

Hybrid Fibre-Bulk Erbium Laser

W. A. Clarkson, J. W. Kim, M. Ibsen and J. K. Sahu
Optoelectronics Research Centre
University of Southampton, Southampton, UK

Abstract

Hybrid fibre-bulk solid-state lasers combine the advantages of cladding-pumped fibre lasers and conventional bulk solid-state lasers to offer an attractive route to high laser pulse energies in the eyesafe wavelength regime around $\sim 1.6\mu\text{m}$ and $\sim 2\mu\text{m}$. This paper describes the results of the first stage of a project aimed at developing a hybrid pulsed erbium laser with high pulse energy ($>100\text{mJ}$) and narrow linewidth output at $\sim 1.6\mu\text{m}$.

Keywords: Fibre lasers, solid-state lasers, erbium lasers, long range sensing

Introduction

High-power solid-state lasers operating in the eyesafe wavelength regime around $1.5\text{-}1.7\mu\text{m}$ have numerous applications (e.g. Burst Illumination Laser Radar, coherent LIDAR, laser vibrometry) and provide an excellent starting point for nonlinear frequency conversion to the mid-infrared spectral region. For many of these applications, the requirement for high pulse energy is frequently accompanied by the need for good beam quality, high overall efficiency and sometimes a narrow-linewidth output, which are often difficult to achieve simultaneously. The standard approach for producing laser output in this wavelength region is via direct diode pumping of erbium-ytterbium co-doped bulk glass or crystal lasers. However, these lasers suffer from the problem that they have a relatively large quantum defect and hence a large fraction of the pump power is converted to heat in the bulk laser material. The latter results in strong thermal lensing, which can severely degrade laser beam quality and efficiency, and leads to thermally-induced stresses, that can cause catastrophic failure of the bulk material.

An alternative approach is to employ an optical parametric oscillator pumped by a diode-pumped Nd or Yb-doped solid-state laser operating in the $\sim 1\mu\text{m}$ regime. This approach also suffers problems associated with heat generation in the bulk laser medium as well as added complexity, which ultimately leads to rather low overall efficiency, limited flexibility and limited scope for power/energy scalability.

Another approach for producing laser emission in the required spectral regime is via a cladding-pumped erbium-ytterbium fibre laser. Fibre lasers are very attractive for cw generation, but, due to their long device lengths and small core size, they suffer from detrimental nonlinear effects, especially when operating in the high peak power pulsed regime, which can limit efficiency. Furthermore, pulse energies are limited by amplified spontaneous emission and by damage to the fibre facets.

The hybrid fibre-bulk laser approach combines the advantages of cladding-pumped fibre lasers for efficient cw high-power generation with the energy storage and high pulse energy capabilities of bulk solid-state lasers. The basic idea is to use a high-power cladding-pumped Er,Yb co-doped fibre laser to ‘in-band’ pump a bulk

solid-state laser based on Er:YAG. In this way most of the heat generated via quantum defect heating (typically ~40%) is deposited in the fibre, with only ~6-7% of the fibre laser output power converted to heat in the Er:YAG crystal. The net result is that thermal effects in the bulk Er laser are dramatically reduced leading to the prospect of much improved efficiency, beam quality and higher output power. The fibre laser benefits from a geometry that can easily handle the generated heat since this can be dissipated over a long device length of several metres, thereby reducing the likelihood of thermally-induced damage. The combination of good beam quality and wavelength tunability, provided by the fibre laser, also allows the use of long bulk crystals with low erbium concentrations. This reduces the deleterious effects of upconversion allowing long energy storage times and hence high pulse energies to be achieved for relatively modest pump powers.

This approach has already been successfully applied to Er:YAG [1,2] and Er:LuAG [3] lasers pumped (in-band) by an erbium fibre laser, with multi-watt average powers and slope efficiencies with respect to incident pump power up to 80% [2]. The main objective of this project is to develop an improved hybrid laser architecture which can be scaled to much higher average power levels (>100W) and much higher pulse energies (>100mJ) in a single-frequency output beam.

Here we describe recent work aimed at improving the design of the Er,Yb fiber pump laser, so that higher power levels can be achieved. In addition, we describe preliminary work on the development of an ultra-thin Er:YAG microchip laser which will ultimately serve as the single-frequency seed laser for the high power Er:YAG slave oscillator that will be developed later in the project.

