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Blue 489-nm picosecond pulses generated by intracavity frequency doubling in a passively mode-locked optically pumped semiconductor disk laser

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ABSTRACT We report the generation of blue 489-nm picosecond laser pulses by intracavity second-harmonic generation in a mode-locked optically pumped InGaAs vertical-external-cavity surface-emitting laser. Mode locking achieved by a semiconductor saturable absorber mirror generated 5.8-ps-long sech^2-shaped pulses at an emission wavelength of 978 nm and a repetition rate of 1.88 GHz. Intracavity frequency doubling in a 5-mm-long lithium triborate crystal generated blue picosecond pulses with a spectral width of 0.15 nm and an average output power of up to 6 mW.

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1 Introduction

Picosecond pulses in the blue spectral range are of interest for applications such as time-resolved fluorescence spectroscopy or biochemical analysis. Blue laser sources commonly used for such applications are e.g. gain-switched InGaN diode lasers emitting pulses with durations of about 90 ps at a repetition rate of 40 MHz [1] and an average output power on the order of 1 mW. Improved pulse properties with respect to pulse duration and spectrum can be achieved by active mode locking. In this way an actively mode-locked InGaN diode laser generated 30-ps pulses at 409 nm with an average power of 2 mW [2]. The time–bandwidth product of the generated pulses was, however, four times above the Fourier limit. Higher powers of up to 3.6 mW have been obtained at 490 nm by frequency doubling the pulses of a gain-switched near-infrared diode laser [3]. The time–bandwidth product of these pulses exceeded 10.

Such sources with pulse durations of tens of picoseconds and repetition rates in the megahertz range are well suited for conventional time-resolved fluorescence spectroscopy with fluorescence lifetimes in the nanosecond range. However, in recent years there has been a growing interest in hemicyanine dyes [4] with applications in various fields ranging from optical data storage to biochemistry. These dyes typically have fluorescence lifetimes from tens to hundreds of picoseconds, so that time-resolved fluorescence measurements require pulse durations of only a few picoseconds on the one hand, and on the other hand tolerate pulse-repetition rates in the lower gigahertz range.

In the continuous-wave (cw) regime, optically pumped vertical-external-cavity surface-emitting lasers (VECSELs) with intracavity frequency doubling are compact and efficient sources of blue radiation with output powers exceeding 10 W [5]. In addition, passively mode-locked VECSEL systems have been used to generate infrared pulses in the picosecond [6] and subpicosecond ranges [7]. Recently, 4.7-ps pulses with an average output power exceeding 2 W and a time–bandwidth product of twice the Fourier limit have been demonstrated at 957 nm [8]. These pulses should be well suited for single-pass frequency doubling in crystals with quasi-phase matching, as demonstrated by using mode-locked radiation of an InGaAs diode-laser mask oscillator power amplifier (MOPA) system [9].

2 Experimental setup

We report a passively mode-locked VECSEL with intracavity frequency doubling, emitting blue second-harmonic radiation at 489 nm. The experimental setup is shown in Fig. 1. The laser cavity is a folded hemispherical V-shaped cavity. It is formed by three components: a semiconductor saturable absorber mirror (SESAM) used as plane end mirror, the optically pumped semiconductor disk as active laser medium, which includes an integrated Bragg mirror as plane

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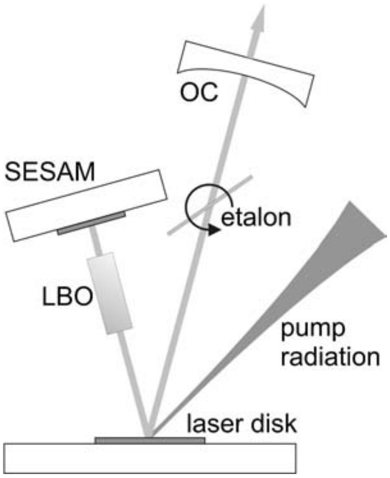

FIGURE 1 Scheme of the laser setup. Using the laser disk as a folding mirror, the hemispherical laser cavity is folded with a full angle of 30°. The output coupler (OC) has a radius of curvature of $r = -75$ mm and is coated for HR at 980 nm and HT at 490 nm. The LBO crystal is positioned at a 3-mm distance from the SESAM. The beam waist is located on the surface of the SESAM

folding mirror, and finally a concave dielectric mirror as output coupler.

