Low timing jitter, 5 GHz optical pulses from monolithic two-section passively mode-locked 1250/1310 nm Quantum Dot lasers for high speed optical interconnects

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Abstract: Sub-picosecond timing jitter is demonstrated for 5GHz, <10ps optical pulses generated from monolithic passively mode-locked quantum dot lasers. Their low cost, compact size and DC-biased operation make them ideal for high speed optical interconnects.

OCIS codes: (140.4050) Mode-locked lasers; (140.5960) Semiconductor lasers, (200.4650) Optical interconnects

1. Introduction

As the speed of today's microprocessors using electrical clock distribution increases beyond 3.6 GHz the challenges and limitations of copper-based metal interconnects are becoming more apparent. With the silicon CMOS feature size shrinking from today's state of the art of 90 nm to 32 nm and beyond, it is expected that serious speed bottlenecks due to RC delays on chip and increasing electrical power consumption will become dominant problems [1]. These problems can be avoided by the use of optical interconnects for clock distribution. Mode-locked semiconductor lasers are very promising candidates for optical interconnects for both on-chip clock distribution [2] as well as for signaling applications at the chip-to-chip and board-to-board level [3].

Semiconductor Mode-Locked Laser (MLL) diodes are ideal sources for multi gigahertz, ultra-short optical pulse generation. The compact size, low power consumption, direct electrical pumping of semiconductor MLL's make them best suited for inter-chip/intra-chip clocking as well as other applications including high bit-rate optical time division multiplexing, electro-optic sampling, and impulse response measurement of optical components. For these applications, low timing jitter of the ultra-short optical pulses is required since the fluctuation of the pulse arrival time degrades bit-error rate and time resolution. Among the different MLL configurations, the monolithic 2-section passively mode-locked semiconductor laser is the most desirable option for low-cost high-volume production due to device compactness and system simplicity. However, previous Quantum Well (QW) monolithic, passively MLL's have suffered from much larger timing jitter compared to active or hybrid MLL's [4]. The timing jitter in passive MLL's arises from the fluctuations in carrier density, photon density, and index of refraction caused by the amplified spontaneous emission (ASE) [5]. Due to the discrete energy levels and low transparency current in a Quantum Dot (QD) gain medium, the portion of carriers involved in the non-stimulated emission is significantly reduced. Therefore, low ASE is expected in QD devices [6], suggesting that a lower timing jitter can be achieved with QD passively MLL's compared to QW passively MLL's. In this paper, the performance of monolithic 2-section QD passively MLL's is presented.

2. Device design and fabrication

The laser epi-structure is a multi-stack "Dots-in-a-WELL" (DWELL^{TM}) structure, an optimized QD active region [7], grown by solid source molecular beam epitaxy on a (001) GaAs substrate using conditions similar to those published previously. Two wavelengths were chosen in this work: a) 1250 nm, which is transparent to Si waveguide and detectable by SiGe photodetector, for intra-chip / inter-chip clocking and signaling applications; and b) 1310 nm, which is compatible with the current platform for data- and telecommunications.

The device is a typical 2-section ridge-waveguide laser with a ridge width of 3.5 μm and a cavity length of 7.8 mm. The absorber length (L_a) is 1 mm. The isolation between the gain and absorber sections is provided by proton implantation, with an isolation resistance of >10 MΩ. The details of the MBE growth and the device processing are similar to [8]. The absorber facet was high reflection (HR)-coated to create self-colliding pulse effects in the saturable absorber for pulse narrowing. For all the results presented here, the measurements were performed at a controlled substrate temperature of 30°C.

3. Results

Figure 1 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. Unlike the first published QD MLL [9], where mode-locking occurred only within the L-I hysteresis region and close to the lower threshold, the mode-locking operation range in our devices extended well beyond threshold, leading to pulses of significantly higher optical power.

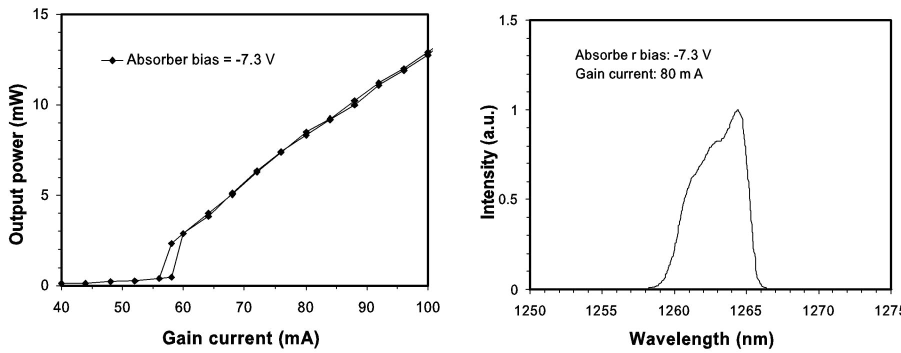

Fig 1. The CW L-I characteristics and optical spectrum of a 1250 nm QD passively MLL under absorber bias of -7.3 V.

