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► **To cite this version:**

Mauro Ettorre, David Gonzalez-Ovejero. High Speed and Resilient Wireless Interconnects in the Near Field. International Workshop on Antenna Technology (iWAT), May 2023, Aalborg, Denmark. 10.1109/IWAT57058.2023.10171697 . hal-04192485

**HAL Id: hal-04192485**

**<https://hal.science/hal-04192485>**

Submitted on 26 Nov 2023

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# High Speed and Resilient Wireless Interconnects in the Near Field

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**Abstract**—Bessel beams present the peculiar properties of being non-diffractive and self-healing within the near field of the radiating aperture. These properties are here exploited to establish robust near-field links with error-free transmission at W-band. These links are generated by using two non-diffractive launchers, consisting of spline-profile metallic horns. An appropriate design of the horn enables the generation of a Bessel beam within a distance, called non-diffractive range, which is typically in the near field of the launcher. This contribution experimentally demonstrates non-diffractive Bessel beams generated by a spline profile horn within the launcher’s non-diffractive range. Besides, the self-healing feature has been tested by placing a metallic object in front of the transmitting horn. Finally, we have evaluated a near-field link by measuring its bit error rate (BER) with and without the metallic obstructions. An error-free communication has been obtained in both cases for a distance approximately twice the non-diffractive range of one horn and for a data stream of 1Gb/s using an on-off keying (OOK) modulation.

**Keywords**—non-diffractive waves, near-field communications, Bessel beams, millimeter-wave links

## I. INTRODUCTION

Bessel-beams are exact solutions of the Helmholtz equation with a transverse field profile taking on a Bessel function [1]. In the ideal case, the transverse profile of the field does not change with the propagation distance, which provides the non-diffractive feature. Such an ideal solution requires an infinite amount of energy and an unbounded radiating aperture. However, devices with a finite radiating aperture can be conceived to generate a non-diffractive Bessel beam in a limited region of space that is called non-diffractive range and typically lies in their near field of the launcher. In addition, Bessel beams present the peculiar property of self-healing, which means that they can reconstruct themselves after an obstruction while propagating [2]. Such a feature will be here exploited to establish a robust near-field link resilient to metallic objects obstructing the line of sight (LOS) between the transmitter and the receiver.

During recent years, the generation of Bessel beams at millimeter waves has attracted a lot of attention and one may find different types of launchers in the open literature. In particular, it is worth mentioning radial waveguides loaded by metasurfaces [3]-[5], radial line slot arrays (RLSA) [6], [7], arrays of patches [8], lenses [9], [10], and spline-profile horns [11]. The non-diffractive behavior of Bessel beams and their capability to provide a robust link may be used in various applications such as wireless personal area networks (WPAN), kiosk downloading, future data centers, wireless power transfer and near-field chip-to-chip communications [12]-[14].

This work explores the possibility of establishing near-field links for robust communications resilient to metallic

obstructions at W-band (75-110 GHz) by exploiting the peculiar non-diffractive and self-healing properties of Bessel beams. Metallic spline-profile horns, as those described in [11], will be used as transmitting and receiving devices in the link to avoid dielectric losses at such high frequencies. The adopted launchers present a radiating aperture with a diameter of 30 mm ( $9\lambda_0$ , with  $\lambda_0$  being the free space wavelength at 90 GHz). The horns synthesize the transverse electric  $TE_{02}$  mode of a circular waveguide over the radiating aperture to generate a non-diffractive Bessel beam. Such a Bessel beam is characterized by an axicon angle of  $15^\circ$  and a non-diffractive range of about 60 mm ( $18\lambda_0$ ) [1], [3].

The transmitting and receiving horns have been fabricated by additive manufacturing using selective laser melting (SLM) and tested at IETR in the 75-105 GHz band. The self-healing feature of the beams has been also validated by considering a metallic obstacle with a diameter  $a_0 = 7$  mm at a distance  $d = 9$  mm in front of the transmitting aperture. Finally, a near-field link has been tested with and without the metallic obstruction over a range of distance from 15 mm to 110 mm. We have adopted an 80 GHz carrier and an on-off keying (OOK) modulation to transmit a 1 GB/s signal. The bit error rate (BER) of the link has been measured for the parameters above, showing that an error-free communication may be established both with and without an obstacle within the 30-84 mm range. This is the first reported example of the capability of Bessel beams to establish a resilient and robust link for near-field communications in the millimeter wave (mm-wave) range.

