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A Free-Space Optical Communication System with Singular Multiplexing of Channels

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Abstract. The paper demonstrates the practical implementation of a free-space optical communication system with singular-channel multiplexing, in which the aggregated arrivals are formed as an incoherent superposition of optical vortex beams. It is experimentally shown that elementary optical vortex beams can be separated by diffracting the aggregated arrivals on a vortex hologram. With the right choice of system parameters, a sufficiently high signal-to-noise ratio can be achieved even if the center of the aggregated arrivals shifts relative to the center of the analyzing vortex hologram.

Keywords: free-space optical communication system, multiplexing, vortex, computer-generated hologram, signal-to-noise ratio, space filtration
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1. Introduction

It can be stated that today, so-called free-space optical (FSO) communication systems are increasingly used for information transmission, serving as channels in which atmospheric optical communication links are formed [1,2].

Increasing the transmission speed in such systems, as in other similar systems, is possible by increasing the number of communication channels and using new signal multiplexing methods, since the transmission speed is directly proportional to the number of channels.

In [3,4], it was shown that, due to the “optical” nature of signal transmission along free-space channels, this task can be successfully solved using singular multiplexing. In such systems, the aggregated arrivals are formed as an incoherent superposition of vortex beams with different topological charges in the region, including the vortex center.

Additionally, it should be noted that, due to the vortex nature of communication channels in such systems, the system exhibits increased resistance to various types of physical disturbances (e.g., turbulence) along the optical route. As is known, this is because orbital angular momentum (OAM) arises in the vortex beams used for signal transmission [5,6]. The law of conservation of angular momentum determines the self-recovery property of such beams [7-11].

The singular multiplexing method described in [3,4] is based on the fact that, due to the orthogonality of channels according to OAM and different topological charges [12-16] in each channel, it is possible to separate such beams using a computer-generated vortex hologram

[17,18]. It has been shown that, in each diffraction order after such a hologram, the vortex of the beam is transformed into a smooth beam, leading to a maximum when it is focused. For the remaining beams of the aggregated arrivals propagating in this direction at the beam center, a deep (zero) minimum persists, allowing easy separation of the smooth beam with simple spatial filtering, thereby effectively demultiplexing the aggregated arrivals.

At the same time, despite the "point" nature (in the mathematical sense) of the singularity located in the center of the beam and in the center of the vortex recorded on the hologram, the mutual, even relatively large displacement of such vortices should not result in a decrease in the characteristics of the system due to singular multiplexing of channels [4].

However, in [4], only fundamental information was presented regarding field changes in the output plane of the system upon transverse displacement of the main element of the receiving unit, the vortex analyzing hologram. It was shown that under the shift of the hologram, the maximum of the smooth beam (compensated vortex), which corresponds to the signal of the corresponding channel, shifts by the same amount and in the same direction as one of the vortices into which all the other beams (uncompensated vortices) disintegrate, arising from the diffraction of the aggregated arrival. As a result, just like in a perfectly tuned system, at the point of the smooth beam maximum, all other signals transmitted by the system form a deep intensity minimum. This allows separating the useful signal from the aggregated arrival.

But no data on the practical simulation of the communication system was provided in the paper [4]. Common characteristics of communication systems, such as bit error rate, which is mainly determined by signal-to-noise ratio (SNR), were not discussed [19].

This paper is actually a continuation of [4], in which we present:

1. Data from experimental simulation of an FSO system with singular multiplexing.
2. Based on experimental data, we estimate the SNR for such systems.

2. Experimental simulation of an FSO system with singular channel multiplexing

Obviously, the simplest way to test the singular multiplexing method is when the number of communication channels is limited. That is why the performance of singular multiplexing was experimentally tested in an FSO system with two vortex communication channels. Computer-generated vortex holograms based on the mask shown in Fig. 1 were used to generate and separate vortices.

