Generation of Ultraviolet Laser Light by Frequency Tripling of a High-Power Infrared Optically Pumped Semiconductor Disk Laser

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We present an ultraviolet (UV) laser with an output power exceeding 23 mW at an emission wavelength of 327 nm. The UV laser is realized by frequency tripling an infrared optically pumped semiconductor disk laser which is capable of an output power above 23 W at a wavelength of 982 nm. To access the UV wavelength regime, sum frequency generation of the frequency-doubled and the fundamental wavelength is utilized.

1. Introduction

The accessible wavelength range for optically pumped semiconductor disk lasers (OPS-DLs) in the InGaAs/GaAs material system can cover a broad regime between 920 and 1180 nm. Utilizing different gain material like GaAlAs or GaInNAs extends the range to even shorter or longer emission wavelengths [1]. Since frequency doubling of the laser device is easily achievable by placing a nonlinear crystal inside the lasers cavity, semiconductor disk lasers grown on GaAs substrate can cover almost the entire visible wavelength spectrum. Adding a birefringent filter into the cavity allows to improve the second harmonic performance and to tune the emission wavelength by a few nanometers. Output powers with tens of watts in the visible range are possible by using second harmonic generation [2]. An ultraviolet emission can either be realized by tripling an infrared disk laser or by doubling an AlGaInP red laser [3, 4].

In order to generate ultraviolet light with an infrared laser it is necessary to frequency triple the laser's emission wavelength. Although it is possible to directly frequency triple the output light of a laser by taking advantage of the third-order nonlinearity, this process is quite uncommon due to the low conversion efficiency. A two-step process which involves mixing the fundamental infrared laser light with the frequency-doubled output of the laser can be far more efficient [5]. This approach can be realized with an optically pumped semiconductor disk laser by placing two nonlinear optical crystals inside the lasers cavity, one for the second-harmonic generation and the other one for the sum-frequency generation. Here, we utilize this two-step process to frequency-triple the output of an optically pumped semiconductor disk laser which is designed for a wavelength of 980 nm [6].

2. Layer Design and Characterization of the Disk Laser

The semiconductor disk lasers structure contains three key elements: A dieletric anti-reflection coating, a resonant periodic gain structure and a double-band Bragg reflector (DBBR). The gain region of the disk laser contains six InGaAs quantum wells which are placed in the anti-nodes of the standing electric field inside of the microresonator. The quantum wells have an indium concentration of 16.5 %. Strain compensation is utilized by GaAsP layers. In order to provide a bottom mirror with a high reflectivity for the laser wavelength as well as for the pump wavelength, a numerically designed DBBR with 33 mirror pairs out of $AlAs/Al_{0.19}Ga_{0.81}As$ is used [7]. The disk structure was designed for an emission wavelength of 980 nm and a pump wavelength of 808 nm. During the processing of the laser devices, the GaAs substrate will be completely removed, which requires growing the epitaxial structure in reverse order. The Bragg mirror is therefore the last layer sequence grown in the chamber of the molecular beam epitaxy machine. To further improve the performance of the barrier pumped laser device, a diamond heat spreader is used. The measured reflectivity spectra of a processed disk laser are shown in Fig. 1.

