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Seeded erbium/ytterbium co-doped fibre amplifier source with 87 W of single-frequency output power

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We report a highly efficient cladding-pumped Er/Yb-doped large-core fibre amplifier, generating up to 87 W of single-frequency continuous-wave output at 1563 nm with a good beam quality ($M^2 \leq 1.7$) in a master oscillator power amplifier configuration. The overall optical power conversion efficiency was 26%.

Subject categories and indexing terms: *Lasers (Fibre lasers), Optics (Optical pumping)*

Introduction: High-power single-frequency sources emitting in the so-called eye-safe 1.5 – 2.0 μm wavelength range are attractive for many applications such as free space and satellite optical communications, range finding, spectroscopy, and high-precision interferometry [1-2]. Erbium/ytterbium (Er/Yb) co-doped fibres make highly efficient gain media at wavelengths around 1.6 μm. A broadband 1560 nm laser at the 100-W level has been reported recently [3], providing a definite demonstration of the power scaling potential of "eye-safe" fibre lasers. However, for high-power single-frequency sources there are additional challenges. High-power operation of a single-frequency oscillator is difficult. Therefore, the so-called master oscillator power amplifier (MOPA) architecture which uses a low-power single-frequency seed followed by high-power amplification is often adopted. Unfortunately single-frequency amplification in optical fibres is troublesome because the relatively long fibres (typically longer than 10 m), and tight confinement (typical core diameter < 10 μm) leads to a low threshold for stimulated Brillouin scattering (SBS), which is highly detrimental to the stable performance. Hence, the highest single-frequency laser output power reported in this wavelength range remains far below that reached in broad-band laser configurations [4-7]. On the other hand, pioneering research on high-power MOPAs in the 1.1 μm range using Yb-doped fibres has resulted in 118 W of single-frequency output power in a nearly diffraction-limited beam, from a 9.4 m long fibre with a 28 μm diameter core [8]. A significant increase in the level of SBS was however observed above 108 W output power. This result demonstrates the significant single-frequency power-scaling capability of optimised fibre MOPAs.

Here, we report single-frequency power-scaling to comparable power levels at an eye-safe wavelength: a highly efficient Er/Yb co-doped fibre MOPA, cladding-pumped by a 975 nm diode stack source, generated up to 87 W of continuous-wave (CW) output power at 1563 nm in a single-frequency beam (linewidth < 1 MHz) with a good spatial beam quality (M^2 < 1.7).

Experiments and Results: The experimental setup is shown in Fig. 1. The entire MOPA system consists of an external-cavity tuneable diode laser (Santec TLS-210) providing a single-frequency seed at 1563 nm (linewidth < 1 MHz) and two stages of fibre amplifiers: the first stage (pre-amplifier) is a 1-W level commercial Er-doped fibre amplifier (Southampton Photonics Inc.) and the second stage (booster amplifier) is a high-power diode stack-pumped large-core Er/Yb-doped fibre amplifier. The power from the seed laser was 9.8 mW. This was amplified to 730 mW by the pre-amplifier. The seed laser and pre-amplifier were pig-tailed with connectorized standard single-mode fibres, providing an in-fibre signal path all the way to the output of the pre-amplifier. The pre-amplifier had built-in isolators at both terminal ends.

The booster amplifier, in particular the doped fibre, is the critical component in our MOPA chain. Short fibres with high pump absorption per unit length are required in order to increase the SBS threshold. A large rare-earth doped core reduces the signal intensity and increase the pump absorption. At the same time, an adequate spatial mode quality must be preserved in the typically multi-moded core, and thermal loading must be maintained at an acceptable level. This limits the permissible core size. Operation at ~1.6 μm is considerably more difficult than at 1.1 μm because of the lower power conversion efficiency, which is typically half of that of Yb-doped fibres. This increases the pump requirements as well as the thermal loading, making it more challenging to use short fibres. The double-clad large-core fibre used in the booster stage was designed and drawn from a preform that was fabricated in-house using the standard modified chemical-vapour deposition (MCVD) and solution doping technique and had an Er/Yb co-doped phosphosilicate core [9]. The fibre had a 24-μm diameter core with a numerical aperture (NA) of 0.20. Before being drawn to fibre, the preform was milled to have a D-shape so as to improve the cladding-mode overlap with the Er/Yb-doped core [10]. As a result, the inner cladding had a 400/360-μm diameter for the longer/shorter axes. It was coated with a low-refractive-index polymer outer cladding which provided a nominal inner-cladding NA of 0.48. The small-signal absorption at the pump wavelength (975 nm) in the inner cladding was ~2.5 dB/m. We evaluated the Yb^{3+}-concentration to be 1% by weight. The fibre was ~4 m long.

