Quantum Well Devices For Mode-Locking Fibre Lasers

D.Atkinson, W.H.Loh+, M. Hopkinson*, R.Grey*, A.Seeds, P.Morkel+ and D.Payne+.

Introduction

The generation of picosecond duration pulses in the 1.55 micron wavelength region is of considerable interest for applications related to telecommunications. In the 1.06 micron region, picosecond pulses are useful for spectroscopy and the electro-optic sampling of high speed integrated circuits [1]. Passive mode-locking of fibre lasers using multiple quantum well (MQW) material can provide optical pulses with picosecond durations in both these wavelength regions.

The optical confinement and long lengths available, give doped fibre lasers high gain together with flexibility in physical configuration. The use of QWs with light incident perpendicular to the epitaxial layers, as passive saturable absorbers to mode-lock these lasers, is attractive because of their polarisation insensitivity and the wide range of wavelengths available. The semiconductor sample operating wavelength is governed by the materials, their compositions and dimensions used. In fibre, gain is provided in the 1.55 micron region by doping with Erbium whilst Neodymium is used for operation in the 1.06 micron region.

By integrating the saturable absorber and laser-cavity end mirror into a single semiconductor device we have generated picosecond pulses in very simple cavity configurations [2-4].

1.55μm Mode-Locked Fibre Lasers

In the 1.55 μm region, commonly used semiconductor materials are InGaAsP, InGaAs and InP, all with compositions lattice matched to InP, which is used as the substrate in epitaxial growth. At these wavelengths, InP is transparent and has a refractive index of approximately 3. Transmission devices suffer from unwanted Fabry Perot cavity effects due to reflection at the air-semiconductor interfaces. A typical wafer thickness of approximately 400 μm gives a Fabry Perot free spectral range of the order 1nm, frustrating the mode-locking performance.

To overcome this problem, the structure shown in Figure 1a was designed and grown by molecular beam epitaxy. This structure incorporates a multilayer Bragg reflector stack adjacent to the quantum well saturable absorption region. The reflector-stack alternate quarter-wave layers were chosen to give the maximum refractive index difference whilst not absorbing significantly at 1.55 microns; this required a quaternary composition of $In_{0.65}Ga_{0.35}As_{0.75}P_{0.25}$. The saturable absorber gave an excitonic absorption peak from the quantum wells at a wavelength of 1.55 μm. The 82 pairs of wells and barriers form the majority of a Fabry Perot cavity between the wafer surface and the Bragg reflector. The number of QWs was chosen to give a large reflectivity change from the sample upon saturation of the absorption. Hence we have a laser-cavity nonlinear end mirror with a semiconductor cavity only a few microns thick, rather than the 400 μm for a transmission device.

Small signal reflectivities from different areas of the wafer are shown in Figure 1b. The spatial variation is caused by a growth rate that decreases radially from the wafer centre. Each curve shows regions of high reflectivity due to reflection from the Bragg stack. Combined with this are the effects of excitonic absorption, reducing sample reflectivity for wavelengths below 1550nm, and, Fabry-Perot

---

Optoelectronics Research Centre, Dept. of Electronic & Electrical Engineering, University College London, Torrington Place, London. WC1E 7JE.

+ Optoelectronics Research Centre, University of Southampton, Southampton. SO9 5NH.

* SERC III-V Facility, Dept. of Electronic & Electrical Engineering, University of Sheffield, Mappin Street, Sheffield, S1 3JD.

resonances. The best mode-locking performance is achieved for regions of wafer close to area B where saturation of absorption should cause the sample reflectivity to rise from approximately 50% to 80%. The siting of the Bragg stack just beneath the QWs simplifies the laser cavity as the fibre end can be brought into contact with the semiconductor sample without requiring intermediate coupling optics.