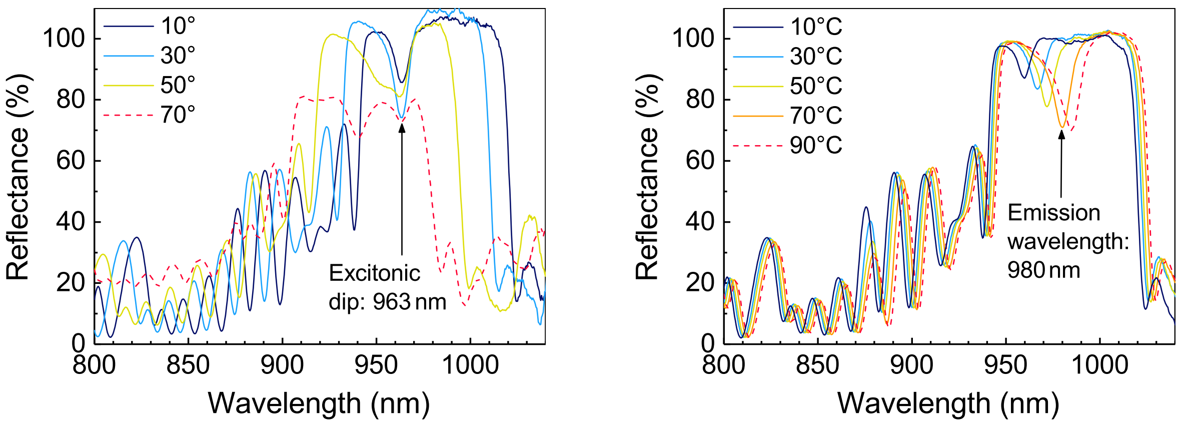

Fig. 1: Reflectivity spectra of a disk laser over the incidence angle at room temperature (left). The reflectivity spectra over the temperature (right) were taken at an angle of 10 °.

From the angle-dependent reflectivity spectra, the excitonic resonance wavelength and a suitable pump angle can be determined. The excitonic dip is located at a wavelength of 963 nm, which is roughly 17 nm shorter than the emission wavelength of the laser device. A slightly greater distance between these to wavelengths would be favorable, since the gain spectrum will shift four to five times faster with increasing temperature than the resonance wavelength. One of the two stop bands of the DBBR is located between 945 and 1015 nm, while the other one lies between 800 and 830 nm. The position of the stop band for the pump wavelength can be determined by measuring the reflectivity spectra of the semiconductor disk lasers backside [7].

In a linear resonator with an outcoupling mirror reflectivity of 99.1 % an optical output power of 23.3 W can be achieved with the optically pumped semiconductor disk laser. The heat sink of the laser device was cooled down to a temperature of −7.5 °C. At higher heat-sink temperatures a decline of the output power is noticeable. Nevertheless an output power beyond 17 W is still possible at a heat-sink temperature of 7.5 °C. The output characteristics of the disk laser measured at four different heat-sink temperatures is displayed in Fig. 2. A diode laser with an emission wavelength of 808 nm is used as a pump source. The spot size of the pump beam on the chip is $600 \times 550\,\mu m^2$. An increase of the absorbed pump power leads to a linear shift of the emission wavelength of approximately 0.19 nm/W. The absorptance rate of the pump power during the four measurements at different heat-sink temperatures is between 89.8 and 97.8 %. It is noticeable that an increase of the chip temperature leads to a decline of the absorptance rate. This can be explained with an increasing reflectance of the semiconductor disk at the pump wavelength, due to the red-shift of the spectrum, for higher temperatures. A larger pump angle may solve this problem.

