10W ASE-free single mode high power double cladding Er^{3+}-Yb^{3+} amplifier

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ABSTRACT

We designed a high output power double cladding erbium-ytterbium fibre amplifier that showed no amplified spontaneous emission (ASE) at 1.0 µm using a quasi singlemode fibre. The reduction of the amplified stimulated emission (ASE) at 1.0 µm was found to be the combination of fibre design and temperature effect in the core. A 10W output double cladding Er-Yb amplifier with a core/cladding fibre diameter of 10/125 µm was realized with a seed signal of 1.4 W at 1563 nm and with counter-propagating pump power of 35 W at 976 nm without any significant ASE generation at 1.0 µm. The fibre also exhibits singlemode behaviour with M^2 <1.1 and a high slope efficiency of 30%. The fibre was designed to minimize ASE at 1.0 µm by heavily doping the fibre and using the appropriate ratio between Yb^{3+} and Er^{3+} ions. By incorporating into our model the core temperature increase coming from the quantum defect of the Er-Yb system, we can also predict a raise in the absorption cross-section of the ytterbium ions around 1060 nm yielding to an increase of the 1 µm ASE threshold from 14 W to 35 W pump power, which allowed us to reach a 10 W output power at 1563 nm instead of 5 W normally predicted by the theory. These results show potential power scaling of the output power or double cladding erbium ytterbium amplifier using quasi singlemode core erbium ytterbium fibre avoiding the need of large core dimension that degrades the beam quality.

Keywords: erbium ytterbium, temperature, modeling, amplified stimulated emission, double cladding fibre, cross-section

1. INTRODUCTION

The output power of fibre laser increased tremendously during the last few years due to the increase of brightness of multimode pump diodes around 910-980 nm and the development of double cladding fibres. The kilowatt diffraction limited output power level was obtained a few years ago already in ytterbium double cladding silica fibre[1,13]. While ytterbium doped fibre present the highest efficiency due to its simple energy level structure, its output wavelength around 1.0 µm does not fit all the desired applications. A longer operation wavelength is often required around 1.5 µm for eye-safe operation in detection applications. A commonly used dopant for this wavelength is erbium, used a lot in telecommunication amplifiers, that emits around 1.55 µm while usually pumped at 980 nm. However, high concentration of erbium cannot be incorporated in silica fibre because of detrimental clustering effects[2,3]. This low doping level becomes unpractical for most high power double cladding fibre lasers because the overlap of the cladding pump power with the doped core is very low and pump absorption becomes negligible. An efficient way to overcome this is to codoped the fibre with ytterbium, which can be incorporated in concentration 10 to 100 times higher than erbium and has an intrinsic cross section absorption superior to erbium. Furthermore, the ytterbium presents a broad absorption from 900 to 1000 nm compared to erbium alone that is limited to 980 nm in that window. When pumped, the energy of the ytterbium is transferred to the erbium through a non-radiative energy transfer. Output power above 100 W at 1.55 um[4] have already been obtained using erbium ytterbium co-doped silica fibres. Nevertheless, there are some drawbacks associated with the ytterbium sensitisation: spurious lasing at 1.0 µm can occur and the energy transfer process from the ytterbium ions to the erbium is not 100% efficient. Furthermore, the wavelength difference between the pump and signal wavelength in erbium ytterbium system makes a large quantum defect that creates heat. Therefore, such high power fibre laser and amplifier have to deal with a high heat load into the fibre core. It is therefore important to understand how this heat load affects the performance of erbium ytterbium double cladding system in the power scaling of such a device.

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In this paper, a 10 W output power diffraction limited erbium ytterbium amplifier that shows no amplified stimulated emission (ASE) at 1.0 µm is presented using a 10 µm core fibre. In the first section, the temperature effects and its influence on the 1.0 µm emission threshold is first discussed. The second section presents the theoretical model which allows us to predict the amplifier output signal at 1.5 µm and ASE at 1.0 µm and to optimize the fibre design. Finally, the experimental amplifier results with 10 W output at 1563 nm and 1.0 µm ASE free emission is presented.

