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Frequency comb with 100 GHz spacing generated by an asymmetric MQW passively mode-locked laser

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A L-band two-section AlGaInAs/InP asymmetric multiple quantum well passively mode locked laser has been used to generate a frequency comb with a 100 GHz spacing at a central wavelength of 1610 nm. The comb contains 10 optical lines within a −3 dB bandwidth of 8.05 nm and 34 optical lines within a −20 dB bandwidth of 30 nm. The mode locked pulse duration was 440 fs. To the best of our knowledge, this is the shortest pulse duration from any directly electrically pumped quantum well semiconductor mode-locked laser.

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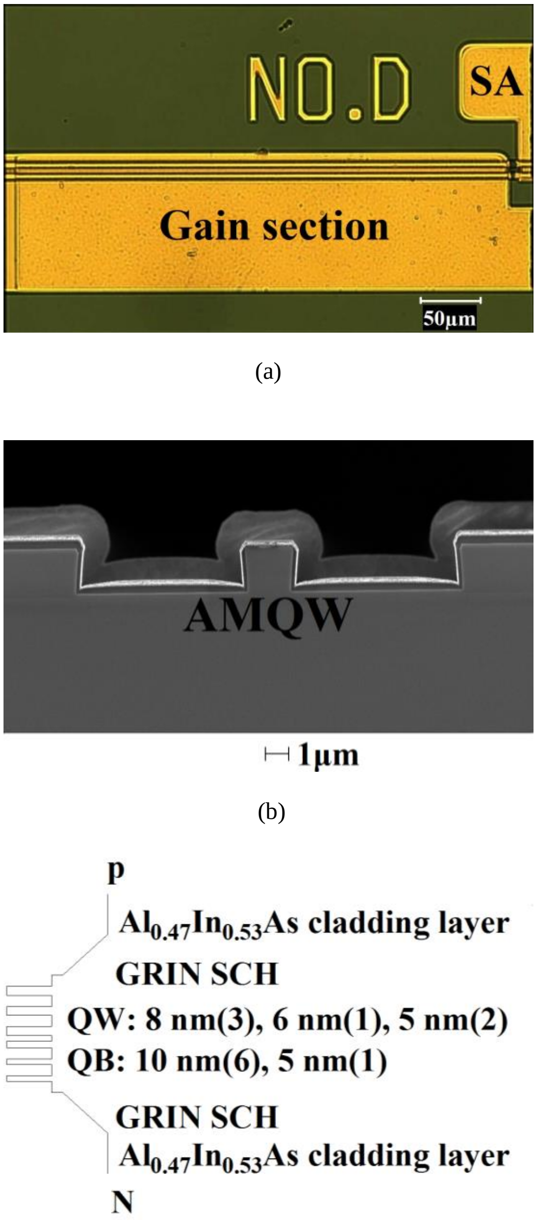
Semiconductor mode locked laser diodes (SMLLDs) are ideal coherent comb laser sources due to their compactness, mechanical stability, robustness, and broad gain spectrum. Monolithic constructions can be designed to mode lock at frequencies from below 10 GHz to more than 100 GHz. Optical frequency combs as a source of multiple spectral lines have been used in a variety of transmission system demonstrations, including long-reach systems with coherent detection, short-reach systems with direct detection, and passive optical networks [1]. Such coherent comb lasers can reduce costs and simplify the packaging issues by replacing many separate lasers for each channel by a single laser diode. Normally quantum dot or quantum dash SMLLDs have been used to produce coherent frequency combs, with the widest reported 3-dB bandwidth being as high as 16 nm [2]. However, two-section 1.55 μm SMLLDs based on InAs/InP quantum-dot materials are still relatively immature, suffer from lower modal gain and have wider reported pulse widths than those of 1.55 μm multiple quantum well (MQW) SMLLDs [3, 4]. Until now the shortest reported pulse width generated by a passively mode locked MQW laser diode has been 490 fs. This was measured from a C-band two-section 40 GHz AlGaInAs/InP SMLLD with a specially designed monolithically integrated passive waveguide made by quantum well intermixing [5] to reduce self-phase modulation (SPM) and pulse broadening in the gain section [6]. Corral et al. [7] reported an optical frequency comb generator that used a passively mode locked MQW ring laser and Mach Zehnder interferometer to flatten the spectrum, but the output power was low (~2 mW), the pulse width was wide (21.2 ps) and the −10-dB bandwidth was only 8.7 nm. Moskalenko et al. [8] reported a coherent frequency comb with a bandwidth of 40 nm at −20 dB, again using a passively mode locked MQW ring laser, however the optical spectrum was not flat with variations up to 20 dB, the 3-dB bandwidth was still narrow (around 6 nm) and the fiber coupled optical average power was only 1 mW.

