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Dependence of beam propagation ratio on waveguide design in edge-emitting diode lasers

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Using an algorithm for calculating the beam propagation ratio M^2, corresponding to the method for its measuring specified in the international standard ISO 11146, the dependence of M^2 values on the thickness of the vertical waveguides of edge-emitting lasers of various designs was analyzed. It is shown that the laser beam quality noticeably deteriorates in the presence of additional maxima in the intensity profile of the optical mode.

Keywords: optical waveguide, diode lasers, beam propagation ratio.

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Introduction

Semiconductor lasers are an essential technological component of a wide range of equipment and systems beginning from optical data transmission systems to ultrapowerful laser welding and cutting systems. The technical features of equipment call for a particular set of requirements for diode lasers used in them. These may be compact low-power vertically-emitting lasers for data transmission or powerful lasers, bars or stacks for optical fiber laser pumping in industrial material processing systems. An important difference between any semiconductor laser and other types of lasers is the small size of the former. Due to this compact size, the diode laser, regardless of the waveguide or resonator design, has a sufficiently high laser beam divergence that achieves, for example, 40° on the fast axis (in the direction perpendicular to the epitaxial layers) in edge-emitting lasers. Therefore, various kinds of laser beam focusing systems are generally used in practice. For effective focusing schemes, a Gaussian beam shall be preferably provided because it is considered as a reference beam with diffraction limit of divergence. In real practice, the laser beam profile may differ significantly from that of the Gaussian beam with the beam propagation ratio M^2 offered by Siegman in the early 1990s being the numerical measure of this difference [1]. The laser beam parameter M^2 is currently included in International Standard ISO 11146 [2] and the identical Russian national standard. The dimensionless invariant parameter M^2 is calculated as follows [1]:

$$M^2 = \frac{d\theta}{d_0\theta_0}, \qquad (1)$$

where d, θ are the beam diameter and divergence in the waist, d_0, θ_0 are the Gaussian beam diameter and divergence. If the investigated beam is Gaussian, then M^2 is equal to 1 for it, and any deviation of the Gaussian profile leads to the increase in M^2. The beam propagation ratio may be defined both for the whole beam and for the principal optic axes individually. For the edge-emitting diode lasers, these are fast (vertical) axis and slow (horizontal) axis.

Design of the vertical semiconductor laser waveguide has a significant influence not only on the laser beam divergence and shape, but also on essential properties such as internal optical loss, thermal and electric resistance and, consequently, efficiency. The decision whether to use a particular solution is made by trading off between the affected laser parameters. For example, expansion of the vertical waveguide provides better localization of the fundamental mode, decrease in overlapping with highly doped claddings and, as a result, reduction of the internal optical loss [3]. Narrow waveguides are used to reduce optical loss due to reduced overlapping of the optical mode and a part of the waveguide layer adjoining the *p*-cladding. To shift the active region as far as possible toward the laser crystal surface to reduce the thermal and electric resistance and to maintain single-mode vertical radiation, extremely asymmetric waveguides [4], waveguides with high-order mode suppression may be used [5]. Laser beam quality parameters shall be also considered at the waveguide design stage. ISO 11146 describes the methods for measuring M^2 implemented in commercial and laboratory systems. Physical principles behind M^2 allow it to be determined analytically and semi-analytically [6]. Adequacy of the final result depends on whether the influence of the laser operating conditions, for example, temperature, on the light beam properties is considered. Calculation or simulation of the beam propagation ratio is generally used to evaluate the minimum value for the investigated waveguide because the real laser operation leads to beam degradation and, therefore, to the increase in M^2.

This study uses numerical simulation to examine the influence of the vertical waveguide thickness and design used in the end-pumped diode laser on the fast-axis beam propagation factor (M_y^2), calculations for some vertical waveguide options are provided and the most quality-critical parameters are discussed.

