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Novel Nonlinear Dynamics in Strongly Gain-switched Semiconductor Lasers

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Abstract–Notable nonlinear dynamics in gain-switched semiconductor quantum-well lasers have been described. Under strong pulsed excitation conditions, second-quantized-state laser oscillations often appear during optical pulse generation. An appropriate level of DC current superposition remarkably enhanced the second-quantized-state laser oscillation, whereas a further increase in the DC current suppressed it.

1. Introduction

In recent years, gain-switched semiconductor laser diode (GS-LD) technologies have been employed in the fields of pulsed laser micromachining [1, 2] and multiphoton biomedical imaging [3-7]. In physical and engineering sciences, several unknown features remain for the generation of short and high-peak-power optical pulses from GS-LDs. One such feature is the second quantized state (SQS) laser oscillation in LDs with quantum-well (QW) structures. Although SQS oscillations have been studied in recent years [8-10], we have recently demonstrated the potential of SQS laser oscillation to generate high-peak-power single picosecond optical pulses under strong pulsed excitation, whereas DC current superposition tends to weaken the SQS laser oscillation [11].

In this paper, we describe novel features of SQS laser oscillations in GS-LDs. An appropriately chosen DC current superposition can enhance the SQS laser oscillation instead of suppressing it, which can dominate the entire laser oscillation dynamics.

2. Results and discussions

2.1. Suppression of SQS laser oscillation

We first describe the suppression of SQS laser oscillations observed in a GS-LD [10]. In this experiment, the device used was a 905 nm band Fabry–Perot (FP) LD (Wavespectrum, Model WSLX-905-002m-4-H14-T-PD, I_{th} = 14 mA). Figure 1 shows the typical optical spectra and oscilloscope waveform. Although the electric pulse excitation conditions were the same, the superposition of a DC current of 10 mA suppressed the SQS oscillation, and the first-quantized-state (FQS) laser oscillation dominated the entire GS operation, as shown in Figs. 1 (c) and (d). Comparing Figs. 1 (a) and (b) with Figs. 1 (c) and (d), we can observe that the SQS laser oscillation contributed to the generation of the initial high-peak-power optical pulses. Numerical calculation analyses yielded similar results, and we obtained an understanding of the operational mechanism [11].

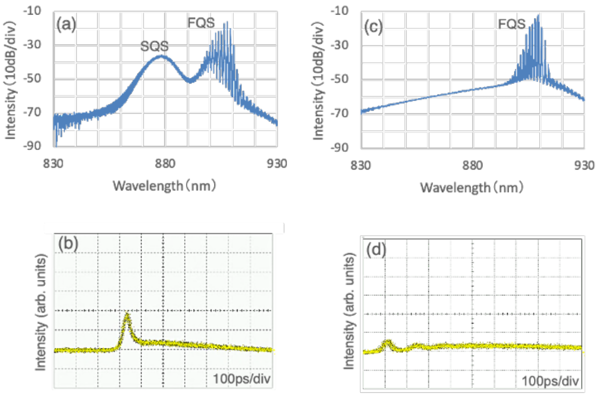

Fig. 1. Optical spectra (upper figures) and the corresponding oscilloscope temporal waveforms (lower figures) for a 905 nm FP-LD under gain-switching operation. (a) and (b) are without DC current superposition, and (c) and (d) are with a DC current of 10 mA. The electric pulse duration was 0.83 ns, and the repetition rate was 10 MHz. The electric pulse amplitude and average optical output power were, respectively, 4.9 V and 130 µW for (a) and (b), and 5.0 V and 250 µW for (c) and (d).

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However, in more recent studies, numerical calculation analyses have indicated that an appropriately chosen DC current superposition can enhance the SQS laser oscillation instead of suppressing it, and this enhancement was also confirmed by experiments.

2.2. Enhancement of SQS laser oscillation

Drastic enhancement of SQS laser oscillation by DC current superposition was observed in the strong GS operation of a different QW-LD fabricated for the 925 nm band.

The LD was an FP device designed for high-power operation at 925 nm (Innolume GmbH, SM-925-PM-150; I_{th} = 80 mA). To induce the SQS laser oscillations, the excitation electric pulse conditions were typically set to be a duration of 2.9 ns and an amplitude of 17 V. Note that the laser oscillation threshold current for the DC operation was 80 mA for this LD, which was several times higher than that of the 905 nm LD, as described above.

