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Stable Mode-Locked Operation With High Temperature Characteristics of a Two-Section InGaAs/GaAs Double Quantum Wells Laser

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ABSTRACT A monolithic two-section InGaAs/GaAs double quantum wells (DQWs) mode-locked laser (MLL) emitting at 1.06 μm is demonstrated. Stable mode locking operation is achieved up to 80 °C. The fundamental repetition rate is at ~9.51 GHz with a signal-to-noise ratio (SNR) of more than 55 dB, and up to the fourth harmonic at ~38.04 GHz is observed. The characteristic temperature (T_0) of the laser and the influences of absorber bias voltage on T_0 have been systematically investigated. From our findings, T_0 shows a two-segment feature, and is slightly affected by the absorber bias voltage for photon saturation.

INDEX TERMS Semiconductor lasers, quantum well lasers, quantum wells, laser modes.

I. INTRODUCTION

In recent years, light sources emitting ultra-short pulses at 1.06 μm is attracting increasing attention in a number of applications, e.g., short link optical fiber communication [1]–[3], biometric imaging [4], [5], two-photon microscopy (TPM) [6], treatment for removing melanocytic nevi and melasma [7], [8], Lidar remote sensing on space-based or measurement of ocean surface effects (wave/ripples) [9], frequency combs [10], etc. Traditionally, such light sources are realized via mode-locked solid-state lasers utilizing material systems, such as Nd:YAG, Nd:YVO_4, Ti:$A1_2O_3$, etc., which are complex and difficult for the control of pulse repetition frequency and for electron synchronization [11], [12]. In contrast, mode-locked semiconductor lasers, taking advantage of compactness, low cost, and high frequency tuning flexibility have garnered considerable interest of late. Up to now, semiconductor quantum well (QW)/quantum dot (QD) MLLs, with multi-section, two-section, and single-section configurations, have been extensively reported at several wavelengths [13]–[16]. However, MLL emitting at 1.06 μm and temperature-related characteristics of such devices are rarely studied. To be exact, study on the effects of absorber voltage on the temperature characteristics in the passive mode locking of a two-section 1.06 μm–wavelength double quantum well (DQW) MLL has not been reported till now.

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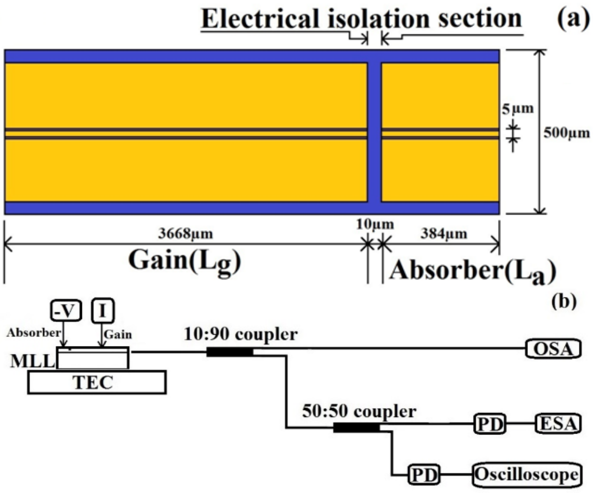

FIGURE 1. (a). Schematic diagram of top view two-section InGaAs/Ga As DQW MLL. (b) Schematic diagram of the measurement setup for characterizing the MLL.

