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# Metasurface-based Bessel-beam launcher with $100\lambda$ non-diffractive range

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**Abstract**—This work presents the design of a metasurface-based Bessel beam launcher in Ka-band. The launcher uses a modulated metasurface to generate the non-diffractive beam in its near-field. The key advantage of the proposed structure is the large non-diffractive range. The radial size of launcher rises up to  $9.95\lambda$ , while the axicon angle decreases to  $\theta_\alpha = 5^\circ$  to achieve the high non-diffractive range. Full-wave numerical results validate the operation of the systems.

**Index Terms**—Bessel beam, metasurface antennas, non-diffractive beam.

## I. INTRODUCTION

Non-diffractive waves and in general localized waves are solutions to the wave equation that do not experience diffraction while propagating [1]. Such a fascinating feature is of interest for a wide range of applications such as wireless power transfer (WPT), secure short-range point-to-point communications and medical imaging among others. This work involves the development of Bessel beams (BBs), the most known type of non-diffractive waves. In practical implementations, these beams do not undergo diffraction in a limited region known as non-diffractive range (NDR).

This work aims at the design of a metasurface-based launcher at Ka band. This kind of launchers have been realized using different technologies such as leaky-wave antennas [2], radial line slot arrays (RLSA) [3] and conical lenses [4], [5]. The employment of a metasurface antenna as a BB launcher was first proposed in [6], but with a limited  $NDR = 4\lambda$ , where  $\lambda$  refers to free space wavelength.

The current study proposes a metasurface-based BB launcher with radial size  $\rho_1 = 9.95\lambda$  and a calculated NDR that reaches up to  $114\lambda$  or  $11.4\rho_1$ . The proposed design is validated with full-wave numerical results. A critical comparison with the current state of the art is also provided for completeness.

## II. DESIGN ANALYSIS

The goal of the proposed launcher is to generate a Bessel beam at  $f = 30$  GHz with a NDR reaching up to  $100\lambda \approx 1$  m. To achieve so, a radially polarized truncated Bessel beam distribution is imposed over the radiating aperture utilizing a modulated metasurface. In particular, this distribution is characterized by an inward cylindrical travelling wave as discussed in [7] and [8], yielding:

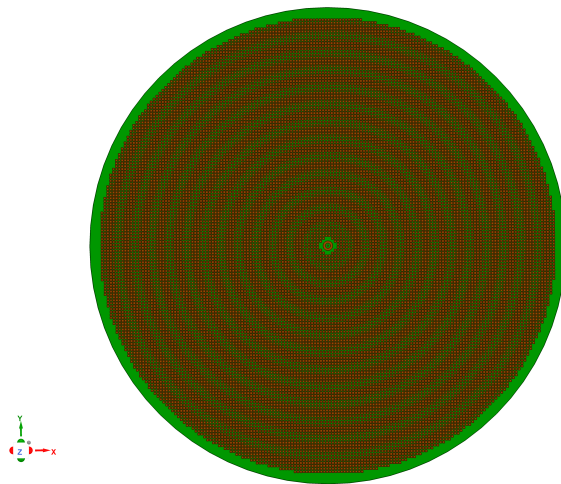


Fig. 1. Top view of the metasurface launcher.

$$\vec{E}_t(\rho, \phi, z = 0) = AH_1^{(1)}(k_\rho\rho)\hat{\rho} \quad (1)$$

where  $A$  is an amplitude factor and  $H_1^{(1)}$  is the first order Hankel function of the 1<sup>st</sup> kind. Respectively,  $\rho, \phi, z$  are the coordinates of a cylindrical coordinate system centered over the radiating aperture as shown in Fig. 1. The substrate used in the current study has a thickness  $h = 0.635$  mm and relative permittivity  $\epsilon_r = 6.15$ . The mean reactance value at the operating frequency is  $\bar{X}_\rho = -288.7\Omega$ . Taking advantage of Oliner's analysis [9], the radiation effect of a propagating plane surface wave (SW) upon a modulated surface impedance is analyzed. Fig. 2 presents the computed solution of a modulated metasurface (MTS) generating a Bessel beam with axicon angle  $\theta_\alpha = 5^\circ$ . In particular, the propagation coefficient ( $\beta_{sw}$ ) and attenuation constant ( $\alpha_{sw}$ ) of the SW are plotted for various values of the modulation index  $M$ .

