In conclusion we have demonstrated a relatively simple, room-temperature operating, resonant cascaded fibre Raman laser that provides a broad band CW output between 1.56 and 1.95μm. We believe this is the first report of a CW fibre Raman laser operating in this spectral region. This laser was pumped by an integrated Yb^{3+}:Er^{3+} fibre laser, which in turn can be pumped either by a compact mini all-solid-state Nd-based laser or laser diodes. Through optimising the fibre lengths employed and output coupling ratios, a considerable increase in the output power levels should be achieved.

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Efficient fibre-coupled laser diode end-pumped NYAB laser

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Indexing terms: Fibre lasers, Solid lasers

Under optimum pump conditions, 60mW of green laser output corresponding to a conversion efficiency 6% was obtained from a self-frequency-doubling NYAB crystal when pumped by a 1W fibre-coupled laser diode. The prospect of higher conversion efficiency is also discussed.

Neodymium yttrium aluminum borate (NYAB) has a number of desirable features that make it an attractive material for a diode pumped compact green laser system. The self-frequency-doubling CW NYAB laser end-pumped by a diode laser has been realised in several laboratories [1 – 4]. However, the conversion efficiency never exceeded 3% in these investigations. In this Letter we demonstrate a highly efficient fibre-coupled diode end-pumped NYAB laser. Under optimum pump conditions, 60mW of green laser output corresponding to a conversion efficiency 6% was obtained from a self-frequency-doubling NYAB crystal when pumped by a 1W fibre-coupled laser diode.

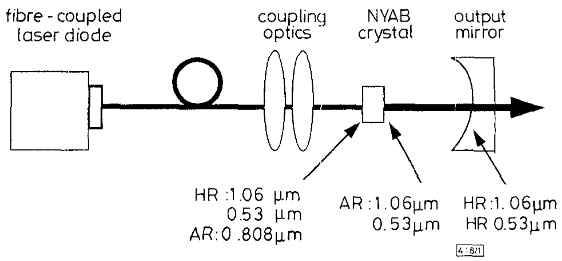

Fig. 1 *Fibre-coupled diode pumping experimental setup*

The NYAB crystal, dimensions 3mm × 3mm × 2mm, was cut at the type I phase-matching angle for second harmonic generation at 1.063μm (θ_m = 32.9°). The experimental setup is shown in Fig. 1. The fibre-coupled laser diode used was an SDL-2372-P2 (Spectra Diode Laser Labs),which has a 200μm core fibre with a ~36° half width at $1/e^2$ of the peak intensity and a maximum CW output power of ~1.2W. The emission wavelength of the diode laser was tuned by controlling the operating temperature control system to match the laser wavelength to the absorption peak of NYAB. The planoconcave configuration of the resonator consisted of one planar crystal surface, high-reflection coated at 1.063μm and 0.532μm and high-transmission coated at 0.808μm for the pump light to enter the rod, and a spherical output mirror. The second surface of the crystal was antireflection coated at 1.063μm and 0.532μm. An ouput mirror with a curvature of 10cm was used and the reflectivities of the mirror were 99.9% and <10% for 1.063μm and 0.532μm, respectively. The mirror was mounted approximately 5cm from the planar reflecting facet. This design yields a 0.13mm TEM_{00} spot size.

The brightness of a single fibre-coupled laser diode (several tens of kW/cm²·sr) is two orders of magnitude less than that of the source diode (several MW/cm²·sr) [5]. Therefore, the characteristic of the pump-beam quality should be taken into account in determining the optimum pump condition of the fibre-coupled laser-diode pumped lasers. Including the effect of the pump-beam quality, the normalised spatial distribution of the pump energy can be described by [6, 7]

$$r_p(x,y,z) = \frac{2\alpha}{\pi\omega_p^2(z)[1-\exp(-\alpha L)]}\exp\left(-2\frac{x^2+y^2}{\omega_p^2(z)}-\alpha z\right) \tag{1}$$

On the basis of the paraxial approximation, $\omega_p(z) = \omega_{po}+\theta_p|z-z_0|$. Here ω_{po} is the radius at the waist, θ_p and z_0 are the far-field half-angle and focal plane of the pump beam in the active medium. The brightness theorem gives a relationship $n\theta_p\omega_{po} = C$, where C is a constant that is a characteristic of the beam quality and n is the refractive index for the pump beam. For a fibre-coupled diode, the

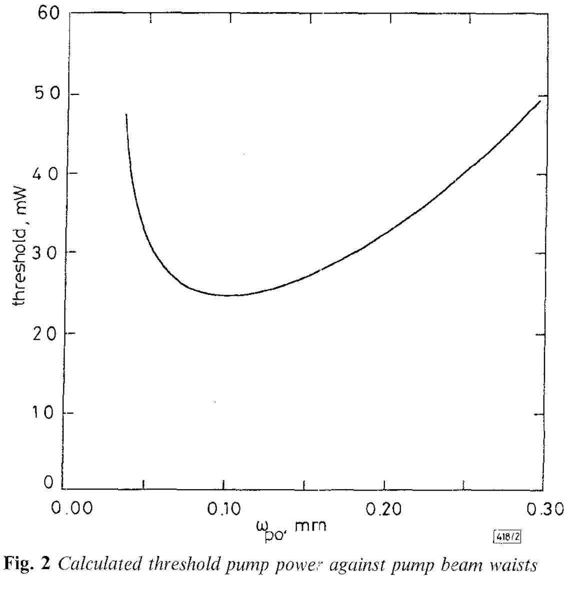

Fig. 2 *Calculated threshold pump power against pump beam waists*

value of C can be easily calculated from its core radius and divergence angle. It can be seen that for small pump beam waists the propagation angles of the beams relative to the optic axis may be too large for good overlap with the resonator mode. Conversely, for small divergence angles the large pump spot sizes may cause a reduction in mode overlap. Optimum pump spot size for the minimum threshold and maximum slope efficiency is expected when these two effects are balanced.

