(\rho, z)$, for the BB distribution. The radius of the aperture and obstacle are 4λ and 8λ , respectively. The minimum shadow distance extends until $z = 0.306$ m.

field distributions have analytical spectral domain representations, as presented in [8]. To go from the spectral domain to the direct space, and vice versa, we use a Hankel Transform [11] based on the Fast Fourier Transform (FFT).

III. NUMERICAL RESULTS

The radiating aperture is placed on the plane $z = 0$, and it is centered at the origin of the cylindrical coordinate system. The obstacle is placed perpendicular to the axis z , at a distance d from the aperture. We have chosen an aperture with a radius of 8λ which operates at 10 GHz, having $\lambda = 0.03$ m. Only TM_z polarized fields are considered.

The NDR of both the Bessel and Bessel-Gauss beams equals 0.99 m (33.15λ), and $k_{\rho} \approx 0.23k_0$. The obstacle and the aperture are axially aligned, and the distance between them is $d = 0.05$ m. For the TEM distribution, the inner radius is 0.8λ , or 10% of the outer radius.

The obstacle chosen is a circular perfect electric conductor (PEC) disk. To study the impact of the obstacle's radius (a) on the electromagnetic fields, we have varied its radius. Thus, we have three different cases, namely A ($a = 1.6\lambda$), B ($a = 2.4\lambda$), and C ($a = 4\lambda$).

The shadow distance [12] is defined as the minimum distance after which the beam is able to self-reconstruct, and can be calculated as in [2]: $z_{min} \approx (ak_0)/(2k_{\rho})$. The calculated minimum shadow distance is 0.102 m, 0.154 m, and 0.256 m for cases A, B, and C, respectively.

Fig. 1 exhibits the case for obstacle C. $|E_{\rho}^{tot}|$, disturbed by the obstacle, is shown propagating along the axis z . We can observe a high resonant region between the obstacle and the source. Furthermore, there is a region of null field just behind the obstacle, until $z = 0.12$ m. Then, the field starts to self-recover, gradually regaining its intensity.

In Fig 2, the total tangential electric field is shown for the three different field distributions at $z = 0.5$ m. The total field

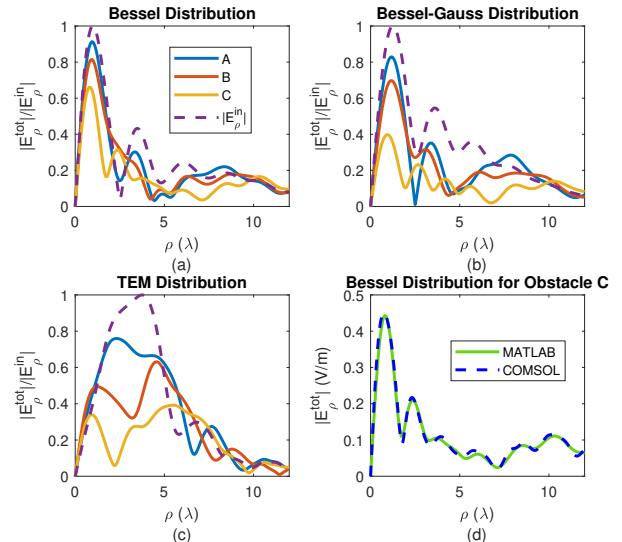


Fig. 2. The images (a), (b) and (c) represent $|E_{\rho}^{tot}|$, normalized by $|E_{\rho}^{in}|$ and distorted by the obstacle on the plane $z = 0.5$ m. The curves A, B and C are referenced to obstacles of radius 1.6λ , 2.4λ and 4λ , respectively. The dashed purple line represents the normalized $|E_{\rho}^{in}|$, plotted here for comparison. Image (d) compares the results obtained from our approach and the results from COMSOL, for $|E_{\rho}^{tot}|$ radiated by the BB distribution on the plane $z = 0.5$ m.

at this plan is compared to the incident tangential field at the same plan. Furthermore, Fig. 2 shows the comparison between the BB results with the commercial full-wave software COMSOL [13] and the approach developed in this work. The results from our diffraction formulation using the PO approximation for the induced currents show good agreement with COMSOL. We can observe the impact of the size of the obstacle in the amplitude of the tangential electric field. For the worst case, obstacle C, $|E_{\rho}^{tot}|$ is approximately $0.66|E_{\rho}^{in}|$, $0.40|E_{\rho}^{in}|$ and $0.30|E_{\rho}^{in}|$ for BB, BG and TEM distributions respectively. We can verify the self-healing effect in the BB and BG beams. However, while the field profile is restored, the amplitude is not fully recovered.

IV. CONCLUSION

We have reported the behavior of three different TM_z polarized field distributions distorted by a circular PEC disk obstacle over a radiating circular aperture. We have modeled the system as a scattering problem by using a PO approach. We verified the self-healing effect for the Bessel and Bessel-Gauss beams. As expected, the TEM field distribution does not present a self-healing behavior. As an extension of this work, we are analyzing the impact of obstacles in the power transfer efficiency between two radiating apertures excited by weakly-diffractive field distributions.

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