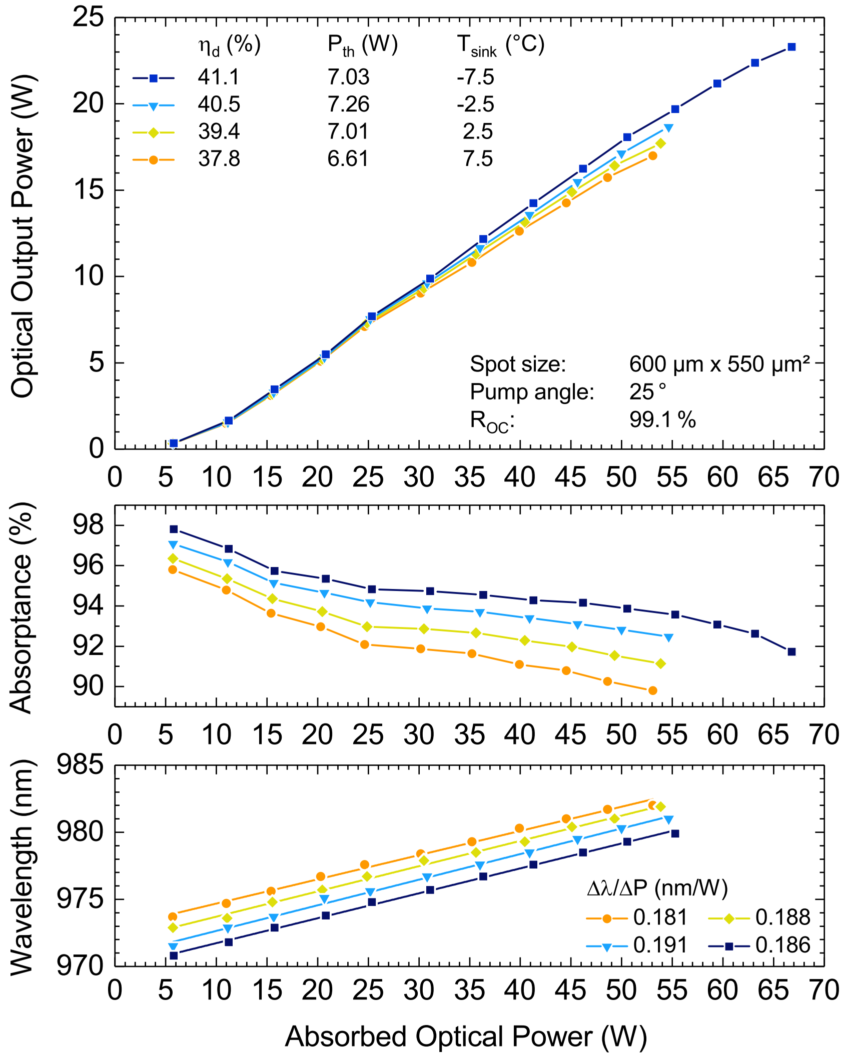

Fig. 2: Output characteristics of the used semiconductor disk laser in a linear resonator setup with an outcoupling mirror reflectivity of 99.1 %. The measurements were taken at four different temperatures of the heat sink.

3. Experimental Setup for Frequency Tripling

For the frequency tripling we used a double-folded resonator with three different mirrors, a birefringent filter and two nonlinear crystals for the second harmonic and sum-frequency generation. Both are lithium triborate (LBO) crystals and have $3 \times 3\,\mathrm{mm}^2$ wide cross-sections. The crystal for the second-harmonic generation is 8 mm, the crystal for the sum-frequency generation 10 mm long. The thickness of the birefringent filter is 4 mm. A sketch of the experimental setup is shown in Fig. 3.