Figure 2 shows the optical spectrum change under the GS operation of the 925 nm FP-LD with varying superimposed DC currents. An apparent increase in the SQS spectral component centered at 905 nm was observed when the DC current was increased to 10 mA, which was much smaller than the laser oscillation threshold current. A further enhancement of the 905 nm SQS laser oscillation was observed by increasing the DC current to 30 mA.

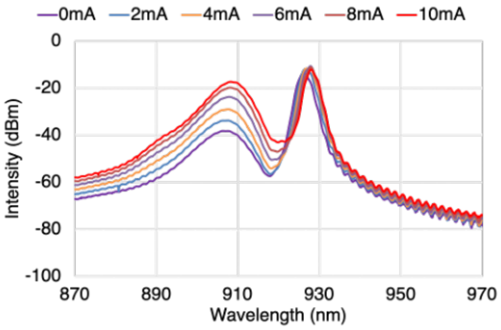

Fig. 2. Changes in the optical spectrum for a gain-switched 925 nm FP-LD with varying superimposed DC currents. The electric pulse duration was 2.9 ns, and the pulse voltage was 17 V. The pulse repetition rate was 10 MHz.

Figure 3 shows the optical spectra and the corresponding oscilloscope temporal waveforms with the superposition of a DC current of 30 mA. Figs. 3 (a) and (b) show cases without spectral extractions; (b) and (d) show the extraction of the SQS spectral components a 10-nm-width band-pass optical filter (BPF) with a transmission peak at 905 nm. In Fig. 3 (b), a trailing pulse component involving secondary optical pulses caused by the FQS laser oscillation exists, whereas the optical pulse form in Fig. 3 (d) does not include the FQS components. However, in Fig. 3 (b), the FQS laser contribution is inferior to the initial high-peak-power optical pulse component in terms of the time-averaged optical power. Therefore, by comparing the temporal waveforms in Figs. 3 (b) and (d), it can be observed that the SQS laser oscillation dominates the entire optical pulse waveform. The initial high-peak-power optical pulses, which are due to the SQS laser oscillation, account for approximately 60% of the entire optical output power from the GS-LD. We then estimated the pulse energy and peak power for the SQS optical pulses to be 260 pJ and 1.8 W, respectively.

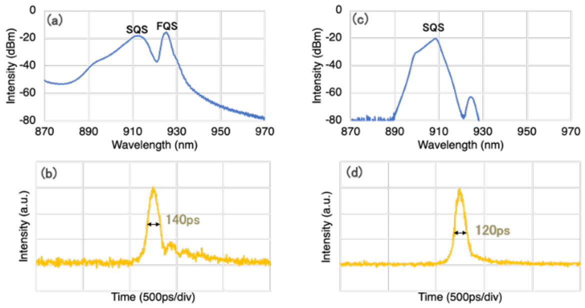

Fig. 3. Optical spectra and oscilloscope waveforms for the 925 nm FP-LD when the device was excited by electric pulses of duration 2.9 ns and voltage 17 V at a repetition rate of 10 MHz with the superposition of a DC current of 30 mA. An optical spectrum without any BPFs is shown in (a), and the corresponding oscilloscope waveform is shown in (b); in this case, the average optical output power was 4.3 mW. (c) and (d) indicate the optical spectrum and the corresponding oscilloscope waveform when the spectral components were extracted using a BPF. The BPF transmission peak was centered at 905 nm, and the BPF spectral bandwidth was 10 nm; in this case, the average optical output power was 0.3 mW.

Further increases in the superposed DC current resulted in a decrease in the SQS laser oscillation. The present results suggest that the superposition of the DC current far below the laser oscillation threshold can enhance the SQS laser operation in a GS-LD with QW structures inside. In contrast, a superposition of the DC current close to the threshold level assists the FQS laser oscillation, which suppresses the SQS laser action, as demonstrated previously [11].

3. Conclusions

In summary, we demonstrated novel nonlinear dynamics in strongly driven GS-LDs. Under strong pulsed excitation schemes, SQS laser oscillations often occur, which contribute to the formation of short optical pulses in the initial stage of the entire laser oscillation. An appropriate DC current superposition can enhance the SQS laser oscillations. However, excessive increases in the DC current suppress the SQS laser action and dominate the FQS laser operation.

A notable feature of the present SQS laser oscillation is that it can provide single-envelope picosecond optical pulses with a peak power much higher than that of conventional GS-LDs based on FQS laser transition. Therefore, we expect that appropriately designed SQS LD pulse sources will provide novel core technologies for functional biomedical imaging and laser micromachining. For these applications, the development of various combination schemes with optical pulse amplification and nonlinear wavelength conversion is also anticipated.

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