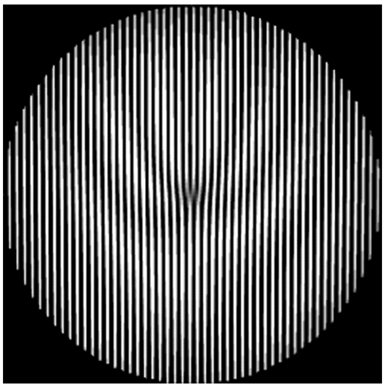

Fig. 1. Structure of the computer-generated vortex hologram.

The experimental arrangement for simulating the communication system is shown in Fig. 2. A beam from laser 1 illuminated vortex hologram 2, which formed a chain of vortices with different topological charges in the diffraction orders. After that, the +1st and -1st diffraction orders were separated by spatial filtering (using appropriate screens). As the result, two vortices with unit charges S=+1 and S=−1, were formed, which propagated in different directions and formed two communication channels of the system. One of them was directed to mirrors 6 and 7. The other, after mirror 3, passed through polarizer 5, which equalized the intensities of both beams. Modulators 4 and 8 were installed in both channels, enabling the generation of the corresponding information signals.

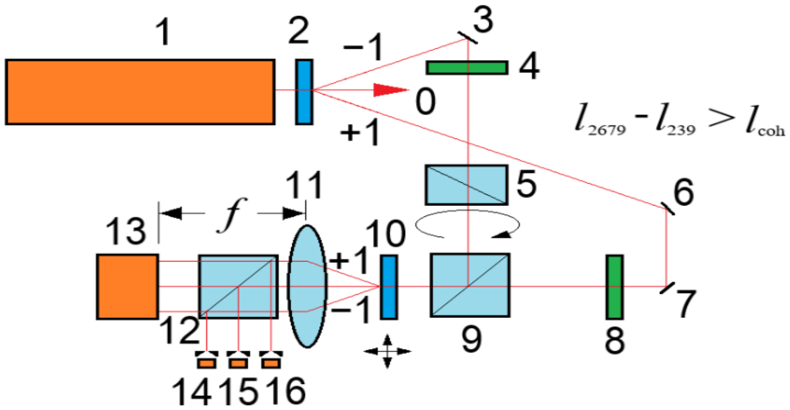

Fig. 2. Experimental setup for testing the performance of singular multiplexing: 1 – Ne-Ne laser; 2–9 – FSO system transmitter unit; 2 – vortex hologram; 3, 6, 7 – mirrors; 4, 8 – modulators; 5 – polarizer; 9 – beam splitter; 10 –16 – receiving unit of the FSO system; 10 – vortex hologram of the receiving unit; 11 – focusing objective; 12 – beam splitter; 13 – CCD camera; 14, 15, 16 – system of photodetectors with pinholes.

It should be noted that to avoid the influence of coherent noise on the operation of the FSO system, the path difference between the vortex hologram 2 and the beam splitter 9 for different channels was greater than the coherence length of the laser. In this case, the intensity of the aggregated arrivals was simply the sum of the intensities formed in each channel.

In the next stage, the vortex beams were combined into one by means of a beam splitter 9, thus forming an aggregated arrival. The intensity distribution in the aggregated arrival is shown in Fig. 3. By sequentially blocking one or the other channel, it was possible to control the centering of the vortices (the coincidence of the vortex centers at the minima of the intensity of the individual beams).

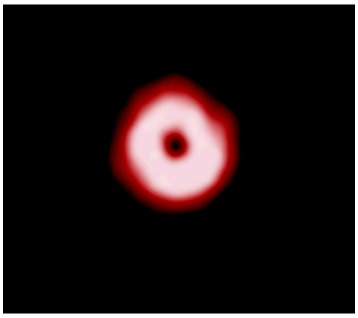

Fig. 3. Intensity distribution in the combined beam (aggregated arrival).

On the system's receiving side, the aggregated arrival was fed to an analyzing vortex hologram 10. The diffracted beams then pass through objective 11, which is located at the hologram's focal length. Spatial filtering then isolates only three diffraction orders (−1, 0, +1), which, after beam splitter 12, are focused onto the receiving platform of CCD camera 13 and a pinhole system with photodetectors 14, 15, and 16.