Asymmetric MQW (AMQW) lasers are MQW lasers with quantum wells (QWs) of different thicknesses and (or) composition within the same active region. QWs of different thicknesses and compositions generally emit at different wavelengths [9]; thus well designed AMQW lasers are suitable for broadband applications including the production of coherent frequency combs with wider optical bandwidth.

In this letter, for the first time, we report coherent frequency combs with 100 GHz spacing using a passive L-band two-section AlGaInAs/InP AMQW SMLLD. The AMQW SMLLD incorporates QWs of different thicknesses, maintaining the same well and barrier compositions across the active region. The use of the AlGaInAs material system for the waveguide core ensures good transport of holes and electrons across the QWs.

Figure 1(a) shows an optical microscope picture of the 100 GHz repetition frequency SMLLD device. The length of the entire cavity length is 432 μm. The length of the saturable absorption (SA) section is 10 μm, the gain section 412 μm and the isolation groove between the gain and SA sections 10 μm.



(a)

(b)

(c)

Fig.1 (a) Optical micrograph of SMLLD device used to produce coherent frequency comb with a 100 GHz spacing, (b) cross sectional SEM micrograph of the waveguide, (c) AMQW bandgap structure.

The fabrication processes were straightforward using conventional photolithography and similar to those described in [10] except that here a 2-μm-wide ridge waveguide was formed by etching 7-μm-wide trenches alongside the ridge, as shown in Fig. 1(b). Electrical isolation between the SA and the gain section contact metals was realized by removing the 250-nm-thick heavily doped top p-type contact layer using wet chemical etching. The typical resistance across the 10 μm gap was 1 kΩ. The sample was cleaved into individual devices with both facets left as-cleaved; the singulated lasers were mounted epilayer up on copper heat sinks and tested under CW conditions at 20 °C.

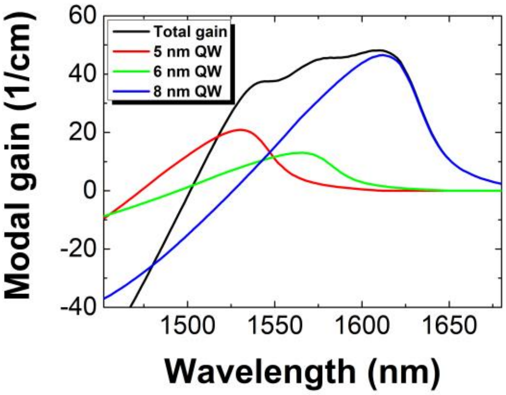


Fig. 2. Calculated modal gain spectra and contributions of the individual QWs to the total gain of the AMQW structure at threshold.

The wafer structure uses the AlGaInAs/InP material system and is similar to that described in [10]. The only difference is that here the active region consists of three 8-nm, one 6-nm, and two 5-nm-thick AlGaInAs compressively strained QWs separated by six 10-nm and one 5-nm tensile strained quantum barrier layers (Fig. 1(c)).

The flatness and width of the optical spectrum depend on the, thicknesses, compositions and number of QWs. We have simulated the contributions to the gain from the 5 nm, 6 nm and 8 nm thick QWs, and the total AMQW modal gain based on the Luttinger–Kohn Hamiltonian approach [11] and many-body theory [12]. With the assumption of the same injection current density across the active region, the calculated modal gain spectra of the AMQW structure and the contributions from the three kinds of QWs with same composition and different thickness at threshold current were investigated. The model for simulating the modal gain used the following experimental measurements: the internal loss measured by the Hakki–Paoli (HP) method was 16.5/cm, the output power slope efficiency was 30% (taking account of both facets) and the cavity facet reflection was 0.28. The internal loss of this AMQW structure is therefore very similar to that of ~20/cm for a conventional AlGaInAs/InP laser [13]. As can be seen from Fig. 2, the contribution from the 8-nm-thick wells is dominant at longer wavelengths (near 1612 nm), the 6 nm thick well dominates the middle wavelength region (around 1566 nm), and 5-nm-thick wells mainly affect the gain at shorter wavelengths (near 1530 nm). The AMQW structure has a relatively flatter and wider gain spectrum than any of the individual QWs.

