Q-switching, mode-locking and tunable operation around 0.9 μm of a neodymium-doped monomode fibre laser

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Abstract: Recent studies of monomode silica fibre which has rare-earth impurity ions incorporated into the core region have shown that it can exhibit laser action with low threshold and high efficiency when end pumped by an external laser source. In the paper we describe the first demonstration of Q-switching of the $^4F_{3/2}$–$^4I_{9/2}$ Nd^{3+} transition at 0.9 μm using a fibre laser of this type. A birefringent filter has been used to tune the laser output over the range 0.900–0.945 μm. We also report on the performance of the laser at 1.08 μm under conditions of Q-switching and active mode-locking. In Q-switched operation an intracavity acousto-optic modulator was used to generate pulses of 200 ns duration and 8.8 W peak power at repetition rates up to 1 kHz. Active mode-locking of the fibre was accomplished using acousto-optic modulation of the cavity losses at 41.4 MHz, converting the laser output to a train of pulses of subnanosecond duration.

1 Introduction

The operation of a neodymium glass laser in the form of a multimode fibre waveguide was first demonstrated by Stone and Burrus [1] who pointed out that very efficient longitudinal laser pumping could be achieved in such a device. In a recent development of this work monomode optical fibre with impurity doping has been used as a laser gain medium [2–8]. Impurities such as rare-earth ions can be incorporated into the core of an optical fibre without significantly degrading the transmission of the fibre in the spectral windows between the impurity absorption bands [5]. The optical transitions of a rare-earth ion in a fused-silica matrix show strong homogeneous broadening due principally to interaction with high-frequency Si–O bond stretching vibrational modes [9] as well as inhomogeneous broadening associated with the disordered nature of the matrix. The fluorescence spectrum therefore exhibits broad bands which are potentially attractive as tunable laser transitions, except that the gain, which varies inversely with linewidth, is correspondingly small. The remarkable property of the monomode fibre geometry which distinguishes it from conventional glass lasers is that confinement of the pump radiation field within a core of small transverse dimensions can allow intense pumping without associated thermal problems [7]. Moreover, since the interaction length can be extended indefinitely it is possible to make use of all the power available in a pump laser source, even when the pump wavelength falls in the weakly absorbing wing of a rare-earth absorption band. Thus one might expect a monomode fibre laser to achieve oscillation on rare-earth transitions which cannot reach threshold when using bulk glass as the gain medium.

In this paper we describe tunable CW operation of a neodymium monomode fibre laser on the $^4F_{3/2} \rightarrow {}^4I_{9/2}$ transition [8]. The terminal level of this transition is thermally populated and hitherto it has only been operated in pulsed mode in a glass host. Like the 1·5 μm erbium fibre laser [6] this system illustrates the effectiveness of the fibre-laser geometry for low-gain transitions. We also discuss the performance of the fibre laser under Q-switched and mode-locked conditions.

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2 Configuration of the fibre laser

All the experiments reported here used silica fibre with a cutoff wavelength of ~ 1 μm and approximately 0.03% of Nd^{3+} ions in the fibre core. The configuration of the laser cavity is shown schematically in Fig. 1. The laser is

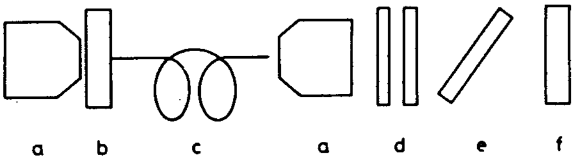

Fig. 1 *Configuration of fibre laser*
a = microscope objective
b = high reflector
c = Nd-doped fibre
d = $\lambda/4$ plates
e = intracavity filter or modulator
f = output coupler

pumped with 590 nm radiation from a rhodamine 6G dye laser. Different fibre lengths were needed for the various experiments reported here, and the absorbed pump power varied accordingly. The pump laser beam is launched into the fibre through a high reflector which is optically contacted to the cleaved fibre end. An intracavity × 10 microscope objective is used to produce a collimated output beam and the airgap between this objective and the output coupler allows optical elements such as filters and modulators to be introduced into the laser cavity. In particular, a pair of $\lambda/4$ plates were used to convert the elliptically polarised output of the non-polarisation-preserving fibre to the linear polarisation required by other intracavity components.