The CCD camera allowed us to analyze the intensity distributions in the diffraction orders including m=−1 and m=+1. When both information channels were open, a superposition of compensated and uncompensated vortices formed in both communication channels was observed in each such order.

Pinholes and photodetectors 14 and 16, located in another channel after beam splitter 12, allow analysis of the results of aggregated arrival demultiplexing. Photodetector 15 allows analysis of intensity modulation in the aggregated arrival (combined beam).

The upper row of Fig. 4 corresponds to the situation when both channels are open. As shown in the figures, maxima corresponding to compensated vortices are observed at the centers of the beams forming the diffraction orders. Recall that the path difference between the beams forming the channels is larger than the coherence length. Accordingly, the superposition of the channels is incoherent and is simply the sum of the intensities formed by the diffraction of elementary single vortices on the analyzing hologram 10.

When one of the channels was blocked, distributions corresponding to a smooth beam and a vortex with a double topological charge were formed in the plane of the CCD camera. At the same time, for different topological charge beams of the aggregated arrival, the compensated vortex was formed on different sides of the diffraction zero-order. The

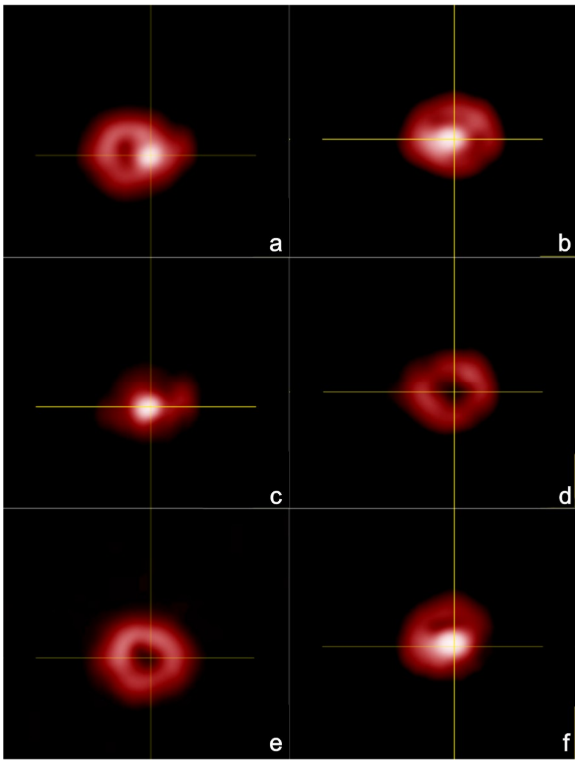

Fig. 4. Intensity distributions in the focal plane of the focusing lens in the +1st and −1st diffraction orders after the analyzing vortex hologram at the optimal position of the aggregated arrivals center and the hologram. The yellow line shows the positions of the intensity maxima in the 1st and 2nd channels in the system's output plane when both channels are open. a, b – both communication channels are open and the intensity distributions in the diffraction orders correspond to the incoherent superposition of compensated and uncompensated (vortices with double modulus charge) vortices; c, d and e, f – one of the channels is blocked and, accordingly, intensity distributions are formed by a vortex with a charge of either + or – 1. c, f – intensity distributions of smooth (compensated vortex) beams; d, e – intensity distributions of vortices with double topological charge modulus.

intensity distributions at the optimal setting of the circuit elements, when the centers of the aggregated vortices' arrivals coincide with the position of the vortex recorded on the hologram in the +1st and –1st diffraction orders, are shown in Fig. 4.

Later in the experiment, the analyzing vortex hologram was shifted transversely from its optimal position. The corresponding intensity distributions shown in Fig. 5 are similar to those shown in Fig. 4. The shift of the hologram relative to its optimal position is approximately 20% of the vortex beam width.

As shown in Fig. 5, the maximum in the superposition region is preserved (see Figs. 5a and 5b). At the same time, in the intensity distributions formed by individual vortices:

• the maxima corresponding to compensated vortices are shifted (see Figs. 5c and f);

• the intensity minima (see Figs. 5d and e) are divided into two deep minima. In other words, a vortex with a double topological charge modulus is divided into two elementary vortices (marked with a white letter V in Figs. 5d and e.

