Study of the Temperature Turbulences Effect upon the Optical Beam in Atmospheric Optical Communications

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Abstract. *The paper deals with the study of the effect of temperature turbulences upon the optical beam. The polarization parameters of optical radiation sources and different optical beam states of polarization have been investigated. The obtained polarization parameters are projected on the Poincaré sphere by means of Stokes vectors. The optical power distribution curves of optical beams are processed into diagrams.*

The horizontal and vertical components of linearly and circularly polarized optical beams have been studied. The turbulence flux has vertical direction and the optical beam is propagating through an atmosphere environment with three different states of turbulence. The evaluation of the obtained data was done by means of variance and correlation functions computing. Different rates of effect of temperature turbulences upon horizontal and vertical components were found. To reduce the rate of effect the advantage of an optical beam with circular polarization has been proposed.

Keywords

Temperature turbulences, optical beam, state of polarization, Poincaré sphere, variance, cross correlation function.

1. Introduction

The need for higher bit rates and better accessibility is increasing due to the development of new technologies and applications. These requirements are increasing in all kinds of human activities. The rapid transition from the electrical domain to the optical domain was the result of these requirements. Due to the modern technologies of photonic components manufacture and license-free band the transmission of information via atmospheric optical communication is becoming affordable.

Optical fibers with better bit rate parameters, allowing the transmission of more information, started to be used in the optical domain. The usage of optical fibers currently holds a predominant role in telecommunication networks. Problems are occurring in ensuring data communication among mobile users [1], such as the creation of spare connections and the creation of temporary networks with high data bit rates. The creation of atmospheric optical communications is one suitable solution in these cases. This solution provides the required bit rate with sufficient reliability and accessibility.

The selection of suitable optical beam parameters is very important for the optimization of information transmission through the atmosphere. Regarding the topicality of atmospheric communication, the geometrical parameters and effect of atmospheric transmission environment features were studied in both communication and sensor areas. The effect of fog and haze upon the propagation of optical beams through the atmosphere for different wavelengths was studied [2], [3]. Atmospheric turbulences are one of the major effects upon the attenuation of optical beam intensity [4], [5].

The design of communication and sensor systems is usually conducted without considering the state of polarization (SOP) aspect of the optical beam used. The polarization properties depend on the laser source used. The beam profile is usually elliptical for most laser diodes (LD) and their SOP of output optical radiation depends on the type of LD used [6]. Gas lasers have better polarization and coherent properties in comparison with laser diodes. The ellipticity of gas laser beams is usually close to zero, and their coherency length depends on the resonant mirrors used. The inhomogeneous turbulent atmosphere can be comprehended as an environment which influences optical intensity fluctuations of the propagated beam. The hypothesis, in which the horizontal and vertical components of a polarized optical beam can be influenced by environment inhomogeneities with different rates, has been raised on the basis of this presumption. The usage of a defined SOP of the optical beam could allow the achievement of better optical system parameters in comparison with systems where the defined polarization of the optical beam is neglected. For experimental verification of this hypothesis we have used different photonic components for wavelengths $\lambda_1 = 780$ nm and $\lambda_2 = 1550$ nm.

2. Workplace and Measuring Conditions

The rate of temperature turbulence effect was studied from the aspect of turbulent flux streaming in the vertical direction. For the study of the effect of temperature turbulence upon the polarized optical beam we have used different laser sources and components. For the $\lambda_1 = 780$ nm wavelength, the laser diode (LD) RLD-78NP10 (RLD), and LD with external resonance cavity GALA 078-04-4-S (GALA) were used. GALA was used instead of a gas laser, due to its coherent length about 6 m. For the second wavelength, $\lambda_2 = 1550$ nm, LD ML925C45F (ML) was used.

2.1 LD RLD and Laser GALA (780 nm)

The arrangement of the workplace for measuring the GALA and RLD polarized beam properties is shown in Fig. 1. The RLD arrangement is the same as for GALA (shown below) except for the first block, which represents the laser GALA. The discrete LD RLD has this first block in the same arrangement as the ML block in Fig. 2. The output linearly polarized beam is obtained by means of a Glan-Thompson (GT) linear polarizer with the desired orientation of 45° polarization plane. The required horizontal and vertical components, which are the subject of our research work, are investigated from this arrangement.

