Monolithic Passively Mode-Locked Lasers using Quantum Dot or Quantum Well Materials Grown on GaAs Substrates

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ABSTRACT

In this work, the optical characteristics of monolithic passively mode-locked lasers (MLLs) fabricated from 1.24-µm InAs dots-in-a-Well (DWELL), 1.25-µm InGaAs single quantum well (SQW), and 1.55-µm GaInNAsSb SQW structures grown using elemental source molecular beam epitaxy (MBE) are reported. 5 GHz optical pulses with sub-picosecond RMS jitter, high pulse peak power (1W) and narrow pulse width (< 10 ps) were demonstrated in monolithic two-section InAs DWELL passive MLLs. With the 42% indium InGaAs SQW MLL, a record high-temperature performance for a monolithic passively mode-locked semiconductor laser is found. Compared with the typical operating range of the InAs DWELL devices (<60°C), the operation is in excess of 100 °C. The first 1.55-µm GaInNAsSb SQW MLL operates at a repetition rate of 5.8 GHz and has a 3-dB bandwidth of 170 kHz in the RF spectrum indicating respectable jitter.

Keywords: quantum dots, passive mode locking, semiconductor lasers

1. INTRODUCTION

As the speed of microprocessors using electrical clock distribution increases beyond 3.6 GHz, the challenges and limitations of copper-based metal interconnects become more apparent. With the silicon CMOS feature size shrinking from today's state-of-the-art 90 nm to 32 nm range and beyond, speed bottlenecks due to RC delays on the chip and increasing electrical power consumption are expected to become serious problems[1,2]. There is renewed interest in semiconductor MLLs as sources for multi-gigahertz, ultra-short optical pulse generation. The compact size, low cost, low power consumption, and direct electrical pumping of semiconductor monolithic mode-locked lasers make them promising candidates for inter-chip/intra-chip clock distribution[3,4] as well as other applications including high bit-rate optical time division multiplexing[5,6,7,8,9], high speed electro-optic sampling[10], and impulse response measurement of optical components[1]. However, the compact diode laser pulse sources have generally not been able to match the pulse quality of the best mode-locked lasers[11]. They suffer from longer pulse durations, impaired stability, asymmetric pulses, chirped spectra and compromised peak power. To improve the characteristics of semiconductor mode-locked lasers, research on physics, materials and devices is necessary[12].

Operating wavelengths between 1250 and 1550 nm are desirable for compatibility with silicon-based waveguides and detectors and optical fiber-based components. These wavelengths are now accessible using GaAs-based materials technologies, which are desirable for MLL components because of their large-scale manufacturing capability and ultra low-loss GaAs/AlGaAs waveguides. In this work, the optical characteristics and physics of passively MLLs fabricated from 1.3-µm InAs dots-in-a-Well (DWELL), 1.25-µm InGaAs single quantum well (SQW), and 1.55-µm GaInNAsSb SQW structures grown using elemental source molecular beam epitaxy (MBE) are described.

