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RESEARCH

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

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Abstract
A method for determining the quantum efficiency and background propagation loss in rare earth-doped silica fibres is presented. These parameters can be determined using straightforward measurements of slope efficiency and emission spectra at various lengths of active fibre. This method has been applied to a thulium-doped silica fibre with a structured 'nested-ring' doping profile. The quantum efficiency of this fibre was 1.93 ± 0.01 and the background propagation loss was 0.15 ± 0.01 dB/m. This characterisation method also allows the relative impact of these parameters on the slope efficiency of an all-fibre high-power system to be predicted. It was found that the non-ideal background propagation loss of this fibre results in a decrease of ~ 18 percentage points on the predicted slope efficiency, whereas the quantum efficiency results in a decrease of ~ 3 percentage points. The predicted slope efficiency with respect to absorbed pump power of $62 \pm 2\%$ for the all-fibre high-power system is consistent with the experimental result of 61.5%. This characterisation provides feedback to the fibre design and fabrication that for efficient power scaling, efforts to decrease the background propagation loss of this fibre can provide a greater increase in efficiency than efforts to further increase the quantum efficiency.

1 Introduction

Thulium (Tm)-doped silica fibre lasers continue to attract growing interest owing to their wide wavelength flexibility (~ 1.65–2.1 µm), power scaling potential and a range of applications in areas such as medicine, materials processing, remote sensing and defence. Strong absorption in C-H bond and water containing materials at specific wavelengths accessible by Tm fibre lasers are a significant benefit to applications such as laser processing of plastics and soft tissue surgery, whereas high atmospheric transmission at ~ 2.1 µm is important for LIDAR and various applications in the defence arena. A further advantage of Tm-doped laser materials is the potential for very high efficiency when using a high Tm concentration and pumping at wavelengths ~ 793 nm via the cross-relaxation process ($^3H_4 + {}^3H_6 \rightarrow {}^3F_4 + {}^3F_4$), which can yield up to two excited Tm ions for each pump photon absorbed. In addition to higher quantum efficiency this implies reduced quantum defect heating, which facilitates scaling output power with the prospect of a theoretical slope efficiency > 80% (depending on operating wavelength). In spite of these benefits, Tm-doped silica fibre lasers trail well behind Yb-doped fibre lasers in the one-micron band in terms of maximum output power and efficiency. The highest continuous-wave power demonstrated to date for a thulium fibre laser in the two-micron band is 1.1 kW at 1950 nm using master-oscillator power-amplifier (MOPA) architecture [1] and the reported slope efficiency with respect to launched power was 51% and hence much lower than the theoretical limit. The story is similar for Tm fibre oscillators with a maximum output power of 567W reported and a slope efficiency of 49.4% with respect to absorbed power [2]. This prompts the question as to why Tm fibre lasers have so far failed to yield their promised potential in terms of output power and efficiency.

The key fibre parameters influencing the slope efficiency are the quantum efficiency (i.e. defined here as the number of active laser ions in the upper laser level for each absorbed pump photon) and the core propagation loss at the lasing wavelength. A knowledge of both is needed to predict the performance of any given laser oscillator or amplifier configuration, and hence is essential when attempting to optimise the Tm fibre design. In double-clad Tm-doped silica fibres, cladding-pumped at ~ 793 nm, significant effort has targeted

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enhancement in the quantum efficiency via exploiting of the 'two-for-one' cross-relaxation process [3]. This generally requires a high Tm concentration (> 3.5 wt% Tm_2O_3) and a host composition (usually alumino-silicate) that can accommodate this without clustering of Tm^{3+} ions [4]. In principle, the quantum efficiency can be determined from measurement of the fluorescence yield under known excitation conditions, but this is a difficult experiment to perform accurately, and is further exacerbated by variation in the Tm concentration across the core region. Determination of core propagation loss at the lasing (or signal) wavelength in a rare earth-doped fibre is generally achieved via the cut-back technique at wavelengths either side of the absorption and emission bands followed by interpolation between the resulting loss values to infer the loss coefficient across the emission band. However, the combination of very broad absorption and emission bands for Tm-doped silica in the ~ 2 μm wavelength regime and strongly increasing loss for silica at longer wavelength makes this extremely challenging with the result that this approach cannot not yield accurate values for propagation loss.

