Femtosecond high-power spontaneous mode-locked operation in vertical-external cavity surface-emitting laser with gigahertz oscillation

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We realize a femtosecond high-power spontaneous mode-locked operation with gigahertz oscillation in a vertical-external cavity surface-emitting laser under the condition of eliminating the internal and external unwanted reflection. We find that the reflectivity of the output coupler has a significant influence not only on the output power but also on the output pulse duration. With an incident pump power of 20 W, we have achieved 2.35 W of average output power with 778 fs pulse duration at a repetition rate of 2.17 GHz. The shortest pulse duration was 654 fs at an average output power of 0.45 W. © 2011 Optical Society of America

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Vertical-external cavity surface-emitting lasers (VECSELs) offer a unique combination of many desirable laser properties such as flexible emission wavelength, high output power, excellent beam quality, and high efficiency. Since the first demonstration of 0.5 W level operation with a circular fundamental Gaussian mode at 1004 nm [1], the VECSEL technology has become one of promising candidates to overcome the limitations of conventional semiconductor lasers for a wide range of laser applications [2–5].

Although most researches on VECSELs were focused on CW operation, spontaneous mode-locking (SML) in a laser cavity without using additional nonlinearity except for the gain medium is an intriguing phenomenon. Lamb and coworkers [6] had theoretically used the semiclassical laser theory in the frequency domain to verify the existence of steady-state SML pulses in multimode lasers without any saturable absorber. Up to now, the SML phenomenon has been observed on different types of semiconductor laser systems [7–10]. Fairly stable SML pulses have also been realized in the diode-pumped Nd-doped vanadate miniature lasers [11] and Nd-doped double clad fiber lasers [12]. Even though Lamb's analysis has been extended to various semiconductor laser systems [13,14], the SML operation in VECSELs with single-pulse emission has not been reported until now.

In this Letter we demonstrate a gigahertz femtosecond high-power SML operation in a VECSEL by avoiding the internal and external unwanted reflection. It is experimentally found that the reflectivity of the output coupler significantly affects not only the output power but also the mode-locked pulse duration. With an output reflectivity of 97.5% and at an incident pump power of 20 W, we can achieve 5.1 W of average output power with 1.17 ps pulse duration at a repetition rate of 2.17 GHz. With an output reflectivity of 99.0% and at an incident pump power of 20 W, the laser can emit 2.35 W of average output power with 778 fs pulse duration. With an output reflectivity of 99.8%, we obtain the shortest pulse duration of 654 fs at an average output power of 0.45 W.

The schematic of the laser experiment is shown in Fig. 1, together with the refractive index profile and E-field distribution in the gain medium. The laser cavity consists of an external mirror, a VECSEL chip, and a pumping laser diode. The structure of the gain chip was grown on a (001) GaAs substrate in an upside-down configuration with a metalorganic vapor phase epitaxy reactor under low pressure. The growth temperature was varied between 600 °C and 750 °C according to the layers. The epitaxial layer structures included 35-pair AlAs/GaAs bottom distributed Bragg reflectors (DBRs) and a resonant periodic gain (RPG) structure. The RPG structure consisted of a total of 15 compressively strained $In_{0.28}Ga_{0.72}As$ quantum wells (QWs) in 15 antinodes. The thickness for the strain compensation was approximately 4 nm. Every one QW with a thickness of 7 nm was placed in each antinode of the standing wave. Note that there are no special differences between the present QW structure and other published designs. The photoluminescence emission wavelength of the gain chip was approximately 1060 nm at room temperature. The barriers between QWs are formed by the strain compensating $GaAs_{0.9}P_{0.1}$ and pump laser absorbing GaAs layers. An $Al_{0.3}Ga_{0.7}As$ barrier was grown to prevent the excited carriers from recombining at the wafer surface. A 10 nm thick GaAs layer was deposited to finish the structure.

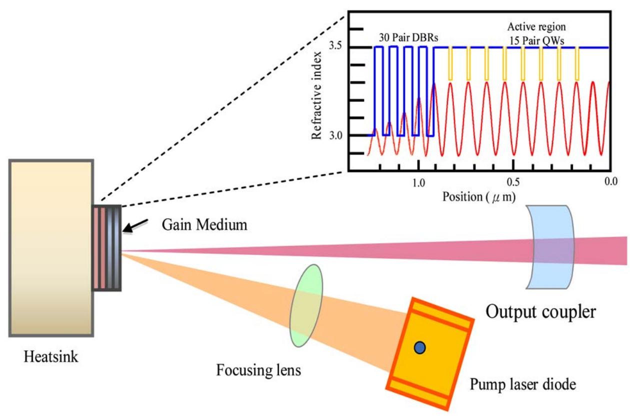

Fig. 1. (Color online) Experimental setup of an SML optically pumped semiconductor laser system. The inset shows the refractive index profile and E-field distribution in the gain medium.

