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Optical implementation of the vortex information channel

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Abstract. Recently, composed vortex fields generated by means of a spatial light modulator working in a dynamical regime have been examined as prospective information carriers. In this paper, an advanced optical set-up utilizing vortices for transfer of information is proposed and experimentally verified. Its operation is based on a sophisticated design of phase-only masks enabling information encoding and decoding. In the proposed vortex communication channel, the photolithographically prepared masks are used for generation of a composed vortex field carrying information. Dynamics of information encoding and decoding is achieved by switching of an array of light sources illuminating the phase masks.

Contents

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1. Introduction

Optical vortices (OVs) represent a very attractive and fast growing area of singular optics [1]. They possess interesting physical properties originating particularly from dislocations of their phase structure. The OVs can be comprehended as dark beams whose wavefront is twisted like a corkscrew around the propagation axis. Along the beam axis, the phase is undefined and the intensity vanishes there. A single OV is characterized by an integer called the topological charge. It can be positive or negative depending on the twist direction of the wavefront and its magnitude defines a pitch of the vortex helical wavefront. The twisted phase structure of the vortex causes spinning of the light energy and results in a nonzero orbital angular momentum (OAM) carried by the vortex beam [2]. Its amount is proportional to the topological charge of the vortex beam. In applications, the mechanical effects of the OAM are utilized for orbiting of trapped particles [3] and for a design of wheels used as a light propeller in micro electro mechanical systems [4]. The OVs are also prospective tools for classical and quantum information. Such applications comprise a possibility to illuminate a target by a vortex field and to acquire information about its geometrical and physical properties by analyzing the eigenstates of the OAM of the transmitted or reflected signal [5]. Optical beams carrying OAM can also be used for super-high density data storage [6] and information encoding. The angular momentum carried by a standard beam has only spin component encoded into its circular polarization. All possible spin states can be constructed with just two polarization states: left-handed and right-handed circular polarizations. In the case of vortex beams, the information can be encoded into multi-dimensional states of their OAM. By this way, the OVs provide additional degrees of freedom which can be utilized for an increase of the information density in the processes of the information encoding and recording.

Recently, a prospective method exploiting the phase topology of vortex fields for encoding, transfer and decoding of information was proposed and experimentally verified. In [7], the pseudo-nondiffracting beams were used as an information carrier while in [8] the Laguerre–Gaussian beams were utilized. The method is based on generation of the composed vortex field representing a superposition of single vortex beams with well defined topological charges. Amplitudes of the separate vortices can be comprehended as weight coefficients which can be switched between values ‘0’ and ‘1’ and represent bits of transferred information. The composed vortex field then serves as a carrier of information and enables information transfer through a free space. Information decoding is based on an identification of single vortices and reading of their amplitudes. In this process, the topological charges of the single vortices are used as markers enabling their spatial separation. In the original proposal [7], the composed vortex field was created from a Gaussian laser beam by means of a spatial light modulation. In experimental verification, the spatial light modulator (SLM) was used for realization of the information encoding. Such implementation is not convenient for practical operation of the information channel because sending of a sequence of information codes is required. This task must be solved by a dynamical spatial light modulation which is strongly restricted by a relatively low refresh rate of the available SLMs.

In this paper, another way to achieve dynamical generation of the composed vortex field is discussed and experimentally tested. In this method, a coaxial superposition of the single vortex beams carrying information is created from a spatially distributed light source illuminating a common phase-only mask prepared photolithographically. In this case, sending of a sequence of information codes is achieved by switching of an array of light sources

