UTILIZATION OF OPTICAL FIBRE COMPONENTS FOR GENERATION OF OPTICAL BEAMS IN FREE SPACE OPTICAL COMMUNICATION

Ing. Martin HAMPL, Doctoral Degree Programme (1)
Dept. of Radio Electronics, FEEC, BUT
E-mail: xhampl01@stud.feec.vutbr.cz

Supervised by Dr. Otakar Wilfert

ABSTRACT

This contribution deals with utilization of fiber optics components for shaping optical beams. The propagation of a light generated by the step-index optical fiber is investigated and distribution of the electric field on the output aperture of the lens, which is irradiated by the step-index fiber, is introduced. Theoretical results are compared with measured values.

1 INTRODUCTION

Recently we are under development telecommunication optic systems witness of replacement electronic or optoelectronic elements by purely optical elements. Not otherwise it is in free space optical communications (FSO). It is reason why we deal with shape of optical beams that are generated by optical fibers. We propose to utilize of optical fibers in FSO as primary light sources. If source of the optical beam is an optical fiber we could take advantage of fiber optical components for shaping the resultant beam. The shape of the resultant beam is determined by distribution of the electromagnetic field on the facet of the optical fiber. That is why we can affect resultant beam by elements as are e.g. mode filters. Very interesting possibility is utilizing optical splitter for division an optical signal into more fibers and consequently shaping the final beam by composition from individual beams. In this article we describe the optical beam that is generated by a step-index optical fiber.

2 THE DIFFRACTED PATTERN OF OPTICAL FIBRE

2.1 ELECTRIC FIELD IN THE OPTICAL FIBRE

In the future we assume that the optical fiber is situated in Cartesian coordinate system so that the axis of the optical fiber coincides with axis z and the fiber is ended by plumb rebate in plane $z = 0$.

For computation diffraction pattern of the optical fiber is necessary to know the electromagnetic field on the facet of the optical fiber. This electric field in the weakly guiding fiber is expressed by equations, [1]

$$\begin{aligned} r_P < a: \; E_x &= -\frac{jC\beta}{k_T} J_m(k_T r_P)\cos(m\varphi_P),\, E_y = E_z = 0\,, \\ r_P > a: \; E_x &= -\frac{jA\beta}{\gamma} K_m(\gamma\, r_P)\cos(m\varphi_P),\, E_y = E_z = 0\,, \end{aligned} \tag{1}$$

where J_m is Bessel function of the firs kind of order m, K_m is modified Bessel function of the second kind of order m, A and C are constants of integration, k_T and γ are transverse constants in core and in cladding, β is propagation constant, m is azimuthally mode number $m = 0,1,2...$, a is radius of core and r_P, φ_P are cylindrical coordinates.

2.2 ELECTRIC FIELD IN FAR ZONE FROM THE OPTICAL FIBRE

Calculation the diffraction pattern of the optical fiber starts from the Hyugens-Fresnel principle [1], [2]. If we use Fraunhoffer's approximation [2] and we take advantage of the Hyugens-Fresnel integral for x-component electric field that is given by (1), we obtain equations:

a) for core of the optical fiber

$$\begin{aligned} E_{core}(r,\vartheta,\varphi) &= \frac{C\beta}{\lambda\, k_T}\frac{\exp(-jkr)}{r}\times \\ &\times\cos(\vartheta)\int_{r_P=0}^{a}\int_{\varphi_P=0}^{2\pi} r_P\, J_m(k_T r_P)\cos(m\varphi_P)\exp(jkr_P\sin(\vartheta)\cos(\varphi_P-\varphi))\,\mathrm{d}\varphi_P\mathrm{d}r_P \end{aligned} \tag{2}$$

b) for cladding of the optical fiber

$$\begin{aligned} E_{cladding}(r,\vartheta,\varphi) &= \frac{A\beta}{\lambda\,\gamma}\frac{\exp(-jkr)}{r}\times \\ &\times\cos(\vartheta)\int_{r_P=a}^{b}\int_{\varphi_P=0}^{2\pi} r_P\, K_m(\gamma\, r_P)\cos(m\varphi_P)\exp(jkr_P\sin(\vartheta)\cos(\varphi_P-\varphi))\,\mathrm{d}\varphi_P\mathrm{d}r_P\,, \end{aligned} \tag{3}$$

where r, ϑ and φ are spherical coordinate of point, where we calculate electric field and b is a radius of cladding of the fiber.