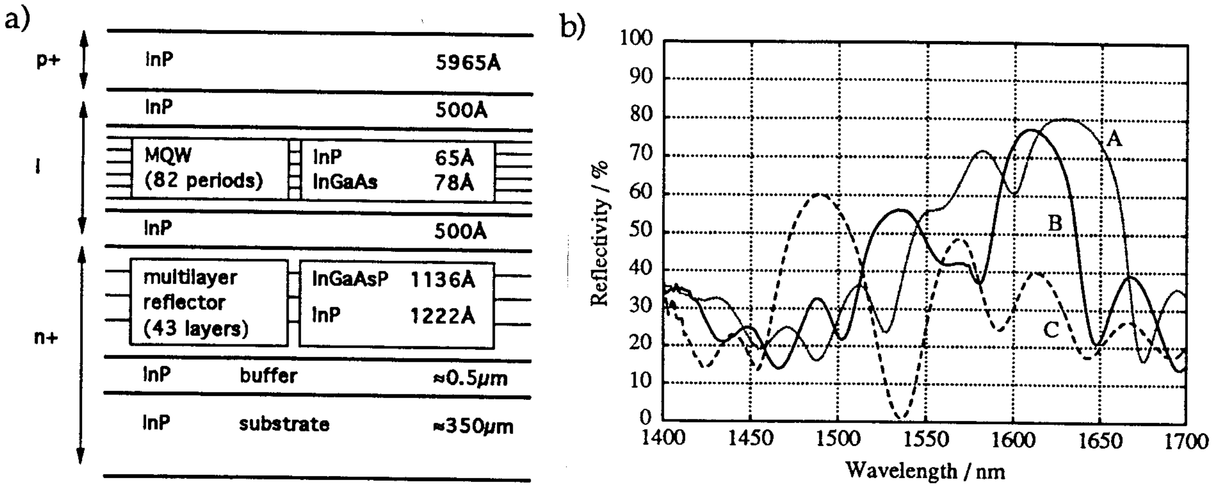

Figure 1a) Schematic of nominal semiconductor structure. Fig. 1b) Small signal reflectivity, normalised to a gold sample, taken at, A - wafer centre, B - 10mm from centre and C - 20mm from centre.

Using this material we achieved self-starting, stable, passively mode-locked pulses [2]. However, there was evidence from the optical spectrum that some light was penetrating the Bragg stack and being reflected from the back of the substrate. The substrate was roughened and the light from a 980nm Ti:sapphire pump was coupled into the Er^{3+} doped fibre using a fibre wavelength division multiplexer, the lasing cavity was formed between just the nonlinear semiconductor mirror and a cleaved fibre end (Figure 2). Mode-locked pulses of width 840fs and energy 2.7nJ were produced at the cavity fundamental round trip frequency of 22MHz [3]. The average ouput power was measured to be 60mW, at the maximum available launched pump power of 400mW. Stable harmonic mode-locking at the second and third harmonic has also been observed. Figure 3 shows the autocorrelation trace and optical spectrum when mode-locking at the third harmonic frequency.

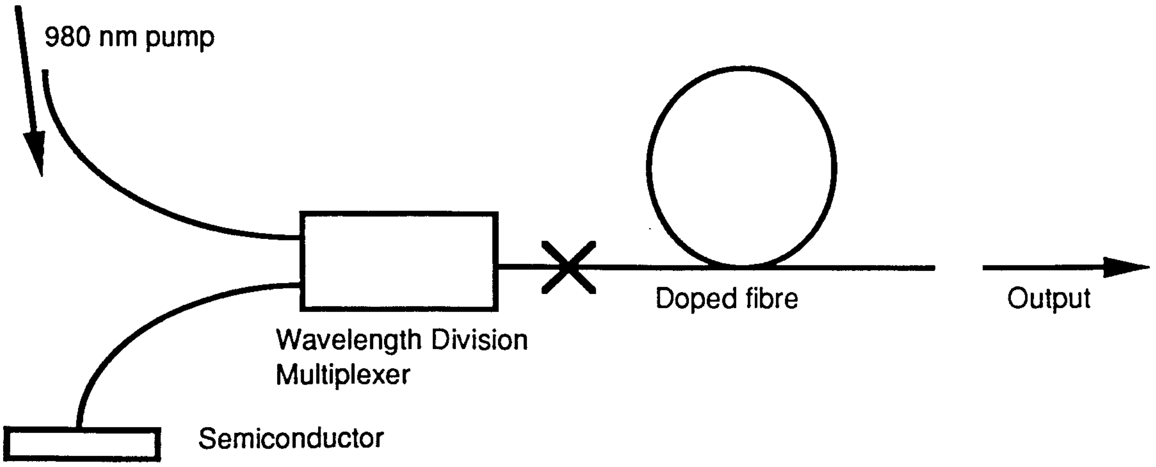

Figure 2. Experimental configuration for 1.55μm operation.

