High-Radiance Optically Pumped Semiconductor Disk Lasers

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We report on high-power operation of an optically pumped external-cavity semiconductor disk laser. 13.2 W optical output power at 970 nm has been achieved in a double-pass pump configuration. The laser Bragg mirror was designed to provide not only high reflectivity for the laser wavelenth but also for the pumping beam. A proper layer structure which supports standing-wave patterns with a node near the semiconductor surface reduces cavity losses and degradation. Compensation of the compressive strain, introduced by the six InGaAs quantum wells is achieved by GaAsP layers. The influence of the cavity geometry and the pump spot size on the laser beam quality and optical output power is investigated. An extention of the well-known equation is presented and compared to experimental results.

1. Introduction

Optically pumped semiconductor disk lasers with external cavities are devices with outstanding properties. Unlike commonly used semiconductor lasers, good lateral mode control is achieved by the external resonator, which can be built up with a geometry that supports fundamental mode operation. In comparison with compact single-mode electrically pumped diode lasers having integrated plane mirrors like vertical-cavity surface-emitting lasers or edge emitters, the need for good spatial beam quality is no stringent limitation of the active emission area and the corresponding maximum output power. Hence, the diameter of the pumped area can be scaled up to several hundreds of micrometers and multi-watt diffraction-limited operation becomes possible. For pump-spot sizes ranging between 500 and 900 µm diameter, 30 W of optical output power at 980 nm already has been demonstrated [1]. Of course, the pump-spot diameter has to be considered in the external cavity setup, with respect to its length, mirror curvature, and the expected beam quality. In Section 2, a simplified model and an analytic equation, that describes the functional dependency between these values, will be given as well as the results of an experimental investigation.

For large emission areas, cooling becomes more and more deteriorated, due to the reduced heat-spreading effect. This plays an important role, because the optical output power of semiconductor disk lasers usually is limited by thermal roll-over. Thus, high conversion efficiencies in order to minimize heat generation as well as a sophisticated thermal management becomes crucial. For that, CVD-diamond heat spreaders can be utilized [1]. Other approaches base upon relatively expensive transparent mono-crystal diamond heat spreaders in an intra-cavity [2] or end-pump configuration [3]. In contrast to that, we investigated the potential for high-power laser operation, without any high thermal conductivity diamond heatspreaders or intra-cavity cooling, but with quite inexpensive copper heatsinks. The characteristics that have been achieved in that way are presented in Section 3.

2. Beam-Parameter Dependency on the Cavity Geometry

2.1 Theory

Since the thickness of the laser chip is several orders of magnitude smaller than the length of the resonator, the plane Bragg reflector of the laser chip and the external mirror establish a cavity that comes close to an ideal hemispherical cavity, whose geometry is given by its length L_c and the mirror radius of curvature R_c. Stable resonance condition implies that the effective radius of curvature of the beam phase fronts are identical with the mirror radius, located at $z = L_\mathrm{c}$, while its waist is located at the same position $z = 0$ as the Bragg mirror. According to Siegman [4], for any nonideal optical beam, travelling in the z-direction, having its beam waist located at $z = 0$, the effective radius of curvature is given by

$$R(z) = z + \frac{z_\mathrm{R}^2}{z}, \tag{1}$$

which is the same as for the ideal TEM_{00} Gaussian beam. The deviation from the ideal beam and the contribution of higher-order modes is taken into account by the beam-quality factor $M^2 \geq 1$, which can be experimentally determined [5], and the subsequent definition of the Rayleigh range

$$z_\mathrm{R} = \frac{4\pi\sigma_0^2}{M^2\lambda}. \tag{2}$$

The spatial variance σ_0 at the beam waist therein can be related to the beam diameter ω_0 by $4\sigma_0 = \omega_0$. Hence, the relation between the real-beam diameter on the chip, the beam-quality factor, and the cavity geometry is given by

$$\omega_0^2 = \frac{4M^2\lambda}{\pi}\sqrt{L_\mathrm{c}(R_\mathrm{c} - L_\mathrm{c})}. \tag{3}$$

