# Polarisation Maintaining Figure-8 Laser

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Passively mode-locked, erbium-doped fibre lasers have received considerable recent attention because of their ability to generate ultrashort, transform-limited soliton pulses. Figure-8 [1,2], ring [3] and linear [4] cavity configurations have been developed based on nonlinear Sagnac and polarisation switches respectively. Pulse durations ranging from several picoseconds down effectively to the limit defined by the erbium bandwidth (~ 100 fs) have now been demonstrated directly at the output of such lasers [5,6]. However, questions concerning the practical application of such lasers remain, particularly the question of environmental stability. The performance of passively mode-locked fibre lasers is generally critically dependant on the exact state of intracavity birefringence and this is sensitive to temperature, pressure and mechanical perturbation. The cleanest way to avoid the problem is to construct a laser system using polarisation-maintaining (PM) components and to operate the system on a single polarisation eigen-mode. A linear cavity PM erbium fibre laser employing bulk elements and a saturable absorber has recently been demonstrated [7]. In this letter we report for the first time the performance of a self-starting, all-fibre, PM Figure-8 laser capable of generating high quality, transform-limited soliton pulses and exhibiting excellent environmental stability.

The experimental setup is shown in Fig.1. The cavity consists entirely of PM fibre components fusion-spliced together into a closed circuit. The birefringence axes of each component were carefully aligned to ensure single polarisation-state operation of the laser. The polarisation cross-talk was directly monitored and found to be < -17 dB at each splice. The output laser polarisation state was linear to better than 25 dB. The unidirectional-ring was 1.5m long and contained a polarizing isolator (loss 1.1 dB) which selected the single linearly-polarised mode of the system. The nonlinear amplifying loop mirror (NALM) loop contained 12m of erbium-doped PM fibre (NA = 0.17, $\lambda_{co}$ = 1060nm, Beat-length = 3 mm at 1550 nm, D = -10 ps/nm/km at 1530 nm, and $Er^{3+}$ conc. = 800 ppm) and a 380 m section of conventional Bow-Tie fibre (NA = 0.18, $\lambda_{co}$ = 1450 nm, Beat-length = 1.7 mm at 1550 nm and dispersion D = 10.0 ps/nm/km on axis A and 16.2 ps/nm/km on axis B at 1530nm) giving a total cavity length of 395m. The central coupler in the system was a tunable polished-block device with an insertion loss of ~ 1dB. The coupling ratio could be tuned between 1% and 80% with little variation in the loss and polarisation cross coupling (<-17dB). The tunable coupling ratio permitted an additional degree of freedom for examining the system behaviour. Unfortunately, mechanical hysteresis in the couplers tuning controls made it impossible to pre-calibrate the device and it was therefore difficult to make accurate in-situ measurements of the coupling ratio as it was tuned. Output coupling was through a polished PM WDM coupler giving 60% output coupling at 1550nm. For convenience, the system was pumped with an actively-stabilised Ti:sapphire laser operating at 978nm although since upto 130 mW of launched pump radiation was used a laser diode could be employed. The performance was first investigated with operation on Axis A of the 380m Bow-Tie fibre, before being partially dissembled and respliced so as to operate on axis B.

The laser behaviour was found to be highly dependant on the tuning ratio at the central coupler, with both cw and pulsed regimes possible. cw operation was obtained for extreme values of coupling ratio and mode-locking at more intermediate values. Broad bandwidth, "square pulse" pulsed operation could also be observed for certain values of coupling ratio. During soliton mode-locked operation, identical temporal and spectral behaviour to that noted in the conventional Figure-8 lasers were observed. In general, a number of pulses were formed within the cavity at the onset of mode-locking and were sometimes accompanied by a cw lasing component. By accurate pump-power control, stable fundamental mode-locking (525 KHz) was obtained (see Fig.2). By tuning the central coupler, two prominent soliton operation regimes were discovered. Background-free autocorrelation traces showed the existence of two preferred modes of soliton operation with pulse durations of $\approx$2.3ps or $\approx$4ps respectively, although once the system was mode-locked more careful tuning of the coupler could produce intermediary pulse durations. The autocorrelation trace of the 2.3 ps pulses is shown in Fig.3 where it is seen that the pulses have a good sech$^2$ form and are pedestal-free. The corresponding optical spectrum is shown in the inset. The time-bandwidth product of the pulses is 0.32, as expected for a sech$^2$ pulse form. The total cavity length corresponds to approximately 2 soliton periods for the 2.3 ps pulses. Spectral side-lobe suppression ($<$-20 dB) could be obtained by fine tuning of the central coupler as demonstrated in the logarithmic spectral plot shown in Fig.4 [8]. The cw laser threshold in this instance was 10mW and the mode-lock self-start threshold $\approx$ 50 mW, although a reduced second-threshold could be obtained by mechanical perturbation of the system i.e. either by tapping or tuning the coupler. An output power of 7.2 mW was obtained for 100 mW input pump power giving a slope efficiency of $\approx$ 8 %.