Figure 3 shows the output power from the SA side as a function of the gain current (I_{Gain}) and the SA reverse bias voltage (V_{SA}) is increased from 0 V to −3 V in steps of −1 V. The threshold current was 30 mA and the slope efficiency was 14.2% at V_{SA} of 0 V. The output power was 17 mW at a gain current of 150 mA and V_{SA} of 0 V, and the plug efficiency was about 14%. When V_{SA} was increased to −3 V, the laser threshold current increased to 34 mA and the slope efficiency decreased to 11.4%.

Passive mode locking (ML) of the device was obtained by forward biasing the gain section and reverse biasing the SA section. The ML behavior of the device was characterized in detail by measuring the optical spectrum, and autocorrelation trace simultaneously, using a setup similar to that described in [13].

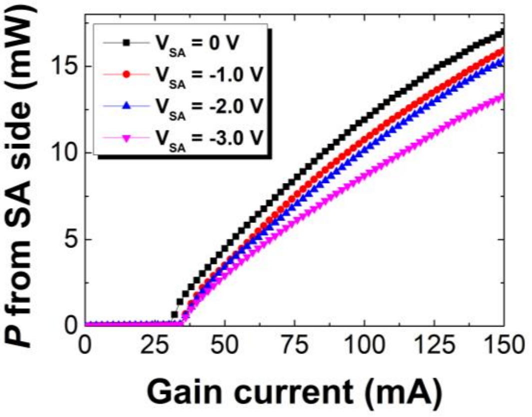
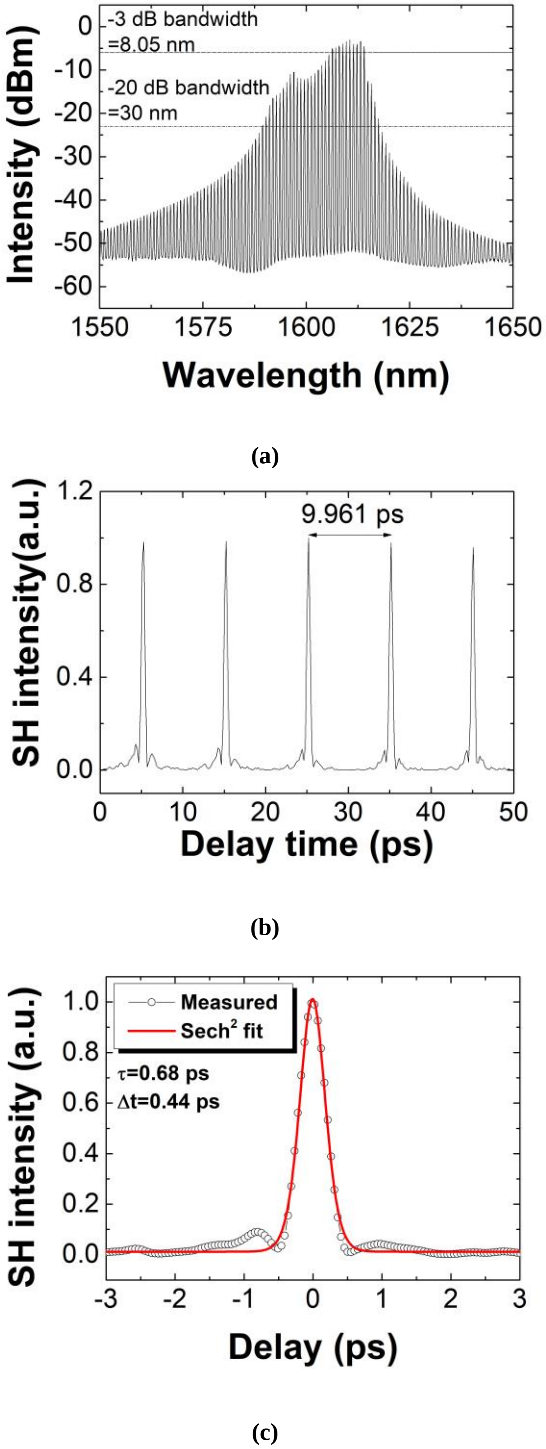


Fig. 3. The output power from SA side as a function of the gain current for SA reverse voltage was increased from 0 V to -3 V in steps of -1 V.