For the boundary case of the ideal TEM_{00} Gaussian beam with $M^2 = 1$, this relation is well-known and reported by Kuznetsov *et al.* [6]. However, the restriction to the lowest order Gaussian mode can be misleading. Actually, higher-order modes can be observed for most resonator geometries, hence there is no stringent physical boundary condition, concerning the beam quality and existence of higher-order modes. On top of Fig. 1, the mode diameter on the chip, calculated by (3), for a mirror radius of 100 mm and different M^2-parameters is shown. Furthermore, another meaningful formulation is given by

$$M^2 = \frac{\pi\omega_0^2}{4\lambda\sqrt{L_\mathrm{c}(R_\mathrm{c} - L_\mathrm{c})}}, \tag{4}$$

for which the graphs for different values of ω_0^2 are shown at the bottom of Fig. 1. If ω_0 and R_c are considered to be constants, determined by the spot size of the pump beam on the

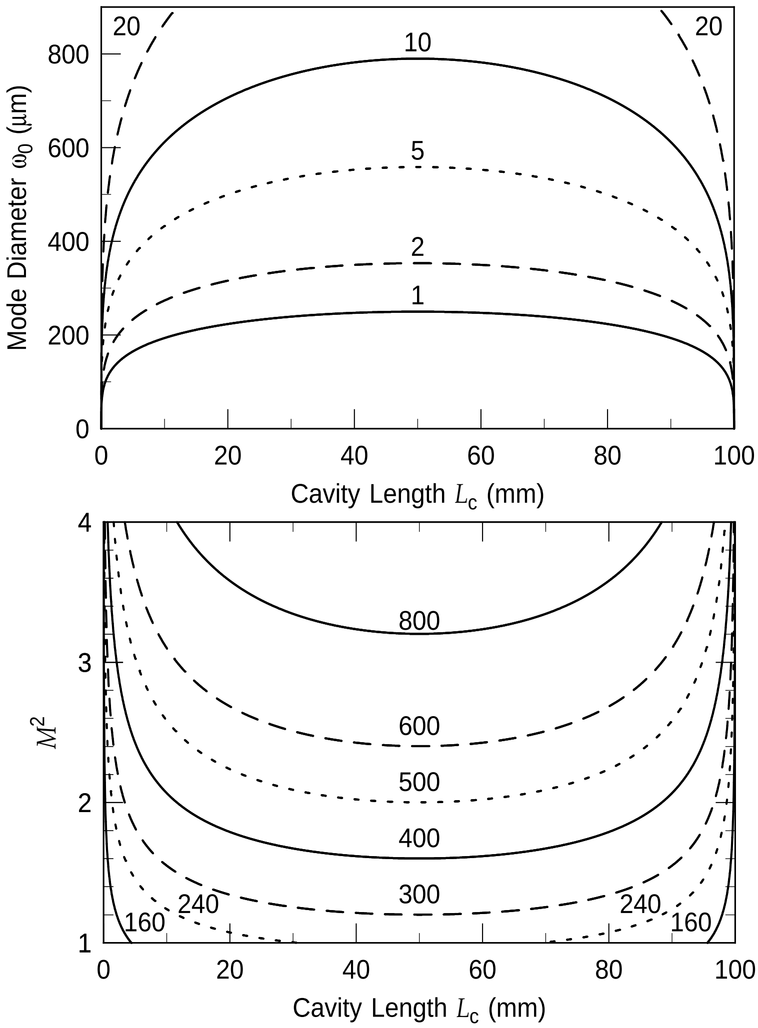

Fig. 1: Calculated function of beam-waist diameter ω_0 and the diffraction-number M^2 on the cavity length for a 100 mm outcoupling mirror radius and a wavelength of 980 nm. On top, the beam-waist diameter at the laser-chip position is given for beams with different diffraction numbers. The bottom diagram shows the dependency of the diffraction number. The different curves are labeled by the beam-waist diameter in units of µm.

chip and the external mirror, whilst M^2 is a function of the resonator length, one would expect a behavior like that. In section 2.2, experimental evidence for such a dependency will be given. It is obvious from the above assumptions, that a limiting condition

$$R_c > \frac{\pi\omega_0^2}{2\lambda} \tag{5}$$

for the mirror radius of curvature exists, at which diffraction limited operation becomes possible. It can be supposed that efficient laser operation only is possible if the laser mode diameter on the chip is not smaller than the pump spot size. If, for example, the pump spot has a diameter of more than 400 µm, then in turn diffraction limited operation for the smaller principal axis can be expected only for a mirror with a radius of curvature longer than 256 mm.

