OPTIMUM DIVERGENCE OF LASER RADIATION IN FSO SYSTEMS

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Abstract

The necessity for higher information capacity and for better operational reliability of FSO systems require more precise selection and adjustment of their parameters. Many factors cause random fluctuations in the direction of propagation of the transmitter radiation, respectively, in the angle of incidence of the optical flow on the receiving aperture. Due to this effects is drawn a serious deterioration in the quality of transmitted information and reducing of the reliability of systems. A significant improvement can be achieved by determining of the optimum divergence of the transmitter optical beam in FSO systems under specific operating conditions. In the work mathematical equations for calculating of optimum deviation angle $\theta_{t,opt}$ of a laser beam are derived. Setting a FSO with this parameter, will provide operation with the highest possible deviation from the main beam direction. This paper deals with studying of dependence on maximal divergence from the power of laser source and the length of communication channel. Calculations are made for two different wavelengths of optical radiation. Manifold graphics, showing the importance of correct setting for the system reliability, are attached.

1. INTRODUCTION

The feasibility of FSO technology in the group of wireless communication systems is increasing constantly. Its mobile version known as MFSO has significant progress over recent years too [1, 2]. The increased interest in FSO systems, however, creates new requirements for improvement of their characteristics, as well as for optimizing some of their parameters, in particular those of the divergence of the transmitter optical radiation [3-7]. In [8] the dependence of $\theta_{t,opt}$ on the BER, the eye-diagram and the quality factor of the system are investigated by numerical simulations under different atmosphere effects. Despite numerous researchs so far has not offered a clear statement to calculate the optimal divergence $\theta_{t,opt}$ of the laser radiation, depending on the FSO system parameters and characteristics of the atmospheric communication channel.

2. STATEMENT OF THE LASER BEAM DIVERGENCE PROBLEM

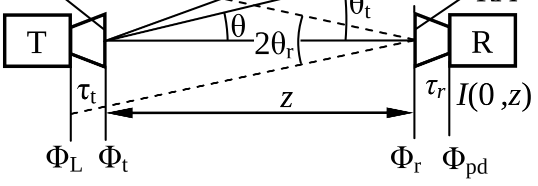

Figure 1. Block diagram of an FSO link between two sites

Figure 1 outlines a block diagram of FSO system when the optical axes of the transmitter (TA) and the receiver (RA) antennas are aligned. The distribution of the optical radiation intensity $I(\rho, z)$ in the plane z = const depends mainly on the phase and amplitude distribution of the field in the TA. For our case we will accept equiphase and Gaussian amplitude distribution. In the figure is shown the optical flux: Φ_L – transmitted by the laser, Φ_t and Φ_r - through the apertures, namely, TA and RA, and at the entrance of the photodetector Φ_{pd}. $I(0, z)$ is the optical radiation intensity along the axis of the antenna. The radius ρ_z of the Gaussian laser beam (with azimuthal symmetry of the radiation) is calculated by the mathematical expression

$$I(\rho_z, z) = \frac{I(0, z)}{e^2} \tag{1}$$

and defines the divergence θ_t of the radiation in the far-field region. With τ_t and τ_r are denoted losses in the definited antennas and τ_a is the transparency of atmospheric channel. $2\theta_r$ is the diagram width of the receiving antenna.

Radial distribution of the optical radiation intensity in the plane z = const, in which receiving aperture is situated, is shown in Figure 2.

According to the assumption for receiving aperture radius $R_r \ll \rho_z$, it can be approximately determined the received optical flux Φ_r as a product of the intensity of optical radiation in the center of the receiving antenna and the surface of antenna, A_r.

$$\begin{aligned} \Phi_{\mathrm{r}} &= I(\rho, z) A_{\mathrm{r}} , \\ A_{\mathrm{r}} &= \pi R_{\mathrm{r}}^2 , \\ \rho &= \theta z , \, (tg\theta = \rho / z) . \end{aligned} \qquad (2)$$

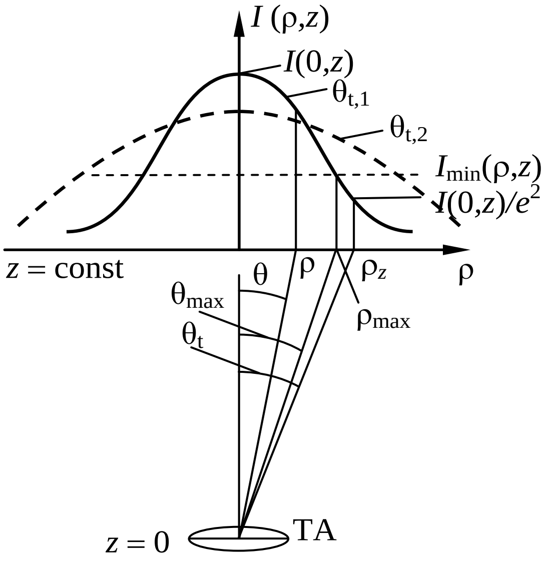

Figure 2. Distribution of intensity in a plane z = const for two values of divergence of optical radiation □t