2. TEMPERATURE EFFECTS

2.1 Temperature effects on cross-section

A setup was developed to measure the relative variation of cross-section with temperature as the absorption and emission cross-section of the dopants in the fibre might be affected significantly with temperature. Because the small signal absorption of the fibre is directly proportional to the absorption cross-section[5]; the core absorption of a few centimeter long erbium ytterbium fibre sample was measured with a white light source (WLS) and an optical spectrum analyzer (OSA) as shown on Figure 1 using a cut-back measurement technique to properly reference the absorption measurement. Several cut-backs were done to ensure a repeatable splice loss with the Corning® HI1060 relay fibre. The emission cross section was measured by pumping a small sample of fibre with 100 mW of 977 nm pump injected in the core as the emission cross section is also directly related to the emission spectrum of the fibre when the ions are totally inverted[5]. A 977/1060 nm multiplexer was used to inject the pump and collect the emission. The sample length was kept below 2 mm to ensure a complete inversion and limit ASE reabsorption. To evaluate the temperature effect, the erbium ytterbium fibre is placed in an oven. The oven temperature governs the fibre core temperature since no significant heat is generated in the core through the pumping.

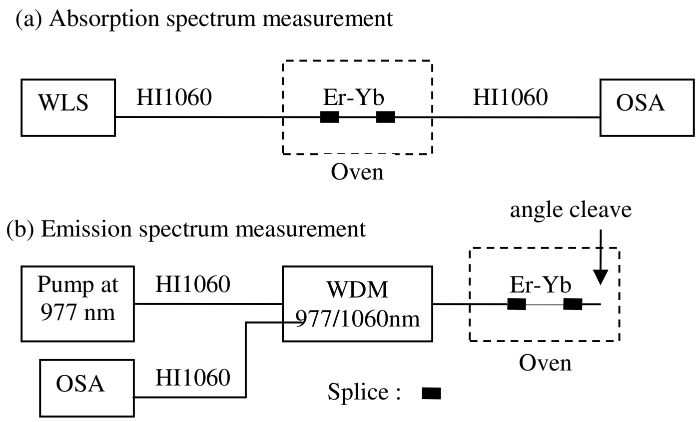

Figure 1. Setup to measure the relative variation of the absorption spectrum (a) and the relative variation of the emission spectrum (b) as a function of temperature.

Figure 2 shows the absorption measured on the CorActive Hpa-Ey-10-01 erbium ytterbium fibre in the 1060 nm region, where most ASE at 1.0 µm is emitted by the ytterbium ions, and around 1.56 µm, where the signal is amplified by the erbium ions. The temperature affects strongly the ytterbium ions absorption while it has no visible effect on the erbium ions. This is an expected behavior because of the high multiplicity of the energy levels and their small separations (< 100 cm^{-1}) maintain a constant population distribution in the erbium ions[5]. However, energy level separations higher than 500 cm^{-1} are found in the ytterbium[6], which make a large fluctuation in the Boltzmann's electronic population distribution among the energy level with temperature.

There is a difference of 8 dB/m at 1060 nm at 130°C compared to room temperature, which represents 6 times greater absorption in linear unit for the same length. It can already be predicted that the temperature will affect the ASE at 1.0 µm emitted by the fibre. This will have to be taken into account when doing simulations to predict the output power.

