Simple method for determining quantum efficiency and background propagation loss in thulium-doped fibres

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Thulium (Tm)-doped silica fibre lasers continue to attract much interest as a wavelength flexible and power-scalable source in the two-micron band, benefiting a diverse range of applications from laser surgery and gas sensing to free-space communications and materials processing [1]. One of the key attractions of Tm-doped silica from a power scaling perspective is the ‘two-for-one’ cross-relaxation process ($^3H_4 + {^3H_6} \rightarrow {^3F_4} + {^3F_4}$), which can yield a quantum efficiency approaching ‘2’ when doped with sufficiently high Tm concentrations (>3 wt.%) and pumped at ~793 nm. This opens up the prospect of optical-to-optical efficiencies of >80%. Slope efficiencies of ~70% and higher have been realised in low to moderate power (<100 W) devices [2,3], but scaling to the kilowatt regime has come at the expense of much lower efficiency. One of the key challenges in designing and fabricating Tm fibres for operation at high power levels is maintaining a high Tm-doping level to promote cross-relaxation whilst avoiding the detrimental impact of high thermal loading. This requires more complex core designs to spread heat loading over a longer fibre length, bringing into play the influence of core propagation loss as well as cross-relaxation on overall efficiency. Knowledge of both is essential to understand their relative impact on laser performance, and for further optimising fibre design; however, a direct measurement has not so far been possible.

In this paper, we present a simple method for determining quantum efficiency and background core propagation loss in Tm-doped fibres. The procedure involves setting up a laser utilising a length of Tm fibre with feedback for lasing provided by the Fresnel reflections (~3.5%) from perpendicularly-cleaved facets at both ends of the fibre. Pump light is provided by a fibre-coupled diode laser at 793 nm launched via a free-space arrangement of lenses into one end of the Tm fibre. Laser performance is evaluated by measuring the combined output power from the two ends of the Tm fibre as a function absorbed pump power for different fibre lengths. An example of the results for the Tm-doped nested-ring silica fibre reported in [3] are shown in Fig.1, where slope efficiency with respect to absorbed pump power normalised by the Stokes efficiency, $\eta_s^{abs}\lambda_L/\lambda_P$, is plotted versus fibre length, l.

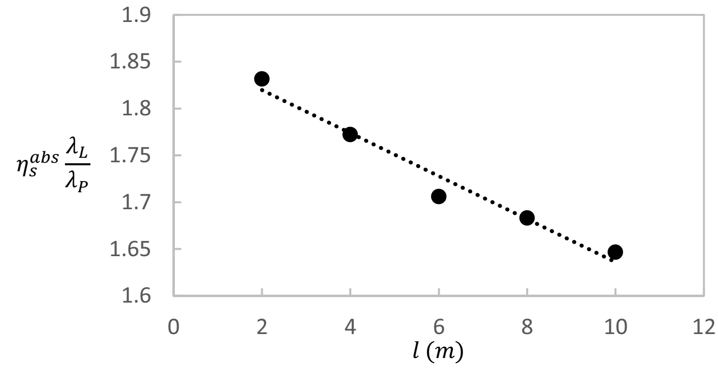

Figure 1: $\eta_s^{abs}\lambda_L/\lambda_P$, versus l for the Tm-doped nested-ring active fibre reported in [3].

An analytical model for laser performance was developed and this shows that the normalised slope efficiency decreases linearly with fibre length, primarily due to core propagation loss. The theory shows that by extrapolating the plot in Fig.1 to the $l = 0$ axis we obtain a value for the quantum efficiency, then from the gradient of a linear fit to the experimental data we can determine the core propagation loss. Details of the model and the operating regimes under which it is valid will be presented. For the Tm-doped nested-ring fibre under study, using the method described above, we determine values for the quantum efficiency and background core propagation loss of 1.87 ± 0.02 and 0.18 ± 0.02 dB/m respectively. It is worth noting that the propagation loss is over an order-of-magnitude higher than would be typically expected for an Yb-doped double-clad fibre. These preliminary findings suggest the key issue to address for power scaling whilst maintaining high efficiency is reducing background loss rather than increasing cross-relaxation efficiency, which is already close to the theoretical limit. The origin of the high background loss and strategies to reduce it are the subject of ongoing studies.

[1] K. Scholle, S. Lamrini, P. Koopmann, and P. Fuhrberg in, *Frontiers in guided wave optics and optoelectronics*, B. Pal ed. (IntechOpen, London,2010), Ch. 22.
[2] P. C. Shardlow et al., “Optimising Tm-Doped Silica Fibres for High Lasing Efficiency”, in CLEO/Europe-EQEC '15.
[3] Matthew J. Barber, et al., "Nested-ring doping for highly efficient 1907 nm short-wavelength cladding-pumped thulium fiber lasers." Optics Letters **45.19**, 5542-5545 (2020).