The intensity Imin shown in Figure 2 corresponds to the minimum power of optical radiation through the aperture of the receiver for which FSO system works reliably. The respectively magnitude of ρ defines the angle $\theta_{\max}$. This is the value of bearable angular misalignment of the laser beam axis from the main direction ($\theta = 0$) due to the different random factors.

With $\theta_{t,1}$ and $\theta_{t,2}$ are shown two distributions of $I(\rho, z)$, corresponding to divergence $\theta_{t,1}$ и $\theta_{t,2}$ ($\theta_{t,1} < \theta_{t,2}$) of the beam transmitter. Figure 2 outlines the case of $\theta_{\max}$ ($\theta_{t,2}$) > $\theta_{\max}$ ($\theta_{t,1}$) . But it is obvious that this trend will continue to the limit value $\theta_{t,opt}$. After this point with increasing θ_t, there will be a decrement in the magnitude of $\theta_{\max}$.

The task of our following analysis is to calculate $\theta_{t,opt}$, and to investigate its dependence on the parameters of the FSO system.

3. MATHEMATICAL DESCRIPTION

Due to Gaussian amplitude distribution of the optical field in the aperture of the transmitting antenna the intensity distribution in the far-field region, in which the receiving antenna is positioning, is also Gaussian.

$$I(\rho, z) = I(0, z) \exp\left(-2 \frac{\rho^2}{\rho_z^2(z)} \right) \qquad (3)$$

When $\rho = \rho_{\max}$ (Fig. 2), the optical radiation intensity $I = I_{\min}$, i.e.

$$I_{\min} = I(0, z) \exp\left(-2 \frac{\rho_{\max}^2}{\rho_z^2(z)} \right) \qquad (4)$$

The optical radiation intensity along the axis of the laser beam depends on the characteristics of the transmitter and the atmospheric communication channel [7]

$$I(0, z) = \frac{2.\tau_{\mathrm{t}}.\tau_a(\lambda_0, S_{\mathrm{M}}, z).\Phi_{\mathrm{L}}}{\pi.\rho_{\mathrm{z}}^2(z)} . \qquad (5)$$

The transparency of the atmosphere is related to meteorological visual range S_M and the wavelength of the transmitter.

$$\tau_{\mathrm{a}}(\lambda_0, S_{\mathrm{M}}, z) = \exp\left[-\frac{3{,}92.z}{S_{\mathrm{M}}[\mathrm{km}]} \left(\frac{\lambda[\mu\mathrm{m}]}{0{,}55} \right)^{-q} \right] \qquad (6)$$

In case of $S_M \leq 10$ km, $q = 0{,}585\sqrt[3]{S_{\mathrm{M}}[\mathrm{km}]}$. From (4) and (5) we draw the formula

$$\rho_{\max} = \frac{1}{\sqrt{2}} \rho_z \sqrt{\ln \frac{2.\tau_{\mathrm{t}}.\tau_{\mathrm{a}}.\Phi_{\mathrm{L}}}{\pi.\rho_{\mathrm{z}}^2.I_{\min}}} . \qquad (7)$$

This mathematical equation allows determination of the extreme magnitude of $\rho_{\max}$ as a function of ρ_z. The value of ρ_z, for which has a maximum $\rho_{\max}$, is

$$\rho_z \equiv \rho_{z,\mathrm{opt}} = \sqrt{\frac{2.\tau_{\mathrm{t}}.\tau_{\mathrm{a}}.\Phi_{\mathrm{L}}}{\pi.\mathrm{e}.I_{\min}}} , \quad \mathrm{e} = 2{,}7183 . \qquad (8)$$

$I_{\min}$ is calculated by the condition

$$I_{\min} = \frac{\Phi_{\mathrm{pd}}\big|_{SNR=\mathrm{const}}}{\pi.\tau_{\mathrm{r}}.R_{\mathrm{r}}^2} . \qquad (9)$$

