THE INVESTIGATION OF OPTICAL BEAMS GENERATING BY OPTICAL FIBRE

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ABSTRACT

This contribution is aimed to investigate the shape of the beam that is generated by a step-index optical fiber and to demonstrate possibilities of the optical beam shaping by the help of optical fibers. Further, we show the practical utilization of the optical beam shaping technology in free space optical communication.

1 INTRODUCTION

Free space optical links (FSO) are a modern technology for communication between two points (the point-to-point connection). The distance between points is under circa 4 km and there is a direct visibility between them. Every link consists of two identical heads (we assume a fully duplex link) and the communication is realized by means of a narrow optical beam. Naturally, there is the endeavour to improve properties of free space optics links, and the optical beam shaping technology (OBS) is one of methods that can upgrade the FSO.

The laser diode in the role of the primary source is the most common active element of the transmitting head. The laser diode is irradiating a lens that forms the resulting narrow optical beam. This configuration of the transmitting head does not provide many possibilities for shaping of the resulting optical beam. This is the reason why we propose the optical fiber as a primary source instead of the laser diode. The configuration with an optical fiber gives many chances for the optical beam shaping, and this is demonstrated below.

2 THE EFFECT OF VIBRATIONS IN FREE SPACE OPTICAL COMMUNICATION

The optical heads are most frequently fixed on the building. Since the divergence of the optical beam in the FSO is usually very small (about several milliradians), the movement of the optical head can cause that the transmitting beam isn't pointed into the center of the receiver aperture, which naturally causes a decrease of the optical power on the receiver. The effect of vibrations was theoretically and experimentally inspected in many publications [3].

The advances in the FSO technology show some possibilities of suppressing fluctuations of the power on the receiver. The optical beam shaping is of these methods. The idea of the OBS is shown in fig. 1.

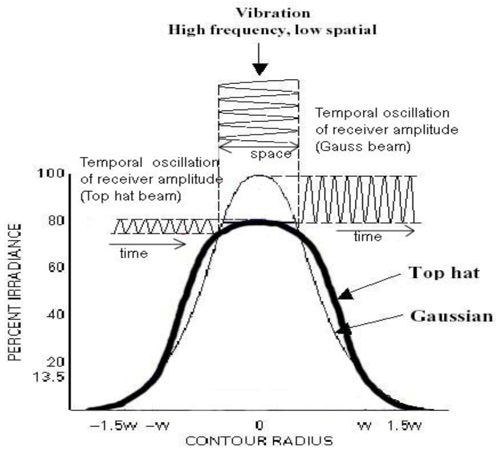

Fig. 1: *The impact of high frequency, low amplitude vibration on the temporal amplitude of the receiver for the Gaussian beam and the top hat beam.*

Fig. 1 shows that the effect of vibrations is smaller for so called "top hat" beams than for "peak profile" beams (for example Gaussian beam). The Gaussian beam is a natural product of the laser resonator cavity. Nevertheless, the location of the laser diode in the focus plane of the lens is the most common arrangement of the transmitting optical head, and therefore, the FSO links use the Gaussian beam. Considering the optical fiber as a primary light source, the resulting optical beam isn't a Gaussian beam. The shape of this beam is described in the next chapter, and we show there also that the optical fiber as a primary source allows shaping of the beam.

3 THE ELECTRIC FIELD IN THE PLANE OF THE RECEIVER

The electromagnetic field on the aperture of the transmitting lens has to be known for computing the distribution of the electromagnetic field in the plane of the receiver. The electromagnetic field on the output aperture of the transmitting lens can be expressed using the far zone pattern of the optical fiber and the transfer function of the lens. The geometrical model of the problem is depicted in fig. 2.

The far field pattern of the optical fiber was studied in [4], and is described by

$$E(r,\vartheta,\varphi) = \mathrm{K}\, R(r)\,\Phi(\varphi)\,\Theta(\vartheta),$$

$$\Theta(\vartheta) = \frac{\cos(\vartheta)\{C_1 \sin(\vartheta) J_{m+1}[ka\sin(\vartheta)] - C_2 J_m[ka\sin(\vartheta)]\}}{\left\{[k\sin(\vartheta)]^2 - k_T^2\right\}\left\{[k\sin(\vartheta)]^2 + \gamma^2\right\}}, \qquad (1)$$

$$R(r) = r^{-1}\exp(-jkr),\ \Phi(\varphi) = \cos(m\varphi),$$

where C_1, C_2 and K are constants:

$$C_1 = kJ_m(k_T a),\ \ C_2 = k_T J_{m+1}(k_T a),\ \mathrm{K} = j^m (ak_T)^{-1} k V^2 \beta C. \qquad (2)$$

In (1) and (2), J_m is Bessel function of the first kind of the order m, K is a constants of integration, k_T and γ are transverse constants in core and in cladding, β is the propagation constant in the fiber, m is the azimuthal mode number $m = 0,1,2...$, a is the radius of core and $V^2 = a^2\left(k_T^2 + \gamma^2\right)$.

