Quantum-Well-Pumped Semiconductor Disk Lasers for Single- and Dual-Wavelength Emission

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We present two quantum-well-pumped semiconductor disk lasers having identical epitaxial layer sequences, besides different resonance wavelengths. One shows an output power exceeding 16 W at a wavelength of 982.6 nm, although mounted on a copper heat sink. The other disk laser emits light with wavelengths of 960.8 nm and 997.5 nm simultaneously. Dual-wavelength emission was detected in a temperature range of 21.3–27.1 °C. The optical output power can be forced to switch from one longitudinal mode of the micro resonator to another, by changing the temperature T_{sink} *of the laser heat sink. Output powers of 10.98 W at a wavelength of 957.0 nm (*$T_{sink} = -15\,°C$*) and 10.24 W at a wavelength of 997.5 nm (*$T_{sink} = 50\,°C$*) were measured. Thermal rollover was not seen, the limiting factor was the available maximum pump power. At a pump wavelength of 940 nm, quantum defects below 1.8 % have been obtained.*

1. Introduction

Semiconductor disk lasers combine two major advantages of semiconductor lasers and solid-state thin-disk lasers in a single device. The result is a semiconductor laser having both, a high output power and a good beam quality [1]. A versatile wavelength range from the ultraviolet to the infrared can be covered with semiconductor devices by changing the material composition and the epitaxial layer sequence of the device [2]. The external out-coupling mirror allows the use of intra-cavity devices, e.g. etalons, birefringent filters, or nonlinear crystals. Dual-wavelength emission from a single laser disk can be forced by placing an etalon inside the cavity of the laser [3]. However, if a wide distance between the two simultaneously emitting wavelengths is required, a special laser design becomes mandatory [4]. Switching between two emission wavelengths can be realized, for instance, by a variation of the pump power [5]. In our approach, wavelength switching is realized by a change of the laser heat-sink temperature. Furthermore, we evaluate the output characteristics of two disk lasers having the same epitaxial layer sequence but with different resonance wavelengths of the internal cavities. One of them shows dual-wavelength emission at room temperature. Obtaining semiconductor chips with different resonance wavelengths from a single wafer is possible due to the decrease of the layer thicknesses from the middle to the edge of the wafer. Since the emission wavelength of a disk laser is given by the resonance wavelength of the micro cavity, a broad wavelength range of 955 to 1000 nm can be selected with laser chips from the same wafer [6]. The reduced amount of heat generated inside the active region of quantum-well-pumped lasers allows high output powers even if the gain-spectrum peak at room temperature has a larger wavelength than the emission wavelength. In conventional barrier-pumped lasers, the amount of heat generated inside the active region is significantly larger than in quantum-well-pumped lasers and therefore the temperature-dependent shifts of emission wavelength and gain spectrum are more critical. For barrier pumped lasers at high output powers, a detuning of 25 nm at room temperature between these two wavelengths is recommended, because of the four to fives times faster temperature-dependent shift of the gain peak compared to the shift in the emission wavelength. Even with the use of diamond heat spreaders and/or intra-cavity heat spreaders, it is impossible to keep the laser at the desired temperature, at high output powers [7]. Thermal rollover is therefore the main reason for the limited output power of semiconductor disk lasers [2].

Quantum well pumping allows to diminish the generated heat inside the active region by reducing the difference between the emission wavelength and the pump wavelength, also known as quantum defect. The smallest quantum defect we measured so far was 1.55 % for a laser with an emission wavelength of 954.8 nm and a pump wavelength of 940 nm. Thermal rollover isn't a large problem with these devices, the problem is the small absorption rate of the pump power which is often below 35 %. The pump absorption of quantum-well-pumped lasers, like the name indicates, solely takes place in the quantum wells. This is disadvantage compared to barrier-pumped disk lasers, where the pump absorption can be controlled by the thickness of the barriers and is independent of the number of quantum wells. Hence, a high absorption rate is much easier realizable with barrier pumped lasers. Nearly all barrier-pumped laser designs allow an absorption rate above 90 %. To achieve the same absorption rate with quantum-well-pumped lasers, a multipass optic is required. With a simple setup containing a parabolic mirror and two prisms acting as retro reflectors, a multipass optic can be realized, which allows three double passes of the pump radiation through the disk. This setup is already sufficient to achieve an absorption rate of the pump power, close to 80 %, from the quantum-well-pumped disk laser design presented here [6].