M^2 calculation method

To calculate M^2 (1), the near-field width and far-field beam divergence shall be known. In [1] and corresponding ISO 11146, these quantities are calculated from the second-order moments of intensity distribution in beam cross-section: width d_σ — from the spatial moment, divergence Θ_σ — from the angular moment:

$$d_\sigma = 4\sigma_y, \tag{2}$$

$$\Theta_\sigma = 4\sigma_\theta, \tag{3}$$

where σ_y, σ_θ is the rms deviation of the near-field intensity distribution $I_i(y)$ and far-field intensity distribution $I_j(\theta)$, respectively. σ_y and σ_θ are calculated using the standard equations:

$$\sigma_y^2 = \frac{\Sigma_{i=1}^N I_i(y)(y_i - \bar{y})^2}{\Sigma_{i=1}^N I_i(y)}, \tag{4}$$

$$\sigma_\Theta^2 = \frac{\Sigma_{j=1}^L I_j(\Theta)(\Theta_j - \bar{\Theta})^2}{\Sigma_{j=1}^L I_j(\Theta)}, \tag{5}$$

where summation is performed over the number of points N and L for the near- and far-fields, respectively; $\bar{y}, \bar{\Theta}$ are the centers of mass of the near-field and far-field intensity distributions, respectively. Since we use the numerical distribution over a finite number of points, summation is used instead of integration, and the indices i and j are introduced for the intensity distributions. Centers of mass are also calculated using the standard equations:

$$\bar{y} = \frac{\Sigma_{i=1}^N I_i(y) y_i}{\Sigma_{i=1}^N I_i(y)}, \tag{6}$$

$$\bar{\Theta} = \frac{\Sigma_{j=1}^L I_j(\Theta)\Theta_j}{\Sigma_{j=1}^L I_j(\Theta)}. \tag{7}$$

Taking into account the diffraction divergence of the Gaussian beam with the radiation wavelength λ, the beam propagation ratio is calculated using equation [6]

$$M_y^2 = \frac{\pi}{\lambda}\frac{d_\sigma \theta_\sigma}{4}. \tag{8}$$

The numerical simulation of the near-field and far-field vertical intensity distributions was performed using FIMMWAVE (Photon Design) software package by the effective refractive index method. Calculation of both distributions used a 500-mesh uniform grid, thus, the grid pitch was omitted in equations (4)−(7) for calculation of the beam propagation ratio. Note that y in M_y^2 will be omitted hereinafter.

Results and discussion

Dependence of M^2 on the waveguide design will be examined beginning from the analysis of the waveguide thickness effect. A narrow and broad waveguide criterium is very conditional, but usually waveguides with thickness less than approx. $0.3\,\mu$m are considered narrow. The optical mode characteristics are affected not only by the waveguide thickness, but also by its contrast (refractive index difference between the waveguide layer and claddings). Both these parameters define the effective refractive index of the optical mode — the higher the refractive index that higher mode localization is within the waveguide layer. Previously [3], we have addressed the parameters of the vertical optical mode with a radiation wavelength of 980 nm depending on the thickness of the GaAs/$Al_{0.15}Ga_{0.85}As$ model symmetric laser waveguide and have shown that a high effective refractive index of the fundamental mode is achieved in a multimode waveguide. Generally, to reduce optical loss in the edge-emitting laser, a broadened vertical multimode waveguide shall be preferably used and high-order modes shall be suppressed in it.

For some applications, solutions with narrow waveguides can be also used effectively to reduce the layer thickness on the side of *p*-region and, thus, to reduce the thermal and electric resistances [7]. In this study, we have calculated M^2 for the model waveguide (Figure 1) that is identical to that described in [3]. The analysis of the beam propagation ratio was limited to the discussion of the vertical fundamental mode. Broad waveguides may be of the multimode type, which requires special provisions to be made to suppress possible high-order mode generation. These provisions generally imply the reduction of spatial overlapping of high-order modes and active region or selective increase in the optical loss for high-order modes. The former is implemented, for example, when the active region is shifted from the center of the waveguide [8]. The example of this selective suppression of high-order modes are coupled-waveguide lasers [3].

