

CFH**10:15 am–12:00 pm**

Room: 100

Lasers Using Waveguides and FibersRalph Henry Page, *Lawrence Livermore Natl. Lab., Presider***CFH1 (Invited)****10:15 am****Advanced pulsed and CW high-power fiber lasers**J. Nilsson, A.B. Grudinin, P.W. Turner, *Optoelectronics Res. Ctr., Univ. of Southampton, Southampton SO17 1BJ, England; E-mail: jn@orc.soton.ac.uk*

Cladding-pumped fiber technology has revolutionized fiber lasers over the last few years. The record average output power is now over 100 W in a nearly diffraction-limited beam.¹ Pulse energies above 2 mJ have been reported from Q-switched fiber lasers.² We will discuss design issues for fiber lasers with performance exceeding that of traditional double-clad fibers end-pumped by laser diodes. The focus will be on high-energy pulsed lasers and high-power cw lasers.

High-brightness, high-power pump diodes are essential for high-power fiber lasers. Currently available diode sources are sufficiently bright and powerful for fiber lasers with 100 W of output power even with traditional end-pumping.¹ However, for currently researched kW (multi-mode) fiber lasers, alternative, multi-point, pumping schemes will be required. We have recently demonstrated single-clad fiber coils for cladding-pumped lasers.³ In this structure, the pump waveguide of the active fiber is directly accessible from the side, so that pump light traveling in separate pump fibers can directly couple over into the active fiber. We measured a slope efficiency of 65% in this configuration, which is 10% less than for the same fiber in a traditional end-pumped double-clad geometry. Efficiency is clearly important for very high power lasers, and the end-pumped double-clad geometry is likely to remain more efficient than alternative configurations. However, for very high powers, the capacity for pump multiplexing and power handling are the overriding issues. Single-clad coiled fiber lasers are ideally suited to large-scale pump multiplexing, and being all glass structures they can also handle very high pump powers. These factors in combination with the relatively small drop in efficiency make them promising candidates for kW fiber lasers.

The power from high-brightness fiber-coupled laser diodes is around an order of magnitude more expensive than the raw power from a diode bar. Diode cost dominates the overall cost for very high-power fiber lasers. The prospect of pumping fibers directly with diode bars is therefore very attractive, but the output from a diode bar cannot be directly launched into a fiber. It was recently proposed to make fiber lasers from a fiber formed into a solid object (e.g., a coil or disk). The low

propagation loss and waveguiding properties of an optical fiber are then retained, with the added advantage that the fiber structure can be arranged and machined for direct pumping with diode bars.⁴

For high-energy Q-switched fiber lasers, the challenge lies in finding core designs that can store a large amount of energy before self-saturation and spurious lasing limits further storage. The solution is to use a large core. This also reduces nonlinear distortions and increases the damage threshold. The downside is that the beam-quality degrades as the core becomes multi-moded. However, it is possible to maintain a good beam-quality even with a large core. One option is to use a small numerical aperture so that even a large core will be single- or few-moded. The active ytterbium ions can be restricted to the center of the core to further select the fundamental mode. This kind of fiber generated pulses with more than 2 mJ of energy in a beam with an M^2 -value of 3.² Mode-selecting ytterbium-doping can be used also in a large multi-mode core with a higher NA. Another option we have tried is to use a tapered-fiber mode filter that only supports the fundamental mode.⁵ With that approach, we have generated pulse energies over 1 mJ in a beam with an M^2 -value of 1.8. The different approaches to high pulse energies can be combined, and we view that 10 mJ of pulse energy may be realistically achieved with a high-brightness fiber laser.

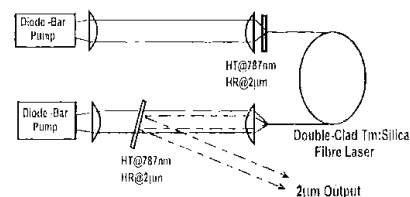
Besides power and energy, advanced designs extend the scope of cladding-pumped fiber lasers in many other ways, e.g., towards new wavelengths, single-polarization operation, narrow linewidths, and tunability. Future design innovations are set to progress cladding-pumped fiber laser technology even further.

