An approach for generating and detecting the signals with the given orbital angular momentum for wireless communication systems

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Abstract. The paper is devoted to the development of methods for increasing the efficiency of wireless communication channels via usage of multiplexing by the orbital angular momentum (OAM), which allows to form an additional basis of orthogonal functions for the simultaneous independent transmission of several signals. In particular, the generation process involves the formation of a beam using an antenna array radiating in the 77-78.5 GHz range, the design of which allows to form various orders of the OAM signals without restructuring. The important points in the design process were ensuring the minimum divergence of the beam during the propagation and obtaining the maximum gain. Regarding receiving, a solution was proposed for detecting an OAM signal in case of misalignment between transmitting and receiving antennas. An antenna array consisting of two perpendicular dipoles has been proposed as a receiving device, which allows receiving the OAM signal from any direction. An important point of detection is the preservation of information about the phase of the received signal. The results of calculations and simulation of the transmission and reception in the range of 77-78.5 GHz are shown.

1. Introduction

Currently, the new information technologies that will increase the efficiency of using the bandwidth of wireless communication channels are actively searched by the global scientific community. One of these directions is the use of the orbital angular momentum (OAM) of electromagnetic waves. OAM is a spiral dislocation of the electromagnetic wave wavefront defined by a phase factor $e^{il\phi}$, where l – an integer specifying the OAM order. So the waves with a non-zero OAM form an orthogonal basis of radio signals that can be used to implement a new method of data multiplexing, along with traditional methods. The secure communication channels, as well as the multiple access can be implemented by using the radio waves with different OAM orders in existing and future radio communication networks significantly saving the frequency resource.

Unfortunately, OAM multiplexing technology is associated with the following difficulties. First, the transmitting and receiving antennas must satisfy the important requirement of the possibility of generating and receiving mixed signals with a complex phase front. Secondly, the OAM electromagnetic waves divergence significantly limits the communication range, which leads to the necessity of searching the methods for controlling the radiation directivity. Thirdly, it is very difficult to estimate the phase on the receiving side due to mismatching between transmitter and receiver and, therefore, significant signal attenuation.

There are three main research directions in the field of wireless communication using OAM radio waves: generating a radio signal with a given OAM order, propagation of this radio signal in the wireless channel, and detecting the OAM signal. A large number of studies confirm the effective transmission using OAM in the frequency range above 30 GHz [1-2], so we will review the existing solutions for millimeter-wave band (W-band).

One of the most popular methods for generating radio signals with the given OAM is the use of spiral phase plates (SPP), which allow forming a required phase front as the signal passes through a system of multi-format holes [3]. The advantages of SPP – small OAM beam divergence and low attenuation, disadvantages – they cannot be used in low-frequency transmission and there is no possibility of simultaneous generation of several OAM modes. The second common approach is the use of uniform circular arrays (UCA) with the power supply system, which allows specifying the required phase shift for each radiator corresponding to the generation of the selected OAM order [4]. Advantages – the ability of simultaneously generating several OAM radio waves, as well as restructuring the OAM order without changing the antenna configuration. The disadvantage is a high divergence; the radio wave energy is lost in the central radiation direction for high OAM orders. Another solution is the metasurfaces application [5]. In this case the OAM generation principle is similar to the SPP case, and the disadvantage is the same – the method is not appropriate for generating several OAM modes.

Different studies of the OAM radio signal propagation in free space are mostly focused on the problem of vortex signal divergence in space, which shortens the transmission distance and decreases the efficiency of spectrum utilization. Highly directional parabolic antennas and focusing lenses are used for providing a high convergence of radio signals, which allows to effectively and simultaneously transmit information with the different OAM order waves [6]. Moreover, the possibility of saving the transmitted phase at the receiving side is another important task, since during the OAM wave propagation the signal phase acquires additional changes due to the channel characteristics in the millimeter-wave range. It is also necessary to take into account that small-scale and large-scale fading of the vortex signal usually occurs when propagating in free space and therefore leading to the amplitude and phase change of the OAM radio signals.

