A Multipass Optics for Quantum-Well-Pumped Semiconductor Disk Lasers

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The pump absorption of quantum-well-pumped semiconductor disk lasers can significantly be improved with a resonant design for the pump wavelength inside the semiconductor disk and an external optics that redirects the reflected pump power several times back onto the disk. Our double-resonant laser, which is designed for an emission wavelength of 985 nm and a pump wavelength of 940 nm, allows a pump absorption of about 35 % in a double pass of the pump radiation through the disk. Here, we demonstrate how the absorption of the pump power can be further improved using a multipass pump optics. This pump optics consists of a parabolic mirror and two retro-reflecting prisms allowing up to three double passes of the pump radiation through the semiconductor disk. This is sufficient for absorption rates above 75 %. The laser disks mounted on copper heat sinks are capable of output powers beyond 16 W and of slope efficiencies above 50 %.

1. Introduction

Using optical pumping of the quantum wells of a semiconductor disk laser directly instead of pumping the surrounding barriers, it is possible to drastically reduce the quantum energy difference between the pump and the laser photon which is called the quantum defect. This wavelength difference can be less than 2.1 nm, which corresponds to a quantum defect below 0.22 % [1]. Consequently, the produced amount of waste heat inside the active region originating from the quantum defect becomes negligible. The elimination of the largest loss mechanism allows to realize high-power lasers that do not depend on strong cooling. The major drawback of such a laser is the low absorption of the pump power. Therefore, investigations are necessary on how the pump absorption can be improved by redirecting the unabsorbed light multiple times back onto the chip. A conventional multipass optics consists of a parabolic mirror and at least two retro-reflecting prisms and provides up to eight double passes of the pump radiation through the disk [2]. More complex pump designs allow 32 double passes [3]. An absorption rate above 70 % was already reported for quantum-well-pumped semiconductor disk lasers using twelve double passes [4]. This result, however, is not necessarily comparable with other quantum-well-pumped disk lasers, since the absorption strongly depends on the layer structure and the difference between the pump and laser wavelength. Our multipass optics allows to experiment with one, two, or three double passes of the pump radiation through the disk, which gives us the ability to predict how the pump absorption behaves in dependence of the number of double passes.

2. Layer Design and Characterization of the Disk Laser

The quantum-well-pumped semiconductor disk laser has a resonant structure for the emission wavelength of 985 nm and for the pump wavelength of 940 nm. The realization of such a double-resonant structure requires to grow an over 1 µm-thick GaAs spacer between two sets of four double quantum wells, as depicted in Fig. 1. The separation of the quantum wells is necessary because of the phase shift between laser and pump field [5, 6]. Another specialty of the design is the top Bragg reflector which increases the finesse of the microcavity and therefore enhances the resonant absorption. Both sides of the semiconductor laser are coated with an ion-beam sputter-deposited dielectric coating. The dielectric layer on top serves as an anti-reflection (AR) coating for the pump radiation, while the bottom coating allows to reduce the mirror pairs of the bottom Bragg reflector from 24.5 to 18.5 without sacrificing a reflection loss. This is possible due to the large refractive index difference between Al_2O_3 and GaAs. The epitaxial growth is performed in reverse order. This allows us to apply the bottom dielectric coating on the whole waver before a Ti/Au metalization is applied. Afterwards, the wafer is cleaved into $2 \times 2\,\text{mm}^2$ large pieces and soldered with indium on copper heat sinks. Then the GaAs substrate is completely removed by wet-chemical etching and the AR coating is applied.

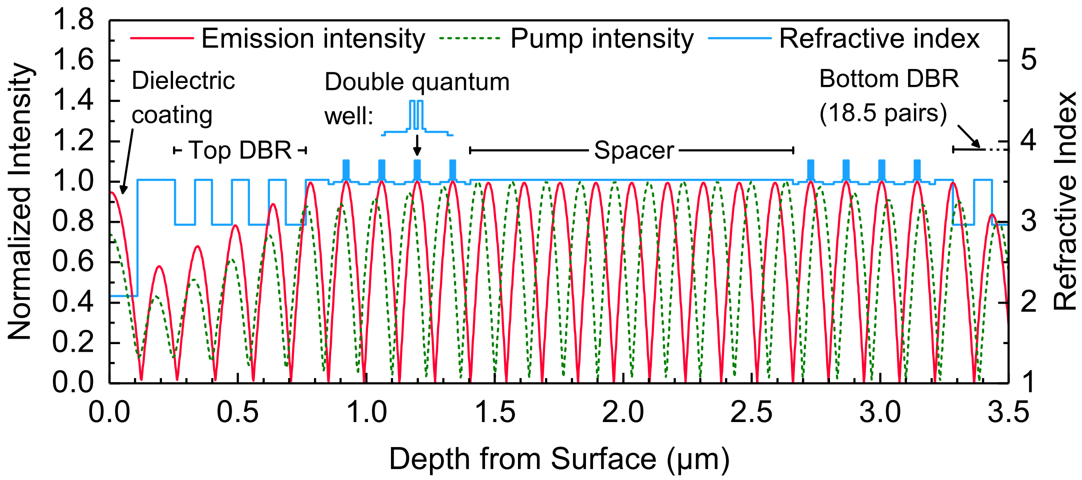

Fig. 1: Layer structure of the disk laser visualized by the refractive index profile as well as calculated TE standing-wave intensities of the laser and pump fields.