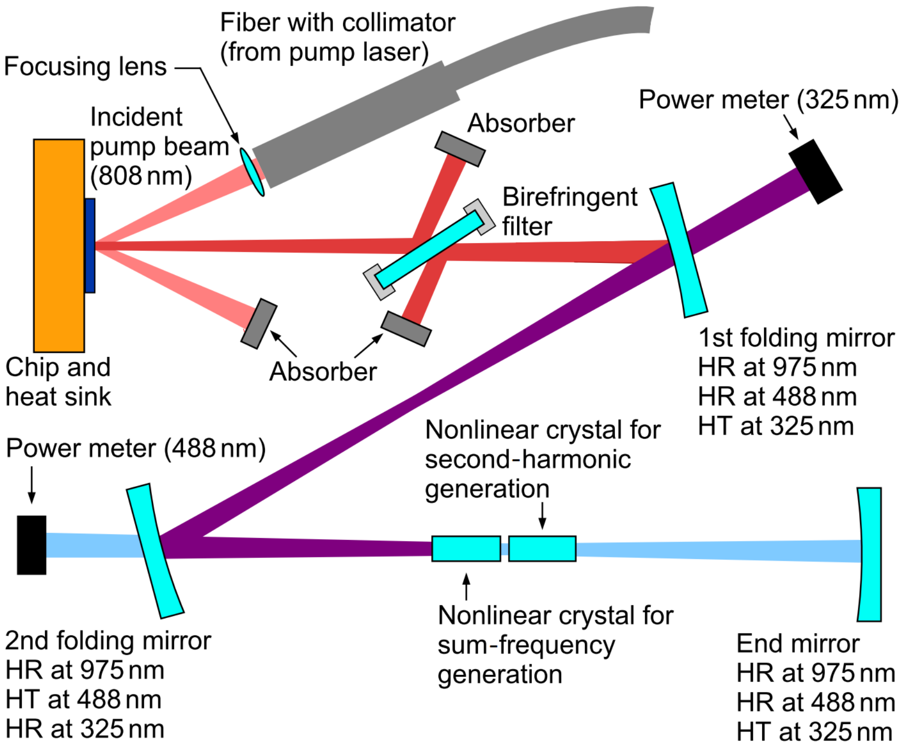

Fig. 3: Sketch of the experimental setup for frequency tripling the infrared laser. The ultraviolet light is coupled out at the first folding mirror and the frequency-doubled light is coupled out at second folding mirror. All resonator mirrors are highly reflective for infrared light.

The first mirror is the integrated Bragg mirror on the semiconductor chip. It is highly reflective for the pump and the fundamental wavelength. Due to the fact that the bandgap of GaAs at room temperature is 1.42 eV, which corresponds to a wavelength of 873.13 nm, the semiconductor disk is absorptive for the second and the third harmonic. To prevent the semiconductor structure from unnecessary heating, we couple the second and third harmonic beam out of the resonator before it can reach the chip. Therefore, we have two different coatings on the first and second folding mirror. The first folding mirror is transmissive for the third and highly reflective for the fundamental wavelength and the second harmonic. The second folding mirror is transmissive for the second and highly reflective for the fundamental wavelength and the third harmonic.

In order to narrow the spectral width and stabilize the emission wavelength the laser, a birefringent filter is placed in the first resonator arm. Although the filter is placed in the Brewster angle inside of the resonator, the filter still couples out a high amount of infrared light, which has to be blocked with suitable absorbers. The two nonlinear crystals are placed right next to each other in the beam waist of the last resonator arm, since high electric field strengths are beneficial to increase the efficiency of the nonlinear conversions. Placing the crystals directly next to each other has in addition the advantage that the influence of the walk-off angle between the first and the second harmonic in the SFG crystal, which is not avoidable with critical phase matching, is small. The standing wave in the laser resonator is a superposition of a forward and a backward traveling wave. As a result, the crystal for the second harmonic generation will also produce a forward and a backward traveling wave. In the crystal for the sum-frequency generation we want to have as much second harmonic electric field strength as possible, so we place the SHG crystal behind the SFG crystal and make the end mirror high reflective for the second harmonic. This positioning of the crystals has the big advantage that the second harmonic photons are traveling only in one direction through the SFG crystal (towards the semiconductor chip). Due to momentum conservation, the generated third harmonic has the same direction as the second harmonic. On the way back towards the chip, the second harmonic is coupled out at the second folding mirror and the third harmonic — the UV light we want to get — is coupled out at the first folding mirror. The captured beam profile of the ultraviolet laser beam and a picture of the experimental setup are shown in Fig. 4.

