Innovative Security Technology for Optical Fiber Data Transmission Using Optical Vortex

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Abstract

This article presents system concept of the use of an optical vortex phenomenon for secure data exchange in the optical fiber line. Optical vortices are obtained in free space, and then they are introduced into the optical fiber. Their properties are examined in the world [1-2], so far, which directly shows the ability to increase the bandwidth of optical fiber. Given the structure and characteristics of the optical vortex, the authors propose to set a secure optical link. Such link can be provided in two ways.

The first method involves coding an information on optical vortex. The data in the optical fiber line can be coded by time-position modeling of the optical properties of the vortex. In addition, changing the topology of the optical vortex and the use of mode dependencies also offer the possibility of information coding.

The second way to use the vortex in the optical fiber is setting of optical fiber sensor, sensitive to the disturbance of fiber-optic transmission line. It can be achieved by propagation both - coded information in basic mode and an optical vortex in a microstructural fiber. In the case of physical impact on optical fiber the vortex disturbs the flow of data, forming the information noise on the output of the fiber.

The article presents the setup of the generation of optical vortex, for the telecommunications bandwidth, developed at the Institute of Optoelectronics, in the Security Systems Group and initial tests of the setup.

Keywords: optical vortex, fiber optic, safe communication

1. Introduction

The work on obtaining and using optical vortices in telecommunications fiber optic networks, undertaken at the Institute of Optoelectronics, is the result of global demand for increasing the speed of information flow and for increasing the security of data transmission. Each day the internet traffic increases. According to MINTS the interpolated growth of demand for data is linear since about 2007 and is projected to remain so [3]. According to R.J. Essiambre and R.W. Tkach we are inevitably approaching the limit of the capacity of optical fibers. The only solution is to search for new methods of data encoding and new possibilities of denser packing data. The solution may be optical vortices, which can propagate in telecommunications optical fiber parallel to data coded current technical solutions. Space Division Multiplexing allows increasing the capacity of an optical fiber.

There must be maintained appropriate conditions for the propagation of optical vortices. First of all optical vortices propagate only multi-core optical fibers [4]. Another problem with working with optical vortices is their instability over long distances. Currently the world record to maintain a stable optical vortex is its propagation on distance 1.1 km [5].

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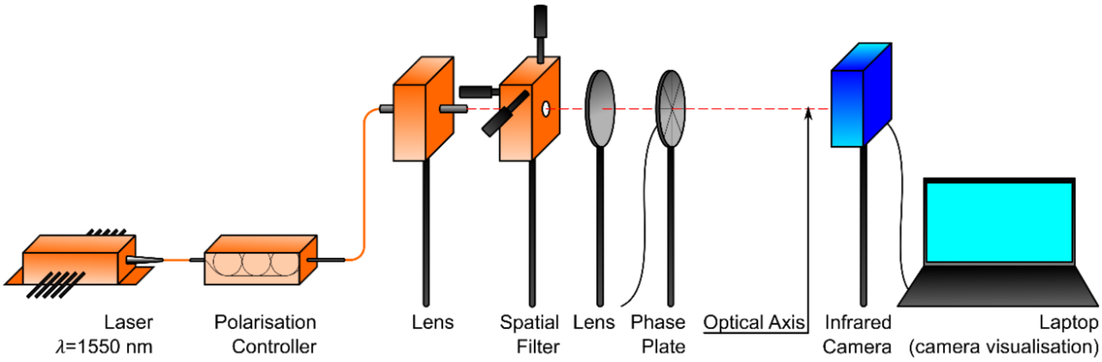
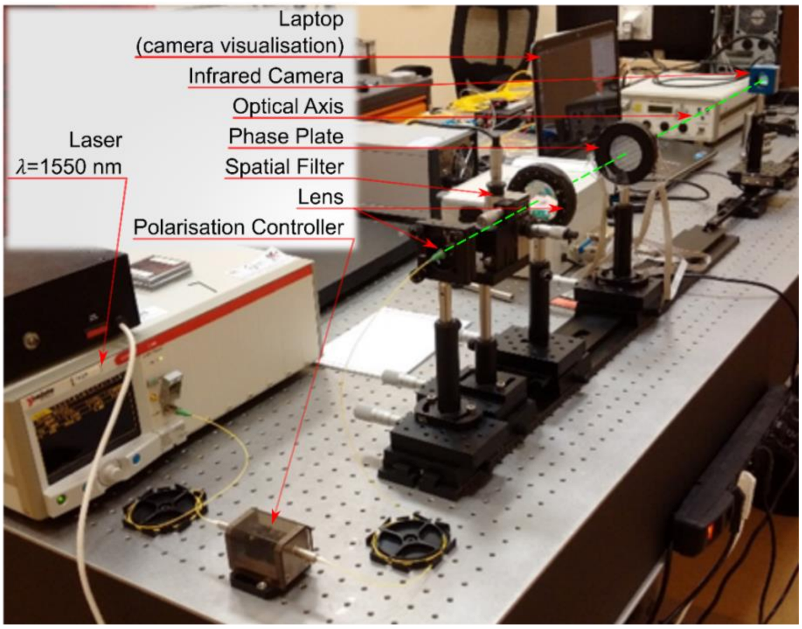
2. Optical Vortex Forming Setup

