

Investigation of regime switching from mode locking to Q-switching in a 2 μm InGaSb/AIGaAsSb quantum well laser

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Abstract: A two-section InGaSb/AlGaAsSb single quantum well (SQW) laser emitting at 2 μ m is presented. By varying the absorber bias voltage with a fixed gain current at 130 mA, passive mode locking at ~18.40 GHz, Q-switched mode locking, and passive Q-switching are observed in this laser. In the Q-switched mode locking regimes, the Q-switched RF signal and mode locked RF signal coexist, and the Q-switched lasing and mode-locked lasing happen at different wavelengths. This is the first observation of these three pulsed working regimes in a GaSb-based diode laser. An analysis of the regime switching mechanism is given based on the interplay between the gain saturation and the saturable absorption.

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OCIS codes: (140.2020) Diode lasers; (140.4050) Mode-locked lasers; (250.5590) Quantum-well, -wire and -dot devices.

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1. Introduction

Ultrafast light sources operating in the 2 µm range are promising for many applications such as molecular spectroscopy, high resolution gas sensing, advanced telecommunications, and eye-safe light detection and ranging (LIDAR) [1-3]. There are two most commonly used techniques to generate ultrafast pulses: Q-switching and mode locking (ML). It has been well known that a saturable absorber incorporated into a laser resonator can cause pure passive Qswitching, continuous wave (cw) passive mode locking, and if desired, Q-switched mode locking (QML, i.e. mode-locked pulses modulated by Q-switched envelope) operations. These pulsed working regimes have been demonstrated in a number of works in different types of lasers [4–16]. Among these lasers, diode lasers with two-section waveguides are desirable for the above mentioned practical applications due to their specific advantages: small size, low power consumption, ability to integrate with Si photonic devices along with easily electrical pump [17, 18], and the saturable absorber can simply be a section of the device with reverse bias [5-7, 13]. Despite the upper state lifetime of the laser medium in a semiconductor diode laser is much shorter (in the nanosecond regime) than that in most solidstate lasers (in the microsecond to millisecond regime), which is considered to strongly reduce the tendency for self-Q-switching instability [4], this Q-switching instability still exists widely in mode-locked diode lasers [6, 12]. By changing the total cavity length and length ratio between two sections, even pure passive Q-switching operation is observed in a modelocked diode laser [11].

Recently, Merghem et al. reported passive mode locking in a monolithic 2 μ m GaSbbased diode laser [7], which first proved the feasibility of the two-section architecture in the 2 μ m range. Our group also fabricated GaSb-based mode-locked lasers with similar structure, and the modal gain characteristics of the lasers were investigated systematically [19]. However, no study on the three different pulsed working regimes and regime switching mechanism of a GaSb-based diode laser has been reported yet.

In this work, a two-section InGaSb/AlGaAsSb single quantum well (SQW) laser emitting at 2 μ m is presented. Observation of cw mode locking, Q-switched mode locking, and pure Q-switching operations in a single GaSb-based diode laser is reported. Since only one

parameter of the bias condition is changed among these three operations, the analysis is simplified, which allows us to have a better understanding of the mechanisms behind these operations and thus guide the laser to work in our favorable regimes.

2. Device overview and experimental setup

The epi-wafer used for device fabrication was grown on an (100) n-GaSb substrate by molecular beam epitaxy (MBE). It comprises a 10 nm-thick In_{0.2}Ga_{0.8}Sb SQW. The detailed laser structure can be found in our previous work [19]. The schematic diagram of the twosection laser is shown in Fig. 1. First, the grown wafer was processed into Fabry-Perot (FP) ridge waveguide lasers. Then, a 10 µm-wide electrical isolation was formed by removing the high-conductivity contact layer and part of the p-cladding layer. A resistance of ~1.1 k Ω was achieved between the two sections with a etch depth of $\sim 1.5 \,\mu m$. For the tested laser in this study, the ridge width is \sim 5 µm, which provides single lateral mode operation. The lengths of the gain section (L_e) and the absorber section (L_a) are 1.89 mm and 0.23 mm, respectively. When working in the pulsed regimes, the gain section is forward biased (I_{e}) while the absorber section need to be reverse biased (V_a) . The experimental setup for characterizing the laser is also shown in Fig. 1. The output light from the gain section facet was coupled into a single mode fiber. Then the light was split into two equal parts by a 50:50 fiber optic coupler: one was fed into a high-speed 2 µm InGaAs PIN detector (EOT ET-5000F with a bandwidth of > 12.5 GHz, and a rise time of < 28 ps) followed by a real-time oscilloscope (DSO93004L); the other part was further split by a 10:90 fiber optic coupler. The 10% part was guided into an optical spectrum analyzer (OSA, AQ6375), and the 90% part was fed into another high-speed detector followed by an electrical spectrum analyzer (ESA, N9030A).



Fig. 1. Schematic diagram of the experimental setup for characterizing the two-section quantum well laser.

