the power efficiency initially increases, but then decreases because junction heating increases carrier leakage and therefore reduces η_d. The maximum power efficiencies are 51% (for 0.6A, P = 0.60 W) at -55°C, 57% (for 0.8A, P = 0.87W) at 25°C, and 46% (for 0.6A, P = 0.48W) at 75°C.

As shown in Fig. 3, for currents below ~1A, V_{fb} decreases with increasing temperature, a consequence of the decrease in the energy gap. The diode series resistance R_s, calculated from the data in the current range between 0.6 and 1.6A, is 0.297W at -55 and 75°C, and 0.219W at 25°C. Although a maximum power level was obtained for the lowest temperature of -55°C, the larger V_{fb} and R_s reduce the power conversion efficiency. As a result, the highest power efficiency is obtained for the device tested at a heat-sink temperature of 25°C.

In conclusion, we have demonstrated strained-layer InGaAs-AlGaAs GRINSCH-SQW diode lasers that have maximum power conversion efficiencies of ≥46% and maximum output power levels of ≥1.8W for temperatures between -55 and 75°C.

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Narrow-linewidth, singlemode erbium-doped fibre laser with intracavity wave mixing in saturable absorber

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Indexing terms: Fibre lasers, Laser linewidth, Electromagnetic wave absorption

Narrow-linewidth, single longitudinal mode operation is demonstrated in an erbium-doped fibre laser with an intracavity nonlinear absorptive wave mixing of the counter propagating beams. An unpumped length of erbium-doped fibre serves as the saturable absorber. Linewidths of the order of a few kilohertz are obtained.

Single frequency, narrow-linewidth erbium-doped fibre lasers can be very important in fibre-optic communication for uses such as wavelength division multiplexing and coherent systems. Conventional methods of using filters in the cavity, such as passive gratings, do not provide an immediate solution for strong narrowing and single mode operation, especially for lasers with long cavities. Long cavities are needed not only for high oscillation powers but also for their inherent potential for very narrow linewidths. In this work we present a demonstration of a method [1] that uses wave mixing of the oscillating beams in an intracavity saturable absorber to reduce the oscillation linewidth and to obtain single longitudinal mode operation. This is carried out in an erbium-doped fibre laser cavity. The narrowing effect seems to be surprising because we know that coupling, interference and spatial hole burning cause a degradation of the oscillation quality of lasers [2–4], a reduction of its coherence and an increase of its linewidth. However, these problems result from saturation of an amplifying medium, and for saturation of an absorber the outcome is quite different. This can be understood by considering the reflections from the induced saturable gain grating due to the interference pattern. These reflections interfere destructively (180° out of phase) with the corresponding copropagating waves [5] and therefore they provide a negative feedback, which in turn tends to eliminate the grating (from which they originate) by a reduction of the coherence. However, in a saturable absorber the nonlinear wave mixing has an opposite effect. The reflections from the induced saturable absorbing grating are in-phase and provide positive feedback. The same conclusion can be obtained [1] by realising that the absorption is lower for light intensity which has a nonuniform periodic distribution along the saturable absorber, than it is in the uniform case. Therefore in the presence of a saturable absorber, coherence and single longitudinal mode operation induce the standing wave and are thus favoured. Moreover, the effect on a third wave with a different frequency is the opposite [1]: the absorption is higher for nonuniform distribution than for the uniform case. Thus the saturable absorber favours elimination of all other longitudinal modes. We note that passive modelocking in such a system that contains erbium doped fibre as a saturable absorber cannot be simply used for passive modelocking because of its long time response (~10ms).

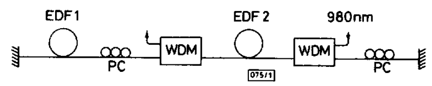

Fig. 1 *Erbium-doped fibre laser system with amplifying part (EDF 2) and intracavity saturable absorber (EDF 1)*

The mirror's reflectivity was ~95%. The polarisation controllers (PC) are adjusted such that the polarisation states of the counterpropagating waves are perpendicular in the amplifier (EDF 2) and parallel in the saturable absorber section (EDF 1)

The experimental setup is shown in Fig. 1. Erbium-doped fibres were used as the amplifying and the saturable absorbing media. The gain section was pumped by a 980nm diode laser and the saturable absorber part was unpumped. The fibres had a 2.5μm alumino-germano-silicate core with a numerical aperture of 0.33 and an erbium concentration of 2500*ppm*. The amplifier and absorber sections had lengths of 50 and 32cm, respectively. The overall cavity length was 10.4m. To reduce the broadening effect in the gain section of the laser (see Fig. 1), the wave mixing was eliminated by making the polarisations of the counterprapogating beams in this section perpendicular, using polarisation controllers. The operation of the laser system with the saturable absorber section in it showed bistable behaviour of the oscillation power as a function of pumping. A detailed theoretical analysis of this effect will be reported elsewhere [1].

