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Efficient Diode-Pumped Single-Frequency Erbium:Ytterbium Fiber Laser

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Abstract—**We report a 7.6-mW single-frequency fiber laser operating at 1545 nm, using for the first time an Er^{3+}:Yb^{3+} doped fiber and a fiber grating output coupler. The laser did not exhibit self-pulsation, which is a typical problem in short three-level fiber lasers, and had a relative intensity noise (RIN) level below −145.5 dB/Hz at frequencies above 10 MHz. The linewidth of the laser was limited by the relaxation oscillation sidebands in the optical spectrum and was typically less than 1 MHz.**

INTRODUCTION

NARROW-LINEWIDTH, single-frequency Er^{3+}-doped fiber laser sources operating at 1.55 μm have potential for use in future high-capacity communications, especially wavelength-division-multiplexed (WDM) and coherent systems. Such lasers will also have applications in fiber sensors and in high-resolution spectroscopy. Advantages of single-frequency fiber lasers over DFB lasers for such applications include potential kHz linewidths, low-intensity noise, scalability to high output power, and direct fiber compatibility.

Traveling-wave loop or ring fiber lasers [1], [2] are relatively complex and are susceptible to mode-hopping owing to the length of fiber employed (a few meters) and the concomitant close-spacing of the axial modes. On the other hand, linear-cavity fiber lasers [3]–[5] using integral fiber grating Bragg reflectors for feedback and mode suppression are simpler, cheaper, and potentially more stable. In order to achieve robust single-mode operation they need to be short (a few centimeters) such that only a few axial modes fall within the reflection bandwidth of the grating (0.1–0.2 nm). Unfortunately, although considerably easing packaging, the short fiber length leads to inadequate pump absorption at 980 nm and low output power (100–200 μW). Short Er^{3+}-doped fiber lasers are also susceptible to strong self-pulsation [5], for reasons that are not yet fully understood.

We report here the solution to both these problems using an Er^{3+}:Yb^{3+} co-doped fiber. The presence of Yb^{3+} increases the pump absorption at 980 nm by more than an order of magnitude compared to Er^{3+} alone and enables efficient, short Fabry–Perot fiber lasers to be constructed having low thresholds and high output powers. This allows us to operate well above threshold using conventional 980-nm laser diodes, and drastically reduces the intensity modulation at the relaxation oscillation frequency, which is strongest just above threshold. We are thus able to achieve for the first time a short single-frequency Fabry–Perot 1.5 μm fiber laser, having an output power of 7.6 mW and a relative intensity noise (RIN) of −145.5 dB/Hz, which compares well with DFB lasers. Similar performance has been reported for a 4-mm-long Er:Yb glass bulk laser [6], however our fiber laser has a substantially lower pump threshold and higher slope efficiency owing to the smaller cross section of the doped fiber, and is fiber compatible.

EXPERIMENT

The laser configuration is shown in Fig. 1. A 7-cm-long alumino-phosphosilicate Er^{3+}:Yb^{3+} co-doped fiber was fusion-spliced (0.6 dB loss) to a fiber grating, which was written into a highly photosensitive fiber developed in our laboratories. The grating had to be spliced to the doped fiber since it could not be written directly into the doped fiber, because efficient Er:Yb-doped fibers require a phosphosilicate host glass [7], which is not photosensitive. The fiber grating had a peak reflectivity at 1545 nm of 40%, which enabled good slope efficiency despite the high splice loss, and a reflection bandwidth of 0.08 nm (10 GHz), which enabled us to use cavity lengths up to at least 10 cm and still obtain single-frequency operation. The single-pass gain required to overcome the total cavity losses was about 2.6 dB. The input end of the Er:Yb-doped fiber was butted to a dichroic mirror that reflected nominally 100% of the laser light and transmitted 97% of the pump light. The pump source was a 980-nm laser diode with 100-mW maximum output power.

RESULTS

Fig. 2 shows the laser output power as a function of the collimated diode laser power, i.e., excluding launch losses, which are estimated to be about 50–65%. The threshold pump power is 7 mW, and the maximum output power is 7.6 mW. The slope efficiency relative to the total collimated pump power is 10%, which, taking account of the launching efficiency, compares favorably with the limiting theoretical slope efficiency relative to the launched pump power for this device of 49%, assuming 100% energy-transfer efficiency between the Er^{3+} and the Yb^{3+} ions.

