DECLARATION

By this letter I confirm that Mr Davide COMITE worked for three months at IETR, from the 24 March to the 22 June 2014, under my supervision, as agreed in the NewFocus proposal. The results of the mentioned working period are described in the attached report.

Furthermore, I declare that this twelve-week period financed by NewFocus was preceded by a further month at IETR, not covered by NewFocus. For this reason, the flight tickets to be refunded through the NewFocus grant refer to the period 27 February 2014 (Rome - Rennes) - 22 June 2014 (Rennes - Rome).

Rennes, 26th July 2014

Guido VALERIO
Researcher at IETR

PROJECT TITLE

Focusing of Orbital Momentum Collimated Beams Through the Synthesis of Low Profile Slotted Antennas

Sending Institution

Dipartimento di Ingegneria dell'Informazione, Informatica e Telecomunicazioni
Università di Roma 'Sapienza'
Via Eudossiana 18, 00184 Roma.

People Involved

Davide Comite
Alessandro Galli

Host Institution

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

People Involved

Guido Valerio
Mauro Ettorre
Ronan Sauleau

1. Introduction and motivation

The capability of focusing electromagnetic radiation in the near field region of an antenna is a very attractive feature for a wide variety of applications such as imaging, diagnostic and wireless power transfer. Generally speaking, non-diffracting solution of the scalar wave equation are named Bessel beam [1], and the possibility to generate this particular configuration by means of leaky radial waveguide made of a capacitive sheet on a ground plane have been investigated in the past years [2,3]. More recently, thanks to a customized optimization algorithm [4] also the capability of Radial Line Slotted Antenna (RLSA) to focus energy in a limited region of space has specifically been exploited: in [5] slot positions and dimensions required to generate a Bessel beam on a certain plane in the near field region have been evaluated. Specifically, a shaped Bessel beam of zero order has been designed, adopting a novel procedure capable to control the normal component of the electric field radiated by the antenna. It very important to note that this kind of antenna is centrally fed by a coaxial probe, thus avoiding lossy and cumbersome feeding networks. By following the interesting results achieved so far, in this project the possibilities to design and focus a higher-order Bessel beam is evaluated. This kind of beam is very attractive because it shows an azimuthal phase variation that basically allows to obtain an “orbital angular momentum” (OAM) beam, recently receiving a great interest at radio frequencies. Indeed, OAM have been shown to be capable, among other application, of an increased capacity of communication channels [7-9], and enhanced remote sensing [10].

2. Problem statement and method

Achieving the excitation of a *n* order Hankel function and thus a focused OAM beam, requires the synthesis of a properly phased aperture field on the slot plane of a RLSA, that should be obtained along the azimuthal angle. Specifically, in the first period the activity has been focused on the analysis of an aperture field capable to radiate a beam whose phase could shows such a rotational variation. As an example, in fig. 1 and 2 a two-dimensional representation of the Hankel function of the order *n* including *n* azimuthal linear phase variation have been shown. After a comprehensive study of an aperture field capable to fulfil the requirement on the beam phase, the position and dimensions of the slots on the aperture plane have been studied. Exploiting the so-called holographic principle, as already shown in [4-5], the incident field radiated in the waveguide by the coaxial probe can be suitable sampled considering the follow equation

$$\angle\left\{\underline{M}_0\left(\underline{\rho}\right)\cdot\underline{H}^{inc}(\underline{\rho}_i)\right\}=\gamma$$

where $\underline{M}_0(\underline{\rho}) = A(\rho)\underline{\rho}_0 + B(\rho)\underline{\phi}_0$ is the desired aperture field , $\underline{H}^{inc}(\underline{\rho}_i) = H^{inc}H_1^{(2)}(k_d\rho)\underline{\phi}_0$ is the feeding field and γ is an arbitrary phase value. By using asymptotic large-argument expansion, as shown in fig 3, previous equation results in the classic spiral slot arrangement for a RLSA antenna.