To create an optical vortex in the optical fiber, it is necessary to create it first in free space. For this purpose, the Gaussian beam must be used of a wavelength $\lambda = 1550\ nm$. In order to generate a proper focused Gaussian beam we used: a laser (of a wavelength $\lambda = 1550\ nm$), spatial filter and a pinhole. This beam is introduced to the optical fiber with a length of 0.5 m by an FC-PC connector. The beam after leaving the fiber goes to the spatial filter. The spatial filter used in the setup is a lowpass filter and this means that peripheral parts of the beam, which contain high frequencies, are being cut. The principle of operation of a spatial filter is based on diffraction, wherein the side bands are filtered off on pinhole, and only a main mod is transmitted further. The spatial filter has an aperture of adjustable diameter and the diameter used in the setup is 5 µm.



(a) Scheme



(b) Photo of the setup

Fig. 1 The setup for an optical vortex forming

There have been added a polarisation controller to the setup of generating the Gaussian beam. Polarised Gaussian beam is designed to fit the phase plate. Consequently, a beam is polarised in the horizontal direction.

The beam, after passing through the phase plate, is delayed in phase from 0 do 2π. We used the cell with the nematic liquid crystal 5CB in the setup forming the optical vortex. It is divided into 16 pieces, each of which is supplied by a different voltage. This implies that each of the 16 pieces has a different refractive index. Thanks to this the Gaussian beam, which propagates by the phase plate is gradually delayed, differently for each piece of the plate. Depending on the number of pieces and the voltage applied to them the topology of the optical vortex changes [6].

Fig. 1 shows the setup for optical vortex forming which is set together at the Institute of Optoelectronics. The setup consists of (in order):

- Laser, $\lambda = 1550$ nm,
- Fiber optic Polarisation controller,
- Lens,
- Spatial filter,
- Lens,
- Phase plate,
- Infrared camera,
- Laptop (which visualises the camera view).

Fig. 2 shows the optical vortex gained at the Institute of Optoelectronics at Military University of Technology.

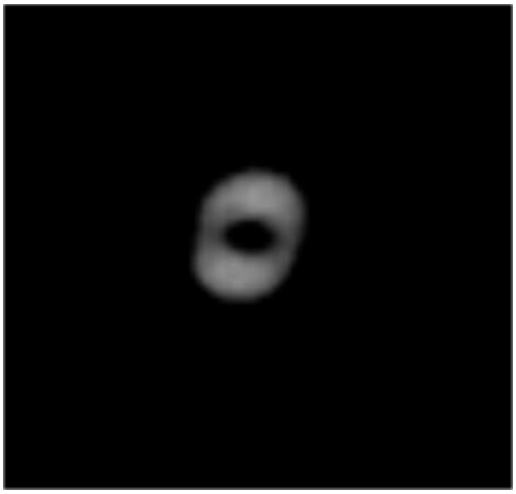


Fig. 2 The Optical Vortex observed at infrared camer

3. Mathematics of Nematic Liquid Crystals

Fig. 3 shows the 5CB nematic molecule. The electrical permeability for such nematic crystal is different for parallel direction $\varepsilon_{\parallel}$ to director $\breve{n}$ and different for perpendicular direction $\varepsilon_{\perp}$ to director $\breve{n}$.