To define the optimal modulation index, the corresponding attenuation constant of the SW should be set in combination with the radius  $\rho_1$  of the radiating MTS. Aiming at a  $NDR = \rho_1\sqrt{\left(\frac{k_0}{k_\rho}\right)^2 - 1} \approx 100\lambda$ , where  $k_\rho = \sin(\theta_\alpha)k_0$  is the radial wavenumber and keeping in mind that the edge of the metasurface should be located at a zero of the

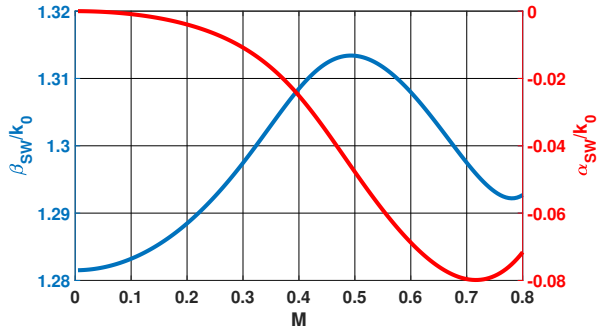


Fig. 2. Solution of SW dispersion equation for scalar sheet transition impedance boundary conditions (IBCs).

Bessel function, we deduce to  $\rho_1 = 9.95\lambda$ . Furthermore, as radius increases the corresponding tapering efficiency ( $\epsilon_{tap}$ ) decreases while the conversion efficiency increases ( $\epsilon_{conv}$ ) [10]. It is proven that the optimal radius for a modulated MTS with a uniform modulation index is found for  $a_{sw}\rho_1 = 0.9$ , which corresponds to an overall efficiency  $\epsilon_{conv}\epsilon_{tap} \approx 58\%$ . Taking into consideration the maximization of the efficiency, the modulation index is defined  $M = 0.33$ .

### III. NUMERICAL ANALYSIS

To verify the aforementioned theoretical analysis the metasurface launcher is designed and simulated with the use of a commercial full-wave simulator. The launcher seen in Fig. 1 consists of rectangular metallic patches lying upon a circular dielectric substrate. A sinusoidal change of the patches' sizes is observed in order to support the necessary modulated impedance boundary condition that is essential for the generation of a propagating field with Bessel profile. Fig. 3 depicts the longitudinal radiated field ( $E_z$ ), where it is clearly distinct the Bessel profile. Concerning the NDR, the beam reaches the calculated theoretical value noted with a dotted blue line.

The simulated  $\phi$ -cut  $E_z$  at  $z = 50\lambda$  (continuous blue line) and  $z = 100\lambda$  (continuous green line) above the launcher at the design frequency of 30 GHz are shown in Fig. 4 and compared with the ideal first kind Bessel distribution of zero order  $J_0$  (dotted black line). It is clearly seen that the Bessel field profile is retained for the radiated field and has almost identical form with the ideal Bessel distribution at  $z = 50\lambda$  above the metasurface. Nevertheless, a slight deformation of the field profile is observed reaching the NDR. In particular the increase of the half power beam-width (HPBW) of the mean beam at  $z = 100\lambda$  is less than 20% that is admissible for the vast majority of applications.

