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Highly-efficient, low-noise grating-feedback Er^{3+}:Yb^{3+} codoped fibre laser

J.T. Kringlebotn, J.-L. Archambault, L. Reekie, J.E. Townsend, G.G. Vienne and D.N. Payne

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The authors report a highly-efficient, short, robustly single-frequency and linearly polarised Er^{3+}:Yb^{3+} codoped fibre laser with fibre-grating Bragg reflectors. An output power of 19mW for 100mW of 980nm diode pump power and a slope efficiency relative to a launched pump power of 55% is demonstrated. The RIN of the laser was < −157 dB/Hz and the laser linewidth was 300kHz.

Single-frequency Er^{3+}-doped Fabry-Perot fibre lasers using fibre-grating Bragg reflectors [1, 2] are emerging as interesting alternatives to DFB diode lasers for use in future optical CATV networks and high-capacity WDM communication systems [3]. They are fibre compatible, simple, are scalable to high output powers, and have low noise and kilohertz linewidths. In addition, the laser wavelength can be determined to an accuracy of ≤0.1nm, which is very difficult with DFB diode lasers.

Fibre lasers are only robustly single-frequency provided that the grating bandwidth is kept below ~0.2nm and the laser length is reduced to a few centimetres to increase the axial mode spacing. Furthermore, it is necessary to keep the Er^{3+} concentration low enough (a few 100*ppm*) to reduce ion-pair quenching, which causes a reduction in the quantum efficiency and in addition may lead to strong self-pulsation of the laser [2–4]. Combining these practical limits means that the pump absorption in the laser length can be as low as a few percent and the slope efficiency of these lasers is therefore very low (~1%) [2]. One solution is to increase the output power by using the residual pump power to pump an erbium-doped fibre amplifier following the fibre laser [5]. However, in this case the amplified spontaneous emission from the amplifier increases the output noise.

Recently, we have presented a solution to these problems by codoping the Er^{3+}-doped fibre with Yb^{3+} [6]. This increases the absorption at the pump wavelength by more than two orders of magnitude and enables highly-efficient operation of centimetre-long lasers with relatively low Er^{3+} concentration. The pump excites the Yb^{3+} ions which efficiently transfer their energy to the Er^{3+} ions by resonant coupling [7]. We report here that by reducing the intra-cavity splice loss and using a new high transfer-efficiency Er^{3+}:Yb^{3+} codoped fibre, we have been able to shorten the laser length to ≤2cm. For this laser we obtain a stable single-frequency output power of 19mW with 100mW of 980nm diode pump power and a slope efficiency relative to the launched pump power of 55%.

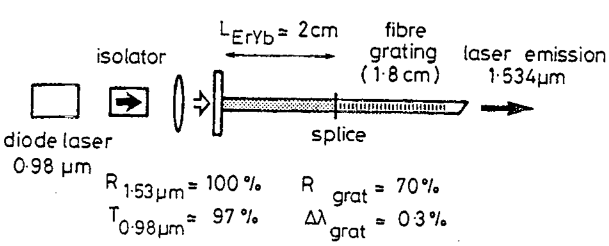

Fig. 1 *Er^{3+}:Yb^{3+}-doped fibre laser configuration*

The laser configuration is shown in Fig. 1, and is similar to that reported in [6–8]. We have been able to reduce the Er^{3+}:Yb^{3+} codoped fibre length to ≤2cm while still providing enough gain for laser action by: reducing the single-pass splice loss to <0.12dB, optimising the grating reflectivity (70%), matching the Bragg wavelength to the peak gain wavelength, and using a new highly-efficient, alumino-phosphosilicate Er^{3+}:Yb^{3+} codoped fibre with optimised dopant distribution and concentrations, and hence an increased energy-transfer efficiency (close to 100%). The P_2O_5 and Al_2O_3 concentrations are 18 and 2wt%, respectively. The erbium concentration is ~1000*ppm* (0.26wt%), which is low enough to eliminate the problem of self-pulsation through ion-pair quenching [3, 4]. The fibre has a Yb^{3+}:Er^{3+} concentration ratio of 12.5:1, an NA of 0.2 and a cutoff wavelength of 1130nm. The fibre grating was fusion-spliced to the doped fibre. The grating reflection bandwidth was 0.3nm and the grating Bragg wavelength (and the laser wavelength) was 1534nm. An optical isolator was used to prevent back-reflections into the pump diode.