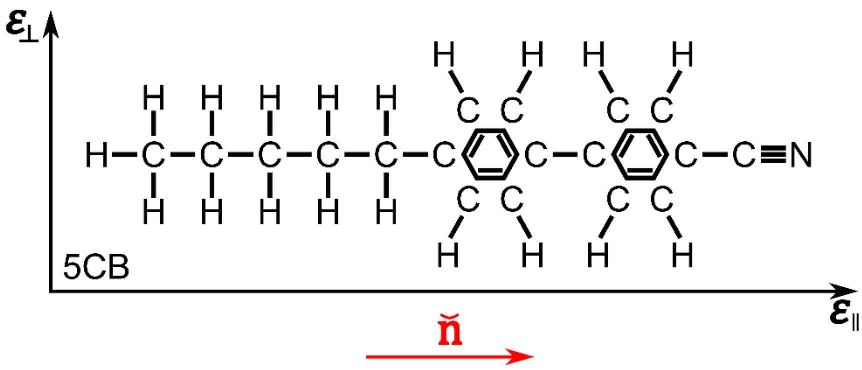


Fig. 3 Nematic 5CB molecule with the marked vectors: parallel and perpendicular to the director $\breve{n}$

The electrical permeability anisotrophy is given by Eq. (1):

$$\varepsilon_a = \varepsilon_{\parallel} - \varepsilon_{\perp} \tag{1}$$

where:

$\varepsilon_{\perp}$ – electrical permeability perpendicular to the molecules director,

$\varepsilon_{\parallel}$ – electrical permeability parallel to the molecules director.

These permeabilities are factors of the continuous medium, not of a single molecule. If $\varepsilon_a > 0$, then we have a positive liquid crystal anisotropy; if $\varepsilon_a < 0$, the crystal is negative. The nematic crystal which is used to form the optical vortex is a positive liquid crystal. The resultant refractive index of the light is given by Eq. (2):

$$n_a = n_e - n_0 \tag{2}$$

where:

n_0 – the ordinary refractive index of the light,

n_e – the extraordinary refractive index of the light,

n_a – the resultant refractive index of the light.

The density of the energy of the interaction of the nematic crystal with the electric field is made by Eq. (3) [7]:

$$f_E = -\frac{1}{2} E \cdot D = -\frac{1}{2}(E_\parallel, E_\perp) \cdot (\varepsilon_0 \varepsilon_\parallel E_\parallel, \varepsilon_0 \varepsilon_\perp E_\perp) = -\frac{1}{2}\varepsilon_0\left(\varepsilon_\parallel {E_\parallel}^2 + \varepsilon_\perp {E_\perp}^2\right) \tag{3}$$

where:

E – external electrical field,

D – electrical induction.

The function f_E depends on the orientation field $\breve{n}$ and its first deriative, the electrical field E is excited in the nematic crystal by the electrical induction D.

The phase shift between the ordinary and extraordinary rays of the light at the exit of nematic crystal can be described by the following Eq. (4):

$$\varphi = \frac{2\pi}{\lambda} d \left[\frac{1}{d}\int_0^d \frac{n_e n_o}{\sqrt{n_e^2 \cdot sin^2 \vartheta(z) + n_o^2 \cdot cos^2 \vartheta(z)}} dz - n_o\right] \tag{4}$$

For $\vartheta(z) = 0$

$$\varphi = \frac{2\pi}{\lambda}(n_e - n_o)\lambda$$

for $\vartheta(z) = \frac{\pi}{2}$

$$\varphi = 0$$

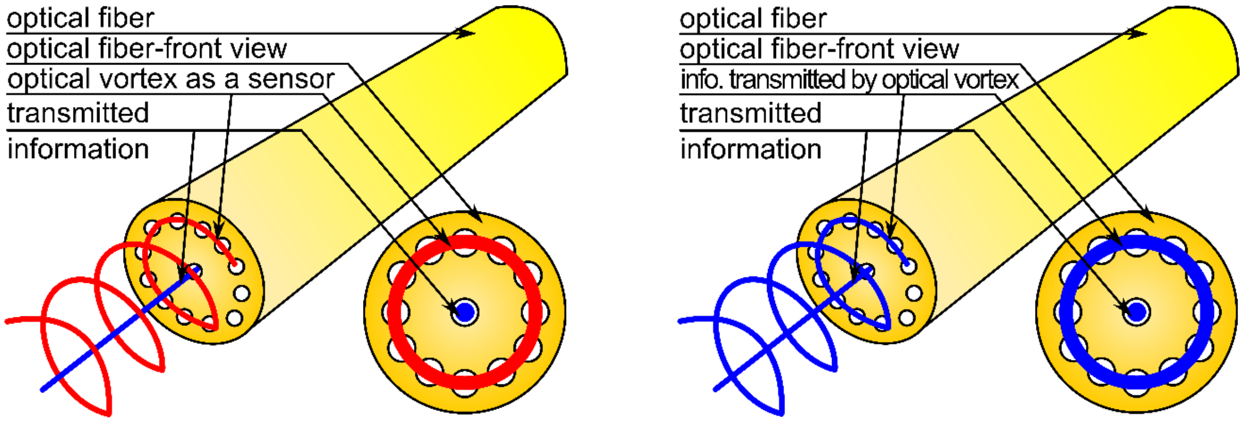
We can see, from the above, that if the liquid crystal molecules are oriented parallel to the phase plate covers, ie. $\vartheta(z) = 0$, then the propagation of light through the liquid crystal is impossible, because the ordinary ray and the extraordinary cannot interfere with each other. When the directors of the liquid crystal molecules are angled to the the covers of phase plate - close to $\vartheta(z) = \frac{\pi}{2}$, then propagation of light through the liquid crystal is possible, because the phase shift between the ordinary and the extraordinary ray of light is zero, so the rays can interfere with each other.