It is more convenient to examine the evolution of M^2 by varying the waveguide width from higher to lower values. In a broad waveguide, where the optical mode profile is close to the Gaussian profile as much as possible, the beam distribution ratio is close its lowest value 1. As the waveguide layer thickness decreases, M^2 increases gradually, which reflects deeper penetration of the optical mode into the claddings where the intensity decreases exponentially. Whereas the laser beam divergence increase gradually. In a narrow waveguide, the mode profile varies significantly, a large share of intensity is in the exponential „wings“. This transition is followed by the decrease in beam divergence and more intense growth M^2. It is significant that the transition is observed approximately in the cut-off region for the first-order mode. In an extremely narrow waveguide 50 nm in thickness, M^2 increases up to 1.5, which is, however, an acceptable value.

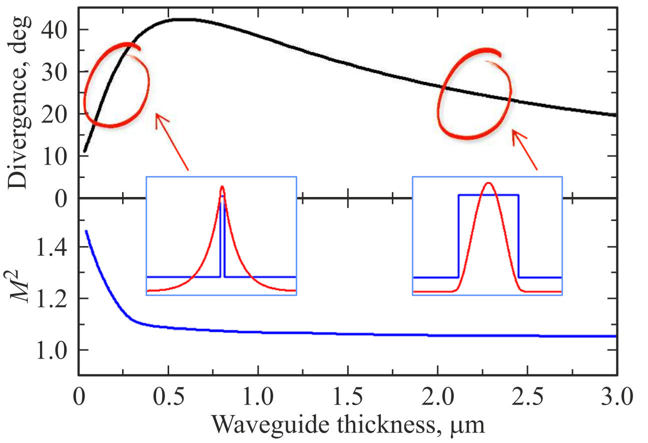

Figure 1. Dependence of the laser beam divergence and beam propagation ratio M^2 on the thickness of the $GaAs/Al_{0.15}Ga_{0.85}As$ model waveguide (radiation wavelength is 980 nm). The insets show schematically the optical mode profiles of the narrow and broad waveguides.

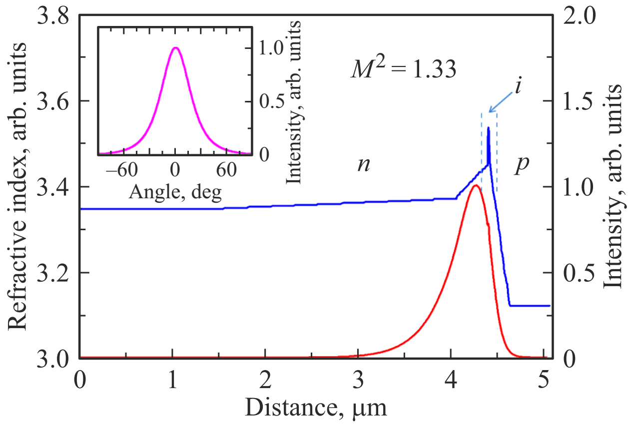

Figure 2. Refractive index and optical mode profile of the ETAS (extreme triple asymmetry) waveguide [4]. Inset — far-field intensity distribution.

Optical loss in the laser waveguide is to a great extent defined by overlapping between the optical mode and regions with high concentration of holes having larger absorption cross-section than that of electrons. Therefore, extensive efforts are currently made to develop asymmetric waveguides, where, first, penetration of the optical mode into the *p*-cladding is minimized, and, second, the active region within the waveguide layer is shifted as much as possible towards the *p*-cladding to minimize mode overlapping and injected hole accumulation region. The example is an extreme triple asymmetric (ETAS) waveguide [4], for which the beam propagations ratio has been also calculated (Figure 2). This waveguide features: asymmetric active region arrangement , high contrast on the *p*-cladding side and very low contrast on the *n*-cladding side, different thickness of the gradient layers adjoining the active region. Triple asymmetry ensures active operation of the laser with continuous pumping, whereas M^2 just a little exceeds 1.3.