High-power Er,Yb fibre pump laser

For efficient operation of Er, Yb fibre lasers at high power levels, efficient launching of pump power from a high-power diode source into the Er,Yb fibre is crucial. This requires a pump launching scheme with a high collection efficiency, high overall transmission and negligible degradation in brightness. Diode-stacks offer the highest output powers, but suffer from reliability problems due to the micro-channel cooling system. To avoid the problems associated with diode-stacks, we have developed a novel multi-bar diode pump module (see figure 1). The basic idea is to employ an arrangement of diode-bars and optical components, so that the output beams from the individual diode bars are spatially multiplexed to mimic the optical output from a fast and slow-axis collimated diode-stack. To achieve this, we employed a modular architecture, with each pump module comprising nine 40W diode-bars at ~975nm. Each bar was mounted on a water-cooled copper heat-sink and was collimated in the fast and slow directions (i.e. perpendicular and parallel to the array) with a cylindrical microlens and a cylindrical microlens array respectively. The collimated output beams from each diode-bar, were then re-directed (as necessary) by an arrangement of mirrors, so that the beams propagate parallel to each other, but stacked underneath each other.

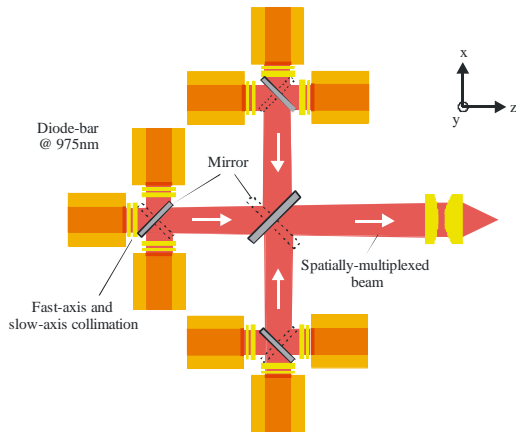


Figure 1: Multi-bar pump module

This approach has many advantages over diode-stacks and facilitates coupling of the pump light into the Er,Yb fibre, since improved beam quality can be obtained compared to diode-stack-based pump sources.

Two nine-bar pump modules were constructed and tested (see figure 2). The pump modules produced maximum powers of 325W and 330W, corresponding to an overall collection/transmission efficiency of >90% (see figure 3). The M^2 parameters for the combined output beams were measured to be <340 (x direction) and <60 (y direction). Using a simple aspheric lens of focal length 25mm, the combined beam could be focussed to a beam with transverse dimensions of $\sim 720\mu\text{m}$ and $\sim 140\mu\text{m}$ as required for efficient coupling into the proposed Er,Yb ribbon-shaped fibres for power scaling.

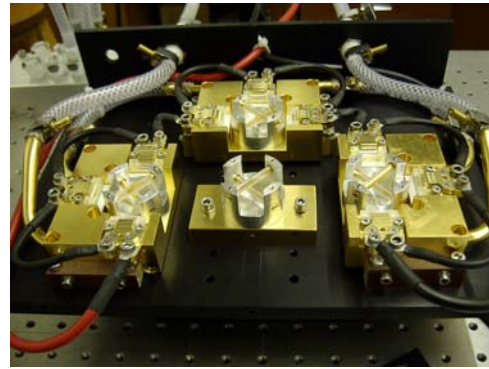


Figure 2: Photograph of pump module.

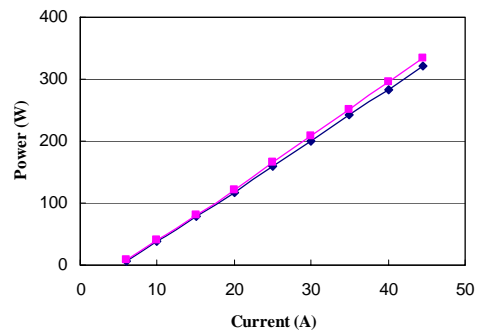


Figure 3: Pump module power versus current

High-power Er,Yb fibre lasers based on standard double-clad Er,Yb doped fibres were constructed and tested. The fibres had a pure silica D-shaped inner-cladding of diameter, $400\mu\text{m}$, and an Er,Yb co-doped phospho-silicate core of diameter $30\mu\text{m}$. To efficiently launch pump light from the multi-bar pump modules into the D-shaped fibre it was necessary to make some modifications to the pump module design to reduce the M^2 parameter for the pump beam in the x direction. This was achieved by simply splitting the beam into two beams (using a knife edge mirror) and then re-combining the two beams into a single beam using a half-wave plate and a polarising beam splitter. Two different resonator configurations were employed as shown in figures 4(a) and 4(b). Pump light was launched into the fibre with a launch efficiency of $\sim 90\%$. The effective

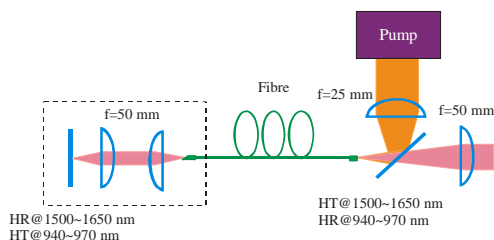


Figure 4(a): Free-running Er,Yb fibre laser

absorption coefficient for pump light centred 975nm was measured to be ~ 9.1dB/m, and hence a relatively short fibre length of ~2m was used. The end section of the fibre through which the pump light was