The paper is organized as follows. Section II illustrates the design of the spline-profile horns, and presents full-wave simulations and measurements that validate the generation of non-diffractive Bessel beams and their self-healing property in the band of interest. Section III introduces the non-diffractive near-field link and reports the measured BER for a link with and without a metallic obstruction within the LOS. Finally, Section IV presents our concluding remarks.

## II. BESSEL BEAM LAUNCHER

Fig. 1 shows the metallic launcher used to generate Bessel beams at W-band. It consists of two parts: a Marié transducer and a spline profile horn. The former presents a standard WR-10 rectangular waveguide input and transforms the  $TE_{10}$  mode into the output  $TE_{01}$  circular waveguide mode, which acts as input for the spline horn. The profile of the horn is designed as described in [11] to synthesize the  $TE_{02}$  circular waveguide mode over the radiating aperture with a 30 mm diameter. The imposed aperture field distribution provides a Bessel beam with an axicon angle of  $15^\circ$  and a non-diffractive range of about 60 mm (2 times the launcher’s diameter). The total length of the spline profile of the horn is about 48 mm, while the total length of the launcher is 104 mm. The metal-only

Bessel beam launcher has been manufactured at IETR by SLM using an aluminum alloy (AlSi10Mg).

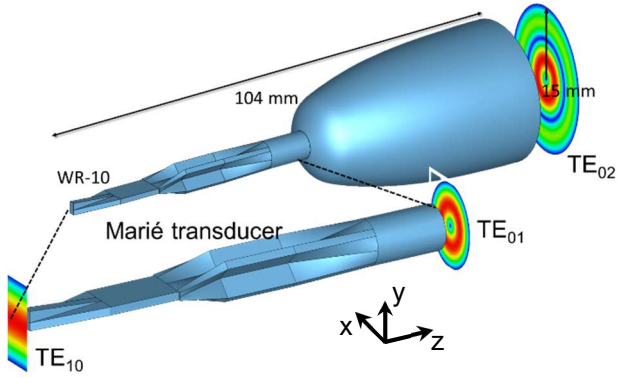


Fig. 1. 3D-view of the interior of the Bessel beam launcher and its modal operation. The launcher is fed by a standard WR-10 rectangular waveguide. A Marié transducer converts the guided mode from the input rectangular waveguide to the circular one used for the horn. All the reported dimensions are in millimeters.

The non-diffractive and self-healing capabilities of the Bessel beam launcher has been validated by measuring the transverse near-field profile with and without obstacle in the 75-110 GHz band. Fig. 2 shows the experimental set-up used to measure the  $E_y$  component of the electric field in the  $xoz$  plane. The transmitted mm-wave signal is photonicly generated. The photonic generation module in Fig. 2 provides two amplitude modulated optical tones around 1550 nm, whose separation corresponds to the desired mm-wave frequency. The two optical wavelengths are modulated by a 100 kHz sinusoidal waveform from a lock-in amplifier. In turn, the optical fiber output of the photonic generation module is used to illuminate a commercial photo-mixing device, which provides an amplitude modulated beat-note. Then, the WR-10 output of the photo-mixing block excites the launcher described above. The fields are sampled by a near-field probe connected to a zero bias Schottky barrier diode detector (ZSBD) and placed in a 3-axis motorized. The RF output of the ZSBD is extracted with a bias-tee connected to the lock-in amplifier input, which measures the detected relative amplitude.

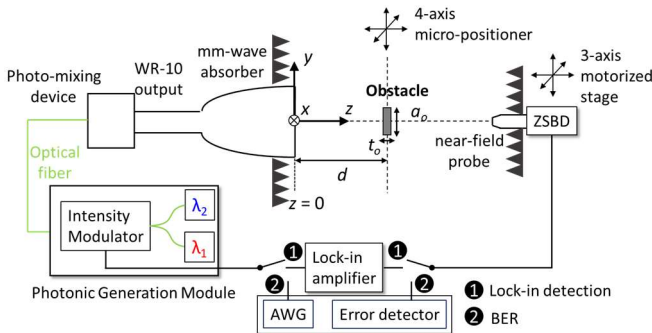


Fig. 2. Schematic representation of the experimental set-up used to sample the near field in the non-diffractive range.

