Invited Paper

Various Phenomena of Self-mode-locked Operation in Optically Pumped Semiconductor Lasers

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ABSTRACT

This work presents several optical experiments to investigate the phenomenon of self-mode locking (SML) in optically pumped semiconductor lasers (OPSLs). First of all, we systematically explore the influence of high-order transverse modes on the SML in an OPSL with a linear cavity. Experimental results reveal that the occurrence of SML can be assisted by the existence of the first high-order transverse mode, and the laser is operated in a well-behaved SML state with the existence of the $TEM_{0,0}$ mode and the first high-order transverse mode. While more high-order transverse modes are excited, it is found that the pulse train is modulated by more beating frequencies of transverse modes. The temporal behavior becomes the random dynamics when too many high-order transverse modes are excited. We observe that the temporal trace exhibits an intermittent mode-locked state in the absence of high-order transverse modes. In addition to typical mode-locked pulses, we originally observe an intriguing phenomenon of SML in an OPSL related to the formation of bright-dark pulse pairs. We experimentally demonstrated that under the influence of the tiny reflection feedback, the phase locking between lasing longitudinal modes can be assisted to form bright-dark pulse pairs in the scale of round-trip time. A theoretical model based on the multiple reflections in a phase-locked multi-longitudinal-mode laser is developed to confirm the formation of bright-dark pulse pairs.

Keywords: Semiconductor laser, Vertical-external-cavity surface-emitting laser, Self-mode locking

1. INTRODUCTION

Since the first demonstration by M. Kuznetsov *et al*[1], optically pumped semiconductor lasers (OPSLs), so called vertical external cavity surface emitting lasers (VECSELs), have become versatile light sources with advantages including high output power, flexible emission wavelength, and nearly diffraction-limited beam quality[2]. In addition to high power continuous-wave (CW) emission[3], methods of generating short pulses in OPSLs are also aroused considerable interest, such as mode-locked operation[4]. The laser operated in mode-locked state is a well-known technique to produce pulses with the pulse duration on the order of picoseconds or femtoseconds[5]. Among numerous mode-locked methods, the phenomenon of self-mode-locking (SML) is of greatly scientific interest in a laser resonator. Here, SML means that no additional active or passive mode-locking elements (such as saturable absorbers) are used in the laser cavity except for the gain medium. In recent years, the SML operation has been reported in OPSLs with different cavity configurations[6-12]. So far, the physical mechanism of SML operation in OPSLs is still worthwhile to explore and investigate in detail.

In this paper, we systematically explore the phenomenon of SML operation in a commercial OPSL module with a linear cavity. At first, with increasing the pump power, we observe that the OPSL displays the SML feature with the co-existence of the $TEM_{0,0}$ mode and the first high-order transverse mode. In the absence of high-order transverse modes, the laser output was found to be in the CW state. It is find that the occurrence of SML is nearly synchronous with the lasing of the first high-order transverse mode. Next, to quantitatively analyze the influence of high-order transverse modes on SML operation, we insert an aperture into the cavity and control the excitation of high-order transverse modes with different aperture sizes. With the appropriate aperture size, the experimental observations reveal that only $TEM_{0,0}$ mode and the first high-order transverse mode are excited in the laser cavity. When more high-order transverse modes are excited with using a larger aperture size, the mode-locked pulse train is found to be modulated with the transverse beat frequency. Furthermore, in the absence of the aperture, the temporal behavior becomes the random dynamics because there are too many beating frequencies of transverse modes. On the other hand, when the aperture size is too small to excite high-order transverse modes, we observe that the laser is operated in an intermittent mode-locked state.

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Generally, the mode-locked pulses are regarded as the bright pulse which means a short intensity peak beyond a continuous wave (CW) background. Intriguingly but rarely observed, the so-called dark pulse can be also observed in mode-locked lasers. In contrast to the bright pulse, a dark pulse is a rapid intensity dip in the intensity of a CW background[13]. In addition to mode-locked bright pulses, we first observe an intriguing phenomenon in an OPSL related to the formation of bright-dark pulse pairs. We find that the tiny reflection feedback can cause the OPSL to emit bright-dark pulse pairs in the SML operation. Although the residual reflection from the plane surface of the OC is quite low, experimental results reveal that it can significantly affect the temporal dynamics of the OPSL. We experimentally find that under the influence of the residual reflection, the phase locking between lasing longitudinal modes can be assisted to form bright-dark pulse pairs in the scale of round-trip time. The present finding not only provides a practical route to achieve bright pulses or bright-dark pulse pairs in an OPSL, but also signifies that OPSLs can be a promising platform to explore the temporal dynamics.