3 Tunable operation on $^4F_{3/2}$–$^4I_{9/2}$ transition around 0.9 μm

The spectrum of photoluminescence from the $^4F_{3/2}$ metastable level to the $^4I_{9/2}$ ground multiplet is shown in Fig. 2. This measurement was made on a section of fibre

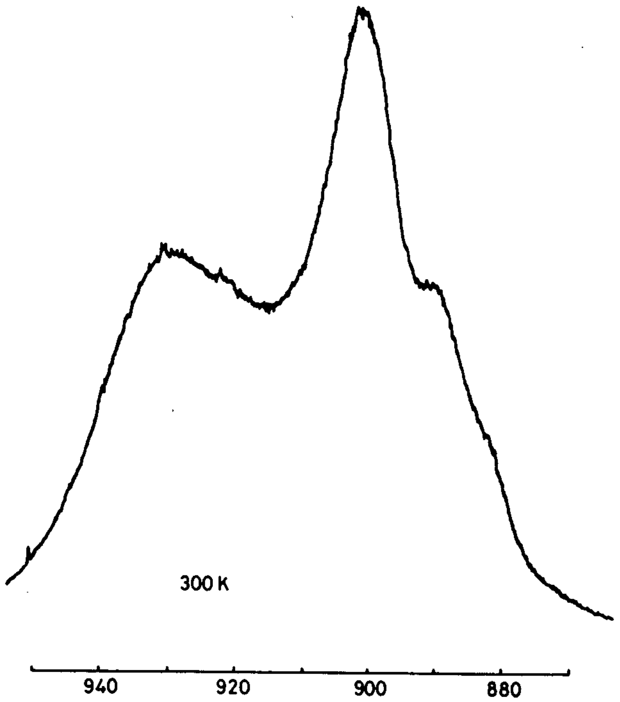

Fig. 2 *Photoluminescence spectrum of Nd ions in fibre preform around 0.9 μm*

preform, and fluorescence which escaped laterally out of the preform core was collected so as to minimise the influence of reabsorption on the spectrum. The band exhibits partially resolved structure corresponding to transitions from the lower energy doublet in $^4F_{3/2}$ to the five doublets composing the $^4I_{9/2}$ multiplet. The shoulder at 890 nm marks the mean energy of transitions to the ground doublet. In thermal equilibrium at room temperature, approximately 30% of the Nd ion population is in the excited state at ~ 170 cm^{-1} and 6% is in the state at ~ 480 cm^{-1}, and the fibre therefore exhibits strong attenuation around 903 nm and weaker attenuation around 930 nm owing to thermal population of these excited states.

To observe laser action on this band we used a 1.2 m length of fibre which absorbed only ~ 53 mW of the available pump power, but which kept cavity losses due to ground-state reabsorption low. Laser action on the $^4F_{3/2}$–$^4I_{11/2}$ transition was suppressed by the high reflector which had 99% reflectivity at 900 nm but only 15% reflectivity at 1.08 μm. An output coupler with 70% reflectivity at 900 nm was used.

