Diode-pumped Self-starting Passively Mode-locked Neodymium-doped Fibre Laser

W H Loh, D Atkinson, P R Morkel, R Grey**, A J Seeds* and D N Payne*

Optoelectronics Research Centre, University of Southampton, Southampton SO9 5NH, United Kingdom

**Optoelectronics Research Centre, Dept of Electronic and Electrical Engineering, University College London, London WC1E 7JE, United Kingdom*

***SERC III-V Semiconductor Facility, Sheffield University, Sheffield S1 4DU, United Kingdom*

Abstract

A Nd^{3+}-fibre laser pumped by a single stripe laser diode has been passively mode-locked using a semiconductor saturable absorber/end mirror as the mode-locking element. A 6 cm length of heavily doped fibre was used to minimise the effects of positive group velocity dispersion, and stable mode-locking with pulses of 4 psec duration was obtained at the laser wavelength of 1053 nm.

Recently, there have been a considerable number of reports on the development of passively mode-locked Nd-doped lasers to generate short pulses in the 1 μm wavelength regime[1-7]. A convenient 1 μm short pulse source should be very useful in a large number of applications, such as spectroscopy and the electro-optic sampling of high speed integrated circuits. Both the Nd:YAG and Nd:YLF lasers have been successfully mode-locked using some new techniques[3-5]. These lasers, however, have relatively narrow gain bandwidths, which limit the shortest possible pulses to more than one picosecond. This limitation may be circumvented by using disordered crystal[6] or glass fibre hosts. With rare-earth doped bulk crystals, however, relatively high pump powers and low-loss laser cavities are typically required, which limit the use of simple intracavity saturable absorbers. The doped fibre thus has its advantages, as its strong waveguiding nature transforms it into a high gain medium with very low pump power requirements. A passively mode-locked Nd-doped fibre laser producing femtosecond pulses has been reported using nonlinear polarization evolution as the mode-locking mechanism[7]. While this technique is capable of producing very short pulses, it is not easily self-starting, and the optical powers and fibre lengths required to achieve sufficient nonlinearity to establish mode-locking are relatively large. With positive group velocity dispersion inevitable at this wavelength, fibre lengths should ideally be kept as short as possible to reduce the need for dispersion compensation with additional components in the laser cavity. This should not be a problem, however, as heavy Nd^{3+} concentrations, and hence short fibres, are readily achievable without adverse clustering effects.

In this letter, we demonstrate a passively mode-locked Nd-doped fibre laser with a short length of heavily doped fibre and pumped with a single stripe laser diode. The laser is mode-locked by an integrated semiconductor intracavity saturable absorber/end mirror which also serves as one end of the laser cavity. A similar integrated semiconductor nonlinear mirror has recently been used to achieve mode-locking with an Er^{3+}-doped fibre laser[8], and the current work also serves to demonstrate the general applicability of this simple technique to fibre lasers operating at various wavelengths. The experimental configuration is shown in Fig. 1. The phosphate glass fibre is heavily doped with 1% wt of Nd^{3+}, and has a length of only 6 cm. It has a spot size of 2.3μm and an NA of 0.18. It is encased in a rigid glass capillary, one end of which is polished flat and a dichroic mirror (transmitting at 800 nm and highly reflecting at 1060 nm) is bonded to it with UV-curing adhesive. The other end is polished at an angle of 15° to eliminate intracavity reflections which tend to degrade mode-locking. An AR-coated lens is used to collimate the light from the angled end of the fibre, and an identical lens is used to re-focus the light onto the semiconductor nonlinear mirror. A pellicle beamsplitter with a reflectivity of 10% is used to couple the light out of the cavity. The fibre is pumped by a single stripe laser diode, with a lasing wavelength at 816 nm and output power of 150 mW.

Fig. 2 shows the semiconductor structure, which acts as an integrated saturable absorber and cavity end mirror at the lasing wavelength of 1.05 μm. The end mirror is composed of 16 periods of 75.5 nm thick GaAs and 89.6 nm thick AlAs layers, grown by MBE on a GaAs substrate at a temperature of 585°C. The saturable absorber consists of 70 pairs of 7 nm $In_{0.285}Ga_{0.715}As$ wells separated by 30 nm GaAs barriers grown on top of the reflector stack at a lower temperature of 515°C (to improve In incorporation at the growth surface). The relatively wide barriers were used to limit the effects of strain, which can lead to dislocation defects. After growth, the material surface was found to have a high oval defect[9] density of $\approx 10^4/cm^2$, believed to be due to a recent change of the gallium crucible.

The semiconductor mirror bears some similarities to that used by Keller et al[3,4] for passive mode-locking of the bulk Nd:YLF laser. However, with the use of the fibre as the gain medium, the additional high reflector needed in the bulk case to separate the absorber from the gain medium is not necessary for stable cw mode-locking to be attained. This simpler design, together with the demonstrated feasibility of pumping with a single stripe laser diode, makes the choice of the fibre geometry an attractive alternative.