2. EXPERIMENTAL SETUP

Figure 1 illustrates the schematic of the laser experiment. The laser cavity consists of a concave mirror, a semiconductor gain chip, a pump laser diode, and an aperture. The gain chip and the pump laser diode were obtained from a commercial OPSL module (Coherent Inc.). The active region was a structure of multiple quantum wells to form a resonant periodic gain. To form a front mirror, the gain chip included a structure of distributed Bragg reflectors (DBRs). The photoluminescence emission wavelength of the gain chip was approximately 1060 nm at room temperature. The gain chip was soldered with indium to chemical vapor deposition diamond heat spreader with DBR side down for effectively removing the heat from the gain structure. The gain structure was antireflection coated at the wavelengths of 808 nm and 1060 nm. The radius of the 808 nm pump beam ω_p was approximately 320 μm. The concave surface of the output coupler was 2% transmission at 1064 nm and the plane surface of the output coupler was antireflection coating at 1064 nm. To avoid unwanted reflection, the plane surface was wedged at 0.5 degree. The temporal dynamics was 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 DSO80000) with 10 GHz electrical bandwidth and a sampling interval of 25 ps. A Fourier optical spectrum analyzer (Advantest Q8347), which was constructed with a Michelson interferometer, was employed to monitor the spectral information with the resolution of 0.002 nm. In the following experiments, we utilized different cavity lengths (L_{cav}) and radii of curvature of the output coupler (R_{oc}) to observe the phenomena of SML operation.

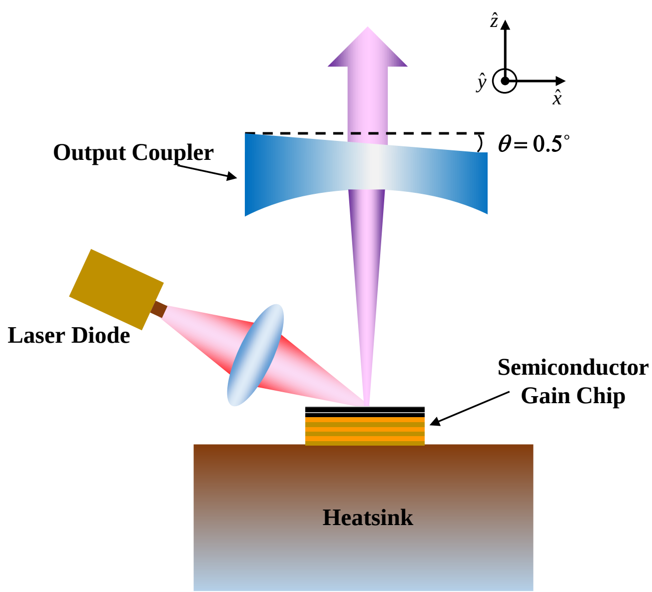

Figure 1. Schematic diagram of the experimental setup for exploring the SML in an OPSL.

3. OBSERVATIONS OF MODE-LOCKED BRIGHT PULSES

At first, we set that the radius of curvature of the output coupler was 300mm and the cavity length was 83 mm. the lasing threshold was experimentally found to be about 5.0 W. For the pump power ranging from lasing threshold to 9.5 W, the laser displayed in the continue-wave (CW) state, as shown in Fig. 2 for the result measured at a pump power of 7 W. The transverse pattern was rather circularly symmetric, as seen in Fig. 2(a). The temporal traces measured with a 10 GHz bandwidth real-time oscilloscope did not reveal any obvious oscillations, as depicted in Fig. 2(b). In Fig. 2(c), there was not any obvious peak which appeared in the RF spectrum. The full width at half maximum (FWHM) in the optical spectrum was found to be as narrow as 0.1 nm, as shown in Fig. 2(d).

