

High-power cladding-pumped Tm-doped silica fiber laser with wavelength tuning from 1860 to 2090 nm

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A high-power double-clad Tm-doped silica fiber laser, pumped by two beam-shaped and polarization-coupled diode bars at 787 nm, was wavelength tuned by use of an external cavity containing a diffraction grating. The Tm fiber laser produced a maximum output power of 7 W at 1940 nm for 40 W of incident diode power and was tuned over a wavelength range of 230 nm from 1860 to 2090 nm, with >5-W output power over the range 1870–2040 nm. The prospects for further improvement in performance and extension of the tuning range are discussed. © 2002 Optical Society of America

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Solid-state laser sources operating in the eye-safe 2- μm spectral region have seen rapid development over the past decade owing to their numerous applications in areas such as lidar and medicine. Conventional, bulk solid-state lasers based on crystals doped with thulium¹ or with thulium and holmium² have been the focus of the most attention because of their compatibility with high-power GaAlAs diode-bar pumping and a fortuitous two-for-one cross-relaxation process³ that can lead to pumping quantum efficiencies approaching 2. However, progress in scaling of the output power of these devices to meet the needs of many applications has been hindered by the need for high pump intensities. This requirement is dictated by the low gain cross sections and quasi-four-level character of these sources and also brings the consequence of the strong thermal effects that result from the high thermal loading density and degrade both efficiency and beam quality at high power levels. A further drawback of these devices is that their range of operating wavelengths is typically rather narrow, which limits their applicability.

An alternative strategy for power scaling in the 2- μm spectral region is to employ a cladding-pumped Tm-doped fiber laser.⁴ This approach has the attraction that the heat generated as a result of the laser pumping cycle is distributed over a long length of fiber, reducing the risk of damage caused by melting or fracture. In addition, the output beam quality is dictated by the waveguiding properties of the Tm-doped core and can easily be designed to ensure a single-spatial-mode output beam. Recently the present authors and others reported a cladding-pumped Tm-doped silica fiber laser that produces 14 W of single-mode output at 2 μm —the highest to our knowledge reported so far for a fiber laser operating in the 2- μm spectral region.⁵ A further advantage that fiber lasers offer is the potential for broad wavelength tunability owing to the broad transition linewidths in glass hosts.

Here we describe a cladding-pumped Tm-doped silica fiber laser with an operating wavelength tunable over a 230-nm range from 1860 to 2090 nm, at multiwatt power levels. To the best of our knowledge, this result represents the broadest tuning range for a cladding-pumped fiber laser reported to date.

The Tm-doped fiber used in our experiments was pulled from a preform fabricated in house by the standard chemical-vapor deposition and solution doping technique. The resulting fiber had a 20- μm diameter aluminosilicate core doped with approximately 1.2% Tm₂O₃ and 2.8% Al₂O₃, and a numerical aperture (NA) of 0.12. The inner cladding was fabricated from pure silica and had a noncircular cross section of $\sim 200\text{-}\mu\text{m}$ outer dimension, as shown in Fig. 1. The noncircular cross section was achieved by milling of two flats inclined at an angle with respect to each other on the preform before pulling the fiber; it served to promote efficient absorption of the diode pump light by preventing skew rays from following paths that avoid the core. The inner cladding was coated with a low-refractive-index ($n = 1.375$) polymer outer cladding, which resulted in a NA calculated as 0.49 for the pump guide. This design of a double-clad fiber with a relatively small inner cladding dimension and a high NA permitted efficient in-coupling of the diode-bar pump sources.

The experimental arrangement used for the tunable Tm-doped fiber laser is shown in Fig. 2. Two diode-bar sources with wavelengths of 787 nm were used to pump the fiber laser. The output from each diode bar was reformatted with a two-mirror beam shaper⁶ to roughly equalize the beam propagation factors in orthogonal planes to $M^2 \approx 70$. The outputs from both beam-shaped diodes were then collimated by 150-mm focal-length cylindrical lenses and then polarization coupled to produce a single pump beam. This beam was focused to a nearly circular spot of

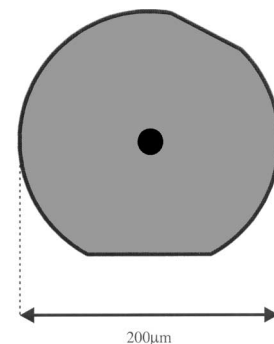


Fig. 1. Cross section of the inner cladding.

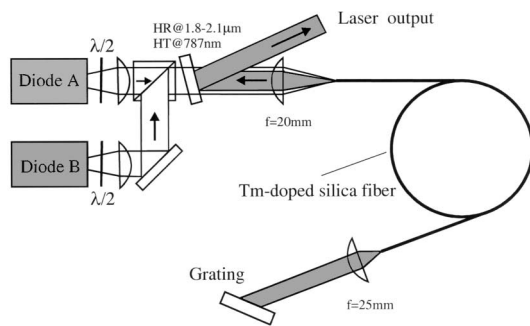


Fig. 2. Tunable Tm-doped silica fiber laser setup.

diameter $\sim 170 \mu\text{m}$ by a Gradium lens of 20-mm focal length for efficient launching into the Tm-doped fiber. After the pump beam optics the maximum available pump power was 42 W.