By using the above parameters, an upper-state lifetime of 60µs, a cross-section of $10 \times 10^{-19}\,\mathrm{cm}^2$, an absorption coefficient of $9.2\,\mathrm{cm}^{-1}$ at the pump wavelength, an absorption coefficient of $1.4\,\mathrm{cm}^{-1}$ at the second harmonic beam wavelength, a nonlinear optical coefficient of 6.82×10^{-9} e.s.u, and an internal loss of $2.8\%\,\mathrm{cm}^{-1}$, we have calculated the threshold pump power as a function of pump beam waists. As shown in Fig. 2, the threshold has a minimum of ~25mW of pump power with the the pump beam waist around 0.12mm. To match this optimum pumping condition, the fibre output was focused into the NYAB crystal by using f = 6.5mm focal length collecting lens (NA = 0.615), and f = 8.0mm focal length focusing lens (NA = 0.5).

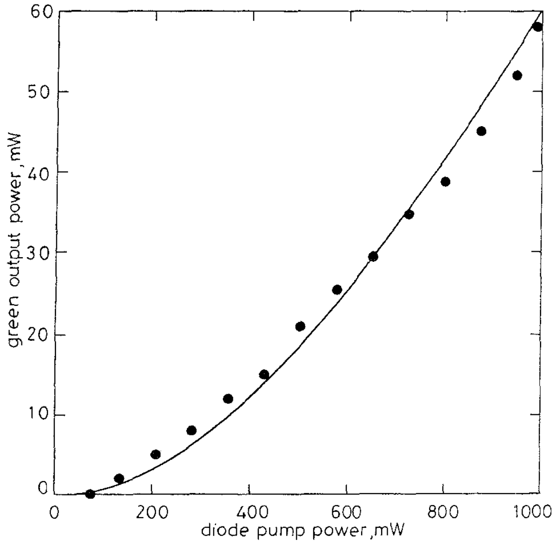

Fig. 3 *Experimental and theoretical results for output power against optical pump power*

——— theory, ● experimental result

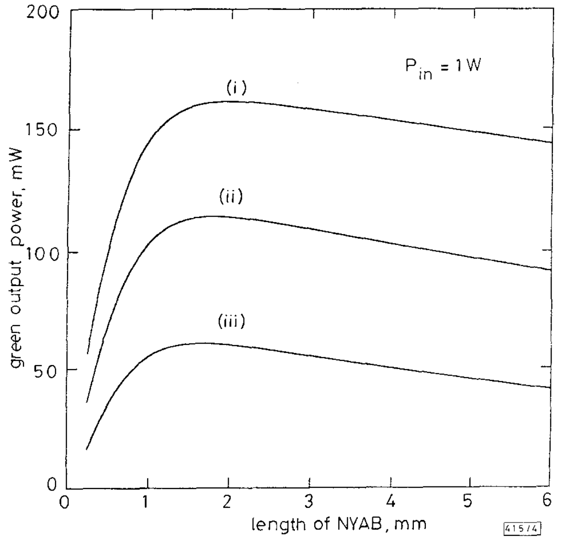

Fig. 4 *Dependence of green output power on internal losses and length of NYAB crystal*

(i) $\alpha_i = 0.7\%\,\mathrm{cm}^{-1}$
(ii) $\alpha_i = 1.4\%\,\mathrm{cm}^{-1}$
(iii) $\alpha_i = 2.8\%\,\mathrm{cm}^{-1}$

The fibre-coupled diode end-pumped NYAB laser was operated using the pumping configuration discussed above. Experimental and theoretical results for output power against optical pump power are shown in Fig. 3. A CW green output power of ~60mW was obtained at a pumping power 1 W corresponding to a conversion efficiency of ~6%. To our knowledge, the present conversion efficiency is the highest reported so far for a self-frequency-doubling CW NYAB laser. Also, it can be seen that the predictions of the analysis agree very well with experimental data.

With NYAB crystals of good optical quality the efficiency and output power can be improved considerably. The dependence of green output power on the length of the NYAB crystal is shown in Fig. 4. It can be seen that the conversion efficiency can be higher than 10% for an NYAB with internal loss less than $1.4\%\,\mathrm{cm}^{-1}$. It can be seen that the optimum crystal length is ~1.5–2.0mm, with almost total insensitivity to internal losses.

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High performance 660nm InGaP/AlGaInP quantum well metal cladding ridge waveguide laser diode

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Indexing terms: Semiconductor junction lasers, Waveguide lasers

A high performance 660nm metal cladding ridge waveguide laser diode was fabricated from a compressively strained $In_{0.6}Ga_{0.4}P/(Al_xGa_{1-x})_{0.5}In_{0.5}P$ single quantum well laser structure. The 4µm wide ridge waveguide diode had a threshold current of 31mA with a differenfial quantum efficiency of 45%/facet (slope efficiency of 0.85W/A) under CW operation. The characteristic temperature was 120K from 20 to 75°C. The diode operated in a single transverse mode up to 22mW/facet.

Red laser diodes are being widely used in applications such as printing, bar code scanning and optical data storage [1]. In applications which need stable single transverse mode beam at power level over tens of milliwatts, a buried ridge waveguide structure has been mostly used to in diode fabrication [2, 3]. Although high