The 4ps solitons were of an equal spectral and temporal quality (see Fig.5) with no significant chance in both threshold and output powers. The ratio of cavity-length to soliton-period was $\approx$ 0.6 in this instance.

Once mode-locked, the various fibres and components could be manhandled without affecting the laser performance, thus demonstrating the inherent environmental stability of the device. The laser would operate for unlimited periods of time, despite large temperature fluctuations within the laboratory, providing that the pump power remained stabilised.

After completing the measurements, the tunable coupler was optimised for 4.0 ps pulse operation and was then removed from the cavity to determine the exact coupler splitting ratio which was found to be 66:34 at 1532 nm. The excess cavity round-trip loss was estimated to be ~6 dB. It was not possible to simultaneously determine the optimal coupling ratio for 2.3 ps operation owing to the previously mentioned tuning hysteresis. The system operation was then further examined by resplicing the NALM fibre loop to lie on axis B in order to investigate the system behaviour for the higher value of dispersion.

The general laser behaviour was identical with two particular regimes of stability once again observed. In this case pulses were obtained either in the range 2.7-3.3 ps or 5.0-6.0 ps, although once again intermediate pulse durations could be obtained by fine tuning. The pulse duration operating ranges agree extremely well with the predicted values (2.9 ps and 5.1 ps) obtained for the respective regimes by scaling the data for the other axis by $(16.2/10)^{0.5}$, i.e. the square root of the ratio of the dispersions, and is commensurate with previous observations that the pulse durations obtainable from such cavities is determined by the dispersion-length product, with the minimum pulse obtained when the cavity length corresponds to ≈ 2 soliton periods [3,9].

**Conclusion :**

We have demonstrated the first self-starting, PM Figure-8 fibre laser and produced clean transform-limited soliton pulses of 2.3ps duration. Despite its considerable length (395m), the device exhibits the excellent environmental stability expected from single polarisation-state operation and constitutes a robust, diode-pumpable source of ultrashort pulses at 1.55$\mu$m. Two discernable pulse duration regimes were found and could be selected by tuning the central coupling ratio. In addition, we have verified that the pulse durations scale with $(DL)^{0.5}$ where DL is the total dispersion in the cavity. By reducing the total cavity length to a few metres, femtosecond operation of the laser should be possible.

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**References**

1. I. Duling III: Electron. Lett. 27, p544- 545 (1991).
2. D.J. Richardson, R.I. Laming, D.N. Payne, V.J. Matsas and M.W.Phillips: Electron Lett., 27, p730-731 (1991).
3. V.J. Matsas, D.J. Richardson, T.P. Newson, D.N. Payne "", Opt. Lett. 18, p358-360 (1993).
4. R.P. Davey, N. Langford and A.I. Ferguson: Electron. lett. 27, p1257-1258 (1991).
5. M. Nakazawa, E. Yoshida, Y. Kimura: Electron. Lett., 29 p63-64 (1993).
6 M.E. Fermann, M.J. Andrejco, M.L. stock, Y. Silberberg, A.M. Weiner: PD16, Tech. Digest OSA annual meeting (Albuquerque), (1992).
7 E.A.Desouza, M.N. Islam, C.E. Soccolich, W. Pleibel, R.H. Stolen, D.J. DiGiovanni, J.R. Simpson: PD19, Tech. Digest OSA annual meeting (Albuquerque), (1992).
8 S.M.J. Kelly: Electron. Lett 28, p806-807 (1992).
9 V.J. Matsas, W.H. Loh, D.J. Richardson, D.N. Payne: Accepted for publication Phot. Tech. Lett. (1993) : M.L. Dennis, I. Duling:submitted Applied Phys. Lett. (1993).

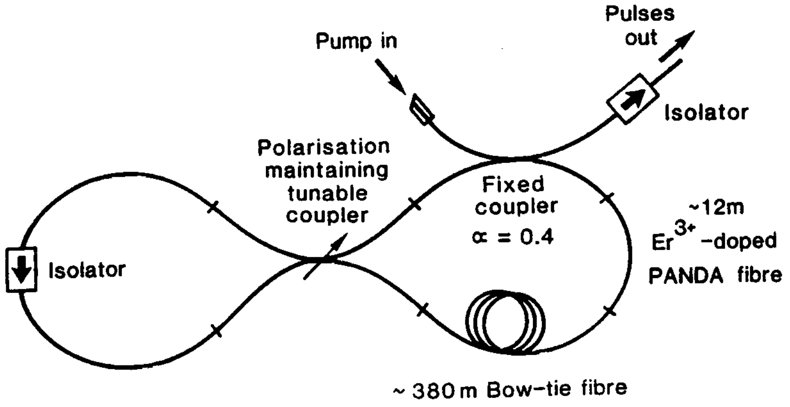

Fig.1 Experimental configuration.