2.2 Experiment

It is well approved by experimental experience that the diffraction number of a semiconductor disk laser increases with increasing pump spot sizes for a given geometry of the cavity. On the other hand, the smaller the pump spot size becomes, the smaller is the range of the cavity lengths in which lasing is possible. Such a behavior can easily be explained by Fig. 1. In order to give a more quantified verification, a series of beam quality and optical-power measurements, shown in Fig. 2 has been performed. In that,

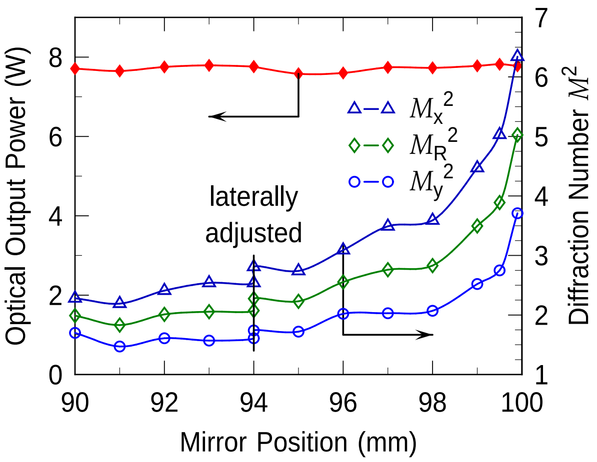

Fig. 2: Series of beam-quality and output-power measurements at different mirror positions. A minor influence on the output power can be observed, whereas there is a significant influence on the vertical and horizontal beam quality.

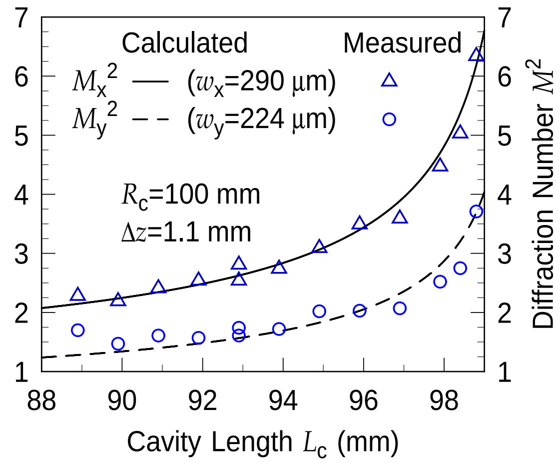

Fig. 3: Fit of the experimental data from Fig. 2 using equation (4). Besides the beam-waist diameters, a slightly position offset Δz, which is within the uncertainty of measurement of the cavity length, was used as a fit parameter.

the cavity length was varied by moving the position of the outcoupling mirror. At a mirror position that corresponds to a cavity length which is close to the mirror's radius of curvature, multi-mode emission with a relatively high diffraction number can be observed. As the laser is pumped under an angle of approximately 25°, the pumped area is elliptical, resulting in different horizontal and vertical diffraction numbers M_x^2 and M_y^2. The geometrical mean M_R^2 represents the effective diffraction number, that corresponds to the diffraction number of a circular beam with the same beam quality. By decreasing the resonator length an increase in the beam quality, which goes ahead with a decrease in the diffraction numbers, can be observed. The correlation with the behavior, predicted by (4) is shown in Fig. 3. The horizontal and vertical beam-waist diameters as well as a position offset Δz are used as fit-parameters. The latter can be justified by the uncertainty of the measured cavity length. The ellipticity of the laser mode on the chip which is achieved that way to be $\omega_x = 290\,\mu\text{m}$ and $\omega_y = 224\,\mu\text{m}$ can not be explained by the pump angle alone. Possible explanations for that are a vertical misalignment of the resonator with respect to the pump spot or a slightly non-planarity of the laser chip and its backside Bragg mirror. Also a misalignment of the traveling stages z-axis with the optical axis has to be taken into account, particularly as a horizontal re-adjustment was necessary at the labelled z-position. The measurement of the pump spot size itself which was performed by imaging the photoluminescence from the laser-chip to a CCD-camera revealed a value of approximately $230 \times 200\,\mu$m. Finally it should be mentioned, that the presence of an adequately large dark-line free region seems to be an essential requirement for the here presented experimental result, because dark lines within the pumped region lead to a distinct decline of the beam quality which is not incorporated by the model.

