

# Monolithic 1.55 $\mu\text{m}$ GaInNAsSb quantum well passively modelocked lasers

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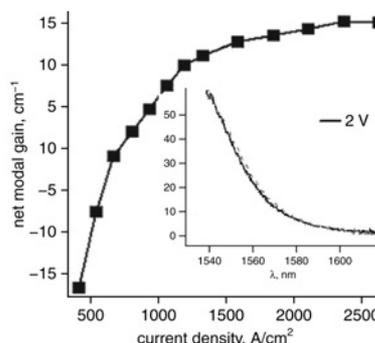
The first monolithic GaInNAsSb quantum well 1.55  $\mu\text{m}$  passively modelocked lasers grown on a GaAs substrate are reported. A repetition rate of up to 13.2 GHz and an optical pulse width as small as 26 ps have been realised.

**Introduction:** The compact size, low power consumption, and direct electrical pumping of monolithic modelocked lasers (MLLs) make them promising candidates for inter-chip/intra-chip clock distribution, high-bit-rate optical time division multiplexing (OTDM), coarse wavelength-division multiplexing (CWDM), impulse response measurement of optical components, electro-optic sampling and arbitrary waveform generation when combined with an external modulator [1, 2]. Quantum dot (QD) active regions in MLLs have received much recent attention in this area of research, but the wavelength of operation for the common InAs QD system on GaAs substrate is limited to about 1.3  $\mu\text{m}$  [3, 4]. The InAs QD or quantum dash (QDash) on InP materials technology that emits in the highly desirable 1.55  $\mu\text{m}$  band is still relatively immature [5] and suffers somewhat from a high threshold current and a high internal loss in the waveguide. Modelocking at 1.55  $\mu\text{m}$  in devices on a GaAs substrate is highly desirable because of the more mature fabrication technology and lower loss optical waveguides compared to InP processes. In this Letter, monolithic passively modelocked lasers emitting at 1.55  $\mu\text{m}$  and fabricated on a GaAs substrate are reported for the first time. The devices used a single quantum well (SQW) GaInNAsSb active region for both the gain and absorber regions. The modal gain and loss of the GaInNAsSb active region were measured using the segmented contact method, and the characteristics that make the GaInNAsSb materials system desirable for semiconductor modelocked lasers are discussed. A repetition rate up to 13.2 GHz and an optical pulse width as small as 26 ps have been realised.

**Device structure and growth:** The laser diode layer structure consisted of a single 75  $\text{\AA}$  Ga<sub>0.62</sub>In<sub>0.38</sub>N<sub>0.03</sub>As<sub>0.943</sub>Sb<sub>0.027</sub> QW (+2.5% strain) surrounded on either side by 210  $\text{\AA}$  GaN<sub>0.04</sub>As<sub>0.96</sub> barriers (-0.81% strain) embedded in a GaAs/Al<sub>0.33</sub>Ga<sub>0.67</sub>As waveguide. The layer design has previously demonstrated significantly lower threshold current density at long wavelengths [6]. A cavity length study of ridge waveguide lasers made from the material, under the assumption of a logarithmic gain-current relation, was performed at room temperature to extract important device quantities: the gain coefficient ( $g_0$ ) was 1800  $\text{cm}^{-1}$ , the internal efficiency ( $\eta_i$ ) equalled 62%, and the internal loss ( $\alpha_i$ ) was 4.8  $\text{cm}^{-1}$ . The characteristic temperatures for the threshold current density ( $T_0$ ) and external efficiency ( $T_1$ ) were 71 and 171 K, respectively, near room temperature [7]. These early results in the GaInNAsSb QW materials system are already competitive with InGaAsP/InP or AlGaInAs/InP-based laser diodes. In addition, except for the case of *p*-type doped QDs, the  $T_0$  value is generally better than that achieved in most QD lasers at 1.55  $\mu\text{m}$ .

**Experiment:** 3  $\mu\text{m}$ -wide ridge waveguides with cavity lengths in the range 3.0–3.5 mm were fabricated with equal-length, electrically-isolated anode contacts, each 0.5 mm in length. One end of the device was used to measure the net modal gain and loss spectra of the GaInNAsSb active region using an improved segmented contact method [8]. Fig. 1 shows the gain and loss data, respectively, which are relatively modest and comparable to QD active region values. The FWHM of the net modal gain spectrum at a current density of 2  $\text{kA}/\text{cm}^2$  is about 96 nm, which is competitive with inhomogeneously broadened QD systems and beneficial for locking many lasing modes. The long-wavelength limit of the loss spectra (about 3  $\text{cm}^{-1}$ ) gives a reliable estimate of the internal loss value that is just slightly higher than the internal loss in GaAs/AlGaAs low-loss waveguides. For lasers with modelocked repetition rates less than about 10 GHz (cavity length greater than 4 mm), this low internal loss is particularly important for realising efficient devices. The segmented waveguides were then reconfigured into MLLs by wire bonding sections together to form separate gain and absorber regions. A highly reflective coating (95%) was applied to the mirror facet next to the absorber. Owing to the higher differential gain in the gain section and similar absorption in the absorber compared with QD materials, smaller ratios between the gain section length and the absorber