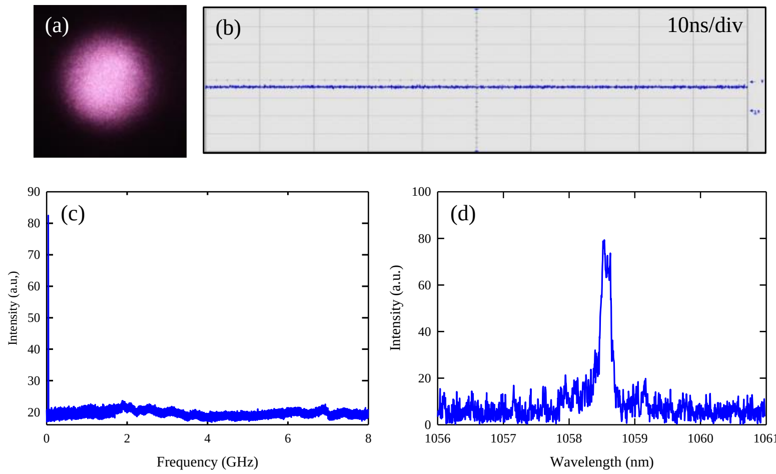

Figure 2. Experimental measurements for overall performances of the laser operated in the CW state: (a) transverse pattern, (b) temporal trace; (c) RF power spectrum; (d) optical spectrum.

For the pump power greater than 10.0 W, the temporal trace in the oscilloscope displayed the laser to be in a continuous mode-locked state and the structure of the pulse train was spatially dependent. Figure 3 shows overall performances for the laser operated in the mode-locked state. The transverse pattern became elliptical and the temporal trace in the center of the transverse pattern displayed full modulation without any CW background, as shown in Fig. 3(a) and 3(b), respectively. In Fig. 3(c), there were two beat peaks which accompanied the harmonics of the longitudinal frequency spacing f_L in the RF spectrum. The beat frequency was measured to be about 380 MHz which corresponded to the transverse frequency spacing f_T. In Fig. 3(d), the full width at half maximum (FWHM) in the optical spectrum was found to be as wide as 1.8 nm. Experimental results imply that the presence of the first high-order transverse modes is intimately associated with the emergence of a long-lasting SML operation.

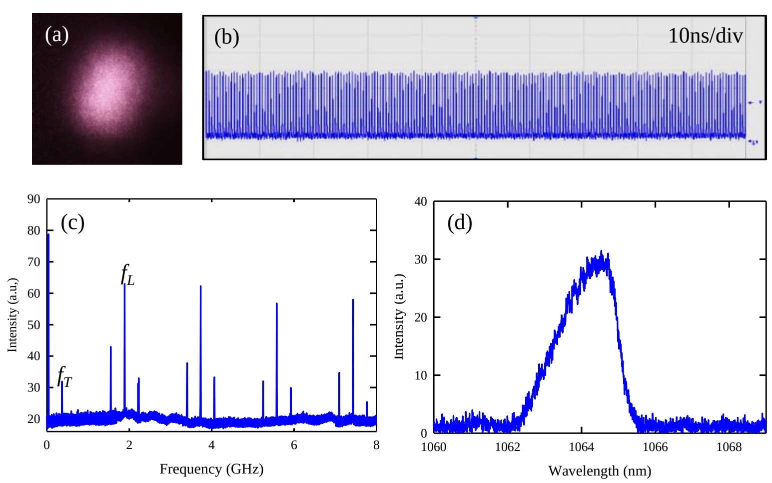

Figure 3. Experimental measurements for overall performances of the laser operated in the CW state: (a) transverse pattern, (b) temporal trace; (c) RF power spectrum; (d) optical spectrum.