3. High-Power Operation

To achieve high conversion efficiencies which are required for the minimization of generated heat, different design features have been utilized in the epitaxial design of the structure whose characteristics is presented here. First, a proper strain compensation that reduces relaxation defects at which nonradiative recombination takes place [7] is necessary. This is introduced by means of GaAsP layers that are placed between the six InGaAs quantum wells of the acitve region. Another measure is the utilization of a double-band Bragg mirror, that provides not only a high-reflectivity band at the emission wavelength around 980 nm, but also another one for the pump radiation with a wavelength of 808 nm [8]. This reduces the heat, generated by the fraction of the pump beam which is transmitted through the Bragg mirror and penetrates the subsequent metalization layers. Furthermore, the double-pass transmission of the pump beam leads to a more homogeneous carrier generation which increases the differential efficiency due to a reduced virtual threshold shift [9]. A third constructive feature which has to be mentioned is that the micro-cavity of the laser-chip has been performed in way that the surface of the semiconductor lies within an antinode of the longitudinal standing wave pattern of the mode. To obtain that, a quarter-wavelength coating of the semiconductors surface is utilized.

The output characteristics of a device with the mentioned features is shown in Fig. 4. The laser was pumped by a fiber-coupled diode laser with a wavelength of 808 nm under a pump angle of 25° what led to a pump-spot area of $450 \times 500\,\mu$m. A mirror with 100 mm radius of curvature was used in the setup, because none with a bigger radius of curvature was available at the time of the measurement. The cavity was adjusted to provide maximum optical output power. The temperature of the copper heatsink of the device was actively controlled by a Peltier cooler. At a temperature of -5 °C and an absorbed optical power of 24.5 W, an output power of 13.2 W was measured in the high-order transverse-modal output beam, that corresponds to a conversion efficiency of 54 %. The output characteristics also has been measured at 0 °C, where thermal roll over took place at 12.3 W output power. In Fig. 5, the absorption characteristics of the same measurement is shown. Both, the absorbed pump power, as well as the absorptance are achieved by measuring the reflected pump power. The absorptance shows a distinct dependency on the temperature and reaches its maximum of 94.5 % at the maximum output power and a heat-sink temperature of 0 °C. Of course, the temperature of the structure itself is increasing with increasing pump power. With increasing temperature, the spectral reflectivity characteristics of the structure's Bragg-mirror is shifted towards longer wavelengths. Hence the observed temperature behavior can be easily explained by the assumption that the pump beam is reflected at the short-wavelength edge of the

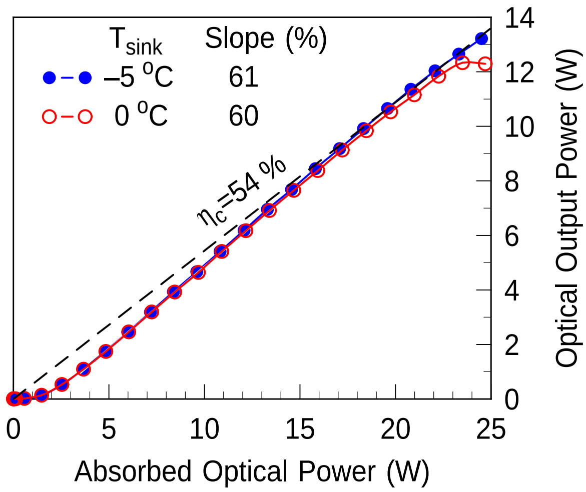

Fig. 4: Output characteristics of a disk laser with an emission wavelength of 970 nm and an outcoupling mirror having a reflectivity of 98 % and a radius of curvature of 100 mm. The pump spot size was measured as 450 × 500 µm.