For the sake of brevity, the following figures only report the simulated and measured E-field profiles at 90 GHz (the central frequency). However, it is important to note that a

similar agreement has been obtained from 75 to 105 GHz. First, Fig. 3 presents the normalized magnitude of the electric field  $E_y$ , obtained for the LOS case, i.e., when the obstacle in Fig. 2 is absent. Fig. 3(a) shows full-wave simulation data, whereas Fig. 3(b) showcases the experimental results. There is a very good agreement between simulations and measurements. Since the transverse profile of the radiated beam is preserved in the near field of the launcher, its non-diffractive behavior up to  $z = 60$  mm is also confirmed.

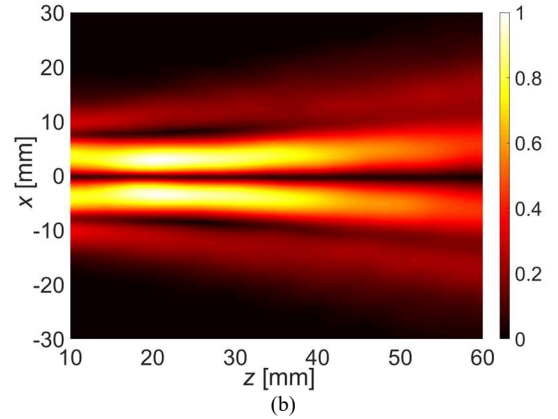
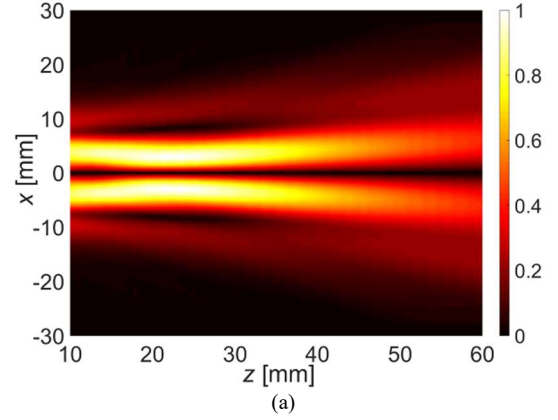


Fig. 3. Normalized electric field in the  $xoz$  plane (see Fig. 2) at 90 GHz for the LOS configuration: (a) Simulation. (b) Measurement.

The reminder of this section deals with the experimental demonstration of the self-healing feature of Bessel beams. To illustrate the non-LOS (NLOS) case, we place a circular metallic obstacle with diameter  $a_0 = 7$  mm and thickness  $t_0 = 0.4$  mm at a distance  $d = 9$  mm from the launcher's aperture and along the horn's axis. Fig. 4 presents the normalized magnitude of the E-field in presence of the obstacle, which position is accurately controlled using a 4-axis micro-positioner (as sketched in Fig. 2). In this case, each sub-figure is normalized with respect to the maximum value along the dashed white line. Such line represents the shadow depth boundary and provides the distance at which the beam heals. Fig. 4(a) and Fig. 4(b) show the results obtained from full-wave simulations and the experimental ones, respectively. The agreement is also very good in this NLOS case and a clear non-diffractive profile can be recognized both in Fig. 4(a) and Fig. 4(b) after the shadow depth. Indeed, the fields measured beyond the shadow depth are similar to those of the non-obstructed launcher reported in Fig. 3.

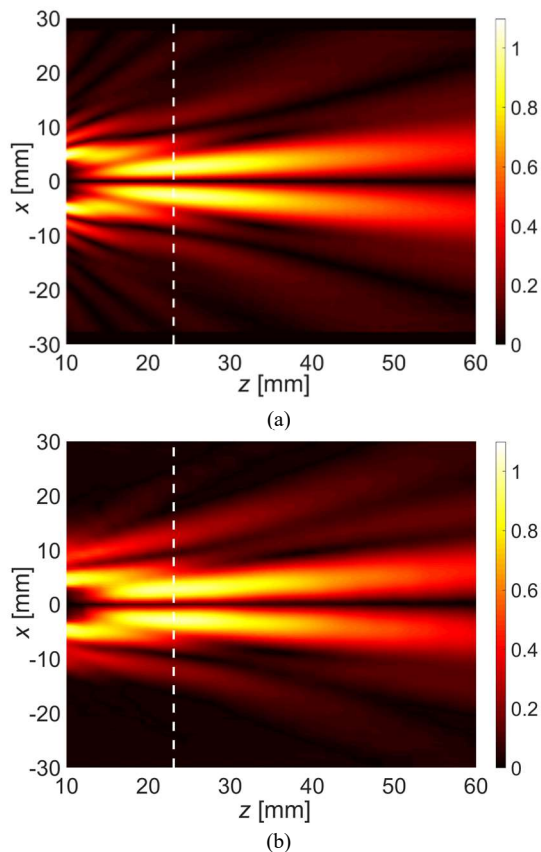
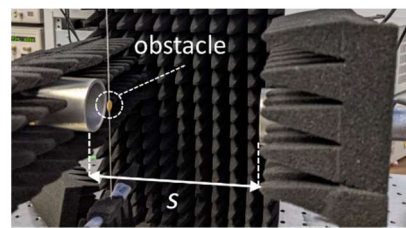