Due to the hemispherical cavity configuration, the mode diameter on the SESAM can be varied by an order of magnitude by changing the cavity length. In this way the optical power density on the SESAM can be adjusted so that the pulse fluence exceeds the saturation fluence on the order of 10 μJ/cm^2 and stable passive mode locking is achieved. The low-finesse SESAM contains a single 8-nm $In_{0.2}Ga_{0.8}As$ quantum well (QW) grown by low-temperature molecular beam epitaxy (MBE) at 315°C. Its surface is not antireflection coated, whereas the absorber thickness is designed antiresonant for the laser wavelength. It is operated at room temperature without any active temperature stabilization.

The optically pumped semiconductor disk contains 13 $In_{0.15}Ga_{0.85}As$ quantum wells, each of them with a thickness of 8 nm and positioned at the antinodes of the standing wave pattern in the laser cavity. The absorber layers are designed for a pump wavelength of 808 nm. They consist of $Al_xGa_{1-x}As$ ($x = 0$–0.2) GRIN layers with decreasing band gap towards the QWs to enhance the carrier capture rate. The spacing of the quantum wells is optimized for an emission wavelength of 980 nm. The epitaxial structure includes strain-compensating $Al_{0.2}Ga_{0.8}As_{0.8}P_{0.2}$ layers between the QWs to avoid defect lines [10]. A high-reflective (HR) Bragg mirror for the laser wavelength is formed by 25 pairs of GaAs/AlAs layers. The 7-μm-thick epitaxial structure was grown by metal organic vapour phase epitaxy (MOVPE) on a GaAs substrate in reversed order and was soldered epi-side down on the heat sink to ensure good thermal contact. Finally, the substrate was removed by chemical etching in order to avoid absorption of the 808-nm pump radiation. The surface was then antireflection coated for the emission wavelength of 980 nm at 0° incident angle and for the 808-nm pump radiation incident at an angle of 45°. The semiconductor disk is pumped with a fiber-coupled diode-laser bar. The temperature of the VECSEL chip is actively stabilized at 0°C. The chip surface is purged with dry nitrogen to avoid water condensation on its surface.

The concave output mirror has a radius of curvature $r = -75$ mm and is HR coated for the fundamental wavelength at 980 nm. The transmission at the wavelength of the second harmonic exceeds 95%. A 30-μm-thick glass etalon inside the cavity allows tuning of the fundamental wavelength within a range of more than 10 nm and reduces the spectral bandwidth of the emitted radiation to about 0.2 nm.

To achieve frequency doubling, a 5-mm-long lithium triborate (LBO) crystal is placed in the laser cavity. LBO is chosen because of its excellent linear optical properties. In particular, the low absorption loss of less than 1%/cm makes LBO an ideal material for intracavity applications. The relatively low nonlinearity of 1 pm/V can be compensated for by high fundamental intracavity peak power, which is on the order of 100 W. The crystal is critically phase matched for second-harmonic generation of 980 nm at room temperature. The surfaces are antireflection coated for the fundamental and the second harmonic. The crystal is positioned between the active medium and the SESAM. The distance from the SESAM is only 3 mm to ensure a small beam diameter inside the crystal and thus high optical power densities, which are of importance for high conversion efficiencies. Intracavity second-harmonic generation of the mode-locked radiation is characterized by this simple, very compact, and cost-effective setup. No active temperature stabilization of the short LBO crystal is required due to the high spectral acceptance bandwidth of 4.4 nm. In contrast, efficient external frequency conversion in single pass requires longer crystals with higher nonlinear coefficients. Suitable materials are potassium niobate as well as nonlinear crystals with quasi-phase matching, e.g. periodically poled lithium niobate or periodically poled potassium titanyl phosphate. In addition to higher costs, the required increase in crystal length results in a significantly smaller acceptance bandwidth, so that temperature stabilization of the crystal may be necessary.