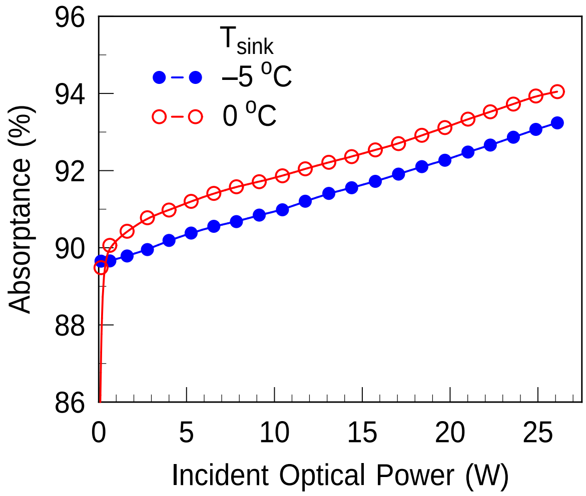

Fig. 5: Corresponding absorption characteristics of the measurement represented in Fig. 4.

mirror's pump-wavelength reflection band. Anyway, due to the high absorptance, even for the low temperature curve, an incident optical power of only 26.1 W was necessary to achieve the maximum output power, resulting in an optical to optical conversion efficiency of more than 50 %.

4. Conclusion and Outlook

The model presented for the influence of the laser cavity geometry on the beam parameters which takes the diffraction number into account appears to be a suitable tool to determine the output behavior of optically-pumped semiconductor disk lasers and for finding a suitable cavity configuration. For large pump-spot areas which are required for high power operation, near diffraction limited operation is possible only for external mirrors with a radius of curvature that extends a certain value, which is given by (5). The basic assumption, that the on-chip beam diameter of the laser mode is determined rather by the pump-spot extension than by the cavity length and the mirror radii appears to be valid at a large extent. The presented design features facilitate high-power operation even with low-cost copper mounts. With CVD-diamond heat spreaders or microchannel coolers [10] even higher optical output powers than the presented 13.2 W appear possible.

References

[1] J. Chilla, S. Butterworth, J. Charles, A. Capra, M. Reed, and L. Spinelli,"High Power optically pumped semiconductor lasers", *Proc. SPIE*, vol. 5332, pp. 143–150, 2004.

[2] A. Härkönen, S. Suomalinen, E. Saarinen, L. Orsila, R. Koskinen, O. Okhotnikov, S. Calvez and M. Dawson, "4 W single-transverse mode VECSEL utilising intra-cavity diamond heat spreader", *Electron. Lett.*, vol. 42, no. 12, pp. 693–694, 2006.

[3] J. Lee, S. Lee, T. Kim and Y. Park,"7 W hight-efficiency continuous-wave green light generation by intracavity frequency doubling of an end-pumped vertical external-cavity surface emitting semiconductor laser", *Appl. Phys. Lett.*, vol. 89, 241107, 2006.

[4] A.E. Siegman, "Defining the effective radius of curvature for a nonideal optical beam", *IEEE J. Quantum Electron.*, vol. 27, no. 5, pp. 1146–1148, 1991.

[5] A.E. Siegman,"Defining and Measuring Laser Beam Quality", in *Solid State Lasers: New Developments and Applications*, M. Incuscio and R. Wallenstein (Ed.), pp. 13–28. New York: Plenum Press, 1993

[6] M. Kuznetsov, F. Hakimi, R. Sprague, and A. Mooradian, "Design and characteristics of high-power (>0.5-W cw) diode-pumped vertical-external-cavity surface-emitting semiconductor lasers with circular TEM_{00} beams", *IEEE J. Select. Topics Quantum Electron.*, vol. 5, no. 3, pp. 561–573, 1999.

[7] F. Demaria, M.C. Riedl, F. Rinaldi, S. Lorch, and U. Brauch, "Advanced Optically-Pumped Semiconductor Disk Lasers With Barrier and Quantum-Well Pumping", *Annual Report 2005, Ulm University, Optoelectronics Department.*

[8] E. Gerster, I. Ecker, S. Lorch, C. Hahn, S. Menzel and P. Unger,"Orange-emitting frequency-doubled AsAsSb/GaAs semiconductor disk laser", *J. Appl. Phys.*, vol. 94, no. 12, pp. 7397–7401, 2003.

[9] O. Casel, *Experimentelle Untersuchung und Modellierung des Einflusses der Epitaxiestruktur auf die physikalischen Eigenschaften optisch angeregter Halbleiterscheibenlaser.* Ph.D. thesis, University of Kaiserslautern, Göttingen: Cuviller, 2005.

[10] E. Gerster, "Semiconductor Disk Laser on Microchannel Cooler", *Annual Report 2004, Ulm University, Optoelectronics Department.*