The specifics of single-mode laser modules application in optical-electronic complexes based on light scattering

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Abstract. The polarization state of edge-emitting single-mode laser modules radiation and their conditions of using in laser measuring systems of scattered radiation diagnosis are considered. For laser modules from two batches, both the polarization degree of collimated radiation and polarization degree spatial dependence in two orthogonal planes when there is no collimation are measured. It is established the angular dependence of non-collimated radiation polarization degree at different planes is various. We also considered the impact laser diodes degradation on these dependencies. It is shown that while exploitation of single-mode laser diodes in laser systems for scattered radiation characteristics researching it is needed to make control the polarization state of their radiation while service.

1. Introduction
Radiation scattering phenomena is widely used at such fields of science as ecology, medicine, astronomy, as well as for study mixture properties containing nanoparticles [1-4]. The scattered radiation properties analyzing need to do taking into account the properties of the specifically analyzed medium. For correct analysis of experimental results in the scattering study it is important to know the probing radiation properties of source itself: power and spectrum, radiation pattern and polarization state. It's known that the last property significant influences on scattered radiation structure – at scattering observation of source radiation p- and s- components all else being equal conditions the pattern of scattered radiation is different principally. This difference makes it possible to obtain more complete information about the characteristics of the test substance and often is taken into account when studying the properties of biological tissues, as well as the characteristics of the atmosphere, various solutions and crystals [5-12].

Depending on the task, LEDs and various types of lasers are used as radiation sources. The coherence and high polarization of the radiation of the latter allows them to occupy their niche in almost all scientific, technical and applied problems associated with the study of the properties of scattered radiation. Of particular interest are single-mode laser modules, which advantages most of all is associated with their compactness, energy efficiency and low cost relatively of gas, solid-state and fiber lasers. Besides, coherence of single-mode laser diodes (LD) radiation as their improvement starts to approach the level of solid-state and fiber lasers. It gives a reason to predict of wider laser diodes use in future at optical-electronic complexes for scattered radiation properties studying.
The free-space radiation of edge-emitting single-mode LD has a large divergence. This feature allows exploring an extensive space near LD. This feature allows you to explore the region of space near the LD within a solid angle of 0.015 sr. But at the moment polarization properties of such radiation are not studied in detail therefore in this work attention is paid to them. It is shown that the degree of linear polarization in different places of the LD radiation pattern may differ. It is also known that as the degradation occurs, the current-voltage and watt-ampere characteristics of the LD, as well as the spectral and polarization properties of its radiation are changed [13-15]. These parameters allow us to estimate the parameters and the possibility of using a separately selected model of a laser module in problems of studying the properties of scattered radiation.

2. Measurement technique and installation scheme

Usually the radiation at the output of laser modules is collimated and transformed into slightly divergent beam with a contrast close to 1. Of particular interest is the radiation into free space, the contrast of which has an angular dependence. In this case, the formation of various normalized indicatrices of scattering from different parts of the medium being probed is occurred. In this work, we studied the contrast of collimated radiation of single-mode LDs and angular dependence of the contrast of their radiation into free space at two planes. However, special attention was paid to the effect of LD degradation on its characteristics.

The polarization state of the radiation at the output of the LD cavity is determined by the anisotropy of the waveguide, the internal stresses of the heterostructure, and the reflectivity of the resonator mirrors for TE and TM modes [16]. The free-space radiation polarization state investigation of considered LD type is difficult because of large radiation divergence which is caused by diffraction on output LD mirror. As will be shown later the polarization degree in various areas of radiation pattern is different. Taking into account the astigmatism of the laser beam, it is analyzed along the wave front in the vertical $XZ$ and horizontal $YZ$ planes to simplify the measurements of the radiation pattern (figure 1).