The pump source comprised multiple laser diode stacks at 975 nm. The pump beam was coupled into the double-clad Er/Yb fibre using a simple combination of lenses consisting of a collimating arrangement followed by an 8-mm focal length lens that focused the pump beam onto the fibre in an end-pumping scheme. We could launch as much as 340 W of pump power, with an estimated launch efficiency of >90% relative to the power incident on the fibre. The output signal from the pre-amplifier was collimated with a lens with an 11-mm focal length and coupled into the pump throughput end of the large-core fibre through an 8-mm focal length lens. Both ends of the fibre were polished at 15° to suppress undesirable feedback from the fibre facets. A dichroic mirror (high reflectivity at ~1.5 μm) separated the output beam, taken from the pump launch end, from the pump beam. Another dichroic mirror (high reflectivity at ~1.1 μm) was inserted between the pump laser and the launch end to separate out any emission component at ~1.1 μm that may arise as the Yb-ion excitation is increased at high pump levels [3]. In addition, both ends of the fibre were held in temperature-controlled metallic V-grooves that were designed to prevent thermal damage to the fibre coating by any non-guided pump/signal power or by the heat generated in the amplification cycle itself.

The MOPA output power characteristics are shown in Fig. 2(a), together with output spectra in Fig. 2(b). The seed power and pre-amplifier were kept constant, while the pump power of the booster stage was varied. The maximum output power was 87 W at the maximum diode stack drive current (50 A) and the beam had a good spatial beam quality (M^2 < 1.7). The laser spectrum was centred at 1563 nm. This was the most efficient wavelength of the system, although the wavelength dependence was weak over tuning range of several nanometers. The overall slope efficiency was 27% with respect to the launched pump power in the booster stage (35% with respect to the absorbed pump power). The overall optical power conversion efficiency was 26%. The output power increased linearly over the whole pump power range and no roll-off due to undesirable nonlinear scattering or indeed any other effect was observed. We believe that the large-core diameter (24 μm) and the short fibre length (4 m) helped to suppress nonlinear scattering within this power range. Parasitic emission at ~1.1 μm arising from Yb ion excitation was relatively low (< 10 W) even at the highest output level. However, we could see an increase of the amplified spontaneous emission around 1540 nm with pump power, even though the degradation of the output signal power was not severe. This suggests that there is room for improving the output power level still further if by increasing the seed power.

Conclusion: We have demonstrated a MOPA with a single-frequency output power of 87 W with a good spatial beam quality ($M^2 < 1.7$) at an eye-safe wavelength of 1563 nm. The output power was limited by the available pump power. The MOPA comprised a large-core cladding-pumped Er/Yb co-doped fibre amplifier in a high-power booster stage. The large-core diameter (24 μm) and the short fibre length (4 m) prevented signal power roll-off due to undesirable nonlinear scattering even at the highest pump powers available in our system. We believe further optimisation of the MOPA system will lead to higher efficiencies as well as improved beam quality in due course.

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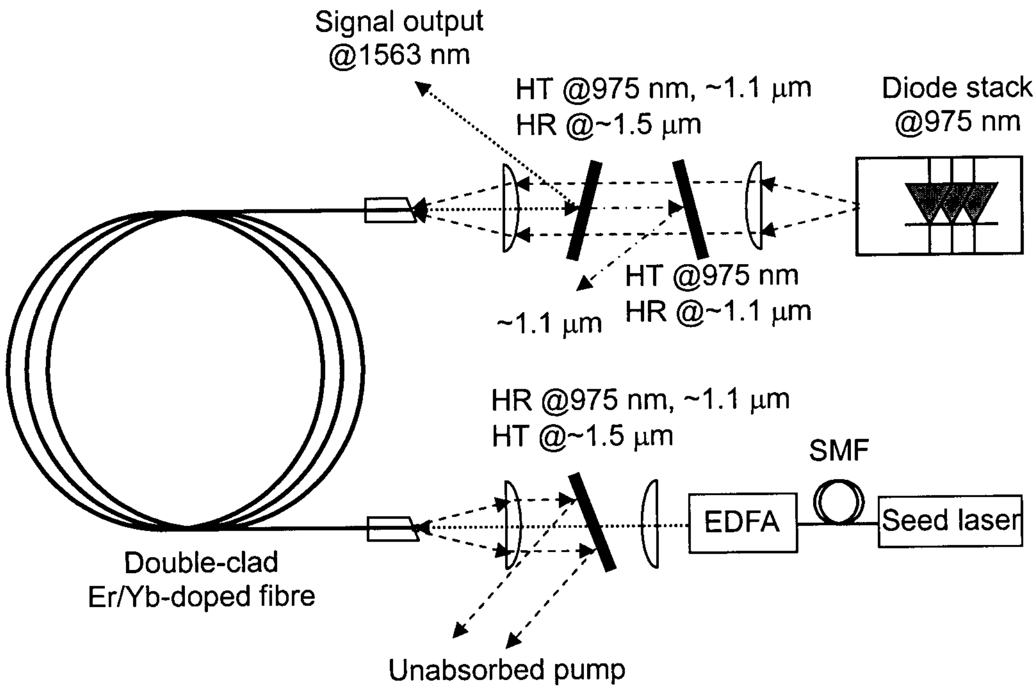
FIGURE CAPTIONS

Fig. 1. Er/Yb-doped fibre MOPA arrangement. HR: high reflectivity, HT: high transmission, EDFA: erbium-dope fibre amplifier, SMF: single-mode fibre.