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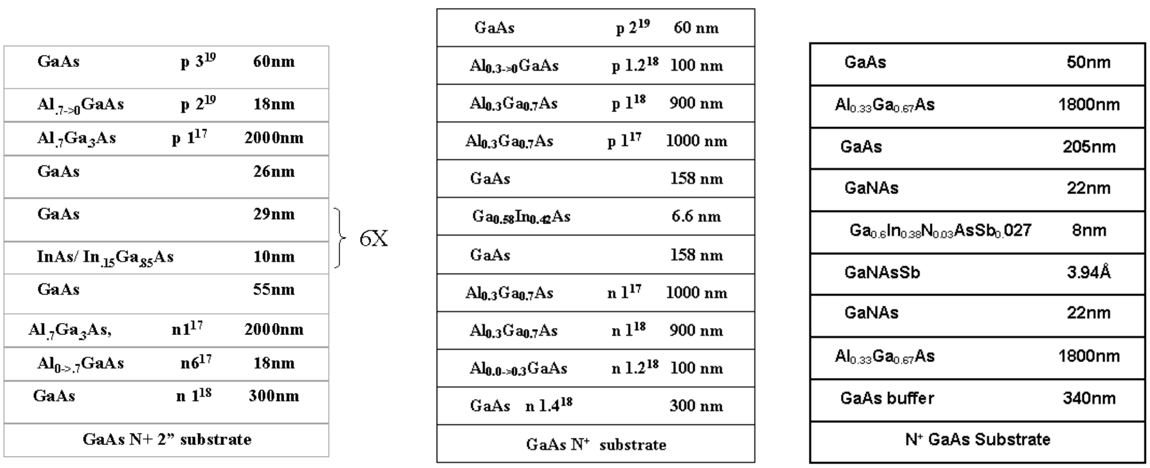
Sub-picosecond RMS jitter and narrow pulse width (< 10 ps) were demonstrated in monolithic two-section InAs DWELL passive MLLs with a low confinement factor waveguide design. In a separate device, a peak power of 1W is achieved with a 5 GHz repetition rate. For the 42% indium InGaAs SQW and the GaInNAsSb SQW MLLs, we hypothesize that the low density of states due to high compressive strain and narrow QW thickness explains why these devices have similar pulse width performance to the DWELL MLLs. However, the SQW MLLs are much more sensitize to the gain/absorber length ratio. With the InGaAs SQW MLL, a record high-temperature performance for a monolithic passively mode-locked semiconductor laser is found. Compared with the typical operating range of the InAs DWELL devices (<60 °C), the operation is in excess of 100 °C, making the InGaAs QW MLL suitable for applications in uncooled environments. The first 1.55-µm GaInNAsSb SQW MLL operates at a repetition rate of 5.8 GHz and has a 3-dB bandwidth of 170 kHz in the RF spectrum indicating potential for low jitter operation.

2. DEVICE DESIGN, FABRICATION AND TEST

2.1 Device structure

We fabricated MLLs from 3 different long wavelength (1250-1550 nm) materials on a GaAs substrate: multi-layer InAs DWELL, InGaAs SQW and GaInNAsSb SQW. All of the laser structures were grown by elemental source molecular beam epitaxy (MBE) on an n^+-doped, <100> oriented GaAs substrate.



(a) (b) (c)

Figure 1 (a) Structure of the 6-stack DWELL laser. (b) Structure of the InGaAs SQW laser. (c) Structure of the GaInNAsSb SQW laser

2.1.1 Multi-layer DWELL laser structure

The multi-layer DWELL laser structure consists of 6 stacks of dots. The epitaxial layers are composed of an n-type (10^{18} cm^{-3}) 300-nm-thick GaAs buffer, an n-type lower $Al_xGa_{1-x}As$ (x=0.2-0.7) cladding layer, a 315-nm-thick GaAs waveguide including the laser active region, a p-type upper cladding layer, and a p-doped (3×10^{19} cm^{-3}) 60-nm-thick GaAs cap. The cladding layers are doped at 10^{17} cm^{-3} and are each 2-µm thick. In the center of the waveguide, 6 DWELL layers with 29 nm GaAs barriers were grown. QDs with an equivalent coverage of approximately 2 monolayers of InAs are confined in the middle of a 10 nm thick $In_{0.15}Ga_{0.85}As$ QW in each layer. The QD's and QW were typically grown at 500 °C, as measured by an optical pyrometer. The QD's formed under these conditions have an areal density of about 3×10^{10} cm^{-2}, a base diameter <40nm, and are 7 nm high. Detailed descriptions of the DWELL growth technique can be found elsewhere[13,14]. A typical structure of multi-layer DWELL is shown in the Figure 1(a). A typical InAs DWELL laser structure has an internal loss of 1-2 cm^{-1} and a maximum modal gain of 2-3 cm^{-1} per QD layer. Using the DWELL technology, the lasing emission wavelength can be adjusted to anywhere between 1100 nm and 1350 nm by design and growth[1].

