Design considerations for short-wavelength operation of 790-nm-pumped Tm-doped fibers

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Received 1 June 2009; accepted 3 July 2009;
posted 26 August 2009 (Doc. ID 112166); published 10 September 2009

Tm-doped 790-nm-pumped silica fiber lasers are excellent candidates for producing emission at $<1.95\,\mu$m, but achieving efficient operation at these wavelengths requires careful attention to fiber design because of the characteristic three-level reabsorption effects. We present a discussion of methods for mitigation of these effects and two high-efficiency systems that are capable of producing up to 70 W at $<1.92\,\mu$m. © 2009 Optical Society of America

OCIS codes: 140.3510, 060.3510.

1. Introduction

Until recently, most high power demonstrations of 790-nm-pumped Tm lasers have been at wavelengths exceeding $2\,\mu$m [1–3], where reabsorption effects are relatively mild. Many applications, such as pumping Ho:YAG [4] and tissue dissection [5], require much shorter wavelengths, namely, 1908 and 1920 nm, respectively. For cladding-pumped Tm-doped fibers that operate below approximately $1.95\,\mu$m, signal reabsorption losses are a significant design concern. Agger and Povlsen recently showed that the signal reabsorption in aluminosilicate Tm-doped fibers rapidly increases below $1.95\,\mu$m [6].

For core-pumped systems, reabsorption is less significant, but schemes such as cascaded pumping (Er:Yb pumped Tm) cannot achieve the same overall quantum efficiencies as pumping at 790 nm because of the absence of the cross-relaxation process. The key to obtaining high efficiency in cladding-pumped Tm-doped fibers at shorter wavelengths therefore involves minimizing the signal attenuation in the core. This is generally achieved through the use of large core-to-cladding diameter ratios; however, for fibers in which high active ion concentrations are desirable to maximize interion energy transfer (such as Er:Yb and 790-nm-pumped Tm), large core-to-cladding ratios can complicate thermal management. Fiber design, therefore, must take into consideration a combination of factors including core composition, core-to-cladding ratio, cladding diameter, and the implied core diameter.

In 790-nm-pumped Tm-doped fibers, processes such as energy transfer upconversion [7] and nonradiative relaxation adversely affect conversion efficiency. These effects are most pronounced in large mode area (LMA) fibers in which the signal mode does not significantly interact with the whole core. One simple way to overcome this problem is to confine the active ions to the center of the core. This has been shown to increase the conversion efficiency in Yb-doped amplifiers [8], but, unfortunately, this method is undesirable for shorter wavelength operation because it effectively reduces the effective core-to-cladding ratio. For shorter wavelength operation the waveguide must therefore be designed to maximize the overlap of the signal mode with the doped region of the core while avoiding excessive bend loss and also maintaining a high core-to-cladding ratio.

We compare the performance of LMA and single-mode fiber designs. For a cw amplifier operating at 1908 nm, we show an improvement in efficiency of greater than 60% through optimization of the fiber

0003-6935/09/275072-04$15.00/0

composition and waveguide. Furthermore, we show that single-mode fibers were able to achieve higher efficiencies than LMA fibers in applications up to approximately 65 W.

2. Experiments

To test the large diameter fibers we constructed a master oscillator–power amplifier system. The master oscillator was a simple end-pumped Fabry–Perot cavity that uses single-mode fiber. Following the master oscillator was a mode-field adaptation stage and finally a large diameter fiber amplifier as shown in Fig. 1.

A. Low Power Oscillator

The single-mode fiber of the low power oscillator had a mode-field diameter (MFD) of ~11 μm, an LP_{11} mode cutoff wavelength of 1.96 μm, and a 130 μm cladding diameter. The thulium concentration was ~2%, resulting in a measured cladding absorption of ~2 dB/m at 790 nm.

Cutback experiments were performed to determine the optimum fiber length for operation at 1908 nm. The optimum length was determined to be 3.5 m, corresponding to ~7 dB of pump absorption. We note that, in previous experiments at 1.95 μm, as much as 6 m (12 dB) could be used without affecting laser stability [9]. This highlights the requirement for high core–cladding ratios when operating at shorter wavelengths. The measured slope efficiency was 48% without the output coupler and 42% with the coupler. The difference in efficiency can be explained by the additional reabsorption loss introduced by the additional cavity reflectivity.