A 2-plate birefringent filter was used to produce a tunable output with a spectral bandwidth of 0.06 nm full width at half maximum (FWHM). A particular advantage of this technique is that with $\lambda/4$ plates in the cavity to control the polarisation of the fibre output the Brewster-angled birefringent filter introduces negligible insertion loss. The dependence of output power on wavelength is shown in Fig. 3. where the broken line indicates

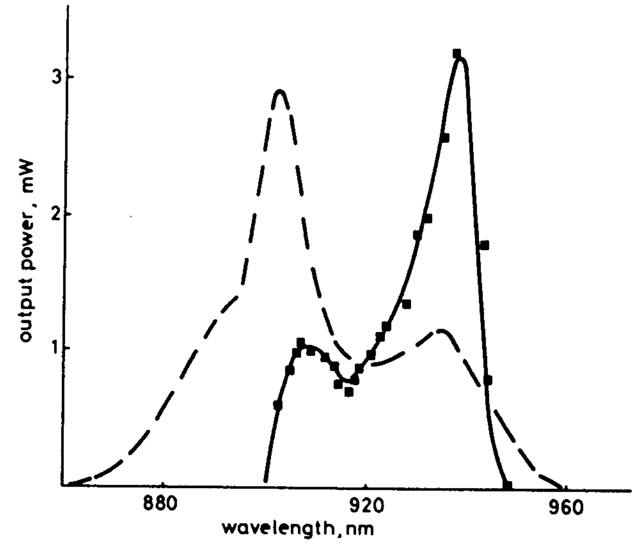

Fig. 3 *Output power versus wavelength for $^4F_{3/2}$–$^4I_{9/2}$ laser transition*
---- position of photoluminescence band

the position of the photoluminescence band. At the peak of the tuning curve at ~ 935 nm the laser reached threshold with 8 mW of absorbed pump power, and with 53 mW of absorbed pump power, 3.2 mW of output power was obtained, representing a conversion efficiency of 6%. This is the same as the conversion efficiency achieved in broadband operation, showing that the homogeneous broadening of this transition is strong enough not to set a limit to the efficiency of narrowband power extraction, at least under CW conditions.

4 Q-switched operation

Q-switched operation of the monomode fibre laser has been demonstrated on the 4-level $^4F_{3/2} \rightarrow {}^4I_{11/2}$ neodymium transition [3]. An intracavity acousto-optic modulator (Isomet 1205C-1) was inserted into the cavity between the intracavity microscope objective and the output coupler, thus ensuring a constant pumping rate unaffected by *Q*-switch losses.

For operation at 1.08 μm a 2.3 m length of fibre was used in which the incident pump power of 80 mW was totally absorbed. The reflectivities of the high reflector and the output coupler were 98% and 60%, respectively. Square-wave modulated RF power was applied to the *Q*-switch producing an estimated 40% modulation in the single-pass transmission. During the low-*Q* half cycle the laser was below threshold. Laser output during the high-*Q* half cycle consisted of an initial large spike followed by several smaller spikes and then by continuous-wave action. By altering the duty cycle to shorten the high-*Q* period relative to the low-*Q* period all laser output after the initial large spike could be suppressed, with a corresponding gain in peak power. Fig. 4 shows a typical output pulse obtained at 100 Hz repetition rate with a high-*Q* period of 5 μs. A peak power of approximately 8.8 W was achieved in a pulse of 200 ns duration. The repetition rate could be increased up to ~ 1 kHz without noticeable loss of peak power.

An estimate of the duration Δt (FWHM) of the Q-switched pulse has been derived from the analysis due to Carlson [9]:

$$\Delta t = \frac{2.48\tau_c}{[x - 1 - \ln x]^{1/2}} \quad (1)$$

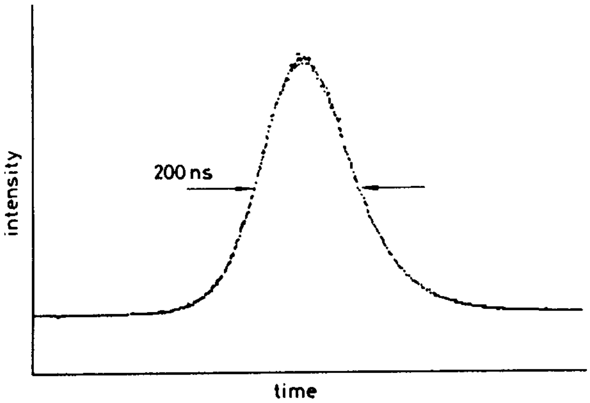

Fig. 4 *Temporal profile of Q-switched pulse at 1.08 µm*

τ_c is the photon lifetime in the resonator in the high-Q state, and x is the ratio of pump rate to threshold pump rate. The photon lifetime was estimated from a measurement of the frequency of relaxation oscillations [11] to be $\sim$35 ns and for this system $x \cong 1.9$. Thus eqn. 1 predicts a duration of 170 ns for the Q-switched pulse, which is close to the experimental value.