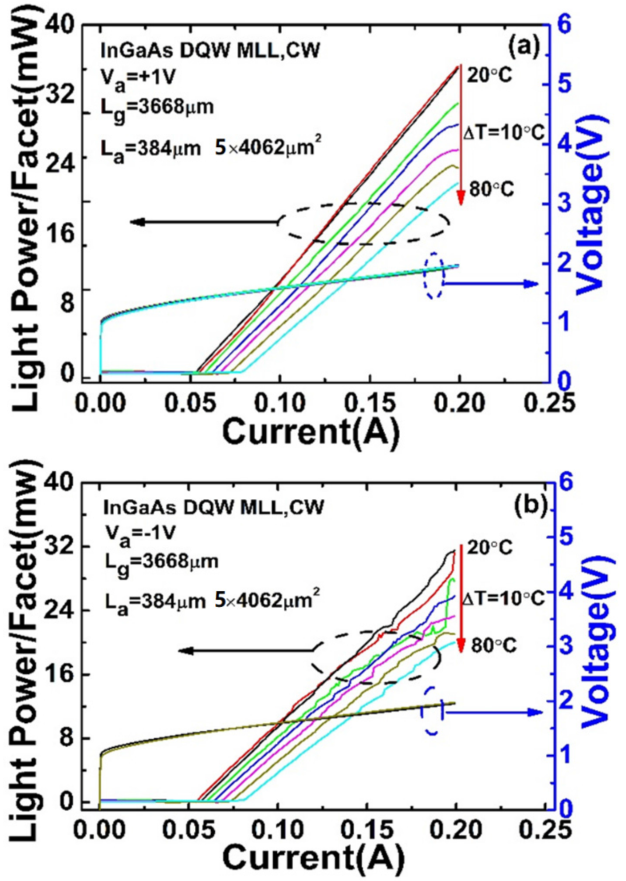

FIGURE 2. (a). Temperature-dependent ($V_a = +1$ V, 20 to 80 °C, a step of 10 °C) P-I-V characteristics of the two-section InGaAs/ GaAs DQW MLL (5 × 4062 μm^2). (b). Temperature-dependent ($V_a = -1$ V, 20 to 80 °C, a step of 10 °C) P-I-V characteristics of the two-section InGaAs/GaAs DQW MLL (5 × 4062μm^2).

In our previous work [17], we have demonstrated a novel high power and high efficiency asymmetric heterostructure laser diode (LD) with DQW, whose operation characteristics show some advantages over traditional SQW/QD structure lasers. And so far, there has not been a systematic study of how the temperature affects the stability of mode-locking in DQW lasers. In this work, we demonstrate stable passive mode-locked operating parameter of a two-section DQW laser at temperatures ranging from 20 to 80 °C, including radio frequency (RF) spectra, power-current-voltage (*P-I-V*), optical spectra, and characteristic temperature (T_0). In additional, the effects of absorber voltage on T_0 of the two-section DQW laser have been reported for the first time. This study demonstrates the feasibility of DQW MLLs as promising sources for ultrafast optical communications, TPM, frequency combs, and other applications. Devices with higher output power as well as higher efficiency, and a lower temperature sensibility can alleviate the requirement on thermoelectric coolers, thereby, decreasing cost and complexity for practical application.

II. DEVICE STRUCTURE, FABRICATION

In this work, 1.06-μm InGaAs/GaAs DQW laser structures, with asymmetric heterostructure layers, were grown on n-GaAs (100) substrates by metalorganic chemical vapor deposition (MOCVD). The structure consists of p-$Al_xGa_{1-x}As$ upper cladding layer, p-$Al_xGa_{1-x}As$ upper waveguide layers, 1.06-μm InGaAs/GaAs DQW, a partly doped $In_{0.03}Ga_{0.97}As_{0.8}P_{0.2}$ lower waveguide layer, and n-$In_{0.32}$ $Ga_{0.68}As_{0.95}P_{0.05}$ lower cladding layers. The detailed laser epitaxial structure is shown in our previous study [17]. This epitaxial structure provides a higher potential barrier for holes and thus reduces the leakage and loss of injecting holes. The MLL fabrication process is similar to those reported in Refs [18]–[20]. First, a 5 μm-wide ridge waveguide was formed by lithography and wet etching. A 300 nm-thick SiO_2 film was deposited as a passivation layer, and a 3 μm-wide window was opened on the 5 μm-wide ridge. Then, a 10 μm-wide electrical isolation region was patterned by another step of lithography. Ti/Au layers were evaporated to form the p-side ohmic contact. After that, lift-off process was carried out to expose the electrical isolation region, and consequent wet etching process realized the isolation. The schematic diagram after p-side process of the 1.06-μm InGaAs/GaAs DQW MLL was shown in Fig.1 (a). Finally, Ni/Ge/Au/Ni/Au layers were evaporated as n-side ohmic contact after substrate thinning of the wafer. The processed wafer was cleaved into laser bars as well as single chips for device characterization. During the characterization, a thermoelectric cooler (TEC), which can be varied from 20 to 80 °C, was used to control the operation temperature of the MLL. For the tested laser in this study, the length of the gain section (L_g) and the absorber section (L_a) are 3668 μm and 384 μm, respectively. The gain section current (I_g) is obtained by forward driving this section while the absorber section is reversely biased by V_a. The experimental setup for characterizing the laser is shown in Fig. 1(b). The output light from the gain section facet was coupled into a single mode fiber. Then the light was split by a 10:90 fiber optic coupler,