The OAM signal detecting task is not enough studied today. The phase should be correctly identified, and there are a few approaches for this. When using spiral phase plates or metasurface, it is possible to detect only one OAM order, since the plate is constructively calculated for a specific order [7]. Receiving on the basis of antenna arrays has great advantages, since it allows detecting several OAM orders, but requires the precise alignment of the receiving and transmitting antennas. It's based on the spatial fast Fourier transform (FFT) algorithm, since it has the following property: after spatially sampling the sum is zero within the interval length except the designed OAM-mode. The other detection methods include phase gradient analysis, angular momentum measurement and triangulation.

Thus, the following actual scientific and technical tasks can be distinguished: the generation of a given OAM radio signal in terms of its minimum divergence during its propagation with the maximum gain of the antenna array, the known transmission line length and the possibility of controlling the orbital momentum; detection of the OAM radio signal in terms of the transmitting and receiving antennas coaxiality offset and reconstitution of the intensity distribution on the basis of partial information about the transmitted OAM radio signal.

The design will be aimed on the band of 77-78.5 GHz as today W-band (75-110 GHz) is the most attractive and promising due to the absence of severe restrictions on the radiated power level and its low workload compared to other radio frequency bands, but only its part (77-78.5 GHz) is allowed for unlicensed usage in the Russian Federation.

2. Transmitting antenna array for OAM generation

As it was mentioned above, the use of UCA for generating OAM radio signals allows quickly changing the OAM order without restructuring the UCA and simultaneously emitting several OAM radio waves, which is not available for other approaches. So the first task solution consists in developing the optimal shape and dimensions of the radiator and the whole UCA, made on the basis of microstrip line technology as the most common and proven technique for creating microwave devices [8].

The antenna array will be composed of eight small antennas, arranged in a circle at a distance of λ/2 from the circle center to the antenna center. The radiators are oriented in the way that provides the ease of feeding, i.e. their tops are directed toward the circle center, and the feeding points are located on the outer circle.

The dimensions of the microstrip antennas are 9.6 mm × 4.8 mm, and they are matched to 50 Ohm impedance. The radiating part of each antenna consists of the circle with the radius of 2.2 mm, so its low profile and provides the array miniaturization. Since we consider W-band, so Rogers RO 3003 laminate and the connectors, operating till 110 GHz, were chosen, and the designed antenna shapes are shown at figure 1.
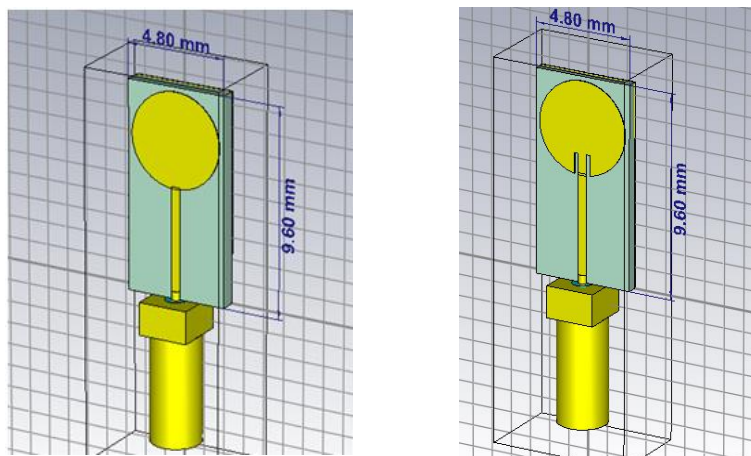

Figure 1. The designed microstrip antennas.

3. Analysis of the OAM radio waves divergence

To analyze the divergence of OAM radio waves at the receiver station a simulation model was developed in Matlab, taking into account the phase distribution of the longitudinal component of the electromagnetic field, the distance between the transmitting antenna array and the point of analysis, the radius of the transmitting antenna array, the size and number of radiators.

