Investigation of vortex laser beam injection into an optical fiber

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Abstract. We investigate Laguerre-Gaussian vortex laser beam injection into an optical fiber. Modelling of radiation entering an optical fiber with plane (cylinder) and axicon (cone with different apex angle) micro-relief is numerically investigated by the finite difference time domain (FDTD) method.

1. Introduction

The state-of-the-art technology of optical communication systems based on the conventional time/frequency division multiplexing is on the brink of reaching the capacity limits [1]. One way to achieve a manifold increase in the communication line capacity is through the use of mode division multiplexing (MDM), which was proposed for optical fibers relatively long ago [2]. Using the MDM, different transverse modes of the same optical fiber are used as a data carrier of a communication system. The data transmitted can be contained either in the mode content or in a proportion of energy carried by a particular laser mode.

A particular advantage for the enhancement of the information channel capacity is delivered by vortex optical beams carrying orbital angular momentum and having an infinite number of possible quantum states [3]. A substantial success of employing such method of channel diversity has been already demonstrated in optical fibers [4] and in free space [5].

Generation and propagation of laser vortices in free-space are studied well enough [6, 7], however, a single vortex excitation or vortex superposition generation in an optical fiber is a big problem [8-12]. As distinct from the classical LP-modes (modes in optical fibers), the vortex modes are scale invariant when entering into the fiber and when analyzed at the fiber output using diffractive microstructures [11-14]. This gives more freedom in choosing parameters of an optical scheme.

However, a particular problem is the introduction of the laser radiation into the optical fiber. And vortex beams with a screw phase singularity and zero intensity at the center, may lead to additional complications. In [15], various types of polarizations of laser radiation and their influence on the focusing of a laser beam were considered in detail. We choose circular polarization for this research.

In this paper, we consider the possibility of vortex laser beam injection into an optical fiber. To the numerical simulation of diffraction considered laser beams used the FDTD-method with high-performance computing [16]. Calculations were made on the computational cluster with power of 775 GFlops.
2. Investigation of vortex laser beam injection

We considered input into an optical fiber (with conical axicon in the first case and with cylinder in the second case at the end of fiber) of two kinds of laser beam: Gaussian beam and Laguerre-Gaussian vortex with the circular polarization. Simulation parameters: the wavelength $\lambda = 0.532$ microns, the size of the computational domain $x, y, z \in [-5.83\lambda; 5.83\lambda]$. The thickness of the absorbing layer PML $\sim 1.13\lambda$ (0.6 micron), the sampling step of space $-\lambda/31$, the sampling step of time $-\lambda/(62c)$, where $c$ is the velocity of light, $\alpha$ - the apex angle of the conical axicon. The radius of the cone base is 2.5 microns. The considered laser beams are shown in figure 1.

![Figure 1](image1.png)

Figure 1. The considered laser beams: (a) Gaussian beam; (b) Laguerre-Gaussian vortex.

The numerical results of investigations are given on figure 2 in the case with conical axicon at the end of fiber. The total intensity in the yz plane is shown for different angle $\alpha$.

![Figure 2](image2.png)

Figure 2. Injection into an optical fiber (cone) with diameter 5 microns: (a) Gaussian beam, $\alpha = 94^\circ$; (b) Laguerre-Gaussian vortex, $\alpha = 94^\circ$; (c) Gaussian beam, $\alpha = 120^\circ$; (d) Laguerre-Gaussian vortex, $\alpha = 120^\circ$. 
It should be noted that the decrease in angle gives better focusing for the considered laser beams. This applies both to the case of a Gaussian beam and to the case of the Laguerre-Gaussian: for Gauss, a narrower light needle is obtained, for a vortex – a ring.

Let us show, for comparison, the injection of the laser beams into an ordinary cylinder with a radius of 2.5 microns. Figure 3 shows the diffraction of laser beams with injection into an optical fiber. The top line is the total intensity, the bottom line is the z-component. It should be noted a narrow light needle, consisting of the z-component, obtained for the case of Laguerre-Gaussian vortex.

Figure 3. Injection into an optical fiber (cylinder) with diameter 5 microns: (a) Gaussian beam, total intensity; (b) Laguerre-Gaussian vortex, total intensity; (c) Gaussian beam, intensity of z-component; (d) Laguerre-Gaussian vortex, intensity of z-component.

3. Conclusion
In this paper shows the effect on the diffraction of considered laser beams when changing the angle of the conical axicon (at the end of optical fiber) with using the FDTD method. It is shown that the presence of the relief in the form of a conical axicon allows getting a narrower light needle compared to entering a conventional cylinder for Gaussian beams and vortex Laguerre-Gaussian beam.

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