Another asymmetric waveguide option is a design with a so-called photonic bandgap crystal [9] that consists of regularly alternating AlGaAs waveguide layers with high and low content of aluminum having different refractive indices. Owing to this, the waveguide may be expanded significantly and the vertical laser beam divergence may be decreased. Figure 3 shows the design near-field and far-field profiles. Conspicuous is the fact of essentially asymmetric intensity profile of the optical mode and the presence of additional peaks in the profile. These two factors affect M^2 that is close to 2.4 according to the calculations. It is believed that it were the additional peaks that degraded the laser beam significantly because they simultaneously increase the near-field width and far-field beam divergence. To illustrate this effect, we have calculated the beam propagation ratio for the second-order vertical mode in the model waveguide 1.5 μm in thickness

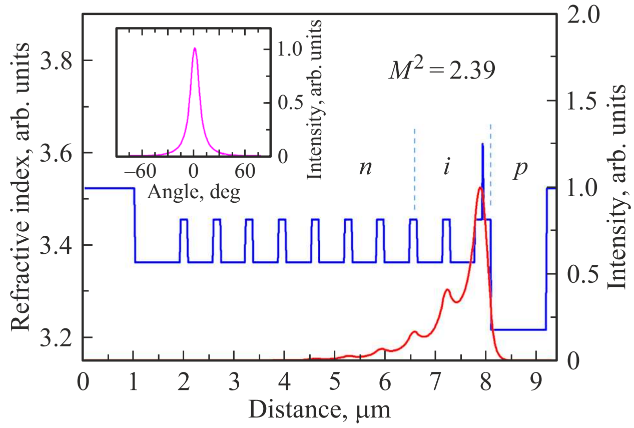

Figure 3. Refractive index and optical mode profile of the photonic bandgap crystal (PBC) waveguide [9]. Inset — far-field intensity distribution.

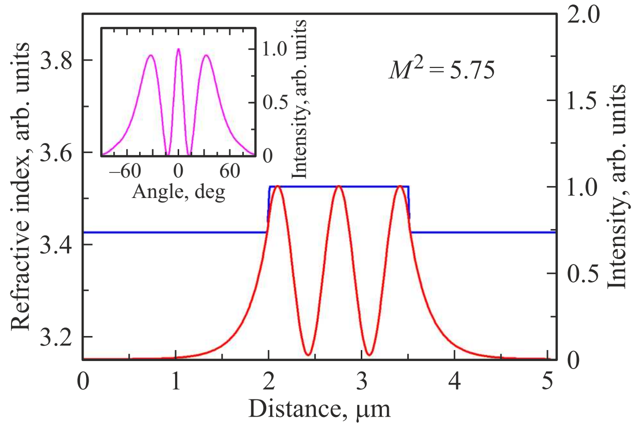

Figure 4. refractive index and second-order optical mode profile of the $GaAs/Al_{0.15}Ga_{0.85}As$ model waveguide with a thickness of 1.5 μm.

(Figure 4). M^2 equal to 5.75 is unacceptable from a practical point of view.

Conclusion

Thus, the numerical simulation methods have been used to analyze the dependence of the beam propagation ratio M^2 on the thickness of the GaAs/$Al_{0.15}Ga_{0.85}As$ model symmetric waveguide, and it has been shown that narrowing up to the minimum values, M^2 increases to approx. 1.5 which is acceptable. The laser beam quality is significantly degraded when there are additional peaks in the laser mode intensity profile. The proposed simple algorithm for calculating M^2 corresponds to the method for measuring M2 described in International Standard ISO 11146 and may be used for designing vertical waveguides of edge-emitting diode lasers.

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Conflict of interest

The authors declare that they have no conflict of interest.

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