Next, an aperture was inserted into the cavity to control the excitation of high-order transverse modes. The distance between the aperture and the output coupler was 5 mm. We changed the cavity length and the radius of curvature of the output to be 96 and 100 mm, respectively. The radii of aperture r_a in experiments were 0.875, 0.75, and 0.5 mm. As shown in Fig. 4(a), the temporal trace displayed an indistinctly mode-locked pulse train on top of a CW background with r_a = 0.875 mm. Besides, the mode-locked pulse train was modulated with the additional envelope caused by a beating frequency. Referring to Fig. 4(a′), the beating frequency was measured to be approximately 186 MHz which was corresponded to $\Delta f_L - 2\Delta f_T$. All frequency peaks in the RF spectrum were measured at the frequencies of $f = q \cdot \Delta f_L \pm p \cdot \Delta f_T$ where q and p were integers. These frequency peaks represented that the first and second high-order transverse modes were excited in the output beam at least. The peak values were generally less than 30 dB which was consistent with the indistinctly mode-locked pulse train. The results revealed that laser output did not operated in a well-behaved SML state with the existence of the first and second high-order transverse modes. When the radius of aperture was reduced to 0.75 mm, we explored that the laser was operated in a long-lasting SML state. In Fig. 4(b), the full modulation of pulse trains without any CW background indicates the realization of complete mode locking, although some slight amplitude fluctuation which was caused by the group velocity dispersion existed in the long span pulse train. In Fig. 4(b′), the peak values of the harmonics of the longitudinal modes spacing in the RF spectrum were increased significantly, and the signal to noise was approximately 60 dB, regarding as larger than the standard value of well-behaved SML operation. In the meantime, there were two beat peaks which accompanied the harmonics of the longitudinal mode spacing in the RF spectrum. The beat frequency was measured to be 687 MHz which was corresponded to the transverse frequency spacing Δf_T. The peak values of beat frequencies were less than 25 dB. The appearance of the beat peaks at the frequencies of $f = u \cdot \Delta f_L \pm \Delta f_T$ with u = 1, 2, 3, 4, 5, 6 in the RF spectrum distinctly revealed the existence of the first high-order transverse mode. Finally, when the radius of aperture was reduced to 0.5 mm, the temporal state displayed in the CW operation, and there was not any obvious peak which appeared in the RF spectrum, as shown in Fig. 4(c) and 4(c′), respectively. Consequently, the experimental measurements indicate that the laser cannot be operated in a stable mode-locked state when the aperture size is too small to excite high-order transverse modes in this experiment.

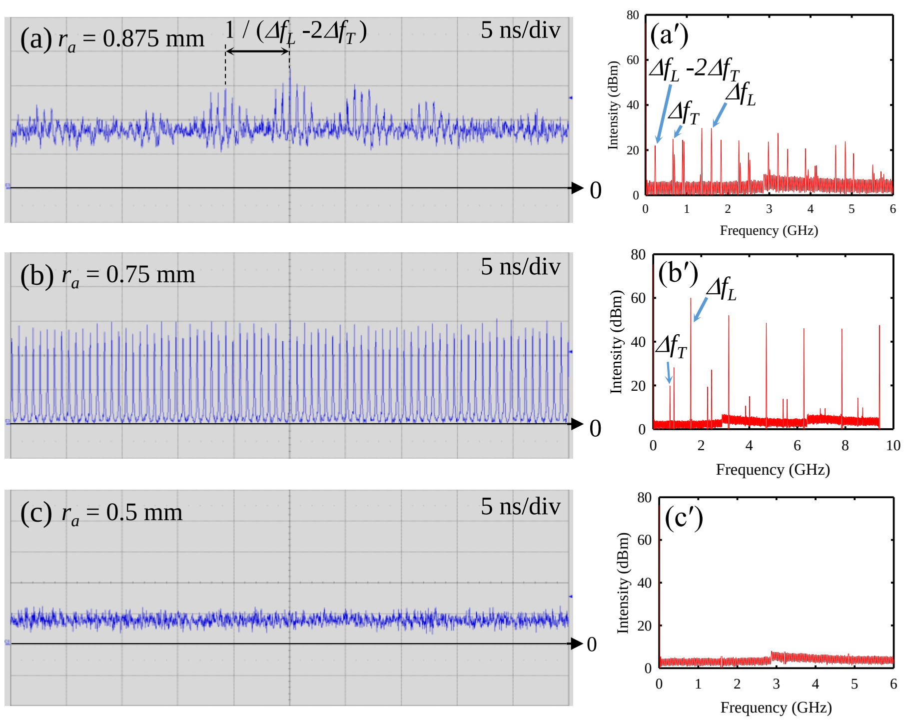

Figure 4. (a)-(c) Temporal traces with three different radii of aperture; (a')-(d') RF power spectra corresponding to temporal traces shown in (a)-(c), respectively.