![Figure 1. General scheme of single-mode LD and its radiation into free-space.](image)

It is determined experimentally that at the scanning along wave front in horizontal the directions of vector $E$ oscillations with maximum and minimum amplitude are oriented along $e_\theta$ and $e_\phi$ basis vectors of spherical coordinate system, respectively. And when scanning in the vertical plane – on the contrary, along the unit vectors $e_\phi$ and $e_\theta$, respectively. Thus there are only two analyzing polarizer positions when the maximum and minimum LD radiation transmission in exploring areas of radiation pattern is provided. Strictly speaking the radiation of explored LD types is not monochromatic and the wave front concept using is not so correct here. It means the scanning along surface the point of which are at equal distance from light spot, and normal radiation incidence on polarizer face and receiving
area of the photoreceiver is provided. If the LD radiation were completely monochromatic, then the wave front would coincide with this surface in a vertical and horizontal plane.

The full width at half maximum (FWHM) of the spectrum of the edge-emitting single-mode LD is 1.0±1.5 nm, which corresponds to the radiation coherence length many times smaller than 1 mm. It means a low degree of mutual coherence between two transversal components of radiation linear polarization at Fraunhofer field. Therefore we may neglect the energy of circular polarization component of radiation. It allows counting that the polarization degree is equal to contrast (1):

\[ K = \frac{P_{\text{max}} - P_{\text{min}}}{P_{\text{max}} + P_{\text{min}}}, \]

where \( P_{\text{max}} \) and \( P_{\text{min}} \) is respectively maximum and minimum power value of radiation transmitting across linear polarizer.

Here it should be noted separately that the concept of “wave front” is usually applicable to monochromatic radiation. The edge-emitting single-mode LD radiation cannot be considered monochromatic, therefore, it means a surface that would coincide with the radiation wave front of the same laser, if it were completely monochromatic. When scanning the radiation pattern along this surface in the considered planes, both the normal incidence of radiation on the receiving optical system and the equidistant location of this system from the light spot are provided.

Measurements were made using a measuring complex, which scheme is shown on a figure 2.

Figure 2. 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, 7 – optical rail, OO’ – rotation axis of a stepper motor, CC’ – laser beam axis.

The laser module (1) is placed in one of the holders (2), the adjustment screws of which allow you to adjust its inclination in a vertical and horizontal direction. It’s necessary the holder also provide LDs rotation around beam axis CC’ what gives possibility for measuring angular dependence of contrast at radiation pattern various planes. The position adjustment of LD in Y’Z’ plane is realizing using two-axis linear positioner (3), on which the holder with LD is mounted. Whole system is mounted on stepper motor (4) (57HM76-3004) which rotation rack axis is denoted as OO’. Thus when rotating LD its radiation always normal incidences both onto polarization prism (5) front surface and on receiving area of the photoreceiver (6) that provides radiation scanning along imaginary wave front. The receiving unit is an aperture diaphragm and a photodiode (FD-24K), the signal from which is read by the Arduino microcontroller board and displayed on the PC screen (is not shown in the figure 2). Whole system is rigidly fixed on optical rail (7).
Insofar as stepper motor has a step discretisation of rotation angle what makes additional limits in measuring system possibilities, it's also possible using the goniometer turntable as device providing rotation around OO’ axis at less step.

3. Measurement of LD radiation contrast and discussion

3.1 The angular dependence study of the radiation contrast

A radiation pattern into free space is characterised by various divergence angles in a vertical and horizontal plane. In a vertical plane the whole divergence angle on half maximum of intensity is 27° and on horizontal is about 8°. The advantage of such LD service mode is possibility of simultaneously probing the mixture large volume. But in this case it is necessary to take into account not only the angular intensity distribution but also the angular radiation contrast distribution.

On figures 3 and 4 the results of the angular dependence measurements of the radiation contrast in a vertical and horizontal plane at various operating time for single-mode laser module LD1 of KLM-E650-5-3 model are presented. The LD1 heterostructure has no quantum well and besides we removed the collimating optics for radiation into free-space analysis. Since the vertical plane is perpendicular to the border of the p-n-junction, and the horizontal plane is parallel to this border, the corresponding contrast distribution distributions for these planes are denoted by $K_\perp(\theta)$ for the vertical plane; $K_{||}(\theta)$ – for the horizontal plane. Dots show experimental results and solid lines are the approximation by smooth functions.