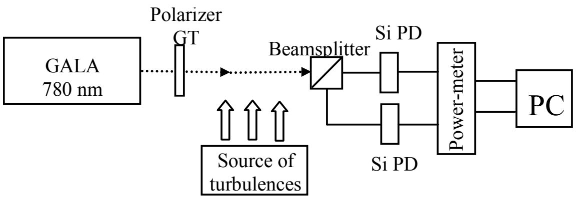

Fig. 1. The arrangement of the measuring set for the measurement of horizontal and vertical components of an optical beam generated from GALA and RLD.

The linearly polarized beam initially passes through the GT polarizer. The transformed optical beam from the GT polarizer propagates through the environment under investigation and hits the beamsplitter. The horizontal and vertical components from the beamsplitter are propagated towards identical Si photodetectors. The diameter of the active surface is 3 mm. The electric signals are led through the power meter to the PC. The computer processing of measurements is conducted using the MATLAB® environment.

2.2 LD ML (1550 nm)

The arrangement of the workplace for the $\lambda_2 = 1550$ nm wavelength is presented in Fig. 2. The discrete laser diode ML is inserted into the mount TCLD M9. Operating current and temperature are stabilized by means of control units TED 200C and LDC 202C. A mounted aspherical lens is used for collimation of the output laser beam.

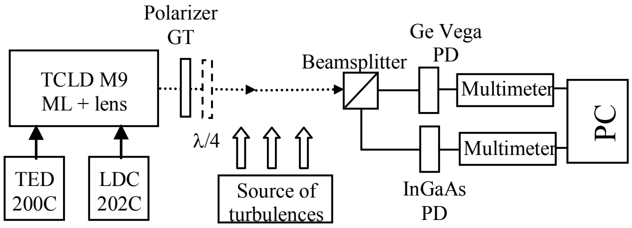

Fig. 2. The arrangement of the measuring set for the measurement of horizontal and vertical components of an optical beam generated from ML.

For the transformation from linear to circular polarization the retarder λ/4 is inserted behind the GT linear polarizer (see Fig. 2). The transformed circularly polarized optical beam is propagating through the environment under investigation and hits the beamsplitter. Both horizontal and vertical investigated components are propagated from the beamsplitter to the different photodetectors. The PD300-IRG-V1 (Ge) and SM05PD5B (InGaAs) photodetectors have been used. The electric signals are led from the photodetectors through Agilent 34401 multimeters to the PC. The computer processing of measurements is the same as in the previous arrangement. The sample period is around 0.65 s for all measurements. As different photodetectors are used in each experiment we can only compare the time development of optical intensity fluctuation to the previous RLD and GALA measurements. The variance of optical intensity for both components was investigated by means of a Ge photodetector. To obtain time development of optical intensity for a particular component the measurement was repeated for each component with an identical arrangement and photodetectors replacement.

The fluctuation of optical intensity of the circular polarized beam was measured in a separate part of the experiment. The beamsplitter was withdrawn and the circular polarized beam was directly hitting the photodetector.

3. Experimental Results

The variance of the time development of optical intensity fluctuation hitting the detectors of the horizontal and vertical components was computed. For evaluation of the effect of turbulent atmosphere upon orthogonal components of a polarized optical beam, computation of variance was used as a basic method. Relative variances were investigated for optical beams, propagating through a clear atmosphere, a turbulent atmosphere and a turbulent atmosphere with a high density of water vapor. The turbulent flux of the investigated environment was verified by means of a turbulence smoke test.