The launch efficiency into the fiber was estimated as $\sim 80\%$ from measurements of the power launched into 150- and 200- μm circular cross-section pure-silica fibers with no core. Direct measurement of the launch efficiency by measurement of the transmitted pump light for short lengths of fiber proved to be rather difficult because of the high thulium concentration.

The tunable fiber laser employed an extended cavity that comprised an antireflection-coated Infrasil plano-convex collimating lens of 25-mm focal length and a diffraction grating with 600 lines/mm in the Littrow configuration to provide wavelength-selective feedback and hence a means for tuning the lasing wavelength. The grating was blazed for a wavelength of $1.85 \mu\text{m}$ and had measured reflectivities of 90% (polarized perpendicularly to the grooves) and 50% (polarized parallel to the grooves) at $2 \mu\text{m}$. The fiber end nearest the grating was angle cleaved to suppress broadband feedback from the uncoated face that might otherwise compete with the wavelength-dependent feedback provided by the grating and thus restrict the tuning range. The pump in-coupling end of the fiber was cleaved perpendicularly to provide the feedback necessary for laser oscillation. This end of the fiber also served as the output coupler and, because of its high transmission ($\sim 96.5\%$), dominated feedback losses at the grating end of the laser. The fiber laser output was extracted by means of a dichroic mirror with high reflectivity (HR) in the range $1.8\text{--}2.1 \mu\text{m}$ and high transmission (HT; 95%) at the pump wavelength, inclined at a small angle ($< 7^\circ$) with respect to the pump beam. With this arrangement the maximum pump power launched into the fiber was 32 W.

Before operating the Tm-doped fiber laser in the tunable configuration (Fig. 2) we conducted preliminary experiments on a simple (nontunable) Tm fiber laser to determine the optimum fiber length. In this case the fiber laser was configured with the dichroic mirror butted to the pump in-coupling end of the fiber; the opposite end was perpendicularly cleaved, with Fresnel reflection ($\sim 3.5\%$) providing feedback for laser oscillation. Measurements of transmitted pump power for a series of different fiber lengths indicated that the pump absorption coefficient was in the range $4\text{--}4.5 \text{ dB/m}$. These values were in good agreement

with expectations based on measurements of the core absorption coefficient in a standard single-mode fiber fabricated from the same preform and the known inner-cladding-to-core area ratio (~ 100) in the double-clad Tm fiber, thus confirming the benefits of our cladding design.

Measurements of the threshold pump power and the laser output power at the maximum incident pump power were made for a series of different fiber lengths. The results, shown in Fig. 3(a), indicate that fiber lengths in the range 3–4 m are optimum, with output power levels in excess of 9 W for $\sim 32 \text{ W}$ of launched pump power. Thresholds are typically just below 5 W, but they increase slowly with fiber length owing to increased reabsorption loss and they increase sharply for fiber lengths of $< 1.5 \text{ m}$ because of the increasing need to highly invert Tm ions to achieve enough gain to overcome cavity losses. From the results for performance of the 1.7-m-long fiber we estimate that the fiber background losses are in the range $0.2\text{--}0.8 \text{ dB/m}$ at $\sim 1.9 \mu\text{m}$. Figure 3(b) shows the variation in operating wavelength with fiber length. As fiber length increases, the operating wavelength increases, as expected, because of decreased reabsorption loss (closer to four-level character) at longer wavelengths. The results indicate that the wavelength can be selected anywhere in the range $1870\text{--}2000 \text{ nm}$ with multiwatt output power levels simply by selection of the appropriate cavity length. However, operation at shorter wavelengths is accompanied by a decrease in overall efficiency and output power that is due to incomplete absorption of the pump radiation. Also, the bandwidth of the laser output was rather larger, typically in the range $10\text{--}15 \text{ nm}$ (FWHM).

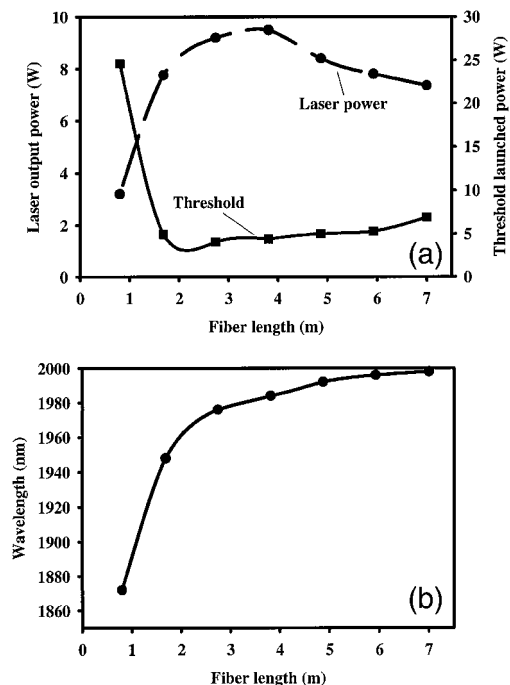


Fig. 3. Tm fiber laser output power at the maximum pump power and threshold pump power as functions of fiber length. (b) Tm fiber laser operating wavelength as a function of fiber length.