Fig. 4. Normalized electric field in the  $xoz$  plane (see Fig. 2) at 90 GHz for the NLOS configuration: (a) Simulation. (b) Measurement.

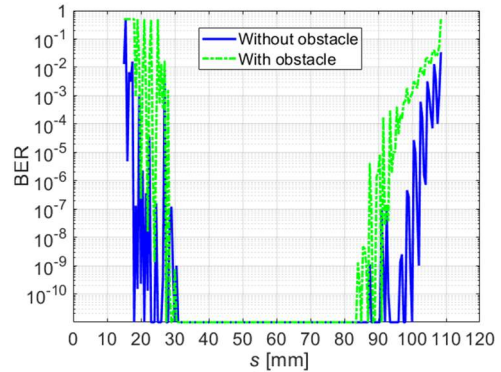
### III. NON-DIFFRACTIVE LINK

The Bessel beam launcher described and characterized in Section II is used in this section as transmitting and receiving device in a near-field link. In other words, the near-field probe in Fig. 2 is replaced with a second launcher. The two launchers were axially aligned and placed at a relative distance ranging  $s$  from 15 mm to 110 mm. Moreover, in order to measure the BER, a pulse pattern generator provides the input for the photonic generation module in Fig. 2 and the output of the ZSBD's bias tee is connected to an error detector.

The pulse pattern generator is used to generate a 1 Gb/s non return to zero (NRZ) OOK signal, which modulates a 80 GHz carrier. The BER has been then measured at the receiving side with and without the obstacle obtruding the link. Fig. 5(a) shows a picture of the measurement set-up and Fig. 5(b) presents the obtained BER versus the distance  $s$  between launchers. An error-free transmission is achieved in the range 30-84 mm in both cases. Such results validate, for the first time, the capability of non-diffractive beams to provide a robust and resilient link for near-field communications. It is worth mentioning that higher data rates can be achieved by using a photo-mixing device with a more stable response in the band of interest and an optimized receiver.



(a)



(b)

Fig. 5. (a) Picture of the non-diffractive near field link . (b) Measured BER of the non-diffractive link with (dashed green line) and without (solid blue line) a metallic obstacle within the operating range.

### IV. CONCLUSION

This contribution reports, for the first time, the use of Bessel beams to establish a robust near-field link with error-free high data rate transmission at W-band. Such link is also resilient to obstructions in the LOS and can be readily applied to near-field communications. The transmitter and the receiver of the reported link are based on metallic spline-profile horns fabricated by additive manufacturing. The operation of the horn as non-diffractive launchers and the self-healing feature of the generated beam have been experimentally validated in the band 75-105 GHz. In addition, a near-field link has been characterized using the horns; we have shown the capability to transmit a 1 Gb/s data stream based on an OOK modulation. In a range of 30 to 84 mm a free error communication has been achieved with and without an obstacle. The distance range is limited by the axicon angle chosen for the Bessel beam. However, smaller axicon angles can be synthesized paving the way to a larger operating distances. In addition, one can use more sophisticated photo-mixing hardware and/or adopt higher order modulations to better exploit the Bessel beam launchers' large bandwidth and increase the data rate.

### ACKNOWLEDGMENT

This work has received support from the French National Research Agency (ANR) through the project LinkAll with reference ANR-21-CE25-0014, and from the French Government through the Labex CominLabs Excellence Laboratory, managed by ANR in the Investing for the Future Program under Reference ANR-10-LABX-07-01.

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