Low-pump-power, short-fiber copropagating dual-pumped (800 and 1050 nm) thulium-doped fiber amplifier

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Using optical frequency-domain reflectometry to reveal the gain distribution and allow us to optimize a thulium-doped fiber amplifier, we have demonstrated 18-dB gain by employing only 5 m of a 2000-parts-in-10^6-Tm-doped fiber pumped with 145 mW of power at dual wavelengths of 800 and 1050 nm.

The role of the 800-nm pump, which by itself does not permit population inversion, was clearly observed experimentally. © 2003 Optical Society of America

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To exploit as much as possible of the available bandwidth that can be transmitted over optical fibers in the low-loss region from 1400 to 1630 nm we require new optical amplifiers with which to compensate for losses in that region: Raman amplifiers, optical parametric amplifiers, semiconductor optical amplifiers, and rare-earth-doped fiber amplifiers are possible choices. Among rare-earth-doped fiber amplifiers, erbium-doped fiber amplifiers cover the C + L (1530–1630-nm) band well, whereas thulium-doped fiber amplifiers (TDFAs) cover the S band (1420–1530 nm). However, TDFAs are not so developed as their Er counterparts, and recent research has opened new avenues for their improvement. In particular, much attention has been paid to use of various pumping schemes. Several dual-wavelength pumping schemes and also fiber codoping have been demonstrated to overcome the inherent inefficiency of TDFAs that is due to the short lifetime of the 3H4 upper amplifying level (∼1 ms) compared with that of the 3F4 lower level (∼10 ms). Most such schemes employ a wavelength combination of 1050 and 1400, 1400 and 1560, 1050 and 1560 nm, or 1400 and 800 nm. Recently some of the present authors described a novel dual-pump scheme in which we use optical frequency-domain reflectometry (OFDR) to infer nondestructively the optimal fiber length for amplification in both counterpropagating and copropagating pump geometries. The optimum length for a given pump power was obtained in the copropagating configuration, whereby a gain of 18 dB with 145-mW total pump power was achieved in only 5 m of a 2000-parts-in-10^6 Tm3+ doped fluorozirconate fiber.

To study gain evolution along the fiber and to optimize the fiber length for this pumping scheme we employed the OFDR technique instead of conventional cutback gain measurements. This method was recently applied to S-band TDFAs by the authors and colleagues. Briefly, OFDR is based on detection of the beat signal produced by the interference between a reference reflection (local oscillator) and the reflected or backscattered signal coming from the device under test when the optical frequency is swept linearly. We directly measured the distributed gain when the pump wavelengths were copropagating and counterpropagating. A diode-pumped ytterbium fiber laser emitting at 1050 nm and a tunable (near 800 nm) cw Ti:sapphire laser were used as pump sources. The signal to be amplified was provided by Le Verre Fluoré in modules that contained either 18 or 40 m of fluorozirconate fiber with 2000-parts-in-10^6 Tm3+ with a 2.8-μm core diameter and 0.24 N.A. spliced to standard silica fiber pigtails. The experimental setup is shown in Fig. 1.
Figure 2 shows the measured distributed gain in the counterpropagating configuration. In this case a module of 18-m fiber length was employed, the signal power was 550 $\mu$W at 1480 nm, and the pump powers were 45 mW at 800 nm and 80 mW at 1050 nm. The crosses show the gain for a 1050 nm pump only, whereas the triangles show the results for the 800–1050-nm dual pump. It is clear that in this counterpropagating pump scheme the entire effect of dual pumping occurs in the last 6 m of fiber and that in the last 2 m the gain has practically saturated with length. Therefore, for the pump powers used here, the fiber could be shortened to 16 m without gain reduction. The fast saturation behavior (in length) for the dual pump is due to the fact that the strong 800-nm ground-state absorption to the upper amplifying level ($^3H_4$) is not able to provide gain because of the long lifetime of the lower amplifying level ($^3F_4$). The addition of a 1050-nm pump is then required for depopulating the $^3F_4$ level. Hence, although the 800-nm intensity is maximum at the fiber end, no further gain is obtained there because the 1050-nm pump is already exhausted in that region, whereas in the first 12 m there is not enough short-wavelength pump.

These results indicate that a shorter fiber will be more efficient in this scheme and also that a copropagating scheme could employ an even shorter fiber length. To verify this prediction we launched both pumps to copropagate and varied their powers. Figures 3(a) and 3(b) show the experimental results. A 40-m module of the same Tm-doped fiber was employed for this study. For single 1050-nm wavelength pumping, as the pump power was increased to 200 mW the gain progressively increased to 16 dB at 18 m and saturated afterward, in what was quite a power- and fiber-consuming scheme. Single-wavelength 800-nm pumping provided loss (2.067 dB/m) rather than gain because of the accumulation of population in the $^3F_4$ state in the first ~7 m of the fiber. When both pump wavelengths were employed with roughly the same powers as for Fig. 2, a gain enhancement of 14 dB was obtained (18-dB gain) but at a fiber length of only 5 m. We could clearly observe the roles of induced absorption and pump penetration depth in the Tm fiber by varying the total power and the power ratio of the two pump wavelengths. The optimum length for a given pump power and power ratio for the dual wavelengths employed was obtained. For the maximum
powers employed (100 mW at 800 nm plus 200 mW at 1050 nm), a 26-dB gain was obtained after only 8 m of this fiber in the copropagating configuration, as shown in Fig. 3(b). It can be clearly seen from Fig. 3(b) that the main effect of the 800-nm pump occurs at the beginning of the fiber, as explained above. Further along the fiber, reabsorption occurs. Considering the input pump and signal powers and the corresponding measured gains shown in Fig. 3, the power conversion efficiency was ~10% in the 5-m fiber and ~30% in the 8-m fiber.

In conclusion, we have improved the 800–1050-nm dual-pump scheme for Tm-doped fiber amplification, which, by unidirectional pumping, leads to a striking reduction in the fiber length that is typically required for a 2000-parts-in-10⁶ Tm-doped fluorozirconate fiber. Given the present cost of fluoride fiber, this is a significant result. Using optical frequency-domain reflectometry, we characterized the distributed gain, achieving optimized fiber lengths of only 5 m for this Tm concentration. In this fiber we obtained a gain of 18 dB by employing 145 mW of total pump power. Further simplifications and cost reductions of the TDFA should be achievable by use of all-diode pumping (laser diodes already exist for both wavelengths) or a diode-pumped Nd-doped fiber laser configuration. It should be noted that an S-band EDFA was recently demonstrated by Arbore et al.,¹⁴ as was a Tm-doped telluride-based TDFA.¹⁵ In the last case, the pumping scheme shown here was applied.

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