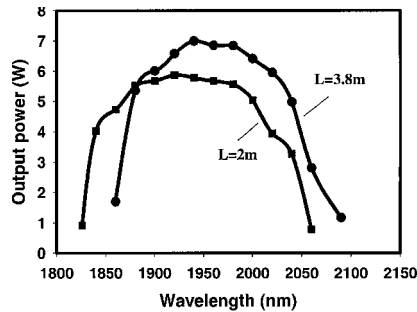


Fig. 4. Tunable Tm fiber laser output power versus operating wavelength for fiber lengths L of 2 and 3.8 m.

The tunable Tm fiber laser setup (Fig. 2) allows the lasing wavelength to be tuned over a wide spectral range by simple adjustment of the grating angle. The laser output power as a function of operating wavelength for fiber lengths of 2 and 3.8 m is shown in Fig. 4. The output power quoted is that which occurs immediately after the fiber output facet, when the transmission of the Gradium lens is taken into account, which was antireflection coated for the pump wavelength but had a transmission of only $\sim 74\%$ at $\sim 2 \mu\text{m}$. For the 3.8-m fiber the maximum output power was 7.0 W at 1940 nm and the tuning range was ~ 230 nm, from 1860 to 2090 nm. For the 2-m fiber the maximum output power was 5.9 W at 1920 nm and the tuning range was ~ 220 nm, from 1830 to 2050 nm. The reduction in power for the shorter fiber length was due primarily to reduced pump absorption, and access to shorter wavelengths was due to reduced reabsorption loss compared with that of the longer fiber. One interesting feature of the temporal stability of the fiber laser output is that at longer wavelengths it became much noisier, with what appeared to be regular spiking or self-Q switching with repetition frequencies of >100 kHz at wavelengths of >2050 nm. At shorter wavelengths (<2000 nm) the laser output was very stable, with power fluctuations of $<5\%$. The reason for the noisy behavior at long wavelengths is unclear and is a subject of further investigation. The fiber core has a cutoff wavelength of $3.1 \mu\text{m}$ and can therefore support multimode propagation. A simple fiber laser configuration⁵ with the same fiber parameters but without grating feedback typically produced a single-mode output beam with $M^2 < 1.1$. However, the tunable fiber laser setup yields a slightly degraded output beam with $M^2 \approx 1.3$. The bandwidth of the tunable laser [typically ~ 2 nm (FWHM)] is much narrower than for the nontunable laser, as expected. As a rough guide, the upper limit on lasing bandwidth is determined by the spectral selectivity of the external cavity, $\Delta\lambda \propto dM^2\lambda \cos(\theta)/\pi\alpha f$, where d is the grating pitch, M^2 is the beam propagation factor, θ is the angle of incidence on the grating, f is the focal length of the collimating lens, and α is the divergence of the laser beam emerging from the fiber. Thus, with relatively simple modifications to the cavity design [e.g., with a longer focal-length collimating lens or a diffraction grating with smaller pitch and (or) a fiber with a single-mode core] it should be possible to reduce the bandwidth to <0.5 nm.

The lower maximum output power of the tunable laser (7.0 W) compared with the nontunable laser (~ 9 W) is due mainly to the losses in the external grating feedback cavity. A comparison of the slope efficiencies for the two laser configurations suggests that the grating-lens combination gives an effective reflectivity of $\sim 40\%$. This is somewhat lower than might be expected based on the grating reflectivity and reflection loss ($<2\%$) at the collimating lens, suggesting that lens aberrations might play a significant role in reducing the efficiency of coupling reflected light back into the fiber. Clearly, there is scope for increasing the effective reflectivity of the external cavity, and hence the fiber laser power, by the use of an aberration-corrected collimating lens and a grating with higher reflectivity. Additionally, a reduction in the fiber output end face's reflectivity (i.e., an increase in output coupling transmission) by, for example, application of a suitable dielectric coating to its surface should also yield an increase in the output power. Further increase in output power and extension of the tuning range could be achieved by modifying the core composition to obtain more-favorable spectroscopic properties and also by in-coupling of additional high-power diode-bar pump sources through the opposite fiber end.

In summary, we have demonstrated a cladding-pumped Tm-doped silica fiber laser with ~ 7.0 W of output power at 1940 nm, tunable from 1860 to 2090 nm at multiwatt power levels. With relatively simple modifications to the fiber laser design and through the use of additional diode pump sources it should be possible to achieve a significant increase in output power and to extend the tuning range to >300 nm. The combination of high output power, good beam quality, and wide tunability in the $2\text{-}\mu\text{m}$ spectral region should make cladding-pumped Tm-doped fiber lasers suitable for a wide range of applications.

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