2.1.2 InGaAs SQW laser structure

The InGaAs SQW laser structures were grown on n-doped GaAs wafers as shown in the Figure 1 (b). After deposition of an n-doped GaAs buffer layer a 1900 nm thick $Al_{0.3}Ga_{0.7}As$ cladding layer was grown, followed by a 320 nm thick GaAs waveguide region containing a single 6.6-nm $In_{0.42}Ga_{0.58}As$ quantum well in the center. An upper 1900-nm thick p-doped $Al_{0.3}Ga_{0.7}As$ cladding layer and a 100 nm thick p^{++} doped GaAs cap concluded the structure. The doping concentration in the cladding layers was reduced near the waveguide region to minimize free carrier absorption losses[15].

2.1.3 GaInNAsSb SQW laser structure

The 1550nm GaInNAsSb SQW laser material was grown in two load-locked Varian Mod. Gen II solid-source MBE machines with nitrogen supplied by an SVT Associates Model 4.5 plasma cell. The cell was operated in a stable inductively-coupled mode with forward RF power and a nitrogen flow. The detailed information of the growth technique are described elsewhere[16]. The laser diode layer structure consisted of a single 75 Å $Ga_{0.62}In_{0.38}N_{0.03}As_{0.943}Sb_{0.027}$ QW (+2.5% strain) surrounded on either side by 210 Å $GaN_{0.04}As_{0.96}$ barriers (-0.81% strain) embedded in a $GaAs/Al_{0.33}Ga_{0.67}As$ waveguide. The structure of the GaInNAsSb SQW laser is shown in the Figure 1 (c).

2.2 Device fabrication

The devices are typical 2-section ridge-waveguide lasers with a ridge width of 3.5 µm as shown in Figure 3. Devices were fabricated according to standard multi-section device processing [17]. After the first lithography with the ridge-waveguide-mask, the sample was etched to form 3-µm wide, 1.8-µm deep ridges by inductively coupled plasma (ICP) etching in BCl_3. Then a BCB layer was applied for isolation between the p-type metal and the etched cladding layer. The two-section contact mask was used to make photoresist patterns for the p-type metal deposition and ion implantation. After depositing Ti/Pt/Au to form the p-metal contact, an isolation between the adjacent sections was provided by proton implantation, with an isolation resistance of >10 MΩ. After the substrate had been thinned and polished, a Au/Ge/Ni/Au n-metal contact was deposited on the backside of the n^+-GaAs substrate and annealed at 380°C for 1 minute to form the n-ohmic contact. A temperature greater than 380°C can crack the BCB. Another Ti/Au metal layer was deposited for n-side mounting, and then the sample was cleaved to form devices with a short absorber section and long gain section. In this work, the InAs DWELL MLL has a 1.2-mm absorber section and a 6.8-mm gain section; the InGaAs SQW MLL has a 0.2-mm absorber section and a 4.1-mm gain section, and the GaInNAsSb SQW MLL has a 0.2-mm absorber section and a 7.2-mm gain section. The cleaved facet near the absorber section was HR-coated (R≈95%) to create self-colliding pulse effects in the saturable absorber for pulse narrowing and the other facet was low reflection (LR)-coated (R≈15%). The devices were mounted on copper heatsinks, and for all the results presented in this paper, the measurements were performed at a controlled substrate temperature of 20^oC if not specified.

2.3 The mode-locked laser measurement setup

The operational characteristics of MLLs that are measured include the repetition rate, the optical pulse width, the optical spectrum, the peak power, the timing jitter, and the threshold current. The test setup includes two main blocks: an electrical-pumping block, and a signal-detection block, as shown in Figure 2. A DC power source was used to apply a reverse bias on the absorber, and a laser diode controller was used to pump the gain section. An integrated optical head mounted on a 5-axis precision linear stage was used to collect the output emission of the mode-locked laser. The integrated optical head consists of a polarization-maintaining fiber (PMF) pigtail, a collection lens, and an isolator. The lens focuses the output light into the PMF through the isolator, which is used to avoid interference effects. The collected emission is fed into the autocorrelator (Femtochrome FR-103XL) to measure the pulse width, and the optical spectrum analyzer to measure the optical spectra through fiber couplers. An RF spectrum analyzer (HP8563E) measures the repetition rate. For the jitter characterization, the single-sideband phase noise spectral density $\mathscr{L}(f)$ was measured using the RF spectrum analyzer with an Agilent Technologies 85671A phase noise utility. The light-current (L-I) characteristics can be obtained if the optical head is replaced with an integrating sphere and photodetector. Therefore, we can obtain the passively mode-locked laser pulse repetition rate, the optical pulse width, the optical spectrum, the average and peak power, and the timing jitter.

