

Recent Advances in Hybrid Fibre-Bulk Erbium Laser Sources

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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 third stage of a project aimed at developing a hybrid pulsed erbium laser with high pulse energy ($>100 \text{ mJ}$) and narrow linewidth output at $\sim 1.6 \mu\text{m}$.



Introduction

Laser sources operating in the eyesafe wavelength regime around $1.5\text{--}1.6 \mu\text{m}$ continue to attract much interest due to a wealth of applications in areas such as spectroscopy, remote sensing, ranging and free-space communications. 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 main objective of our project is to explore an alternative strategy for scaling output power and pulse energy in the $\sim 1.6 \mu\text{m}$ wavelength regime by employing a hybrid laser architecture that combines the advantages of cladding-pumped fibre lasers for high-power cw generation with the energy storage and high pulse energy capabilities of conventional 'bulk' solid-state lasers.

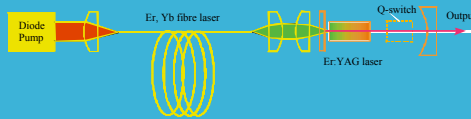


Figure 1. Hybrid Fibre-Bulk Erbium Laser Concept.

High-power Er,Yb fibre pump laser

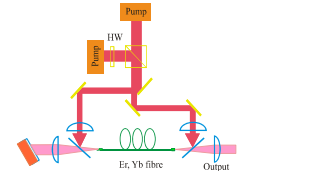


Figure 2. Experimental set-up for Er,Yb fibre laser.

- Er,Yb co-doped fibre with a $400\text{-}\mu\text{m}$ diameter D-shaped silica inner-cladding and a $30\text{-}\mu\text{m}$ diameter core
- Pump source: 9-bar diode pump module at 975 nm

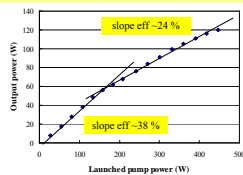


Figure 3. Fibre laser output at 1532 nm .

High-power Er,Yb ribbon fibre laser

- The advantages of a ribbon-shaped inner-cladding fibre are
 - Efficient launching of pump light without complex pump-beam re-formatting schemes due to the highly elongated rectangular inner-cladding shape
 - Easier and more efficient heat sinking

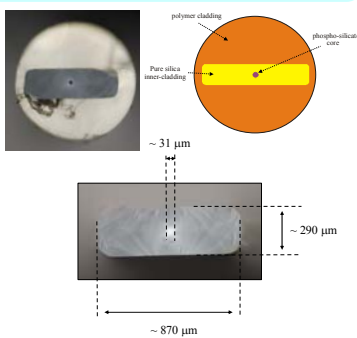


Figure 4. Cross-section of the Er,Yb ribbon fibre.

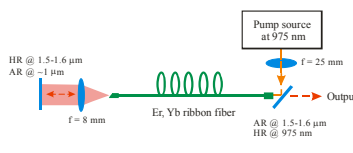


Figure 5. Experimental set-up for the Er,Yb ribbon fibre laser.

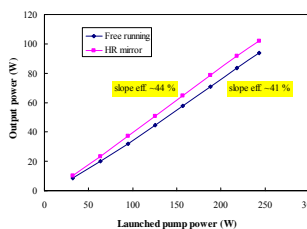


Figure 6. Laser output power for the Er,Yb ribbon fibre laser.

Er,Yb fibre laser with a Bragg grating in the core

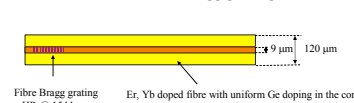


Figure 7. Schematic diagram for the Er,Yb fibre with the in-fibre Bragg grating.

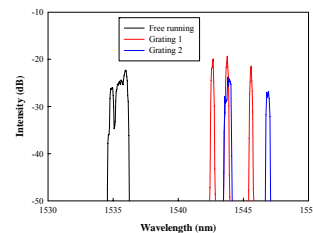


Figure 8. Output spectra for Er,Yb fibre lasers with or without in-fibre Bragg gratings.

Er,Yb fibre laser using a Volume Bragg grating

A Volume Bragg grating (VBG) is a promising element for wavelength selection in high-power solid-state lasers due to

- High reflectivity with relatively narrow bandwidth
- High laser damage threshold
- Compact size

- The VBG parameters in our experiment
 - $\lambda_{\text{centre}} = 1552.7 \text{ nm}$ & $\Delta\lambda = 0.44 \text{ nm}$
 - Reflectivity: 96%
 - $5 \text{ mm} \times 7 \text{ mm} \times 5 \text{ mm}$

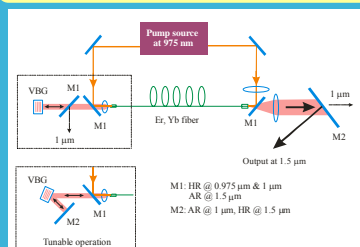


Figure 9. Experimental set-up for Er,Yb fibre lasers using Volume Bragg gratings.

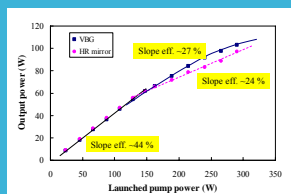


Figure 10. Laser output power for the Er,Yb fibre laser using the Volume Bragg grating.