2. Laser Design and Fabrication

The layer design of the quantum-well-pumped laser is visualized in Fig. 1. A resonant design for the emission and pump wavelength was chosen. The eight double quantum wells are placed inside the active region at the anti nodes of the emission field. Because of the wavelength difference between the emission and the pump wavelength, the field intensities drift apart inside the device. Therefore, a 1.2 µm long GaAs spacer is grown after the first four double quantum wells, since a quantum well placed inside a node of the pump field isn't able to provide any gain to the laser field [8].

Both sides of the active region are terminated by a AlAs/GaAs Bragg mirror. The top mirror contains 3.5 pairs and the bottom mirror consists of 18.5 pairs. A dielectric coating is sputter deposited onto the last bottom mirror facet, before a metalization is evaporated onto the wafer. The purpose of this coating is to achieve a reflectivity over 99.95 % for the emission wavelength at the bottom of the device. A dielectric coating is also placed onto the surface of the device, acting as an anti-reflection (AR) coating. Additional information about the fabrication of the quantum-well-pumped disk lasers can be found in [9].

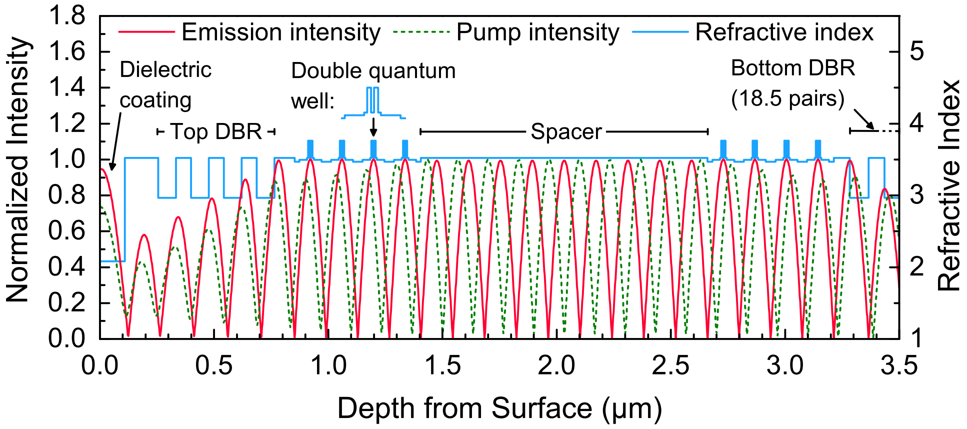

Fig. 1: Structure of the disk laser visualized in terms of the refractive index. Plotted are the calculated field intensities of the laser and pump fields (TE-component). Only one layer pair of the bottom Bragg mirror is displayed. On the top of the semiconductor device a dielectric coating is applied.

The flip-chip technique allows the complete removal of the substrate after the laser disk is mounted onto a heat sink. Since the design wavelength of 980 nm and the intended pump wavelength of 940 nm are larger than the absorption wavelength of GaAs. Laser emission is also possible without removing the GaAs substrate at the top of the laser, but even with undoped substrate, a small absorption in the substrate was still present and output powers over 1 W required a strong cooling of the device [6]. To conclude, removing the substrate for high power operation is still necessary.

3. Reflectivity Spectra

Measuring the reflectivity spectra of a disk lasers allows to determine a few important properties of the device, e.g., the positions of the resonance wavelength and the exciton absorption. Varying the detection angle from 10 to 70 °, the resonance wavelengths experience cosine shifts to the small wavelengths, while the excitonic dip stays at one position [10]. The two diagrams on the left-hand side of Fig. 2 show the result of such a measurement.

At a distance of $r = 10.5$ mm from the middle of the wafer, the resonance wavelengths are located at 910, 945 and 980 nm. Only the first two resonance wavelengths are visible at a detection angle of 10 °, due to lack of absorption of the quantum films at larger wavelengths. Measured at a distance of $r = 5.5$ mm, a shift of the resonance wavelength of 13 nm is noticeable. The approximate position of the excitonic dip only changed by 6 nm.