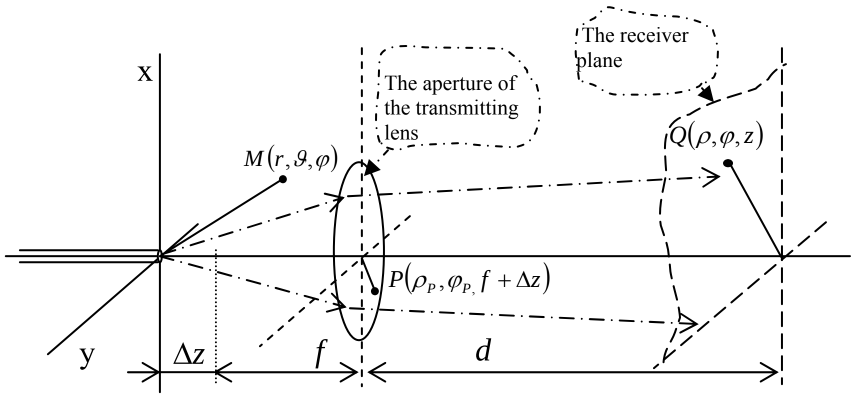

Fig. 2: *The geometrical configuration of the problem.*

The equation (1) was derived assuming weakly guided optical fibre with the linearly polarized mode (E is a Cartesian component of the electrical filed vector). The electric field on the output aperture of the lens is given by the product of the electric field on the input aperture of the lens and the transfer function of the lens that is given by

$$T(\rho_P) = \exp\left(jk\frac{\rho_P^2}{2f} \right), \tag{3}$$

where f is a focal length of the lens.

The electrical field on the input aperture of the lens is determined by equations (1). In the future we modify this electric field by means of the so-called paraxial approximation: we assume the angle ϑ in (1) is small, and therefore

$$\vartheta \cong \sin(\vartheta) \cong \tan(\vartheta) = \frac{r_P}{f}, \cos(\vartheta) \cong 1. \tag{4}$$

Further, we use Fresnel's approximation of the spherical wave for the function $R(r)$ in (1) and if we assume that $\Delta z << f$. Therefore the function $R(r)$ is given by

$$R(r) = \frac{\exp(-jkr)}{r} \cong \frac{\exp[-jk(f+\Delta z)]}{f+\Delta z}\exp\left(-jk\frac{\rho_P^2}{2(f+\Delta z)}\right). \tag{5}$$

The term Δz in (5) represents the displacement of the end of the optical fibre from the focal plane of the lens according to fig. 2. Using equations (1)-(5), the electric field on the output aperture of the transmitting lens can be expressed as

$$E(\rho_P,\varphi_P,f) = \overline{\mathrm{K}}\, j^m \cos(m\varphi_P)\frac{\rho_P t\, J_m(X)\, J_{m+1}(\rho_P t) - X\, J_{m+1}(X)\, J_m(\rho_P t)}{\left(\rho_P^2 t^2 - X^2\right)\left(\rho_P^2 t^2 + Y^2\right)}\exp\left(jk\rho_P^2\Delta\right),$$
$$\Delta = \frac{\Delta z}{2f^2}, t = f^{-1}k\,a,\ X = k_T a,\ Y = a\gamma,\ \overline{\mathrm{K}} = const. \tag{6}$$

The calculation of the distribution of the electric filed in the receiver plane is based on Fresnel's approximation of the Rayleigh-Sommerfeld diffraction integral [1]. The electric field in the point $Q(\rho,\varphi,z)$ can be expressed by means of this integral in the form

$$E(\rho,\varphi,z) = \overline{\overline{\mathrm{K}}}\, j^{2m} \frac{\exp\left[-jk\left(d+\frac{\rho^2}{2d}\right)\right]}{z}\cos(m\varphi)\times$$
$$\times \int_{\rho_P=0}^{b} \rho_P \exp\left[-jk\rho_P^2\left(\frac{1}{2d}+\Delta\right)\right] J_m\left(k\frac{\rho}{d}\rho_P\right)\frac{\rho_P t\, J_m(X)\, J_{m+1}(\rho_P t) - X\, J_{m+1}(X)\, J_m(\rho_P t)}{\left(\rho_P^2 t^2 - X^2\right)\left(\rho_P^2 t^2 + Y^2\right)} d\rho_P, \quad (7)$$

where b is a diameter of the transmitting lens, $\overline{\overline{\mathrm{K}}}$ is a constant and $d = z - f - \Delta z$.

The point Q (or the distance between point P and Q) has to satisfy the condition for Fresnel's diffraction [2]. The equation (7) describes the electric field in the plane of the receiver separately for every LP mode. Unfortunately, the integral in (7) is too complex and must be solved numerically.

