## Antennas for generating electromagnetic waves bearing OAM momentum

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Orbital angular momentum (OAM) has been proposed to improve spectral efficiency [1] [2] [3] in radio, by creating multiple sub-channels of communications corresponding to the twisting degree of the electromagnetic (EM) wave. Whereas the phase of a usual plane wave is constant on the wavefront, the phase  $\alpha$  of OAM waves undergoes a linear variation along the angular coordinate  $\varphi$  (roll angle):  $\alpha = \ell . \varphi$ , where  $\ell$  is an integer called the "topological charge" or the order of the OAM mode.

In the radio frequency bands, two main families of antennas have been proposed to generate OAM waves. In the first one, the OAM wave is generated by a transformation of a plane wave. For example, an 80-cm twisted parabolic reflector dish working has been used in the first experimental transmission, in the 2.4 GHz frequency band [2]. More recently, inspired from what is done in optics [4], spiral phase plates have been realized in the 30 GHz frequency band [5]. The second one relies mainly on circular phased array [6]. It is generally composed of N short dipoles or patches, where each element is fed by the same signal with a  $\pm 2\pi \ell N$  phase shift compared to its neighbor. Alternatively, it has been proposed to use a circular time-switched array [7] for similar results at a lower cost. More recently, a Butler matrix has been devised to feed the antenna elements [8]. However, these structures are remained mainly at simulation level.

In this communication, some antennas developed at the University of Rennes 1, are presented. The first ones consist of phase plates working in the 30 GHz frequency band. Inspired from what is done in optics, a spiral phase plate using a variable thickness and a fixed permittivity, have been realized to produce linear variation along the roll angle  $\varphi$ . Another antenna uses an original concept. It is designed using a constant thickness and a variable permittivity. This latest phase plate is composed of a set of sub-plates in which holes are drilled to control the permittivity (Figure 1). Finally, we present a circular phased array using an original phase shifter to generate an OAM mode l = 1. This OAM-wave generator uses four patches, working at a frequency of 2.5 GHz. They are fed by a single transmission line of special form. The structure is simple, compact, easy to realise, and can be used in many domains like radio communications and radar applications.

Besides the design procedure and the simulation data, the full experimental characteristics are given as a function of frequency for both the phase plate antennas and the circular phased patch array, designed respectively at a frequency of f = 32 GHz (Figure 2) and 2.5 GHz (Figure 3), for a  $\ell = 1$  OAM topological charge.



Figure 1. Top view of the flat phase plate and generated field (magnitude and phase). (a) Schematical Variation of permittivity as a function of the number of drilled holes. (b, c) Representation of the phase distribution (b) and energy distribution (in dB) (c) on the wavefront of an EM wave bearing OAM onto a plane. (grey-scale patterns 0 to 27 dB amplitude and 0 to  $2\pi$  phase).



Figure 2. Wave front copolarization of the flat phase plate antenna. (Left column) Phase distribution. (Right column) Beam directivity, with the characteristical "donut" shape. (a) and (b) are results of numerical simulation (CST) and (c) and (d) are measurements in anechoic chamber, all at the frequency of *32 GHz*. Each concentric circle represents a *3* degrees step for the elevation angle  $\varphi$ .



Figure 3. Simulated and measured radiation and phase patterns of OAM antenna at 2.5GHz a, b) Normalised radiation patterns ; c, d) Normalised phase patterns (in degree)

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