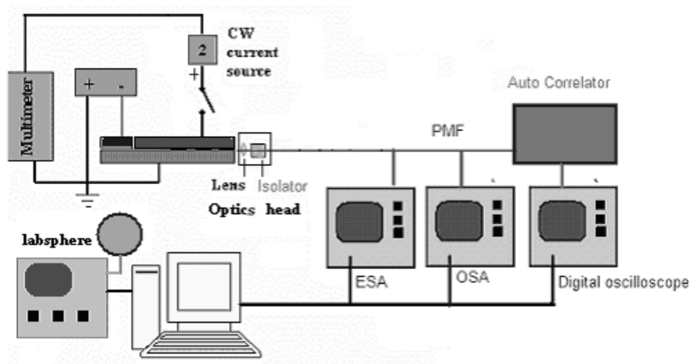


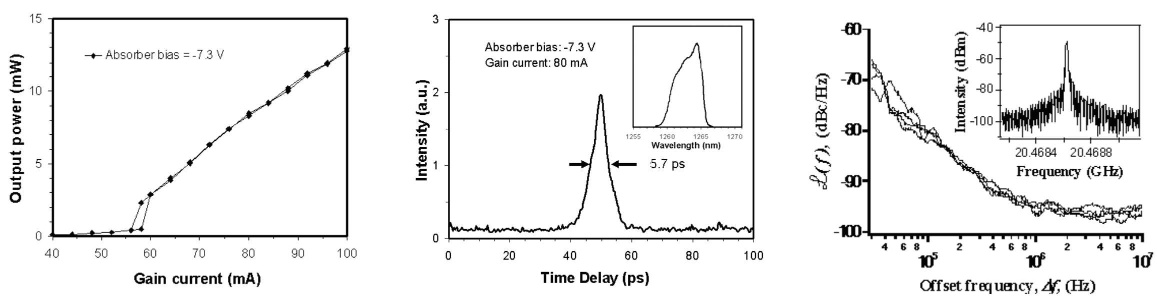
Figure 2 Schematic diagram of the mode-locked laser measurement setup

3. RESULTS

3.1 InAs DWELL MLLs

Some unique characteristics of QD lasers, such as the ultra-broad bandwidth, ultra-fast gain dynamics, easily saturated absorption, strong inversion, low alpha parameter and wide gain bandwidth, make them an ideal choice for semiconductor monolithic mode-locked lasers[18,19,20,21]. Also the 1.25-μm emission wavelength, which is transparent to Si waveguides and detectable by SiGe photodetectors, makes the InAs QD mode-locked lasers suitable for Si-based optoelectronic integrated-circuits[22, 23]. Two kinds of InAs DWELL MLLs were fabricated: with an optimized QD active region for low jitter and an optimized optical waveguide for high power.

The InAs DWELL MLL optimized for low jitter is designed with a high confinement factor waveguide. Figure 3(a) displays the light output as a function of the current of the gain region (I_g) and the optical spectrum under an absorber bias (V_a) of -7.3 V, for a 1250 nm QD passively MLL. The lasing occurred at the QD ground state (λ = 1264 nm) with a forward scan turn-on threshold of 60 mA and a backward scan turn-off threshold of 58 mA, corresponding to a threshold current density of approximately 220 A/cm^2.[1]

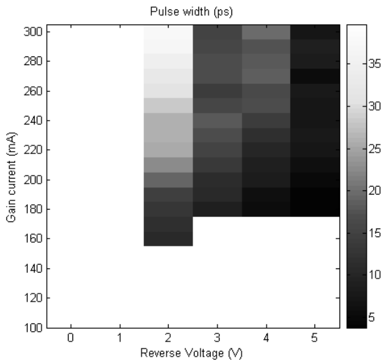


(a) (b) (c)