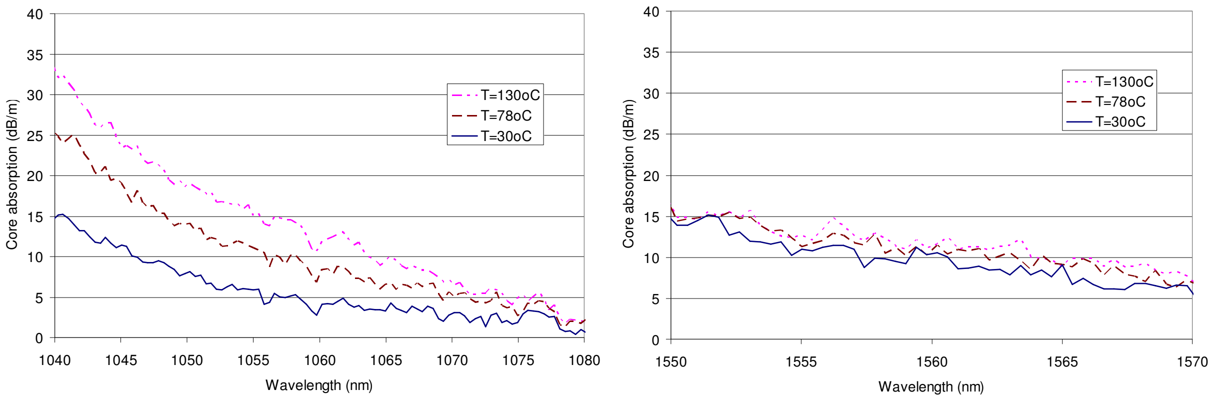

Figure 2. Core absorption of Hpa-Ey-10-01 as a function of temperature around 1060 nm on the left and around 1560 nm on the right.

Figure 3 shows the emission measurements done on the Hpa-Ey-10-01. The effect of temperature around 1060 and 1560 nm is way less significant than for the absorption for both the erbium and ytterbium. However, the emission spectrum is increased by 6 dB around the 900 nm region, which is consistent with the 8 dB increase in absorption at 1060 nm as expected from the McCumber theory[12]. But this does not influence erbium ytterbium amplifiers since no amplified stimulated emission (ASE) is generated around 900 nm.

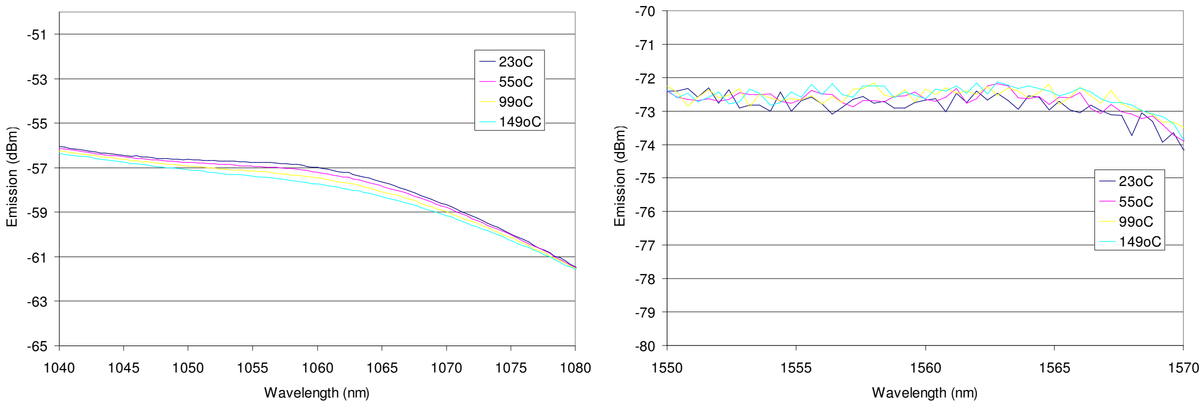

Figure 3. Emission spectrum of Hpa-Ey-10-01 under complete ions inversion as a function of temperature: around 1060 nm on the left and 1560 nm on the right.