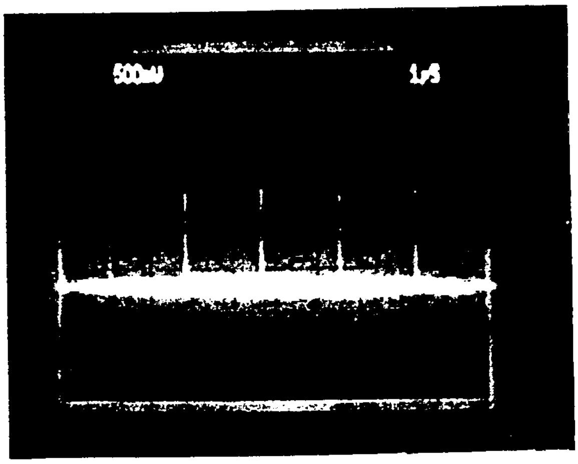

Fig.2 Laser output obtained during fundamental mode-locking.

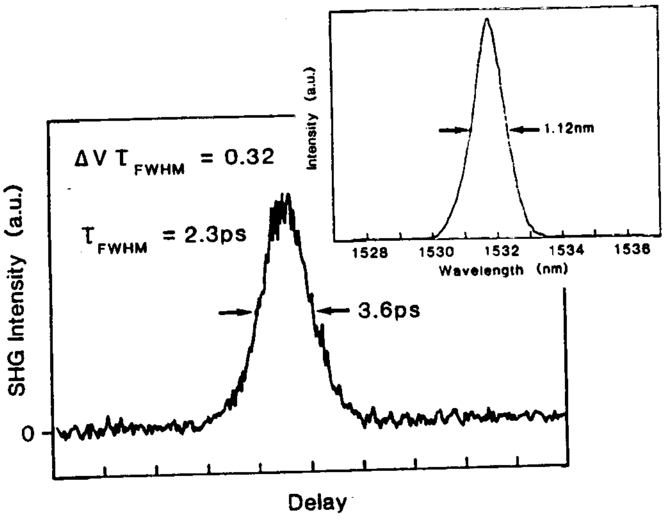

Fig.3 Background free autocorrelation trace and optical spectrum of 2.3 ps pulses obtained on axis A.

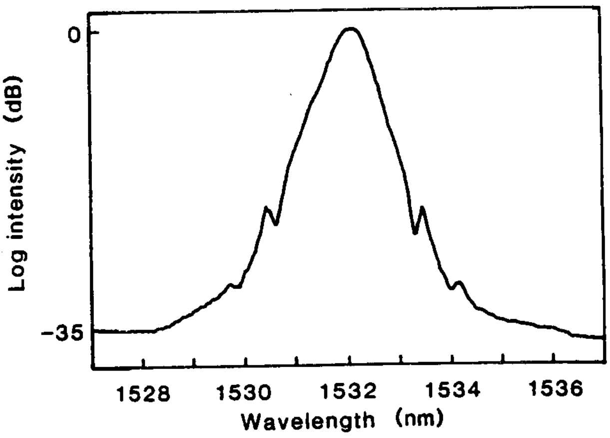

Fig.4 Optical spectrum of 2.3ps pulses on log scale indicating typical side-lobe suppression.

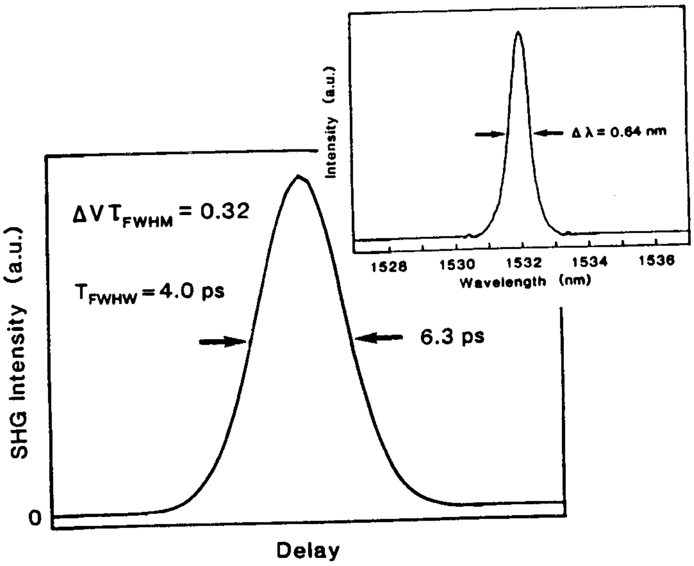

Fig.5 Background free autocorrelation trace and optical spectrum of 4.0 ps pulses obtained on axis A.