In our experiments, we use a wavelength-stabilized pump laser with a wavelength of 940 nm. For a good absorption rate of the pump power, it is important that the emission of the pump laser hits a resonance wavelength of the micro cavity. It is therefore necessary to pump the chips under a certain angle. In the case of the disk laser with $r = 10.5$ mm, a pump angle around 35 ° is favorable. However, a shift of the resonance wavelength

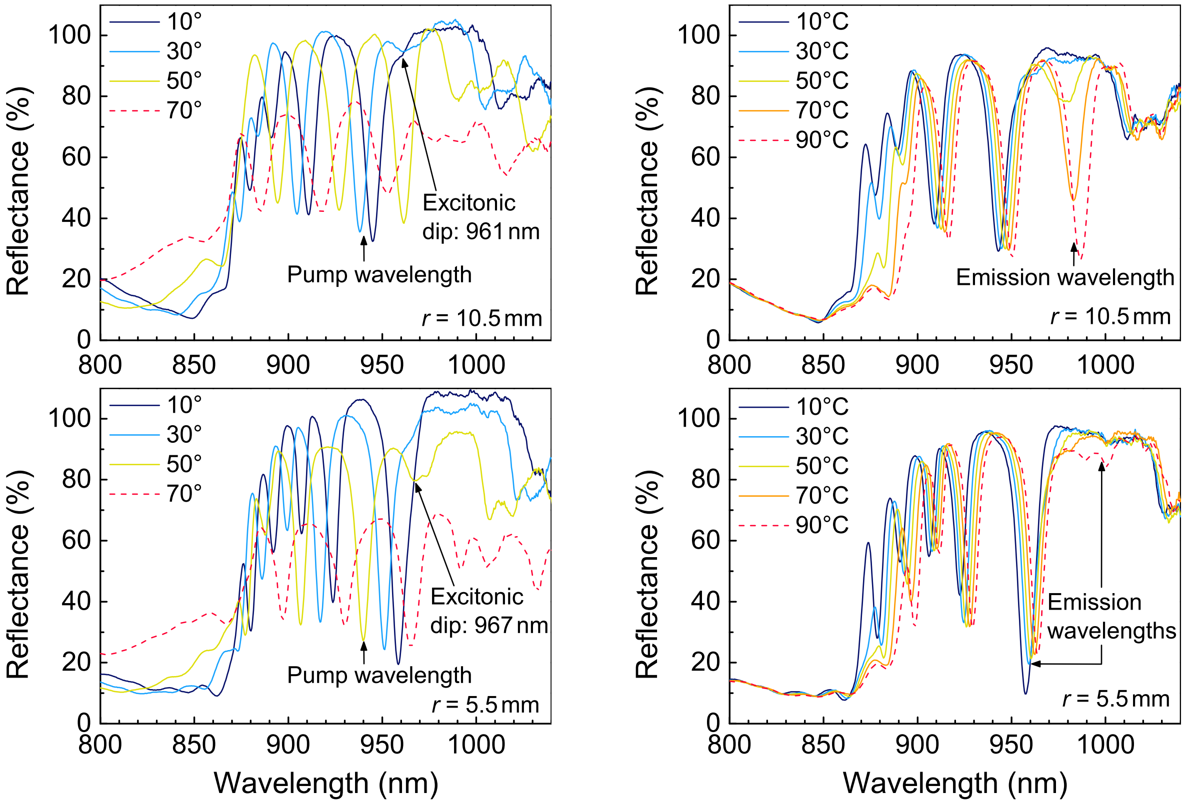

Fig. 2: Measured reflectivity spectra of two disk lasers from the same wafer. The two lasers have a different distance from the center of the wafer r, which causes a shift of the resonance wavelengths. Only the device with $r = 5.5$ mm is capable of dual-wavelength emission at room temperature. The left diagrams show the dependency of the reflectivity spectra from the detection angle and the diagrams on the right side show the dependency of the spectra from the temperature.

will occur if the temperature of the device changes. This is visible in the diagrams on the right-hand side of Fig. 2. The temperature-dependent spectra were measured at a detection angle of 10 ° and temperatures from 10 to 90 °C. For the resonance wavelength, a shift of 0.09 nm/K can be calculated and the wavelength shift due to the shrinkage of the bandgap with rising temperature is 0.32 nm/K. The dependency of the bandgap size on the temperature is clearly visible in the range of 865 to 890 nm, in the measured temperature-dependent reflectivity spectra. Only the device with $r = 5.5$ mm is capable of dual-wavelength emission at room temperature. To force the other disk laser into lasing at the smaller resonance wavelength at 958 nm, subzero temperatures are necessary. We therefore only examined the single-wavelength emission of this device.