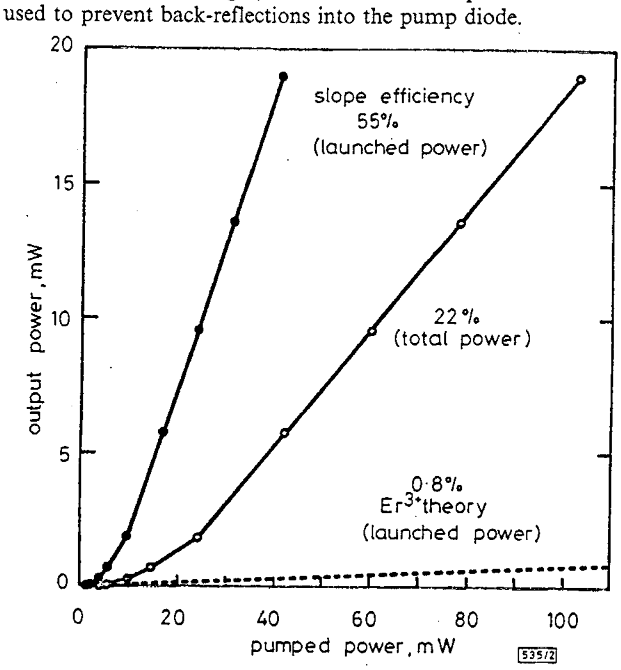

Fig. 2 *Measured laser output power as function of total and launched diode pump power*

The output power calculated as a function of launched pump power for a 2cm-long fibre laser doped with Er^{3+} alone (with the same mirror reflectivities, but no intracavity loss) is shown for comparison

The Er^{3+}:Yb^{3+} codoped fibre laser characteristics are shown in Fig. 2. The threshold diode laser power is 4mW (1.6mW launched). The slope efficiency relative to the diode output is as high as 22%, which for an estimated launch efficiency of 40% yields a slope efficiency relative to the launched pump power of 55%, close to the quantum limit of 64%. Virtually all of the pump power was absorbed in the fibre, owing to the high Yb^{3+} absorption. The slope efficiency was limited by the roundtrip intra-cavity splice loss of ~0.24dB, as confirmed by a theoretical calculation. The splice loss could be eliminated by writing the grating directly into the doped fibre. However, at present Er^{3+}:Yb^{3+} codoped fibres cannot be made both efficient and photosensitive, because efficient energy transfer between the Yb^{3+} and Er^{3+} ions requires the fibre core to be doped with large concentrations of P_2O_5 and Al_2O_3, i.e. without GeO_2 which is normally required to make the fibre photosensitive. The slope efficiency and threshold pump power of a similar, lossless Er^{3+}-doped fibre laser is calculated to be 0.8% and 8.1 mW, respectively (see Fig. 2). This convincingly illustrates the advantage of including Yb^{3+}.

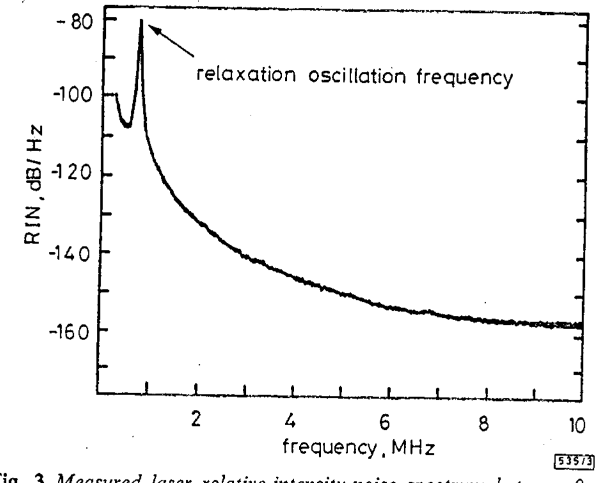

Fig. 3 *Measured laser relative-intensity-noise spectrum between 0 and 10MHz*

Resolution bandwidth is 10kHz

The laser oscillated in one longitudinal mode, although the long-term stability in this case was limited to several minutes by the relatively broadband grating used in our experiment (0.3nm). Robust single frequency operation can readily be achieved by using two narrow grating end reflectors and a shorter cavity length, as described later in this Letter. The laser output was very quiet, with only a very small modulation at the relaxation-oscillation frequency. Fig. 3 shows the laser relative-intensity-noise (RIN) spectrum from 0 to 10MHz for maximum output power. Above the relaxation-oscillation frequency (810kHz) the RIN decreases to a level below −157dB/Hz which is an improvement of ~11dB compared with our previous result [6]. This is due to the pump isolator, and the use of an improved Er^{3+}:Yb^{3+} codoped fibre. Note that the relaxation oscillation noise peak can be substantially reduced by means of electronic feedback [9].