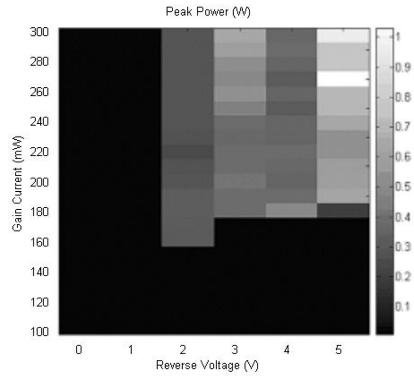
Figure 3 (a) The CW L-I characteristics and optical spectrum of a 1250 nm QD passively MLL under absorber bias of -7.3 V. (b) Pulse width and optical spectrum under a gain current of 80mA and absorber bias of –7.3V. (c) The single-sideband phase noise spectral density *L(f)* of the 2-section QD passively MLL and the ESA spectrum of the 4th harmonic. [1]

The autocorrelation signal exhibits a pulse width of 5.7 ps at a repetition rate of 5.17 GHz. As shown in Figure 3(b), an average power of 8.5 mW and a pulse peak power of approximately 290 mW were achieved at the laser facet. The RMS timing jitter of the device was 0.91 ps, calculated from the integration of the $\mathscr{L}(f)$[24] over the offset frequency range of 30 kHz to 30 MHz. Compared to the jitter value of 12.5 ps (integrated over an offset frequency range of 150 kHz to 50 MHz) of a typical QW passive MLL[25], the QD device demonstrates more than one order of magnitude improvement. Such a dramatic improvement in the jitter may be attributed to the low amplified spontaneous emission in the QD active region.[1]

For improving the peak power, a low confinement factor waveguide with 20% AlGaAs cladding layers was designed in the high-power InAs DWELL structures. Figure 4 shows the pulse characteristics of the high power QD passive MLL module at 20°C as a function of the gain current and the absorber bias voltage. As the map shows, with an absorber bias of -5 V, the device produced 5 GHz optical pulses with a pulse width of less than 10 ps and a peak power of more than 550mW over a wide operating gain current range of 190 to 300 mA.



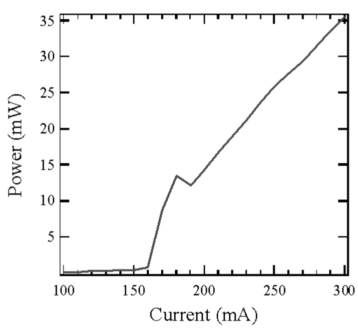
(a)



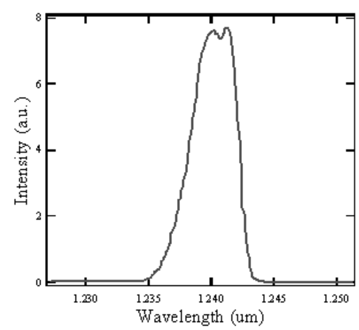
(b)

Figure 4 (a) Pulse width and (b) peak power mapping of the high-power QD passive MLL chip at 20°C with a reverse bias of 0-5 V and gain current of 100-300 mA

Figure 5 displays the L-I curve and the optical spectrum under an absorber bias of –5V. The lasing occurred at the QD ground state (λ = 1240 nm) with a forward scan turn-on threshold of 160 mA, corresponding to a threshold current density of approximately 580 A/cm^2. Under a gain current of 270 mA and an absorber bias voltage of -5V, the device had a pulse width (Δt) of 5.7 ps as shown in Figure 6 (b). The electrical spectrum under the same bias conditions is shown in Figure 6 (a) and the repetition rate f is 4.97 GHz. Therefore, the laser achieved a high peak power of 1.04 W, which is about 5 times higher than the peak power (≈200 mW) of QD MLLs with a high confinement factor waveguide[1].