3.1 States of Polarization of Optical Sources and their Projection on the Poincaré Sphere

For representation of SOP of the optical beam we can utilize Stokes vector and its projection on the Poincaré sphere. Stokes vector can be found by measuring 6 optical intensities I for different arrangements of the linear polarizer and retarder λ/4 in the measuring layout [7], [8]. Stokes vector can be written in the following form

$$\mathbf{S}=\begin{pmatrix} I \\ Q \\ U \\ V \end{pmatrix}=\begin{pmatrix} I(0°,0)+I(90°,0) \\ I(0°,0)-I(90°,0) \\ I(45°,0)-I(135°,0) \\ I\left(45°,\frac{\pi}{2}\right)-I\left(135°,\frac{\pi}{2}\right) \end{pmatrix} \tag{1}$$

where I, Q, U, V are Stokes vector elements, $I(\theta,\varepsilon)$ denotes 6 measured intensities of optical wave with orientation of linear polarizer θ and retardation ε between horizontal and vertical components. From the Stokes vector analysis we can express the meaning of Stokes vector elements:

- I total optical wave intensity,
- Q horizontal preference intensity,
- U ± 45° preference intensity,
- V left or right circular preference intensity.

Laser source		Stokes elements			
No.	Type	I	Q	U	V
1	GALA	1	0.97	-0.02	-0.02
2	RLD	1	0.99	0.07	0.21
3	ML	1	0.99	0.08	0.1

Tab. 1. The Stokes vector elements for laser sources.

The obtained Stokes vectors for particular laser sources are presented in Tab. 1. States of polarization of laser sources are projected on the Poincaré sphere as shown in Fig. 3.

The RLD and ML output optical beam states of polarization are elliptical with an orientation of polarization plane close to horizontal. The laser GALA with external resonation cavity has an output optical beam with almost linear horizontal polarization. The obtained Stoke elements Q, U and V of the RLD mismatch the equation $I^2=Q^2+U^2+V^2$, which is valid for a fully polarized optical beam [7]. The exceeded value is 0.0014 and can be neglected with respect to the uncertainty of measurement [9].

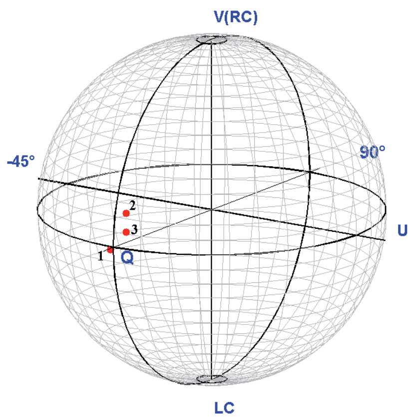

Fig. 3. Laser sources states of polarization.

3.2 The Polarization Properties of Optical Beams in Measuring Scheme

The different types and forms of polarization are occurring in particular parts of the measuring scheme. These SOPs were investigated by means of optical beam power distributions. The GT polarizer is rotated from 0° to 360° to obtain power distribution. The obtained data is processed onto the polar diagrams presented in Fig.4 and 5.

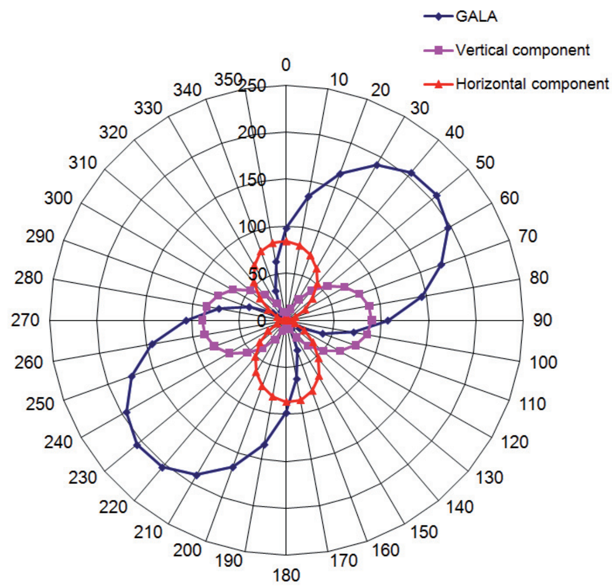

Fig. 4. LD GALA polar diagram of optical power distribution.

The power distributions of the GALA laser optical beam with 45° linear polarization and both its horizontal and vertical components are shown in Fig. 4. Both horizontal and vertical components were measured beyond the beamsplitter.