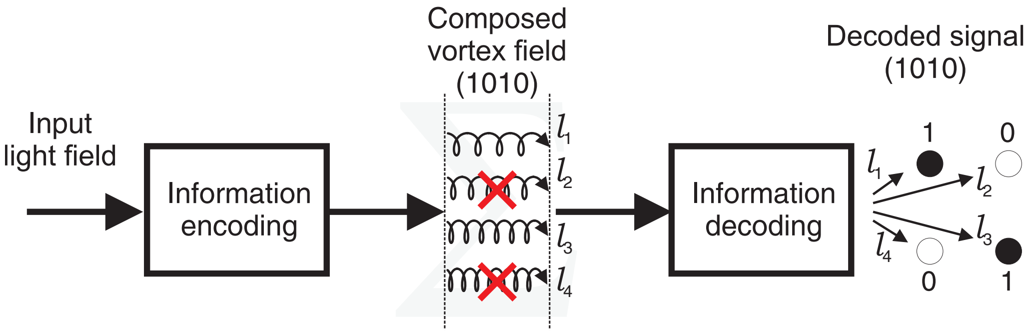

Figure 1. Principle of the vortex information encoding and decoding.

illuminating the phase mask so that a restricting dynamical spatial light modulation is not required. A basic principle of the method was discussed in [9]. In this paper, an optical implementation of the method is proposed and achieved experimental results are presented and discussed.

2. Implementation of the information channel

2.1. Principle of the information encoding

An operation of the vortex information channel is based on utilization of additional degrees of freedom of the composed vortex field. It follows from a possibility to encode information into multi-dimensional states of the OAM of the composed vortex field. A basic principle of the method is illustrated in figure 1. In this scheme, an input light field comes into the system ensuring information encoding. It consists of generation of the composed vortex field available at the output of the system. The created vortex field represents coaxial superposition of a finite number of the OVs with different topological charges. As an example, the superposition of four vortex modes is illustrated but in general, there is no physical constraint designating the dimension of the superposition. An actual information code carried by the composed vortex field is created by switching amplitudes of the separate modes used in the superposition. The composed vortex field propagates through a free space and delivers information to the receiver where the information decoding is performed. This is realized by the optical system enabling spatial separation of the OVs used in the superposition. Their intensities represent bits of transferred information and can be measured at the positions specified by means of the topological charges of the OVs.

In practical operation of the vortex information channel, the information codes must be sent subsequently. This can be ensured by generation of time variable composed vortex fields. There are two ways to realize this decisive process. Their principles can be clarified by means of figure 2. In the former case (figure 2(a)), the sequences of variable vortex fields arise from a continual single laser beam due to its dynamical spatial light modulation. This method is unsuitable for practical purposes because a low refresh rate of available SLMs restricts operation of the communication channel. In the latter case (figure 2(b)), the dynamics of the information encoding is ensured by switching of the angularly separated beams illuminating a static phase mask. The impinging beams are collimated and have planar wavefronts. By means of the phase mask, they are converted to the vortex modes with coinciding propagation directions. The

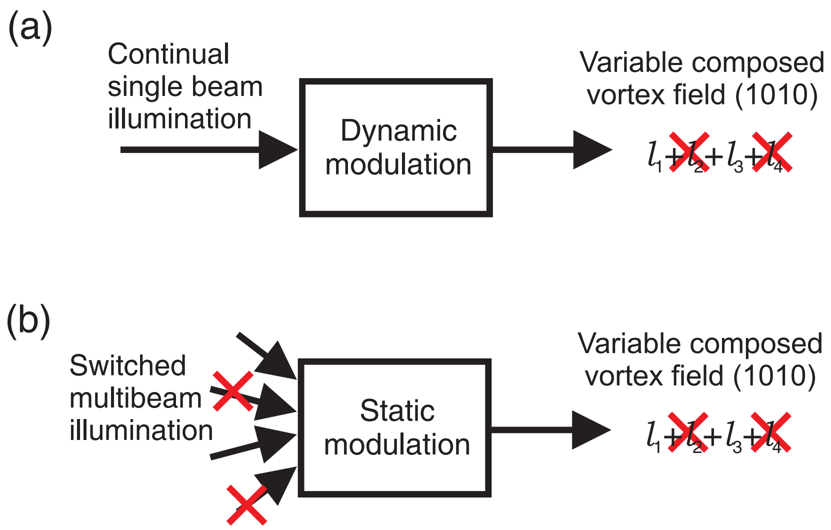

Figure 2. Generation of a time variable composed vortex field. (a) Dynamical spatial modulation of the continual single laser beam. (b) Static phase-only modulation of a time variable illumination.