In this paper, we describe an alternative and self-consistent method for determining both quantum efficiency and core propagation loss in rare earth-doped fibres via a set of simple laser experiments. We have applied this measurement technique to the case of a double-clad Tm fibre with a structured (nested-ring) core design to evaluate its potential for efficient operation at high power levels. Our technique exploits the fact that the laser slope efficiency with respect to absorbed pump power depends on both quantum efficiency and propagation loss. Thus, from a measurement of the slope efficiency with respect to absorbed pump power for different Tm fibre lengths, one can estimate both quantum efficiency and core propagation loss. The procedure can be explained with reference to Fig. 1 which shows a very simple Tm-doped fibre laser set-up with a variable length of the Tm fibre gain medium with feedback for lasing provided by perpendicularly cleaved fibre facets at both ends of the fibre to yield a double ended laser output. In this case, the Tm-doped active fibre under investigation was the structured core (nested-ring) fibre described in [5]. In this fibre the Tm dopant is confined to a thin ring located towards the edge of the core and the core diameter, 8.2 μm, was selected to ensure that only the fundamental mode was guided. The cladding of the fibre was octagonal, with a diameter of 132 μm between opposite corners and 122 μm between opposite flat sides. This gave a cladding cross-sectional area equal to that of a circular 125 μm diameter fibre. The fibre was coated with a low-index PC-373-AP polymer coating of 180 μm diameter to provide 0.46 NA guidance in the cladding for pump light.

Pump light was supplied by a 35W fibre-coupled diode laser at 793 nm, with a 105 μm diameter core (0.22 NA) and a 125 μm diameter cladding. This was spliced to a 12 m length high hydroxyl (OH) content fibre with a matched core diameter and NA using a Fujikura fusion splicer to ensure negligible splice loss. The high OH fibre exhibits strong absorption in the two-micron band (~ 2000 dB/km) and low absorption at 793 nm (~ 6 dB/km). This provided protection to the diode laser from any residual signal light transmitted by dichroic mirror 1 (see Fig. 1). The pump beam was collimated and then focussed into the Tm gain fibre with a simple arrangement of antireflection coated 8 mm focal length aspheric lenses. In this simple arrangement, the Tm fibre laser yields outputs from both ends, which were monitored by two power meters (PM1 and PM2) to determine the combined output power. Dichroic mirrors 1 and 2 with high transmission for pump light at 793 nm and high reflectivity over the lasing wavelength

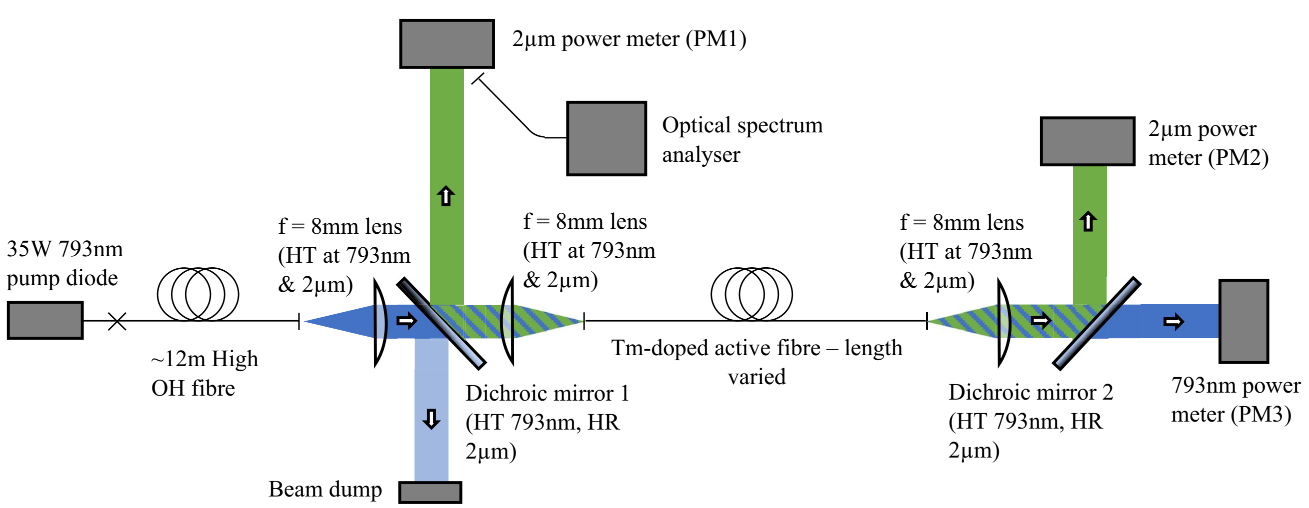

Fig. 1 The experimental set-up used to characterise quantum efficiency and background core propagation loss of a Tm-doped fibre. Signal light is shown in green and pump light is shown in blue