The reflectivity spectrum of a fully processed disk laser is shown in Fig. 2. The spectrum was recorded under an angle of 10° at a temperature of 80°C. Inside the stop band extending between 905 and 1015 nm, three resonance wavelengths are visible. The 953 nm long resonance wavelength is important for pumping the device because under a certain angle of incidence the 940 nm pump light is in resonance with cavity. A pump angle of 35° is therefore required in order to achieve a good absorption of the pump power. The laser emission takes place at the 988 nm long resonance wavelength. Even at output powers beyond 15 W the spectral width of the laser is below 1.1 nm (full width at half maximum). This makes the laser especially suitable for frequency doubling applications, since no birefringent filter is necessary to narrow the spectral width. The recorded photoluminescence spectrum shows a good overlap with the measured reflectivity spectrum. The photoluminescence spectrum was measured under an angle of 0° and at a heat-sink temperature of 50°C.

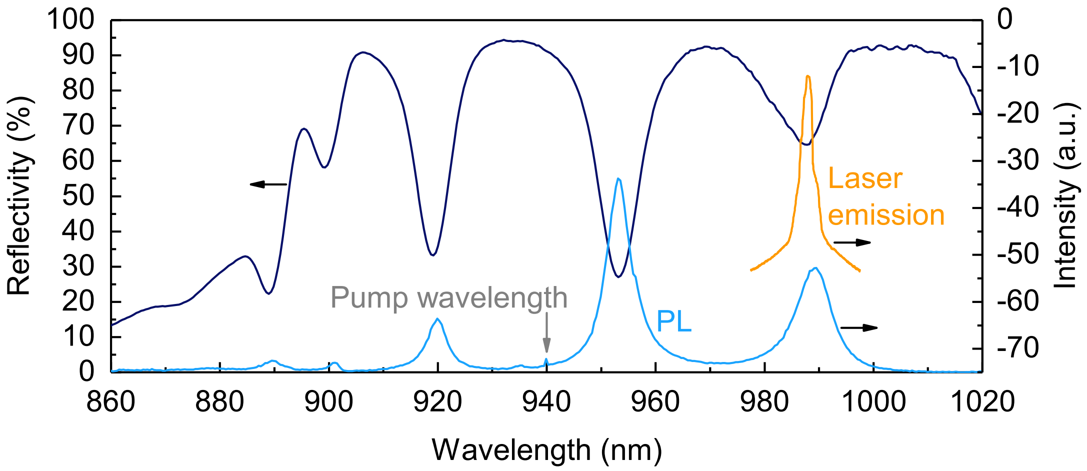

Fig. 2: Measured reflectivity, photoluminescence (PL) and emission spectrum of a quantum-well-pumped semiconductor disk laser.

3. Multipass-Pumped Semiconductor Disk Laser

One double pass of the pump radiation through the disk allows a pump power absorption of approximately 35 %. A significant improvement of the laser's efficiency is therefore possible by recycling the unused power. In order to achieve two double passes of the pump radiation through the disk and be able to measure the reflected pump power, an experimental setup as illustrated in Fig. 3 is used. The disk laser is operated in a linear resonator with an external mirror that has a reflectivity of 96 %. The pump optics consists of a parabolic mirror and a prism acting as a retro reflector. The collimated pump beam is propagating parallel to the linear resonator until it hits the parabolic mirror. The parabolic mirror focuses the pump light onto the semiconductor disk which is placed in the focal point of the parabolic mirror. The pump spot size of the multipass optics is determined by the diameter of the pump source, the focal length of the collimator lens, and by the focal length of the parabolic mirror [2]. A change of the spot size is therefore not possible without changing the used optics. The purpose of the prism is to perform a retro-reflection of the pump beam and to displace the beam by a few millimeters, so that the 180° turned beam hits the parabolic mirror on another position. From there the beam is focused again onto the chip. The experimentally determined loss factor of the pump optics is 14.7 %. By adding another prism to the pump optics, a third double pass of the pump radiation through the disk can be achieved. Due to space restrictions it not possible to measure the absorbed power in this configuration. The absorbed power shown in Fig. 4 for three double passes was therefore calculated from a reference measurement with two double passes.

