TuG5 771 **3:00 pm**

Efficient low-noise grating-feedback fiber laser doped with $Er^{3+}:Yb^{3+}$

J. T. Kringlebotn, J.-L. Archambault, L. Reekie, J. E. Townsend, G. G. Vienne, D. N. Payne,
Optoelectronics Research Centre, University of Southampton, Southampton S09 5NH, U.K.

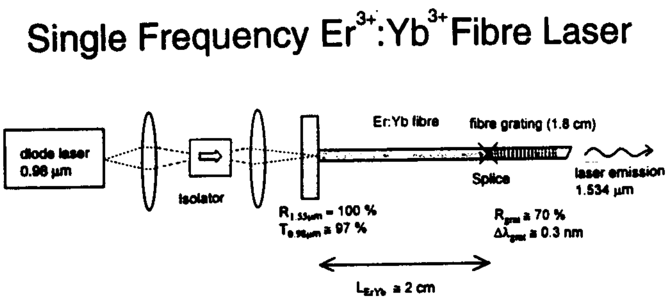
Single-frequency Er^{3+}-doped Fabry–Perot fiber lasers using fiber-grating Bragg reflectors[1,2] are emerging as interesting alternatives to distributed-feedback (DFB) diode lasers for use in future high-capacity wavelength-division multiplexed (WDM) communication systems.[3] They are fiber compatible, scaleable to high output powers (>1 W), and have low noise and kilohertz linewidths.

Fiber lasers are only robustly single frequency provided that the laser length is reduced to a few centimeters to increase the axial mode spacing and the grating bandwidth is kept below approximately 0.2 nm. It is also necessary to keep the Er^{3+} concentration low to avoid a reduction in efficiency by ion-pair quenching, and this combination of factors means that the pump absorption in the laser length can be as low as a few percent. Hence the slope efficiency of these lasers is very low.[2] It is possible to increase the output power by using the residual pump power to pump an erbium-doped fiber amplifier (EDFA) following the fiber laser. However, the presence of the amplifier amplified spontaneous emission (ASE) increases the output noise. In addition, it has been reported that these lasers are susceptible to strong self-pulsation.[2-4]

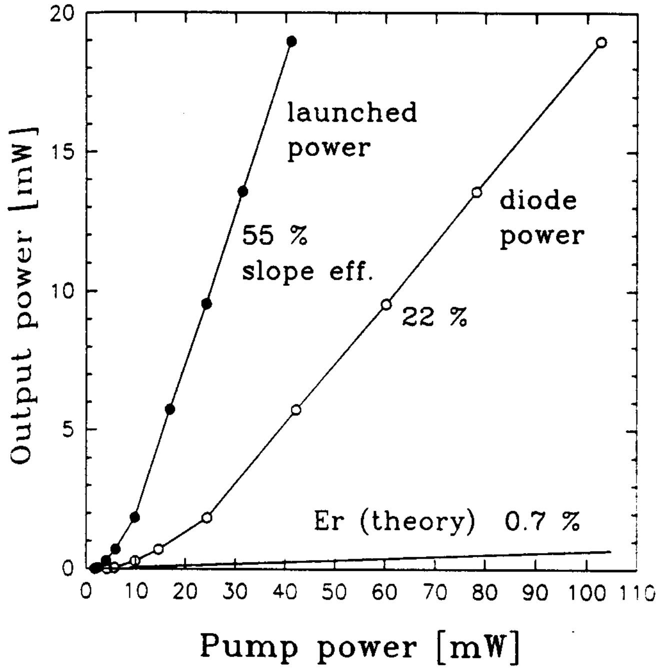
We have presented a solution[5] to these problems by codoping the Er^{3+}-doped fiber with Yb^{3+}, which increases the absorption at the pump wavelength by more than 2 orders of magnitude and permits highly efficient operation in centimeter-long lasers. Here the pump excites the Yb^{3+} ions, and energy is efficiently transferred to the Er^{3+} ions by resonant coupling. In this paper we present results significantly improved over those reported previously. By shortening the laser to only 2 cm and using a new high-transfer-efficiency $Er^{3+}:Yb^{3+}$-doped fiber, we demonstrate a stable single-frequency output power of 19 mW with 100 mW of 980-nm diode pump power, a slope efficiency relative to the launched pump power of 55%, and a relative intensity noise (RIN) less than −157 dB/Hz. Since the fiber-to-fiber launch efficiency can be close to 100%, this performance should be compared with that of a DFB laser having approximately twice the output power (i.e., 40 mW).

