

# Ultra wideband vortex antenna array design for high capacity radio links

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**Abstract.** In this paper the development principles for calculation and construction of the antenna for «smooth» transmission and reception of multichannel ultra-wideband signals with a given spiral phase front applied in Radio-over-fiber system for the seamless data transmission are discussed. The detail description of the current state of research in this field is presented and deeply analyzed, so finally the new unique solutions are proposed and described in detail. Since the transceiver antenna has a significant effect on the signal shape working as a spatio-temporal filter, then the phase of the emitted wave (spin-orbital state) depends only on the antenna geometry. So the inverse problem of the antenna theory should be solved, when the antenna array configuration is synthesized on the basis of the given aperture. The antenna is considered as distributed in-space volume antenna array based on tripoles, providing the reception of a «tangled» signal with wave division and spin-orbital state multiplexing. The antenna is calculated using a mathematical and computer modelling and characterized with stable characteristics in the ultra-wide frequency band.

**Keywords:** Vortex beams, phased antenna array, ultra wideband, tripole, PAN.

## 1. Introduction

Nowadays telecommunication networks are characterized with a huge number of devices connected to the Internet. Since this number is increasing exponentially in the nearest future the lack of the channels and communication links capacity will not be able to provide the suitable quality of service. On the other hand, the constantly growing amount of data transferred set more severe requirements for data rate even in wireless links that are getting more popular due to their flexibility.

The most promising solution satisfying the aforementioned requirements is the Radio-over-Fiber (RoF) technology which combines high data rate and huge capacity of fiber links with the mobility and scalability of radio channels. The optimization of RoF technology was of the highest interest in the scientific society in the recent years and has already come to the lack of new ideas. Hence, the development of fundamentally new technology operating on the physical layer which would increase the efficiency of the optical and wireless links exploitation is the challenging task.

One of the main ideas in the front line of optical communications is the data transmission based on the spin or orbital angular momentum (OAM) utilization of the electromagnetic field considering as the new degree of freedom. Mathematically, the utilization of spiral (vortex) beams with a given spin-orbital state enables the additional basis of orthogonal functions available for data transmission and enhancement for noise immunity. Thus, the multiplexing by the spin-orbital state becomes possible in

addition to the existing wave division multiplexing. This technology enables high-speed and ultra-wideband access (up to 100 Gbit/s) to the global network over the vast territories.

Nowadays the application of vortex technology is also limited due to the lack of devices capable of providing a «smooth» undistorted transformation of the optical signal into the radio domain and vice versa. The optics-to-radio transformation in a narrow frequency band also one of the hot topics in the scientific society that can be confirmed by the large number of publications all over the world. The optics-to-radio transformations topic in the ultra-wide frequency band remains open, since the received ultra-wideband signal is represented by a complex interference of a «tangled» multi-channel signal with external radiation. Furthermore, the transceiver antenna also has a significant effect on the signal shape working as a spatio-temporal filter.

There is a huge number of papers in the domestic and foreign scientific resources, in which antenna prototypes for transmitting-receiving signals with a given spin-orbital state are proposed. These antennas are distinguished by a variety of designs and demonstrate acceptable radiation characteristics at short distances (up to 10 m) in a narrow frequency band. In contrast to the analogues considered, we propose to develop the volume antenna array which would be capable of transmitting/receiving signals with a given spin-orbital state in an ultra-wide frequency band. It can be achieved due to the space distribution of the antenna array system based on tripoles, providing the reception of a «tangled» signal with wave division and spin-orbital state multiplexing. Furthermore, the proposed volume antenna array allows detecting the signal, hidden in the noise level, providing the competitive advantage since it has no analogues in the world.

In this regard, it is necessary to ensure the constancy of antennas frequency characteristics in the ultra-wide frequency band. Consequently, the principles development for calculation and construction of the antenna for transmission and reception of multichannel ultra-wideband signals with a given spiral phase front applied in Radio-over-fiber system for the seamless data transmission is an actual scientific and technical task.

The paper is devoted to developing a new method for constructing of transmitting-receiving antennas, based on the distributed in-space volume broadband antenna array. Since the received signal is a complex multimode «tangled» ultra-wideband signal interfering with noise, it cannot be received on a single antenna or on a typical antenna array. In this case, it is necessary to use an antenna array system located in space in such a way to ensure the reception of this «volume» signal and, at the same time, have stable characteristics in the ultra-wide frequency band. As the radiators it is proposed to use tripoles, which are three perpendicular dipoles.