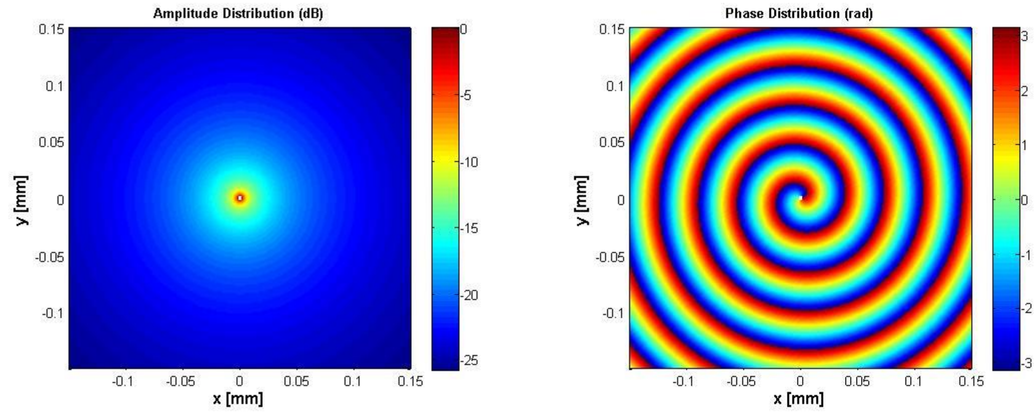


Fig. 1 - Two-dimensional picture of an Hankel function of second kind with *n* azimuthal linear phase variation and order *n* =1.
(a) Amplitude distribution in dB. (b) Phase distribution in radiant

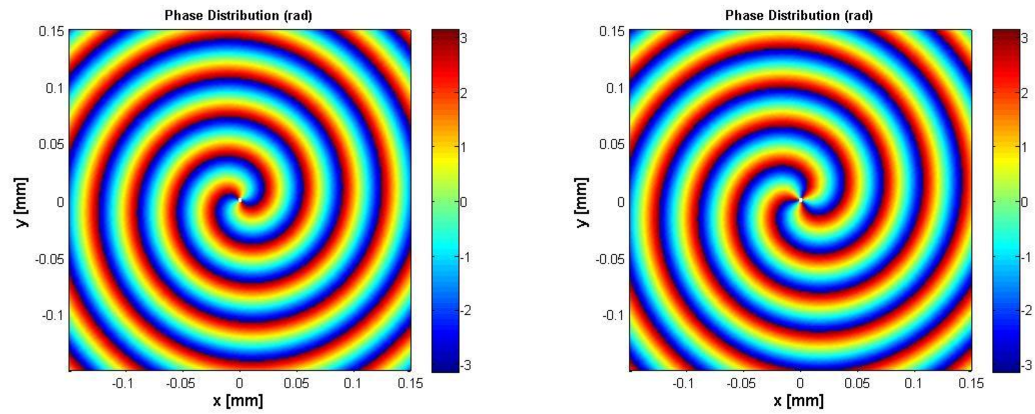


Fig. 2 - Two-dimensional picture of an Hankel function of second kind and order n =2,3 with *n* azimuthal linear phase variation

Even though the considered optimal aperture illumination allows to precisely determine slots position, due to a strong couple phenomena between adjacent slots an optimization method has to be introduced, as generally outlined in [5]. Each slot will be associated to an equivalent magnetic dipole, related to the aperture electric field sampled in the slot centers. Such a procedure has been suitably reformulated by relaxing the hypothesis of azimuthally invariant aperture. Thus, the fitness function is adapted to the new goal, and the method has been generalized in order to achieve the wanted azimuthal variation (i.e., azimuthal phase gradient).

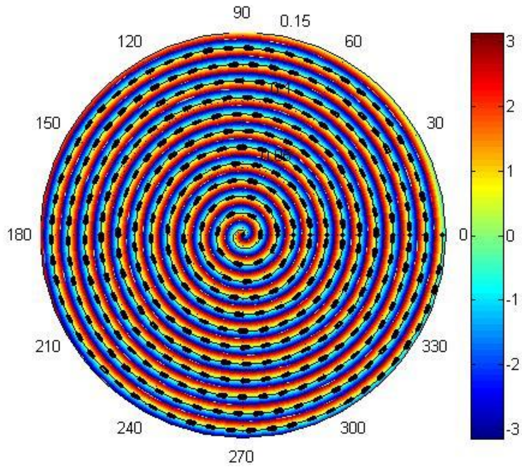
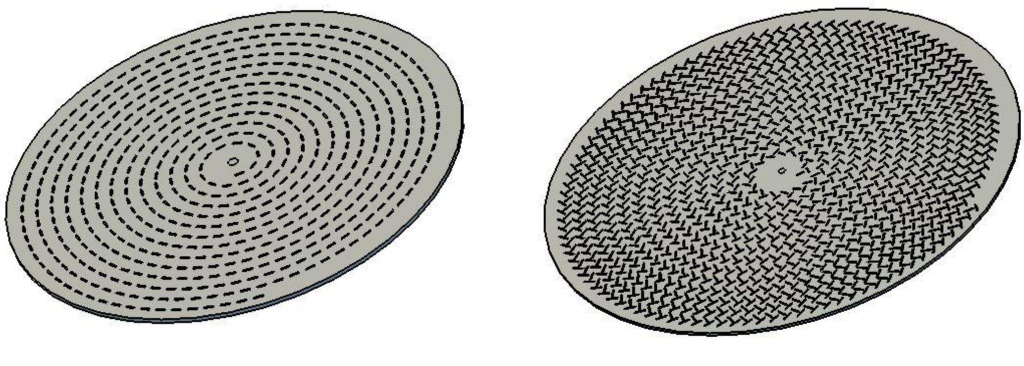