During the simulation study the following conclusions were drawn: in order to reduce the OAM radio wave divergence while propagating in free space it is necessary to increase the radius of the transmitting antenna array, since this allows reducing the size of receiving antenna array consisting of two perpendicular dipoles for OAM signals and increasing the wireless transmission distance [9]; in the case of transmitting an OAM radio signal over a distance many times exceeding the wavelength, the OAM radio signal degrades dramatically, which does not allow the OAM order to be identified with a receiving antenna of limited resolution; as the radius of the transmitting antenna array is increased the wavefront lines with constant phase are shortened, which in turn indicates a low divergence of the OAM radio signal (figure 2).
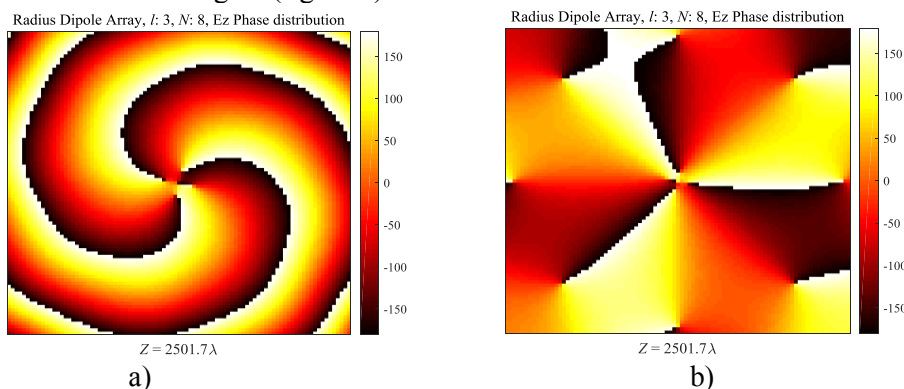

Figure 2. Wavefront lines with constant phase for different radius of transmitting antenna array: (a) radius of antenna array – 5 cm (b) radius of antenna array – 1 cm.

4. Principles for detection of OAM radio signals

When identifying the order of the transmitted OAM signal at the receiving station, problems arise in the case of misalignment of the transmitting and receiving systems. This is due to the fact that when the coordinate system is rotated, the OAM signal harmonics $e^{im\phi}$, $e^{i(m-1)\phi}$, $e^{i(m+1)\phi}$ are mixed. This problem can be avoided by using vector spherical harmonics $\vec{Y}_{l,m}(\theta,\phi)$ [10-12], which form a complete orthonormal set of rotationally invariant functions.

In this paper, it is proposed to use the model of the transmitting system specified by the spectral components of the multipole decomposition of the radiated electromagnetic field $\{a_{lm}\}$ [10]. In case of misalignment of the transmitting and receiving systems is detected by the correlation method, the relative rotation determined by three Euler angles α, β, γ is compensated based on the transformation of vector spherical harmonics [11]:

$$\vec{Y}_{l,m}(\theta',\phi') = \sum_{k \le l} D_{m,k}(\alpha,\beta,\gamma)\vec{Y}_{l,k}(\theta,\phi), \tag{1}$$

where $D_{m,k}(\alpha,\beta,\gamma)$ are Wigner functions.

When compensating for the rotation in the process of minimizing the correlation functional, the original values of the spectral coefficients $\{a_{lm}\}$ are restored to uniquely determine the structure of OAM radiation.

5. Conclusions

In this paper three important tasks regarding wireless transmission on the basis of OAM radio signals application were considered. Firstly, the task of generating such signals with the uniform circular array, composed from small microstrip antennas with the size of 9.6 mm × 4.8 mm and radiating in the band 77-78.5 GHz, was solved with the possibility of controlling the orbital momentum (its order). Secondly, the divergence of OAM radio signal was simulated and estimated. And finally the detecting principles in case when there is no coaxiality between transmitting and receiving antennas were developed on the basis of multipole decomposition of the field which contains only partial information about the transmitted signal. In total these solutions provide opportunities for implementing OAM signals multiplexing which can increase the efficiency of modern wireless communication channels.

6. References

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