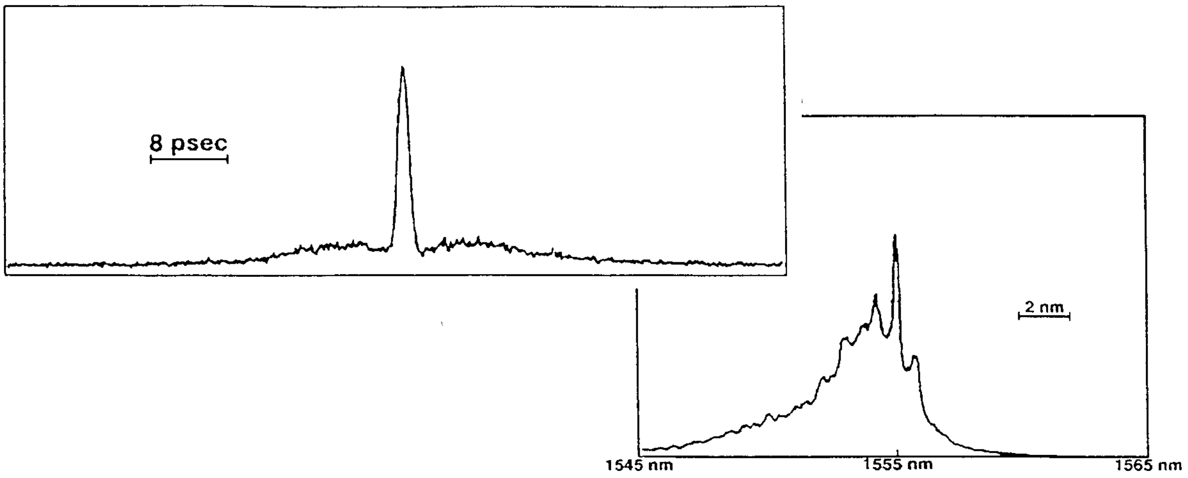

Figure 3. Autocorrelation (left) and corresponding optical spectrum (right) for third harmonically mode-locked pulses. Vertical scales are linear in intensity.

1.06µm Mode-Locked Fibre Lasers

For operation in the 1.06 micron region, the semiconductor structure shown in Figure 4a was grown, its small signal reflectivity is shown in Figure 4b. The design is similar to the 1.55 micron structure, although the materials are different. AlAs and GaAs are used for the Bragg stack; this system offers a larger refractive index difference between layers requiring a stack of fewer periods. The QW region contains lattice mismatched $In_{0.285}Ga_{0.715}As$ wells, separated by relatively thick (30nm) barriers, chosen to reduce the effects of strain relaxation in the structure[5]. The mismatch introduces strain into the wells, necessary to obtain absorption at 1.06 microns. If present, strain relaxation can lead to dislocation defects forming within the semiconductor. After growth the sample was found to have a high density of oval defects [6] $(10^4/cm^2)$, thought to be due to a recent change of the Gallium crucible. Both of these defect types may reduce the lifetime of photogenerated carriers in our sample and aid mode-locking. A single stripe laser diode pump and a 6cm length of fibre, doped heavily with Neodymium was used in the configuration shown in Figure 5. Pulses of 4ps duration and 18pJ energy were obtained.