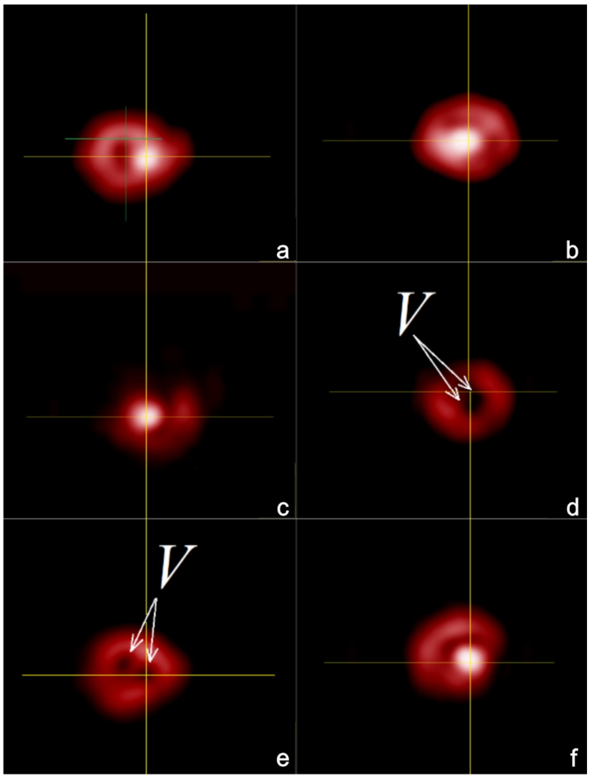

Fig. 5. Intensity distributions in the focal plane of the focusing lens in the +1st and -1st diffraction orders after the analyzing vortex hologram when the hologram is shifted relative to the optimal position by an amount close to 20% of the width of the vortex beams. The yellow line shows the positions of the intensity maxima in the 1st and 2nd channels in the system's output plane when both channels are open. The green cross in panel (a) indicates the initial position of the intensity maximum with the optimal system setting. a, b – both communication channels are open and the intensity distributions in the diffraction orders correspond to the incoherent superposition of compensated and uncompensated (vortices with double modulus charge) vortices; c, d, and e, f – one of the channels is blocked and, accordingly, intensity distributions are formed by vortices with a charge of either + or – 1. c, f – intensity distributions of smooth (compensated vortex) beams; d, e – intensity distributions of vortices with double topological charge modulus. The white letter V in figures c and f denotes elementary vortices into which vortices with double charge are divided.

Note that one of these vortices shifts by the same value and in the same direction as the maximum formed by the smooth beam (look at the position of the yellow line in Figs. 5d and e). Due to that, such a shift should not significantly affect the SNR in the communication channel. As a consequence, it can be considered experimentally established that even significant displacements of the analyzing hologram (about 20% of the beam width of the vortex beams) should not result in deterioration in system characteristics.

Simultaneously, the demultiplexed information signals and the signal carried by the aggregated arrivals were detected in another channel of the receiving unit using a system of photodetectors with pinholes 14–16.

The results of signal separation are shown in Fig. 6. Figs. 6a and b correspond to the original signals generated by modulators 4 and 8, which can be detected, for example, using photodetector 15 when one of the information channels in the transmitting unit is blocked. Fig. 6c illustrates the modulation of the beams forming the aggregated arrivals. Finally, Fig. 6d and e correspond to the modulation of the separated signals.