4. Single-Wavelength Emission

In this measurement, we demonstrate the capabilities of the used quantum-well-pumped disk laser design. As shown in Fig. 3 we have characterized one of the disk lasers for different pump angles to determine the optimum direction of the pump-laser beam. For these measurements, the chip already mentioned in the previous chapter coming from a position of $r = 10.5\,\mathrm{mm}$ on the wafer, was mounted on a copper heat sink. A wavelength-stabilized pump laser emitting at 940 nm is focused under angles of 17, 23, 27 or 35 ° onto the chip. The temperature of the laser is controlled by a temperature sensor on the heat sinks and a Peltier cooler. The backside of the Peltier device is water cooled. All measurements were performed at a heat-sink temperature of 0 °C and with an out-coupling mirror reflectivity of 96 %.

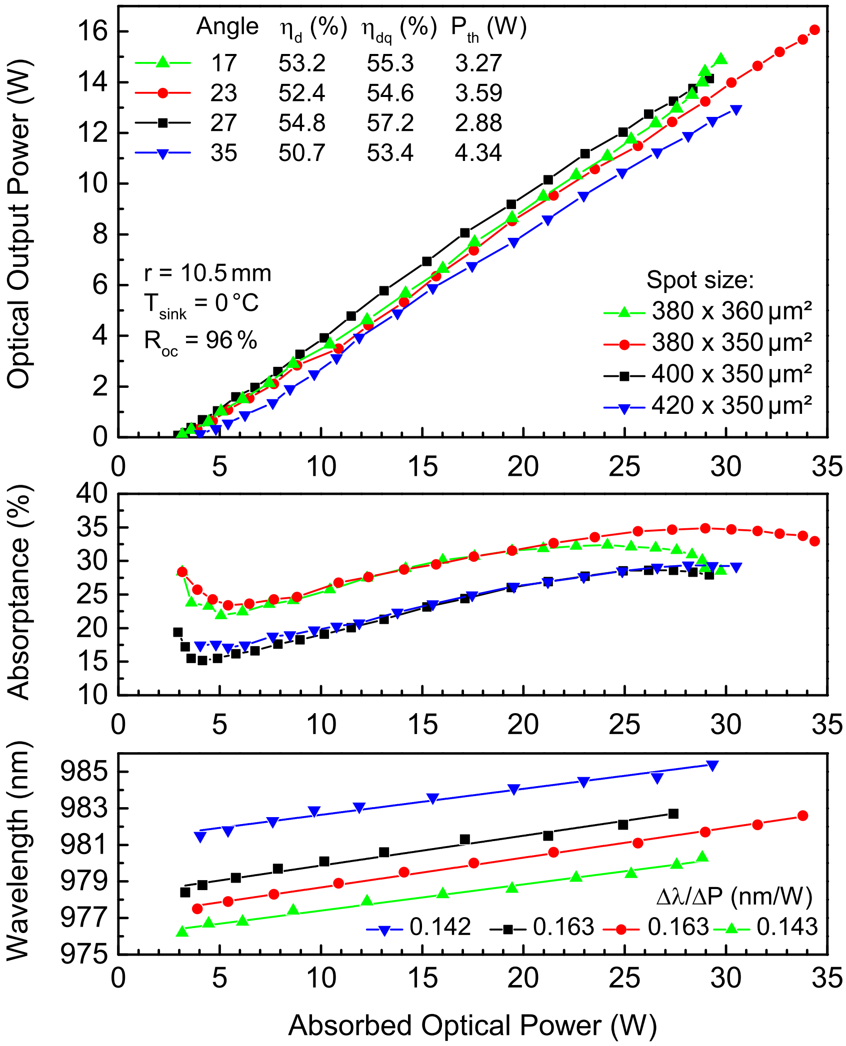

Fig. 3: Output characteristics of a quantum-well-pumped semiconductor disk laser pumped with a wavelength of 940 nm. The measurements were taken at four different pump angles.