The linewidth of the laser was measured using a conventional delayed self-heterodyne setup with a length difference between the two arms of 50km (i.e. an inverse transit time of 4kHz). An optical isolator was used between the laser and the setup to prevent feedback-induced linewidth narrowing [8]. The laser linewidth was measured to be 300kHz, independently of the laser output power. The spectrum analyser sweep time was 44s. Because the relaxation oscillation frequency at the maximum power level was ~810kHz, the linewidth was not limited by the relaxation oscillation sidebands as reported in [8].

In a further experiment we made an all-fibre laser by replacing the input mirror with a fibre grating having a reflectivity R_1>99.9% and a bandwidth of 0.5nm. The output grating had a reflectivity R_2 = 89% and a bandwidth of 0.26nm. The length of the Er^{3+}:Yb^{3+} codoped fibre in this case was 17mm. The maximum output power was obtained when the Bragg wavelengths of the two gratings were separated through temperature tuning by ~0.35 mm, yielding a product $R_1 \cdot R_2$ of ~0.4. The output power was then approximately the same from both ends; yielding a total slope efficiency relative to the launched pump power of ≥46%. The reduced slope efficiency compared with the previous experiment is due to the extra splice loss introduced by the second grating. The fractional absorbed pump power was measured to be 95%. Because of the use of two narrowband gratings and a very short cavity length, this laser was robustly singlemode, with no mode hopping. In addition the output was linearly polarised for output signal powers <10mw. At higher powers the orthogonal polarisation mode, separated from the first mode by ~3.5GHz, was also present. This is attributed to increased spatial holeburning. Single polarisation operation should also be possible at higher power levels by using narrower gratings to discriminate against one of the polarisation modes.

In conclusion, we have demonstrated a ≤2cm-long, highly-efficient, diode-pumped 1534nm single-frequency Er^{3+}:Yb^{3+} codoped fibre laser with a slope efficiency relative to the launched pump power of 55% and an output power of 19mW. Our experimental results are in good agreement with theoretical predictions, indicating a quantum efficiency close to 100%. The RIN at maximum output power was <−157dB/Hz for frequencies above 10MHz and the linewidth was approximately 300kHz. Robustly single-frequency, linearly-polarised output was demonstrated in a 17mm long laser with two grating reflectors.

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Low threshold current 1.6μm InGaAsP/InP tapered active layer multiquantum well laser with improved coupling to cleaved singlemode fibre

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The authors report low threshold current large spot size MQW BH lasers. Coupling losses to 10μm core cleaved singlemode fibre down to 4.1dB have been obtained for devices with threshold currents of 4.9 and 15mA at 20 and 80°C, respectively.

Introduction: The cost of packaged 1.3 and 1.55μm wavelength semiconductor lasers is an important issue for fibre to the home. A large proportion of the cost of the laser is incurred in device packaging, where major items are the cost of fibre lenses, the need to use active fibre alignment techniques, the requirement for high accuracy fibre positioning and the need for temperature control. We have previously reported a laser design that increased both the coupling efficiency to cleaved fibre and fibre alignment tolerances [1]. This used a tapered MQW active layer, and underlying passive guide (Fig. 1). It was chosen because of its flexibility, the output spot size being determined solely by the design of the passive guide. This allows the active layer to be optimised for specific applications such as high speed or power. The 16 well active layer used in [1] was chosen because of its high T_0, and yielded devices with threshold currents of ~35mA at 80°C. Reducing the threshold current could allow further cost savings in operation because the laser drive circuitry can be simplified if modulation from zero bias can be employed. Several authors have shown that the use of strained quantum wells can reduce threshold current and improve high temperature performance [2–4]. In this Letter we report a laser that uses an 8well strained MQW active layer to produce a low threshold current tapered active layer laser with reduced far field and improved coupling to cleaved fibre.

Growth and fabrication: The planar design used in this device was similar to that of [1], the main difference being the design of the active layer. The planar was epitaxially grown on an *n*-doped InP substrate by atmospheric pressure MOVPE and consisted of a 3μm thick *n*-doped InP buffer layer, a 0.16μm thick *n*-doped 1.1μm wavelength quaternary guide, a 0.2μm thick *n*-doped InP spacer layer, an undoped 8well strained MQW active layer [4], and a 0.2μm thick *p*-doped InP cap. The MQW active layer con