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10 GHz passively mode-locked external-cavity semiconductor laser with 1.4 W average output power

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We present a 10 GHz passively mode-locked vertical external-cavity surface-emitting semiconductor laser (VECSEL) with 1.4 W average output power in 6.1 ps pulses. The output features a very good pulse quality with a time–bandwidth product of 0.42 in a nearly diffraction-limited beam. This demonstrates that passively mode-locked VECSELs are suitable for generating high powers in high-repetition-rate pulse trains. © *2005 American Institute of Physics*. [DOI: 10.1063/1.1890485]

Passively mode-locked multigigahertz lasers with multiwatt average output powers are potential sources for optical clocking of highly integrated circuits.[1] For this purpose, high average power is necessary in order to distribute the clock signal to many points on a chip. Passively mode-locked lasers are capable of generating pulse trains with very high repetition rates up to 160 GHz[2] with very low timing jitter.[3] Apart from optical clocking, mode-locked lasers may be used in telecommunication or optical sampling techniques.[4] High peak power lasers may be used for efficient frequency conversion, e.g., for frequency doubling or for pumping optical parametric oscillators,[5,6] with applications, e.g., in digital projection displays.

With passively mode-locked solid-state lasers, up to 2.1 W average output power in 13.7 ps pulses at a repetition rate of 10 GHz and 110 mW at 157 GHz in 2.7 ps pulses have been demonstrated.[2] Pulse trains with up to 1.5 THz repetition rate have been generated with harmonic passive mode locking of a distributed-Bragg-reflector semiconductor laser, however at a low power level.[7] To overcome the power limitations of edge-emitting semiconductor lasers, we have demonstrated the concept of an optically pumped vertical external-cavity surface-emitting laser (VECSEL) passively mode locked with a semiconductor saturable absorber[8–10] (SESAM). At lower pulse repetition rates we could achieve up to 2.1 W average power in 4.7 ps pulses.[11,12] In this letter, a 10 GHz VECSEL with up to 1.4 W average output power in 6.1 ps pulses is demonstrated. The laser provides a good pulse quality with a time–bandwidth product of only 0.42.

The concept of optical pumping and passive mode locking of a semiconductor laser allows to pump large spots on the gain chip, while the low gain saturation energy leads to a reduced tendency for *Q*-switched mode locking.[13,14] The large amplification bandwidth of semiconductor lasers provides the potential to generate short pulses in the sub-500 fs regime,[15] even at high repetition rates of 10 GHz,[16] but so far at much lower average output powers. The thermal impedance of the gain structure can be drastically reduced by using proper processing of the device.[11] The option to increase the mode area to rather large values while maintaining a roughly longitudinal heat flow makes the VECSEL power scalable.

Our gain structure consists of three parts: the bottom mirror, the active region, and an antireflective structure. The design is optimized for the laser wavelength around 960 nm (at 0° angle of incidence) and the pump wavelength of 808 nm (at 45° angle of incidence). The reflectivity of the $Al_{0.2}Ga_{0.8}As/AlAs$ bottom mirror is $>99.95\%$ for the laser wavelength and $>97\%$ for the pump wavelength. The $Al_{0.2}Ga_{0.8}As/AlAs$ antireflective structure reflects less than 1% of the laser power and less than 3% of the pump power. The residual reflectivity of the antireflective structure at the laser wavelength produces a cavity effect together with the bottom mirror, which results in an oscillating spectrum of the group delay dispersion (GDD) similar to that of a Gires-Tournois interferometer[17] (GTI). Numerical simulations have shown that positive GDD can be used to achieve nearly transform-limited pulses from a VECSEL.[18] In the device presented here, the amount of GDD at the laser wavelength around 960 nm was adjusted by the total thickness of the active region. A similar but much weaker GTI effect occurs in the SESAM.

The pump light is absorbed in the active region, which consists of $In_{0.13}Ga_{0.87}As/GaAs_{0.94}P_{0.06}/GaAs$ layers. The seven $In_{0.13}Ga_{0.87}As$ quantum wells (QWs) are placed in the antinodes of the standing-wave pattern of the laser field. The compressive strain of the QWs is compensated by tensile strained $GaAs_{0.94}P_{0.06}$ layers, which are placed on both sides of the wells.

The structure was grown in reverse order by metalorganic vapor-phase epitaxy (MOVPE) on a GaAs substrate and soldered onto a copper heat sink in an rf soldering procedure in vacuum. Subsequently the GaAs substrate is removed in a wet chemical etching procedure. The resulting

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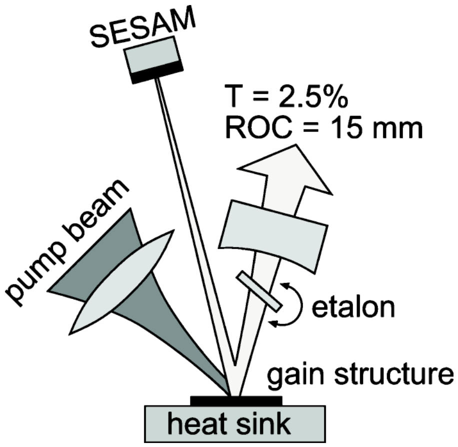

FIG. 1. Cavity setup for the passively mode-locked VECSEL.