Q-switching was also observed with the intracavity modulator replaced by an optomechanical chopper wheel. Remarkably we found that peak powers approaching half those achieved acousto-optically could be achieved, although the switch-on time of the chopper was a few hundred cavity round-trip times and the laser output contained a number of spikes in the high-Q period. This cheap and easy technique recommends itself strongly for applications where optimum pulse shape and peak power are not required.

The same techniques have been used to Q-switch the neodymium fibre laser on the $^4F_{3/2} \rightarrow {}^4I_{9/2}$ transition at 0.9 µm. The photon lifetime is significantly smaller in this system because a shorter fibre, and therefore a shorter resonator, is used, and because the photons suffer ground-state reabsorption. Q-switched pulses of $\sim$70 ns and a few Watts peak power could readily be obtained. However, the Carlson theory cannot be used to predict pulse durations for this 3-level laser transition.

5 Mode-locking

To mode-lock the fibre laser operating on the $^4F_{3/2}$–$^4I_{11/2}$ transition an acousto-optic rhomb mode-locker (Crystal Technology) with Brewster-angled surfaces inserted between the intracavity microscope objective and the output coupler has been used [4]. Since the resonances of the high-Q transducer were highly temperature dependent it was found necessary to mount the mode-locker in a temperature-stabilised enclosure. The output coupler was mounted on a translation stage so that the frequency difference between longitudinal cavity mode beats could be matched to the loss modulation frequency.

The laser output was detected by a Ge photodiode and the amplified photocurrent was fed into a Tektronix 7L14 RF spectrum analyser. With no RF power applied to the mode-locker the laser output contained weak longitudinal cavity mode beats. When RF power at 20.723 MHz was applied to the mode-locker and the cavity length was adjusted to match the loss modulation frequency, the beats became strong and narrower. Eventually higher harmonics appeared and dramatically increased in intensity as the RF power was increased. Fig. 5 shows the comb of RF beat frequencies obtained with

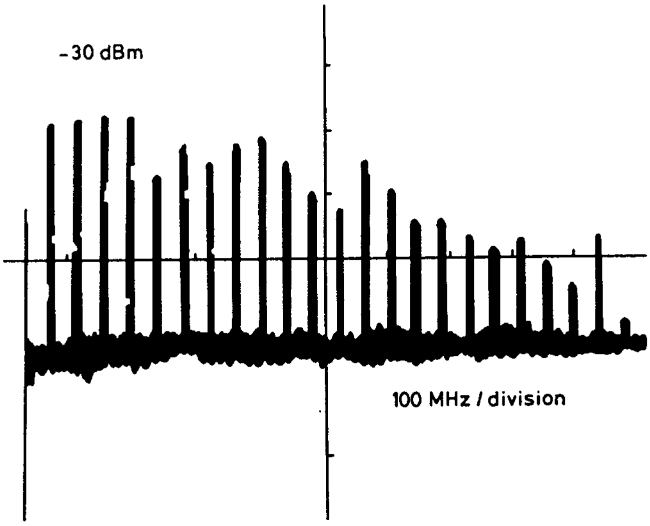

Fig. 5 *Radio-frequency beat spectrum of mode-locked fibre laser*

250 mW of applied RF power. The high frequency rolloff is due to the bandwidth of the amplifier and detector.