When *SNR* value is given, Φ_{pd} is calculated from the expression [7]

$$SNR = \frac{R_{\mathrm{I}}.\Phi_{\mathrm{pd}}}{\sqrt{\mathrm{C}_{\mathrm{I}} \left[\frac{2.k_{\mathrm{B}}.T.A}{R_{\mathrm{Fb}}} + e^{-}.R_{\mathrm{I}}.(\Phi_{\mathrm{pd}} + \Phi_{\mathrm{B}}) \right]}} \qquad (10)$$

In (10) R_I is the integral sensitivity for current of the photodetector

$$R_I(\lambda_0)=8{,}06.10^5\eta(\lambda_0)\lambda_0\,, \qquad (11)$$

$\eta(\lambda_0)$ is the quantum efficiency of the photodetector material, C_I is the information capacity of digital communication system, k_B = 1,38.10^{-23} J/K is the Boltzmann constant, T is the absolute temperature, A is a constant of receiver, R_{Fb} is the value of the resistor in the feedback of the preamplifier, e^- = 1,602.10^{-19} C is the charge of the electron.

Background optical flux Φ_B depends on the spectral brightness of the background radiation $L_{\lambda,B}$ and the parameters of receiver: the aperture radius R_r, the transmission coefficient τ_r and the angular width of the receiving antenna θ_r [7]

$$\Phi_B=\pi^2.\tau_r.L_{\lambda,B}.R_r^2.\theta_r^2.\Delta\lambda_F\,. \qquad (12)$$

With $\Delta_{\lambda,F}$ is denoted the transmission wavelength of the interference filter before the photodetector.

From (10) and from physical considerations we reach to a clear result for calculating the value of the optical signal flux in the entrance of the photodetector

$$\Phi_{pd}=\frac{1}{2}\left[\frac{SNR^2.C_I.e^-}{R_I}+\left(\left(-\frac{SNR^2.C_I.e^-}{R_I}\right)^2+\frac{4SNR^2.C_I}{R_I}\left(\frac{2k_B.T.A}{R_I.R_{Fb}}+e^-.\Phi_B\right)\right)^{\frac{1}{2}}\right] \qquad (13)$$

Having used the expression (13), (9) and (8) we compute $\rho_{z,opt}$, respectively,

$$\theta_{t,opt}=\frac{\rho_{t,opt}}{z}\,[\mathrm{rad}] \qquad (14)$$

as a function of parameters of FSO system and communication channel.

4. SIMULATION RESULTS

For numerical calculations we choose the following typical values of the parameters of the FSO system and atmospheric communication channel: C_I = 100 Mbps; $\eta(\lambda_0)$ = 0,7; SNR = 11,2 (corresponds to BER = 10^{-8}); λ_0 = 0,85 and 1,55 μm; T = 300 K; A = 5; R_{Fb} = 1 kΩ; τ_r = τ_t = 0,85; R_r = 5,5 cm; $\Delta\lambda_{,F}$ = 10 nm; $L\lambda_{,B}$ = 10^{-2} (corresponds to bright day); θ_r = 5 mrad; S_M = 10 km.

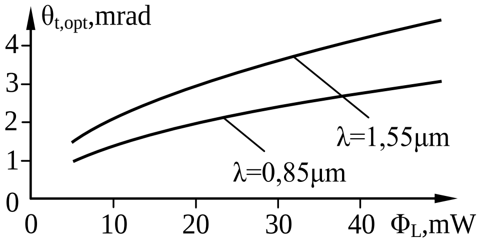

Figure 3. Dependence of $\theta_{t,opt}$ from Φ_L (z = 2 km)

Figure 3 shows the $\theta_{t,opt}$ dependence from the power of the transmitter, and Figure 4 from the length of the communication channel.

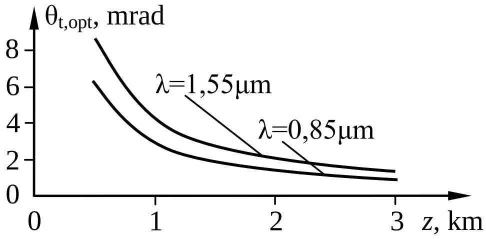

Figure 4. Dependence of $\theta_{t,opt}$ from z (Φ_L = 10 mW)

We see the strong dependence on $\theta_{t,opt}$ within an order of magnitude (1 mrad to 10 mrad). This is a prerequisite for the importance of the correct selection of the optimal divergence of the laser beam for the reliable operation of FSO system in each one case.

5. CONCLUSION

The optimal magnitude of the laser beam divergence is influenced much more by the length of the communication channel than the power of the laser source. In case of six times increasing in the distance between communication parts the value of optimal divergence decreases eight times. In compareson, five times reducing of transmitter power leads to four times decreasing of the optimal divergence. The dependence of the optimal divergence of the transmitter on the wavelength is much weaker.

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