2.2 Core temperature evaluation

The temperature of the fibre core needs to be calculated with enough precision to evaluate the impact of the heat generated inside the fibre. Measuring directly the fibre core temperature is not straightforward, but it can be evaluated by considering the fibre as a cylindrical long medium with a heat generation occurring in the core and solving the heat diffusion equation for the heat flow[7]. The core temperature T_{core} of a fibre of core radius a and cladding radius b can then be expressed as a function of air temperature T_{air} and the heat generated in the core Q as follow:

$$T_{core} = T_{air} + \frac{Qa^2}{4k}\left(1 + 2\ln\left(\frac{a}{b}\right) + \frac{2k}{bh}\right) \qquad (1)$$

Where k =1.38 W m^{-1} K^{-1} is the thermal conductivity of the silica glass. $Q = P/(L\pi a^2)$ is the heat density generated in the core of the fibre, which is simply the power converted to heat divided by the core volume of length L and radius a. In an erbium ytterbium fibre, P is mainly produced by the quantum defect, which is the output signal power minus the injected pump power. The number h = 115 W m^{-2} K^{-1} is the convective coefficient of air, which will depend of the boundary condition between the fibre and the ambient air.

The model was validated by dissipating 500 mW of 915 nm pump power in a 6.5 mm long high attenuating fibre of 75µm/200µm core/cladding diameter. The silica fibre was brought to its melting point around 1100°C, which is consistent with the core temperature of 1055°C calculated from the above model.

Looking at the thermal aspect of the 10 W amplifier realized in this study, we estimated Q=5.78x10^{10} W/m^3 of heat generated along the core with 35 W pump power dissipating 25 W along 5.5 m of the 5 µm core radius fibre. An average heat dissipation along the entire length was considered fair enough to evaluate the impact of temperature effect on the output power. By applying Equation (1), a core temperature of 85°C is calculated. This value can be used to find the relative variation of absorption and emission cross-section measured in Section 2.1 above. From interpolations of data shown on Figure 2 and Figure 3, the absorption cross-section at 85°C is five times higher than at room temperature, while the emission cross-section at 85°C is reduced by 20% around 1060 nm. These scaling factors can be applied to the cross-sections used in the model to predict the performances of the erbium ytterbium fibre presented in Section 3.1. It is important to stress that even if the core temperature is raised to 85°C, the cladding temperature remains within a safe range for long term operation.

3. ERBIUM YTTERBIUM THEORETICAL MODEL

3.1 Model description

A general theoretical model that can predict the behaviour of any fibre laser or amplifier was developed. The model is based on standard rate equations [5,8]. In this work, a version that specifically addresses erbium ytterbium amplifiers is presented. The model uses the electronic level diagram shown on Figure 4. Stimulated transitions between levels i and j are represented by W_{ij}, spontaneous transitions by τ_{ij}, electronic populations by N_i, and the transfer rate between ytterbium and erbium by K_{tr}. This simplified structure happens to adequately model the system without the need to take into consideration secondary energy transfer phenomena such as upconversion or quenching phenomena[9]; The energy transfer between erbium and ytterbium ions has proven to be the main parameter of the erbium ytterbium system and this model has been validated in a previous paper and was shown to adequately predict the performance of erbium ytterbium codoped silica fibre[10].

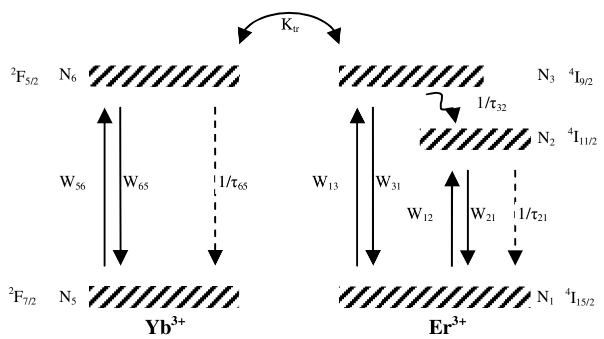

Figure 4. **Diagram of the electronic levels of the system erbium ytterbium used for the model**