B. Mode Field Adapter

The output signal from the oscillator was launched into a passive fiber that had been mode matched to the LMA active fibers under test in the amplifier. Since the mode-matched fiber theoretically supported two transverse modes, it was coiled to remove any coupled higher-order modes. Stripped modes were removed from the cladding before delivering the signal to the amplifier. The cladding light stripper also served to remove any residual unabsorbed pump from the counterpumped amplifier stage.

C. Amplifier

Taking into consideration both the brightness of the available pump sources and the desired output power of >50 W, we selected a pump cladding size of 250 μm. While employing as large a core-to-clad ratio as possible is beneficial to reducing reabsorption losses, practical considerations such as thermal management, mode control (beam quality), and operating threshold place an upper limit on suitable core size.

Three fibers were tested in the amplifier. The first two fibers had 25 μm cores doped with ~2% Tm; one had a simple step-index core resulting in a numerical aperture (NA) of ~0.2, thus making it multimode; the other incorporated a raised refractive-index pedestal surrounding the core to reduce its effective core NA to ~0.1 [10]. The third fiber had ~4% Tm, a slightly smaller core (23 μm), and a slightly lower effective core NA (0.08).

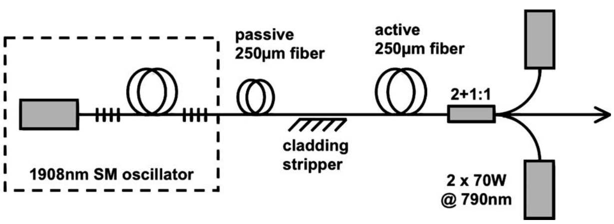

Fig. 1. Schematic of the laser system.

1. Amplifier Configuration

Through experimentation, the best efficiency and stability was observed when counterpumping the amplifier. The output from two diodes, each, delivering up to approximately 65 W at 790 nm into 200/220, 0.22 NA fiber, were coupled into the amplifier using a 2+1:1 pump and signal multiplexer.

The sensitivity of the optical efficiency of 790-nm-pumped Tm fibers to variations in fiber temperature has been known for some time [11]. Given the relatively high absorption of these fibers, careful attention to thermal management was essential to maintain reliability and efficiency. A 90 mm diameter mandrel with a helically cut U-shape channel ensured highly effective heat removal and provided sufficient mode control to ensure excellent beam quality.

The results for the three different fibers are shown in Table 1. We see that, for the multimode fiber, the efficiency (28%) was quite low. This can be explained by the poor overlap of the fundamental mode and the core. The low-concentration LMA fiber had a slightly larger MFD resulting in a marginal improvement in efficiency (33%).

Redesigning the LMA fiber to improve the modal overlap with the core resulted in a significant improvement in efficiency. We should note that this fiber also incorporated a higher Tm concentration, which also would have aided the efficiency [12]. Using the 4% Tm fiber we were able to achieve up to 70 W of output power with 53% slope efficiency as shown in Fig. 2. Although some roll-off was observed at the highest pump powers, we believe these effects to be pump wavelength related as discussed in Subsection 2.D.

Table 1. Performance of 250 μm Fibers in a Counterpumped 1908 nm Amplifier

Tm Concentration	Core Size (μm)	MFD at 1908 nm (μm)	LP_{01} Mode Area / Core Area (%)	Slope Efficiency (%)
2%	25	18	50	28
2%	25	21	67	33
4%	23	22	92	53

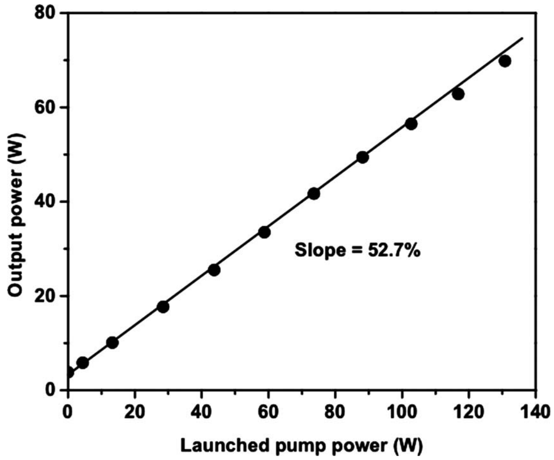

Fig. 2. Slope efficiency of the amplifier stage.