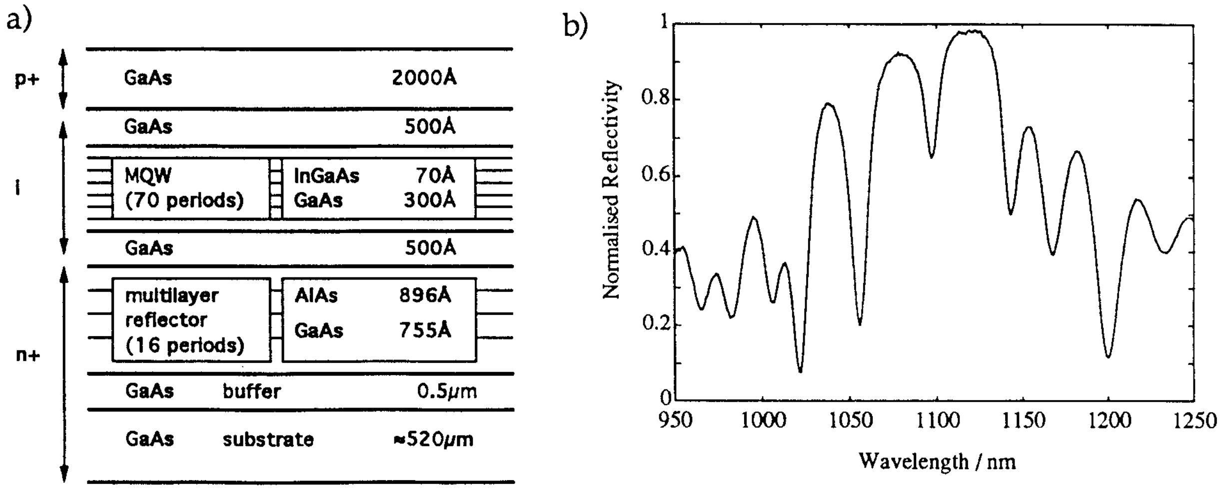

Figure 4a) Intended semiconductor structure for operation in 1.06µm region. Fig. 4b) Small signal reflectivity, normalised to a gold sample, taken from an area of wafer close to where mode-locking was observed.

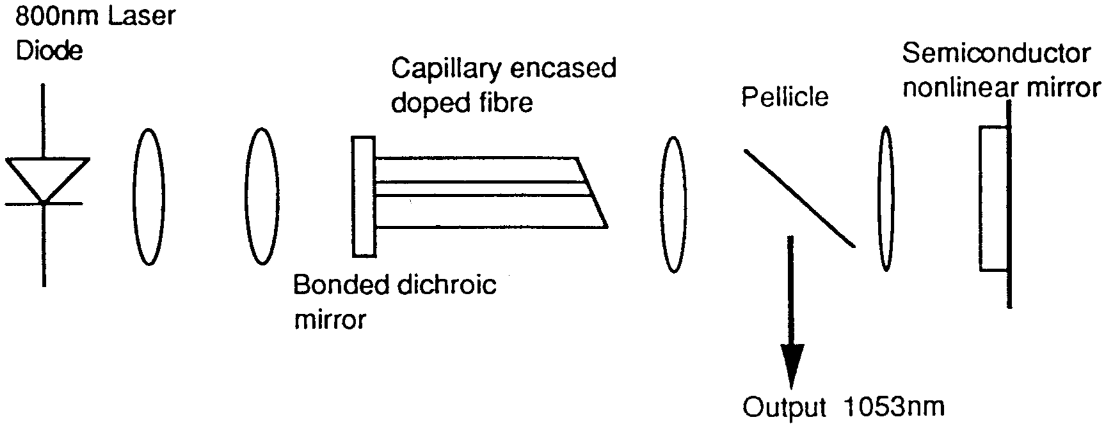

Figure 5. Mode-Locked configuration of diode-pumped Nd-fibre laser.

Conclusion

We have demonstrated that integrated semiconductor saturable absorber/cavity end mirrors can be used with doped fibre lasers to produce self-starting, passively mode-locked pulses. From very simple laser configurations we obtained picosecond and subpicosecond pulses. These systems are of interest as investigative tools in spectroscopy and for other applications requiring short optical pulses.

References

[1] K.J. Weingarten, M.J.W. Rodwell & D.M. Bloom "Picosecond optical sampling of GaAs Integrated Circuits" IEEE Journal of Quantum Electronics Vol 24(2) pp198-220 (1988)

[2] W.H. Loh, D. Atkinson, P.R. Morkel, M. Hopkinson, A. Rivers, A.J. Seeds & D.N. Payne "Passively Mode-Locked Er^{3+} Fiber Laser Using a Semiconductor Nonlinear Mirror" IEEE Photonics Technology Letters Vol 5(1) pp35-37 (1993)

[3] W.H. Loh, D. Atkinson, P.R. Morkel, M. Hopkinson, A. Rivers, A.J. Seeds & D.N. Payne "All solid-state subpicosecond passively mode-locked erbium-doped fiber laser" Accepted, subject to revision, by Applied Physics Letters

[4] W.H. Loh, D. Atkinson, P.R. Morkel, M. Hopkinson, A.J. Seeds & D.N. Payne "Passive Mode-Locking of Er^{3+} - Doped Fibre Lasers Using a Semiconductor Saturable Absorber and Integrated Bragg Stack" Optical Fiber Conference, San Jose, 1993

[5] R. Grey, J.P.R. David, P.A. Claxton, F. Gonzalez Sanz & J. Woodhead "Relaxation of strain within multilayer InGaAs/GaAs pseudomorphic structures" Journal of Applied Physics Vol 66(2) pp 975-977 (1989)

[6] P.S. Kop'ev, S.V. Ivanov, A.Yu Yegorov & D.Yu. Uglov "Influence of growth parameters and conditions on the oval defect density in GaAs layers grown by MBE" Journal of Crystal Growth Vol 96 pp 533-540 (1989)