3. Experimental results and discussion

Prior to testing the laser's ultrafast characteristics, its light output power (collected from the gain section facet) as a function of the injection current (*L-I*) in the cw mode at room temperature (RT) was measured as shown in Fig. 2. The bias voltage applied to the absorber section (V_a) was varied from 0 to -4 V, and the injection current into the gain section (I_g) was increased from 0 to 200 mA at each V_a . The threshold current increases consistently with increasing negative V_a owing to the stronger absorption. The light output power reached ~10 mW at 200 mA when the absorber was left open ($V_a = 0$ V), and the current-voltage characteristics (*I-V*) of the gain section under this condition is also shown in the figure.



Fig. 2. *L-I* curves of the laser at room temperature with the absorber section bias V_a varied from 0 to -4 V. The *I-V* curve of the gain section at $V_a = 0$ V is also shown in the figure.



Fig. 3. RF spectra of the laser at different V_a when I_g is fixed at 130 mA to work in different regimes: (a) cw mode locking ($V_a = -1.5$ V), and the inset shows the RF peak in greater detail. (b) QML-1 ($V_a = -1.9$ V). (c) QML-2 ($V_a = -2.1$ V). (d) pure Q-switching ($V_a = -2.6$ V).

Figure 3 shows the RF spectra at different V_a when I_g was fixed at 130 mA (well above lasing threshold). Three pulsed working regimes are clearly shown. At $V_a = -1.5$ V as shown in Fig. 3(a), stable cw mode locking is achieved. This is characterized by a strong RF peak with more than 40 dB signal to noise ratio at ~18.40 GHz, corresponding to the photon round-trip time in the 2.13 mm-long laser cavity. The RF peak is shown in greater detail in the inset

of Fig. 3(a). It has a linewidth of ~1.1 MHz, which indicates an efficient mode locking mechanism. When V_a is varied to -1.9 V, Q-switched signal emerges to coexist with the mode locked signal (QML regime). The fundamental Q-switched frequency is at 900 MHz, with clear higher harmonics. At a more negative V_a of -2.1 V, both Q-switched signal and mode locked signal still remain with only relative intensities changed. The weight of Q-switched signal increases and its fundamental frequency increases slightly to 950 MHz. When the negative V_a is further increased to -2.6 V, pure Q-switching operation emerges with a fundamental frequency of 850 MHz. The reasons for the bias-dependent operations will be discussed later.

The pulse trains and optical spectra under the above four bias conditions are shown in Fig. 4. When the laser works in the cw mode locking regime as shown in the lowest panel of Fig. 4(a), a uniform mode-locked pulse train is exhibited. The time interval between two pulses is \sim 54.41 ps as shown in the partially enlarged view besides, corresponding well to the RF peak at \sim 18.40 GHz in Fig. 3(a). Its corresponding optical spectrum shown in the lowest panel of Fig. 4(b) is wide and symmetric with a full width at half maximum (FWHM) of \sim 3.6 nm, and more than 40 longitudinal modes spaced by \sim 0.238 nm are included. If sech² pulses are assumed which have a time-bandwidth product of \sim 0.315, a pulse width of \sim 1.12 ps is expected. Using the pulse width estimation method in Ref. 7 gives a similar result.

For the two QML regimes, the mode-locked pulse energy becomes no longer constant, but modulated according to a Q-switched envelope, i.e. several bunches of pulses instead of a uniform pulse train is shown. The time interval between two pulses within each bunch keeps unchanged (~54.41 ps). The time interval between two bunches is ~0.77 ns (1/1.30 GHz), corresponding to a value between the fundamental frequency and second harmonic in Fig. 2(b) and 2(c). The Q-switched lasing and mode-locked lasing happen at different wavelengths and it is perfectly exhibited in the figure. Their spectra coexist with changes in the relative intensities, which have the same trend as it shows in the RF signals. Compared to that of the mode locking, the spectra of Q-switching are narrow. According to our previous modal gain study [19], a more negative V_a causes a redshift of the lasing spectra in such two-section lasers. When V_a is varied to a more negative value (e.g., from -1.5 to -1.9 V), Q-switching tendency will be induced, but the mode locking operation is already very well established around 1960 nm, this forces the Q-switching operation to happen at longer wavelengths (~1970 nm in this case).

A more negative V_a takes the laser to the pure Q-switching regime as shown in the highest panel of Fig. 4(a). The Q-switched pulse width is ~0.17 ns, and the pulse interval is ~1.18 ns as shown in the thumbnail view besides, which corresponds well to the fundamental frequency of the Q-switched signal.



Fig. 4. (a) Pulse trains and (b) optical spectra under the four bias conditions in Fig. 3. From the lowest panels to the highest ones for both (a) and (b): cw mode locking ($I_g = 130$ mA, $V_a = -1.5$ V); QML-1 ($I_g = 130$ mA, $V_a = -1.9$ V); QML-2 ($I_g = 130$ mA, $V_a = -2.1$ V); pure Q-switching ($I_g = 130$ mA, $V_a = -2.6$ V).

It is well known that the working regime of a saturable absorber incorporated laser depends on the interplay between the gain saturation and the saturable absorption [20]. The tested laser has gone through all the three pulsed working regimes which are commonly observed in a saturable absorber incorporated laser, and the only thing changed is the voltage applied to the absorber V_a . It seems the analysis of the working regimes has been brought to a simple situation.