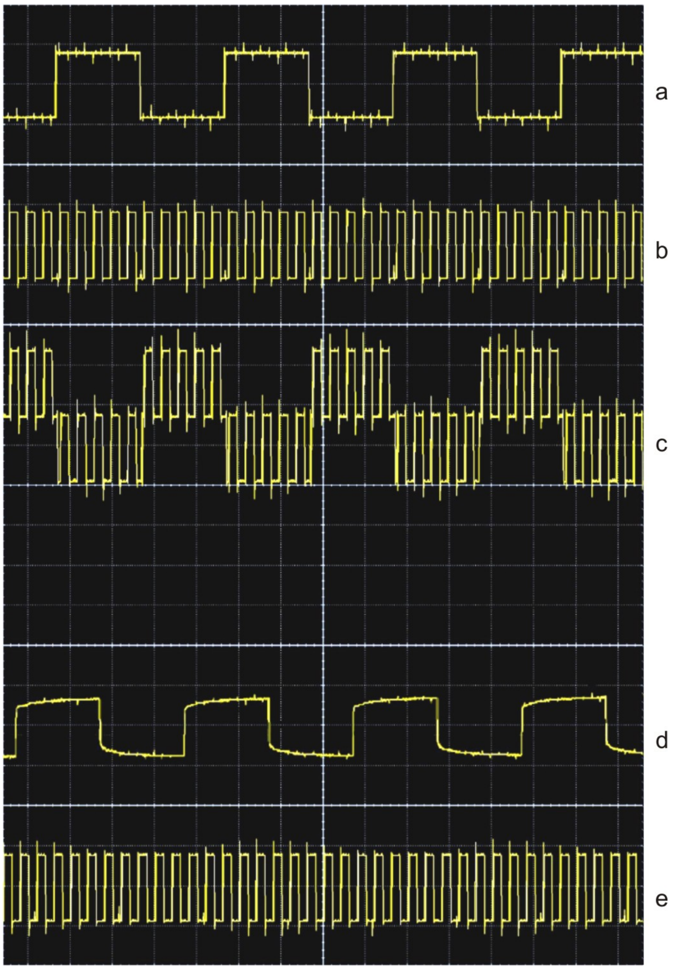

Fig. 6. Result of demultiplexing information signals. a, b – modulation of the original signals; c - aggregated arrivals; d, e – demultiplexed signals.

Thus, as shown by the results, the proposed algorithm for singular multiplexing/demultiplexing can be used to construct FSO information transmission systems.

3. Signal-to-noise ratio in an FSO system with singular channel multiplexing

As it was shown in [4], one of the factors that determines the SNR is the diameter of the pinhole $d_{\rm diskr}$, which is placed in the focusing lens's focal plane. The pinhole's center is placed in the middle of the area where the intensity distribution of the incoherent superposition is maximal.

Fig. 7 shows the experimentally obtained intensity distribution of light spots, corresponding to one of the communication channel superpositions in the focal plane of the focusing lens. The structure of the spot is shown in the upper right part of the figure. The intensity distribution was obtained in the direction indicated by the yellow line in the figure.

The pinhole diameter was determined in parts of the focused beam width, as is done for a classic zero-order Gaussian beam. As is known for a Gaussian beam, the beam width is determined by its radius at the coordinate where the beam intensity is about 37% of the maximum. The beam width calculated in this way is marked in the figure by a segment with red arrows.

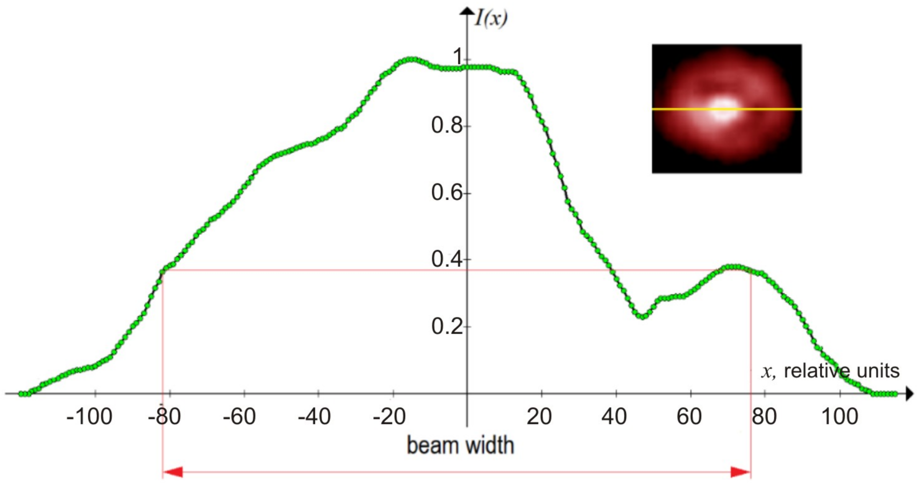

Fig. 7. Experimentally obtained intensity distribution in one of the light spots corresponding to one of the communication channel superpositions in the focusing lens focal plane.