$$\frac{dN_2}{dt} = W_{12}N_1 - W_{21}N_2 - 1/\tau_{21}\,N_2 + 1/\tau_{32}\,N_3 \quad ; \quad \frac{dN_3}{dt} = W_{13}N_1 - W_{31}N_3 - 1/\tau_{32}\,N_3 + K_{tr}N_1N_6 - K_{tr}N_3N_5 \quad ; \quad \rho_{er} = N_1 + N_2 + N_3 \tag{2}$$

$$\frac{dN_5}{dt} = W_{65}N_6 - W_{56}N_5 + 1/\tau_{65}\,N_6 + K_{tr}N_1N_6 - K_{tr}N_3N_5 \quad ; \quad \rho_{yb} = N_5 + N_6 \tag{3}$$

$$W_{ij}(r) = \int \frac{\sigma_{ij}(\lambda)P_{in}^{+,-}(\lambda)\psi(r,\lambda)}{E_{ij}(\lambda)}d\lambda \quad ; \quad \frac{dP}{dz} = 2\pi\int_0^{r_o}\Big[\big(\sigma_{ji}N_j(r) - \sigma_{ij}N_i(r)\big)P_{in}\psi(r,\lambda)rdr + 2E\sigma_{ji}N_j\psi(r,\lambda)rdr\Big] \tag{4}$$

The rate equations for the electronic population ion are given by Equation (2) for erbium and by Equation (3) for ytterbium, where ρ_{er} and ρ_{yb} are the dopant concentrations of erbium and ytterbium. These two sets of equations can be solved analytically by putting the time derivatives equal to zero. Stimulated transitions between levels i and j and amplification of light of power P along the fibre coordinate z are given by Equation (4) knowing the cross-sections σ_{ij} of the transitions, the radius r_o of the cylindrical volume where the dopants are uniformly distributed, the energy separation of the electronic levels E, and the normalized mode profile ψ evolving into the fibre. The absorption cross-sections are calculated from the absorption measurement along with the overlap and dopant concentration measurement of the fibre and the emission cross-section are derived using the McCumber relationship[12]. The generation of amplified stimulated emission (ASE) is also included in the model. The pump mode profile is considered uniform in the inner cladding and a LP_{01} mode profile is used for the singlemode propagation in the core. The signs of Equation (4) for propagation are inverted for negative propagation. These equations are implemented numerically and solved using a Runge-Kutta routine for differentiation in the longitudinal propagation and a trapezoidal rule method for integration of the radial mode profile; a relaxation algorithm is used to reach convergence[11].

3.2 Fibre optimization

This model allows to study the impact of the fibre parameters on the output power of erbium ytterbium fibre amplifiers while maintaining a low level of ASE at 1.0 µm. In a double cladding fibre, the geometrical parameters of the core such as numerical aperture does not have a major impact on the output power of the fibre compared to single cladding amplification. The concentration of erbium and ytterbium has to be optimized to get good transfer efficiency from the ytterbium to the erbium ions. As shown in Figure 5 the erbium and ytterbium concentration must be maximized both to prevent the 1.0 µm emission and to optimize the output signal. These results are obtained for an amplifier with 5 mW input signal at 1563 nm pumped in counter-propagation with 25 W at 915 nm. The fibre is a 10um/125um core/cladding diameter and the powers are shown at the optimal length for each given ion concentrations.