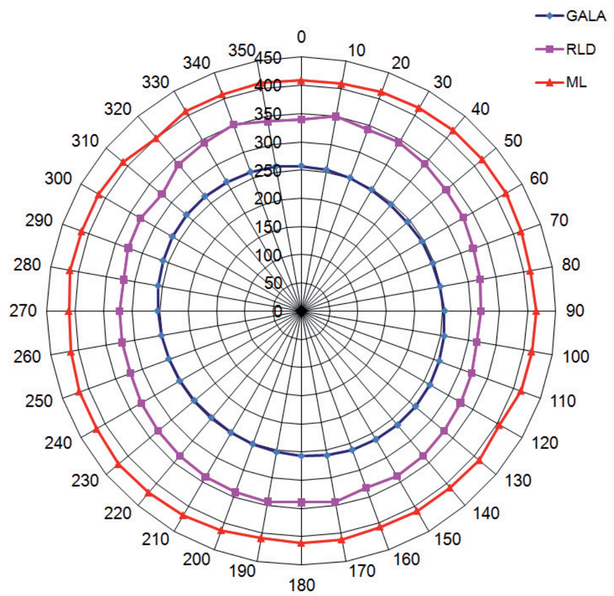

Fig. 5. Laser sources power distribution diagram with circular polarizations.

The measurements show the linearly horizontal polarized optical beam of the GALA laser with ellipticity -0.01 and extinction ratio between orthogonal components of 200. The circular polarizations of the transformed optical beams have an average deviation of less than 5 % (see Fig. 5).

3.3 Relative Variance of Optical Intensity

The relative variance of optical beam intensity was used as a metric for determination of the effect of atmospheric turbulence. The relative variance of optical intensity is a statistic dimensionless quantity, which allows the characterizing of fluctuations in optical intensity (Fig. 6) in the photodetector plane. The relative variance of optical intensity was investigated for all laser sources and each SOP in all different states of atmosphere. The obtained relative variances were computed by means of the var(x) MATLAB function and are presented in Tab. 2, 3 and 4. Relative variance can be written as [10]

$$\mathrm{var}_{rel}(x) = \frac{\frac{1}{n}\sum_{i=1}^{n}(x_i - \bar{x})^2}{\bar{x}^2} = \frac{\frac{1}{n}\sum_{i=1}^{n}x_i^2 - \left(\frac{1}{n}\sum_{i=1}^{n}x_i\right)^2}{\left(\frac{1}{n}\sum_{i=1}^{n}x_i\right)^2} \quad (2)$$

where n is the total number of samples, x_i is a particular optical intensity sample, and $\bar{x}$ is the mean value.

The relative variance of a circularly polarized optical beam was measured in a separate part of the experiment. For this measurement the beamsplitter was withdrawn and the propagating optical beam was directly hitting the photodetector.

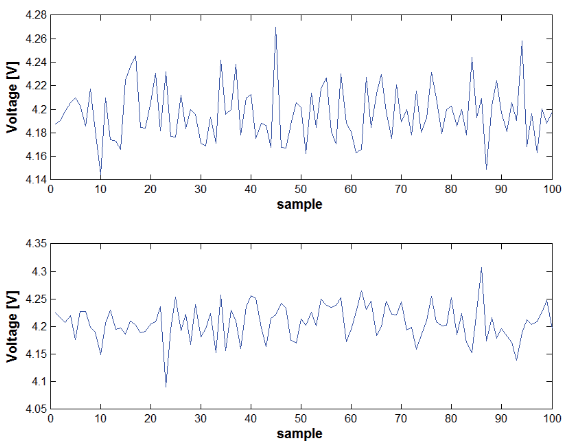

Fig. 6. Optical intensity fluctuations of vertical (upper) and horizontal components for the GALA laser, turbulent atmosphere.

The measurement for one type of atmosphere condition shows different variances in optical intensity for horizontal and vertical polarized components (see Tab. 2 – 4). The clear atmosphere had the greatest variance of optical intensity with random character and depended on the actual state in the laboratory. For this reason we can consider the data obtained for clear atmosphere as merely orientation results. The effect of the random environment can be neglected for excitation of temperature turbulences by means of temperature sources.

