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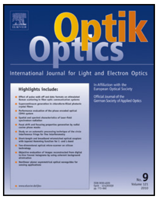

Analysis on thermal characteristics of annular beam pumped vertical-external-cavity surface-emitting lasers by finite element method

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ABSTRACT

The annular beam as a pump light of VECSELs is presented for the first time in this study. The thermal characteristics of VECSELs were calculated and simulated by finite element method, and the influence of the annular beam's annulus radius, the annulus width, and the pumping power to the VECSELs' thermal characteristics was analyzed in detail. The results indicated that the annular beam can improve the VECSELs' thermal characteristics efficiently, and provide a favorable term to generate laser in the central part of the annular. The theoretical results provided theoretical reference and experimental study for the design of high-power optically pumped VECSELs.

1. Introduction

With the development of semiconductor laser technology, more and more researchers are paying attention to a novel class of semiconductor laser-optically pumped semiconductor vertical-external-cavity surface-emitting lasers (OPS-VECSELs) [1–4]. OPS-VECSELs, which are in fact a class of diode-pumped solid-state disk lasers, with the advantages of edge-emitting lasers and vertical-cavity surface-emitting lasers, possess high output power, high conversion efficiency, wavelength versatile, good beam quality (low divergence, circularly symmetric output beam), and compact structure. It has been widely used in the fields of laser show, laser communication, biomedical instrument, laser radar, high-speed printing, etc.

The key to widen the application of OPS-VECSELs is to increase the laser output power, conversion efficiency, beam quality, etc. [5–8]. With the increase in pump power, the temperature of device increases, and the output performance parameters of OPS-VECSELs deteriorated. Hence, the question of how to improve the thermal properties of VECSEL chip is becoming the focus of research. Waste heat deposited in the VECSEL chip comes from the absorption of pump light by cap layer, active region, and reflective mirror. A part of pump light absorbed by quantum wells (QWs) in the active region is converted to waste heat. The waste heat deposited in the VECSEL chip will lead to two serious consequences. The first is the reduction in the peak gain of a single QW. The second is that the QW thin layer will produce a deformation, and the antinodes position of the cavity standing wave will not be overlapped with the QWs, resulting in the effective gain reduction and no power output. This phenomenon is the so-called thermal roll over effect [9].

Effective thermal management is the key to improve the output performance of OPS-VECSELs. There are mainly two approaches used to improve thermal performance of OPS-VECSELs. The first is improving the packaging technology of devices, such as thinned or removed substrate with direct mounting on a heat sink [10] and heat spreader with higher thermal conductivity bonded on the top of the VECSEL chip [11]. The second is optimizing the design of the VECSEL chip's structure, such as designing double-band mirror (DBM) [12,13] and quantum dot [14] in the VECSEL chip's structure.

In addition to the two above-mentioned thermal management approaches, the distribution of pump light has an important influence on the thermal performance of VECSELs. Annular beam as a pump light is proposed in the paper for the first time, and annular beam pumped VECSELs is analyzed using finite element method.

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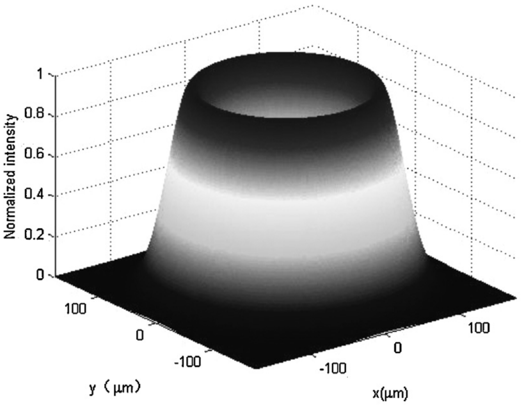

Fig. 1. The distribution of normalization of light intensity.

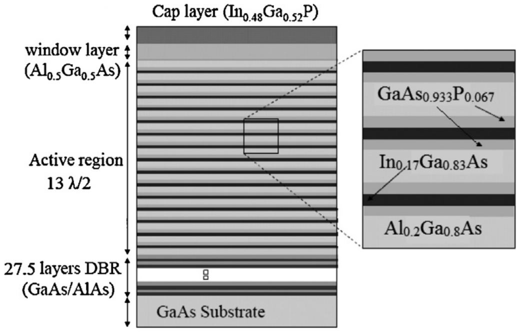

Fig. 2. Schematic of VECSEL structure.