Fig. 3 - Phase pattern of the holographic principle and slots arrangement along the obtained spiral.

3. Numerical results

In this project two different prototypes have been designed, one shown in fig. 4 (a) working in linear polarization, and one shown in fig. 4 (b) designed to radiate a circular polarized field. For both cases, an aperture fields described by the Hankel function of first kind and order n=-1, including n azimuthal linear phase variation, was required. In the following, the near-field focusing capabilities of this kind of radiator and the far field characteristic will be highlighted and discussed, but for sake of brevity only the circular polarized system will be considered, whose main parameters are shown in tab. 1.



(a) (b)

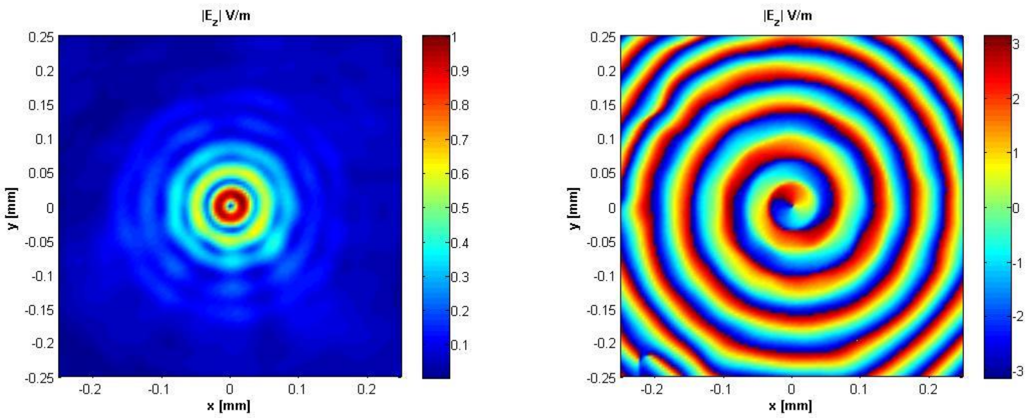
Fig. 4 - Virtual prototype of a RLSA antenna, slots are arranged along an Archimedes Spiral.
(a) Linear Polarized. (b) Circular Polarized

After a first step, based on the application of the holographic principle, slot positions and dimensions can be obtained. Thanks to an ad-hoc efficient MoM formulation [6] the aperture field can be evaluated and compared with the desired distribution. Thus, in order to increase the radiation efficiency and at the same time face slots coupling phenomena an iterative algorithm has been introduced.

Design frequency	**12.5 GHz**
Antenna diameter	**300 mm**
Waveguide thickness	**3.125 mm**
Slots number LP antenna	**760**
Slots number CP antenna	**1558**
Relative permittivity	**1.06**
Slots width	**0.6 mm**
Slots length	**8.8 – 11.3 mm**
Spillover Efficiency	**98.8 %**

Tab. 1 – Antenna optimized parameters

Exploiting a suitable fitness function, for each step of the process, slot position and length can be corrected and the overall error can be assessed. After a number of iteration the optimization algorithm reaches the convergences, then the obtained near field distribution is shown in fig. 5.

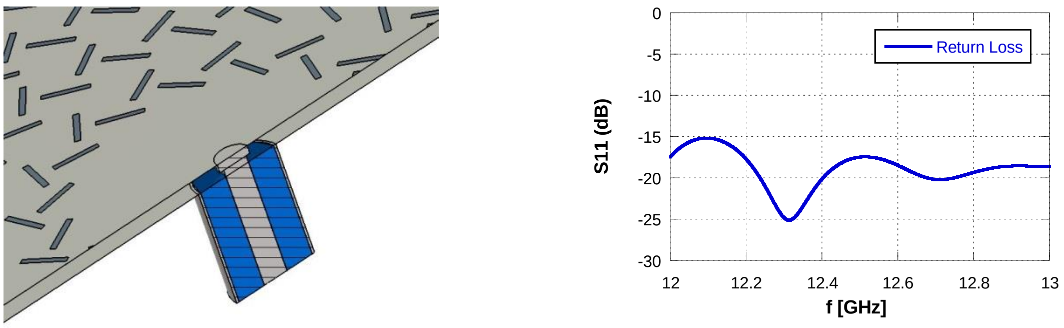


(a) (b)