The pulse width was measured using an autocorrelator. For the jitter characterization, the single-sideband phase noise spectral density L(*f*) was measured using HP8563E ESA with an Agilent Technologies 85671A phase noise utility. Figure 2 displays the autocorrelation signal (left) and the L(*f*) curves at the 4th harmonic (right) of the optical pulses of the QD passively MLL shown in Figure 1 under bias conditions of I_g = 80mA and V_a = -7.3V. The inset shows the ESA spectrum of the 4th harmonic. The autocorrelation signal exhibits a pulse width of 5.7 ps at a repetition rate of 5.17 GHz. As shown in Figure 1, 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 L(*f*) [10] 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 passively MLL [4], Zia's QD passively MLL demonstrates more than one order of magnitude improvement. Such a drastic improvement of the jitter in QD passively MLL's may be attributed to the low ASE rate in QD active regions.

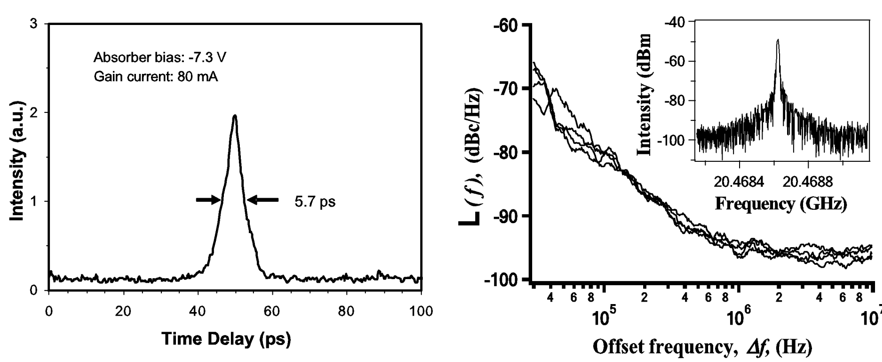

Fig 2. The autocorrelation signal and the single-sideband phase noise spectral density L(*f*) of the 2-section QD passively MLL shown in Figure 1. The inset is the ESA spectrum of the 4th harmonic. The bias condition is: I_g = 80 mA and V_a = -7.3 V. Optical pulses with pulse width of 5.7 ps and RMS jitter of 0.91 ps at a 5.17 GHz repetition rate were obtained.

Similar performance was obtained by a 2-section QD passively MLL emitting at 1310 nm. The window of operation leading to mode-locked pulses with RMS timing jitter <3 ps and pulse width <10 ps was determined by the performance of the MLL as a function of the gain current (I_g) and absorber bias (V_a), as shown in Figure 3. Less than 10 ps wide pulses with low jitter were realized over a wide operating range. The pulse width increased with increasing gain current or decreasing absorber bias voltage. The same trend applied to the average power, resulting in a relatively constant pulse peak power. This was attributed to the gain saturation in QD lasers, a phenomena observed in 1310 nm QD DFB [11] and FP lasers [12]. For a given absorber bias, the jitter improved as the gain current increased. This trend appeared only within a certain operating window above threshold. As the gain current increased beyond this operation window, the jitter started to degrade, usually accompanied with mode hopping. The operation window for the gain current ranged from 5 to 30 mA, depending on the gain and loss of the QD material, the waveguide design, the absorber length, and the facet coating. For the device shown in Figure 3, an operation window of >15 mA in gain current at absorber bias from 6 to 7.5 V was obtained, leading to pulses with <10 ps pulse width and <3 ps RMS jitter.

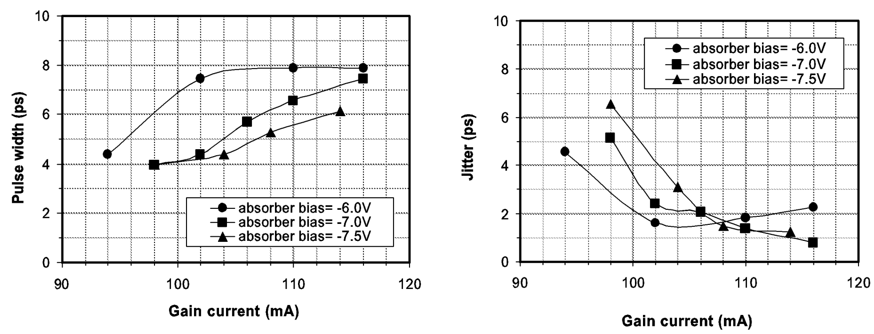

Fig 3. The pulse width (left) and jitter (right) of a 1310 nm QD passively MLL as a function of the gain current and absorber bias. An operation window of >15 mA in gain current at absorber bias from 6 to 7.5 V was obtained, leading to pulses with <10 ps pulse width and <3 ps RMS jitter.

Industry-standard 14-pin butterfly packages were used for packaging similar QD passively MLL's. While the jitter and pulse width remain unchanged, the pulse peak power ex-fiber was reduced to approximately 100 mW due to relatively low coupling efficiency. With further optimization of the epitaxial structure design a pulse peak power of greater than 200 mW is expected.

4. Conclusion

5 GHz optical pulses with sub-picosecond RMS jitter, high pulse peak power (approx 290 mW), and narrow pulse width (< 10 ps) were demonstrated in 1250 / 1310 nm monolithic two-section QD passively MLL's. These results constitute significant progress towards the realization of a high performance, low cost, compact source for next generation high speed optical clocks and interconnects.

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