band around 2 μm were used to separate laser output from the pump beam. At the pump input end of the Tm fibre reflected pump light from the uncoated face of the dichroic mirror was collected using a beam dump and, at the opposite end, unabsorbed pump was monitored using power meter PM3 to allow the absorbed pump power to be determined. The pump diode was mounted to a water-cooled plate with a setpoint of 17 °C. The pump diode output power and spectrum were characterised to ensure that the heat-sinking was sufficiently effective to avoid thermally induced changes in pump power and wavelength. Prior to launching pump power into the Tm fibre an accurate determination of the launched pump power was made by coupling into a length of circular 125 μm passive fibre using the same pump launching scheme. The pump launch efficiency was measured to be 85% by comparing the transmitted power with the incident power, taking into account the Fresnel reflection loss at the output of the passive fibre. After measuring the pump launch efficiency, the Tm active fibre was positioned in place of the passive fibre and aligned to yield the maximum combined output power with both end sections mounted in water-cooled aluminium V-grooves with the remaining fibre submerged in a water bath to ensure effective heat-sinking. Both the water in the bath and the water-cooled V-grooves were maintained at a temperature of 7 °C, in order to ensure that the heat-sinking of the fibre was sufficient. Finally, the laser emission spectrum was monitored from scattered light from PM1 with the aid of a spectrum analyser. One of the key attractions of this laser set-up is that the Tm fibre laser has no splices, so the total resonator loss is due output coupling loss at both ends and the core propagation loss. Under these operating conditions, it can be shown (see Appendix A) that quantum efficiency, η_q and background loss coefficient, α_L are related to the slope efficiency with respect to absorbed pump power, η_s^{abs} and Stokes efficiency, ν_P/ν_L via the approximate expression:

$$\eta_s^{\text{abs}} \frac{\nu_P}{\nu_L} = \left(1 + \frac{\alpha_L l}{\ln(R)}\right)\eta_q, \tag{1}$$

where l is the length of Tm fibre and R is the reflectivity of the fibre end facets. This expression assumes that (i) the background propagation loss does not vary considerably across the emission wavelength range measured, (ii) the quantum efficiency does not vary significantly due to variation in the excitation density, within the range of measurements, (iii) the gain and background core propagation loss coefficients (g and α_L) are constant along the length of the Tm-doped fibre and (iv) thermal effects have negligible impact on efficiency. Under these conditions, it can be seen from Eq. (1) that by measuring η_s^{abs} and ν_P/ν_L as a function of Tm fibre length (l) and plotting $\eta_s^{\text{abs}}\,\nu_P/\nu_L$ as a function of l one can determine η_q and α_L. In our study described here, the length of fibre was varied from 12 to 2 m, in steps of 2 m maintaining pump launch efficiency.

2 Results

Figure 2 shows $\eta_s^{\text{abs}}\,\nu_P/\nu_L$ plotted against fibre length, l for the Tm-doped nested-ring fibre.

From the y-intercept, the quantum efficiency, η_q was determined as 1.93 ± 0.01. From the gradient, the background propagation loss, α_L was determined to be 0.15 ± 0.01 dB/m. The emission wavelength varied from 2014 to 1962 nm as the Tm fibre was reduced in length and the overall pump absorption in the fibre decreased approximately linearly from 25.5 to 4.5 dB, for fibre lengths of 12–2 m, respectively.

The theoretical ideal value for η_q and α_L are 2 and 0 dB/m, respectively, representing perfect two-for-one cross-relaxation and no background propagation loss. At first glance, the measured value of quantum efficiency appears to suggest that efficient two-for-one cross-relaxation is taking place for the most-part in the doped region of the core. The background loss appears large, over an order-of-magnitude higher than would be typically expected for an Yb-doped double-clad fibre. To better understand the relative impact of the measured values of quantum efficiency and background propagation loss on the performance of this fibre, consider a hypothetical cavity utilising a 6 m length of nested-ring fibre, as shown in Fig. 3.

