Spectral, Space—Energy, and Polarization Characteristics of Laser Diodes with Lasing Wavelengths of 530 nm

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Abstract—The characteristics of laser diodes (LDs) with quantum-well (QW) InGaN layers with lasing wavelengths of 530 nm are studied experimentally. It is shown that the LD radiation contrast at the initial phase of operation is quite low (it does not exceed 0.85). It is found that the time dependences of radiation contrast and spectrum become apparent after just 300 h of operation, and the radiation power starts to fall after 1200–1300 h of operation.

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INTRODUCTION

The rapid expansion of the range of laser diodes (LDs) with QW heterostructures led to the problem of predicting their service life. This problem is usually solved by investigating the time dependences of the energy and spectral characteristics of LD radiation and the threshold pumping current density [1–3].

Polarization characteristics and parameters of LDs (the polarization indicatrix and state and degree of polarization of laser radiation) have been investigated much less frequently. This can be attributed to the complexity of the classical technique for measuring the Stokes parameters. This technique involves using a quarter-wave plate that has a limited (due to dispersion) spectral range. In addition to coherence and radiance, polarization is a fundamental property of laser radiation. Laser polarization parameters depend on resonator parameters, and on the properties and state of the active medium. We can observe the processes that occur within a laser (including its degradation) by monitoring the radiation polarization.

The obvious need to measure the polarization parameters of LD radiation and the complexity of the classical technique for measuring the Stokes parameters stimulate the interest in developing and applying new and simpler techniques for making such measurements.

STANDARDIZING MEASUREMENTS OF THE POLARIZATION PARAMETERS OF LD RADIATION

A technique for automated measurements of the Stokes parameters of LD radiation was proposed in [4]. The technique was based on fixing the coordinate system to the studied laser. When an original phase plate calibrated with a Fresnel rhomb is used as a compensator, polarization characteristics can be measured over a wide range of wavelengths, from 400 to 1300 nm. In an elaboration of this idea, an achromatic zero-order quartet-wave plate that allowed us to measure polarization parameters in the range of 400–600 nm was used as a compensator in the diagnostics of LD radiation at 530 and 532 nm. An achromatic zero-order quarter-wave plate with an operating spectral range of 600–1450 nm was used to measure the polarization parameters of LDs with lasing wavelengths of 635, 650, and 980 nm.

The enforcement (as of January 1, 2015) of the standard in [5], which is identical to the international standard in [6], was an important milestone in LD metrology. This standard establishes a prompt and simple method for determining the state and degree of polarization of continuous laser radiation. This method is applicable to lasers with wide angles of divergence and wide-aperture beams, thus offering an opportunity to probe LD radiation. The method for determining the state and the degree of polarization of LD radiation specified by the standard in [5] was used in this work.

INVESTIGATING THE POLARIZATION PARAMETERS OF LD RADIATION

Figure 1 shows a generalized optical layout of the measurement setup used in this work to investigate the state of radiation polarization both in narrow laser beams and in beams with large angles of divergence.

The basic elements of this layout, which was used to measure all states of polarization of LD radiation, were LD (1); reference axis (2); polarizer (3), which
could be rotated within 180°; radiation detector (4); and a laser beam (5). This arrangement was used to determine the linear polarization of radiation. In order to check for circular or elliptic polarization, a quarter-wave plate (6) that could be rotated within 180° was placed between elements (2) and (3). To determine the state of polarization of laser beams with wide angles of divergence, collimator (7) was introduced between elements (1) and (2).

In accordance with [5], the linear polarizer was rotated while measuring the linear polarization of radiation until the maximum and minimum output signals of the radiation detector were obtained. The contrast was then calculated based on power $P$ values measured in two orthogonal directions, $x$ and $y$:

$$\text{Contrast} = \frac{P_x - P_y}{P_x + P_y}. \quad (1)$$

Measurements were repeated at least ten times, and the average contrast ($C_{av1}$) was then calculated. If this value was below 0.9, a second measurement with quarter-wave plate (6) introduced into the setup was performed. The quarter-wave plate and the polarizer were rotated until it became clear that the absolute maximum and minimum of the output signal were functions of the angular position of the quarter-wave plate and the polarizer. The average contrast was then calculated. This average value was denoted as $C_{av2}$ in order to distinguish it from the contrast determined in measuring the linear polarization.

The results from determining the state and, when possible, the degree of polarization in only one or two measurements in accordance with [5] are listed in the table.

It can be seen from the table that the beam was polarized linearly if the average contrast $C_{av1}$ was above 0.9. In this case, the degree of polarization equaled the contrast. If $C_{av1}$ fell within the interval of 0.1–0.9 and $C_{av2}$ was below 0.1, partial polarization with a degree of $C_{av1}$ was observed.

If $C_{av1}$ was lower than 0.1 and $C_{av2}$ was higher than 0.9, the radiation was polarized circularly. If $C_{av1}$ was lower than 0.1 and $C_{av2}$ fell within the interval of 0.1–0.9, partial circular polarization with a degree of $C_{av2}$ was observed.