According to Ref. 20, to theoretically analyze the stability of the mode-locked pulse, which decides the switching between cw mode locking and Q-switched mode locking, we can set up coupled differential equations for the evolution of the mode-locked pulse energy E_P and the laser gain g. Here the pulse energy is defined as the average intracavity laser power times the cavity round-trip time T_R . In this way, quite similar equations as usually used for the analysis of simple Q-switching are obtained:

$$T_R \frac{dE_P}{dt} = [g - l - q_P(E_P)]E_P \tag{1}$$

$$\frac{dg}{dt} = -\frac{g - g_0}{\tau_L} - \frac{E_P}{E_{sat,L}T_R}g$$
(2)

where l is the linear internal loss due to crystal defects and dopant atoms in the laser waveguide, q_P is the round-trip loss in pulse energy introduced by the saturable absorber, g_0 is the laser gain when pulse energy equals 0, τ_L is upper-state lifetime of the laser medium. $E_{sat,L}$ is the saturation energy of the gain. Then, two reasonable assumptions are made. First, the duration of the mode-locked pulses is not obviously longer than the absorber recovery time. Second, the absorber recovery time must be much shorter than the cavity round-trip time. With these assumptions the pulse energy-dependent loss introduced by the absorber can be expressed as

$$q_{P}(E_{P}) = q_{0} \frac{E_{sat,A}}{E_{P}} [1 - \exp(-\frac{E_{P}}{E_{sat,A}})]$$
(3)

where q_0 is the saturable absorption of the absorber when pulse energy equals 0, $E_{sat,A}$ is the absorber saturation energy.

By solving these equations, a criterion can be obtained:

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$$E_{P} \left| \frac{dq_{P}}{dE_{P}} \right| < \frac{T_{R}}{\tau_{L}} + \frac{E_{P}}{E_{sat,L}}$$

$$\tag{4}$$

if the laser operates well above threshold, which is the case in this work, the first term on the right-hand side of relation (4) can be neglected. This eliminates the effects of the upper-state lifetime, and the saturation energy becomes the only relevant parameter of the gain medium. The physical background of this criterion, combining with the real case in this work, can be understood as follows.

For the cw mode locking and QML regimes, the mode-locked pulses are able to be formed. At $V_a = -1.5$ V (cw mode locking), the pulse energy is large, and if it rises slightly owing to relaxation oscillations, the pulse energy first grows exponentially owing to the stronger bleaching of the absorber. However, since the pulse energy is large enough, the increased pulse energy starts to saturate the gain. As a result, the pulse energy is pulled back to the previous value [20]. In contrast, at $V_a = -1.9$ or -2.1 V, the pulse energy decreases compared to that at $V_a = -1.5$ V due to the stronger absorption of the absorber. The gain saturation will be insufficient to stop an exponential pulse energy rise caused by relaxation oscillations. Subsequently, the pulse energy cannot be sustained at a constant, and QML operation is formed. For pure Q-switching regime ($V_a = -2.6$ V in this case) on the other hand, the intracavity intensity decreases further, causing the mode-locked pulses unable to be formed. The total cw intensity inside the cavity increases as the absorber is bleached. If the gain cannot respond fast enough, pure Q-switching operation will be formed [4].

4. Conclusions

In conclusion, a two-section InGaSb/AlGaAsSb SQW laser emitting at 2 μ m is fabricated and its ultrafast characteristics have been investigated. By fixing the gain current at 130 mA and varying the absorber bias voltage from -1.5 to -2.6 V, the tested laser goes through three distinct pulsed regimes: cw mode locking, Q-switched mode locking, and pure Q-switching. Specifically, at $V_a = -1.5$ V, the laser works in the cw mode locking regime with a fundamental repetition frequency at ~18.40 GHz. A pulse duration of ~1.12 ps can be expected. At $V_a = -1.9$ and -2.1 V, QML operation is observed. In this situation, mode locked and Q-switched signals coexist in both RF and optical spectra. At $V_a = -2.6$ V, pure Qswitching operation emerges with a fundamental repetition frequency at ~850 MHz and a pulse duration of ~0.17 ns. The mechanisms behind these operations are analyzed based on the interplay between the gain saturation and the saturable absorption.

The absorber bias voltage V_a is a simple and reliable method to control the switching among the three pulsed working regimes in such two-section lasers, which means the device can be driven to our favorable working regimes easily. Regarding the cw mode locking and pure Q-switching operations, their applications have been mentioned at the beginning. As for the QML operation, Q-switching typically leads to instabilities. It is unwanted for many applications especially in telecommunications where constant pulse energy is needed. However, as mentioned in Ref. 12 and Ref. 20, there are still some applications can be expected since the peak power of the mode-locked pulses in this regime is significantly increased compared to that in the cw mode locking regime. The potential applications include nonlinear frequency conversion, precise fabrication of microstructures, surgery, and measurement of two-photon absorption (TPA) by loss modulation.

Funding

This work was supported in part by the National Research Foundation of Singapore (NRF-CRP12-2013-04), and National Natural Science Foundation of China (61790582, 61435012, 61308051).