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CONTINUOUS-WAVE OSCILLATION OF A MONOMODE NEODYMIUM-DOPED FIBRE LASER AT 0.9 μm ON THE $^4F_{3/2} \to {}^4I_{9/2}$ TRANSITION

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A monomode silica fibre doped with Nd has allowed the first demonstration of cw laser action on the $^4F_{3/2} \to {}^4I_{9/2}$ transition of Nd in a glass host, with tuning over the range 900–945 nm.

Recent experiments have demonstrated the possibility of incorporating high concentrations of impurity ions onto a monomode fibre structure [1,2] and the achievement of laser action in such fibres [3–5]. Initial experiments have studied the $^4F_{3/2}$–$^4I_{11/2}$ transition in Nd doped fibre, operating at 1.08 μm, with demonstrated performance on this transition so far including pumping with a CW dye laser [3,5], an Ar ion laser [4], a GaAs diode laser [3] and both Q-switched [5] and actively mode-locked operation [6] of the fibre laser.

End pumping of the fibre by a laser source allows very efficient pumping and, by virtue of the small core size, very intense pumping. The small transverse dimensions of the fibre also means that the thermal effects which plague bulk glass lasers are reduced to a negligible level. Given this ability to achieve and to withstand intense pumping, and the ability to incorporate a wide variety of dopant ions [2], one now has greatly extended prospects for lasing from impurities in a glass host. For example it should be possible to achieve lasing on transitions which have not hitherto only shown pulsed operation. An example of the latter is the first demonstration of CW laser action on the 1.54 μm line in a Er^{3+} doped fibre [4]. In this letter we report a further example – the first demonstration of CW operation of the $^4F_{3/2}$–$^4I_{9/2}$ transition of Nd in glass around 0.9 μm.

A brief summary of the laser performance is given here and a more detailed description of its performance, which includes Q-switched operation, and mode-locked operation over a wide tuning range, from 0.90 μm to 0.945 μm, will be given in a later paper. First however we give some indication of the extent by which the gain in a fibre laser can exceed the typical gains achievable in bulk glass pumped by thermal light sources. We also provide some estimates of the limitations on gain imposed by fibre stress, heating and pump saturation.

When a conventional cylindrical glass laser rod is pumped by a flash lamp or arc lamp the limit on average pump power input to the rod is imposed by stress resulting from the radial thermal gradient and its associated differential expansion. A glass host is much more seriously limited by this compared to crystalline hosts, such as YAG since the thermal conductivity of glass is typically an order of magnitude smaller. In addition, the threshold pump power for a glass laser is typically more than an order of magnitude greater than for the same transition in a crystal host since the transition linewidth in glass is much greater. These two characteristics of glass lasers have made CW operation difficult to achieve. However the thermal gradient can be reduced by using a rod of smaller radius. In fact, for the same pump density in the rod, hence the same heat dissipated per unit volume, and the same population inversion density produced, the thermal gradient is proportional to the radius of the rod and the maximum stress is proportional to the square of the radius [7]. This implies that the maximum population in-

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version density, and hence gain, that can be sustained continuously without incurring fracture, is inversely proportional to the square of the rod radius. This feature was exploited by Young [8] in the first demonstration of a CW glass laser, with the medium in the form of a short length (few cm) of multimode cladded glass fibre. The same principle, of using a small rod diameter, was used by Uchida et al. [9] who demonstrated CW oscillation in a SELFOC Nd glass rod of 1.5 mm diameter, pumped by a Kr arc lamp. An alternative approach, which achieves the same end, is to use a laser to end pump a glass rod [10]. Since the pump beam spot size can be kept small, a high inversion density can be achieved for a small heat load, and furthermore the thermally induced birefringence is small over the narrow cross section of the pump beam.

In this way Kishida et al. [10] achieved the first CW oscillation in Nd phosphate glass. The laser-pumped monomode fibre laser takes this approach to the limit where the pump beam is confined by waveguiding in a doped core of few microns diameter and the small diameter of the cladding ensures a small radial temperature gradient.