The paper is organized as follows: in Section II the current state of the mentioned research is described in detail. Section III is devoted to specifying the scientific task and proposing the solutions. The conclusions are done in Section IV.

## 2. State of the art for antennas generating radio OAM beams

Recently, vortex beam has attracted much attention and have been successfully employed for widespread applications by lots of researchers in many fields, however, the majority of them are conducted in the optical domain. It was not found until very recently that the photon vortex beams can be used in the low frequency radio domain. From that moment on, many optical methods were introduced to give rise to vortex radio beams. However, in microwave regime, the selectable methods for vortex beams generation are still rare.

Single vortex modes can be generated in many ways: antenna array, spiral phase plate (SPP), holographic plate and etc. For example, [1] proposes the antenna with working frequency of 2 GHz that combines the circular patch and 3 dB quadrature hybrid to generate radio beams with good defined vortex mode, and the signs of vortex mode are reconfigurable. This decision is simply geometry, low cost, but due to the divergence of vortex waves, beam focusing is necessary.

In [2] a multi-layer phase shifting surface based flat plate is designed to offer a combination of lens and SPP for vortex beam generation and convergence at 60 GHz. The proposed design consists of a series of phase-shift unit cells to control the emergent phase and form a flat lens for beam focusing. Eight different PSS unit cells are used to control the phase of transmitted wave, which are arranged to

form the expected array. However, the bandwidth of generated signal is limited to 20 kHz, so this solution cannot be used for spin-orbital momentum multiplexing.

Another common solution in microwave domain relies mainly on the circular arrays, and the element is fed with the uniform amplitude but with a successive phase difference. In this way [3] provides an effective solution of generating dual circularly-polarized (CP) dual-mode vortex beams. The antenna consists of four dual-CP elements that are sequentially rotated 90 degrees in the clockwise direction. The dual-mode operation for vortex signal is achieved through the opposite phase differences generated for and, when the dual-CP elements are sequentially rotated in the clockwise direction. As one parabolic dish or one SPP corresponds to only one vortex mode, the multiplexing of different vortex beams is not simple to be implemented, which restricts the extensive applications. Up to the date, only a few antennas for a mixed vortex beams generation were proposed. In some publications the planar circuit structure is used as a promising solution for vortex beams generation with less space occupancy, weight and cost.

The half-mode substrate integrated waveguide is regarded as planar waveguide structure in [4]. It has got more compact dimensions and better radiation efficiency comparing with common substrate integrated waveguide. For the purpose of multiplexing multi-vortex modes, different resonators with two feeds of 90 degrees phase difference are put together to operate at frequency of 10 GHz.

The Rotman lens-fed antenna array is used in [5] providing an effective design of generating five-mode vortex radio beams. The Rotman lens is a viable beam forming approach instead of electronically scanned arrays for its low cost and the ease of implementation. The lens-fed array employs a two-layer structure for size reduction, and the lens body and the antenna array are segregated by a common ground plane to eliminate spurious radiation and thus improve the performance of the vortex beams.

In [6] eight circular polarized corner cutting micro-strip patch antenna elements are arranged equidistantly along the circumference to form a 8-element multimodal vortex electromagnetic wave micro-strip array antenna which can work at 2,45 GHz frequency band and generate vortex electromagnetic wave with double characteristics of circular polarization and a variety of vortex modes at the same frequency.

Finally, only a few researches were conducted to construct antennas generating arbitrary mixed vortex modes so far. In [7] a series of planar vortex antennas to generate arbitrary single-mode and mixed-mode vortex waves were experimentally investigated. The proposed antennas adopt planar quasi-period air holes that are drilled in the substrate to form the proposed planar-SPP, which is used to compensate the phase delay associated with incident radio waves from different paths and generates the desired outputting phase distribution. The generation of vortex waves with arbitrary mixed modes is achieved by properly dividing the proposed structure into several small parts to implement individual vortex mode.

Most of the methods for getting multi-mode vortex radio beams remain up to now mainly at simulation level, since their implementations are of complicated structure, feeding elements are difficult to realize in real practice, which also restrict the application. Furthermore, to the best of our knowledge no single antenna has been reported to generate multi-mode broadband vortex signal with stable characteristics in the ultra-wide frequency band.

### 3. The volume broadband antenna array proposal

It is specifically proposed to develop and theoretically substantiate the methodology for the synthesis of volume antenna arrays receiving ultra-wideband (UWB) radio signals with a given spin-orbital state, in reliance on the generality of the orthogonal spherical functions set that form the mathematical basis of the arbitrary radiation field represented by the superposition of point sources with a certain symmetric configuration - multipoles - and the Eigen functions of the angular momentum operators defining the spin-orbital state of the electromagnetic field. To achieve this goal the specific tasks to be solved are the following:

- The mathematical and simulation model of volume antenna arrays for transmission / reception of broadband signals with a given spin-orbital state of the electromagnetic field should be developed for seamless transmission as part of the Radio-over-fiber system.