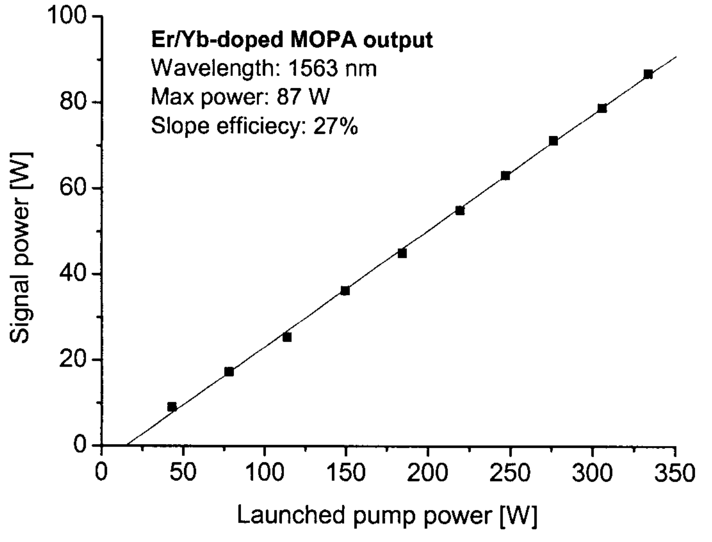
Fig. 2. (a) Amplified output power *vs*. launched pump power. (b) Output spectra from the booster stage at 17 and 87 W of output power, as well as from the seed laser and the pre-amplifier (measurement resolution 0.5 nm).

Fig. 1



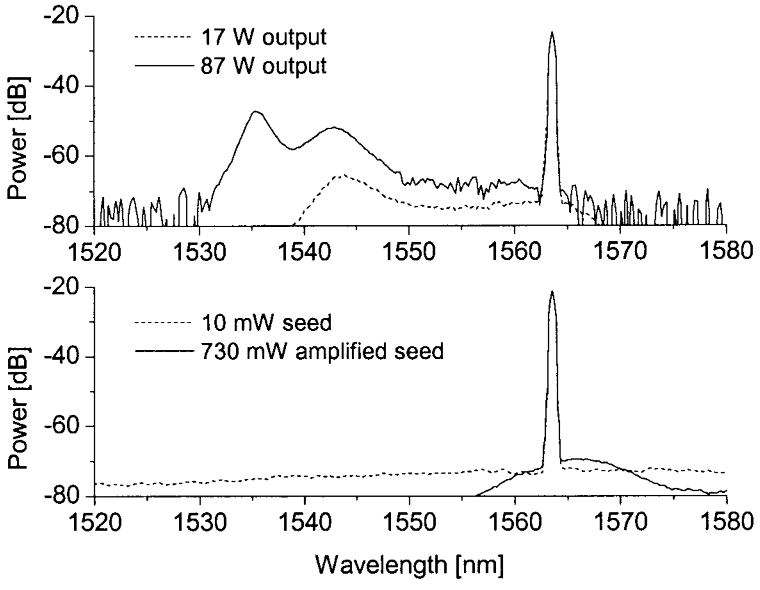
Signal output
@1563 nm
HT @975 nm, ~1.1 μm
HR @~1.5 μm
Diode stack
@975 nm
HT @975 nm
HR @~1.1 μm
~1.1 μm
HR @975 nm, ~1.1 μm
HT @~1.5 μm
SMF
EDFA
Seed laser
Double-clad
Er/Yb-doped fibre
Unabsorbed pump

Fig. 2(a)



Er/Yb-doped MOPA output
Wavelength: 1563 nm
Max power: 87 W
Slope efficiecy: 27%
Signal power [W]
100
80
60
40
20
0
0
50
100
150
200
250
300
350
Launched pump power [W]

Fig. 2(b)



17 W output
87 W output
Power [dB]
-20
-40
-60
-80
1520
1530
1540
1550
1560
1570
1580
10 mW seed
730 mW amplified seed
Power [dB]
-20
-40
-60
-80
1520
1530
1540
1550
1560
1570
1580
Wavelength [nm]