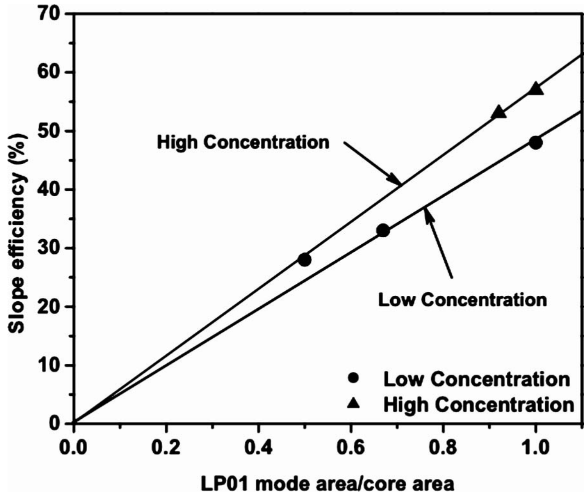

Fig. 4. Slope efficiencies versus modal overlap.

D. High Power Oscillator

A high power oscillator was constructed using a single-mode fiber consisting of ~4% Tm. The core and cladding sizes remained the same as the lower concentration single-mode fiber. Because of the higher Tm concentration, a pedestal was incorporated to maintain the same effective core NA as the 2% Tm fiber. This experiment was performed at 1917 μm. Similar to the 2% Tm fiber operating at 1908 nm, the optimum fiber length was found to correspond to ~7 dB of pump absorption. The laser was end pumped with 123 W at 790 nm. Because of the very high heat loading of the fiber, attention to thermal management was paramount. At full pump power we were able to achieve 66 W with 57% slope efficiency as shown in Fig. 3. Although some roll-off was observed, by looking at the slope relative to absorbed pump (Fig. 3 inset), we can deduce that this was due to pump wavelength drift rather than saturation or thermal effects in the fiber. We also note that the slope relative to absorbed pump was 69%. This indicates that, at longer wavelengths where longer fiber lengths can be used, lasers with >60% efficiency can be demonstrated.

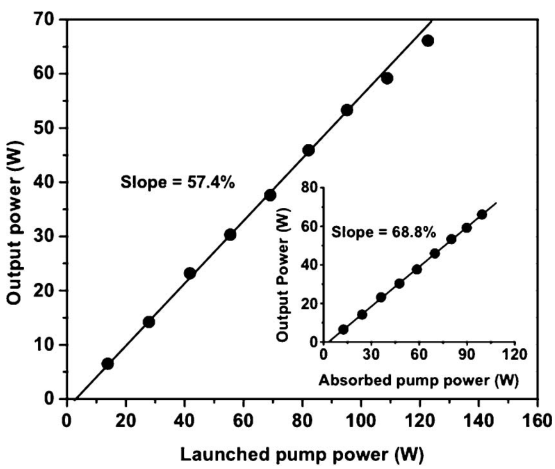

Fig. 3. Laser slope efficiency relative to launched power. Inset: slope efficiency relative to absorbed power.

3. Discussion

Figure 4 shows the relative performance of each of the fibers that we studied as a function of their modal overlap and appears to suggest a linear correlation between the modal overlap and the slope efficiency. The one exception to this trend is the multimode fiber that showed a higher than predicted efficiency. This anomaly might be due to the seed coupling into higher-order modes and subsequently extracting more energy than the LP_{01} mode would alone.

In all cases, for a given Tm concentration, higher efficiencies were obtained in single-mode rather than LMA fibers. Furthermore, there are several other advantages for using single-mode fibers in low-to-moderate power applications including cost and availability of components, ease in maintaining good output beam quality, and device manufacturability (specifically splicing).

Clearly the maximum achievable output power obtainable from single-mode fibers is limited by the available brightness of pump sources and eventually the thermomechanical limitations of the fiber. Although high brightness pumps tend to be much more expensive than lower brightness equivalents, their cost is offset by the reduced fiber and components costs combined with reduced device manufacturing costs.

4. Conclusions

By optimizing both the fiber composition and the waveguide parameters, we were able to improve efficiency by greater than 60% in a single-mode seeded LMA amplifier. The efficiency was further improved by use of high-brightness diodes and single-mode fiber. For high-brightness, 790 nm pumps are becoming more readily available and thermal management techniques are being refined. Single-mode Tm-doped fibers are expected to present better candidates than

LMA fibers in cw applications with output powers less than approximately 75 W.

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