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# Investigation of spectrally broad gain multiple-width quantum well material for colliding pulse mode-locked operation

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**Abstract:** The first colliding pulse mode-locked operation of devices fabricated from broad gain spectrum multiple-width quantum well material is reported. Using multiple-width quantum wells in the active region of the InGaAs/InAlGaAs material system, 35% broader gain bandwidth has been obtained in comparison to the conventional identical width quantum well material. For the colliding pulse mode-locked operation, observation made from the optical spectra showed that the multiple-width quantum well laser provided one extra optical mode with the pulse width narrowing by 7% in comparison to the identical width quantum well laser.

## 1 Introduction

Multiple-width quantum well (MWQW) semiconductor lasers have been successful in the past for achieving broad tunability ( $> 50$  nm) [1], as well as for studying carrier non-uniformity across the active region of a multi-quantum well (MQW) lasers [2]. Lee and Lin [3] in recent years have reported on the active mode-locking of MWQW lasers, where they obtained pulse widths in the range 13–21 ps over a tuning range of 795–857 nm. The aim of this work was to investigate the usage of MWQW lasers in achieving colliding pulse mode-locked (CPM) operation and to carry out comparison with devices made from conventional identical-width quantum well (IWQW) material. Employing multiple-width wells in an active region increases the gain bandwidth, and for mode-locked operation the MWQW CPM device should provide a wider optical spectrum in comparison to the IWQW device. In addition, for mode-locked operation, since the optical pulse width is inversely proportional to the gain bandwidth [4], employing multiple-width wells in an active region should provide a shorter optical pulse width in comparison to that for IWQW material.

## 2 Wafer structures

The two structures employed for the experiment were as follows: the wafers were grown on n-doped InP substrate by metal organic vapour phase epitaxy (MOVPE) at the III–V semiconductor facility at Sheffield University. Both wafers consisted of heavily p-doped ( $5 \times 10^{18} \text{ cm}^{-3}$ ) InGaAs contact layers; p-doped ( $5 \times 10^{17} \text{ cm}^{-3}$ ) and n-doped

( $5 \times 10^{17} \text{ cm}^{-3}$ ) InP cladding layers and undoped InAlGaAs waveguide core, with the active region placed at the centre of the core. The active region of IWQW wafers consisted of six lattice-matched  $\text{In}_{0.52}\text{Ga}_{0.47}\text{As}$  quantum wells of width 6.7 nm with 9 nm wide InAlGaAs barriers. For MWQW wafer structure, the active region included (from the p-side of the cladding layer) three 7.4 nm, three 6.7 nm and three 6.0 nm lattice-matched wells separated by 9 nm wide InAlGaAs barriers. The energy gaps between  $E_1$ – $\text{HH}_1$  transitions for quantum wells of width 6, 6.7 and 7.4 nm were calculated to be 807, 794, and 785 meV, respectively, using a Schrödinger numerical problem solver.

## 3 Spectral gain measurements

The experimental method used to carry out spectral gain measurement is described elsewhere [5]. The gain measurements were carried out under pulsed current injection with the devices being temperature controlled and all the data taken at room temperature. The TE gain spectra, obtained below threshold for the IWQW and MWQW devices, are shown in Fig. 1. At zero net modal gain, confined material gain is equal to the internal optical losses [5]. From Fig. 1a, for the IWQW device, it can be seen that, at current density just below  $1.5 \text{ kA cm}^{-2}$ , the net modal gain contribution is zero at 1560 nm, corresponding to the calculated 6.7 nm QW TE emission wavelength.

For the MWQW device (Fig. 1b), the 7.4 nm QWs with lower density of states, in comparison to the 6.7 and 6.0 nm QWs, reached the transparency level first, and hence contributed to the zero net modal gain before the narrow wells at a current density of  $2\text{--}3 \text{ kA cm}^{-2}$ . The 6.7 nm QW contributed to gain at  $3\text{--}4 \text{ kA cm}^{-2}$  and the 6.0 nm QWs contributed to gain at current density just below  $6 \text{ kA cm}^{-2}$ .

From the TE gain spectra, at approximately 2.5 times above the zero net modal gain current density, the full-width at half-maximum (FWHM) measured for the MWQW device showed an increase of 35% in comparison to the IWQW device. A greater gain peak shift was observed for the MWQW device than for the IWQW device. For example, the peak shift observed when varying between zero net modal gain current density and twice the zero net modal gain current density for MWQW material was 32.7 nm in comparison to 18.5 nm for IWQW material.