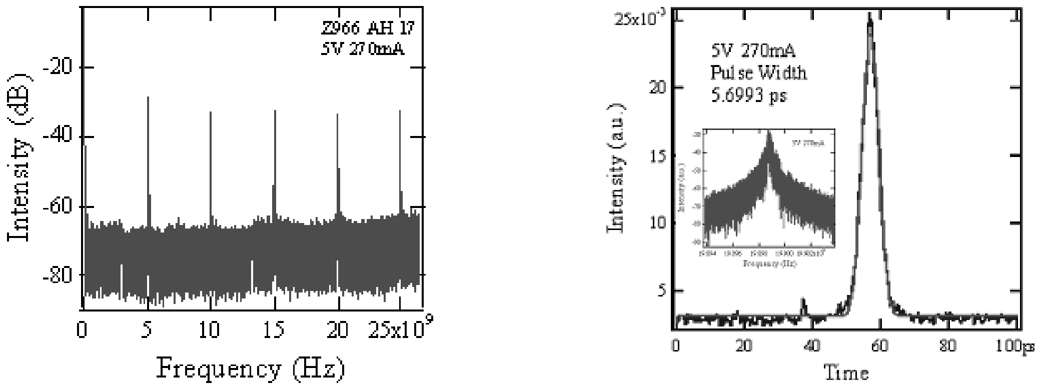


(a)



(b)

Figure 5 The CW L-I characteristics (a) and optical spectrum (b) of a 1240 nm QD passive MLL under absorber bias of -5 V. For the optical spectrum, the gain current is 270 mA.

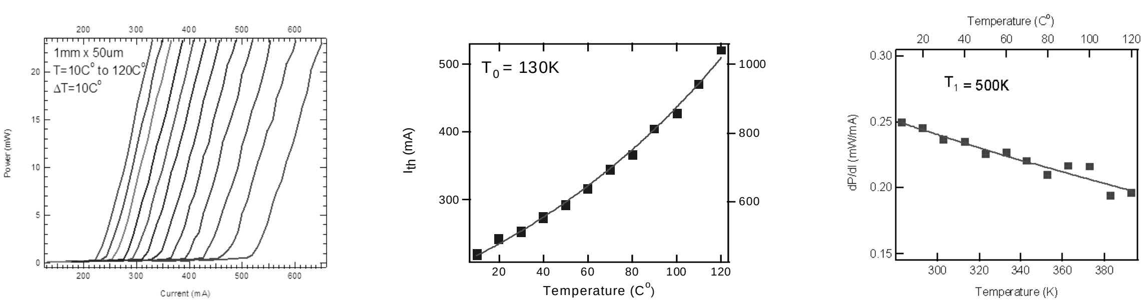


(a) (b)

Figure 6 Mode-locked optical pulse characteristics of the high-power QD passive MLL module at 20°C with a reverse bias of 5V and a gain current of 270 mA. (a) Electrical spectrum showing a pulse repetition rate of 4.97 GHz. (b) The auto-correlation signal showing a pulse width of 5.7 ps. The inset figure shows the 4th harmonic electrical spectrum with a span of 10 MHz.

3.2 InGaAs SQW MLLs

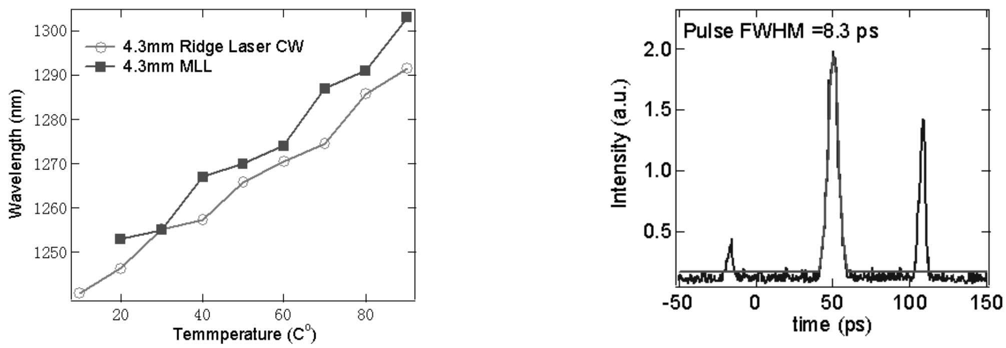
As clock rates rise in the microprocessor, so does power consumption, heat production and electromagnetic interference. One important requirement for the semiconductor MLLs working as the clock in microprocessors is the capability of operating above at least 100 °C. This specification is very challenging for laser diodes, which generally degrade in temperature performance as the wavelength is increased. In addition, considering that germanium on silicon detectors are typically more efficient and that silicon waveguides are more convenient, wavelength operation beyond 1200 nm is desirable for the clock[15]. Recent results demonstrate that InGaAs/GaAs quantum well lasers with wavelengths greater than 1200 nm have superior temperature insensitivity and are attractive candidates for applications requiring greater than 100 °C operation[26]. In this work, we report on passive mode-locked semiconductor quantum well lasers operating above 100 °C using this InGaAs materials system on a GaAs substrate.