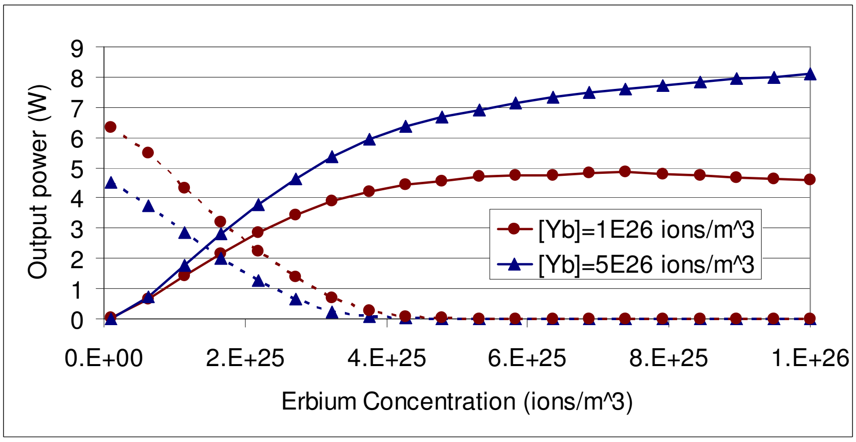

Figure 5. Output signal power (full line) and ASE at 1.0 µm (dashed line) as a function of erbium and ytterbium concentration for an amplifier seeded with 5 mW at 1563 nm and pumped in counter-propagation with 25 W at 915 nm. Two different ytterbium concentrations are used: circle and triangle points represents ytterbium concentration of $1\text{x}10^{26}$ and $5\text{x}10^{26}$ ions/m^3 respectively.

4. EXPERIMENTAL MEASUREMENTS

4.1 Experimental setup

Figure 6 shows the basic amplifier setup developed for the experiment. The fibre used is CorActive Hpa-Ey-10-01, with a 0.17 numerical aperture 10 µm diameter core and a 125 µm diameter cladding. Cladding absorption is 1.5 dB/m at 915 nm. The signal and pump powers are injected in the erbium ytterbium fibre using a multimode pump combiner with a signal feedthrough. Single emitter diodes are used to emit the pump power and a 10 mW distributed feedback (DFB) diode at 1545 nm is used for the signal. When a greater input signal power is needed, a pre-amplifier stage built on CorActive Hpa-Ey-07-02 was done, which is a 7µm /125µm core/cladding diameter erbium ytterbium fibre with 0.17 numerical aperture and a 0.9 dB/m cladding absorption at 915 nm. An isolator is used at the input end of the signal feedthrough and the output fibre is angle cleaved to avoid back reflection. The output is either launched to a thermopile or an optical spectrum analyser (OSA) with proper attenuation. A 1060nm/1550nm multiplexer (WDM) is used at the input to separate the forward injected signal and the backward generated ASE at 1.06 µm. The ASE at 1.06 µm is measured with a power meter.

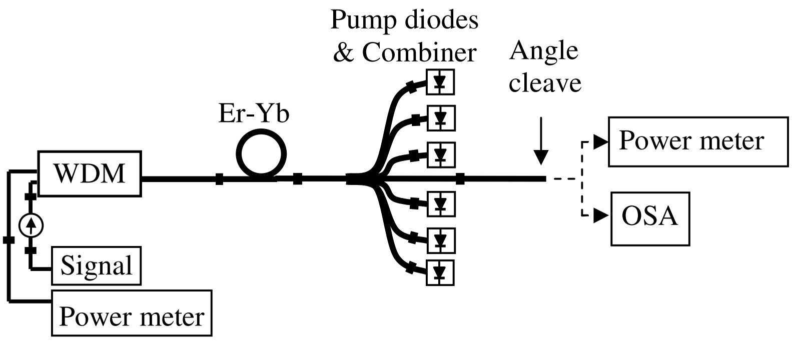

Figure 6. Experimental setup used to conduct counter-propagation amplifier experiment.

4.2 10 W amplifier

An amplifier was realized with the experimental setup described previously. The seed signal at 1563 nm was preamplified to a power level of 1.4 W and launched in the main amplifier consisting of 5.5 m of Hpa-Ey-10-01 fibre. The fibre was pumped in counter-propagation with 6 single emitters at 976 nm providing a total of 38 W of pump power launched in the fibre. Figure 7 shows the output signal power as a function of launched pump power. 10 W output signal was reached with a slope efficiency of 31% with respect to launched pump power. After 35 W of pump power, no more output signal is generated because of the onset of ASE at 1.0 µm, which limits the ultimate power level of the system. ASE at 1.0 µm stays in the mW range and starts to grow dramatically to several watts after the pump power goes beyond 35 W.