In this hypothetical cavity, fibre Bragg gratings (FBGs) are fusion spliced to each end of the active fibre to provide the necessary feedback for lasing, which are optimised for emission at 1940 nm in this hypothetical case. The output coupler reflectivity was chosen to be 15%. An active fibre length of 6 m is chosen here, because the slope efficiency with respect to launched power reached a maximum value of approximately 69% in the range 6–8 m during the characterisation measurements. At 6 m, the pump absorption within the nested-ring fibre was 13 dB. As before, the pump source is a 793 nm fibre-coupled diode source. This cavity is typical of the type of oscillator that may be constructed using the nested-ring fibre to produce two-micron emission at the 100W-class level.

Here, the assumption is made that the length of passive fibre in the FBGs is short, hence the background loss in the FBGs is negligible. It is also assumed that the reflectivity of the HR FBG is 100% and the splice losses in the system are negligible. Because the lasing signal light in this cavity now experiences two trips through the active fibre before encountering the output coupler, Eq. 1 becomes

$$\eta_s^{\text{abs}} = \frac{\nu_L}{\nu_P}\left(1 + \frac{2\alpha_L l}{\ln(R)}\right)\eta_q. \tag{2}$$

Using Eq. 2, values of α_L and η_q can be substituted to predict the absorbed slope efficiency of this cavity under different conditions. Table 1 shows the expected slope efficiency of this oscillator for different values of α_L and η_q to gauge their relative importance in a realistic laser configuration.

From Table 1, it is observed that if the background loss was ideal, the impact of this fibre exhibiting a quantum efficiency of 1.93, rather than 2, decreases the expected slope efficiency with respect to absorbed pump power by ~ 3 percentage points. If the quantum efficiency is ideal, the impact of this fibre exhibiting a background loss of 0.15 dB/m, rather than 0 dB/m, decreases the expected slope efficiency with respect to absorbed pump power by ~ 18 percentage points. Together, the impact of both parameters leads to a decrease of ~ 21 percentage points, compared to the performance expected if this fibre exhibited ideal values for each.

With the values of quantum efficiency and background loss that have been determined by this analysis, an absorbed slope efficiency of 62 ± 2% is predicted for the oscillator described in Fig. 3. A 1940 nm oscillator such as this was constructed, producing a maximum power of 120W. The measured slope efficiency was 61.5% with respect to absorbed pump power.

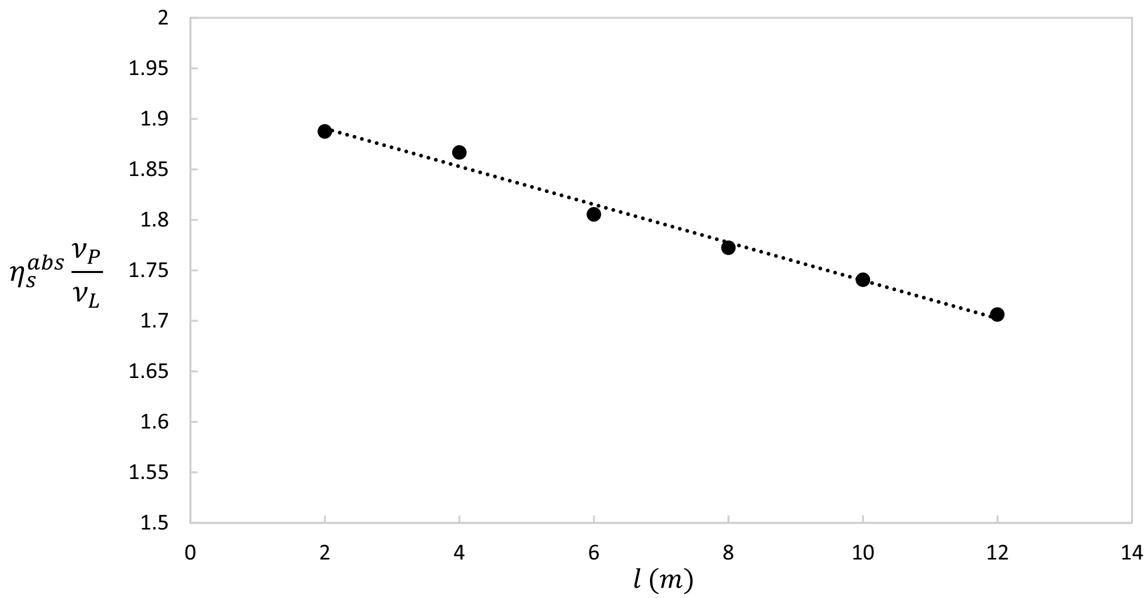

Fig. 2 Plot of $\eta_s^{\mathrm{abs}}\frac{\nu_P}{\nu_L}$ against fibre length, l for the Tm-doped nested-ring fibre