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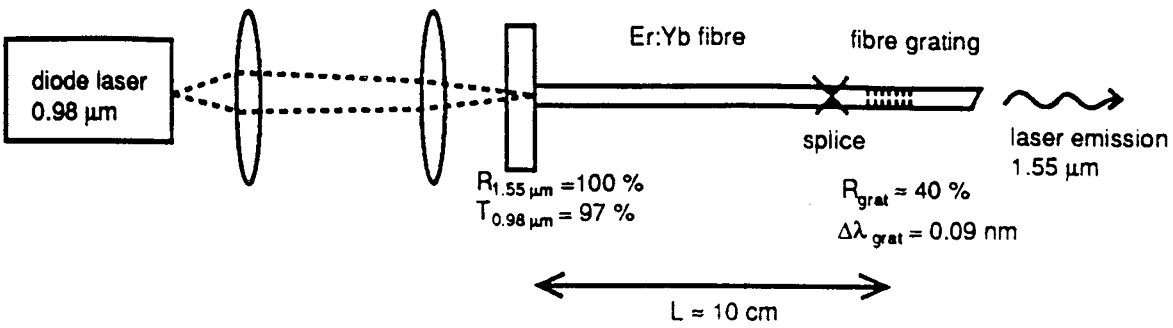

Fig. 1. Er:Yb fiber laser configuration.

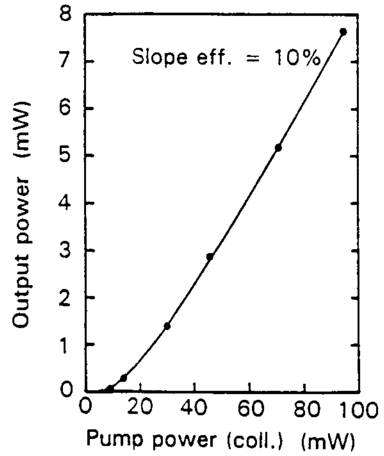

Fig. 2. Laser output power as a function of collimated diode pump power.

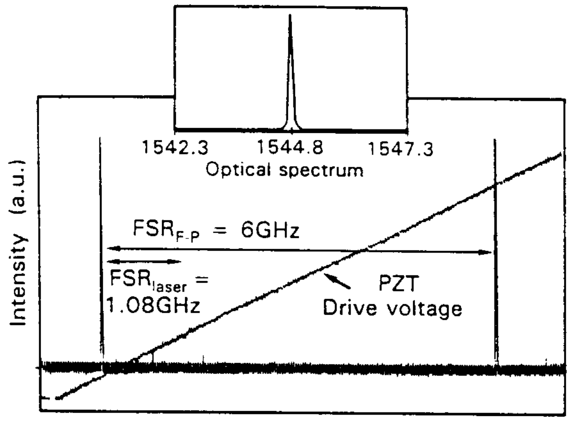

Fig. 3. Single-frequency operation verified using a scanning Fabry–Perot interferometer with FSR = 6 GHz. The FSR of the laser is 1.08 GHz. The inset shows the optical spectrum measured with an optical spectrum analyzer with 0.1 nm resolution.

When the intracavity splice loss was eliminated by replacing the fiber grating with a plane mirror of 90% reflectivity, the threshold pump power, slope efficiency relative to the collimated pump power, and the maximum output power were 1 mW, 25%, and 18.6 mW, respectively. It has been calculated that with no splice losses, i.e., with the fiber grating written directly into the doped fiber, and an optimum output coupling, an Er:Yb laser with a cavity length shorter than 1 cm and a slope efficiency relative to the launched pump power close to the quantum limit of 63% can be made.

Single-frequency operation of the 1545-nm laser was verified with a Newport Supercavity scanning Fabry–Perot interferometer, which has a free spectral range (FSR) of 6 GHz and a resolution of 1.2 MHz. Fig. 3 shows a scan over one FSR and confirms that only one longitudinal laser mode is present. Mode-hopping occasionally occurred on a time scale of 1 min owing to environmental perturbations and should be relatively straightforward to eliminate. The mode-spacing (FSR) of the laser was observed to be 1.08 GHz, corresponding to a total cavity length of 9.6 cm. This length was found to be the maximum length for reliable single-frequency operation with the grating available and was chosen to achieve maximum output power with the high intracavity splice loss of this laser. To obtain robust single-frequency operation a shorter laser cavity is required [5]; however, as we have seen, this will require a reduction of the intracavity splice loss. Replacing the 0.08 nm bandwidth grating with a 0.2-nm grating caused the 10-cm-long laser to oscillate in two longitudinal modes, owing to the reduced mode selectivity. The inset in Fig. 3 shows the optical spectrum of the laser output at a wavelength of 1544.8 nm.