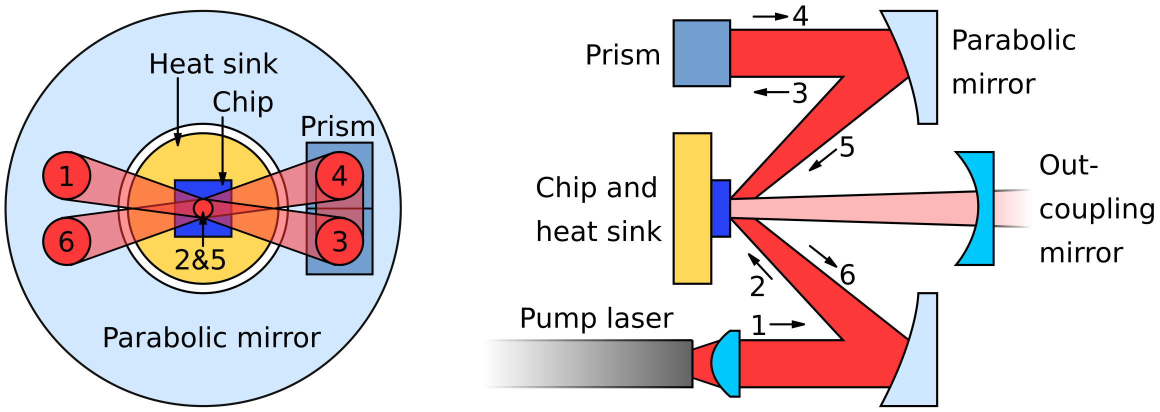

Fig. 3: Front view (left) and top view (right) of a pump optics for two double passes of the pump radiation through the semiconductor disk. The numbers 1 to 6 indicate the path of the pump beam.

Without using the multipass pump optics, the disk laser is capable of a slope efficiency of 56.7 % and an output power of 13.37 W. The maximum output power was limited by the available pump power. The threshold of the laser is 2.03 W. A threshold power density of 1.8 kW/cm^2 can be calculated considering the $400 \times 350\,\mu m^2$ large elliptical pump spot. The measured spot size of the multipass optics of $750 \times 650\,\mu m^2$ is almost 250 % larger than without the pump optics. Consequently, the threshold power increases. A large pump spot can cause additional heating problems, hence a larger spot size also increases the probability of semiconductor defects inside the pumped area. In addition, further heating problems may be expected, due to the compromised heat spreading. Nevertheless, only a minor decrease of the slope efficiency by 7.3 % is noticeable. A threshold pump power of 12.24 W and a threshold power density of 3.2 kW/cm^2 are measured with the multipass optics. The maximum achievable output power is 16.23 W for two double passes through the disk. The absorption of the pump power is between 50.7 and 61.9 %. The conversion of the pump optics into an optics which allows three double passes, without changing any other laser conditions, results in absorption rate in between 65.4 and 76.1 %. The other output characteristics of the laser are almost identical, except of a minor decrease of the achievable output power by 0.5 W. The power loss can be attributed to the elliptical shape of the pump spot, which does not allow a perfect overlap of all three pump spots on the disk, since the elliptical spots are tilted by the prisms. A pump optics for three double passes requires, as illustrated in Fig. 5, to overlap six spots on the chip by proper alignment of the pump optics and the external outcoupling mirror.

A clear disadvantage of the pump optics is its restriction to a few degrees around 19° for the pump angle. It is therefore required, that the microcavity of the disk laser has a suitable resonance wavelength for the pump wavelength of 940 nm. Otherwise, a weak absorption rate is unavoidable. A shift of 5 nm in the resonance wavelength, for instance, will result in an absorption of only 35.7 % instead of 61.9 % for two double passes of the pump radiation through the disk [7]. The thermal roll-over of the laser device when exceeding 45 W of absorbed pump power exceeds may be avoided by improvements of the cooling setup, which in our experiments does not allow heat-sink temperatures below 4°C and lacks in temperature stabilization.