The generated pulses at the fundamental wavelength are characterized by noncollinear intensity autocorrelation (APE Pulse Check 150 ps). In addition, an optical spectrum analyzer (Ando AQ-6315 A) with a spectral resolution of 0.05 nm is used to measure the spectrum of both the fundamental and the second-harmonic radiation. The RF spectrum of the blue radiation is measured with a fast photodiode (New Focus model 1454) and a RF spectrum analyzer (HP E4407B). In these measurements the second harmonic is separated from the residual radiation at the fundamental wavelength by a 1-mm-thick BG39 filter.

3 Experimental results

Without the LBO crystal the VECSEL emitted transform-limited 3.8-ps pulses at 975 nm with an output coupler of $T = 2\%$. The sech^2-shaped pulses had a time–bandwidth product of 0.35. The average power was 83 mW at an incident pump power of 5.0 W. The etalon was essential for obtaining pulses with high spectro-temporal quality, i.e. a low time–bandwidth product. Without the etalon, the pulse width of the fundamental pulses increased typically by 50%, whereas the spectral width increased by a factor of 20. With the LBO crystal in the cavity and an HR 980/HT 490 (HT = high transmission) output coupler the laser system generated a second-harmonic TEM_{00} output with an average power of 6 mW at an incident pump power of 6.1 W. In addition to the second harmonic, the system emitted a small amount of fundamental laser radiation.

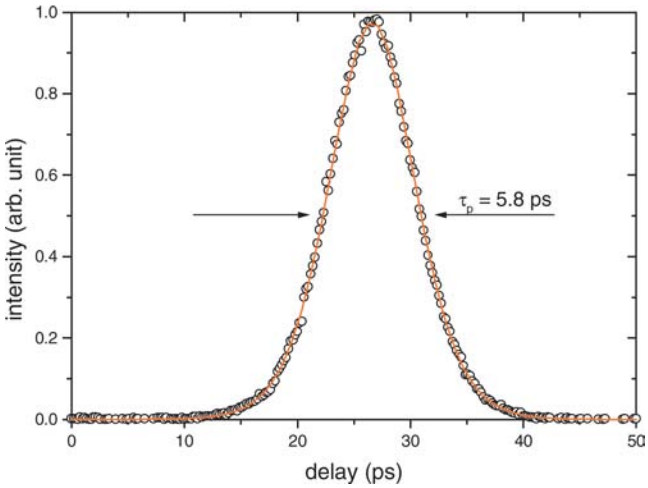

FIGURE 2 Autocorrelation of the fundamental laser radiation at a second-harmonic output power of 6 mW. The *circles* show the measured data whereas the *solid line* is a $sech^2$ fit representing a 5.8-ps FWHM pulse

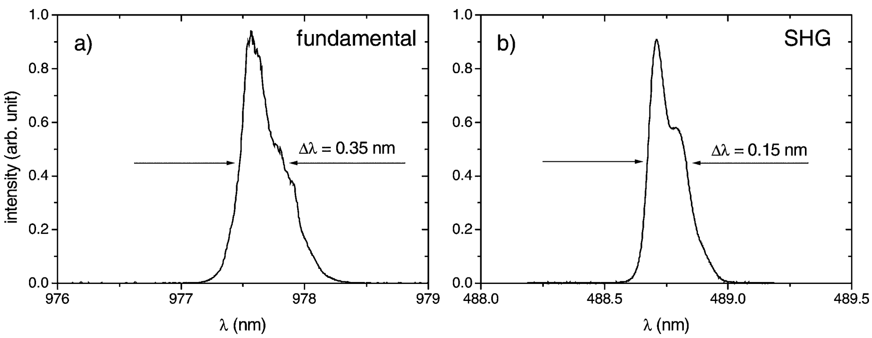

FIGURE 3 Spectra of the fundamental (**a**) and the second-harmonic (**b**) radiation. Both spectra were measured at mode-locked operation and a second-harmonic output power of 6 mW. The spectral resolution is 0.05 nm