topological charges are assigned to the separate vortex modes selectively depending on their inclinations in front of the phase mask. In this way, a coaxial superposition of vortex fields with different topological charges is settled. The complex amplitude of such a composed vortex field propagating along the z-axis is of the form

$$U = \sum_{m=1}^{M} a_m u_m(r, z) \exp(\mathrm{i} l_m \varphi), \tag{1}$$

where M, l_m and u_m are the total number, the topological charge and the spatial profile of the vortex beams, respectively, and r and φ denote the circular cylindrical coordinates. The coefficients a_m with admissible values '0' and '1' represent an actual information code and can be adjusted by switching the beams illuminating the phase mask.

2.2. Transfer of information through a free space

Propagation properties of the composed vortex field used for transfer of information strongly depend on its spatial structure. It is created by the phase-only mask whose role is twofold: it transforms planar wavefronts of separate input beams into helical wavefronts with different topological charges and redirects oblique impinging beams into a coaxial superposition. Since the helical phase of the OVs is compatible with diverse amplitude profiles, the phase mask can be also used for shaping of the created vortex modes into a desired form of the amplitude distribution. The best known vortex modes are higher-order Laguerre–Gauss and Bessel–Gauss beams. In both the cases, the vortex structure is robust because the total OAM must be conserved during free propagation. While the Laguerre–Gauss beams exhibit common diffractive spread during free propagation, the Bessel–Gauss beams belong to the class of so called pseudo-nondiffracting beams. This means that both the shape and the size of their transverse intensity profile remain approximately unchanged during propagation on distances of a controllable

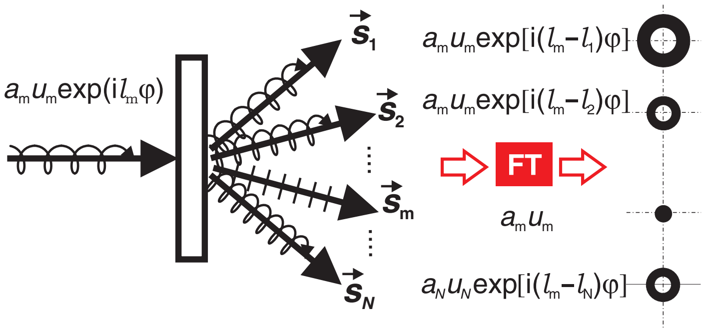

Figure 3. Transformation of a single vortex beam by the decoding phase mask.

length. Additionally, the Bessel–Gauss beams possess a self-healing ability. This can manifest itself as a self-reparation of local amplitude and phase distortions of the beam occurring during its free propagation [10]. These properties of Bessel–Gauss beams are promising for applications in optical manipulations [11] but their expedience for wireless communications is less evident. The self-healing effect does not assert whether the random aberrations caused by atmospheric turbulence strike the whole cross-section of the beam [12]. Furthermore, the Bessel–Gauss beams are generated with a relatively low energetic efficiency.

2.3. *Principle of the information decoding*

At the output of the vortex information channel, information carried by the composed vortex field is decoded by means of a specially designed phase mask. Its action is obvious from figure 3. For simplicity, the effect of the mask is examined for a single vortex beam with the topological charge l_m. Its complex amplitude is given by $U_m = a_m u_m(r)\exp(\mathrm{i}l_m\varphi)$, where a_m and $u_m(r)$ denote the constant amplitude and the transverse amplitude profile, respectively. The phase mask causes splitting of the impinging vortex into N beams propagating along directions well defined by the direction vectors $\mathbf{s_n}$. The directional transformation realized by the mask is also accompanied by a phase transformation. Inclination of the light to the direction $\mathbf{s_n}$ is performed simultaneously with addition of the helical phase $\exp(-\mathrm{i}l_n\varphi)$. The resulting fields propagating along directions $\mathbf{s_n}$ for which $n \not\equiv m$ possess helical wavefronts given by the term $\exp[\mathrm{i}(l_m - l_n)\varphi]$. If the field with the helical wavefront $\exp(\mathrm{i}l_m\varphi)$ is inclined to the direction $\mathbf{s_m}$, a complex conjugate helical phase is laid on it. As a result, the helical phase is compensated and the resulting beam has an approximately planar wavefront. The field appearing behind the phase mask is processed by means of an optical Fourier transform. The directional separated beams are localized at the positions of the Fourier plane unambiguously specified by the direction vectors $\mathbf{s_n}$. At the positions related to directions $\mathbf{s_n}$ for which $n \not\equiv m$, intensity spots with an annular shape can be observed. This is caused by the helical wavefront of the fields propagating along these directions. The bright spot is detected only at the position related to the direction $\mathbf{s_m}$. In this case, the helical wavefront of the input vortex beam is eliminated by the phase mask so that the beam with approximately planar wavefront is focused to this position. The intensity of the spot is proportional to the constant amplitude a_m of the vortex beam impinging on the phase mask. In a practical operation of the information channel, the composed vortex field with the complex amplitude (1) impinges on the phase mask. An actual information code is then represented by a chain of vortex amplitude weights $(a_1, a_2, \ldots, a_M)$. It is created by adjusting