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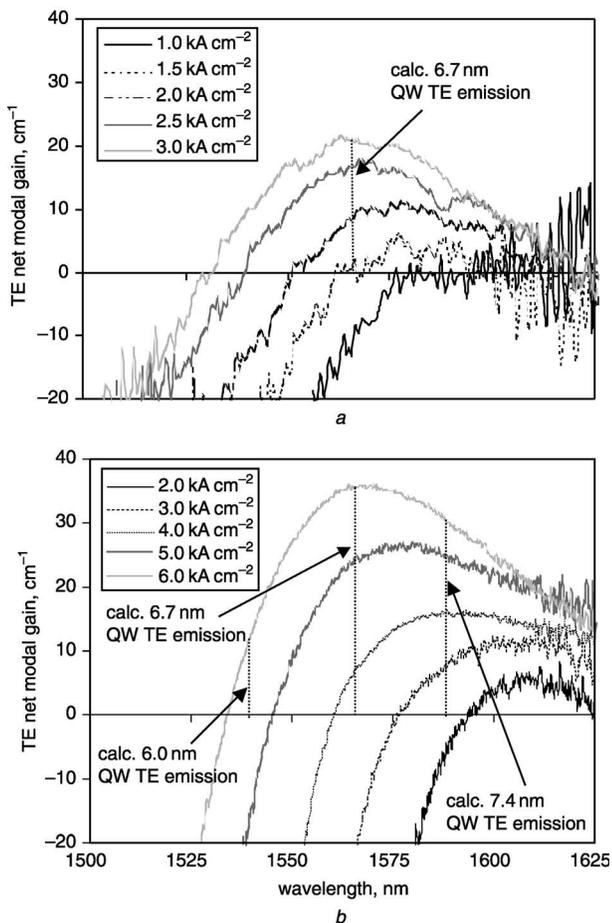
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**Fig. 1** TE gain spectra

a IWQW material

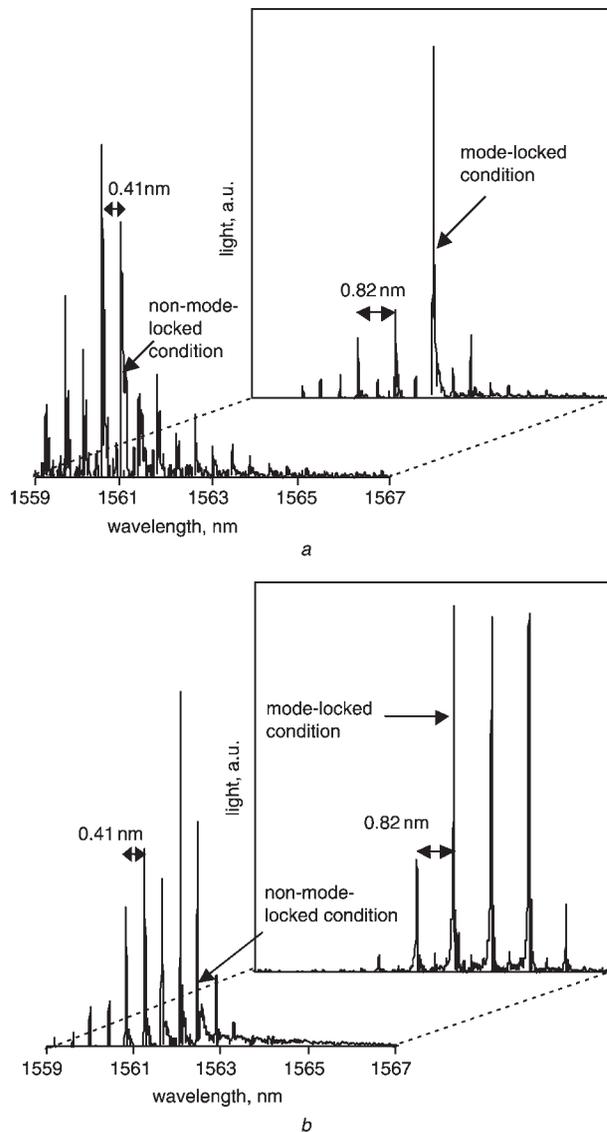
b MWQW InGaAs/InAlGaAs QW material

The IWQW gain spectra showed that, as current density increased, the gain spectra broadened towards shorter wavelength. However, the MWQW gain spectra showed that, as current density increased, the gain spectra broadened towards both longer and shorter wavelengths, indicating asymmetric broadening of the gain in MWQW material.