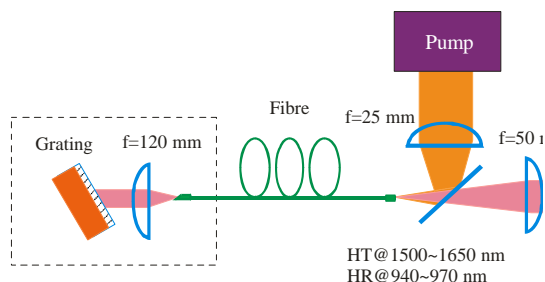


Figure 4(b): Tunable Er,Yb fibre laser

launched was carefully mounted in a water-cooled V-groove heat-sink to prevent thermally-induced damage to the fibre's outer-coating due to heat generated in the core via quantum defect heating. The remaining section of fiber was cooled by winding it on to a metal cylinder or by direct water-cooling. For the free-running laser configuration (see figure 4(a)), feedback for laser oscillation was provided by the 3.6% Fresnel reflection from a perpendicularly-cleaved fibre end facet, at one end of the fibre, and, at the opposite end, by a simple external cavity comprising a plane mirror with high reflectivity (>99.5%) at 1500-1650nm and high transmission (>95%) at 940-970 nm, and an anti-reflection coated 50mm focal length collimating and focusing lenses. Using this

arrangement, the laser generated a maximum output power of 55W at 1565nm with a linewidth of ~ 2.6nm (FWHM) for a total incident pump power of 160W (146W launched), corresponding to an average slope efficiency (with respect to launched power) of ~ 40% (see figure 5). At pump powers in excess of 170W the fibre coating

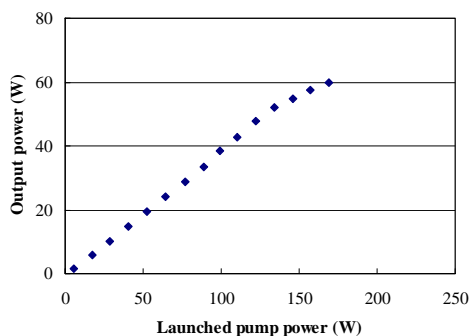


Figure 5: Free-running Er,Yb fibre laser power output power versus pump power

was prone to damage due to heating in the core. More aggressive cooling of the fibre may help to alleviate this problem. Tunable operation of the Er,Yb fibre laser was achieved using the modified resonator configuration (see figure 4(b)) comprising an antireflection coated collimating lens of focal length 120mm and a simple replica diffraction grating (600 lines/mm) mounted on a copper substrate to facilitate removal of waste heat. The fibre end facet nearest the grating was angle-polished at ~10° to suppress parasitic lasing between the two fibre end facets. A shorter fibre length of ~1.5m was selected for the tunable operation to reduce the re-absorption loss at short wavelengths. Using this resonator configuration, the lasing wavelength could be tuned from 1532 to 1570nm with a linewidth (FWHM) of ~1nm (figure 6) and

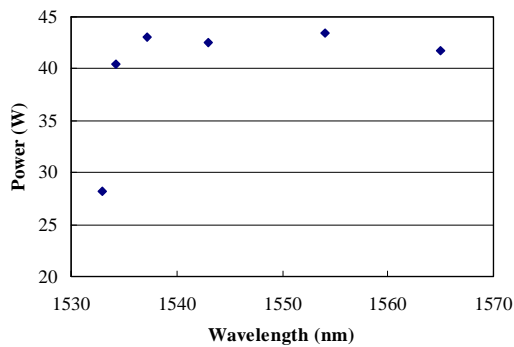


Figure 6: Output power versus wavelength

the maximum output power was 70W at 1546nm and 56W at 1532 nm for 206W of launched pump power. Scaling to power levels >100W at 1532nm is quite challenging for this D-shaped fibre design due to thermally-induced damage to the fibre coating. A more effective heat-sinking arrangement and coupling pump light in from both ends of the fibre to further distribute the heat-load will help, but at the expense of added complexity. The proposed ribbon fibre geometry is a far more elegant and practical solution.