It was found in measuring the state and the degree of polarization of radiation of seven LDs that the values of $C_{av1}$ varied from 0.50 to 0.85, while contrast $C_{av2}$

<table>
<thead>
<tr>
<th>$C_{av1}$</th>
<th>$C_{av2}$</th>
<th>State (type) of polarization</th>
<th>Degree of polarization</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt;0.1</td>
<td>&lt;0.1</td>
<td>Partially linearly polarized</td>
<td>$C_{av1}$</td>
</tr>
<tr>
<td>&gt;0.1</td>
<td>&gt;0.9</td>
<td>Elliptically polarized</td>
<td></td>
</tr>
<tr>
<td>&gt;0.1</td>
<td>&gt;0.9</td>
<td>Partially elliptically polarized</td>
<td>$C_{av2}$</td>
</tr>
<tr>
<td>&lt;0.1</td>
<td>&gt;0.9</td>
<td>Circularly polarized</td>
<td>$C_{av2}$</td>
</tr>
<tr>
<td>&lt;0.1</td>
<td>&gt;0.1</td>
<td>Partially circularly polarized</td>
<td>$C_{av2}$</td>
</tr>
<tr>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
<td>Nonpolarized</td>
<td>0</td>
</tr>
</tbody>
</table>

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Dependences of the state (type) and degree of polarization on average contrast values $C_{av1}$ and $C_{av2}$
varied from 0.03 to 0.07. This implies that their polarization was partially linearly polarized.

It was thus shown that the technique proposed in [5] for determining the state and degree of polarization of high-directivity or collimated laser radiation allows us to measure these polarization parameters promptly and easily without having to determine the Stokes parameters.

Measuring the polarization parameters of LDs attracts great attention because these parameters are, along with spectral characteristics, especially sensitive to changes in their heterostructure. This allows us to determine the minimum operating time of LDs (the temporal degradation threshold) in which their degradation starts to become apparent [7].

For example, our earlier studies of a previous batch of five LDs with a lasing wavelength of 530 nm showed that their contrast was reduced from 0.80 to 0.60 after 3000 h of operation. The changes in contrast and the spectral characteristics of LDs became apparent after just 300 h of operation, while the radiation power of the studied LDs started going down after only 1200–1300 h of operation (Fig. 2).

RESULTS AND DISCUSSION

The new batch of seven LDs with lasing wavelengths of 530 nm that were tested in this work was specific in that the devices had exceptionally narrow angles of radiation divergence (about 1°). This allowed us to perform contrast measurements in accordance with [5] without the use of a collimator. The LDs had accumulated no more than 20 service hours, so they were far from the temporal degradation threshold that was determined earlier in the diagnostics of an earlier batch of five LDs. It was found experimentally that the radiation power of all LDs matched their specifications, while the radiation contrast varied from 0.53 to 0.85. This was indicative of a low degree of linear polarization of their radiation. According to the results from studies of LD parameters in [8], such contrast values are typical for heavily degraded LDs with strained QW heterostructures; this strain is relieved gradually, due to the emergence of defects and dislocations in the process of operation.

However, our technique for estimating the service life of LDs with a strained QW heterostructure must be used with great care in studies of genuinely green lasers produced recently (2011–2015) with lasing wavelengths in the region of 515–530 nm. The reason for this lies in their heterostructure:

QW InGaN layers are used as the active layers in such LDs. The radiation is put out through a GaN substrate that is transparent in the spectral range of 515 to 530 nm and is oriented at a certain angle to the QW InGaN layer. An n-type GaN layer is grown directly on a GaN substrate. A coating (emitter) n-type InAlGaN layer, a waveguide n-type InGaN layer, an active region formed by several quantum wells made from p-type InGaN, a barrier p-type AlGaN layer, a waveguide p-type InGaN layer, a coating p-type InAlGaN layer, and a contact p-type GaN layer follow [9].

The effect of optical anisotropy on strained layers shapes the specific characteristics of genuinely green lasers.

It is known that optical anisotropy exerts a strong influence on the optical properties (primarily the polarization of radiation) of known anisotropic wurtzite-type crystalline structures. Optical transitions with vector $\vec{E}$ of the electric field of a wave perpendicular to the optical axis of the crystal are allowed for all subbands of the valence band (most notably, for the subband of heavy holes), while transitions with vector $\vec{E}$ of the electric field of a wave parallel to the optical axis of the crystal are forbidden. This is because of the effect the crystalline field has on the matrix transition elements.