#### 4 Colliding pulse mode-locked experiment

To investigate the effect of the broad gain spectrum provided by the MWQW device, optical spectra were obtained under the mode-locked condition for both IWQW and MWQW CPM lasers. For the CPM devices under investigation, the total cavity length of each device was 800  $\mu\text{m}$ , with a 20  $\mu\text{m}$  wide absorber located at the centre of the laser cavity. The current was injected into the device through a 3.5  $\mu\text{m}$  wide ridge waveguide. The calculated repetition rate in mode-locked condition is around 104 GHz. **Figure 2** shows the optical spectra of the output from the (a) IWQW and (b) MWQW CPM laser diodes under non-mode-locked and mode-locked operation. The mode spacing for both IWQW and MWQW CPM devices for the non-mode-locked condition is 0.41 nm.

To achieve mode-locking, the gain and absorber sections were biased appropriately in both the devices to produce mode-space doubling from 0.41 to 0.82 nm. This feature of mode-space doubling is well known for CPM operation, which arises from the coherent interaction of two optical pulses in the saturable absorber section. In addition, from [6] it has been theoretically proven that for CPM the observation of mode-space doubling is a signature of



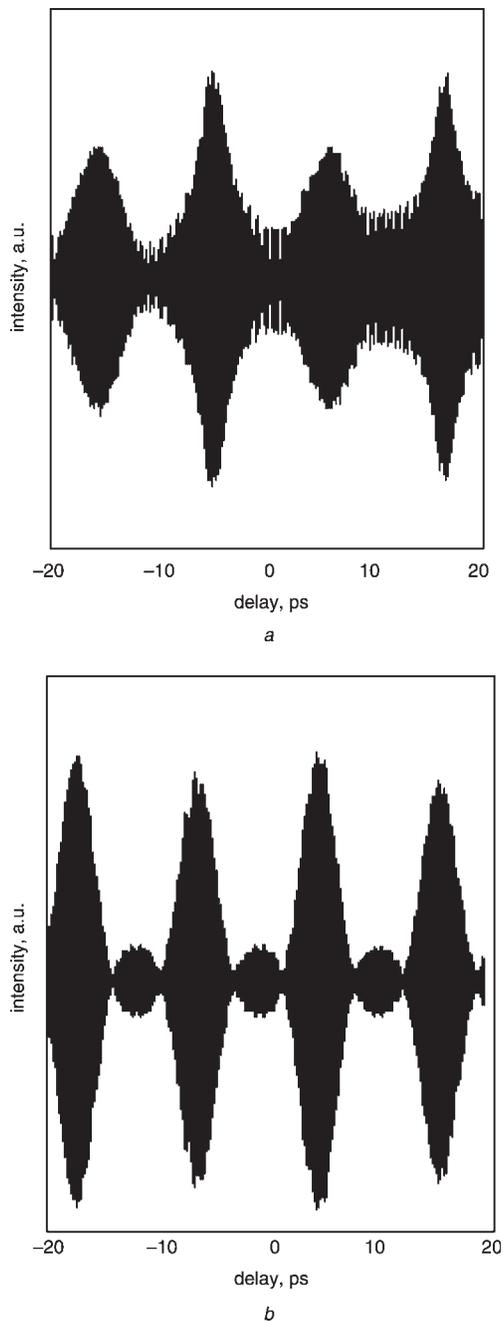
**Fig. 2** Optical spectra of mode-locked and non-mode-locked conditions

a IWQW laser diodes

b MWQW CPM laser diodes

mode-locked operation. From **Fig. 2** it can be seen that, for the mode-locked condition, the MWQW device provides one extra optical mode in comparison to the IWQW CPM device.

From the early days of ultra-short optical pulse measurements, it has been known that transform limited pulse widths can be measured using an electric field (linear) autocorrelation technique [7]. In general, it has been previously observed that the pulse width obtained from the colliding pulse mode-locked semiconductor lasers were transform limited [8, 9], probably because the pulses have low peak powers. To verify the advantage of broad gain spectrum provided by the MWQW device, we carried out electric field autocorrelation of both IWQW and MWQW CPM lasers, under mode-locked conditions. From the electric-field autocorrelation trace (**Fig. 3**), for both the IWQW and MWQW devices, it can be seen that the phases between each of the successive pulses are related, which is a clear signature of mode-locking and is presented in both cases. Pulse widths of 3.0 and 2.8 ps were measured for IWQW and MWQW devices, respectively. This demonstrates that the pulse width obtained for the MWQW device shortened by approximately 7% in comparison to that of the IWQW device.