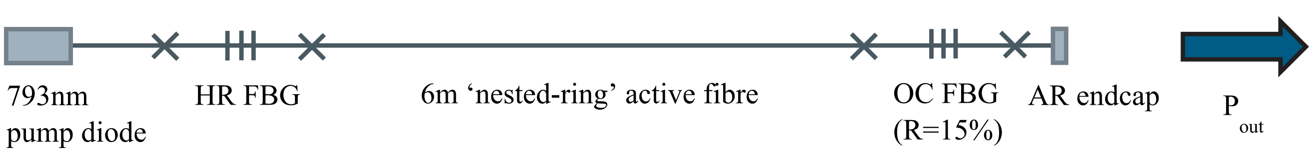

Fig. 3 A typical fibre laser cavity using the nested-ring fibre

Table 1 Predicted values of slope efficiency with respect to absorbed pump power for the laser cavity shown in Fig. 3, based on different values of quantum efficiency and background propagation loss

Fibre parameters	Quantum efficiency, η_q	Background loss, α_L (dB/m)	Absorbed slope efficiency, η_s^{abs}
Ideal quantum efficiency and background loss	2	0	83%
Measured value of quantum efficiency, ideal background loss	1.93 ± 0.01	0	80 ± 1%
Ideal quantum efficiency, measured value of background loss	2	0.15 ± 0.01	65 ± 2%
Measured values of quantum efficiency and background loss	1.93 ± 0.01	0.15 ± 0.01	62 ± 2%

This prediction is consistent with the measured performance of 100W-class systems that have been built using the Tm-doped nested-ring fibre. This provides confidence that the analysis provides accurate determinations of the quantum efficiency and background loss. It also provides confidence that the measurements of slope efficiency during this characterisation are within a regime where the assumptions that have been made are valid.

This analysis has shown that the impact of the background loss on limiting the performance of this fibre is much larger than the impact of the quantum efficiency. Efforts to further improve the quantum efficiency of this fibre can only increase the performance by a maximum of a few percent. Therefore, investigations into the source of the background propagation loss and methods to reduce it should be the priority of future work. It is hoped that these future studies will inform the next generation of fibre designs on methods to reduce background propagation loss, hence opening up the prospect of significant improvement in the efficiency for future Tm fibre laser systems.

3 Conclusions

A novel method of determining the quantum efficiency and background propagation loss of any rare earth-doped silica fibre has been presented. This method makes use of relatively straightforward measurements of laser slope efficiency and output spectrum to determine the quantum efficiency and background propagation loss of the fibre. This characterisation method was applied to a Tm-doped silica fibre with a structured doping profile across the fibre core. This nested-ring fibre was determined to have a quantum efficiency of 1.93 ± 0.01 and a background propagation loss of 0.15 ± 0.01 dB/m. These values were used to predict the slope efficiency of a 6 m long cavity with feedback for lasing provided by high reflectivity and output coupler FBGs at 1940 nm. The predicted value of slope efficiency with respect to absorbed pump power is 62 ± 2% and consistent with the real measured value of 61.5% for this system. It can be concluded that the reduction of the laser slope efficiency from the ideal value of 83% was dominated by the impact of the background propagation loss, not the non-ideal 'two-for-one' quantum efficiency. Determining these intrinsic fibre properties has many challenges when employing traditional measurement methods. This method of fibre characterisation now enables the laser user to determine values of quantum efficiency and background propagation loss of quasi-three-level fibre systems, providing valuable feedback into fibre design and fabrication.

Appendix

Appendix A

Consider a simple generic laser cavity comprising length l of Tm-doped fibre with feedback for lasing provided by mirrors of reflectivity R_1 and R_2 at opposite ends 1 and 2 of the fibre, respectively. The laser yields output powers P_1 and P_2 from ends 1 and 2 as shown in Fig. 4A. Note that there are no splices present, which means that the background propagation loss and outcoupling mirrors are the only sources of loss within the cavity.