Transitions of the first type give rise to TE polarization in standard laser diodes with bulk active layer based on GaAlAs or GaInAs with a sphalerite structure and no anisotropy of structure or optical properties. If vector $\vec{E}$ of the electric field of a wave is parallel to the optical axis, optical transitions in wurtzite-type crystals are forbidden for the upper subband of heavy holes and are allowed for two lower subbands. These transitions give rise to TM polarization in traditional semiconductor lasers with isotropic bulk active layers. This polarization usually has a considerably lower amplification factor than TE polarization, due to the influence of boundary conditions at the boundary between waveguide layers and the active region. As a
high radiation contrast (0.99) is observed even for an isotropic bulk crystalline layer. Owing to the thinness of a QW, the anisotropy of properties is observed in strained layers of QW heterostructures even in crystals with a sphalerite structure [10]. The influence of strain in a quantum well is similar to the effect of pressure applied to a semiconductor crystal in one direction. The valence band structure is strongly deformed in such structures, leading to considerable detachment of the subband of light holes. As a result, they are not involved in radiative transitions. Owing to the symmetry of this subband, light holes primarily give rise to transitions with TM polarization, so the radiation contrast of LDs with QW heterostructures remains high (0.95).

As an LD accumulates service hours, strain is relieved, the subband of light holes of the valence band is lifted, and light holes start contributing to TM polarization. This explains why the contrast of the radiation of an LD with a QW heterostructure is reduced over time. Since active layers are initially inhomogeneous, it is likely that the contrast of radiation at the start of operation of LDs (and thus their service life) will vary.

A combination of factors could influence the contrast in modern green lasers. The strong anisotropy of GaN and InGaN crystals is the key difference between green lasers and red and infrared lasers with isotropic crystals with sphalerite structures. If the C axis of the substrate is perpendicular to the active layer, the transitions with vector $\vec{E}$ perpendicular to the crystal axis and parallel to the active layer (TE polarization) have a considerable advantage. However, the optical axis in such crystals is rotated somewhat [11]; as a result, the contribution from TM polarization should be enhanced.

Since optical transitions in an active layer with the involvement of heavy holes are allowed only for single light polarization under which vector $\vec{E}$ of the electric field of radiation lies within the active layer plane, the LD radiation contrast should theoretically be around 100%. However, the presence of heteroboundaries and the reduction in the symmetry of atomic bonding at the boundaries due to morphological features of epitaxial growth result in the mixing of states of heavy and light holes. In addition, the deviation of the potential profile of the active layer from rectangular lowers the contrast by 2–5%. This influence gets stronger over time, and dislocation and defects that relieve the strain and affect the structure of the active layer emerge during LD operation. A reduction in the degree of anisotropy leads to enhancement of the contribution from light holes (TM polarization), and their levels near those of heavy holes.

Our experiments showed that the contrast of radiation of genuinely green LDs was low at the initial stage of their operation and varied considerably (from 0.53 to 0.85). In addition, the waveguide properties of those green lasers that put radiation out through a transparent substrate (the so-called leaking mode) deteriorated; since these properties influence the radiation contrast, it was reduced further. However, such lasers also have a significant advantage: the radiation divergence is reduced to several degrees. A change in contrast of the radiation of lasers of this type could indicate that the structure of the active QW layer is altered and thus deteriorates rapidly.

Measurements of radiation contrast in the first tens of hours of laser operation could help estimate the service life of lasers, but this issue requires further study.

Figure 3 shows the radiation spectra of two single-mode LDs with lasing wavelengths of 530 nm and different contrasts after the first 20 h of operation. It can be seen that the shape of the radiation spectrum of an LD with a higher contrast is typical for a single-mode LD. The radiation spectrum of an LD with a
contrast of 0.53 has three peaks. This is indicative of the heterostructure damage typical of a strongly degraded laser. This allows us to relate contrast to the spectra of radiation of LDs with lasing wavelengths of 530 nm in order to estimate their service life.

The above observations were confirmed experimentally in studies of the radiation parameters of LDs with lasing wavelengths of 650 nm and no more than 30 accumulated service hours. These lasers were specific in that their heterostructures had no strained QW layers. The interest in such studies was motivated by the LD radiation contrast being almost equal to unity (it varied from 0.992 to 0.997) and having no angular dependence. The radiation spectra of these LDs were similar to those of single-mode LDs, and the radiation power matched their specifications.

According to the studies of polarization parameters of LDs with wavelengths of 650 nm, their service life can be as long as 4000 h, and their contrast is reduced only to 0.9 in this interval of time [7]. This suggests that the polarization parameters of LD radiation are a versatile tool for estimating the service life of lasers, both with strained QW layers and with bulk isotropic active layers.

Our explanation of the high values of contrast of LD radiation with no quantum wells remains within the concept laid out when the polarization parameters of radiation of genuinely green LDs were considered.

CONCLUSIONS

We demonstrated that the slow deterioration of LDs with a QW heterostructure is related to the contrast of their radiation. It was shown that the service life of genuinely green LDs can be estimated by performing simultaneous measurements of the time dependences of both the contrast and the spectral parameters of their radiation. These dependences produce the most complete description of the state of an LD’s heterostructure at the initial stage of operation.

REFERENCES


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