# Efficient high power operation of erbium 3μm fibre laser diode-pumped at 975nm

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Efficient CW operation of a 2.71μm Er,Pr:ZBLAN double-clad fibre laser pumped with a single diode laser operating at a wavelength of 975nm is described. A maximum output power of 0.5W and a slope efficiency of 25% (with respect to the launched pump power) were obtained. Threshold pump powers of < 200mW launched were measured and consistent relaxation oscillations in the output from the fibre laser indicate the presence of a saturable absorption mechanism.

*Introduction:* Fibre lasers operating at mid-infrared wavelengths have a number of potential applications, for example in medicine and remote sensing. In particular, high power 3 μm fibre lasers (operating on the $^4I_{11/2} \rightarrow {}^4I_{13/2}$ transition of $Er^{3+}$) would have a number of important medical applications owing to the relatively large water absorption at these wavelengths. Recently, we demonstrated 1.7W of unsaturated output from a 2.71μm Er,Pr:ZBLAN double-clad fibre laser that was pumped at a wavelength of 790 nm [1]. > 1W output has also been recently obtained from a singly doped high $Er^{3+}$ concentration M-profile fluoride glass laser [2] when diode-pumped at a wavelength of 970nm. In this Letter, we report the efficient CW operation of an Er,Pr:ZBLAN double-clad fibre laser that is pumped with the 975nm output from a single diode laser.

*Experiment and results:* As described previously [1], the double-clad fibre had an $Er^{3+}$ concentration of 35000ppm (parts in $10^6$) molar and a $Pr^{3+}$ concentration of 3000ppm molar. The core had a diameter of 15μm and a numerical aperture (NA) of 0.16. The pump cladding of the fibre had a 200μm × 100μm rectangular cross-section. Surrounding the pump cladding was a transparent fluororesin second cladding layer (300μm diameter and with a refractive index of 1.38) which provided an NA of 0.55 for the pump cladding. The pump diode used to pump the Er,Pr:ZBLAN fibre was a high brightness 980nm InGaAs/AlGaAs tapered array [3] that provided ~0.8W/A at a wavelength of 975nm after a threshold current of ~0.5A. The diode laser beam was characterised by a relatively low horizontal divergence of ~$7^0$ (full-width at $1/e^2$).

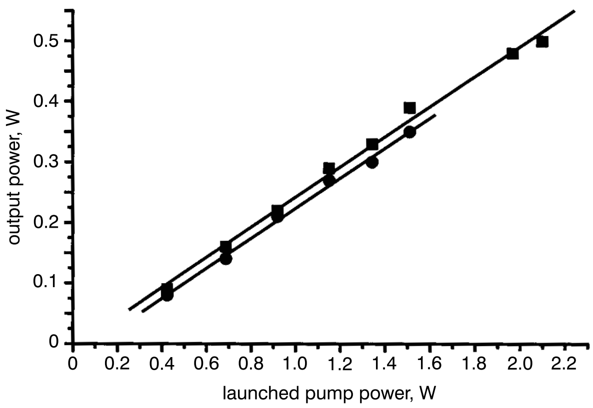


**Fig. 1** *Fibre laser output against launched pump power at 975nm for two different fibre laser arrangements*

● 1.9m
■ 4.5m

The light from the diode laser was collimated with the use of a standard triplet lens arrangement (Melles Griot part number 06 GLC 001) and shaped with a standard ×4 anamorphic prism pair (Melles Griot part number 06 GPA 002). Since the coatings on these optics were not optimised for high transmission at 975nm, 87% of the light emitted from the diode laser was transmitted through this collection of optics. The pump light was focused onto the pump cladding of the fibre with the use of a 0.32 NA ×16 microscope objective (Melles Griot part number 04 OAS 012) which transmitted 82% of the diode light. ~80% of the pump light incident on the pump cladding of the fibre was launched. Overall, ~57% of the light emitted from the diode laser was launched into the fibre. A mirror that was highly (~99%) reflecting between 770 and 990nm was placed at 45° to the pump-light direction and steered the pump light onto the input end of the fibre. This mirror also transmitted > 99.5% of the light between 2700 and 2800nm in order to obtain the fibre laser output. At the distal end of the fibre, a mirror which was highly reflecting at both the pump (> 99.9% reflecting) and laser (> 99.7% reflecting) wavelengths was carefully butted against the fibre.