Depending on the deviation angle $\vartheta(z)$ of the liquid crystal molecules from the covers of phase plate the light phase is delayed from 0 to 2π, forming the optical vortex this way.

4. The Concept of Using the Optical Vortex

So far, the IOE WAT group performed numerical analysis of the forming and carrying the optical vortex in the optical fiber. On that basis the vortex forming setup was made. It allowed the study of stable spatial structure of optical vortex in the optical telecommunications.

In cooperation with the team of Dr. Paweł Mergo from UMCS in Lublin, we made microstructural fibers appropriate (according to calculations) to carry an optical vortex. Currently the technical study is focused on the correct introducing vortex to a microstructural fiber and obtaining a stable and long distance propagation in it. The idea of maintaining the optical vortex in a telecommunication fiber is to use it to secure data exchange. According to our conceptual analysis optical vortices can be used for data protection. This application can be done in various ways by using the specific properties of optical vortices. Adequately to standard fiber optic systems, we recommend the use of light intensity changes of an optical vortex as a fiber optic sensor. In addition, there is a possibility of modulating the optical vortex to falsify positions of bits in space and time so that the reproducing of the information is not possible. Fig. 4 shows schematic concept of using the optical vortex for building safe data transfer system.



(a) The optical fiber sensor (b) An information carrier

Fig. 4 A simplified diagram of the concept of using an optical vortex as: a. the optical fiber sensor, b. an information carrier - for an optical encoding; blue color is for the information flow, red is for sensor element

In the first case, according to the assumptions, the information bit (highlited with a blue line on Fig. 4 a.) propagates in the main core of the optical fiber. The optical vortex (highlited with a red line on Fig. 4 a.) propagates in the rest of the cores. The main core of the fiber is now the main communication channel. The external optical fiber cores carry constant or freely modulated optical vortex light.

In the situation of physical violation, the optical fiber the optical vortex is leaking and mixing with the encoded information. It starts a flow of light energy, which in effect falsifies the wiretapping detector. In addition, at the time of disturbance on the output of the microstructural fiber, there is being created an information noise that goes to main receiving element. On the basis of this intensity effect, the alarm of attempt of wiretapping the information transmitted in the optical fiber can be generated.

In the second case, we use the optical vortex modulation. Fig. 4(b). shows the concept of using the optical vortex as a modulated information carrier. Optical vortex, according to the assumptions, can be spatially modulated or time modulated by changing its topology and adjusting its phase delay. This modulation allows encoding information bit on the optical vortex. Spatial-time change of the position of the individual optical bits prevents correct reading it – without building a proper detection system and without access to the entire structure of the core. Wiretapping with a traditional method, eg. by using a clip-on coupler is impossible. Compared to known methods of securing the information in the fiber optic track, such as interference sensors, QKD systems, these systems bring new types of functional characteristics and they can be used to build secure tracks of classified/confidential data exchange.

5. Summary

We briefly described the idea of the formation and operation of the optical vortex obtained at the Institute of Optoelectronics at Military University of Technology. We also showed physics phenomena and mathematical description of the changes taking place in the nematic liquid crystals, which are responsible for the formation of an optical vortex. We introduced the concept of using an optical vortex both to encode information in the optical fiber track and to protect data which is transmitted in this track. As part of the work, we achieved a stable distribution of optical vortex for optical telecommunications range of the generated light - 1550 nm. In addition, we developed and made microstructural optical fiber that is suitable for carrying vortices and allows implementation of the described setup concepts. Our further studies are aimed on a deeper understanding and improving systems using optical vortices to safe information carrying.

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