

# Rare-Earth-Doped Fiber Lasers and Amplifiers

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# Rare-Earth-Doped Fiber Lasers and Amplifiers

Second Edition, Revised and Expanded

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Since this work, extremely efficient 1.48- $\mu\text{m}$ -pumped Er-doped fiber laser in fact been reported by Wagener et al. at Stanford University [107]. This study established that a key factor that needs to be optimized to maximize the conversion efficiency is the erbium concentration. Measurements indicated that fibers with increasingly high erbium concentrations have increasingly high thresholds and low slope efficiencies. These effects were attributed to the presence of an increasing percentage of  $\text{Er}^{3+}$  clusters to the fact that clusters dramatically reduce the excited lifetime [133], and therefore the quantum efficiency of the transition. The most efficient fiber laser reported in this study used a low-concentration fiber (110 mol ppm  $\text{Er}_2\text{O}_3$ ) and a correspondingly long fiber (42.6 m) [107]. The cleaved fiber ends ( $\sim 3.5\%$  reflections) formed the laser Fabry-resonator. In spite of the high cavity loss ( $\sim 29$  dB), the threshold was low ( $\sim 4.8$  mW) and the laser was successfully pumped with a low-power laser diode. It emitted simultaneously in the forward and backward direction, with a forward slope efficiency of  $31.8\%$  [107]. This is the highest slope efficiency and the highest conversion efficiency reported in an Er-doped fiber laser (see Table 3). The backward slope efficiency was  $31.8\%$ . A dichroic high reflector was placed at the pump input end, a total slope efficiency of approximately the sum of these two figures, or  $\sim 90.4\%$ , would be expected, as well as a substantial reduction in threshold.

This study showed that Er-doped fiber lasers, when pumped near 1.48  $\mu\text{m}$ , are at least as efficient as 980-nm pumped lasers. The reasons for this high performance are the low Er concentration and the similarity between the pump and laser photon energies [107]. The slope efficiency of  $90.4\%$  is, in fact, very close to the quantum limit of  $\lambda_p/\lambda_s \approx 95\%$  predicted for the ratio of pump to signal photon energies. It confirms that the quantum efficiency of this transition can be within a few percent of unity. In this light, concentration quenching may well explain the suboptimal efficiencies and thresholds reported in Er-doped fiber lasers (see Table 3). It points to the importance of selecting a sufficiently low rare earth concentration to maximize the performance of fiber lasers or amplifiers. This requirement was confirmed in a more recent report of a ring fiber laser that used a very low-concentration fiber (see Table 3) [21]. After optimizing the fiber length and output coupler transmission, the laser had a low threshold (6.5 mW) and a fairly high slope efficiency of  $38.8\%$ . Tuning from 1525 to 1570 nm was achieved with an intracavity tunable filter.

### 3.6.8 Summary

In summary, Er-doped fiber lasers operating close to 1.55  $\mu\text{m}$  are extremely efficient. When pumped at 1.48  $\mu\text{m}$ , their slope efficiency can be within a few percent of the theoretical limit  $\lambda_p/\lambda_s \approx 95\%$ . Pumping at 980 nm produces a lower, although still substantial slope efficiency (theoretical limit of  $\sim 63\%$ ). Pumping at about 800 nm is unfortunately less efficient ( $\sim 15\%$ ) because of pump ESA, even with Yb co-doping. Er-doped fiber lasers are now almost exclusively pumped close to 980 or 1480 nm. They have also been operated at multiple wavelengths simultaneously. This feature, of great importance in dense WDM systems, is reviewed in Chapter 5.

## 3.7 YTTERBIUM

### 3.7.1 Basic Spectroscopy

Ytterbium is one of the most versatile laser ions in a silica-based host. It offers several very attractive features, in particular an unusually broad absorption band that str

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