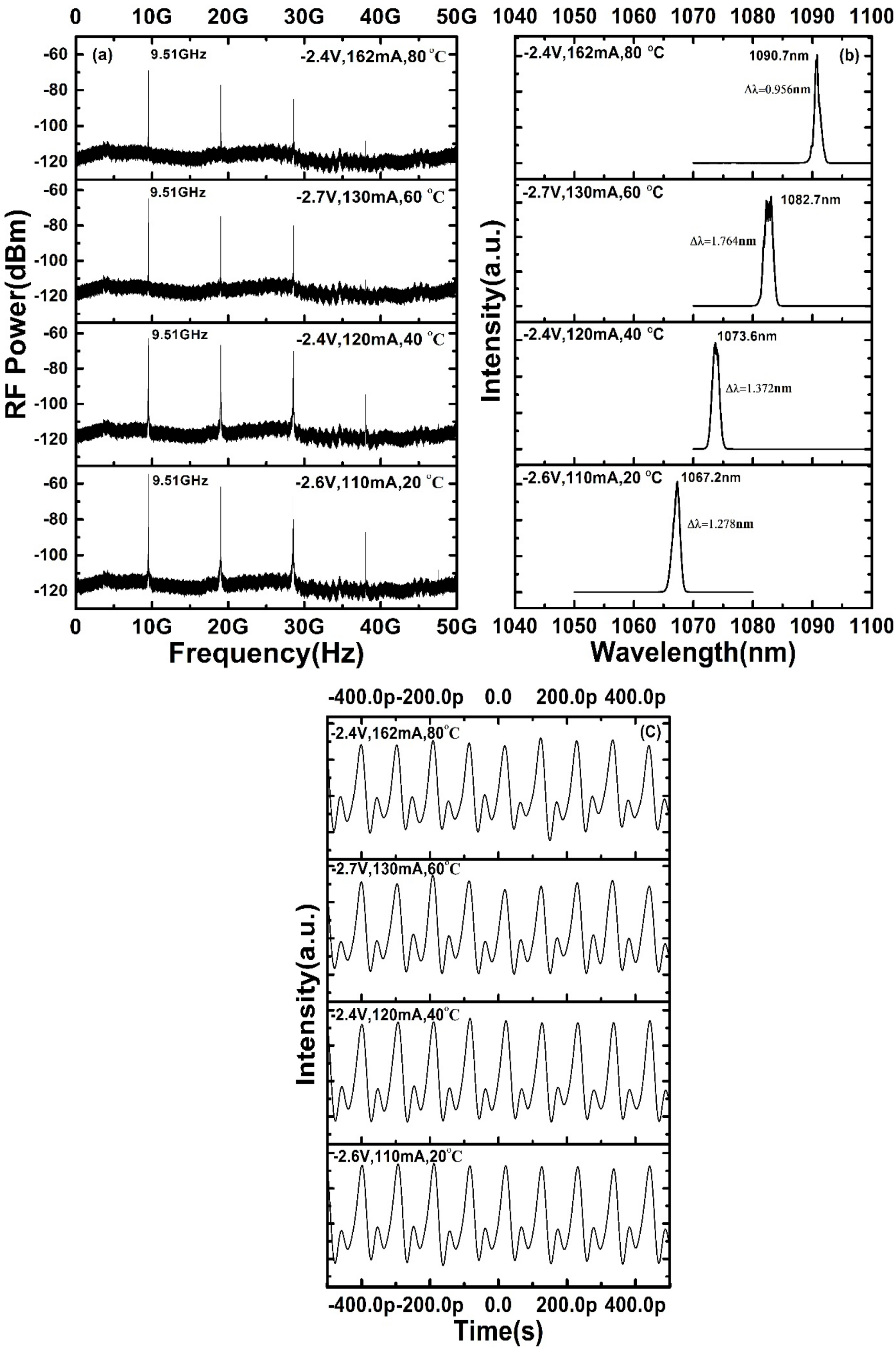

FIGURE 3. Temperature characteristics of the two-section InGaAs/ GaAs DQW MLL: (a) RF spectra (b). Spectra (c) Pulse trains.

