ACTIVE MODE-LOCKING OF AN Yb : Er FIBRE LASER

Indexing terms: Optical fibres, Lasers

We report FM mode-locked operation of a single-mode Yb : Er fibre laser at 1·56 μm. To date pulses of 70 ps duration and peak output powers of 90 mW have been achieved.

Introduction: Laser sources producing short pulses in the 1·5 μm wavelength region are of interest for several reasons. This spectral region is important for silica based communications systems and is also of interest for studying nonlinear pulse propagation in the negative group velocity dispersion regime of silica.

We have previously described[1] the AM mode-locking of a bulk Yb : Er glass rod using an acousto-optic modulator. In this letter we describe an Yb : Er fibre laser which has been FM mode-locked using the technique recently used[2] to mode-lock a Nd-doped fibre laser. Geister and Ulrich have also recently reported[3] mode-locking of a Nd fibre laser using an integrated optical modulator. In this letter we give the first report of mode-locked operation on the $^4I_{13/2}$ to $^4I_{15/2}$ transition at 1·56 μm in an Er-doped fibre laser. This type of laser is of particular interest because the fibre already incorporates those features which are necessary for achieving pulse compression, that is, a Kerr nonlinearity to produce temporally chirped pulses and negative group velocity dispersion to cause the compression.

The fibre used in this experiment and its CW operation has been described elsewhere.[4] In summary, the fibre (core diameter 4·6 μm, NA = 0·25) is doped with 1·5% Yb and 0·08% Er. Pump light at 1·06 μm is absorbed by the Yb ions. This excitation is efficiently transferred to the Er ions and lasing action occurs on the familiar 1·5 μm transition in the Er.

Experimental: Fig. 1 shows a schematic diagram of the experimental arrangement used. The pump laser was a CW Nd : YAG laser capable of delivering several watts of power. The pump light was focused into a 60 cm length of fibre using a 10× microscope objective (MSO). The input mirror (M1) was highly reflecting at 1·56 μm and transmitted ~90% of the pump light. This mirror was butted to the fibre end. Because optical damage to the mirror coating occurred for pump powers of the order of 400–500 mW, the pump power was kept below 300 mW. The other fibre end was terminated in index-matching liquid (IM) to avoid backreflections into the fibre. Such reflections are detrimental to the mode-locked operation[2] and may even cause unwanted laser oscillations in the fibre. The output light from this end was collimated with another 10× microscope objective and was focused through the mode-locker (ML) onto the output coupler (M2) which had a transmission of 4·5% at 1·56 μm.

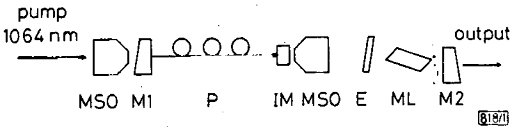

Fig. 1 *Experimental arrangement*

The mode-locker used was a 3 cm long $LiNbO_3$ phase modulator with Brewster cut ends in order to give a small loss for a single polarisation state. The crystal was mounted in a resonant *LC* circuit housing with inductive RF signal coupling. The voltage was applied to the crystal *z*-axis to take advantage of the largest electro-optic coefficient r_{33}. The circuit could be tuned over several MHz near 100 MHz. Efficient mode-locking was achieved by applying RF powers of 0·5–1·0 W.

The addition of two more cavity elements was found to be important. The first was a 0·25 mm thick uncoated étalon (E) which was used to control the oscillation bandwidth. This helped stabilise the output pulses. The second was a polarisation controller (P).[5] Initially, this consisted of a 3 cm disc around which the fibre was wound once. By rotating this loop about the fibre axis some control of the polarisation incident on the mode-locker could be achieved. With this polarisation controller the ratio of horizontal to vertical polarisation at the output was limited to 3–4 : 1. Under CW conditions this cavity was found to have an incident power threshold of 150 mW. Since the launch efficiency was approximately 50%, the launched power at threshold was ~75 mW. At 1·064 μm the absorption coefficient is 3·4 dB/m, so for the 60 cm fibre length used, the absorbed power at threshold was 28 mW.

The mode-locked pulses were observed using a fast GaInAs photodiode in conjunction with a sampling scope. The combined risetime of this system was approximately 60 ps. Fig. 2 shows a picture of a typical sampling scope trace when the mode-locker was turned on. The measured FWHM duration is 90 ps, which implies an actual pulsewidth of ~70 ps. The corresponding bandwidth was found to be 11·5 GHz using a scanning Fabry–Perot interferometer. This gives a time-bandwidth product of 0·8, which is comparable to that expected[6] for chirped FM mode-locked pulses with a Gaussian shape (0·63). With 300 mW of incident pump power the average output power with this cavity was limited to 100 μW, indicating peak output powers of 17 mW.

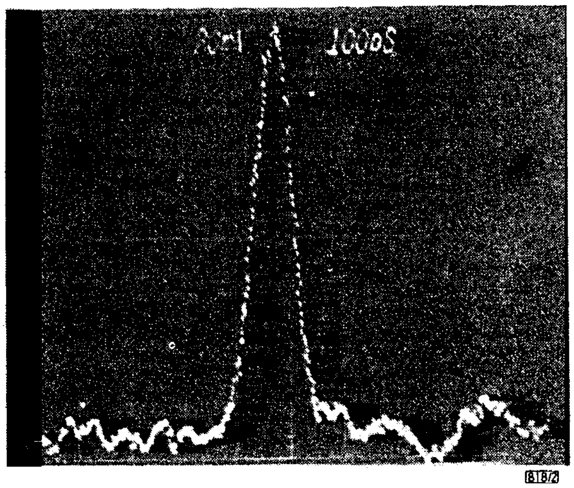

Fig. 2 *Typical sampling scope trace showing stable mode-locked pulses*

Baseline structure results from detection system used, and is not optical in origin

Several factors are responsible for the relatively low output powers. Fresnel reflections off various intracavity elements contribute significantly to the cavity loss as does the poor polarisation control. Two improvements were subsequently made which serve to indicate the importance of minimising the cavity losses. The uncoated index matching cell window was replaced by a window AR-coated at 1·56 μm. The single polarisation controller disc was replaced by a set of three discs of the diameter (17 mm) appropriate for the given fibre size and the operating wavelength.[5] This disc combination permitted a polarisation extinction ratio in excess of 100 : 1. With these simple improvements the CW threshold power was reduced to 100 mW incident (~50 mW launched, 19 mW absorbed). With 300 mW incident pump power, the average output power increased to 620 μW. The pulse width remained the same as before and consequently the peak output power is approximately 90 mW.

Discussion: The laser we have described has to date produced external peak powers of 90 mW. With the 4·5% output coupling we have used this corresponds to an intracavity peak power of 2·0 W. Using data for undoped silica glass (nonlinear refractive index $3{\cdot}2 \times 10^{-16}\,\mathrm{cm^2/W}$) we estimate that the pulses experience single pass frequency chirps of the order of 200 MHz. This chirp is still somewhat smaller than the pulse bandwidth. Moderate increases in the peak power would make the chirp significant compared with the bandwidth. We expect this to result in noticeable changes in the pulse duration as a result of self-phase modulation.

Further work is aimed at increasing the peak power. Some possible approaches which are under investigation are:

(*a*) coupling in more pump power by means of a dichroic coupler to avoid mirror damage

(*b*) using a shorter pump wavelength to increase the Yb absorption

(*c*) reducing the cavity losses. One possibility here is the use of a modulator applied externally in direct contact with the fibre.*

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