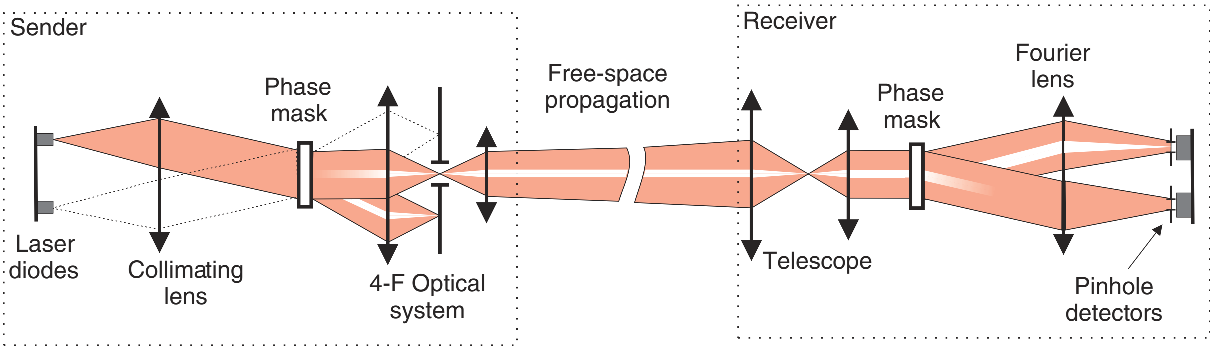

Figure 4. Optical schema of the vortex information channel.

the coefficients a_m to the values '0' or '1'. If the composed vortex field is transformed by the phase mask and processed by the Fourier lens, the information bits '0' or '1' can be determined by intensity detection at the well defined positions of the lens focal plane.

3. Experimental realization

The vortex information channel is composed of two basic subsystems. The former one performs information encoding into the composed vortex field while the latter one realizes optical processing of the incoming light field resulting in a decoding of information. The optical set-up proposed for verification of a functionality of the vortex information channel is illustrated in figure 4. The light waves coming from spatially separated laser diodes are collimated by a lens and impinge on the phase mask. Due to an action of the mask, each collimated beam splits into a collection of helical waves propagating in different directions. Their topological charges are assigned depending on the inclination of the impinging beams so that the helical waves originating from different laser diodes possess distinct topological charges. By means of the 4-f optical system placed behind the phase mask, the coaxial waves propagating along the optical axis are separated. They represent a composed vortex field whose components are mutually incoherent vortex modes originating from the separate laser diodes. They possess different topological charges and their amplitudes are adjusted to values '1' or '0' by switching of the laser diodes. The amplitudes represent bits of information carried by the composed vortex field through a free space. At the receiver, the incoming light field is transformed by a telescope and subsequently impinges on the decoding phase mask. This causes decomposition of the input vortex field. Behind the phase mask, the separate vortex modes split into a collection of waves with different propagation directions. The helical wavefront of each wave is altered by the helical phase introduced by the phase mask. Topological charges of the additional helical phase terms are assigned depending on the propagation direction of the transformed wave. The waves whose helicity was eliminated are focused to the bright intensity spots placed at the predetermined positions of the back focal plane of the Fourier lens. They can be comprehended as information bits '1'. The waves with unremoved helicity are focused to the annular spots so that the related detection positions remain dark. Such waves represent information bits '0'. In this way, the information carried by the composed vortex field can be decoded by means of the intensity detection performed at the specified positions of the focal plane of the used Fourier lens.