An analysis of the temperature distribution and associated stress distribution in the fibre, assuming uniform heat deposition in the core (radius R_1) yields a maximum stress σ_{max}, which occurs at the outer surface of the cladding (radius R_2), given by

$$\sigma_{max} = \frac{2^{1/2}\alpha E P_a}{8k(1-\nu)}\,[2-(R_1/R_2)^2]$$

where k is the thermal conductivity, α the thermal expansion coefficient, E is Young's Modulus, ν is Poisson's ratio and P_a is the heat deposition per unit length of fibre. Thus, as far as the fracture limit is concerned the fibre laser can operate at a gain which is $\sim\frac{1}{2}(R_2/R_1)^2$ greater than possible in a uniformly doped rod of radius R_2 subject to uniform heat deposition of the same value P_a i.e. it appears that a much higher gain can be achieved in the fibre. However, for single mode fibre, where R_1 may be only a few microns, the maximum value of P_a, and hence the gain, will be limited in practice neither by the fracture limit nor, as estimates show, by stress-induced birefringence effects. Instead, in the case of a lightly doped single mode fibre such as we have used the maximum achievable P_a will be limited by saturation of the pump transition. In the case of non-saturating fibre (e.g. heavily doped or having a large diameter core) the maximum allowable P_a will be limited by the overall temperature rise that can be tolerated. A rough estimate of the maximum permissible heat deposition in a fibre of cladding diameter ~100 μm, cooled by unforced convection in air, indicates 1 W/m (for ~100°C temperature rise) whereas the fracture limit would be much higher, ~100 W/m. Our estimate below indicates that for the Nd doped fibre we have used (core diameter ~6 μm, Nd^{3+} concentration ~300 ppm the pump absorption saturates at ~100 mW absorbed power per metre length.

An estimate of the absorbed pump power P (photon energy $h\nu$) which produces saturation when absorbed in a length L of core (radius R_1) is given by

$$N\pi R_1^2 L/2\tau = P/h\nu, \qquad (2)$$

where N is the total impurity concentration, and τ is the decay time of the upper laser level. Eq. (2) expresses the condition for the pump to maintain half the dopant population in the upper laser level, and thus also indicates the threshold pump power for three level laser operation to be achieved. For four-level laser operation the gain exponent for an upper laser level population of $N/2$ where σ_e is the emission cross-section, and using (2) thus becomes

$$N\sigma_e L/2 = P\tau\sigma_e/h\nu\pi R_1^2. \qquad (3)$$

Inserting typical figures for the 1.08 μm, $^4F_{3/2} \rightarrow {}^4I_{11/2}$ transition in Nd^{3+} for a 6 μm core diameter yields a gain per unit length, $N\sigma_e/2$ of ~6 m^{-1} for an absorbed power per unit length, P/L of 0.1 W m^{-1}. By using a length of several metres, a very high gain can be achieved under these conditions (say e^{30} for 5 m length). By contrast a typical lamp-pumped Nd glass rod (under pulsed conditions) would provide a gain exponent of 2–3. These simple estimates illustrate the much higher gain achievable in a fibre laser. They also confirm the possibility of CW 3-level operation on the $^4F_{3/2} \rightarrow {}^4I_{9/2}$ transition in Nd^{3+}. Assuming σ_e for this transition to be comparable to that for the $^4F_{3/2}$–$^4I_{11/2}$ transition (indicated by the similar branching ratios in other glasses [11]), and allowing for the fact that the upper levels of the $^4I_{9/2}$ manifold are significantly less populated than the lower levels (see [12] for example) threshold pump powers

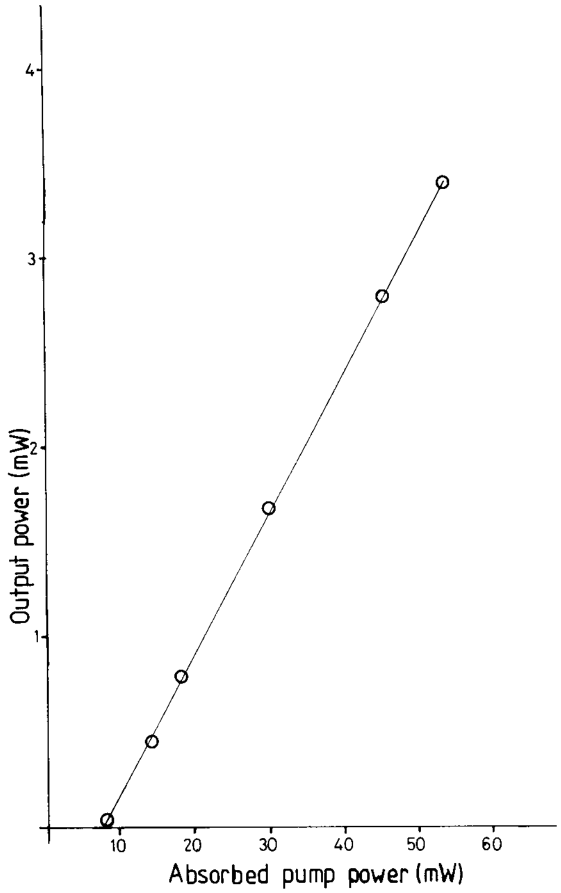

Fig. 1. Schematic of fibre laser resonator with provision for insertion of intracavity control devices such as Q-switch, mode-locker or birefringent filter.