The linewidth of the laser was measured using a conventional delayed self-heterodyne setup with a length difference between the two arms of 50 km and a frequency shift of 100 MHz. Fig. 4 shows that the laser linewidth, which is equal to the half-width of the output electrical beat-spectrum, is about 1.5 MHz for maximum pump power. This linewidth is limited by the relaxation oscillation sidebands in the optical spectrum. The relaxation oscillation frequency at maximum laser output power is 350 kHz, and hence the sidebands in the electrical beat-spectrum are centered around 100 MHz ± 700 kHz, as observed in Fig. 4. When the optical isolator between the laser and the interferometer was removed, we observed a strong, narrow peak in the beat spectrum, as shown in Fig. 4, due to the feedback from the long delay-line. Such feedback causes substantial optical linewidth narrowing, as is known from semiconductor lasers [8]. The half-width of the peak in Fig. 4 was found to be 2.5 kHz, which is smaller than the inverse of the transit time of our delay-line (4 kHz). From this we can conclude that the linewidth of the laser with feedback is

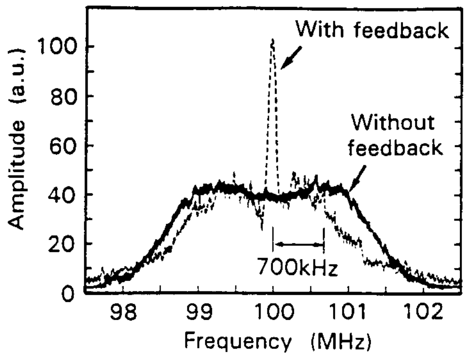

Fig. 4. Self-heterodyne measurement of laser linewidth using a 50-km delay line. The measured linewidth is less than 1.5 MHz. Also shown is the spectral narrowing with feedback into the laser. The resolution bandwidth is 100 kHz.

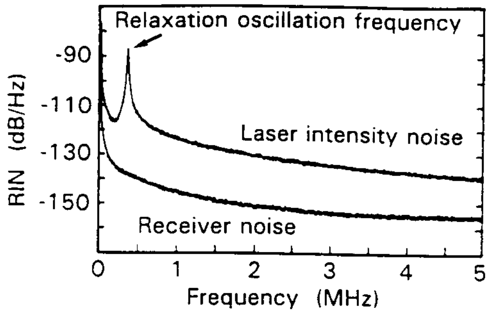

Fig. 5. Laser relative intensity noise spectrum between 0 and 5 MHz. The resolution bandwidth is 10 kHz. The receiver noise spectrum is shown for comparison.

< 2.5 kHz [6]. Note that the Schawlow–Townes limit of the laser is about 5 Hz.

Finally, we measured the RIN of our laser source. The intensity noise was measured using an Epitaxx ETX-300 detector with 50-Ω load, and a bandwidth of around 250 MHz. Fig. 5 shows the laser RIN spectrum from 0 to 5 MHz. The spectrum has a peak at 350 kHz, which is the relaxation oscillation frequency of the laser. The relative intensity modulation at the relaxation oscillation frequency was less than 10% for pump powers higher than three times the threshold pump power. The laser did not exhibit self-pulsation at any pump power level. With maximum pump power the RIN at the relaxation oscillation frequency is around -88 dB/Hz. Above this frequency the RIN decreases to -140 dB/Hz at 5 MHz and -145.5 dB/Hz at 10 MHz. Above 100 MHz the measured noise is dominated by the receiver noise, which corresponds to a RIN of -157 dB/Hz.

CONCLUSION

We have demonstrated single-frequency operation of a 10-cm-long Er:Yb fiber laser operating at 1545 nm. The maximum output power was 7.6 mW, almost two orders of magnitude higher than previously reported for short erbium-doped fiber lasers. The slope efficiency relative to the collimated pump power was 10%. Improved performance with substantial shorter cavities, as required for robust single-frequency operation, is expected if fiber gratings can be written directly into the Er:Yb fiber so as to avoid splices inside the cavity. This will also enable the input mirror to be replaced with a high-reflectivity fiber grating, yielding an all-fiber laser. The measured RIN was smaller than -145.5 dB/Hz above 10 MHz, which compares favorably with commercially available DFB diode lasers. The linewidth of the laser was limited by the relaxation oscillation sidebands in the optical spectrum. To obtain a narrower spectrum the laser has to be stabilized. The laser did not exhibit self-pulsation.

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