**Figure 3.** Normalized measured radiation pattern of LD1 in a vertical plane and the angular dependence of contrast $K_\perp(\theta)$: (a) at the beginning of operation, (b) after 50 hours of operation, (c) after 100 hours of operation.
Figure 4. Normalized measured radiation pattern of LD1 in a horizontal plane and the angular dependence of contrast $K_\parallel(\theta)$: (a) after 50 hours of operation, (b) after 100 hours of operation.

Let us now consider the polarization properties the radiation of a single-mode laser module of KLM-D650-5-5 model (LD2) with a nanoheterostructure. Here, just as in the case of LD1, radiation into free space was investigated, without using collimating optics. The results of the measurements in a vertical plane at various operation times are presented in figure 5.

Figure 5. Normalized measured radiation pattern of LD2 in a vertical plane and the angular dependence of contrast $K_\perp(\theta)$: (a) at the beginning of operation, (b) after 50 hours of operation.

In figure 6 the measurements in a horizontal plane at 50 hours of operation time are also shown.

Analysis of the measurement results when scanning a beam along a wave front in a vertical plane showed that as the laser operating time increases, there is a general tendency for the contrast to decrease both on the axis and on the periphery of the beam. In the initial period of operation, when scanning the beam in the indicated plane for LD1 and LD2, one can note a value of contrast close to 1 in the entire scanning area. However, in the case of LD1, over time, the contrast at the periphery of the beam decreases somewhat faster than on the axis, and then, as shown in figure 3 (c), the graph of the contrast function $K_\parallel(\theta)$ is smoothed again. At the same time, its value in the entire scanning area in just 100 hours of operating time decreases by 25%.
In the horizontal plane $YZ$ a pronounced angular dependence of the contrast $K_{\parallel}(\theta)$ is observed for both LDs. In figures 4 and 6, it is shown that its value rapidly decreases with distance from the beam axis at any operating time. From this it follows that the radiation pattern of orthogonal linearly polarized components in this plane is different – the normalized radiation pattern, due to the diffraction of the TM mode on the output mirror, has a flatter appearance in the peripheral region than the normalized radiation pattern, due to the diffraction of the TE mode. This is due primarily to the different amplitude-phase of the TE and TM modes energy distribution on the output mirror in the direction under consideration. In addition, here the cylindrical shape of the wave surface also affects [16]. Because of this, in the $YZ$ plane there are differences between the diffraction conditions for the TE and TM field components at the laser output mirror, which also affects the shape of the angular dependence $K_{\parallel}(\theta)$.

Separately, we note the effect of increasing the operating time on the radiation polarization state of this LD type. Such a change is associated with the redistribution of energy between the TE and TM modes due to changes in the properties of the heterostructure. As degradation occurs, additional stresses arise in it due to the uneven temperature distribution associated with a non-uniform pump current density in a semiconductor. The reason for this is the formation of defects in the process of the heterostructure creation during its production. As a result, the energy of the TE mode goes into the TM mode, while the total radiation energy at the first stages of the degradation onset does not significantly decrease and the distribution of the total intensity on the LD light spot does not change. Therefore, the radiation pattern of the entire radiation almost completely retains its spatial-energy characteristics. However, the distribution of LD radiation contrast undergoes significant changes. Although we considered only two planes of scanning the radiation pattern, it is also worth assuming that the angular distribution of contrast changes in other areas of the radiation pattern as the operating time increases.

In laser-measuring complexes for diagnosing scattered radiation, the stability of the polarization characteristics of the probing radiation is often important. Since the state of polarization of LD radiation into free space changes rather quickly, their use in such systems must be accompanied by preliminary measurements of the contrast angular distribution within the beam region used for probing the medium. At the same time, such monitoring should be carried out before each series of measurements of the scattered radiation indicatrices.