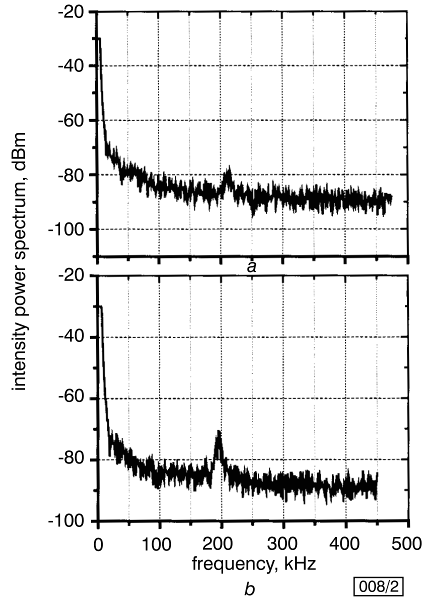


**Fig. 2** *RF spectrum of fibre laser output for 1.9m long Er,Pr:ZBLAN fibre laser arrangement for 1.15W launched pump power*

*a* Only Fresnel reflection used for feedback
*b* With highly reflecting mirror butted against distal end of fibre

The fibre laser output as a function of launched pump power is shown in Fig. 1. As can be observed, 0.5W of unsaturated output was obtained from a 1.9m long fibre laser when 2.1W of pump light was launched into the fibre. The threshold pump power for this fibre laser arrangement was < 0.2W launched and the fibre laser operated at a slope efficiency of ~25%. For comparison, the fibre laser characteristic for a 4.5m long fibre laser is also shown. As can be observed, the fibre laser characteristic is very similar, operating with a comparable slope efficiency and threshold pump power. For optimally coated pump optics, ~700mW of fibre laser output is predicted for a maximum drive current of 5.2A which was applied to the diode laser pump source in these experiments.

The stability of the fibre laser output was analysed with the use of an RF spectrum analyser (Tektronix 492P), the results from which are shown in Fig. 2 for the 1.9m long fibre laser arrangement. It can be observed that, for each fibre laser configuration, consistent relaxation oscillations were observed which had a centre frequency of 210kHz for the Fresnel-Fresnel cavity (Fig. 2*a*) and a centre frequency of 197kHz for the Fresnel-mirror cavity (Fig. 2*b*). The observation of self-consistent relaxation oscillations is usually an indication of some saturable absorption process which, at this stage, has not been identified.

*Discussion:* Pumping Er,Pr:ZBLAN fibre lasers at 975nm improves the Stokes' efficiency limit as compared to pumping at 790nm [1] and, consequently, a significantly higher slope efficiency of 25% (compared to 17.3% [1]) was obtained. However, some discrepancy exists between this result and the slope efficiency of 17.3% obtained for 790nm pumping if the Stokes' efficiency limit is the only contributing factor. The fact that the slope efficiencies for the 1.9m long fibre laser and the 4.5m long fibre laser presented in Fig. 1 are approximately identical may indicate that, for reasonably short fibre lengths, the intrinsic loss is negligible. The disparity between 975nm and 790nm pumping results is currently under investigation.

Pumping at 975nm coincides with the peak in the $^4I_{11/2}$ ground state absorption spectrum of $Er^{3+}$ doped into ZBLAN glass and has an absorption cross-section of ~$2 \times 10^{-25} m^2$ [4] at this wavelength. Assuming that the concentration of $Er^{3+}$ ions is $6.3 \times 10^{26} m^{-3}$ [1], we can calculate the effective absorption coefficient for the fibre to be ~$1.11 m^{-1}$. From cutback measurements, we determined that the fibre had an overall absorption coefficient of $1.16 m^{-1}$ indicating that the effects from pump excited state absorption from the $^4I_{11/2}$ upper laser level (which has a similar absorption cross-section at this pump wavelength [4]), were minor.

*Conclusion:* The high power operation of a 2.71 µm Er,Pr:ZBLAN double-clad fibre laser pumped with a single diode laser which operated at a wavelength of 975 nm was presented. An unsaturated output power of 0.5 W was obtained at a slope efficiency of 25% with respect to the launched pump power. The observation of self-consistent relaxation oscillations in the output from the fibre laser indicates the presence of a saturable absorption mechanism.

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