Fig. 8 shows the intensity distributions in the pinhole zone for various channel diameters, in channels where compensated and uncompensated vortices are formed in the optimal FSO system configuration.

Based on experimental data, SNRs were calculated for different pinhole sizes using the ratio

$$\mathrm{SNR} = \frac{I_{s+n}}{I_n}, \qquad (1)$$

where I_{s+n} is the total intensity of the demultiplexed beam field entering the pinhole area, and I_n is the total intensity of the uncompensated vortex field at the same location on the output plane over the same area.

The calculations showed that the SNR reaches a value close to 30 when the pinhole size is about 10% of the beam width.

The dependence of the SNR on the pinhole size is shown in Fig. 9. Obviously, the SNR will continue to increase if the pinhole diameter is decreased. However, reducing this

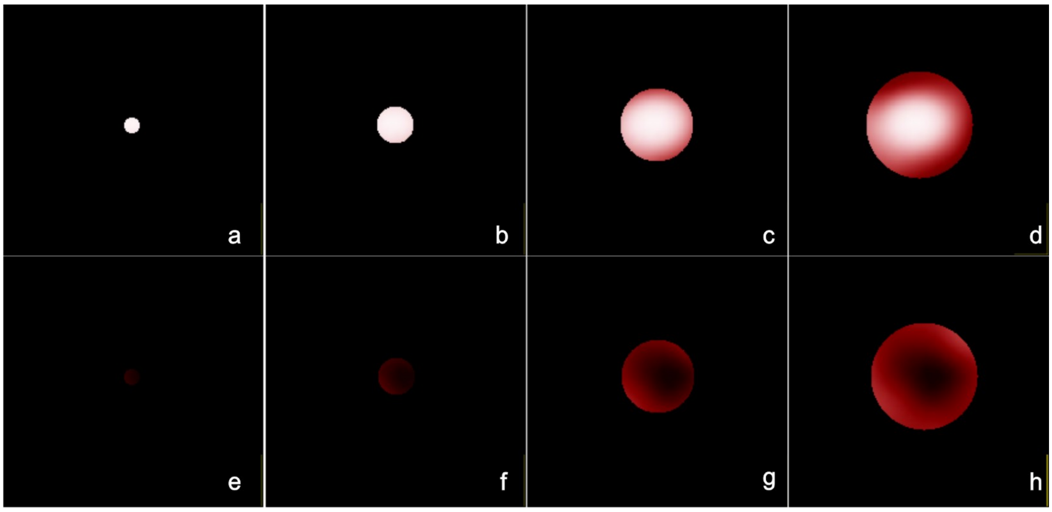

Fig. 8. Intensity distributions in the pinhole zone for its various diameters for channels in which compensated and uncompensated vortices are formed in the optimal FSO system configuration. a-d – field in the pinhole zone for a smooth beam; e-h – intensity in the same place of an uncompensated vortex; figures a, e – pinhole diameter ~10%, b, f – pinhole diameter ~20% of the beam width, c, g – ~30%, d, h – ~70% of the beam width, respectively.