4 OPTICAL BEAM SHAPING

In this chapter, we would like to demonstrate possibilities of shaping the optical beam when we use an optical fiber as a light source irradiating the transmitting lens. The idea is following. We consider a few mode fiber (a multimode fiber with a low number of the guided mode) and using filters or a special excitation (excited only some one groups of mode) of the fiber we can affect a distribution of the power between individual guided modes. Every mode has an own distribution of the electromagnetic filed on the plane of the receiver and the resulting optical intensity on the receiver plane is composed from separate modes. That is way we can shape the optical beam. When composing the resulting beam, we have to distinguish two principal cases: an ideal coherent light and an ideal non-coherent light. The first case faces to sum of the electrical intensity and the second one faces to sum of the optical intensity. In the future, we assume optical beams, which correspond to the fact that the individual guided modes are non-coherent. This presumption can be ensured, e.g. by the sufficient length of the fiber.

For example, we calculated and displayed the optical intensity in the case that only two modes, LP_{01} and LP_{11}, propagate. We consider the optical fiber with parameters: $NA = 0.117$, $a = 4.1\,\mu\mathrm{m}$ and wavelength $\lambda = 785\,\mathrm{nm}$. Parameters of the calculation are: focal length of the transmitting lens $f = 20\,\mathrm{cm}$, the radius of the transmitting lens is $b = 3\,\mathrm{cm}$, distances between transmitter and receiver are 500 m and 700 m. We are expected the excitation of the mode LP_{11} in both possible configurations, the function *cos* and so with the function *sin* in equation (1), with the same energy. The quotient between the power of the mode LP_{11} and the power of the mode LP_{01} was chosen 1,1. We consider the non-coherent superposition between separate beams that are corresponding to individual guided modes. The displacement Δz enables to regulate the divergence of the resulting beam. We consider the displacement $\Delta z = -1{,}5$ mm in our example. This displacement causes that the size of the spot of the beam in the receiver plane is in a commonly used dimension [3].

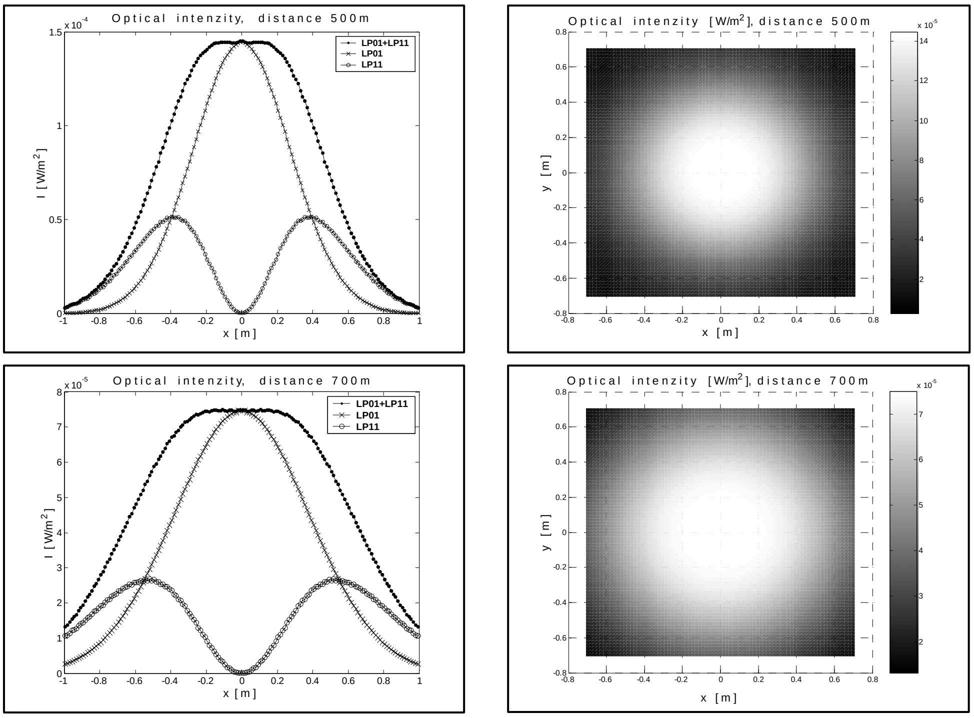

Fig. 3: *The distribution of the optical intensity in the plane of receiver.*

5 CONCLUSIONS

The optical beam shaping is the effective method for suppressing the influence of vibrations in the free space optical communication. We proposed the utilization of the step index-optical fibre for generating optical beams. We characterized these beams by equation (7), and we specified the principle of the shaping optical beams using the optical fibre and fibre optics components. The idea is based on the superposition (coherent or non coherent) of the optical beams that are generated by individual guided modes in the optical fibre. The shape of the optical beam can be changed by means of the special excitation of the optical fibre or by the help of mode filters.

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