### IV. COMPARISON

Table I lists the main characteristics of various type BB launchers operating at microwave frequencies. Precisely, the table exhibits the radial wavenumber  $k_\rho/k_0$ , the NDR expressed both in free space wavelength and in comparison with aperture's radius, the aspect ratio of the structures  $\rho_1/h$ , where

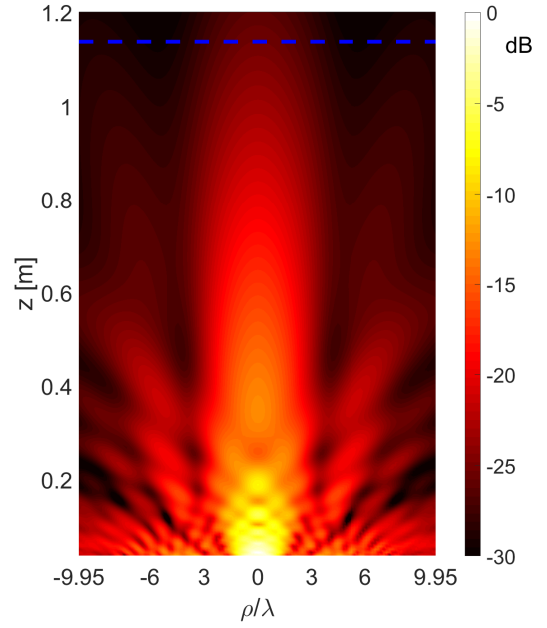


Fig. 3. Normalized  $\phi = 0 |E_z|$  in logarithmic scale radiated by the metasurface launcher. The blue dotted line indicates the calculated NDR.

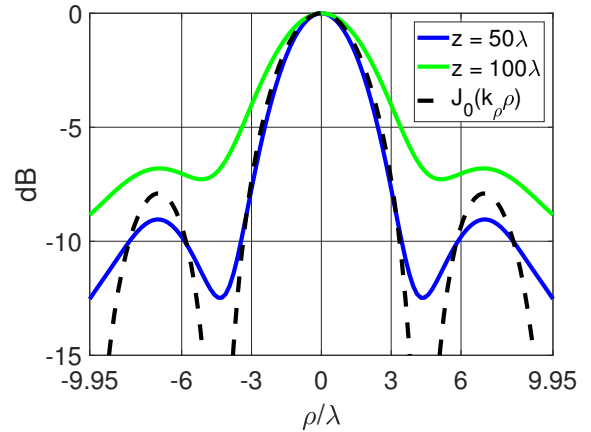


Fig. 4. Normalized  $\phi = 0 |E_z|$  in logarithmic scale at  $z = 50\lambda$  (continuous blue line) and  $z = 100\lambda$  (continuous green line) above the launcher and the distribution of the ideal Bessel function (dotted black line).

$\rho_1$  and  $h$  refers to the radius and the height of each launcher, respectively, and the supporting polarizations. It is clearly evident that the proposed metasurface launcher achieves a NDR far beyond the corresponding ones of other known designs in literature. This extended NDR is attained thanks to significantly low  $k_\rho$  and not in detriment of the radial size of the launcher. This can be also seen in the large value of structure's aspect ratio, which is even higher from the resonant LWA-based launcher, rendering the proposed design as an extremely planar one. The proposed metasurface launcher supports radially polarized excitation either TM or TE.

TABLE I  
COMPARISON OF BESSEL BEAM LAUNCHERS AT MICROWAVE  
FREQUENCIES

Concept	$k_\rho/k_0$	NDR [ $\lambda \rho_1$ ]	$\rho_1/h$	Polar.
MS (proposed)	0.087	100 11.4	156.7	TM (TE)
Resonant LWA [2]	0.8	2.22 1.52	88.9	TM (TE)
RLSA [3]	0.27	37.3 3.73	20	CP
Conical Lens [4]	0.18	6.7 4.06	0.4	TM
Metallic horn [5]	0.2	23 4.5	0.4	TM (TE)

## V. CONCLUSION

In this contribution, a metasurface-based Bessel beam launcher operating at Ka band was presented. Based on the fundamental theoretical principles of metasurface antennas, the launchers is designed and simulated using a full-wave simulator. The achievable NDR is shown reaching the value of  $100\lambda_0$ , rendering the configuration compelling in comparison with various existing alternatives in literature. This advantage of the proposed launcher can be clearly observed in table I, where the principal characteristics of different kind BB launchers are listed.

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