Polarization stability of the single-mode laser diodes radiation applied in radiation scattering study complexes

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Abstract. Key features of semiconductor lasers and its serially manufacturing technology modernization have greatly expanded of its using at applied studies at last 20 years. But there is set of factors restricting such lasers application in a number of optical-electronic measuring complexes. Particularly in particle image velocimetry (PIV) and laser Doppler velocimetry (LDV) complexes commonly the gas and solid-state lasers is used due to more stability of spectral, energy and polarization characteristics of radiation then semiconductor lasers have. However gradual introduction of the serially manufacturing laser diodes into such systems picking up the pace that certainly characterizes the progress of reaching the required stability of its output laser radiation parameters. In laser measurement systems where medium investigation carried out by analyzing of scattering radiation in it the probe radiation polarization is often important. So the using in such systems the laser diodes as sources of radiation need to be followed by stability monitoring of its polarization characteristics which may be violated both by the outer factors and by natural degradation of inner laser diode structure. This work is devoted to the issues of monitoring the radiation polarization characteristics of the serially manufacturing single-mode laser diodes.

1. Introduction

The radiation scattering phenomena is spreadly use in such areas of sciences as chemistry, ecology, biology, medicine and for study of atmosphere and mixes containing nanoparticles [1–12]. In modern laser measuring systems where the scattered radiation characteristics measurement results depend of probe radiation polarization the stability of polarization is playing crucial role. In particular the particle image velocimetry (PIV) and laser Doppler velocimetry (LDV) complexes are such systems. At using the gas, fiber and solid-state lasers the stability of the probe radiation output parameters is saved during the tens of thousands hours of service. But the such type lasers exploitation requires the large power consumption, introduction of often bulky cool systems and the increasing of whole dimensions of system. These disadvantages may be eliminated by using semiconductor laser diodes (LD), which are characterized by easy operation, high radiation power with low power consumption and small dimensions. The significant disadvantage of the LD is the pronounced dependence of its output radiation parameters from the external ambient factors. These factors include ambient temperature or the presence of external electromagnetic fields.

When using spatially single-mode LDs as sources of probing radiation, the output power and the
state of polarization of the laser radiation should be monitored. Moreover the latter property of radiation is most sensitive to changes in the waveguide and active medium associated with the degradation of the device. Thus, it is necessary to regularly monitor the state of polarization of the probe radiation the source of which is a single-mode commercially available LD. This paper presents examples of transformation of the polarization characteristics of commercially available laser modules. The analysis of degradation changes in the waveguide and the active medium of the LD is also carried out on the basis of the results of measurements of its radiation spatial-energy and polarization characteristics.

2. Measurement complex for analysis the space-energy and polarization characteristics of LD radiation

The most complete information of the LDs waveguide and heterostructure state can be obtained by analyzing the radiation pattern into free space. In this case, the analysis of the spatial-polarization characteristics of radiation can be carried out by scanning the radiation pattern using a polarizing prism [13]. The diagram of the measuring complex is shown in figure 1.

![Figure 1. Measuring complex scheme: 1 – explored laser module, 2 – optical holders with adjusting screws, 3 – two-axis linear positioner, 4 – stepper motor, 5 – Thompson-Glan polarization prism, 6 – receiver unit with diaphragm, OX’ – rotation axis of the motorized platform, CC’ – laser beam axis.](image)

The laser module 1 is mounted on a two-axis linear positioner so that the axis of the motorized platform OX’ passes approximately through the center of the LD output mirror. In this case, the LD can be rotated around the beam axis, which makes it possible to scan the radiation pattern in different planes. The polarizing prism 5 carries out polarization selection of radiation.

To analyze the polarization stability of LD radiation into free space it is sufficient to scan the radiation pattern in the plane where the divergence angle is maximal or minimal. This planes of the radiation pattern is called vertical and horizontal respectively. It was shown in [13] that when scanning radiation along these planes it is possible to set only two positions of the polarization prism at which it will transmit either the maximum or minimum of the radiation flux at any observation angle θ. Thus the angular dependence of the linear polarization degree or contrast $K(\theta)$ can be determined

$$K(\theta) = \frac{P_{\text{max}}(\theta) - P_{\text{min}}(\theta)}{P_{\text{max}}(\theta) + P_{\text{min}}(\theta)},$$  \hspace{1cm} (1)
where $P_{\text{max}}(\theta)$ and $P_{\text{min}}(\theta)$ is respectively maximum and minimum power value of radiation transmitting across linear polarizer at observation angle $\theta$.