(a) (b) (c)

Figure 7 The temperature characteristics of InGaAs SQW lasers

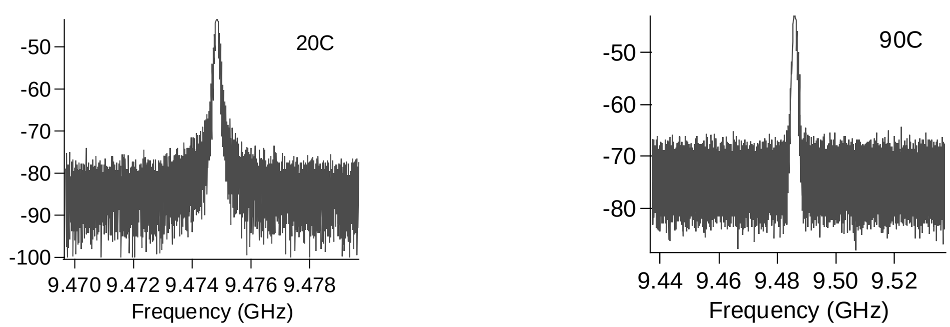
With a 1-mm cavity length broad area laser, the temperature characteristics under pulsed current were tested and plotted in Figure 7(a). A pulse width of 0.5 µs and a duty cycle of 1% were employed. From this data, a T_0=130K and T_1=500K are calculated across the whole temperature range as shown in Figure 7(a) and (c). An injection efficiency of 73% and an internal loss of 4.4 cm^{-1} are found from the data of the inverse slope efficiency vs. cavity length.



(a) (b)

Figure 8 (a) Operation wavelength of the InGaAs MLL as a function of heat sink temperature. (b) Autocorrelator trace of the 2-section laser at 302 mA on the 4.1-mm gain section and –1 V bias on the 0.2-mm absorber at a TE cooler temperature of 90 C. The time difference between the peaks is the pulse period. The pulse width is 8.3 ps.

A 3.5-micron ridge waveguide InGaAs SQW MLL is comprised of a 0.2-mm absorber section and a 4.1- mm gain section for a total cavity length of 4.3-mm. The devices were tested with the heat sink temperature varied from 20 °C to 90 °C. To obtain the corresponding junction temperature, the two sections were pumped uniformly making this an "all-active" design to observe the operation wavelength shift as shown in Figure 8(a). The wavelength range of operation is 1253 to 1303 nm. From the change in wavelength with temperature monitored under pulsed conditions on a separate laser device, the actual temperature of the junction is estimated to be 110 °C when the heat sink was set at 90 °C. The device passively mode-locks from 20 °C to 90 °C heat sink temperature as shown by the spectrum analyzer data in Figure 9. At 90 °C heat sink temperature the measured pulse width at 302 mA on the gain section and –1 V on the absorber is 8.3 ps as displayed in Figure 8(b). This is the highest recorded temperature for a monolithic passively mode-locked device and demonstrates the potential of this technology for optical clocking on silicon ICs.