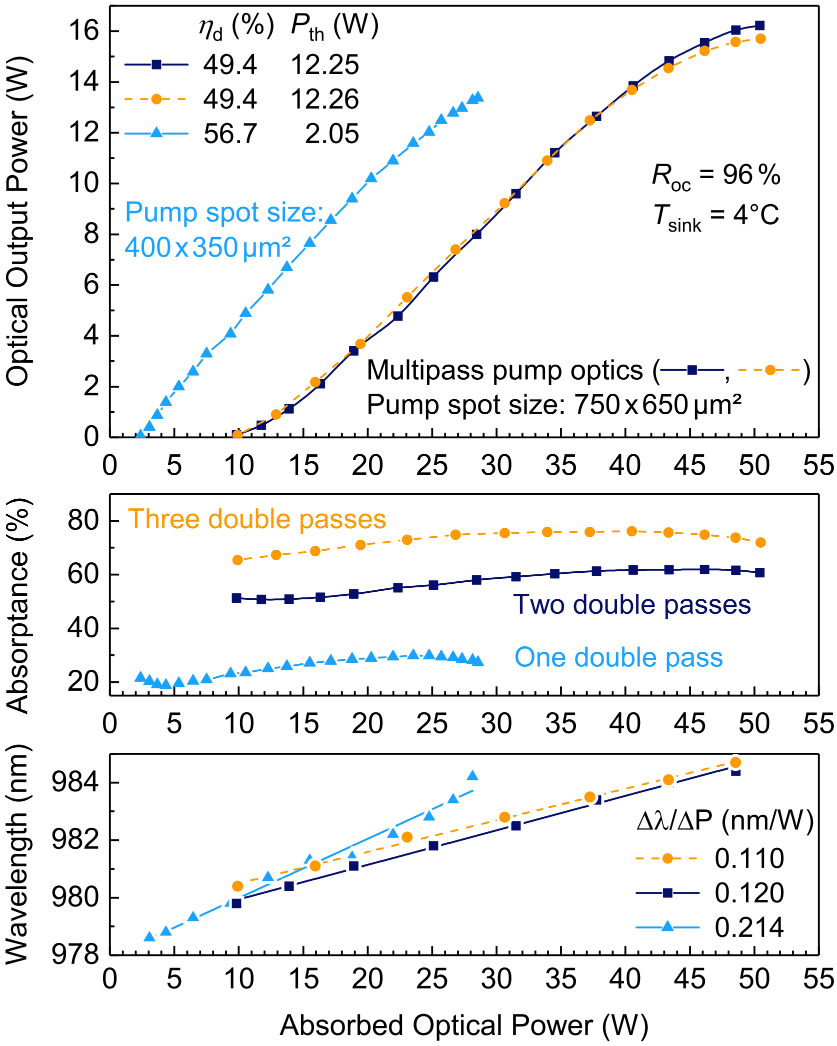

Fig. 4: Output characteristics of a quantum-well-pumped disk laser without a multipass pump optics and with a pump optics that allows two or three double passes of the pump radiation through the disk.

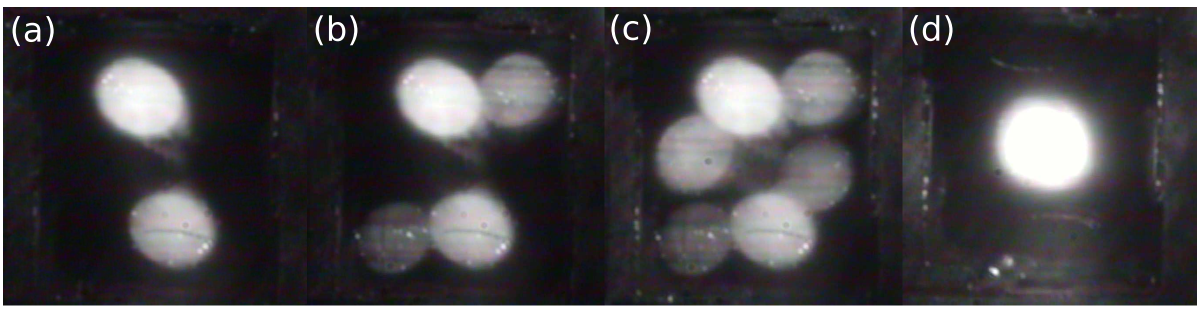

Fig. 5: Pictures of the disk laser's surface for one (a), two (b), or three (c) double passes of the pump radiation through the disk. The case of an aligned resonator and pump optics is shown in (d).

4. Conclusion and Outlook

By recycling the otherwise unused pump power with a multipass pump optics it was possible to significantly improve the pump power absorption of the investigated quantum-well-pumped semiconductor disk laser. The maximum achievable absorption of the disk laser is about 35 % during a single double pass of the pump radiation through the disk. With the used multipass pump optics, a second and third double pass was realized. This leads to a maximum absorption of 61.9 % and 76.1 %, respectively. By adding a third retro-reflecting prism and a flat end mirror which reverses the beam path, it will be possible to achieve eight double passes of the pump radiation through the disk. This may be sufficient for pump power absorptions above 95 % [7]. A temperature-stabilized cooling setup and the use of diamond heat spreaders may improve the output power beyond the value of 16.23 W, which has been achieved in this presentation.

Acknowledgment

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