The laser configuration, shown in Fig. 1, is similar to that reported in Ref. 5. We have been able to reduce the length of the $Er^{3+}:Yb^{3+}$-doped fiber to 2 cm while still providing enough gain for laser action by (i) reducing the splice loss to less than −0.2 dB, (ii) optimizing the grating reflectivity (70%), and (iii) using a highly efficient, aluminophosphosilicate $Er^{3+}:Yb^{3+}$-codoped fiber with an optimized dopant distribution, and hence an increased transfer efficiency. The erbium peak absorption at 1530 nm has been measured to be approximately 0.4 dB/cm, yielding an erbium concentration of approximately 600 parts in 10^6, which is low enough to eliminate the problem of self-pulsation.[3,4] The fiber had an $Yb^{3+}:Er^{3+}$-concentration ratio of 12.5:1, a numerical aperture of 0.2, and a cutoff wavelength of 1120 nm. The pump absorption at 980 nm is difficult to measure but is in the region of 100 dB/cm. The grating was spliced to the doped fiber since at present $Er^{3+}:Yb^{3+}$ fibers cannot be made both efficient and photosensitive, owing to their P_2O_5 content. The grating reflection bandwidth was 0.3 nm, and the grating Bragg wavelength (and the laser wavelength) was 1.534 μm. An optical isolator was used to prevent back-reflections into the pump diode, although other techniques (e.g., an angled launch) would also suffice.

Characteristics of the $Er^{3+}:Yb^{3+}$ laser are shown in Fig. 2. The slope efficiency relative to the diode output is as high as

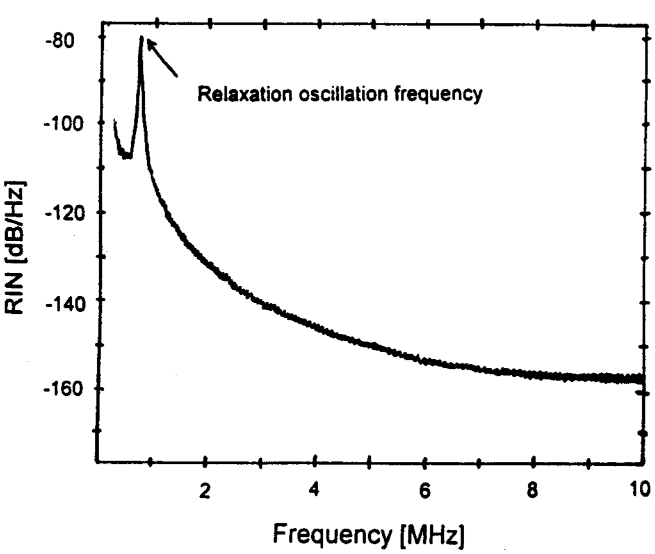


TuG5 Fig. 1. Configuration of $Er^{3+}:Yb^{3+}$-doped fiber laser.



TuG5 Fig. 2. Laser output power as a function of total and launched diode pump power. The output power as a function of total pump power for an ideal lossless fiber laser doped with Er^{3+} alone is shown for comparison.

Relative Intensity Noise



TuG5 Fig. 3. Laser RIN spectrum between 0 and 10 MHz. The resolution bandwidth is 10 kHz.

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%. The slope efficiency was limited by the intracavity splice loss (less than −0.2dB) since owing to the high Yb^{3+} absorption virtually all the pump power was absorbed in the fiber. The threshold diode laser power was 4 mW. Figure 2 also shows the calculated laser characteristics of an ideal lossless 2-cm-long fiber laser (with an output coupling of 10%) doped with Er^{3+} alone. In this case the threshold diode pump power is 9 mW, and the overall slope efficiency is only 0.7% owing to the low pump absorption. This comparison with our experimental results on Er^{3+}:Yb^{3+} convincingly illustrates the advantage of adding Yb^{3+}. 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 (0.3 nm). Robust single-frequency operation can readily be achieved by using a more typical grating with reflection bandwidths <0.2 nm, as we have shown previously.[5] The laser output was very quiet, with only a very small modulation at the relaxation-oscillation frequency. Figure 3 shows the laser RIN spectrum from 0 to 10 MHz. Above the relaxation-oscillation frequency the RIN decreases to a level below −157 dB/Hz, which is an improvement of approximately 11 dB over our previous result.[5] This is due to (i) the pump isolator and (ii) the use of an improved Er^{3+}:Yb^{3+}-doped fiber.

In conclusion, we have demonstrated a 2-cm-long, highly efficient (>20%) 1.534-μm single-frequency Er^{3+}:Yb^{3+}-doped fiber laser with an output power of 19 mW and a RIN of less than −157 dB/Hz above 10 MHz. Since gratings greater than 2 cm long (i.e., the full length of this laser) can readily be made, our results are a precursor to a highly efficient and stable Er^{3+}:Yb^{3+}-doped fiber DFB laser.

1. G. A. Ball, W. W. Morey, and W. H. Glenn, IEEE Photon. Technol. Lett. **3,** 613 (1991).
2. J. L. Zyskind, V. Mizrahi, D. J. DiGiovanni, and J. W. Sulhoff, Electron. Lett. **28,** 1385 (1992).
3. J. L. Zyskind, J. W. Sulhoff, P. D. Magill, K. C. Reichmann, V. Mizrahi, and D. J. DiGiovanni, Electron. Lett. **29,** 1105 (1993).
4. P. L. Boudec, P. L. Francois, E. Delevaque, F. Sanchez, G. M. Stephan, Opt. Quantum Electron. **25,** 501 (1993).
5. J. T. Kringlebotn, P. R. Morkel, L. Reekie, J.-L. Archambault, and D. N. Payne, in *Proc. 19th European Conference on Optical Communication,* Vol. 2, 1993, paper TuC3.2.