With the 150 mW pump diode, an estimated 70 mW is launched into the fibre and 50 mW absorbed. Self-starting stable cw mode-locking is observed with a total laser cavity length of 130 cm, with one pulse observed every cavity round trip period. The average output power is 2 mW, with the pulse energy 18 pJ and the peak power 4.5 W. Autocorrelation traces indicate the pulses are 3.9 psec in duration (Fig. 3a). However, the optical spectrum (Fig. 3b) indicates that the pulses are not transform limited.

We find that the mode-locking behaviour is very sensitive to the position of the focussed spot on the semiconductor, with lateral translations on the order of 10 μm on the semiconductor surface capable of changing the behaviour of the laser from stable cw mode-locking to Q-switching. The mode-locking may thus be aided by the presence of the defects mentioned earlier, which should help to decrease the carrier recombination times. Attempts to increase the mode-locking frequency by reducing the cavity length have so far not been successful. When the cavity length is reduced by half, substantial relaxation oscillation fluctuations are observed and the pulse train is degraded significantly. This frequency limitation is unlikely to be due simply to insufficiently short carrier recovery times, as with a beam diameter of about 5 μm on the semiconductor, the diffusion component of the absorption recovery time alone should be less than a nsec[10]. Probably the pump power available is insufficient to support the greater number of pulses for passive mode-locking to be sustained in a stable regime.

In conclusion, we have reported the first demonstration of a single stripe diode pumped Nd^{3+}-fibre laser, which is passively mode-locked by a semiconductor nonlinear mirror, producing 4 psec pulses at a repetition frequency of 110 MHz.

References

1 WIGLEY, P. G. J., FRENCH, P. M. W. and TAYLOR, J. R., 'Mode locking of a continous wave neodymium doped fibre laser with a linear external cavity', Electron. Lett., 1990, **26**, pp. 1238-1240.

2 KRAUSZ, F., FERMANN, M. E., BRABEC, T., CURLEY, P., HOFER, M., OBER, M. H., SPIELMANN, C., WINTNER, E. and SCHMIDT, A. J., 'Femtosecond Solid-State Lasers', IEEE J. Quant. Electron., 1992, **28**, pp. 2097-2121.

3. KELLER, U., WOODWARD, T. K., SIVCO, D. L. and CHO, A. Y., 'Coupled-cavity resonant passive mode-locked Nd:yttrium lithium fluoride laser', Opt. Lett., 1991, **16**, pp. 390-392.

4. KELLER, U., MILLER, D. A. B., BOYD, G. D., CHIU, T. H., FERGUSON, J. F. and ASOM, M. T., 'Solid-state low-loss intracavity saturable absorber for Nd:YLF lasers: an antiresonant semiconductor Fabry-Perot saturable absorber', Opt. Lett., 1992, **17**, pp. 505-507.

5. MALCOLM, G. P. A. and FERGUSON, A. I., 'Self-mode locking of a diode-pumped Nd:YLF laser', Opt. Lett., 1991, **16**, pp. 1967-1969.

6. OBER, M. H., SOROKIN, E., SOROKINA, I., KRAUSZ, F., WINTNER, E. and SHCHERBAKOV, I. A., 'Subpicosecond mode-locking of a Nd^{3+}-doped garnet laser' Opt. Lett., 1992, **17**, pp. 1364-1366.

7. HOFER, M., FERMANN, M. E., HABERL, F., OBER, M. H. and SCHMIDT, A. J., 'Mode locking with cross-phase modulation and self-phase modulation', Opt. Lett., 1991, **16**, pp. 502-504.

8. LOH, W. H., ATKINSON, D., MORKEL, P. R., HOPKINSON, M., RIVERS, A., SEEDS, A. J. and PAYNE, D. N., 'Passively mode-locked Er^{3+} fiber laser using a semiconductor nonlinear mirror', IEEE Photon. Technol. Lett., 1993, **5**, pp. 35-37.

9. KOP'EV, P. S., IVANOV, S. V., YEGOROV, A. Yu. and UGLOV, D. Yu., 'Influence of growth parameters and conditions on the oval defect density in GaAs layers grown by MBE', J. Crys. Growth, 1989, **96**, pp. 533-540.

10. SMITH, P. W., SILBERBERG, Y. and MILLER, D. A. B., 'Mode-locking of semiconductor diode lasers using saturable excitonic nonlinearities', J. Opt. Soc. Am. B, 1985, **2**, pp. 1228-1235.

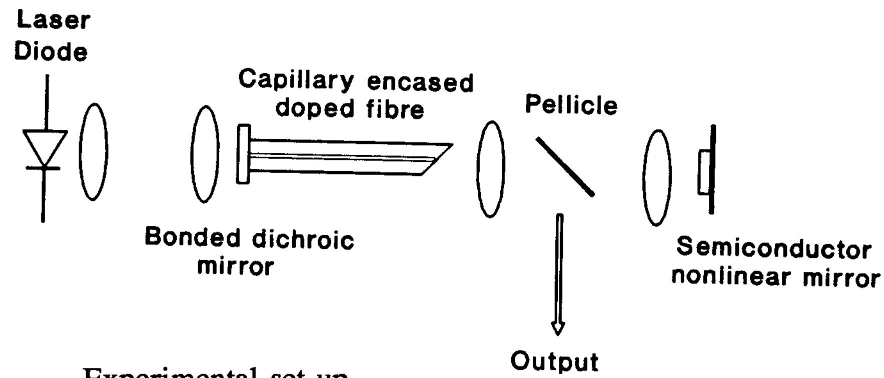

Fig. 1 Experimental set-up.