2. Finite element model of VECSELS pumped by annular beam

2.1. Model of annular beam

The wavelength of pump light is assumed to be 808 nm, and the distribution of pump light is annular beam. The light intensity distribution of annular beam is assumed as [15]

$$I(r) = I_0 \left\{ \exp\left[-2\frac{(r-R_0)^2}{\omega_h^2}\right] + \exp\left[-2\frac{(r+R_0)^2}{\omega_h^2}\right] + 2\exp\left[-\frac{(r-R_0)^2}{\omega_h^2}\right] \cdot \exp\left[-\frac{(r+R_0)^2}{\omega_h^2}\right] \right\} \quad (1)$$

$$I_0 = \frac{P_{in}}{2\pi \int_0^{+\infty} \left\{ \exp\left[-2\frac{(r-R_0)^2}{\omega_h^2}\right] + \exp\left[-2\frac{(r+R_0)^2}{\omega_h^2}\right] + 2\exp\left[-\frac{(r-R_0)^2}{\omega_h^2}\right] \cdot \exp\left[-\frac{(r+R_0)^2}{\omega_h^2}\right] \right\} dr} \quad (2)$$

where I_0 is the relative light intensity, r is the radial coordinate, R_0 is the radial coordinate of peak light intensity, and ω_h is the half width of annular beam. $(R_0 - \omega_h)$ and $(R_0 + \omega_h)$ are the inner and outer radius of annular beam, respectively. Fig. 1 shows the distribution of normalization of light intensity.

2.2. Structure of VECSEL chip

Typically, the cap layer, window layer, active region, and DBR are included in the VECSEL wafer. Fig. 2 shows the structure of VECSEL chip. DBR is made of 27.5 pairs of AlAs/GaAs. The active region consists of 13 pairs of $Al_{0.2}Ga_{0.8}As/GaAs_{0.933}P_{0.067}/In_{0.17}Ga_{0.83}As/GaAs_{0.933}P_{0.067}$, strain compensation QWs. $Al_{0.2}Ga_{0.8}As$ is used to absorb pump light and provide carriers for QWs and $GaAs_{0.933}P_{0.067}$ is used to compensate strain. On the top of the active region is a 303.4-nm-thick $Al_{0.5}Ga_{0.5}As$ window layer used to provide carrier confinement, and a 150.4-nm $In_{0.48}Ga_{0.52}P$ cap used to prevent oxidation. To overcome thermal roll-over, the substrate is removed by mechanical polishing and chemical etching, and then the thin epilayer is bonded to the heat sink and the cap is bonded to 500-μm-thick diamond head spreader, using liquid capillary bonding [16], to improve the thermal characteristic of the VECSEL wafer. At last, the VECSEL wafer is welded to the heat spreader-copper.

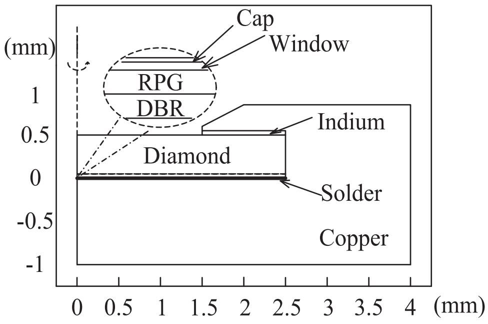

Fig. 3. Geometry structure of VECSELs.

2.3. Thermal model of VECSEL

Fig. 3 shows the geometry structure of VECSELs. The cap layer and window layer are treated as a composite layer, while the active region and DBR are, respectively, treated as different thermal conductivity anisotropic composite layer. The thermal conductivity of the composite layer consists of vertical and parallel anisotropic thermal conductivities.

The steady-state heat conduction equation is as follows:

$$-\nabla \cdot [k(r,z) \times \nabla T(r,z)] = Q(r,z) \quad (3)$$

where $k(r,z)$, $T(r,z)$, and $Q(r,z)$ are thermal conductivity, temperature, and heat loading density, respectively. The boundary temperature in the bottom of the heat sink is assumed to be the constant T_0, and the other boundary conditions are assumed to be heat insulation. The temperature distribution in the VECSELs can be calculated from heat conduction equation.

The thermal conductivities in the radial and axial directions of the composite layer can be given as [9]

$$k_r = \frac{\sum_{i=1}^{N} d_{z,i} \cdot k_i}{\sum_{i=1}^{N} d_{z,i}} \quad (4)$$

$$k_z = \frac{\sum_{i=1}^{N} d_{z,i}}{\sum_{i=1}^{N} d_{z,i}/k_i} \quad (5)$$

where $d_{z,i}$ is the thicknesses of the individual epilayer, k_i is the thermal conductivities of the individual epilayer, and N is the total number of epilayers.

The heat loading in the active region and DBR can be given by [9]

$$Q_g = I \cdot \eta_g \cdot \alpha_g \cdot e^{-\alpha_g(z_{og}-z)} \quad (6)$$

$$Q_d = I \cdot \eta_d \cdot \alpha_d \cdot e^{-\alpha_d(z_{od}-z)} \cdot e^{-\alpha_g(z_{og}-z_{od})} \quad (7)$$

where I is the intensity of pump light, and Z_{og} and Z_{od} are the top coordinates of active region and DBR, respectively. Other parameters used in the calculation are shown in Table 1.