During the measurements under a pump angle of 23 °, the highest output powers up to 16.07 W were obtained. The measured optical output for all four pump angles was limited by the highest available pump power of 104 W. No indication of thermal rollover was observed. The values of the differential efficiency are between 50.7 and 54.8 %. The highest absorption rate of the pump power with 34.8 %, was measured at an angle of 23 °, while 29 W of the pump power is absorbed. A small decrease in the pump absorptance is noticeable at higher pump powers, likely caused by the temperature raise of the disk with increasing pump power. The highest shift of the resonance wavelength with increasing absorption power is 0.163 nm/K. Typically, the wavelength shift of barrier-pumped disk lasers is slightly larger.

A dependency of the emission wavelength on the pump angle can be observed. Choosing a larger pump angle results in a longer emission wavelength. The explanation for this behavior is simple: When changing the pump angle, the setup is readjusted for maximum output power also by finding a optimum position for the pump spot on the laser chip. Since the output power for all pumping angles is limited by the pump power, the highest output power is observed at the position on the chip, where the highest pump absorption takes place, resulting in a different emission wavelength.

5. Switching Between Longitudinal Modes

A change in the lasers heat sink temperature causes the gain peak to shift with 0.33 nm/K. Lasing favorably occurs at the longitudinal mode which is closest to the gain peak. Since the resonance wavelength only shifts with 0.07 nm/K, a switch between two longitudinal laser modes can be realized by changing the laser temperature. The problem of a temperature-induced longitudinal mode switching is the incidental shift of the resonance wavelengths of the micro cavity. A temperature change therefore always has an impact on the pump absorption rate at a fixed pump wavelength. Some output characteristics of a disk laser for dual-wavelength emission are summarized in Fig. 4, showing the optical output power, the absorbed optical power, and the measured emission wavelength of the laser at different temperatures of the heat sink and at different pump angles. In this measurement, the quantum-well-pumped disk laser with $r = 10.5$ mm is used. This particular chip is mounted on a diamond heat spreader. However, similar results can be obtained with copper-mounted chips as well [6].

An output power of 10.24 W is possible, while the temperature of the heat sink is set to 50 °C. The pump absorption stays constant at about 30 % during the whole measurement and the wavelength shifts with 0.082 nm/K. A change of the heat-sink temperature of ±50 °C is causing a bisection of the pump absorption rate and in the case of the reduction of the temperature, a step in the emission wavelength from the longitudinal mode at 997.5 nm to the mode at 957.0 nm. For the measurement of the output characteristics at −15 °C, the pump angle was reduced to 45 °, so that a reasonable absorption rate of the pump power was guaranteed. At this heat-sink temperature, an output power of 10.98 W and the smallest threshold pump power with 2.91 W was measured. A differential efficiency of 57.3 % was determined. The shift of the 957 nm long emission wavelength,