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The gain chip was soldered with indium to a chemical vapor deposition diamond heat spreader with DBR side down for effectively removing the heat from the gain structure. After In soldering on the heat spreader, the GaAs substrate on gain chip was then chemically etched to an InGaP etch stop layer.

The cavity of the laser comprised a DBR and an external concave output coupler with a radius of curvature of 100 mm. Three different output couplers (OCs), $R = 97.5\%$, 99.0%, and 99.8%, were used to explore the performance. The external flat side of the OC was cut with a wedge angle of 1° for avoiding the unwanted reflection. The external reflection was found to cause the laser to be in the operation of multipulse mode locking. An 808 nm pump beam was focused on to a VECSEL chip at an angle of 20° to the surface normal. The incident angle of the pump beam was found to be not critical for reaching an SML operation. The cavity length was set to be approximately 70 mm. The mode diameter was calculated to be approximately 250 μm. Experimental results revealed that the cavity length needed to be considerably shorter than 150 mm for obtaining a stable single-pulse SML operation.

The temperature of semiconductor gain chip was controlled by thermal electronic cooler maintained around 25 °C to ensure stable laser output. The mode-locked pulses were detected by a high-speed InGaAs photodetector (Electro-optics Technology, Inc. ET-3500 with rise time 35 ps) whose output signal was connected to a digital oscilloscope (Agilent DSO 80000) with 10 GHz electrical bandwidth and a sampling interval of 25 ps. The output signal of the photodetector was also analyzed by an RF spectrum analyzer (Advantest, R3265A) with a bandwidth of 8 GHz. The spectral information of the laser was monitored by a Fourier optical spectrum analyzer (Advantest Q8347) containing a Michelson interferometer with resolution of 0.003 nm.

The pump diameter was designed to be approximately 300 μm for the proper mode-size matching. It was experimentally found that the mode-to-pump size ratio played a critical role in realizing SML operation. Experimental results revealed that the mode-to-pump size ratio should be in the range of 0.7–1.3 for achieving the high-quality SML performance. With a suitable mode-to-pump size ratio, the mode-locking quality is nearly independent of the pump power. The performance of the mode-locking operation could be straightforwardly optimized by monitoring the real-time trace of the pulse train in the digital oscilloscope. The mode-locked operation was found to sustain robustly for all pump powers from the onset of lasing.

All the following results were obtained with a mode-to-pump size ratio to be approximately 0.8. Figure 2 shows the average output powers versus the incident pump powers for three different OCs. With an incident pump power of 20 W, the average output powers can be seen to be 5.1, 2.35, and 0.45 W for the output reflectivities of 97.5%, 99.0%, and 99.8%, respectively. The presented average output power is limited by the maximum output power of the pumping laser diode and could be expected of more power with a higher output laser diode. At a pump power of 20 W, the overall beam quality was found

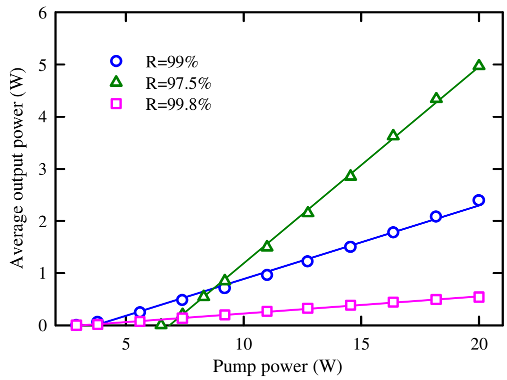

Fig. 2. (Color online) Average output power versus incident pump power for the stable CW mode locking.

to be better than 1.2 and 1.4 in the horizontal and vertical directions, respectively.

Figure 3(a) shows the pulse train measured with a 10 GHz bandwidth real-time oscilloscope. It can be seen that the pulse trains display full modulation without any CW background, indicating that complete mode locking is achieved. The mode-locked pulse duration was measured with an autocorrelator (APE Pulse Check, Angewandte Physic & Elektronik GmbH). Figure 3(b) shows a large enough autocorrelator delay for confirming the single-pulse trains. The corresponding power spectrum is measured by an RF spectrum analyzer with a bandwidth of 8 GHz in Fig. 3(c), demonstrating the signal to noise to be greater than 40 dB. The high resolution of power spectrum spanned of 50 MHz with 10 KHz resolution bandwidth and 10 KHz video bandwidth is shown in Fig. 3(d).