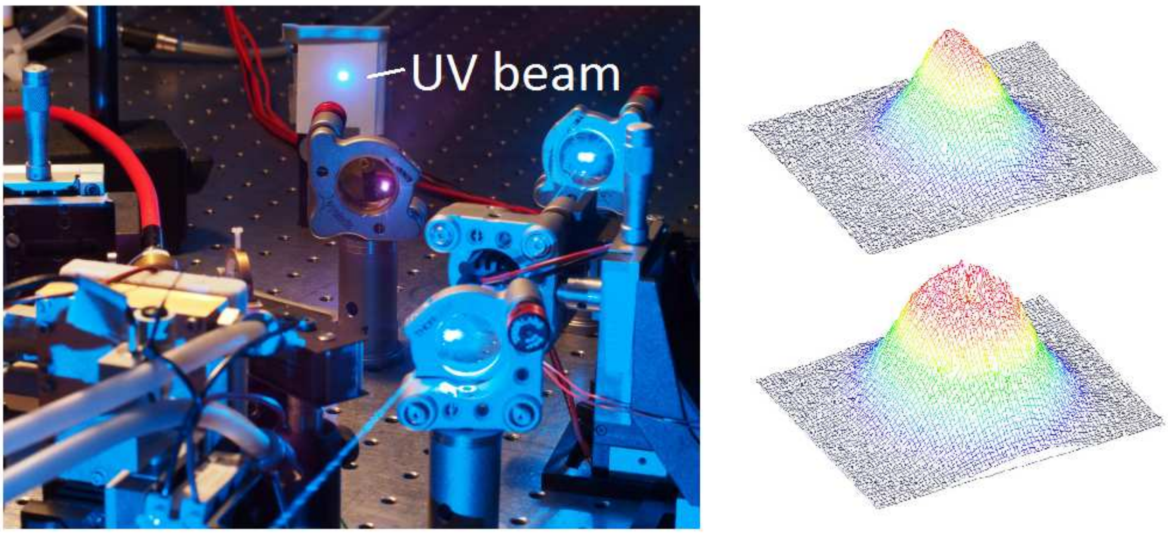

Fig. 4: Picture of the experimental setup (left). The ultraviolet laser beam is visible on a piece of paper due to fluorescence. A CMOS camera was used to measure the beam profile of the ultraviolet beam at a pump power of 10 W (top right) and 33 W (bottom right).

4. Output Characteristics of the Ultraviolet Laser

The experimental setup allows a tuning of the fundamental wavelength from 970 to 985 nm (full width at half maximum) with the birefringent filter. However, a significant drop in the ultraviolet output power takes place if the fundamental wavelength is detuned away from the adjusted wavelength. Tuning of the emission wavelength requires a realignment of the two nonlinear crystals due to the loss of the phase matching. Although the spectral width of the ultraviolet light could not be directly measured, it is expected to be 0.08 nm, since the spectral width of the fundamental wavelength is 0.24 nm at −3 dB clip level. Without a birefringent filter in the resonator, the spectral width of the fundamental emission at −3 dB is 2.4 nm wide. In our experiment, the fundamental wavelength of the laser of 982 nm leads to a second harmonic wavelength of 491 nm. The sum-frequency generation of the first and the second-harmonic results in a third-harmonic wavelength of 327 nm. In Fig. 5 the output characteristics of the second and the third harmonic are shown.

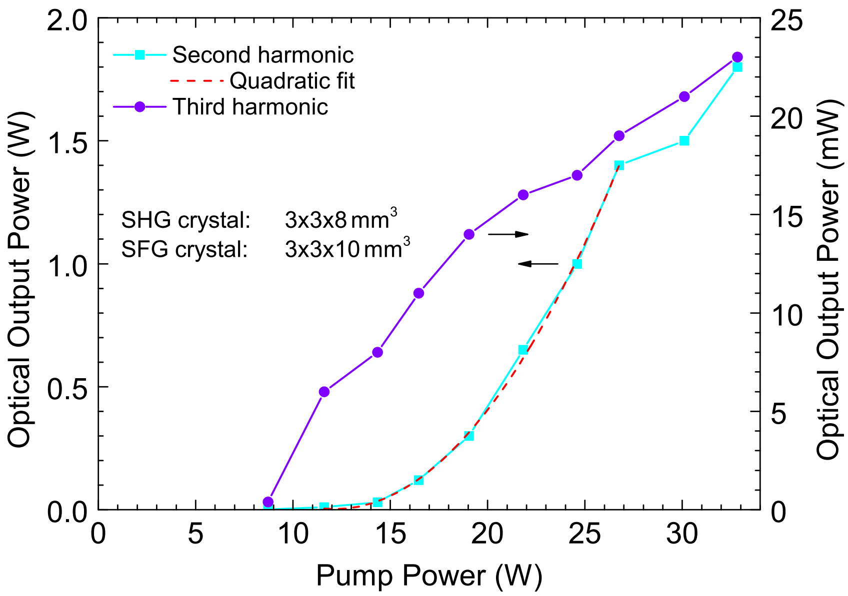

Fig. 5: Second and third harmonic output power. A quadratic fit of the second harmonic output power is possible for pump powers below 27 W.