3.1. Design, realization and testing of the phase-only mask

Basic optical elements used in the proposed set-up are the phase-only masks enabling information encoding and decoding. An operation of the encoding mask is obvious from figure 4. An information code that is to be transferred into a composed vortex light field is created as an array of laser diodes placed at the front focal plane of the collimating lens. The optical field behind the collimating lens then can be comprehended as a plane wave superposition with the complex amplitude A given by

$$A = \sum_{n=1}^{N} a_n \exp(-\mathrm{i}\mathbf{k}_{\perp,n} \cdot \mathbf{r}_\perp - \mathrm{i}k_{z,n} z), \tag{2}$$

where $\mathbf{r}_\perp = (x, y)$ and a_n are related to amplitudes of the separate sources. They can be regarded as switching coefficients with values '0' or '1'. The transverse and longitudinal components of the wavevectors of the plane waves $\mathbf{k}_{\perp,n} = (k_{x,n}, k_{y,n})$ and $k_{z,n}$ are given by the positions of the light sources at the focal plane of the collimating lens and by its focal length. The role of the encoding mask is to redirect the incoming plane waves into a coaxial superposition and to perform their direction selective phase modulation. Each incoming plane wave is transformed to the vortex beam with the topological charge assigned depending on the inclination of the plane wave. The required transformation can be achieved by means of the complex mask enabling simultaneous amplitude and phase modulation. Its complex transparency t can be written as

$$t = \sum_{m=1}^{M=N} b_m \exp(\mathrm{i}\mathbf{k}_{\perp,m} \cdot \mathbf{r}_\perp + \mathrm{i}l_m \varphi), \tag{3}$$

where b_m are coefficients enabling power tuning of the separate vortex modes. After the transformation realized by the mask, each incoming plane wave from the superposition (2) splits up into N additional helical waves so that the total number of waves behind the mask is N^2. They propagate along directions defined by the wavevectors whose transverse components are given as $\Delta\mathbf{k}_{m,n} = \mathbf{k}_{\perp,n} - \mathbf{k}_{\perp,m}$. Behind the mask, there are N waves fulfilling the condition $\Delta\mathbf{k}_{n,n} = 0$. Such waves propagate along the z-axis and possess helical wavefronts given by the term $\exp(\mathrm{i}l_n\varphi)$, where l_n denotes the topological charge. It is an integer which gathers different values for different indices n. The axial waves represent the required composed vortex field. It carries information settled by switching of the array of sources placed in front of the collimating lens. Creation of this field can be comprehended as a process of the information encoding. The off-axis waves are undesirable and can be removed by means of the Fourier filtration.

The information encoding performed by means of the mask with the complex transparency (3) is impractical. Such a mask is hardly manufacturable and its power efficiency is low. In our set-up, a more suitable phase-only mask is used. The transparency of the mask can be written as

$$T = \exp(\mathrm{i}\psi). \tag{4}$$

Due to an optimized design, it can approximate the operation of the required complex mask (3). For the design of the phase-only mask, an iteration procedure proposed in [13] was adopted.

The used iteration algorithm operates with the phase ψ given by

$$\psi = \mathrm{Re}\left\{-\mathrm{i}\ln\left[\sum_{n=1}^{N} C_n \exp\left(-\mathrm{i}\mathbf{k}_{\perp,n}\cdot\mathbf{r}_{\perp} + \mathrm{i}l_n\varphi\right)\right]\right\}, \tag{5}$$