Equations (2) and (3) are valid for points that lie in the far zone from the optical fiber, more detailed in [2]. According to superposition principle is the resulting electric field given by

$$E = E_{core} + E_{cladding} \tag{4}$$

If we solve integrals (2) and (3) and then we make use of dispersion equation of weakly guiding fiber [1], sum (4) can be written as

$$E(r,\vartheta,\varphi) = K\, R(r)\,\Phi(\varphi)\,\Theta(\vartheta), \tag{5}$$

$$\Theta(\vartheta) = \frac{\cos(\vartheta)}{\left\{[k\sin(\vartheta)]^2 - k_T^2\right\}\left\{[k\sin(\vartheta)]^2 + \gamma^2\right\}}\left\{C_1\sin(\vartheta)J_{m+1}[ka\sin(\vartheta)] - C_2 J_m[ka\sin(\vartheta)]\right\}, \tag{6}$$

$$R(r) = \frac{\exp(-jkr)}{r},\ \Phi(\varphi) = \cos(m\varphi), \tag{7}$$

where C_1, C_2 and K are constants, but they are different for every modes.

These equations, (5) - (7), describe electric field in arbitrary point in far zone from the optical fiber, but they describe the far-field every mode separately.

2.3 ELECTRIC FIELD ON THE OUTPUT APERTURE OF THE LENS

If we know the electric field in far zone from the optical fiber we can determine the electric field on the output aperture of a lens irradiated by the fiber. Geometrical configuration is shown in fig. 2. Electric field on the output aperture of the lens is given by the product of electric field on the input aperture of the lens and the transfer function of the lens (more detailed in [1]) that is given by

$$T(r_P) = \exp\left(jk\frac{r_P^2}{2f}\right), \tag{8}$$

where r_P is a radial distance from a centre of the lens and f is a focal length of the lens.

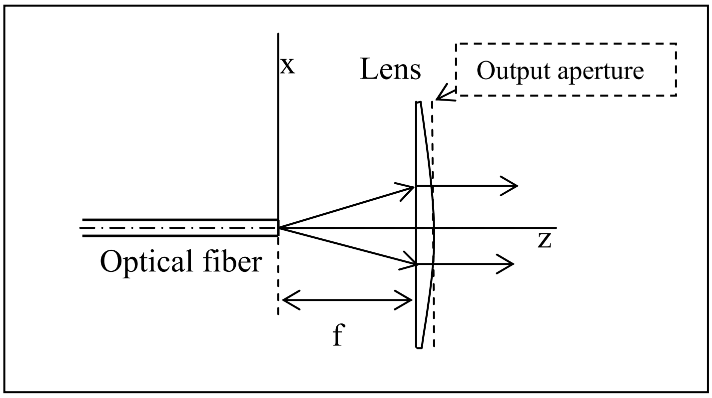

Fig. 1: *Geometrical configuration.*

Electrical field on the input aperture is determined by equations (5), (6) and (7). In the future we modify this electric field by means of so-called paraxial approximation. It comes to this, that angle ϑ in (6) is such small that is valid

$$\sin(\vartheta) \cong \vartheta \cong \frac{r_P}{f},\ \cos(\vartheta) \cong 1. \tag{9}$$

For the function $R(r)$ in (7) we use Fresnel's approximation of spherical wave, more detailed in [1]. The electric field on the output aperture of the lens is then given by

$$E(r_P,\varphi_P) = K_1 \frac{r_P t\, J_m(X) J_{m+1}(r_P t) - X\, J_{m+1}(X) J_m(r_P t)}{\left(r_P^2 t^2 - X^2\right)\left(r_P^2 t^2 + Y^2\right)} \cos(m\varphi_P), \qquad (8)$$

where $t = \frac{ak}{f}$, $X = k_T a$, $Y = \gamma\, a$, where r_P and φ_P are polar coordinates of a point in the plane of the output aperture and K_1 is a constant.

Graphic representation of this equation is shown in fig. 2 for wavelength $\lambda = 850$nm and for the optical fiber with parameters: $a = 4.5$µm, $NA = 0.122$. The focal length of the lens is 50cm.

