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Coherent Frequency Comb with 100 GHz Spacing Generated by an Asymmetric MQW Mode-Locked Laser

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Abstract: A coherent frequency comb with a 100 GHz frequency spacing, −3 dB bandwidth of 8.05 nm and pulse width of 440 fs, was generated using an asymmetric multiple quantum well mode locked laser.

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Integrated semiconductor mode locked laser diodes (SMLLDs) are compact and robust sources for generating coherent frequency combs. 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]. 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, 1.55 µm SMLLDs based on InAs–InP quantum-dot materials are still relatively immature and suffer from lower modal gain and have wider reported pulse widths than those of 1.55 µm multiple quantum well (MQW) SMLLDs. Corral et al. [3] 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. [4] 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 as low as 1 mW. Here we report an asymmetric MQW (AMQW) SMLLD that incorporates quantum wells (QWs) of different thicknesses, maintaining the same well and barrier compositions across the active region. QWs of different thicknesses and compositions generally emit at different wavelengths; thus well designed AMQW lasers are suitable for broadband applications including the production of coherent frequency combs with wider optical bandwidth.

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 is 412 µm and the isolation groove between the gain and SA sections is 10 µm. The fabrication processes were similar to those described in [5] 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). The wafer structure uses the AlGaInAs/InP material system and is similar to that described in [5]. 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 barrier layers (Fig. 1(c)). 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.

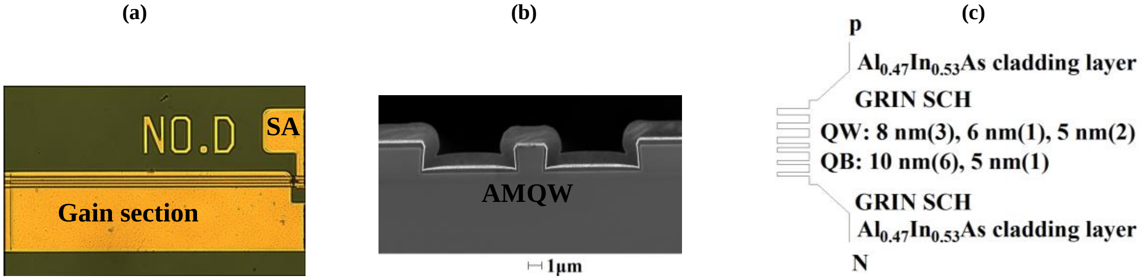

Fig. 1. (a) Optical micrograph of SMLLD device used to produce coherent frequency comb with a 100 GHz spacing, (b) cross sectional SEM micrograph of the waveguide, (c) AMQW bandgap structure.

The threshold current was 30 mA and the slope efficiency was 14.2% at 0 V SA reverse voltage (V_{SA}). The output power was 17 mW at a gain current of 150 mA. Pure mode locking 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 and V_{SA}= −2.0 V, with Fig. 2(a) showing the optical spectrum under these 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 −20 dB bandwidth was 30 nm which covers 34 optical lines of 100 GHz spacing. Fig. 2(b) 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 sech^2 pulse shape is assumed. To our knowledge, this 440 fs pulse width is the shortest ever reported from a 1.55-µm-range QW SMLLD. The measured period of the emitted pulse train is 9.961 ps, which corresponds to a repetition rate of 100.4 GHz and is consistent with the spectral line spacing 0.868 nm in Fig. 2(a). 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 sech^2 profile. The output average power is 10.15 mW and peak power is 202 mW.

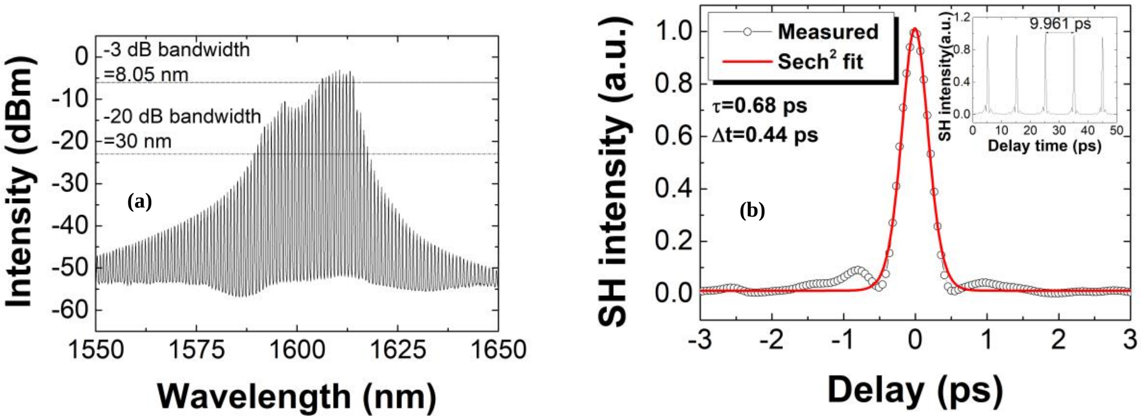

Fig .2. (a) Measured optical spectrum of the pulse train, and (b) autocorrelation trace of an isolated pulse with the autocorrelation pulse train shown inset for gain current of 100 mA and V_{SA}= −2.0 V.

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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