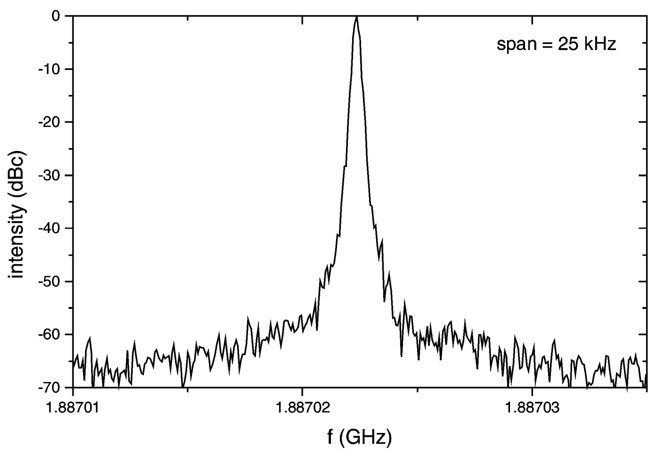

FIGURE 4 RF spectrum of the second-harmonic radiation confirming mode-locked operation. The spectral resolution of the analyzer is 100 Hz. The photodiode used has a rise time of 18.5 ps

The autocorrelation of these laser pulses at the fundamental wavelength indicated $sech^2$-shaped pulses with a pulse duration of 5.8 ps as shown in Fig. 2. The corresponding spectrum shown in Fig. 3a had a bandwidth of 0.35 nm (FWHM). The corresponding time–bandwidth product was 0.64, which is about twice the Fourier limit. As expected, the spectral width of the second harmonic $\Delta\lambda = 0.15$ nm was approximately half the width of the fundamental laser spectrum (Fig. 3b). Since no autocorrelator for the second-harmonic pulses was available, the RF spectrum of the blue radiation was investigated. In the RF spectrum peaks were found at the cavity round-trip frequency of 1.88 GHz and its harmonics. Typically, the peak intensity at the fundamental round-trip frequency was more than 50 dB above the noise level (Fig. 4). The measured average power of 6 mW and the repetition rate of 1.88 GHz correspond to a blue pulse energy of 3 pJ. The peak power of the second harmonic can be estimated from the average power, the repetition rate, and the fundamental pulse duration. In the 5-mm-long LBO crystal the temporal walk-off between the infrared and blue pulses is only 0.3 ps and thus negligible. In this case a frequency-doubled $sech^2$ pulse is shorter by a factor of 0.67 than the fundamental pulse, yielding a pulse duration of 3.9 ps and a peak power of approximately 0.7 W.

In the presented concept, limitations may be caused by competition between the pulse-forming process and the frequency conversion. Whereas the saturable absorption favors mode-locked pulses by lower absorption losses for the fundamental laser radiation, the pulse peak power enhances the nonlinear conversion efficiency, which causes higher losses for the fundamental intracavity radiation compared to cw operation. Thus, the modulation depth of the saturable absorber has to be sufficiently high to compensate the nonlinear reduction of the pulsed intracavity power by frequency conversion. However, it can be expected that the blue output power can be increased by an order of magnitude with further optimization of the cavity configuration and the semiconductor components used. Nevertheless, we expect that the peak power will not exceed the cw power level of 15 W, which was recently obtained by intracavity second-harmonic generation of a cw semiconductor disk laser [5].

The scheme described in this paper is of interest for applications where mode-locked operation with pulse durations in the picosecond range is essential. Intracavity frequency doubling is especially suited for ultra-compact, low-power sources of mode-locked blue radiation. For high-power applications, however, external frequency doubling of the picosecond pulses of a mode-locked VECSEL will be a more promising approach. For comparison, the radiation of the mode-locked VECSEL was frequency doubled in a 5-mm-long potassium niobate crystal in single pass. An average blue output power of up to 3 mW was achieved with an optical-to-optical conversion efficiency as high as 26%/W.

4 Conclusion

In summary, we reported a compact passively mode-locked VECSEL system with intracavity frequency doubling. This laser system generated mode-locked 489-nm pulses with a repetition rate of 1.88 GHz, a spectral width of 0.15 nm, and an average power of 6 mW. The fundamental 978-nm laser pulses had a pulse duration of 5.8 ps; their time–bandwidth product was 0.64. From this fundamental pulse duration a duration of the second-harmonic pulses of 3.9 ps was calculated with a corresponding time–bandwidth product of 0.78 and a peak power of 0.7 W.

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