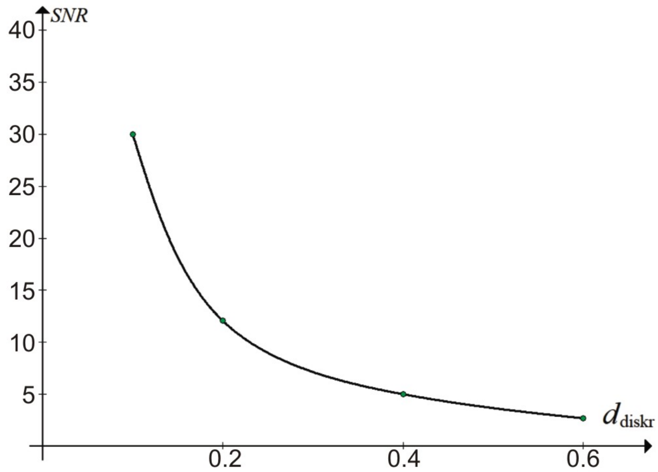

Fig. 9. Dependence of SNR on pinhole size. The pinhole diameter is given as in parts of the focused beam width.

parameter will result in lower energy efficiency. In other words, choosing the pinhole diameter requires a reasonable compromise between achieving a certain SNR value and other parameters of the FSO system.

In conclusion, we note that the SNR value calculated in the same way, with a pinhole diameter of ~10% of the beam width in a situation where the analyzing hologram is shifted by approximately 20% of the vortex beam width relative to the optimal position, remained virtually unchanged compared to the "perfectly" tuned system.

4. Discussion

Thus, based on the research results, it can be concluded that the effective implementation of FSO systems with singular multiplexing is possible not only in principle but also in practice. At the same time, it is clear that results from a two-channel system can be successfully applied to evaluate a system with a large number of channels.

It is necessary to discuss the system's energy efficiency separately. This is necessary for the following reasons. As follows from the singular multiplexing principle, a device that, in any case, functions as a diffraction element is used to create a communication channel, whether it is a computer-generated hologram or a spatial-temporal light modulator. This leads to inevitable power losses at the light source’s input, as such an element has a finite diffraction efficiency. Also, as we have shown above, the lower the pinhole diameter in the output block, the higher the signal-to-noise ratio of the transmitted signal. This is especially important for systems with a large number of channels. As a result, constructing a system with a large number of channels requires a radiation source with high output power. However, considering that the group flux at the transmitting unit output is formed as an incoherent superposition of beams, it is evident that the solution in this situation can be the formation of each channel by its own individual source.

It is necessary to emphasize that for the system with singular multiplexing to function correctly, it is essential that all beams forming the aggregated arrivals are coaxially propagated in the same direction. Therefore, in a real-acting system, a device must be provided at the output of the transmitting block to control the beam angle parameters and the coordinates of their centers (zero intensity points).

5. Conclusions

Research results show the following:

1. Based on the results of the experimental investigation, it can indeed be argued that one of the best ways to speed up and increase the volume of signals transmitted in an FSO system is to use singular multiplexing/demultiplexing of communication channels.
2. A prototype FSO system with two vortex channels has been realized and tested.
3. Demultiplexing of aggregated arrival channels is possible due to the vortex beam transformation by diffraction on a computer-generated analyzing vortex hologram. In this case, in each diffraction order, only one of the vortex beams of the aggregated arrivals becomes smooth. Such a beam forms a maximum intensity when focused. All other beams propagating in the direction of this diffraction order remain vortex ones and form a deep minimum in the center of the receiving plane.
4. Experimental dependencies for the signal-to-noise ratio for different pinhole diameters have been obtained. It was shown that even with a significant shift of the analyzing hologram (about 20% of the width of the vortex beams) relative to the optimal position for the pinhole diameter value of ~10% of the focused spot width, the signal-to-noise ratio remains the same.

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Conflict of interest. The authors declare no conflict of interest.

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Анотація. *У статті демонструється практична реалізація FSO системи зв'язку з сингулярним мультиплексуванням каналів, в якій груповий потік формуються як некогерентна суперпозиція вихрових пучків. Експериментально показано, що елементарні вихрові пучки можуть бути розділені шляхом дифракції групового потоку на вихровій голограмі. При правильному виборі параметрів системи можна досягти достатньо високого співвідношення сигнал/шум, навіть якщо центр групового потоку зміщується відносно центру аналізуючої вихрової голограми.*

Ключові слова: *FSO система зв'язку, мультиплексування, вихор, комп'ютерно-генерована голограма, співвідношення сигнал/шум, просторова фільтрація*