4. FORMATION OF BRIGHT-DARK PULSE PAIRS

When we observed the typical mode-locked pulses in the OPSL, the tiny reflection caused from the plane surface of the output coupler was unwanted. Therefore, the plane surface was wedged at 0.5 degree to avoid the reflection feedback. However, in the following section, we explore that this tiny reflection can trigger the formation of bright-dark pulse pairs in the OPSL. Experimentally, we compared the temporal states which were under the influence of reflection feedback or not. In the following section, we considered that only the fundamental transverse mode was excited in the laser cavity. The cavity length and the radius of curvature of the output coupler were set to be 200 and 800 mm, respectively. Hence the cavity mode size on the gain chip was calculated to be approximately 342 μm. The pump threshold for high-order transverse modes could be increased significantly because the cavity mode size on the gain chip was larger than the radius of the pump beam. For the pump power ranging from the lasing threshold to the maximum pump power of 22.08 W, the laser output was experimentally found to display the fundamental transverse mode. Without the existence of high-order transverse modes, this OPSL cannot emit mode-locked bright pulses.

Figure 5 illustrates overall performances for the laser operated in the CW operation at a pump power of 14.4 W. Meanwhile, the tiny reflection from the plane surface of the output coupler was eliminated. The temporal trace did not exhibit any distinct oscillations, as shown in Fig. 5(a). Referring to Fig. 5(b), there was not any obvious peak which appeared in the RF spectrum. As seen in Fig. 5(c), the optical spectrum was found to be centered at 1061.86 nm, and the full width at half maximum (FWHM) was found to be as narrow as 0.04 nm. Note that there was no any periodic modulation in the optical spectrum. Therefore, the results exhibited that the laser was operated in the CW operation when only the $TEM_{0,0}$ mode was excited and the influence of the tiny reflection feedback was avoided.

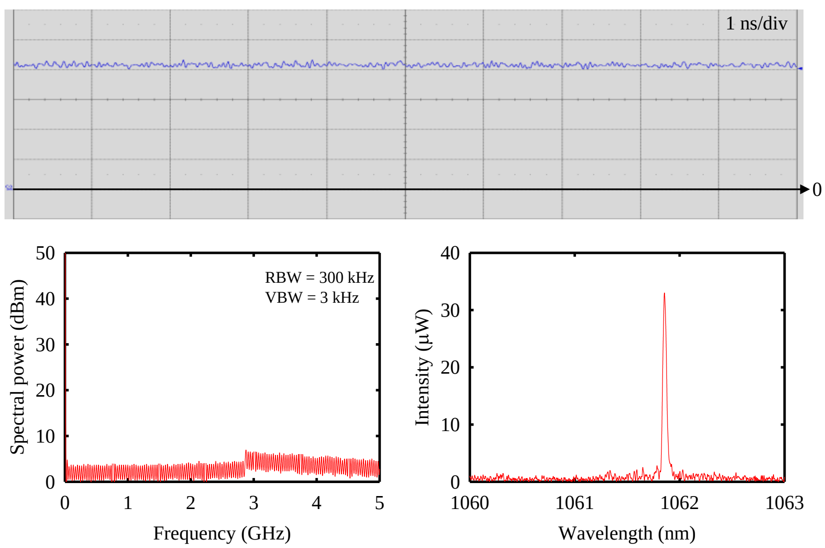

Figure 5. Experimental results for the laser in the CW operation without the tiny reflection feedback: (a) the temporal trace, (b) the RF spectrum, and (c) the optical spectrum.