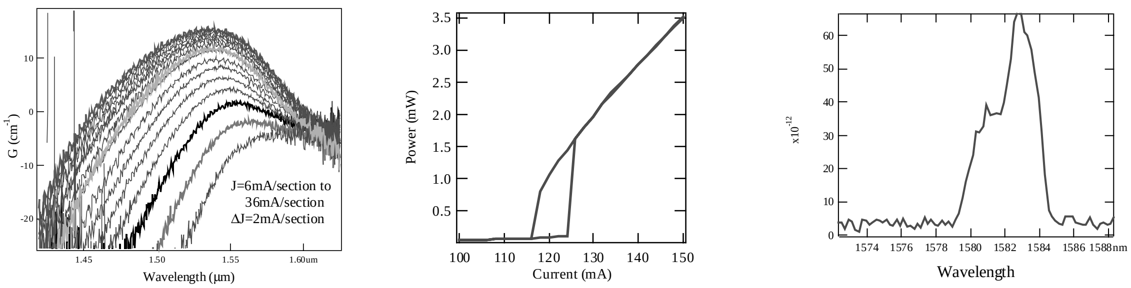


(a) (b)

Figure 9 Spectrum analyzer data showing the mode-locking frequencies at a heat sink temperature of 20 °C (a) and 90 °C (b).

3.3 GaInNAsSb SQW MLLs

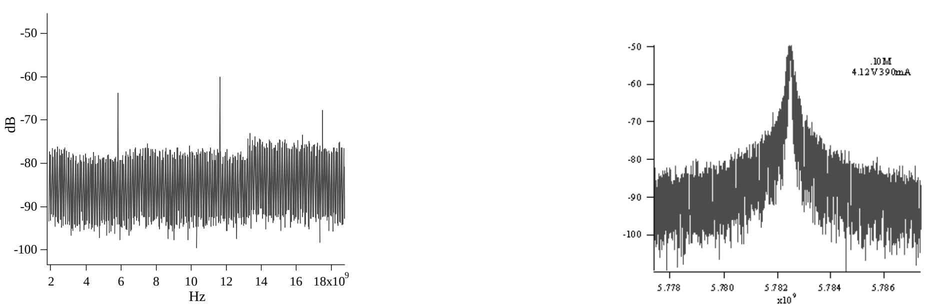
Since the GaInNAsSb is relatively immature QW laser material system, the net modal gain as shown in Figure 10(a) and loss spectra of the GaInNAsSb active region were obtained with the improved segmented contact method[17] to assess the material's suitability for mode-locked devices. The net modal gain saturates at about 15 cm^{-1} and the internal loss is about 4 cm^{-1}, which are relatively modest and comparable to the QD active region values due to the use of a single QW and the low density of states from high compressive strain. The FWHM of the gain curve at 34 mA/section (2kA/cm^2 current density) is about 7%, which is competitive with inhomogeneously broadened quantum dot systems and beneficial for locking many lasing modes.



(a) (b) (C)

Figure 10 (a) Net modal gain measured using the segmented contact method. (b) The CW L-I characteristics under absorber bias of –4.1 V. (c) The optical spectrum under the gain current of 390 mA and an absorber bias of -4.1 V

The 2-section GaInNAsSb SQW MLLs were fabricated with a total cavity length of 7.2 mm and an absorber length of 0.2 mm. The L-I curve in Figure 10(b) displays a threshold current density of 475 A/cm^2, and Figure 10(c) demonstrates a 3.6-nm FWHM mode-locked spectrum at a gain current bias of 390 mA and an absorber bias of -4.1 V. Under these conditions, stable mode-locking at 5.78 GHz was observed with a clean harmonic spectrum as shown in Figure 11. From Figure 11(a) we can recognize that the laser is mode locking and there is no self-pulsation. A separate measurement around the peak at the fundamental frequency yielded a 3-dB bandwidth of 170 kHz that indicates a good jitter in these passively mode-locked devices.



(a) (b)

Figure 11 Spectrum analyzer data showing the mode-locking frequencies under different span ranges. (a) 26GHz. (b) 10MHz.

6. SUMMARY

A high peak power of 1W and low < 1 ps jitter were achieved with 5 GHz InAs DWELL MLLs. We have demonstrated record high temperature performance for a semiconductor mode-locked laser using the InGaAs/GaAs SQW material system. The operation in excess of 100 °C makes this device suitable for optical clocking applications in uncooled environments. We also demonstrated the first GaInNAsSb SQW MLLs. Both of the InGaAs SQW and the GaInNAsSb SQW MLL devices have similar pulse width performance to the DWELL MLLs. However, the SQW MLLs are much more sensitive to the gain/absorber length ratio.

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