FINAL REPORT
PROJECT:
RLSA BESSEL BEAM LAUNCHERS USING INWARD HANKEL APERTURE DISTRIBUTIONS FOR FOCUSING AND COLLIMATING APPLICATIONS

Author: Santi Concetto Pavone

SENDING INSTITUTION

Dipartimento di Ingegneria dell'Informazione e Scienze Matematiche
Università degli Studi di Siena
Via Roma, 56 - 53100, Siena, Italy.

HOST INSTITUTION

Institut d'Electronique et des Télécommunications de Rennes (IETR), UMR CNRS 6164
Département Antennes et Dispositifs Hyperfréquences
Equipe Systèmes Rayonnants Complexes
Université de Rennes 1
35042, Rennes, France.

TIME SCHEDULE

- Project duration: **5 months (21 weeks)**
- Start date: **15/01/2015**
- Duration: **11/06/2015**

1. INTRODUCTION AND MOTIVATION

The limitation of the physical phenomenon of diffraction is an important requirement in many applications, as near-field focusing, radiometry, and sensing. Therefore, recently there has been a growing interest in the analysis of the so-called "diffraction-less" beams. Among those, Bessel beams can be considered promising solutions for focusing applications. Since the early works of Durnin [1]-[2], who proved that Bessel beams are an exact solution to the scalar Helmholtz (or wave) equation, different structures (Bessel launchers) have been proposed to practically generate Bessel beams [3-10]. It is worth noting that ideal Bessel beams require infinite energy and infinite radiating apertures, thus are inherently non-physical. However, finite-energy Bessel beams can be generated by using finite apertures, thus carrying finite energy. In this case, a "pseudo-Bessel beam" is

established having a non-diffractive behavior in a limited space range called "non-diffractive range" (NDR).
At optical frequencies, Bessel beams are usually generated by using a conical lens ("axicon" [11]).
At microwaves, few solutions have been proposed to generate "non-diffractive" beams [12]-[13]. Such solutions are based on resonant apertures, thus inherently narrow-band. In a recent work [14], it has been demonstrated that an inward Hankel current distribution can generate a Bessel beam in a well-defined conical region close to the axis of symmetry of the planar radiating aperture.
The approach proposed in [14] differs from [12]-[13] by the fact that the Hankel distribution does not require a resonant aperture. In this case, a holographic approach is proposed to synthetize the inward Hankel current distribution by using circular metallic gratings in parallel plate environment. In particular, an optimization procedure as in [16]-[17] is adopted to finely tune the position and size of the metallic gratings. The final prototype is shown in Fig.1. It was developed and measured at IETR.

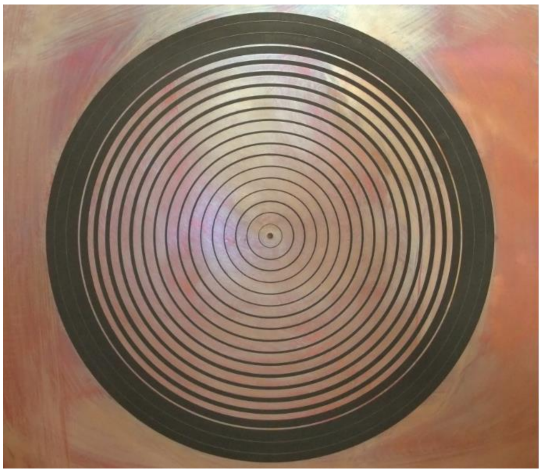

Figure 1: Realized prototype of Bessel beam launcher at 30GHz.

The measured near field was in excellent agreement with the simulations over a wide-band range of operation with respect to other solutions proposed in literature. During the present visiting program, Mr. Pavone has participated to the measurements of the prototype. Recently, a journal paper has been submitted [18] to present the obtained results (please refer to Section 4).