1. V. Dominic, S. MacCormack, R. Waarts, S. Sanders, S. Bicknese, R. Dohle, E. Wolak, P.S. Yeh, and E. Zucker, "110 W fiber laser," *Conference on Lasers and Electro-Optics*, 1999, Tech. Digest paper CP126.
2. H.L. Offerhaus, J.A. Alvarez-Chavez, J. Nilsson, P.W. Turner, W.A. Clarkson, and D.J. Richardson, "Multi-mJ, multi-watt Q-switched fiber laser," *Conference on Lasers and Electro-Optics*, 1999, Tech. Digest paper CPD10.
3. A.B. Grudinin, J. Nilsson, P.W. Turner, C.C. Renaud, W.A. Clarkson, and D.N. Payne, "Single clad coiled optical fibre for high power lasers and amplifiers," *Conference on Lasers and Electro-Optics*, 1999, Tech. Digest paper CPD26.
4. H. Sekiguchi, G.G. Vienne, A. Tanaka, Y. Senda, K. Ito, Y. Matsuoka, H. Toratani, S. Takahashi, H. Miyajima, H. Kan, and K. Ueda, "New Concept: fiber embedded disk and tube lasers," International Forum on Advanced high-power lasers and Applications (AHP/LA'99) Osaka, Japan, Nov. 1–5, 1999.
5. J.A. Alvarez-Chavez, A.B. Grudinin, J. Nilsson, P.W. Turner, and W.A. Clarkson, "Mode selection in high power cladding pumped fiber lasers with tapered section," in *Conference on Lasers and Electro-Optics*, Technical Digest (Optical Society of America, Washington, DC 1999), pp. 247–248.

CFH2**10:45 am****High power double-clad Tm-doped fibre laser with >12 W single-mode output at 2 μ m**R.A. Hayward, W.A. Clarkson, P.W. Turner, J. Nilsson, A.B. Grudinin, D.C. Hanna, *Optoelectronics Res. Ctr., Univ. of Southampton, Southampton, SO17 1BJ, UK; E-mail: wac@orc.soton.ac.uk*

High power sources operating in the 2 μ m region have applications in medicine and LIDAR, and also provide an ideal starting wavelength for nonlinear frequency conversion to the mid-infrared (3–5 μ m) spectral region. For many of these applications the need for high power and high efficiency are also accompanied by the requirement for good beam quality. This combination of operating characteristics is often difficult to achieve in 'bulk' solid-state lasers due to strong thermal effects which degrade beam quality and reduce efficiency. Cladding-pumped fibre lasers offer an alternative route to power-scaling¹ with the attraction that heat generated due to the laser pumping cycle can be dissipated over a long length of fibre, minimising the risk of thermally induced damage. In addition, the output beam quality is determined by the waveguiding properties of the doped core, which can easily be tailored to produce a single-mode output. In this paper we report a Tm-doped silica fibre laser with a single-mode power of 12.2 W for 38.3 W of launched diode pump power. To the best of our knowledge, this is the highest power in the 2 μ m spectral region so far reported for a fibre laser.

The experimental set-up is shown in Fig. 1. The double-clad fibre was fabricated in-house with a 20 μ m diameter Tm-doped alumino-silica core (0.12 NA), which was slightly offset from the centre of the silica inner cladding to improve the pump absorption.² The inner cladding had an outer dimension of approximately 200 μ m, with a low refractive index ($n = 1.375$) polymer outer cladding resulting in a calculated numerical aperture of 0.49. A small inner cladding size was chosen to minimise the cladding-to-core area ratio whilst ensuring a good launch efficiency for the diode pump. The fibre was pumped by two diode bars operating at ~ 787 nm, where the effective absorption coefficient was measured to be ~ 4.6 dB/m. The output from each bar was re-formatted using a two-mirror beam shaper³ to equalise the M^2 values in orthogonal planes and so allow tight focussing into the inner cladding. The maximum combined



CFH2 Fig. 1.