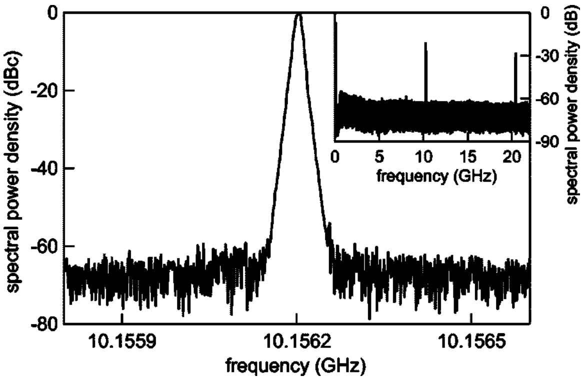

FIG. 3. rf spectrum of the fast photodiode signal at 1.4 W average output power around 10 GHz at 1 MHz span with 10 kHz resolution bandwidth. The inset shows a measurement over a 22 GHz span.

≈7-μm-thick structure on the copper heat sink provides a minimized thermal impedance, so that excessive heating is avoided even at high output power operation.[11]

In the V-shaped cavity (see Fig. 1) with a cavity angle of 15°, the gain structure serves as a folding mirror. The two end mirrors are the SESAM on the one side and the output coupler with a radius of curvature of 15 mm and a transmission of 2.5% on the other. The SESAM was grown by MOVPE and contains a 5-nm-thick $\mathrm{In_{0.15}Ga_{0.85}As}$ QW with a band gap wavelength between 985 and 995 nm. It has a modulation depth of about 1%. The gain structure is pumped on a spot with 175 μm radius using a fiber coupled laser diode array. Due to growth errors, the GDD spectrum of the gain structure was shifted compared to the initial design, so that the GDD was negative at the emission wavelength. Mode locking was only observed after we inserted a 50 -μm-thick uncoated fused silica etalon into the cavity. The pulse duration and time–bandwidth product of the output pulse train showed significant variations as the wavelength of the laser was tuned by changing the etalon angle. The shortest pulses were obtained at a wavelength of 960 nm, where the calculated GDD of the gain structure was $-1800\ \mathrm{fs}^2$. Although the GDD of the etalon is zero at its transmission peak, it can be up to $\pm 3500\ \mathrm{fs}^2$ at the edges of its 99% transmission bandwidth (we estimate the maximum tolerable loss under the operating conditions described here to be on the order of 1%). Since the value of the GDD contributed by the etalon cannot be easily determined,[12] no definitive statement can be made on the exact value or even the sign of the total intracavity GDD in this experiment. The challenges involved in comparing the results of simulations with experimental data are discussed in Ref. 12 and further investigations of this issue will be necessary. However, it is clear that by inserting the etalon we obtain another degree of freedom which we can use to optimize the performance of the VECSEL, even if the exact mechanisms behind its influence on the operation characteristics are not fully understood.

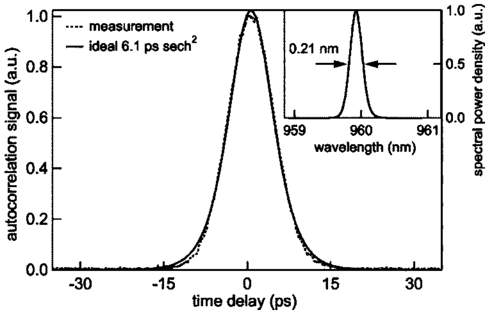

FIG. 2. Autocorrelation and optical spectrum (inset) at 1.4 W average output power. The pulse width is 6.1 ps assuming a sech^2 pulse shape. The spectral width is 0.21 nm.

Best performance of the VECSEL with 1.4 W average output power at a 10 GHz repetition rate has been achieved with 17 W of pump power. The threshold pump power was 5.8 W. The heat sink was held at a temperature of 5 °C. The output polarization was linear. Figure 2 shows the autocorrelation trace of the 6.1 ps pulses and the optical spectrum, which is centered around 960 nm and has a bandwidth of 0.21 nm (assuming sech^2 shapes in time and frequency domain). The pulses are not far from the transform limit, with a time–bandwidth product of only 0.42. The mode locking is clean, as can be seen in the rf signal from a fast photodiode displayed in Fig. 3. The wide span measurement over 22 GHz indicates that the laser is operating in a single transverse mode, since higher-order transverse modes would be visible as additional beat signals. Also, visual inspection of the output beam showed at Gaussian-like beam profile. It must be stated that the operation at 1.4 W output power was at the performance limit of this laser, where the laser reacted quite sensitively to external disturbances. The stability improved greatly at reduced power levels. However, we believe that the performance values demonstrated here are attainable in a stable and long-term reliable device if the epitaxial growth, mounting, and processing of the gain structure and SESAM are carried out using current state-of-the-art industry-compliant processes and techniques.

In conclusion, we have demonstrated an optically pumped passively mode-locked vertical-external-cavity surface-emitting semiconductor laser at 10 GHz which delivers up to 1.4 W average output power in nearly transform-limited 6.1 ps pulses and in a nearly diffraction-limited output beam. The high average output power at 10 GHz confirms that the VECSEL is a promising laser source for achieving high powers at high repetition rates. Further development toward higher repetition rates up to 100 GHz should be possible, when several issues concerning cavity and SESAM are observed, as discussed in Ref. 19.

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