Although the existence of self-starting pulses in different semiconductor lasers has been reported [7–10], there is as yet no consistent explanation for the phenomenon of SML. In [7] the authors give an interpretation of their results in terms of Kerr-lens self-mode locking; however, in [8,9] the authors simply suggest the four-wave mixing in the gain section as the major phenomenon leading to mode locking. We conjecture that the large number of QWs is responsible for the present mode-locked scenario. When the pump does mange to provide enough inversion in all QWs, the saturable absorption might be

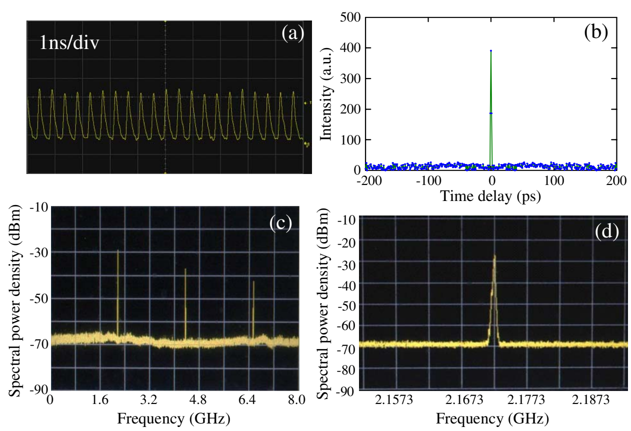

Fig. 3. (Color online) (a) Real-time trace of pulse train. (b) Autocorrelation trace for showing the single-pulse trains. (c) RF power spectrum of the pulse train. (d) Power spectrum with a high resolution of 10 kHz and a span of 50 MHz.

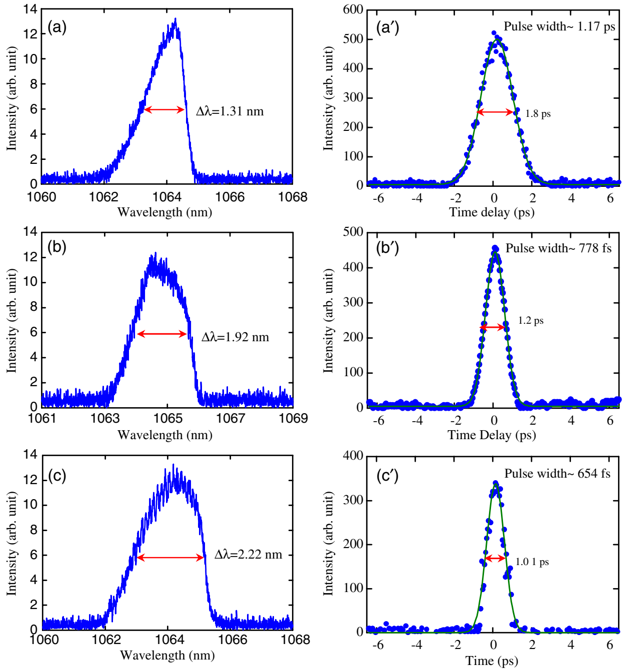

Fig. 4. (Color online) (a)–(c) Lasing spectra for the SML operations obtained with the output reflectivities of 97.5%, 99.0%, and 99.8%, respectively. (a′)–(c′) Autocorrelation traces corresponding to the optical spectra shown in (a)–(c), respectively.

provided by unpumped QWs of gain element, similar to the optical pumped mode-locked integrated external-cavity surface-emitting laser [15].

The spectrum information of the laser was monitored by a Fourier optical spectrum analyzer. Figures 4(a)–4(c) show the lasing spectra for the SML operations obtained with three different OCs. It can be seen that the optical spectral widths are 1.49, 1.92, and 2.22 nm for the output reflectivities of 97.5%, 99.0%, and 99.8%, respectively. Figures 4(a′), 4(b′), and 4(c′) depict the measured results corresponding to the optical spectra shown in Figs. 4(a)–4(c), respectively. It can be seen that the autocorrelation traces are approximately 1.8, 1.2, and 1.01 ps for the output reflectivities of 97.5%, 99.0%, and 99.8%, respectively. Assuming temporal intensity to be a sech^2 shape, the mode-locked pulse durations can be deduced to be as short as 1.17 ps, 778 fs, and 654 fs, respectively. Consequently, the time–bandwidth product of the mode-locked pulse can be found to be in the range of 0.38–0.41 that is quite close to the Fourier-limited value. To the best of our knowledge, this is the first time that a femtosecond high-power VECSEL was realized with the SML operation. The present average output power and peak power are comparable with the recent results obtained with additional QW saturable absorbers [16]. Therefore, the current result has a great chance to be a practical laser for high-power applications.

In summary, we have demonstrated a femtosecond high-power SML operation with gigahertz oscillation in a VECSEL under the condition of eliminating the internal and external unwanted reflection. We explored the influence of output reflectivity on the average output power and the pulse duration. With an incident pump power of 20 W, we have achieved 2.35 W of average output power with 778 fs pulse duration at a repetition rate of 2.17 GHz. The shortest pulse duration was 654 fs at an average output power of 0.45 W. This femtosecond high-power VECSEL is expected to be potentially beneficial to many applications.

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