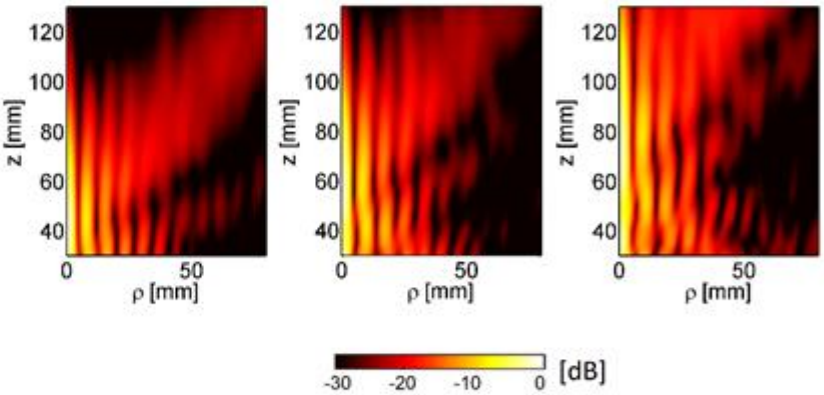

Figure 2: Normalized longitudinal electric field component in the ρz plane at various frequencies: 29GHz (left), 30GHz (center), and 31GHz (right). The focusing capabilities are evident in the measured band (6.7% around 30 GHz).

2. CIRCULAR POLARIZED BESSEL BEAM LAUNCHER

During the timeframe of the present visiting program, the procedure outlined in [14]-[16] has been extended to the case of more general polarizations. In particular, a circularly-polarized Bessel beam launcher has been investigated. In this case, the transverse radiated electric field is circularly polarized and takes on a zeroth order Bessel distribution.

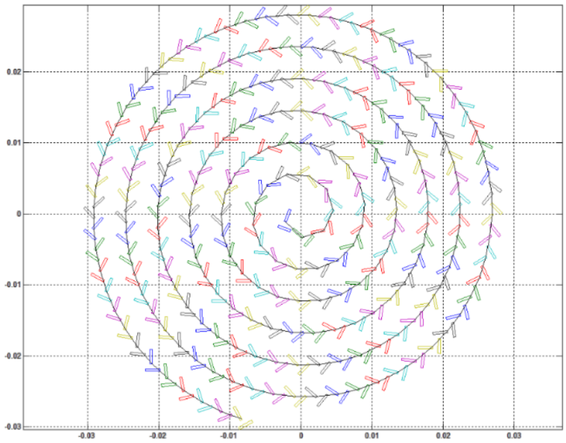

Figure 3: Geometry of a circularly polarized Bessel beam launcher made by an RLSA structure.

An RLSA (Radial Line Slot Array) structure as in Fig. 3 has been designed to generate the required near field. Each radiating element is a couple of very small slots (in terms of wavelength), placed both in spatial and in temporal quadrature [16]. Also for this structure, an optimization process is used to place and size the slots in such a way to synthesize the desired aperture field distribution, namely an inward Hankel aperture distribution. The optimization procedure has been developed and linked to a high-performance in-house Method of Moments developed at IETR. An approach based on two different complex functionals have been considered for the synthesis of the desired inward Hankel aperture distribution. The first functional controls the aperture field distribution whereas the second one reduce the level of the cross-polar component of the electric field. In both cases, the position and length of the slots of the RLSA structure are tailored to minimize the used functional. The final tool has been tested and is able to automatically design circularly-polarized Bessel beams. As an example, a Bessel beam launcher with the following parameters has been designed:

Parameter	Description	Value
F	Frequency	60 GHz
R	Aperture radius	30 mm
θ_a	Design Angle	20°
NDR	Non-diffractive Range	80 mm
ε_r	Substrate permittivity	1.04
h	Substrate thickness	1.7 mm
W	Slot width	0.33 mm

in which θ_a is defined as $\theta_a = \arcsin(k_\rho / k)$, being *k* the free-space wavenumber.

In Fig. 4, the average aperture distribution error is shown together with the spill-over efficiency, with respect to the iteration steps [17]. It is clear that after few steps the optimization procedure converge, providing a good accuracy for the synthesized distribution and high values of spill-over efficiency (larger than 90%).

Fig. 5 shows the co- and cross-polar components of the synthetized magnetic current distribution with respect to the ideal inward Hankel current distribution. It is clear that after few steps of the optimization process, the "noisy" behaviour in Fig. 4 is progressively reduced for the co-polar component. In addition, the latter component is dominant with respect to the cross-polar one.