- The theoretical foundation of volume antenna arrays synthesis methodology, calculating and constructing principles should be considered.
- Various geometric configurations of the antenna array with different shapes of radiating elements should be tested to find the optimum solution.
- Simulation results analysis should be performed, including analysis of the main characteristics of volume antenna arrays (radiation patterns, reflection coefficient, input impedance, voltage standing wave ratio, gain).

The essence of the task to be solved consists in following: when multiplexing on the spin-orbital state, the phase of the emitted wave (spin-orbital state) depends only on the antenna geometry. In this connection, the inverse problem of the antenna theory should be solved, when the antenna array configuration is synthesized on the basis of the given aperture. It is known that the aperture is the area forming the antenna field and it is the coordinates function, determining the radiation intensity in a given angle of space. The radiation pattern is a Fourier transform from the aperture function and it is determined by the amplitude-phase distribution. The phase represents a given spin-orbital state, which is used for multiplexing.

Thus, the antenna is a spatio-temporal selective filter, which output is a convolution, i.e. the result of integrating the intensity distribution along the antenna plane, and the weight function is the initially defined aperture. Since the transceiver antenna also has a significant influence on the shape of the signal, since it is a spatio-temporal filter, then it is necessary to provide the constancy of the frequency characteristics of antenna devices in the ultra-wide frequency band when designing the antenna. When the given aperture function is defined, then the geometry of the antenna array will be calculated in such a way as to ensure the receiving a "volume" ultra-wideband signal interfering with noise.

The development of the mathematical model of volume antenna arrays is meant to be based on using the mathematical apparatus of quantum mechanics and the basic concepts of antenna theory, fiber optics, spectral analysis, radio wave propagation, electrical coupling and algorithms. For the synthesizing methodology and constructing principles development for the volume antenna arrays we propose to use the principles of designing antenna-feeder devices, and the inverse antenna synthesis theory on the basis of aperture function radio waves propagation theory, electrical coupling and algorithms. The methods of mathematical and computer modeling, including programming, will be applied.

The effectiveness evaluation of the proposed methodology, models, developed radiators and configurations will be done with numerical experiment. On the basis of the data obtained, the structures of transmitting and receiving volume antenna arrays will be optimized to ensure stable frequency characteristics.

The obtained results will form a new knowledge base in the area of antenna systems that can receive radio signals with a given spin-orbital state.

#### 4. Conclusions

In this paper we propose the methodology for the synthesis of volume antenna arrays receiving UWB radio signals with a given spin-orbital state which can be applied to gain into the efficiency of RoF telecommunication systems. The needful tasks to achieve this goal are considered. Also the possible solutions are suggested for the proposed concepts. The expected result is a configuration of the volume antenna array, the structure of which is calculated using a mathematical and computer modelling providing the radio signals reception with a given spin-orbital state of the electromagnetic field.

The scientific significance is the development of new methods and algorithms for calculating a new class of volume antenna systems providing the transmission/reception of the radio-vortex with spin-orbital state multiplexing of the electromagnetic waves and the transformation of the UWB signal from optical to the radio domain while preserving the specified wave characteristics (polarization and spiral phase front). This, in turn, will create the background for conducting new researches of proposed class of antenna systems, studying and optimizing their designs and calculation algorithms, expanding the scope of application areas and identifying prospects for their utilization.

In aggregate, a new base will be formed to expand the knowledge base on the scientific and technological problem of increasing the capacity and noise immunity of hybrid fiber-optic wireless communication links by using multimode compositions with a given spin-orbital state of the electromagnetic field.

The social significance is improving the quality of data services provided by the data rate incensement, due to the absence of temporary delays on additional transformations, the absence of errors and distortions, and the expansion of wireless distance due to the volume antenna radiation pattern control. In addition, the utilization of the proposed antenna systems enables services that were previously unavailable due to the narrow bandwidth of traditional radio technologies (Wi-Fi, Wi MAX, LTE, LTE Advanced, Wi-Gig, UWB) and hence will increase the number of services provided for the user. For telecom operators, the utilization of the proposed volume antenna arrays will significantly improve the usage efficiency of existing equipment and reduce construction costs of new communication links, and thus, will create the possibility of service area expanding.

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