Fig. 5 – Near field distribution of the design CP-RLSA antenna at *z* = 40 cm
(a) Amplitude (b) Phase

As expected an azimuthal phase gradient has been obtained and a focused amplitude can be observed on the considered z-plane.

In order to validate the obtained prototype and to design a feeding system for the considered antenna, a full-wave implementation on a commercial CAD tool has been introduced.
Due to a very large amount of slots, all with different size and position, an automatic design procedure was considered. Specifically, an ad-hoc Macro capable to read a txt file and to automatic plot the slots has been implemented.



(a) (b)

Fig. 6 – (a)Return Loss for the realized prototype inside the operational bandwidth
(b) Virtual prototype of the optimized feeding system for the designed antenna

The designed feeding system is shown in fig. 6 (a), while the obtained return loss for the final prototype is highlighted in fig 6 (b), showing an excellent impedance matching.

4. Conclusions

Thanks to the financial support of the 'European Science Foundation', during this weeks the capabilities of a RLSA antenna to radiate and focus a higher order Hankel function with linear phase variation along the azimuthal angle has been investigated. These beams are very interesting due to the azimuthal phase gradient, that can be exploited for the so-called OAM application. Two different virtual prototype have been designed and a very simple feeding system has been optimized. In the next future a prototype will be manufactured and measured to further validate and enhance the impact of the present work. Specifically, overall results will be described and published on the highest level specialized journals. More details about optimization procedure and design parameters will be highlighted and every time the financial support from the foundation will be gratefully acknowledged.

References

[1] J. Durnin, “Exact solutions for nondiffracting beams. I. The scalar theory,” *J. Opt. Soc. Amer.* vol. 4, no. 4, pp. 651–654, Apr. 1987.

[2] M. Ettorre and A. Grbic, “Generation of Propagating Bessel Beams Using Leaky-Wav Modes,” *IEEE Trans. Antennas Propag.*, vol. 60, no. 8, pp. 3605-3613, Aug. 2012.

[3] 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, no. 6, pp. 2645-653, June 2012.

[4] M. Albani, A. Mazzinghi, and A. Freni, “Automatic design of CP-RLSAantennas,” *IEEE Trans. Antennas Propag.*, vol. 60, no. 12, pp. 5538-5547, Dec. 2012.

[5] M. Ettorre, M. Casaletti, G. Valerio, R. Sauleau, L. Le Coq, S.C. Pavone, M. Albani, “On the near-field shaping and focusing capability of a radial line slot array,”, *IEEE Trans. Antennas Propag*., vol. 62, no. 4, pp. 1991-1999, Apr. 2014.

[6] M. Casaletti, G. Valerio, J. Seljan, M. Ettorre, and R. Sauleau, “A full-wave hybrid method for the analysis of multilayered SIW-based antennas,” *IEEE Trans. Antennas Propag.*, vol. 61 no. 11, 2013, pp. 5575-5588, doi:10.1109/TAP.2013.2279795.

[7] S. V. Mohommadi, L.K. Daldorff, J. E. Bergaman, R. L. Karlesson, B. Thidé, K. Forozech T. D. Carozzi, B. Isham "Orbital angular momentum in radio - A system study," *IEEE Trans. Antennas Propag.*, vol. 58, no. 2, pp. 565-572, Februrary 2010.

[8] F. Tamburini, E. Mari, A. Sponselli, B. Thidé, A. Bianchini and F. Romanato, "Encoding many channels on the same frequency through radio vorticity: first experimental test," *New Journal of Physics* 14, pp 18, March 2012.

[9] F. Tamburini, E. Mari, A. Sponselli, B. Thidé, C. Barbieri and F. Romanato, "Experimental verification of photon angular momentum and vorticity with radio techniques," *Applied Physics Letter* 99, pp 4 November 2011.

[10] N. Urribe-Patarroyo, A. Fraine, D.S. Simon, O. Minaeva, A. V. Sergienko, "Object identification using correlated orbital angular momentum states," *Quantum Physics*, pp 5, September 2012.