The output power of the second harmonic rises from zero to 1.8 W when the pump power is raised from 8.7 to 32.8 W. A quadratic fit to the output curve could be applied for pump powers below 26.8 W. At higher pump powers a deviation from the quadratic fit is observed. The reason for this behavior is the temperature rise of the nonlinear crystal which leads to a phase mismatch with higher powers. With a second harmonic power of 1.8 W, the third harmonic output power reaches 23 mW.

The pump conversion efficiency is calculated as the ratio between the output power and the pump power. The results for the second and third harmonic are displayed in Fig. 6. For the second harmonic a nearly linear behavior for pump powers between 14.4 and 26.8 W is noticeable. This corresponds to the quadratic curve of the output power. An explanation for this behavior is the proportionality of the second harmonic output to the square of the fundamental laser power. The fundamental power itself is proportional to the pump power. So the second harmonic output divided by the pump power must be linear.

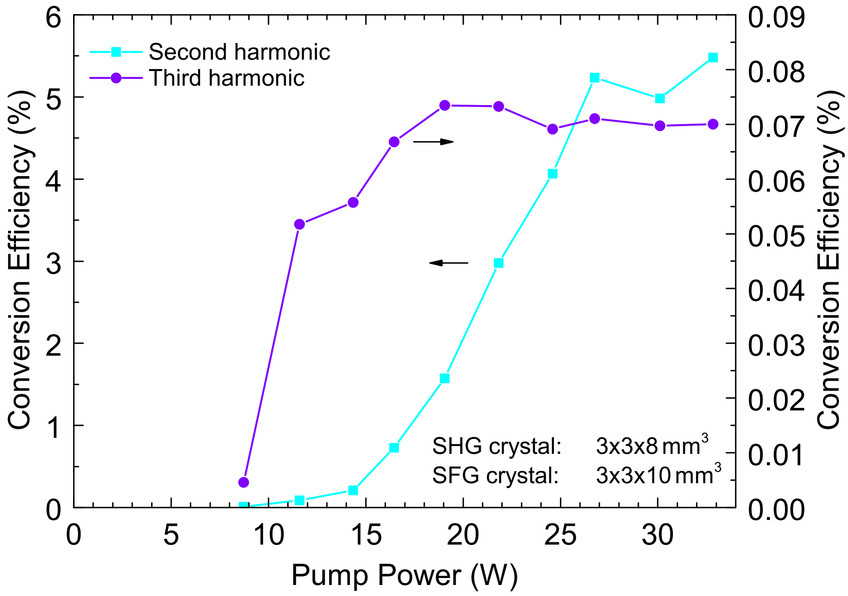

Fig. 6: Pump conversion efficiencies of the second and third harmonic of the laser from Fig. 5.

5. Conclusion

We demonstrated the output characteristics of an intra-cavity frequency-tripled infrared laser. Frequency tripling was achieved by mixing the fundamental wavelength of the semiconductor disk laser of 982 nm with the second harmonic. While it was possible to achieve an output power of more than 23 W at the fundamental wavelength of the laser, the double-folded resonator with two nonlinear crystals inside it only allowed a second-harmonic output power of 1.8 W. With a value beneath 6 %, the conversion efficiency of the second harmonic is over three times lower than the anticipated efficiency from previous frequency doubling experiments [8]. Nevertheless, an ultraviolet output power of 23 mW at a wavelength of 327 nm was possible. Further improvements of the second-harmonic power should also increase the ultraviolet output, since the third harmonic generation highly depends on the second harmonic field strength in the sum-frequency generation crystal.

Acknowledgment

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