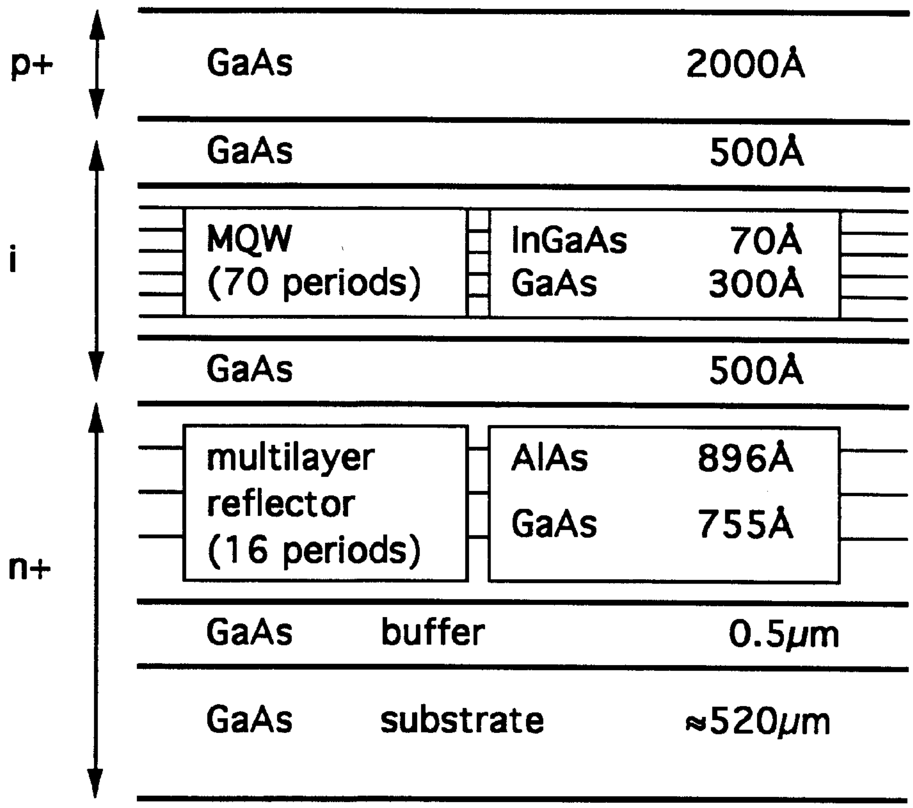

Fig. 2 Schematic of semiconductor structure.

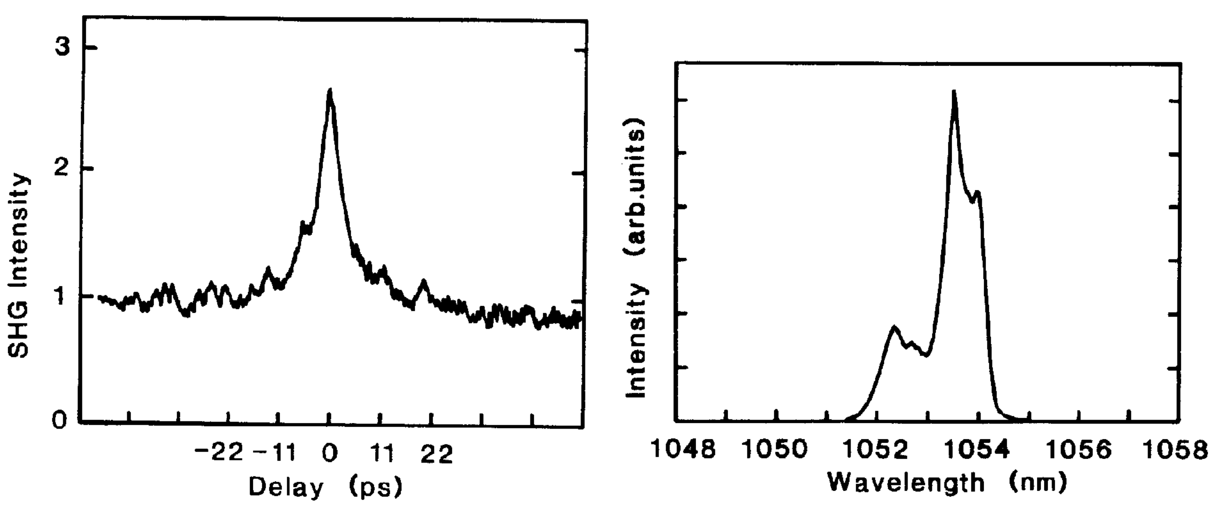

Fig. 3 (a) Collinear autocorrelation trace showing optical pulse width of 3.9 psec, assuming Gaussian pulse shape, and (b) corresponding optical spectrum.