Atmosphere	Polarization		
	Horizontal	Vertical	Circular
Clear	2.77E-08	4.30E-08	3.68E-07
Turbulent	4.73E-05	7.09E-05	1.06E-05
Vapor	5.81E-05	8.87E-05	8.33E-05

Tab. 2. Measured relative variances of optical intensity for the GALA laser.

Atmosphere	Polarization		
	Horizontal	Vertical	Circular
Clear	1.72E-06	7.56E-06	1.05E-05
Turbulent	1.04E-05	2.01E-04	4.79E-05
Vapor	2.98E-05	1.62E-04	3.18E-05

Tab. 3. Measured relative variances of optical intensity for the RLD.

Atmosphere	Polarization		
	Horizontal	Vertical	Circular
Clear	1.98E-06	2.07E-07	1.04E-06
Turbulent	1.64E-05	6.80E-05	5.97E-05
Vapor	5.15E-05	7.96E-05	7.46E-05

Tab. 4. Measured relative variances of optical intensity for the ML.

For all measurements in cases of turbulent atmosphere and turbulent atmosphere with high density of water vapor the rate of effect was greater for the vertical component. The vertical component is parallel with the direction of the turbulent environment in the atmosphere. The measurement of the circularly polarized beam variance showed a rate of effect, whose value was inside the limited interval. The limits of interval are expressed by the minimum rate of effect for the horizontal component and the maximum rate of effect for the vertical component.

3.4 Cross Correlation

We have used a correlation function between synchronous recorded vectors of the measured data. The function was used for evaluation of the rate of effect of turbulence upon orthogonal (horizontal and vertical) polarized components of an optical beam with circular polarization and 45° linear polarization. The correlation function can be written as

$$C(x) = \frac{1}{n}\sum_{i=1}^{n}\delta H_i \cdot \delta V_{x+i} \quad (3)$$

where n is the total number of samples and δH and δV are horizontal and vertical component deviations from optical intensity mean values, respectively.

The correlation allows the investigation of the similarity between signal variations of horizontal and vertical components and their initial (mean) value. The peak magnitude of the mutual correlation function represents the rate of similarity. For a sufficiently great rate of correlation the particular components with the same time moment are similarly affected. For decreasing correlation rate of effect the mutual cohesion of optical intensity variances is also decreasing from the initial value. The values of correlation maximums are presented in Fig. 7 – 12. The correlation function analysis shows the least correlation between the optical beam variances of the horizontal and vertical polarized components. For the GALA laser the mutual dependence of variances was totally uncorrelated as shown in Fig. 7 and 8.

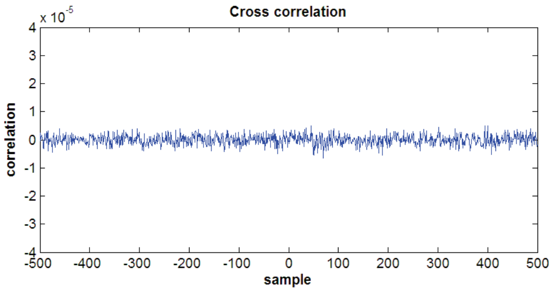

Fig. 7. Cross correlation for laser Gala 780 nm, turbulent atmosphere.

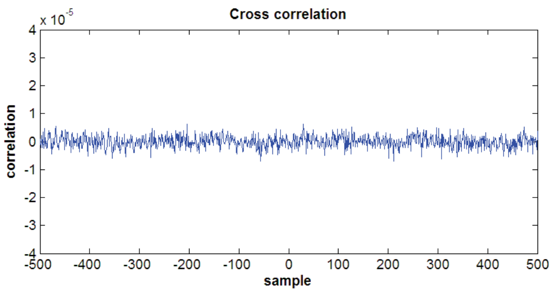

Fig. 8. Cross correlation for laser Gala 780 nm, turbulent atmosphere with water vapor.

The measurement of RLD shows the opposite correlation peak. It means that energy was redistributed between horizontal and vertical components and indicates convolution of the polarization plane. The measurement of RLD shows a slight correlation of orthogonal components for a turbulent atmosphere with a high density of water vapor. The small beam width and the emphasis of absorbance phenomena caused the slight correlation (see Fig. 10). The measurement of RLD was most influenced by atmospheric effects. This could be caused by the small beam width. The obtained results of correlation analysis are different between GALA and RLD in spite of the same wavelength. The reasons for different results are due to a great difference in coherence lengths and different optical beam widths.