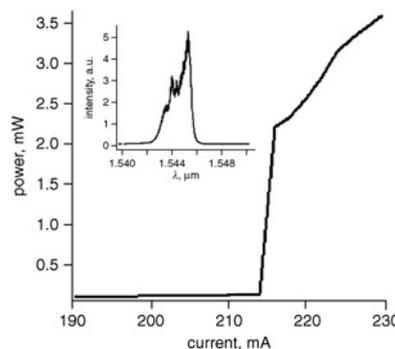
length were chosen [9, 10]. Two 2-section MLLs were fabricated and tested including: a 3.5 mm cavity with a 1 mm absorber ( $A_{1,0}G_{2,5}$ ) and a 3 mm cavity with 1 mm absorber ( $A_{1,0}G_{2,0}$ ). Both the  $A_{1,0}G_{2,5}$  and  $A_{1,0}G_{2,0}$  devices realised stable and complete modelocking.



**Fig. 1** Room-temperature net modal gain of GaInNAsSb single quantum well measured using segmented contact method

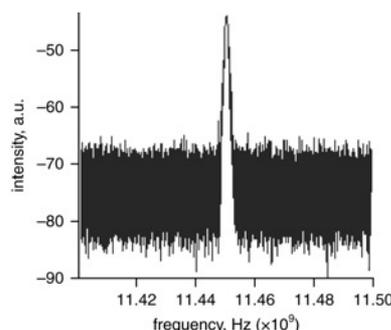
Inset: absorption spectrum in units of  $\text{cm}^{-1}$  at reverse voltage of 2 V

The L-I curve and optical spectrum of device  $A_{1,0}G_{2,5}$  are shown in Fig. 2. The device operation was centred at a wavelength of 1.545  $\mu\text{m}$ , at room temperature, with a threshold current density of 2430  $\text{A}/\text{cm}^2$ . With a gain current of 250 mA and a reverse bias of 2 V on the absorber, the device  $A_{1,0}G_{2,5}$  had a repetition rate of 11.4 GHz, as shown in the Fig. 3. The complete modelocking was confirmed with both the autocorrelator and a high-speed digital oscilloscope. The pulse shapes, which are shown in Fig. 4, were obtained from a background-free Femtochrome model autocorrelator, and the pulse width was 32 ps at the stated bias conditions. The device  $A_{1,0}G_{2,0}$  operated at a repetition rate of 13.2 GHz with a pulse width of 26 ps under a reverse bias of -1.9 V and gain current of 200 mA.

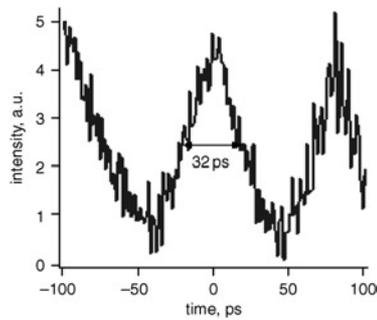


**Fig. 2** L-I curve and modelocked lasing spectrum of device  $A_{1,0}G_{2,5}$

Inset: optical spectrum uses a 250 mA gain current on 2.5 mm gain section and reverse bias of -2 V applied on 1 mm absorber



**Fig. 3** ESA spectrum of device  $A_{1,0}G_{2,5}$  with 250 mA gain current on 2.5 mm gain section and reverse bias of -2 V applied on 1 mm absorber



**Fig. 4** Optical pulse shape of device  $A_{1.0}G_{2.5}$  with 250 mA gain current on 2.5 mm gain section and reverse bias of  $-2$  V applied on 1 mm absorber, obtained by autocorrelator

**Conclusions:** We have demonstrated 1.55  $\mu\text{m}$  passive MLLs with a single GaInNAsSb quantum well active region. Complete modelocking up to 13.2 GHz and a pulse width as small as 26 ps were achieved under room temperature operation. It is the first GaAs-based passively semiconductor modelocked laser that emits in the highly desirable 1.55  $\mu\text{m}$  band.

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