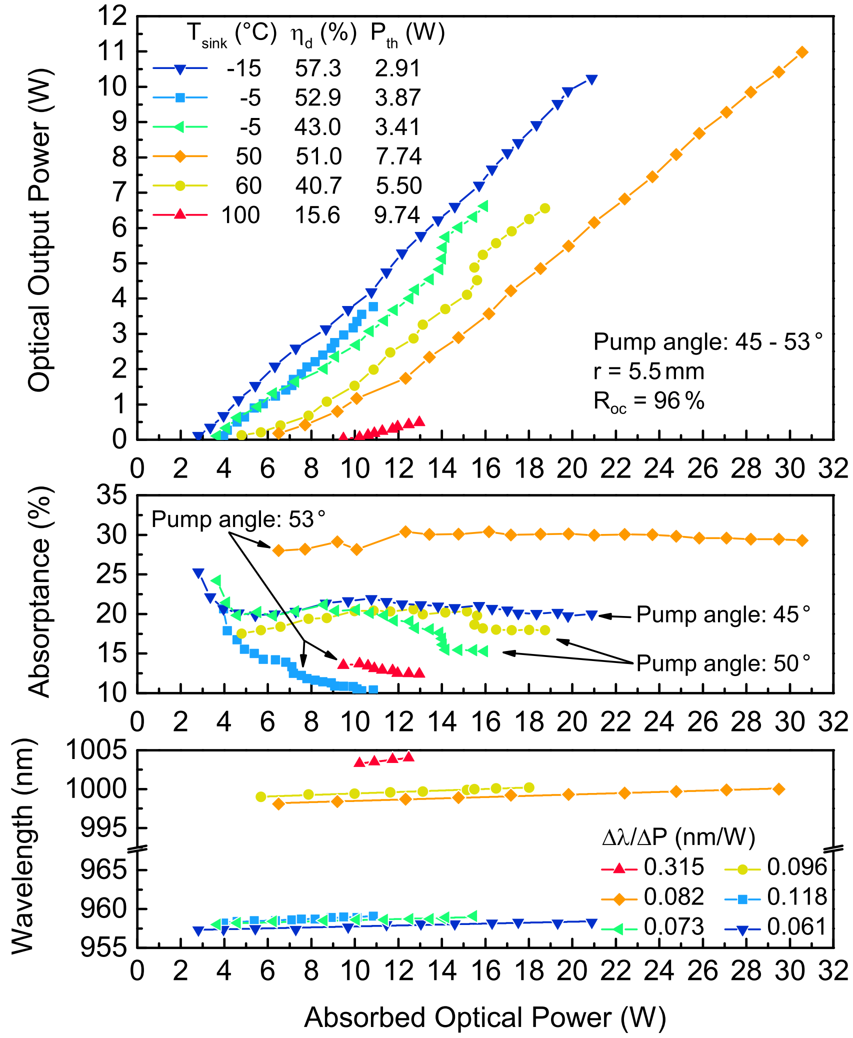

Fig. 4: Output characteristics of a quantum-well-pumped semiconductor disk laser, at a pump wavelength of 940 nm. The measurements were taken at five different temperatures and three different pump angles.

with absorbed optical power, only has a value of 0.061 nm/K, which is reasonable for a quantum defect under 1.8 %.

The measurements demonstrate, that a wavelength switch can be induced by a change of the laser temperature and that thermal rollover is successfully avoided because of the declining pump absorption rate at high pump powers. This behavior is mainly caused by the red shifting resonance.

The temperature dependency of the optical output power and the absorption rate is shown in Fig. 5. The disk laser was adjusted for maximum output power at a heat-sink temperature of 50 °C. Then, without readjusting or changing the pump power, the heat-sink temperature was changed. The used pump power during this measurement was 104 W. Raising the laser heat-sink temperature above 50 °C caused a quick decline of the output power and of the pump absorption. A similar behavior is seen while decreasing the temperature below 50 °C, until a temperature of 25 °C is reached. In the temperature range from 25 to 40 °C, a constant change of the pump absorptance with 0.681 %/K can be observed. At a temperature of the heat-sink below 21.3 °C, the laser stops emitting at 997.5 nm and only emits at 960.8 nm. The optical output power measurement shows a clear kink while the temperature induced wavelength switch occurs. A small kink can also be noticed in the behavior of the pump absorptance at the wavelength switch. A change of the heat-sink temperature, while the device is lasing at the smaller wavelength, induced an absorption rate change of 0.295 %/K. Below −10 °C humidity is freezing on the chip surface preventing further measurements.