where the term $\mathbf{k}_{\perp,m}\cdot\mathbf{r}_{\perp}$ is responsible for elimination of the inclination of the incoming plane waves and l_n denotes the topological charge of the helical waves shaped by the mask. The coefficients C_n determine a power distribution of the helical waves creating the composed vortex field. Their values follow from an iterative procedure including several steps. At the beginning, the phase mask defined by (4) and (5) is illuminated by a superposition of N plane waves (2) with equal powers. Behind the mask, a collection of N^2 helical waves is formed. Particular interest is focused on N coaxial waves propagating along the optical axis. They are separated by the numerical Fourier filtration and represent the composed vortex field carrying information. In the further step, the field is decomposed into the Fourier series and the weights of the separate vortex components are determined. Their values are compared with the required distribution of the amplitudes of the vortex modes defined by the carried information code. The determined differences are processed in the algorithm [13]. As a result, correction of the coefficients C_n is obtained. The method has a fast convergence and in several iterations provides final values of the coefficients. If they are used in (5), the phase-only mask (4) substitutes the action of the complex mask whose transparency t is given by (3).

In the information encoding, the phase-only mask (4) is illuminated by the inclined plane waves (2). Behind the phase mask, the optical Fourier transform of the transmitted field is realized. The off-axis spatial spectrum is removed by means of the 4-f optical system so that the superposition of the vortex beams propagating along the z-axis is obtained. The complex amplitude of the composed vortex field can then be approximated by

$$U \approx \sum_{n=1}^{N} a_n u_n(r, z)\exp(\mathrm{i}l_n\varphi), \tag{6}$$

where l_n is the topological charge of the separate vortex modes and u_n denotes their slowly varying complex amplitude. The created composed vortex field carries N bits of information represented by the coefficients a_n. Their values '0' or '1' are settled by switching of the light sources which are transformed to the inclined plane waves (2) illuminating the phase mask. The phase-only mask is also used for determination of the information bits a_n in the procedure of the information decoding.

In an optical implementation of the vortex information channel, two phase-only masks prepared photolithographically are needed to perform encoding and decoding of information. Before production of the designed phase-only masks, their operation was verified by means of the SLM [14]. The roles of the phase-only masks in the sender and the receiver are different and they were tested separately. In the sender set-up, the phase mask is illuminated by an array of light sources placed at the focal plane of the lens so that a superposition of the inclined collimated beams impinges on the mask. A required action of the mask is to redirect the inclined beams into a coinciding propagation direction and to transform them into vortex beams with the topological charge assigned depending on the inclination of the input beam. This operation of the mask was proved in a simple optical set-up. Instead of the source array, a fiber end face mounted on the two-dimensional (2D) kinematic table enabling transversal displacement was used. By movement of the fiber, separate positions of the sources of the original source