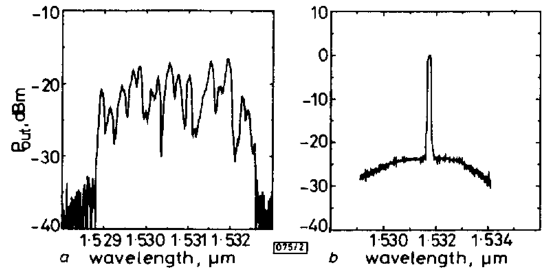

Fig. 2 *Spectra of fibre without and with saturable absorber section*

a Without saturable absorber
b With saturable absorber

The spectrum of the fibre laser without the saturable absorber section (replaced by a regular singlemode fibre) is shown in Fig. 2*a*. The spectrum was very broad and erratic. In this case, the threshold pumping light power (of 980nm) was ~10mW. With the saturable absorber section, we obtained a much narrower linewidth (Fig. 2*b*). Here, the linewidth measurement is limited by the resolving power of the grating-based spectrum analyser which was 0.1 nm. The spectrum was stable for periods of minutes. The threshold pumping light power (of 980nm) in this configuration was 50mW. To verify singlemode operation and to evaluate the linewidth more carefully, we also used a Fabry-Perot etalon, RF spectrum analyser, as well as delayed self-homodyning (Mach-Zehnder interferometer). From the RF spectra we have found that for most of the time (90%) the laser oscillated in a single longitudinal mode, as indicated by the absence of a peak at 9.6MHz, the frequency corresponding to the beating between adjacent cavity modes. From time to time the laser did build up a second mode, as indicated by the momentary presence of the peak at 9.6MHz (Fig. 3). The width of this peak was below 5kHz. The Mach-Zehnder interferometer showed a strong interference between the two split arms having a mutual delay of 7.5km (corresponding to an upper limit of 20kHz for the linewidth). In curve (i) of Fig. 4, the interference is evident in the strong fluctuations seen in the time domain which are related to thermal changes of the refractive index in the long fibres. Curve (ii) in Fig. 4 is the output intensity of the interferometer when one branch was blocked.

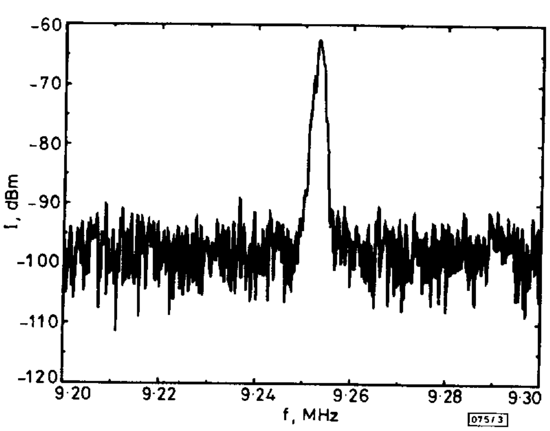

Fig. 3 *RF spectrum of output detected light, observed at instances when two longitudinal modes existed*

The singlemode operation is a result of the nonlinear wave mixing and the induced grating which enhance the coherence and eliminate other modes, as explained above. A first estimate of the

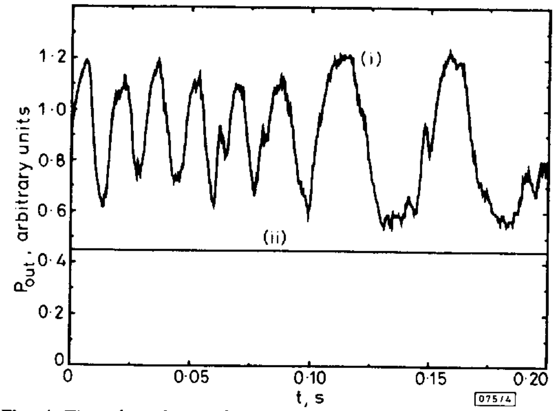

Fig. 4 *Time dependence of interference in delayed self homodyning experiment (Mach-Zehnder interferometer) and output when one branch is blocked*

(i) Time dependence of interference: The path difference between the two branches was 7.5km
(ii) Output when one branch is locked

filtering effect can be obtained by considering a simple passive grating. Note that the possibility of self-induced distributed grating in long fibres in the cavity is by itself an advantage, which is difficult to achieve in other ways. For such a passive grating with length l, the filtering width is given by $\delta\nu_{grating} \simeq c/(2nl) \simeq$ 312MHz. This is larger than the longitudinal mode spacing $\Delta\nu = c/(2nL) \simeq$ 9.6MHz, where now L ($\simeq$ 10.4m) is the laser cavity length. Note however, that the active parts in the cavity in our experiment had a length of only 0.82m; therefore the overall length could have been shortened to make the mode spacing comparable to the frequency width of the passive grating. Adding to this filtering effect the mechanism of the nonlinear wave mixing described earlier, causes the strong tendency to a singlemode oscillation. The theoretical linewidth-limit of a singlemode laser can be very narrow due to the long cavity. According to the Schawlow-Townes formula with values of 95% mirror reflectivity, cavity length of 10m, one roundtrip absorption of 50% and power of 0.1mW, the theoretical limit can reach 10^{-1} to 10^{-2}Hz. Therefore, a linewidth in the kilohertz regime is not surprising, and we expect that by proper thermal and acoustical stabilisation, as well as optimisations of the lengths of the erbium-doped fibres, it will be possible to reduce the linewidth and ensure the robustness of singlemode operation.

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