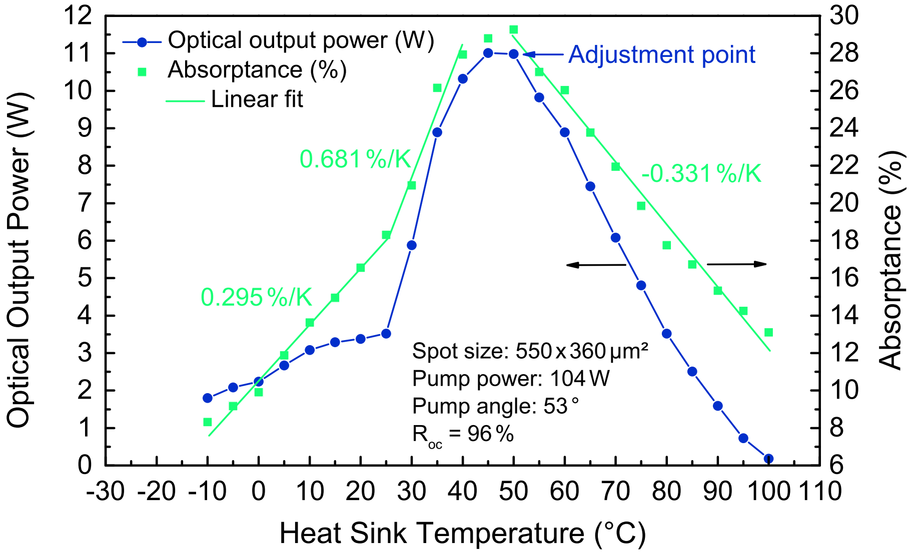

Fig. 5: Optical output power and pump power absorptance over the temperature of the heat sink. The chip was adjusted at 50 °C for maximum output power. While the temperature of the heat sink was varied, the pump power stayed constant at a value of 104 W.

6. Dual-Wavelength Emission

Dual-wavelength emission can be detected while the temperature of the heat sink is between 21.3 and 27.1 °C. The measured emission spectra at different temperatures of the heat sink are displayed in Fig. 6. The quantum-well-pumped disk laser has the same output power at both wavelengths at a temperature of the heat sink around 22.0 °C. The rising temperature causes a quick decrease of the output power of the smaller longitudinal mode. At a temperature above 27.1 °C only the longer longitudinal mode can be detected. The opposite occurs at temperatures below 21.3 °C. The spectral widths of the measured spectra are quite small. Even at output powers larger than 10 W the FWHM (full width at half maximum) wavelength of the spectrum is below 1.1 nm. This makes this quantum-well-pumped laser design particular interesting for frequency doubling applications. Using a birefringent filter for narrowing the spectral width is no longer mandatory.

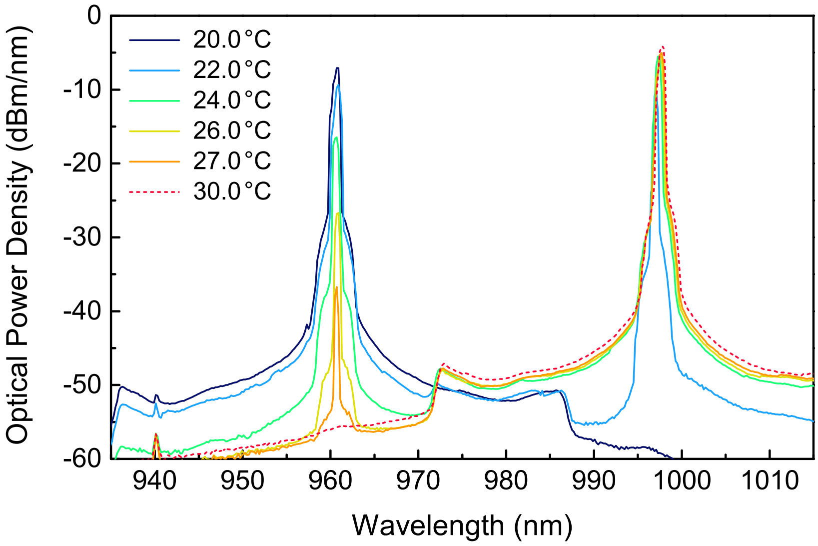

Fig. 6: Measured spectra of a quantum-well-pumped semiconductor disk laser at different temperatures of the heat sink. Dual-wavelength emission of the laser occurs at the wavelengths 960.8 and 997.5 nm, while the temperature of the heat sink is between 21.3 and 27.1 °C. The small peak at 940 nm is caused by the pump laser.

7. Conclusion

In this work we demonstrated the benefits of laser operation with low quantum defect, which was enabled by quantum-well pumping of the disk laser. A high output power exceeding 16 W was easily achievable, although no diamond heat spreader was used. The small spectral width of under 1.1 nm at high output powers will make the in-well pumped disk laser peculiar interesting for frequency-doubling applications. Furthermore, the emission wavelength can be easily switched from emitting at 957 nm to 998 nm just by changing the temperature of the lasers heat sink. A dual-wavelength emission with a distance between the emissions wavelengths of 36.7 nm is also possible without the use of intra-cavity elements.

8. Acknowledgment

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