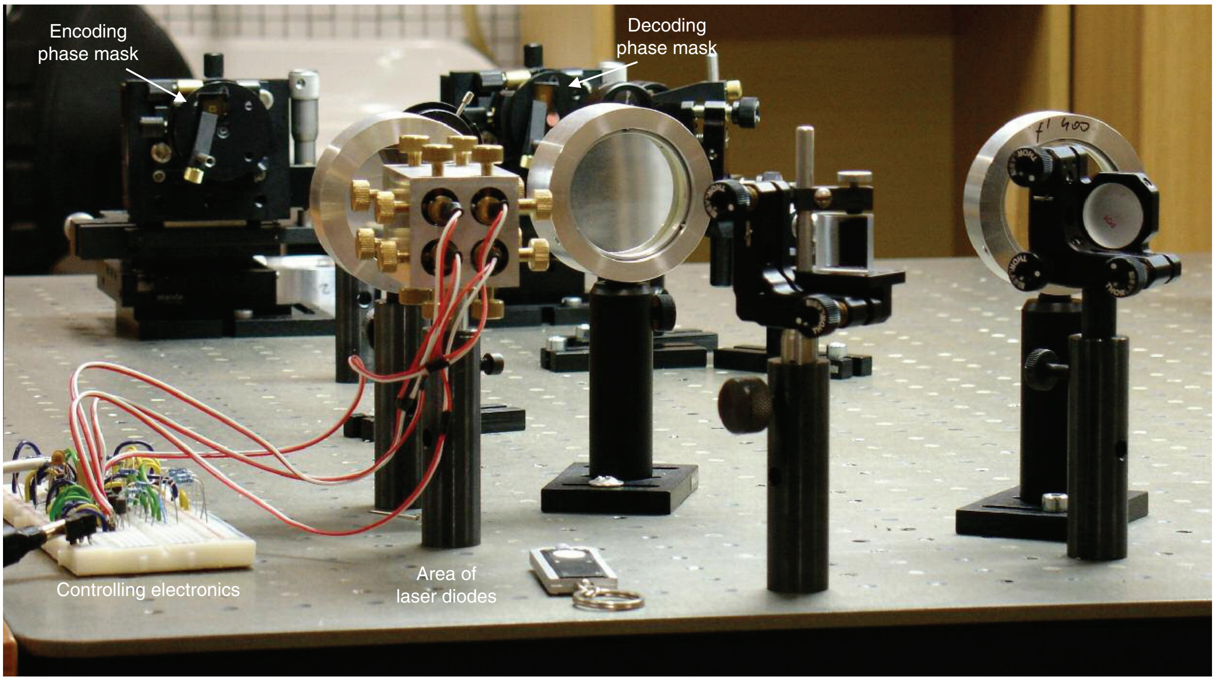

Figure 5. Snapshot of the realized vortex information channel.

array were tested. The light field emanating from the fiber end face was collected by the lens and directed to the reflective phase SLM (Boulder, 512×512 pixels). Phase changes introduced by the SLM were adjusted in such a way that the transmittance of the designed phase-only mask (4) was realized. After transformation by the SLM, the propagation direction and the topological charge of the created vortex beams were checked by means of a charge-coupled device (CCD) camera and software for image processing. In this way, correct operation of the phase mask simulated by the SLM was approved. The generated vortex beams were coaxial and their topological charges gathered well defined values specified by the positions of the fiber end face. Action of the phase mask in the receiver set-up was tested by means of two SLMs [14]. The composed vortex field carrying information was prepared by means of the amplitude SLM (CRL Opto, 1024×768 pixels). The created vortex field was directed towards the designed phase mask realized by the reflective phase SLM. The reflected field was transformed by the Fourier lens and its information content was examined by intensity detection realized by the pinhole and the CCD camera. In this way, correct action of the designed phase mask was verified. It enabled distinct spatial separation of the single vortices used in the composed vortex field so that measurement of their amplitudes representing bits of information was possible. After successful testing of the designed phase masks by means of the SLMs, they were customized photolithographically. The phase masks were realized as eight-level reflecting masks with 1500×1500 pixels in the area of $3 \times 3\,\mathrm{mm}^2$. For demonstration of the principle of the proposed method, the phase mask enabling generation of the vortex field composed of four vortex modes was prepared. The topological charges of the OVs were chosen as -8, -4, 4 and 8. The photolithographically realized masks were tested as encoding and decoding masks in the set-up demonstrating transfer of information by means of the composed vortex field.