Simulations were carried out to evaluate the theoretical output power and are also shown on Figure 7. When considering the temperature effects in the cross-section of the ytterbium as described in Section 2, the model accurately predicts the output power. Without taking into account this thermal effect and using room temperature cross-sections, the onset of ASE at 1.0 µm generation is much lower and limits the possible output power extracted from the amplifier to 5 W. This indeed demonstrates that the temperature increase of the erbium ytterbium fibre has a beneficial impact on the amplifier performance as already discussed in the literature[14].

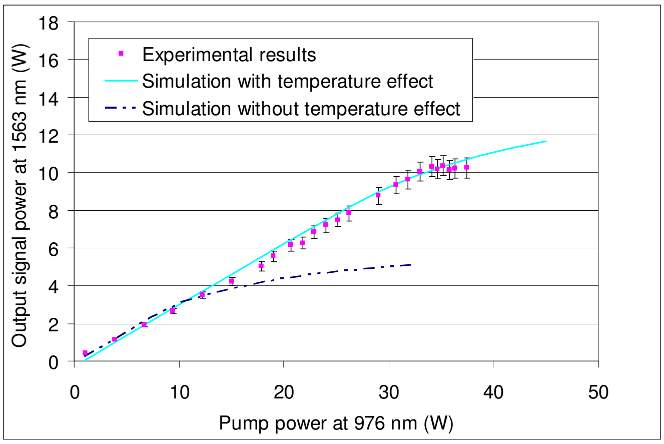

Figure 7. Experimental results of counter-propagation amplifier realized with 5.5 m of Hpa-Ey-10-01 fibre with a seed signal of 1.4 W at 1563 nm. Simulation results are also shown considering or not the temperature increase in the core.

The beam quality of the amplifier was also measured to ensure singlemode operation out of the fibre. This information is also important for the modeling since the theoretical simulation assumes fundamental mode propagation in the fibre. The measured beam waist as a function of position is given on Figure 8. M^2 value of 1.03 is obtained for the fibre. This measurement was performed on the beam exiting the erbium ytterbium fibre that was pumped in co-propagation. A coupling efficiency to Corning® SMF-28 fibre greater than 97% was also observed, which reinforces the singlemode properties of the amplification.

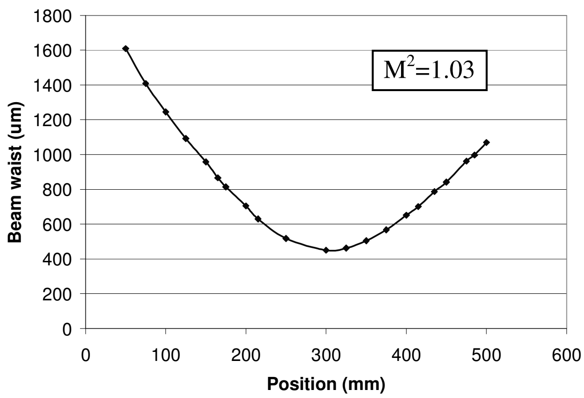

Figure 8. Measured beam waist exiting the erbium ytterbium fibre as a function of the propagation distance. It is consistent with a M^2 value of 1.03

5. CONCLUSION

A singlemode 10 W output power erbium ytterbium amplifier at 1563 nm was realized showing no 1.0 µm ASE using a 10 µm core diameter fibre. This result is believed to be the consequence of beneficial temperature effects taking place in an optimized highly co-doped fibre. An analysis of heat dissipation in the fibre shows an inner core temperature elevation to 85°C that significantly increasing the ytterbium absorption cross-sections around 1060 nm. Taking into account this variation of cross-section into a complete erbium ytterbium theoretical model, an increase in the output signal power from 5 W to 10 W without ASE at 1.0 µm is predicted. This model is also used to optimize the concentration of dopants in the fibre, where it is shown that a high concentration of dopant along with an appropriate ratio of the codopants provides the highest output power without generation of ASE at 1.0 µm.

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