However, under the influence of the residual reflection, the observations of temporal dynamics was beyond expectations. Figure 6 depicts the experimental measurements for the laser operated at the same pump power of 14.4 W but the plane surface of the output coupler was perpendicular to the optical axis. As shown in Fig. 6(a), the temporal trace exhibited a distinctly pulse train of bright-dark pulse pairs. It could be seen that a bright pulse followed a dark pulse in the single pulse of bright-dark pulse pairs. The depth of the dark pulse was approximately equal to the intensity of the bright pulse in the CW background. Figure 6(b) illustrates the single bright-dark pulse pair, where the pulse widths of bright and dark pulses were measured of 18 ps. The pulse duration did not changed with varying the pump power in the range of 11.52-15.36 W. In Fig. 6(c), there were several frequency peaks in the RF spectrum corresponded to the harmonics of the longitudinal mode spacing Δf_L = 765 MHz, and the peak values were approximately 30 dBm. Without any additional active or passive mode-locking element, the results revealed that the emission of bright-dark pulse pairs was in the SML operation. As a result of the nonzero CW background, the signal to noise of bright-dark pulse pairs was smaller than the standard value of bright pulses in mode-locked lasers. Referring to Fig. 6(d), it could be seen that there was the obviously periodic modulation in the optical spectrum. The spacing between two periodic peaks was measured to be 0.12

nm which was corresponded to the optical length of the OC of 4.7 mm. The time-bandwidth product was calculated to be 0.575. The results revealed that under the influence of the residual reflection, the multi-longitudinal modes could be phase-locked to form bright-dark pulse pairs in the scale of round-trip time. Comparing the results in Fig. 5 and 6, it signifies that the reflection feedback is necessary for the formation of bright-dark pulse pairs in an OPSL.

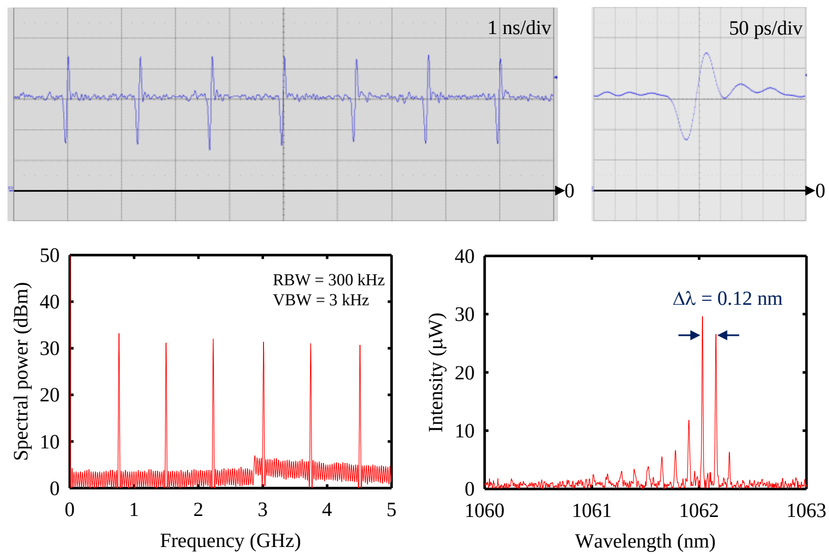

Fig. 5. Experimental observations for overall performances of bright-dark pulse pairs: (a) the temporal trace, (b) the RF spectrum, and (c) the optical spectrum.

5. CONCLUSION

In conclusion, we have systematically investigated the SML operation in an OPSL with a linear cavity. It has been observed that the occurrence of SML is nearly synchronous with the lasing of high-order transverse modes. We have employed the different aperture sizes to control the excitation of high-order transverse modes. Experimental results have indicated that the SML operation can be achieved with the appropriate aperture size which only allows the existence of fundamental transverse mode and the first high-order transverse mode. We have demonstrated that the pulse train is modulated with the transverse beat frequency when we use the larger aperture size to excite more high-order transverse modes. Moreover, the random dynamics of the laser output has been observed while there are too many beating frequencies of transverse modes. Eventually, it has been found that the laser is operated in an intermittent mode-locked state when the aperture size is too small to permit the excitation of high-order transverse modes. In addition to typical mode-locked pulses, it was experimentally found that under the influence of the residual reflection, distinct bright-dark pulse pairs at the scale of round-trip time could be observed in the absence of high-order transverse modes.

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