**Fig. 3** Electric-field autocorrelation traces

a IWQW devices  
b MWQW CPM devices

Although the gain bandwidth obtained for the MWQW device was 35% broader, the pulse width for the MWQW device narrowed only by 7% in comparison to the IWQW device. To investigate the small decrement in the pulse width of the MWQW device (in comparison to the IWQW device) under mode-locked condition, a broad area laser optical spectra comparison was carried out between the 500  $\mu\text{m}$  long IWQW and MWQW lasers, as illustrated in Fig. 4. From Fig. 4a, for the MWQW broad area laser at current injection just above threshold, a wide optical spectrum is obtained. However, at an injection current of 1.5 times above threshold (Fig. 4b) the laser output is dominated by recombination in the 7.4 nm wells with almost no contribution from the narrow 6.7 and 6.0 nm wells. When the current injection in the MWQW broad area device is 1.7 times above threshold (Fig. 4c), there are 1–2 longitudinal modes visible at shorter wavelength

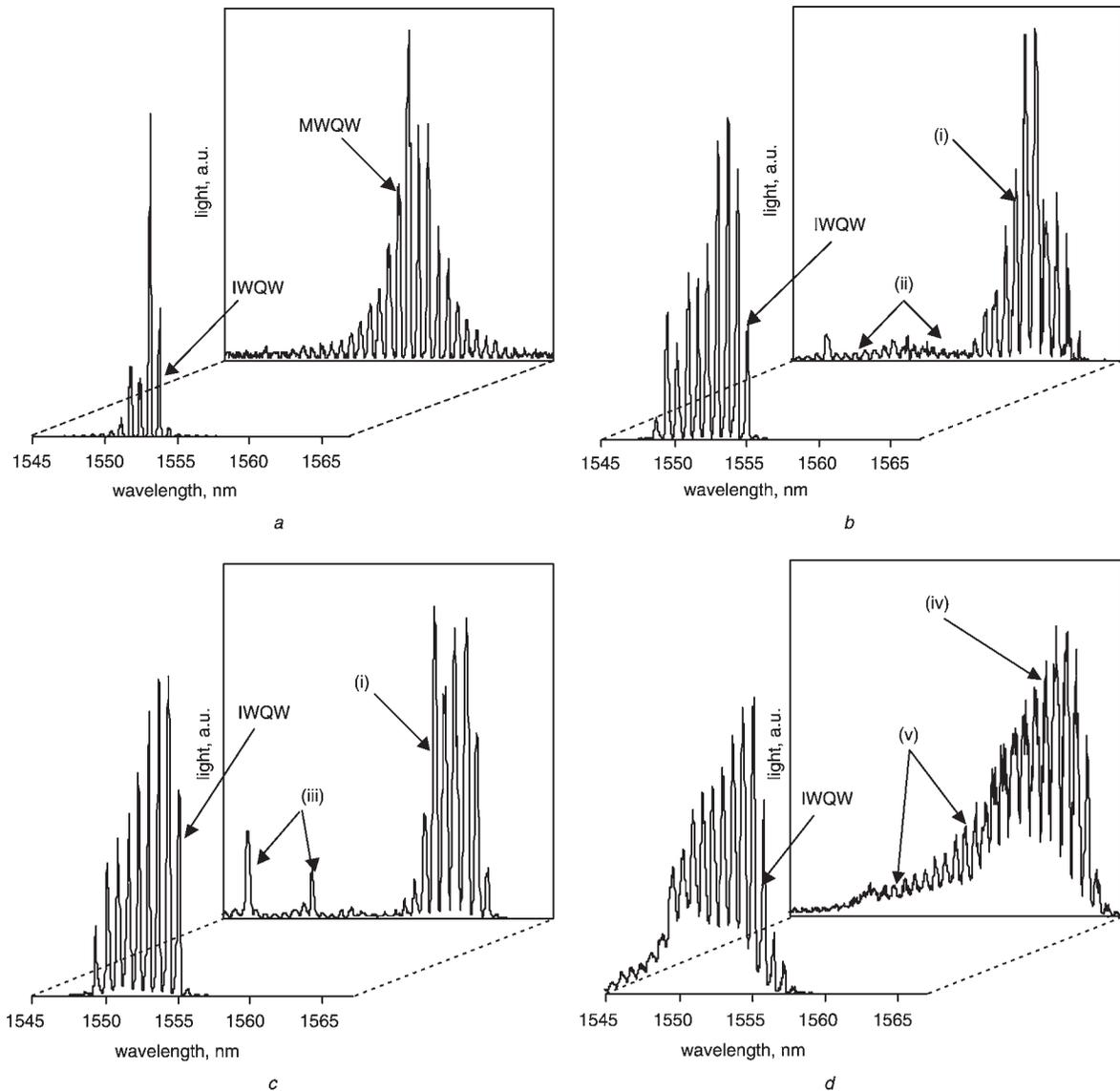
(<1555 nm). However, it is not until the MWQW laser is pumped approximately 2.6 times above threshold that the narrower 6.7 and 6.0 nm QWs contribute to laser operation, as shown in Fig. 4d.