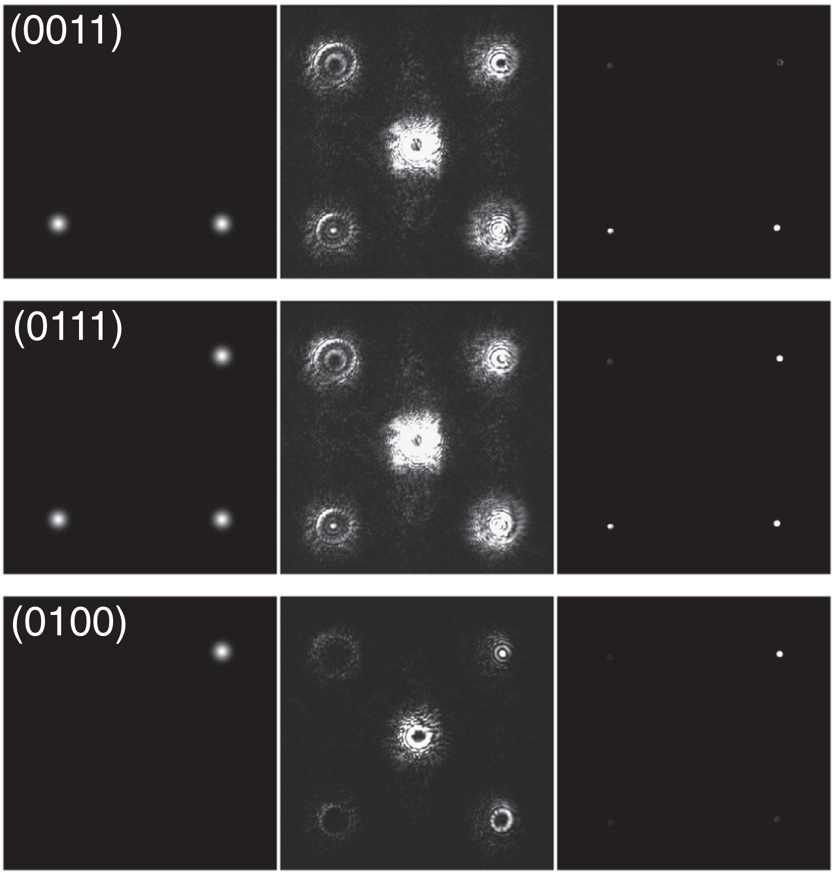

Figure 6. Experimental results demonstrating transfer of four bits of information by means of the composed vortex field: laser diodes switch-on (left column), signal decoded without pinholes (middle column), signal decoded with pinholes (right column).

3.2. Experimental results

The optical set-up used is illustrated in figure 4. It is capable of demonstrating transfer of four information bits encoded into the spatial structure of the vortex field composed of four vortex modes. An actual information code is adjusted by switching of the four light sources realized by low-cost laser diodes (635 nm and 5 mW) mounted on specially manufactured socket enabling transverse positioning and tilting of each laser diode. A lens with the focal length $f_c' = 540\,\mathrm{mm}$ was used for collimation of the light beams emitted by the laser diodes. The intensity of the separate beams was driven by a PC. The light field behind the phase mask was spatially filtered in the 4-f optical system composed of the lenses with the focal length $f_1' = 200\,\mathrm{mm}$ and $f_2' = 200\,\mathrm{mm}$. The propagation distance of the created composed vortex field between the sender and the receiver was 6 m. Information decoding was performed by means of the photolithographically prepared mask, the Fourier lens with the focal length $f_d' = 150\,\mathrm{mm}$ and by the CCD camera (F-view II, 1367×1032 pixels). A snapshot of the realized optical set-up is shown in figure 5 and the obtained experimental results are illustrated in figure 6. In the left column, the various information codes adjusted by switching of the laser diodes are shown. By means of the phase-only mask, an actual information code is recorded into the spatial structure of the composed vortex field and transferred through a free space towards the receiver. By means of the decoding set-up, the vortex field is decomposed and the separate information bits are resolved by means of the intensity detection. The output signals detected at the CCD camera with and without pinholes are illustrated in the right and middle column, respectively. In our demonstrational experiment, the laser diodes were driven by a PC in a dynamical regime. A sequence of information codes realizable with four information bits are completely demonstrated in movie 1.

4. Conclusions

In this paper, an optical implementation of the vortex information channel is proposed and discussed. An operation of the system is based on a free-space transfer of information performed by means of the composed vortex field. Information encoding and decoding is enabled by a phase modulation realized by the specially designed and photolithographically prepared phase-only masks. Dynamical operation of the information channel is realized by switching of an array of laser diodes driven by a PC. Experimental results demonstrating transfer of four information bits on a distance of six metres are also presented. The composed vortex field used as an information carrier possesses a multi-dimensional state of the OAM and represents a superposition of the single vortex modes with different topological charges. As the dimension of the superposition has technical rather than physical constraints, the method can improve performance of optical wireless communications by an increase of the density of the transferred information. Having regard to recent progress in the selective excitation of vortex fiber modes [15, 16], the vortex information encoding becomes promising also for fiber communications. At the state-of-the-art, a practical exploitation of fiber vortices is restricted by effects caused by bending or stressing a low mode fiber [17].

Acknowledgments

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