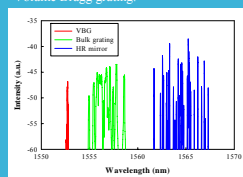


Figure 11. Output spectra for Er,Yb fibre lasers.

The experimental results show that VBGs provide an attractive way to select the operating wavelength of high-power cladding-pumped fiber lasers.

Unidirectional single-frequency operation of an Er:YAG laser

Employing a travelling-wave acousto-optic modulator (AOM) in a ring resonator for unidirectional and hence single frequency operation has several attractions, such as

- Minimises resonator loss and complexity
- Wide spectral operating range
- Q-switched operation

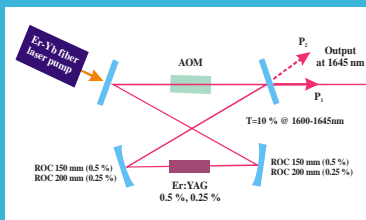


Figure 12. Experimental set-up for a single-frequency Er:YAG laser using an AOM.

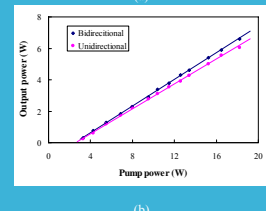
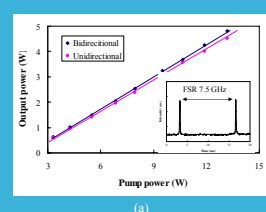


Figure 13. Laser output powers for the Er:YAG laser of (a) a $0.5 \text{ at.}\%$ Er^{3+} doping and (b) a $0.25 \text{ at.}\%$ Er^{3+} doping concentration in a ring resonator. The inset is the trace of the Fabry-Perrot interferometer.

Analytical model for the threshold pump power including energy transfer upconversion

Energy-transfer-upconversion (ETU) can have dramatic effect on the performance of in-band pumped Er:YAG lasers. We developed a simple analytical expression for the threshold pump power in an Er:YAG laser including the influence of ETU.

The threshold pump power in a quasi-three-level laser is

$$P_t(\text{with ETU}) = P_t(\text{without ETU}) \left(1 + \frac{L_{\text{ETU}}}{F \eta_{\text{sp}}} \right)$$

where $\frac{L_{\text{ETU}}}{2\sigma} = \frac{L_{\text{ETU}}}{2\sigma} + f_1 \eta_{\text{ETU}} N_1 l_k$ and $F = 4\sigma(f_1 + f_2) / (W_{\text{sp}} \tau \alpha_p)$.

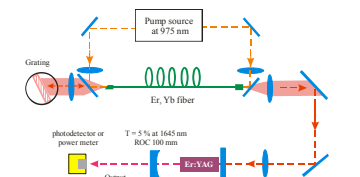


Figure 14. Experimental set-up for investigating the impact of ETU on laser performance.

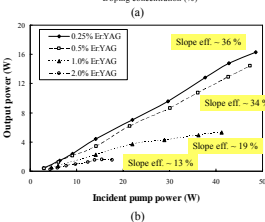
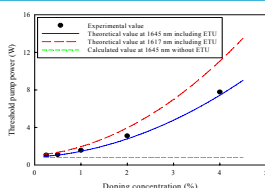


Figure 15. Experimental results for (a) threshold pump power and (b) the output power for Er:YAG lasers of different doping concentrations.

⇒ The use of low Er^{3+} doped levels is crucial for high-power and high-energy operation.

Q-switched Er:YAG laser

A Q-switched Er:YAG laser incorporating a RTP Pockels cell and two undoped YAG plates at Brewster's angle yielded $\sim 30 \text{ mJ}$ of output with a pulse duration of less than 20 ns at a 20 Hz repetition rate, corresponding to a peak power of $>1.5 \text{ MW}$ for 55 W of pump power. The beam quality was measured to be ~ 4.1 . However, the pulse energy was limited by coating damage to the dichroic mirror.

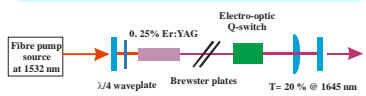


Figure 16. Experimental set-up for Q-switched Er:YAG lasers.

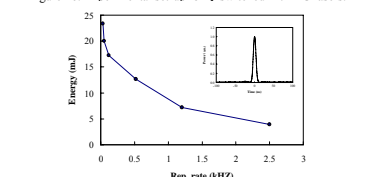


Figure 17. Q-switched pulse energy and pulse shape (the inset).

Summary

We have demonstrated a high-power Er,Yb double-clad fibre laser with ribbon-shaped inner-cladding, which yielded 102 W of output power at 1566 nm for 244 W of launched pump power. We also constructed Er,Yb fiber laser employing an external cavity using a Volume Bragg grating and demonstrated that it is a promising technique for wavelength selection in a high-power fibre laser. With the aid of the Er,Yb fibre laser pump source at 1532 nm , we have demonstrated in-band pumped Er:YAG lasers with up to 58 W of multi-axial-mode cw output and $\sim 6.1 \text{ W}$ of single-axial-mode cw output and 30 mJ of Q-switched pulsed output at 1645 nm . We have developed a simple analytical expression for the threshold pump power in a quasi-three-level laser including energy-transfer-upconversion and compared it with the experimental results. It showed that using a low Er^{3+} doped Er:YAG crystal is essential for efficient laser operation in cw and Q-switched mode.