the 10 percent was guided into an optical spectrum analyzer (OSA, AQ6370), and the 90 percent was further split into two equal parts: one was fed into a high-speed detector followed by a real-time oscilloscope (DSO93004L), another was fed into high-speed detector followed by an electrical spectrum analyzer (ESA, N9030A).

III. RESULT AND DISCUSSION

Stable mode locking was achieved under a wide range of bias conditions up to 80 °C without anti-reflective (AR) and high reflective (HR) coating. This is the highest operation temperature of such two-section DQW MLLs ever reported. Power-current-voltage (*PIV*) characteristics of a fabricated DQW MLL in the temperature range of 20 to 80 °C are shown in Fig. 2 with V_a setting at +1 V (a) and −1 V (b), respectively. At $V_a = +1$ V, the laser exhibited low threshold currents (I_{th}) of ∼54.6 mA at 20 °C and ∼78.7 mA at 80 °C. The light output power reached ∼36 mW/facet at 200 mA. At both absorber bias voltages, the threshold current increases consistently with increasing temperature owing to thermal carrier leakage in QWs. It is found that the output powers at $V_a = +1$V are higher than those at $V_a = -1$V, which indicates a stronger absorption of the latter absorber bias. Comparing $V_a = +1$V and $V_a = -1$V, it is found that the larger reverse bias voltage is easier to form a saturated photocurrent in the saturation absorption region, and it is easier to achieve stable mode locking for the higher power output of gain section. The instability of slope efficiency is caused by heat accumulation when I_g is more than 0.15A in the Fig. 2(b). The heat accumulation can affect the refractive index of active region and waveguide layers, and then causes mode jump. This is why the slope efficiency curve is unstable at higher injection levels. Fortunately, according to our observation, stable mode locking generally occurs among 1.5 to 3 times the threshold current.

Figure 3 shows the typical mode locking characteristics, i.e., RF spectra, optical spectra, and pulse train, of the tested laser when it operates at four different temperature conditions. Fig. 3(a) gives the RF spectra obtained by Agilent technologies PXA Signal Analyzer (N9030A, 3 Hz-50 GHz). The fundamental repetition frequencies are all at ∼9.51 GHz, for different temperatures operation with signal to noise ratio (SNR) up to 55 dB, and the RF signals at the fundamental repetition frequency have a full width at half maximum (FWHM) of ∼20 kHz, which indicates an efficient mode locking mechanism. The repetition frequency almost has no obvious changes with I_g at fixed V_a at all temperatures, and only the position and the intensity of harmonic frequency signal decreases slightly from 20 to 80^{o}C. This frequency corresponds to the photon round-trip time in the 4062 μm-long laser cavity. Meanwhile, multiple harmonics are present at ∼19.02, ∼28.53, and ∼38.04 GHz, respectively up to 80 °C. As shown in the figure, as V_a becomes more negative, larger I_g is needed to provide enough pulse energy so as to achieve stable mode locking. The corresponding optical spectra and pulse trains under the four bias conditions are shown in Fig. 3(b) and 3(c), respectively. According to Fig. 3(b), 0.02nm resolution and 0.001nm step resolution were used. The bias condition was adjusted at each temperature to obtain the strongest RF signal. The central lasing wavelength shifts from 1067.2 nm to 1090.7 nm when operation temperature is varied from 20 to 80 °C, and the $d\lambda/dT$ is determined