Single-frequency master-oscillator

A low power single-frequency oscillator is required for injection seeding of the high-power Q-switched Er:YAG laser to enforce single-frequency operation. Our approach is to use an ultra-thin face-cooled Er:YAG microchip laser. The basic idea is to use a very thin (perhaps only a few tens-of-microns thick) microchip resonator that is faced-cooled in the same manner as a thin disc laser, and pumped via a simple double-pass non-collinear pumping scheme with the pump power provided by one of the high-power Er,Yb fibre pump sources (see figure 7). Only a small fraction (perhaps a few percent) of the pump power is absorbed, but this may be equivalent to several watt at high power levels and hence

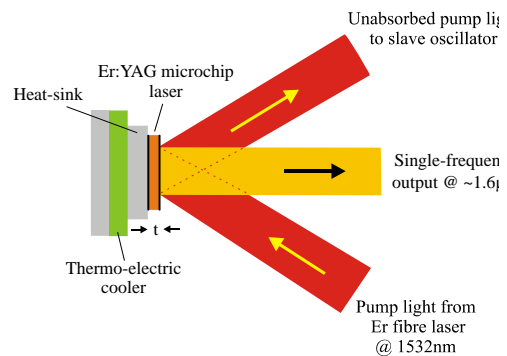


Figure 7: Ultra-thin Er:YAG microchip laser

will be more than enough for efficient operation of the Er:YAG laser at single-frequency power levels >0.5W. The unabsorbed pump can be used to pump the Er:YAG slave oscillator. This approach has the attraction of simplicity and high overall efficiency, and avoids the need for an extra Er,Yb fibre laser or diode laser pump source. Moreover, it allows the use of very thin microchip resonator designs with the potential for wide tunability of the output.

The design of the microchip laser is extremely important. For robust single-longitudinal-mode operation (i.e. high discrimination against adjacent longitudinal modes) and for a wide wavelength tuning range, the microchip cavity length should be as short as possible. The shortest cavity length that can be used in practice is determined by the cavity loss and the round-trip gain that can be achieved. The maximum gain is determined by the Er^{3+} doping level, the length of the gain medium and the emission cross-section at the lasing wavelength. Threshold for lasing can only be reached if it is possible to obtain sufficient gain to off-set the cavity loss. The situation is further complicated by a number of other factors (e.g. ground-state depletion, energy-transfer-upconversion, temperature), which make an accurate prediction of threshold pump power and hence a determination of the minimum

microchip thickness that can be used rather complicated. We have therefore generated a theoretical model for this purpose. Our model takes into account ground-state bleaching and energy-transfer-upconversion.

Figure 8 shows the predicted threshold pump power as a function of microchip laser thickness for an Er:YAG microchip laser with an output coupling transmission of 1%, and Er³⁺ concentration of 1at.% and a pump beam diameter of 100µm. It can be seen that threshold increases quite dramatically as the crystal length is decreased. This shows very clearly that there is a lower limit on the crystal length. Moreover, the impact of upconversion on

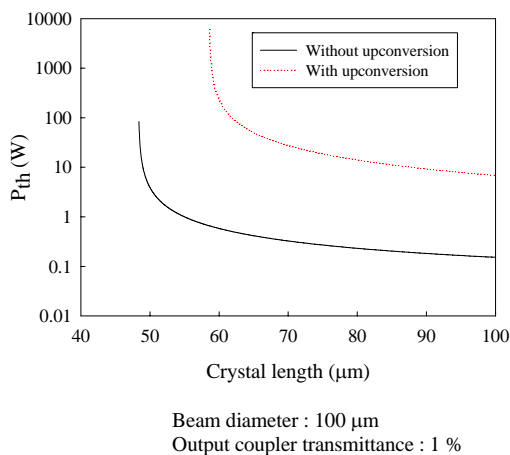


Figure 8: Er:YAG microchip laser threshold versus crystal thickness

threshold is very pronounced and must be taken into account when choosing the crystal length, doping level and output coupling transmission.

Conclusion

Two multi-bar diode pump modules have been developed for pumping Er,Yb ribbon fibres. The pump modules have been used to pump Er,Yb fibre lasers based on

standard D-shaped double-clad fibres, yielding a maximum output power at 1532nm of 56W. The maximum output power was limited by the onset of thermally-induced damage to the fibre's outer-coating. This problem should be remedied by employing ribbon-shaped double-clad fibres to facilitate cooling and pump launching. Finally, detailed theoretical modelling of the Er:YAG microchip single-frequency master-oscillator has been completed and used to aid the design of a prototype laser.

References

1. Y. E. Young, S. D. Setzler, K. J. Snell, P. A. Budni, T. M. Pollak and E. P. Chicklis, *Opt. Lett.*, 29, pp.1075-1077, 2004.
2. D. Y. Shen, J. K. Sahu and W. A. Clarkson, *Opt. Lett.*, vol.31, issue 6, (2006).
3. S. D. Setzler, K. J. Snell, T. M. Pollak, P. A. Budni, Y. E. Young and E. P. Chicklis, *Opt. Lett.*, 28, pp.1787-1789, 2003.

Acknowledgements

The work reported in this paper was funded by the Electro-Magnetic Remote Sensing (EMRS) Defence Technology Centre, established by the UK Ministry of Defence.