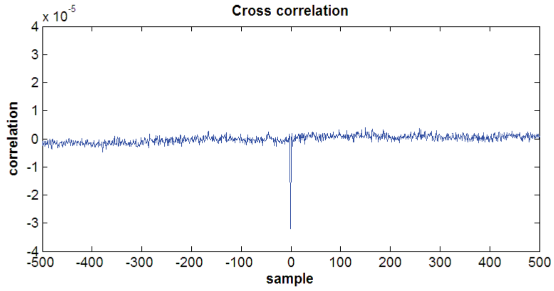

Fig. 9. Cross correlation for laser diode RLD, turbulent atmosphere.

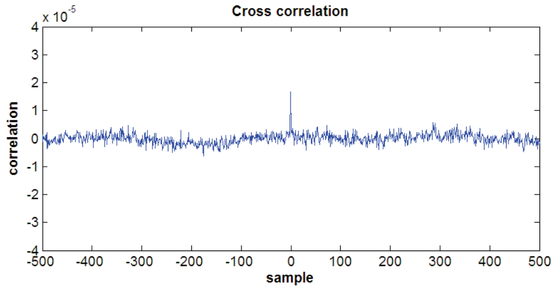

Fig. 10. Cross correlation for laser diode RLD, turbulent atmosphere with water vapor.

The measurement of ML shows the least correlation between the optical beam variances of horizontal and vertical polarized components (see Fig. 11and 12). It is similar to the GALA laser.

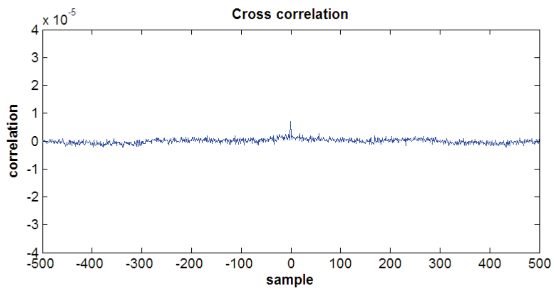

Fig. 11. Cross correlation for ML, turbulent atmosphere.

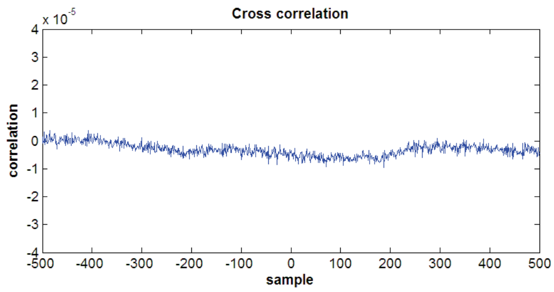

Fig. 12. Cross correlation for ML, turbulent atmosphere with water vapor.

4. Conclusions

The turbulent atmosphere rate of effect upon the optical intensity fluctuation of horizontal and vertical components for circularly and linearly polarized optical beams was studied. Within the frame of experimental work the output optical beam polarization parameters of optical sources have been investigated in a particular part of the measuring scheme.

The correlation analysis of variances from the mean optical value was conducted for horizontal and vertical components. The correlation analysis allowed determination of mutual dependence between both components. The minimal mutual dependence was found from the obtained data. The different effects of turbulent atmosphere and turbulent atmosphere with a high density of water vapor, towards the horizontal and vertical components, were found. The presented results were obtained on the basis of computed values of optical intensity variances.

In all conducted measurements the effect rate was greater in the parallel component having the same direction as the turbulent flux. On the basis of this observation we can conclude that the turbulence effect rate is dependent upon the turbulent flux direction. The circularly polarized optical beam can be used to reduce the turbulence effect rate of the turbulence flux direction. The circularly polarized beam variance is inside the interval between the variances of horizontal and vertical components.

The aim of our next work is verification of temperature turbulence dependence in relation to other directions and different parameters of turbulent flux atmosphere. All measuring conditions and environment will remain the same.

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