Pure ML, i.e., a pulse train with close to 100% modulation showing no Q-switching instabilities, self-pulsations or unstable/incomplete (less than 100% modulation) ML [13], could be achieved for a V_{SA} range from −1.1 V to −2.3 V and gain current from 30 mA to 150 mA. Typical trends associated with SMLLDs were observed, with the pulse width shortening as the reverse voltage was increased and widening as the gain current was increased. The shortest pulse width was obtained at a gain current of 100 mA, where the impact of SPM [6] is smallest, and with V_{SA}= −2.0 V, which we attribute to a short SA recovery time [14]. Figure 4(a) shows the optical spectrum (measured with 0.07 nm resolution bandwidth) under these operating conditions. The central wavelength is at 1610.0 nm and the −3 dB bandwidth is 8.05 nm, which covers 10 optical lines with a spacing of 0.868 nm (~100 GHz). The central wavelength of 1610 nm is nearly the same as that of the simulation result of 1612 nm in Fig. 2. The −20 dB bandwidth was 30 nm which covers 34 optical lines of 100 GHz spacing. For the pulse measurements, a Femtochrome background-free intensity autocorrelator was used. Figure 4(b) shows the SH intensity autocorrelation of the pulse train with a period of 9.961 ps, which corresponds to a repetition frequency of 100.4 GHz and is consistent with the spectral line spacing of 0.868 nm in Fig. 4(a). Figure 4(c) shows the autocorrelation signal of an isolated pulse with a pulse width of 0.68 ps (FWHM), which deconvolves to 0.44 ps pulse duration if a sech2 pulse shape is assumed. To our knowledge, this 440 fs pulse width is the shortest ever reported from any directly electrically pumped QW SMLL without external pulse compression. It can even be compared to the pulse length of 312 fs reported for a single-section 1.55 μm InAs/InP quantum dot SMLLD operating at 92 GHz [15]. The improvement in pulse width reported here compared to those from conventional SMLLDs in which the MQWs have the same QW thickness reported in [8] (0.7 ps) can be attributed to the AMQW configuration, which increases the optical bandwidth in the gain section. The time-bandwidth product of the pulse is equal to 0.41, which is somewhat larger than the transform limit (0.315) of a pulse with sech2 profile, implying there is still chirp imposed on the generated pulses and the pulse width may be reduced further by implementing external compressing schemes. This chirp is likely to be arise from SPM in the gain section [6]. The output average power is 10.15 mW and peak power is 202 mW.



(a)

(b)

(c)

Fig. 4. (a) Measured optical spectrum of the pulse train, (b) autocorrelation pulse train, and (c) autocorrelation trace of an isolated pulse for gain current of 100 mA and V_{SA}= −2.0 V.

The AMQW SMLLD can be used as it stands as a practical comb source in WDM communications systems. Such systems can also make use of phase coherence across the comb to simplify the digital signal processing at the receiver [16]. Applications which require higher optical precision will generally need carrier–envelope phase (CEP) stabilization [17] but it can be assumed that the optical spectral shape will not change significantly after stabilization. Therefore, conclusions can be made about the AMQW SMLLD's properties as a comb source from its unstabilized performance. A more detailed analysis of the ML properties and temperature behavior is currently being carried out, including measurements of CEP, timing jitter, low-frequency noise, phase noise and relative intensity noise.

In conclusion, a coherent frequency comb with a 100 GHz line spacing based on an AMQW SMLLD has been demonstrated. Device fabrication is straightforward using conventional photolithography. The widest −3 dB optical bandwidth is 8.05 nm and −20 dB bandwidth is 30 nm. These bandwidths are comparable to those of optical frequency combs generated by quantum dot or quantum dash SMLLDs and ring-based MQW designs, but the output power is higher (10 mW average) and the pulse width is much shorter with a record short pulse width of 440 fs being achieved.

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