3. Theoretical description the space-energy and polarization LD radiation characteristics dependence of waveguide parameters

The contrast angular distribution (1) substantially depends on the waveguide anisotropy, heterostructure internal stresses and the reflectivity of the resonator mirrors for the TE and TM modes [14]. Figure 2 shows the theoretical dependences of the contrast angular distribution and radiation pattern in two planes at variations in the difference between the effective refractive indices for ordinary ($n_{1o}$) and extraordinary ($n_{1e}$) waves inside the single-mode edge-emitting LD waveguide.

![Figure 2](image)

*Figure 2.* Normalized radiation pattern and contrast angular dependence in vertical (a) and horizontal (b) planes at various difference between ordinary $n_{1o}$ and extraordinary $n_{1e}$ effective refractive index of waveguide: I – radiation pattern, II – $K(\theta)$ at $n_{1e} - n_{1o} = 0.003$, III – $K(\theta)$ at $n_{1e} - n_{1o} = 0$.

Also the distribution of the total radiation energy between the TE and TM modes significantly influences on the single-mode strip lasers radiation contrast angular dependence. As a result the analysis of the radiation pattern and the contrast angular dependence of a single-mode edge-emitting LD with a strip, ridge, or rectangular waveguide makes it possible to: 1) estimate the parameters of the waveguide and the active medium including the degree of anisotropy and the energy distribution between the TE and TM modes; 2) to trace the dynamics of changes in these parameters by carrying out measurements at different times of the LDs operating time. As a result of such an analysis it is possible not only to control the stability of the radiation source polarization characteristics but also to select optimal sources from a batch of commercially available devices for solving problems of studying the characteristics of scattered radiation.
4. Analysis of the free space radiation polarization stability and waveguide parameters of the edge-emitting single-mode LD

Let us consider the change dynamics in time of the radiation polarization state and the waveguide parameters of the commercially available KLM-D650-5-5 laser module by comparing the calculation and measurement results of its radiation characteristics. Determination of the waveguide parameters and LDs active medium from the characteristics of its radiation is an inverse problem. For an unambiguous solution to this problem it is required to have information about the values of some input parameters of the waveguide and plates. For example if the materials stoichiometric composition included in the LD structure is known then the refractive indices values of the heterostructure layers materials can be set approximately. In this case solving the inverse problem is reduced to determining only the geometric parameters of the waveguide. Then having determined the geometry of the LD it is possible to refine the optical parameters of waveguide and the plates from the characteristics of radiation. Thus by comparing the found parameters of the LD heterostructure layers with the parameters used in solving the inverse problem it is possible to conclude the degree of their correspondence.

However the information about the material and geometry of LD layers is rarely disclosed by the manufacturer. But as a first approximation the composition of the waveguide and active medium can be indirectly determined from the wavelength of the laser radiation. Thus when determining the material of a waveguide, it is possible to narrow the range of its search by semiconductor structures that are transparent to radiation of a known wavelength. In addition knowing the LD radiation wavelength one can determine the bandgap of the active region and find a material for which a direct quantum transition between laser levels is possible.

The data sheet KLM-D650-5-5 does not contain information on the laser waveguide parameters. Therefore all further calculations are carried out by selection according to the methodology described in the previous paragraph. First the results of measurement and modeling of the normalized radiation pattern and contrast angular dependence in the vertical plane of the KLM-D650-5-5 radiation are compared at the device operation initial stage. To describe the computational model, the following waveguide parameters are used (figure 3): ordinary and extraordinary refractive indices $n_{1o} = 3.650$, $n_{1e} = 3.654$, refractive indices of plates $n_2 = n_3 = 3.600$, waveguide thickness $a = 0.45 \, \mu m$.