## 5 Discussion

It has been observed that the spectral gain bandwidth provided by the MWQW device is 35% broader than that for the IWQW device. However, for the MWQW device, the gain bandwidth utilised for the mode-locked operation provided only one extra optical mode with the optical pulse width shortening by 7% in comparison to that of the IWQW device.

Past work on carrier distribution across the MQW structure has shown that holes, with lower mobility than electrons, are a dominating factor for determining the distribution of carriers across the active region [10]. Tessler and Eisenstein [11] reported that the carrier lifetime is also a crucial factor in carrier distribution in quantum well lasers, where the carrier lifetime above threshold is short in comparison to the transport time of the carriers between the wells. The decrease in the carrier lifetime above threshold is due to an increase in the stimulated emission rate, which results in most of the holes being trapped near the p-side of the active region with fewer holes reaching the wells closer to the n-side. In addition, Piprek *et al.* [12] reported an increase in the Auger recombination losses with rising current above threshold, reducing the carrier lifetime and consequently preventing a uniform carrier distribution. There is evidence that the MWQW structure in our experiment experienced strong non-uniform carrier distribution in comparison to the IWQW structure. This was apparent from the broad area optical spectra of the MWQW device (Fig. 4), where the MWQW laser preferred to operate at the wide 7.4 nm QW (located near the p-side of its active region). Because all the multiple-width wells in the MWQW structure did not contribute to the laser operation, the gain bandwidth utilised for mode-locked operation only broadened enough to provide one extra optical mode in comparison to the IWQW device.

Hence, to improve the carrier distribution across the active region of a MWQW structure, we recommend a MWQW structure such that the narrower QW, with shallower band offset discontinuity, is located near the p-side of the active region and the wider QW, with deeper band offset discontinuity, is located near the n-side of the active region. First, the holes are more likely to escape thermally from the shallow wells and move across the structure to the wells closer to the n-side of the active region, leading to a more uniform carrier density. Secondly, the narrow QWs have higher density of states in comparison to the wide QWs (hence requiring relatively greater number of carriers to reach the transparency), and as the carrier concentration decreases away from the p-side of the active region [13, 14], having a narrow well on the p-side may improve its probability of carrier capture because the carrier distribution is dominated by the holes, which are injected from the p-side of the active region. This way the carriers are more likely to be uniformly distributed across the active region of a MWQW structure. However, as reported in some literature [11, 15, 16], it is also likely that electrons are not evenly distributed across the active region, owing to coulomb attraction between electrons and holes, which make the electrons follow the hole concentration profile and pile up near the p-side of the active region. Therefore, if the hole distribution is more even, the electrons will distribute more evenly across the active region and consequently



**Fig. 4** Optical spectra comparison between IWQW and MWQW 500  $\mu\text{m}$  long broad area lasers

- (i) MWQW laser operating on wide 7.4 nm QW, located on the p-side of the active region
  - (ii) Suppressed optical modes
  - (iii) Optical modes operating on narrow QWs in a MWQW laser
  - (iv) MWQW laser optical modes operating on a wide 7.4 nm QW
  - (v) MWQW laser operating on narrow 6.7 and 6 nm QWs at high current injection; optical modes are more suppressed than 7.4 nm modes
- a Just above threshold  $J$   
 b  $1.5 \times J_{th}$   
 c  $1.7 \times J_{th}$   
 d  $2.6 \times J_{th}$

improve the overall device performance. A structure similar to the one we have recommended for improving the carrier distribution has in recent years been experimentally shown by Lin *et al.* to provide a much wider spectral bandwidth ( $\sim 300$  nm) in comparison to that of the two other MWQW structures investigated by them [17].

## 6 Conclusions

To our knowledge, this is the first report of CPM operation of lasers fabricated from spectrally broad MWQW material. However, the observations made from the optical spectra of the MWQW CPM laser, in mode-locked condition, showed only one extra optical mode, with the pulse width shortening by 7% in comparison to that of IWQW CPM laser. This is probably due of the strong non-uniform carrier distribution in the active region of the MWQW laser, which was observed experimentally from the optical spectra of

MWQW broad area laser at different current injections, where most of the gain was located on the p-side of the active region. Nevertheless, the successful mode-locking of the MWQW laser has ensured a possibility of mode-locking the MWQW laser which, with the aid of improvements in the carrier distribution across the active region, has a potential of producing a broader optical spectrum and consequently providing a shorter optical pulse width in comparison to the IWQW laser.

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