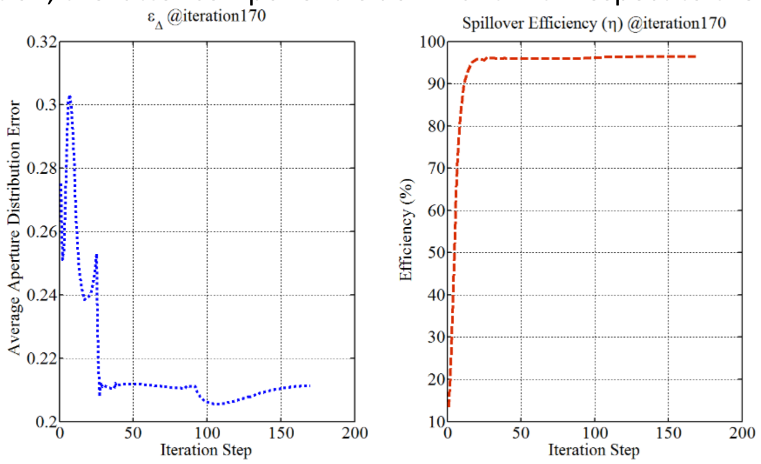

Figure 4: Average aperture distribution errorand spill-over efficiency vs iteration steps for the circularly-polarized Bessel beam launcher. An efficiency greater than 95% is rapidly achieved.

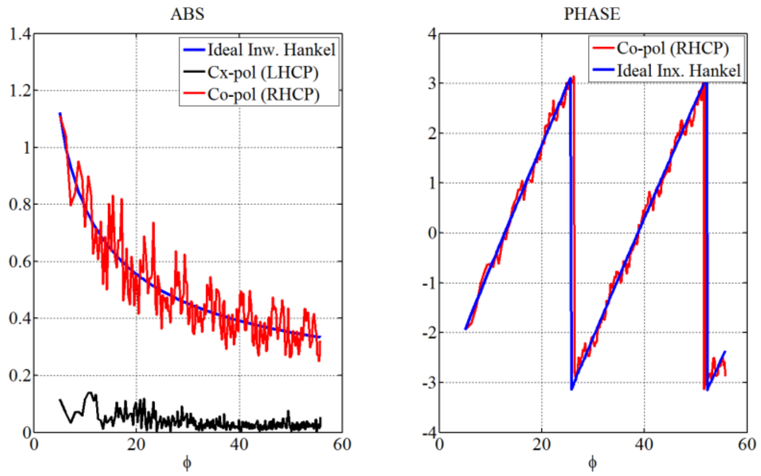

Figure 5: Co-polar (RHCP) and cx-polar (LHCP) components of the synthesized aperture distribution during the optimization procedure. A remarkable rejection of the cx-polar component is easily achieved.

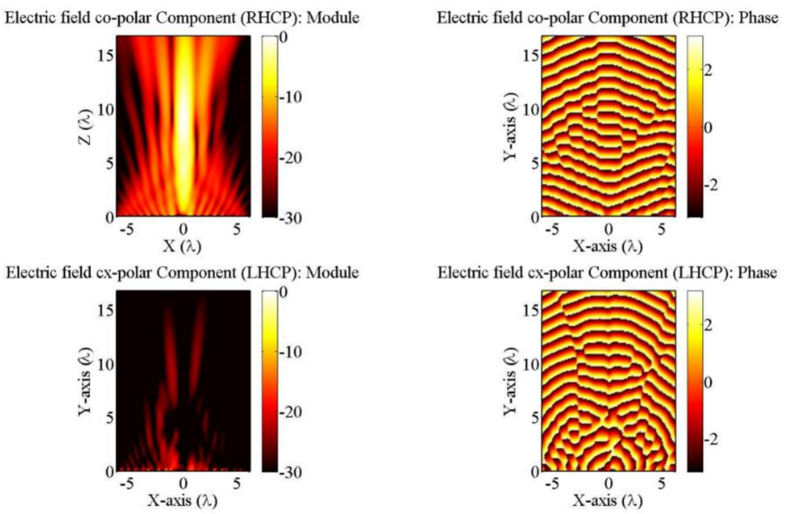

Figure 6: Radiated co/cx-polar components of the electric field. A Bessel profile is recognized for the co-polar component of the electric field. The fields are normalized to the maximum of the co-polar component.

Finally, Fig. 6 reports the co/cx-polar components of the electric field in the near field of the structure. A “non-diffractive” Bessel beam is recognized for the co-polar component of the electric field. In addition, the cx-polar component of the electric field is extremely weak (lower than -20dB) with respect to the co-polar one. These results validate the proposed approach and design.

At the moment, a prototype is under development and measurement results are expected in the coming months.

3. CONCLUSIONS

In this project the focusing capability of a circularly-polarized Bessel beam launcher has been investigated. A powerful and rapidly convergent algorithm has been used for the analysis and design of a circularly polarized Bessel beam launcher using an RLSA structure. The achieved results are promising and clearly show that a collimated circularly-polarized Bessel beam launcher can be designed by using the above mentioned procedure. A prototype is under development and measurement results are expected in the coming months.