![Figure 3](image)

**Figure 3.** Simplified scheme of active three-layer waveguide (a): 1 – the waveguide core, 2 – the waveguide plates, $J_{pump}$ – the pumping current density; parabolic gain profile (b): $g(y)$ – the parabolic gain factor, $\Delta g$ – the difference between maximum gain and losses.
For the indicated refractive indices at a wavelength of 650 nm the following variants of semiconductor compounds are possible: Al$_{x}$Ga$_{1-x}$As ($0.15 < x < 0.29$), Ga$_{x}$In$_{1-x}$P ($0.49 < x < 0.5$) [15, 16]. The axial value of the radiation contrast of the KLM-D650-5-5 equal to 0.95 corresponds to the TM and TE modes amplitudes ratio at the output mirror of the laser $A_{TM}/A_{TE} = 0.23$.

The measurement results and modeling of the KLM-D650-5-5 radiation characteristics with the above parameters of its waveguide are shown in figure 4. Confidence intervals are marked with vertical lines over the points. In the radiation pattern the designations of these intervals are set in the places of experimental points greatest deviation from the theoretical curve.

The results of measuring the radiation pattern and $K(\theta)$ within the error limits are in good agreement with the simulation results. Separately it should be noted that in the area of space adjacent to the vertical plane the radiation contrast of the KLM-D650-5-5 at the beginning of its operation was constant and close to 1 which also coincides with the calculation results. The description of radiation pattern and angular contrast distribution modeling is presented in [17].

Figure 5 shows the measurement results and modeling the normalized radiation patterns and contrast angular dependencies in the vertical plane after 50 and 100 hours of operating the KLM-D650-5-5.

**Figure 4.** Comparison of measurement results and simulation of KLM-D650-5-5 radiation characteristics in the vertical plane at the beginning of its operation: the lines represent the simulation results, the points are the experimental results.

**Figure 5.** Comparison of measurement results and simulation of KLM-D650-5-5 radiation characteristics in the vertical plane after 50 (a) and 100 (b) operating hours: the lines represent the simulation results, the points are the experimental results.
The figures show that after only 50 hours of operation the state of radiation polarization into free space has changed. The ratio of the amplitudes at the output mirror of the $A_{TM}/A_{TE}$ laser increased to 0.47 and after 100 hours of operation to 0.50. The $A_{TM}/A_{TE}$ value itself indirectly characterizes the ratio of the radiation amplification indices for each of the modes, which can be determined if the corresponding reflection coefficients of the resonator mirrors are known.

Figure 5 especially shows the effect of waveguide anisotropy on the $K(0)$ dependence, in particular, in the form of a noticeable decrease in contrast with increasing angle $\theta$. This indicates the formation of internal stresses in the waveguide which violate the polarization stability of the radiation. In the future such violations can lead to rapid degradation of the LD and a significant decrease in the radiation power. Thus control of the single-mode edge-emitting LDs radiation polarization stability makes it possible to define the instant of the onset of degradation.

5. Conclusion
In this paper we show the relationship between the dynamics of changes in the parameters of the commercially available single-mode edge-emitting LDs waveguide and the polarization stability of its radiation. It is noted that the change in the polarization stability of laser radiation is associated with the appearance of internal stresses in the waveguide, which is an indicator of the onset of degradation. Thus the most effective application of this type of LD in laser systems for diagnostics of scattered radiation should be accompanied by control of the spatial-energy and polarization characteristics of its radiation. In the case when the radiation is collimated the violation of polarization stability is registered much later than that of radiation propagating into free space [13]. However it is precisely the control of non-collimated radiation polarization state that makes it possible to define the moment of the onset of degradation. This makes it possible to predict an early failure of the LD or a significant deterioration in the energy and polarization characteristics of its collimated radiation.

An additional and most undesirable factor in the development of degradation is fluctuations in the power and polarization state of the LD radiation within the continuous operating time. It has an extremely negative effect on the scattering indicatrix measuring results accuracy in the case when it is registered at various angles of observation occurs at different times. Therefore the registration of the radiation polarization state constancy of commercially available single-mode edge-emitting LDs from the moment of its operation is an important component of the effective use such devices in laser measuring systems.

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