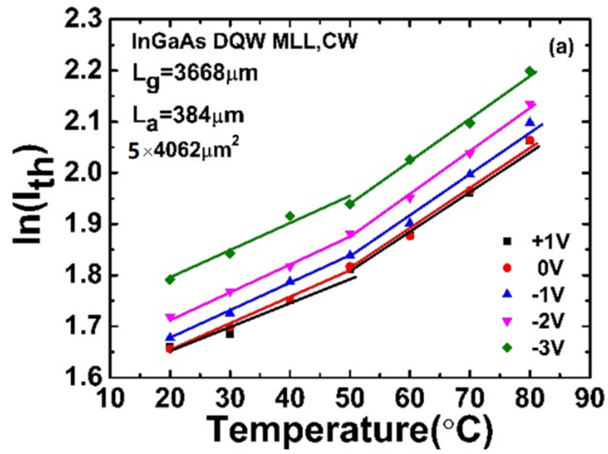

FIGURE 4. Threshold current (I_{th}) versus temperature (T) of 1.06-μm InGaAs DQW laser under different reverse bias (V_a).

to be ∼0.39 nm/K. This value shows good agreement with our previous results on traditional single-section lasers with the same epitaxial structure [20]. At 20 °C, the FWHM of the optical spectrum ($\Delta\lambda$) is ∼1.278 nm by a Lorentz fit, and the central spectrum at 1067.2nm. If sech^2 pulses are assumed which have an ideal time-bandwidth product of ∼ 0.315, then a pulse width (PW, Δt) of 0.93 ps and a peak power of 0.9W/facet can be expected with an average output power of 8mW/facet. A similar pulse width estimation method is provided in Ref. [21], [22]. It can be recognized that the resulting pulse train in Fig. 3(c) is the superposition of two sub-pulse trains with different intervals in real time oscilloscope after a PIN detector with a bandwidth of > 12.5 GHz. Signals in Fig. 3(c) are superpositions of pulse trains at different repetition frequencies, including the fundamental repetition frequency, the second harmonic and other harmonics. So the Fig.3 shows that the two-section InGaAs/GaAs DQW laser can achieve stable mode locking under a wide range of temperature changes, following that the operating current and reverse bias voltage at each temperature need to be adjusted appropriately. This result proves the stability and reliability of the device. On the other hand, it also shows that the gain region has to provide sufficient optical gain to achieve stable mode locking. These are of special significance for the study of frequency combs.

Figure.4 shows $ln(I_{th})$ *versus* temperature under different absorber bias (V_a). From the figure, the characteristics temperature T_0 is determined to be higher than 200 K in the temperature range of 20 to 50 °C, and ∼118 K in the temperature range of 50 to 80 °C, respectively. T_0 values change minutely with V_a, when V_a is varied from +1 to −3 V. On the other hand, the T_0 value of this tested MLL is slightly lower than the single-section counterpart [17], which we believe is resultant from the loss introduced by the absorber section. It is apparent that an additional loss is introduced when the absorber section is negatively biased. The results suggest a similar trend that T_0 is V_a-independent have also been reported in studies of GaAs-based QD MLL and GaSb-based QW MLL [21]–[23].

IV. CONCLUSION

We have fabricated and demonstrated a 1.06 μm two-section InGaAs/GaAs DQW MLL in this work. Its output characteristics, including RF spectra, *LIV*, spectrum, and T_0 have been investigated. Especially, the output characteristics dependence on temperature and absorber voltage of two-section InGaAs/GaAs DQW MMLs has been focused on the analysis. The prepared DQW MLL has exhibited a high threshold current characteristic temperature (T_0) of more than 200 K while operating under continuous wave (CW) condition in the temperature range of 20 to 50°C. At temperature above 50 °C, T_0 are more stable and nearly independent with the reverse bias voltage. Repetition rate, Spectra, and pulse trains, have been obtained at different temperatures. As for stable mode-locking operation, the influence of gain biased current (I_g) is more dominant than the reverse biased (V_a) on the absorber section. The excellent operation characteristics of 1.06-μm InGaAs/GaAs DQW MLLs indicate that the prepared MLL can produce higher and more stable locked frequency and will be one of the best choices for frequency combs, near-infrared wavelength ultra-short pulse light sources, and other applications.

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