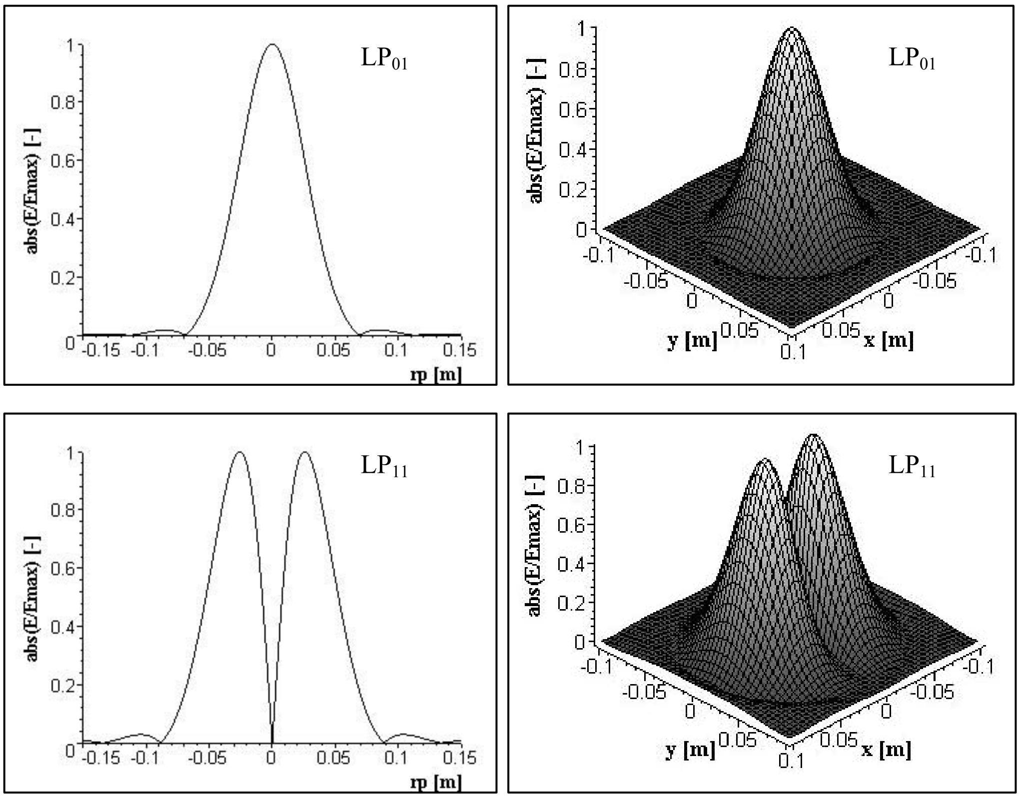

Fig. 2: *Computed electric field on the output aperture of the lens for mode LP_{01} and mode LP_{11}.*

3 EXPERIMENTS

The theoretic result express by equations (5), (6) and (7) is confronted with measured values for a single mode fiber. In this case we haven't to deal with distribution energy between particular modes and we assume propagation only dominant LP_{01} mode. Result is shown in fig. 3. Quantity *f* in fig. 3 is a normalized optical intensity that is direct proportional of the square electrical field $f \approx |E|^2$ and it is display in logarithmic scale. Picture on the left side is photo of the end of the measured fiber. Measured values are obtained in method what is called scanning of far field, more detailed in [3].

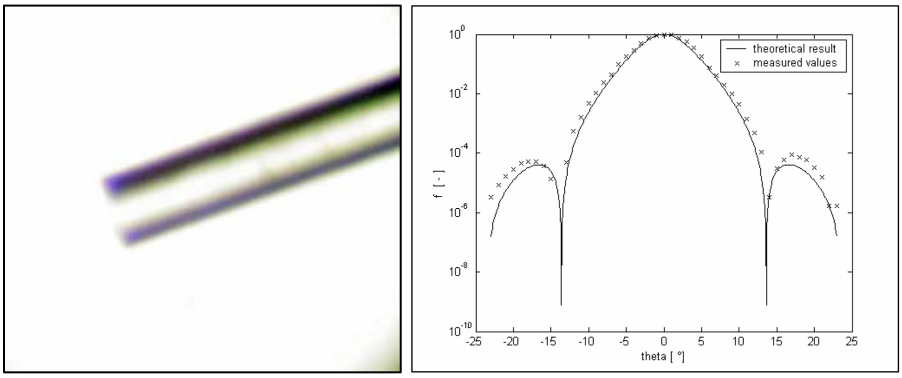

Fig. 3: *Comparison theoretical and measured values. Parameters of the measured optical fiber:* $a = 4.5\mu\mathrm{m}, b = 62.5\mu\mathrm{m}$, $NA = 0.122$, *length of the fiber: 2m. Wavelength:* $\lambda = 1550\mathrm{nm}$. *Distance between the end facet of the fiber and detector:* $d = 10\mathrm{cm}$.

4 CONCLUSION

We described radiation of a step-index optical fiber. As results are equations (5), (6) and (7). Furthermore we described distribution of the electric field on the output aperture of a lens irradiated by the fiber, equation (8). Theoretical results were confronted with measured values for a single mode fiber. Equation (5) describes radiation of each of mode separately. If we know distribution energy between separated modes, we can compute radiation of a multimode fiber according to superposition principle. This principle is suitable to advantage for determination of diffraction patterns of the multimode fiber with low number of guided modes. For a common multimode fiber, where number of guided modes is very high, is superposition principle practically unusable, because we don't know distribution of the power between separately modes. If we use a multimode fiber we can affect the shape of the resultant beam by change of distribution energy between modes e.g. via mode filters. Other way how we can form the resultant beam is division an optical signal into more optical fibers and than composite the resultant beam from the individual beams. This principle is also possible to use for shaping beams that are generated by single mode fibers.

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