Figure 6. Normalized measured radiation pattern of LD2 in a horizontal plane and the angular dependence of contrast $K_{\parallel}(\theta)$ after 50 hours of operation.
3.2 Measurements of collimated radiation contrast

For laser modules of the same models, the total contrast $K_\Sigma$ of collimated radiation was measured at the beginning of operation, and then after 50 and 100 hours of operating time. Measurements have shown that during the specified time the LD degradation does not affect $K_\Sigma$ which remains close to 1. However, with longer operating times, from 500 hours, the contrast of even collimated radiation decreases with degradation along with changes in the spectrum and the onset of a fall in the total output power of the laser radiation. Thus, a decrease in the contrast of $K_\Sigma$ signals a change in the other parameters and characteristics of the radiation. This means that with long-term use in measuring systems with LD with collimating optics, it is also worthwhile to periodically control the state of polarization of its radiation.

A detailed analysis of the distribution of contrast in the cross section of a collimated beam of the investigated LDs wasn't made in this paper. However, it is known that the use of optics changes the state of polarization of radiation transmitted through it. Therefore, it should be expected that the distribution of contrast in the beam cross section during collimation won't be equivalent to its angular dependence in the case of freely propagating radiation. To study the collimated beam in the scheme in figure 2, the receiving unit 6 should be replaced with a calibrated CCD array, which provides a one-time measurement of the intensity distribution for each polarization component of the laser beam. But the taking into account the effect of the nonuniform distribution of the collimated beam contrast on the scattering indicatrix is a rather laborious task. In the diagnosis of scattering, this is usually neglected, considering that at each point of the cross section the contrast is equal to its total value $K_\Sigma \approx 1$; the probe radiation of the LD in this case is considered as linearly polarized with the plane of polarization lying in the horizontal plane $YZ$.

Also, one of the main methods of ensuring a high degree of linear polarization of probe radiation is its transmission through a linear polarizer which the transmission axis is oriented along the direction of the electromagnetic field oscillations maximum amplitude. For other types of polarization the phase plates are additionally used. However, as the contrast of the probe radiation of the LD decreases as it passes through the polarizer, the energy loss will be more significant. In this connection, even when polarization optical elements are used into the measurement complexes for the scattering diagnostics a preliminary monitoring of the LD radiation polarization state is also required.

4. Conclusion

The choice of radiation sources in laser measuring systems for diagnosing the properties of various media is based on the requirements for such radiation characteristics as spectrum, power density and polarization state. It is especially important to ensure the stability of these characteristics over a long period of the source operation. In some cases, the properties of the scattered radiation substantially depend on the polarization of the probing radiation [1-12].

We have considered the specifics of the radiation polarization structure of single-mode edge-emitting LD from two batches for two cases: when the radiation is collimated by an optical system and when it propagates into free space. It is shown that the integral contrast $K_\Sigma$ of their collimated radiation is almost equal to 1 retaining its value for about 500 hours of operation. At the same time, the radiation in free space is characterized by a complex angular distribution of contrast along the radiation pattern. In addition, for two different types of end LDs, the same angular dependence of contrast is observed in the vertical and horizontal planes. Separately, it should be noted that in the central region of the beam, within a solid angle of 0.004 sr, the contrast retains approximately the same value in these planes. Therefore, in the absence of collimation it is recommended that this area of the beam be used to probe the medium. This eliminates that part of the measurement error of the normalized scattering indicatrices, which is associated with an uneven contrast distribution of within the laser beam.

The influence of LD degradation on the contrast of its radiation which is sensitive to the heterostructure degradation, especially in the absence of collimation, is considered separately. Therefore, in the measuring systems of the scattering radiation diagnosis where edge-emitting single-
mode LD is used as a source its operation should be accompanied by preliminary measurements and subsequent monitoring of the state of polarization of its probing radiation. Also, in order to slow down the rate of degradation it is necessary to optimize its operation which includes both control over the stability of the power supply and ensuring uniform cooling of the LD crystal. Fulfillment of these conditions ensures the most efficient use of the considered types of LD in the composition of such measuring systems.

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