The laser output was then observed in the time domain using a fast detector (RCA CA 309709E) and oscilloscope. The laser output consisted of a train of short pulses with a repetition rate corresponding to the cavity round-trip time. Fig. 6 shows a single pulse from

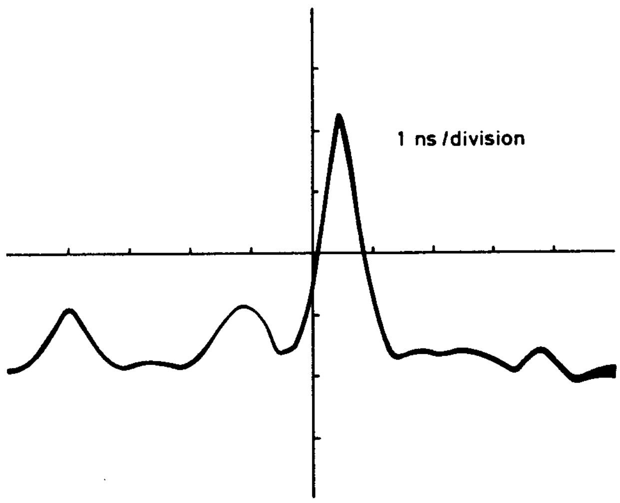

Fig. 6 *Temporal profile of mode-locked laser pulse*

the train, with an FWHM of less than 1 ns limited by the 400 MHz bandwidth of the oscilloscope and an energy of $\sim$17 pJ. The structure around the pulse is believed to be due to étalon effects in the cavity.

The effect of simultaneous Q-switching and mode-locking on the $^4F_{3/2}$–$^4I_{11/2}$ transition was also studied by inserting a mechanical chopper wheel between the mode-locker and the intracavity microscope objective. The output then had the form shown in Fig. 7; a train of short pulses under a Q-switched envelope of $\sim$690 ns duration. Individual pulses in the train are longer than in the CW case because the build-up time for the Q-switching is not long enough to allow a steady state to be reached. The energy of the largest pulse in the train is ~20 nJ, and its duration is less than 3 ns FWHM.

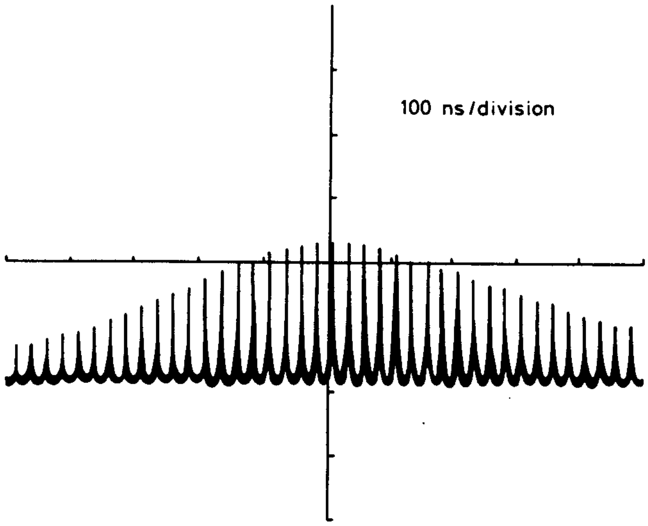

Fig. 7 *Q-switched and mode-locked train of pulses*

So far the potential of the broad gain bandwidth of the neodymium fibre laser for generating short mode-locked pulses has not been fully realised. One technical problem is the difficulty of eliminating feedback into the laser cavity from reflections off the free fibre end, and various possible solutions are currently under investigation. On a more fundamental level, the monomode fibre laser combines a high intensity in the laser radiation field with a long path through the gain medium, so that not only will dispersion play a greater role than in a conventional glass laser but also nonlinear effects such as self-phase modulation and stimulated Raman scattering may become significant. At 1.08 μm such nonlinear processes might be expected to impose limits on the pulse duration and peak pulse power. However, in the negative group-velocity dispersion region the interesting possibility of pulse compression and even soliton propagation in the laser medium arises.

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