Photon Dynamics in Chip-Scale High-Peak-Power Semiconductor/Solid-state Vertically Integrated Laser

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Abstract: We experimentally verified the temporal dynamics of photons during passively Q-switched oscillation in semiconductor/solid-state vertically integrated laser cavities, which agrees well with the results predicted theoretically by a simultaneous rate equations model. As a new approach for peak-power scaling of chip-scale lasers, we have demonstrated a vertically integrated semiconductor/solid-state laser for high-peak-power operation exceeding kilowatt, in which two cavities are optically coupled at the solid-state laser gain medium [1] [2]. This new laser concept is expected to have applications in a wide range of fields, including laser remote sensing [3], laser micromachining [4], and biomedical photonics [5]. In the previous study, a simultaneous rate equations model was developed to theoretically elucidate the laser oscillation mechanism. Since the validity of the simulation model is still unknown, the phenomena predicted by the theoretical analysis model need to be verified experimentally.

In this work, the temporal dynamics of photons in the semiconductor laser cavity is experimentally verified and compared with the results of the theoretical analysis model. The theoretical analysis results show that the Q-switched laser pulse in the solid-state laser cavity reduces the photon density in the semiconductor laser cavity by about 4%, and the reduction in photon density predicted by the theoretical analysis model was also confirmed experimentally. This phenomenon is unique to our lasers and does not occur with conventional laser-diode-pumped solid-state lasers. The study on photon dynamics not only clarifies the principles of laser operation for the first time, but may also contribute to further improvement of output stability and accuracy of the passively Q-switched oscillation timing control in the future.

Fig. 1 (a) Schematic structure and photograph of the chip-scale high-peak-power semiconductor/solid-state vertically integrated laser. (b) I–L characteristics.

The schematic structure and the photograph of the chip-scale high-peak-power semiconductor/solid-state vertically integrated laser is shown in Fig. 1(a). The first cavity is a vertical-external-cavity surface-emitting laser (VECSEL) for intra-pumping of the ytterbium-doped yttrium-aluminum-garnet (Yb:YAG) with a wavelength of 940 nm, and the second cavity is for passive Q-switching that consists of Yb:YAG and chromium-doped yttrium-aluminum-garnet.
(Cr:YAG) with a wavelength of 1030 nm. Figures 1(b) shows the current–output (I–L) characteristics. A passively Q-switched laser oscillation with a typical pulse width of 450 ps is confirmed at a current threshold of 270 mA. The average pulse energy is 44.7 μJ and the repetition frequency is 6.8 kHz under a current injection of 600 mA. The peak power estimated from the obtained pulse energy and the pulse waveform is as high as 72.8 kW. The experimental results successfully demonstrate that our proposed laser configuration can realize a high-peak-power over kilowatts at the same chip-scale size as semiconductor lasers.

In the previous study, we also developed a simultaneous rate equations model to elucidate the laser oscillation mechanism. In this work, the simulation results were verified experimentally to prove the validity of the theoretical analysis model. Figure 2(a) illustrates the temporal dynamics of carriers and photons in 940 nm VECSEL cavity and 1030 nm passively Q-switched laser cavity, respectively. From the top of Fig. 2(a), it is found that generating a 1030 nm picosecond pulse (t around t=470 μs) reduces the photon density at 940 nm (S) by about 4%. This phenomenon occurs because the ground-state population density of Yb³⁺ ion and the absorption at 940 nm increase by Q-switched laser pulse oscillation, and the photon density at 940 nm decreases after laser pulse oscillation. To confirm this phenomenon, the time variation of the 940 nm leakage laser from the VECSEL cavity was evaluated. The intensity of 940 nm laser around the time of Q-switched laser pulse oscillation (t=470 μs) was measured and compared with the theoretical analysis results, which are shown in Fig. 2(b). From Fig. 2(b), we found good agreement between the theoretical result and the experimental result, and the validity of the photon dynamics calculation in the 940 nm cavity by the simultaneous rate equations model was proved. The fall time of the 940 nm laser is about 10 μs, which is much longer than the fall time of the photon density in the 940 nm VECSEL cavity predicted by the theoretical model, probably due to the transmittance change of Cr:YAG during the passively Q-switched oscillation.

In conclusion, the temporal dynamics of photons in the cavities of semiconductor/solid-state vertically integrated laser was measured and compared with the theoretical analysis results. The phenomenon predicted by the simulation model was confirmed experimentally and it is expected to help improve the laser output stability and the accuracy of the passively Q-switched oscillation timing control in the future.

Fig. 2 Simulation results of the simultaneous rate equations model. (a) (top) Temporal dynamics of the carrier and photon densities at 940 nm in the VECSEL cavity; (bottom) temporal dynamics of the population inversion density at Yb:YAG, ground-state population density at Cr:YAG, and photon density at 1030 nm in the passively Q-switched laser cavity. (b) Theoretical and experimental results comparison of the 940 nm leakage laser intensity.

References
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