The total power that exits the fibre laser (i.e. useful and non-useful) over one round trip is equal to the power generated, P_G in the fibre laser is defined by

$$P_G = P_1 + P_2 + P_L^+ + P_L^- \tag{3}$$

Here, P_L^+ and P_L^- represent the power generated in the fibre propagating in the $+z$ and $-z$ directions that is subsequently lost due to the background propagation loss of the fibre core. The power in the fibre at an arbitrary position z can be expressed as

$$P(z) = P(0)e^{(g-\alpha_L)z} \tag{4}$$

Here, g and α_L represent the gain coefficient per unit length and background loss coefficient per unit length respectively. This assumes that g and α_L are independent of position z. Hence, when taking into account core propagation loss, the net single pass gain, G can written as

$$G = \frac{1}{\sqrt{R_1R_2}} = e^{(g-\alpha_L)l} \tag{5}$$

The power lost to background propagation loss per unit length is given by

$$-P(0) * \mathrm{e}^{gz} * \frac{\mathrm{d}}{\mathrm{d}z}(\mathrm{e}^{-\alpha_L z}) = P(0) * \alpha_L * \mathrm{e}^{gz} * \mathrm{e}^{-\alpha_L z} \tag{6}$$

Integrating Eq. 6 along the length of the fibre now yields the power lost to background propagation loss for a single pass through the gain medium, P_L as

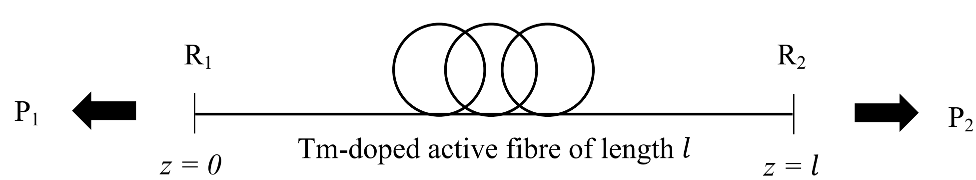

Fig. 4 Generic fibre laser resonator

$$P_L = P(0) * \alpha_L \int_0^l e^{(g-\alpha_L)z} dz = P(0) * \frac{\alpha_L}{g - \alpha_L} * \left(e^{(g-\alpha_L)l} - 1\right), \tag{7}$$

where $P(0)$ is the power at $z=0$ for propagation in the $+z$ direction and at $z=l$ for propagation in the $-z$. Substituting the relevant expressions for $P(0)$ and using Eq. 5, we obtain the following expressions for P_L^+ and P_L^-:

$$P_L^+ = \frac{P_1 R_1}{1 - R_1} * \frac{-2\alpha_L l}{\ln(R_1 R_2)} * \left(\frac{1}{\sqrt{R_1 R_2}} - 1\right) \tag{8}$$

$$P_L^- = \frac{P_1 R_1 R_2 G}{1 - R_1} * \frac{-2\alpha_L l}{\ln(R_1 R_2)} * \left(\frac{1}{\sqrt{R_1 R_2}} - 1\right) \tag{9}$$

The ratio of useful power coupled out of the laser to the total power generated, η_G can be written as

$$\eta_G = \frac{P_1 + P_2}{P_G} = \frac{P_1 + P_2}{P_1 + P_2 + P_L^+ + P_L^-} \tag{10}$$

In the case where the feedback for lasing is provided by perpendicular cleaves at each end of the fibre, $R_1 = R_2 = R \approx 3.4\%$ and $P_1 = P_2$. Under these conditions, it can be shown that η_G is given by

$$\eta_G = \frac{1}{1 - \frac{\alpha_L l}{\ln(R)}}. \tag{11}$$

The slope efficiency with respect to absorbed power, η_s^{abs}, can be written as

$$\eta_s^{abs} = \eta_G \frac{\nu_L}{\nu_P} \eta_q, \tag{12}$$

where η_q is quantum efficiency, and ν_L and ν_P are the lasing and pump frequencies, respectively. Under the assumption that $\alpha_L l \ll -\ln(R)$, we obtain from Eqs. 11 and 12, the following approximate expression relating η_s^{abs}, α_L and η_q.

$$\eta_s^{abs} \frac{\nu_P}{\nu_L} = \left(1 + \frac{\alpha_L l}{\ln(R)}\right) \eta_q. \tag{13}$$

It should be noted that providing feedback for lasing with perpendicular cleaves provides no wavelength selection. The free-running wavelength of a Tm-doped fibre is dependent on the overall length of active fibre due to the quasi-three-level nature of the laser transition, with shorter lengths emitting at a shorter wavelength. As a result, the term $\frac{\nu_L}{\nu_P}$ will vary with respect to fibre length, l.

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Data availability All data supporting this study are openly available from the University of Southampton repository at https://doi.org/10.5258/SOTON/D2748.

Declarations

Conflict of interest The authors declare no competing interests.

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