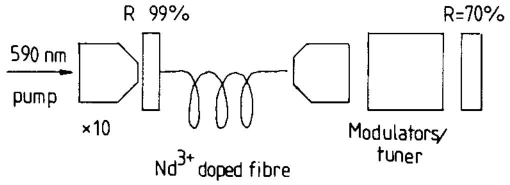

Fig. 2. Output power versus absorbed pump power for the resonator of fig. 1 without tuner or modulator.

of ~10 mW absorbed in a 1 m length are indicated.

The arrangement used to achieve oscillation on the $^4F_{3/2} \rightarrow {}^4I_{11/2}$ transition is shown in fig. 1. The cw dye laser used to pump the Nd ions was tuned to the strong absorption at ~590 nm. The pump beam was launched into the fibre core (~6 μm diameter) using a X10 microscope objective. The fibre laser mirror at this input end was butted against the fibre end face to minimise coupling losses for the fibre resonator. The output mirror was located away from the fibre output face, to allow insertion of intracavity control devices, and a microscope objective was used to collimate the beam in this section of the resonator.

The input mirror, chosen to suppress lasing on the 1.08 μm line, had a low reflectivity at 1.08 μm and high reflectivity (~99%) in the range 900–945 nm. The output mirror transmission was ~30%. With these mirrors and using a 1 m length of fibre with 300 ppm Nd^{3+} concentration it was found that the threshold for oscillation for the resonator without tuning element or modulator present corresponded to an absorbed pump power of 8 mW. Fig. 2 shows a plot of output power versus input power, with an output of 3.4 mW for the maximum available absorbed pump power of 53 mW. At this maximum pump level only a few milliwatts of pump emerged from the output end of the fibre, indicating that saturation was not significant.

The optimum length of fibre has not been determined experimentally. It depends on a compromise betweei the need to avoid excessive absorption loss at the laser frequency due to the unpumped fibre. The significance of this absorption loss was shown by the observation that while oscillation readily occurred in the 1 m fibre, it was not possible to achieve oscillation in a 2 m length At 1.08 μm such reabsorption losses are not significant. With the 1 m fibre sufficient gain could be achieved to demonstrate mode-locking and Q-switching with acousto-optic modulators and tuned operation using a two-plate birefringent filter. Q-switched operation produced pulses of 75 ns duration. Tuned operation was achieved continuously over the range 900 nm to 945 nm, covering most of the range of the fluorescence spectrum. A detailed description of the tuning, mode-locking and Q-switching results is being prepared for a further publication, but these results already suggest that this fibre laser shows promise as a convenient source of coherent radiation in the near infrared.

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References

[1] S.B. Poole, D.N. Payne and M.E. Fermann, Electron. Lett. 21 (1985) 737.
[2] S.B. Poole, D.N. Payne, R.J. Mears and M. Fermann, to appear in Journal of Light Wave Technology.
[3] R.J. Mears, L. Reekie, S.B. Poole and D.N. Payne, Electron. Lett. 21 (1985) 738.
[4] R.J. Mears, L. Reekie, S.B. Poole and D.N. Payne, Electron. Lett. 22 (1986) 159.
[5] I.P. Alcock, A.C. Tropper, A.I. Ferguson and D.C. Hanna, to appear in Electron. Lett.
[6] I.P. Alcock, A.I. Ferguson, D.C. Hanna and A.C. Tropper, submitted to Electron. Lett.
[7] W. Koechner, Solid State Laser Engineering, Vol. 1 Springer Series in Optical Sciences (Springer-Verlag, 1976).
[8] C.G. Young, Appl. Phys. Letts. 2 (1963) 126.
[9] T. Uchida, S. Yoshikawa, K. Washio, R. Tatsumi, K. Tsushima, I. Kitano, K. Koisumi and Y. Ikeda, Jap. J.A.P. 12 (1973) 126.
[10] S. Kishida, K. Washio and S. Yoshikawa, Appl. Phys. Lett. 34 (1979) 273.
[11] M.J. Weber, D.C. Zeigler and C.A. Angell, J. Appl. Phys. 53 (1982) 4344.
[12] M.M. Maun and L.G. De Shazer, J. Appl. Phys. 41 (1970) 2951.