4. SUBMITTED JOURNAL PAPER

The following paper has been submitted for review:
S. C. Pavone, M. Ettore, and M. Albani, “Analysis and Design of Bessel Beam launchers: Longitudinal Polarization”, submitted to IEEE Transactions on Antennas and Propagation, under revision.

5. REFERENCES

[1] J. Durnin, “Exact solutions for nondiffracting beams. I. The scalar theory,” J. Opt. Soc. Am. A 4, 651–654, (1987).
[2] J. Durnin, J. J. Miceli, Jr., and J. H. Eberly, “Diffraction-free beams,” Phys. Rev. Lett. 58, 1499, (1987).
[3] M. Lapointe, “Review of non-diffracting Bessel beam experiments,” Opt. Laser Technol. 24, 315–321, (1992).
[4] J. Arlt and K. Dholakia, “Generation of high-order Bessel-beams by use of an axicon,” Opt. Commun. 177, 297–301 (2000).
[5] R. M. Herman and T. A.Wiggins, “Production and uses of diffractionless beams,” J. Opt. Soc. Am. A 8, 932–942, (1991).
[6] W. B. Williams and J. B. Pendry, “Generating Bessel beams by use of localized modes,” J. Opt. Soc. Am. A 22, 992–997, (2005).
[7] A. Mazzinghi, M. Balma, D. Devona, G. Guarnieri, G. Mauriello, M. Albani, and A. Freni, “Large depth of field pseudo Bessel beam generation with a RLSA antenna,” IEEE Trans. Ant. and Propag., vol. 62, no. 8, pp. 3911-3918, Aug. 2014.
[8] J. C. Gutierrez-Vega, M. D. Iturbe-Castillo, and S. Chavez-Cerda, “Alternative formulation for invariant optical fields: Mathieu beams,” Opt. Lett. 25, 1493–1495 (2000).
[9] J. Salo, J. Fagerholm, A. T. Friberg, and M. M. Salomaa, “Unified description of nondiffracting X and Y waves”, Phys. Rev. A, 62, 4261 (2000).
[10] M. Anguiano-Morales, M. M.Mendez-Otero, M. D. Iturbe-Castillo, and S. Chavez-Cerda, “Near field diffraction of Hankel beams,” in Frontiers in Optics, OSA Technical Digest (CD) (Optical Society of America, 2006), paper JSuA36.
[11] J. Arlt and K. Dholakia, “Generation of high-order Bessel-beams by use of an axicon,” Opt. Commun., vol. 177, p. 297-301, 2000.
[12] M. Ettorre and A. Grbic, “Generation of propagating Bessel beams using leaky-wave modes,” IEEE Trans. Antennas Propag., vol. 60, p. 3605–3613, 2012.
[13] M. Ettorre, S. M. Rudolph, and A. Grbic, “Generation of propagating Bessel beams using leaky-wave modes: experimental validation,” IEEE Trans. Antennas Propag. vol. 60, p. 2645–2653, 2012.
[14] M. Albani, S. C. Pavone, M. Casaletti, and M. Ettorre, “Generation of non-diffractive Bessel beams by inward cylindrical traveling wave aperture distributions,” Opt. Express, vol. 22, no. 15, p. 18354-18364, Jul. 2014.
[15] R. Cicchetti, A. Faraone, “Incomplete Hankel and modified Bessel functions: a class of special functions for electromagnetics,” IEEE Trans. Antennas Propag., vol. 52, no. 12, p. 3373-3389, 2004.

[16] M. Albani, A. Mazzinghi, and A. Freni, "Automatic design of CP-RLSA antennas," IEEE Trans. Antennas Propag., vol. 60, p. 5538–5547, 2012.
[17] M. Ettorre, M. Casaletti, G. Valerio, L. Le Coq, R. Sauleau, S. C. Pavone, and M. Albani, "On the near-field shaping and focusing capability of a radial line slot array," IEEE Trans. Antennas Propag., vol. 62, no. 4, p. 1991-1999, 2014.
[18] S. C. Pavone, M. Ettore, and M. Albani, "Analysis and Design of Bessel Beam launchers: Longitudinal Polarization", submitted to IEEE Transactions on Antennas and Propagation, under revision, 2015.
[19] M. Ettorre, S. C. Pavone, M. Casaletti, and M. Albani, «Experimental validation of Bessel beam generation using an inward Hankel aperture distribution», IEEE Trans. Antennas Propag., publ. June 2015.