Diode pumped operation of thulium doped fluoride fibre amplifier suitable for first window systems

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A fully connectorised diode laser pumped first window amplifier has been constructed, for the first time, around a thulium doped fluoride fibre. For a 780/806nm combination of pump and signal wavelengths, small signal gains of 25–26dB and gain efficiencies of 2.4dB/mW have been achieved. In addition, output powers approaching +13dBm are possible for a launched pump power of 31mW, which corresponds to a conversion efficiency of around 65%.

Introduction: Commercial exploitation of optical amplifiers for telecommunications applications is now well advanced with the erbium doped silica fibre amplifier at 1.55μm which has been on the market for a couple of years and the praseodymium doped fluoride fibre amplifier at 1.3μm which has just become commercially available. Although much effort has been spent on the related InGaAs component technologies around 1.3 and 1.55μm, historically the 800nm wavelength region covered by silicon is much more mature. As a consequence the related components are available off the shelf in greater quantities and at lower cost [1]. It is conceivable therefore that for a distribution network, with a high component count and a high level of power splitting interspersed by fibre spans of around 2–3km, a first window system employing a thulium doped fluoride fibre amplifier, similar to that described here, could have significant commercial impact.

Experiment: The fibre used for this work was of ZHBLYANLiP composition, with a nominal Tm^{3+} concentration of 1000ppmw. The numerical aperture, NA, and the LP_{11} mode cutoff of the fibre were 0.4 and 750nm, respectively. The background loss was measured using a cutback technique to be 0.15dB/m at 1μm.

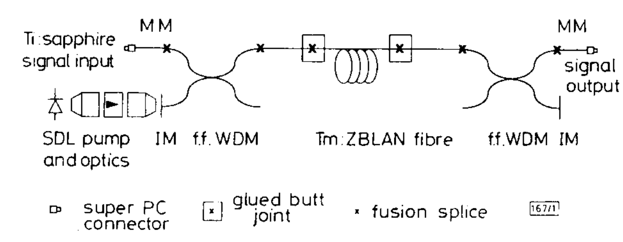

Fig 1 *Experimental configuration for thulium doped fibre amplifier*

The experimental arrangement used to demonstrate amplification in this fibre is illustrated in Fig. 1. Both ends of the doped fibre were carefully cleaved and butt-joined to a high NA silica fibre before being glued in place. Using this technique joint losses of ~0.4dB were obtained. The pump and signal fields were multiplexed into and out of the high NA silica tails by fusion splicing a fused fibre type WDM coupler at each end. These couplers were fabricated to give a minimum insertion loss of <0.5dB for a pump/signal combination of 780 and 815nm, respectively (Sifam model Nos P22SWM780/815). However at 806nm, where most of the measurements were taken, and the amplifier gain peaks, the overall input and output losses were found to be 5.9 and 3.3dB, respectively. The difference between the input and output losses (~3dB) can be attributed to the mismatch in going from a standard telecom pigtail which is multimoded at 800nnm to the WDM fibre which is singlemoded. There is also an excess loss of ~1.3dB at the input and output arising from the WDM couplers which are being used at 806nnm rather than at their specified wavelength of 815nm.

The pump and signal fields were launched copropagating throughout the course of these amplifier experiments. The pump source was provided by an optically isolated 100mW single stripe diode device, and gave a launch efficiency into the doped fibre of

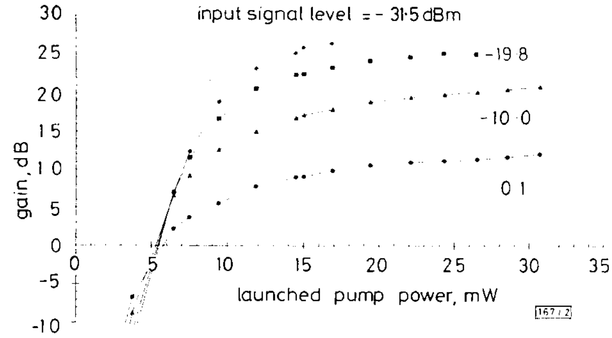

Fig. 2 *Gain against launched pump power, for 9m length of doped fibre, at 806nm for input signal levels of* –*31.5,* –*19.8,* –*10.0, and 0.1dBm*

~35%. The signal source was provided by a Ti:sapphire laser with suitable attenuation of the output. The signal input and output ports were connectorised so that gain measurements could be made with an optical spectrum analyser. To minimise the effect of back reflections both pump ports and the opposite end of the connectorised tail for the signal launch were index matched against 1 mm quartz discs.

Results and discussion: The 800nm amplifier transition in thulium doped fluoride fibre is analogous to that in erbium doped silica fibre at 1.53μm, i.e. it is a quasi-three-level system in which pumping into the short wavelength wing of the $^3H_6$ - $^3F_4$ absorption then leads to emission, on the same transition, down to the ground state at around 805nm. The optimum pump wavelength for this transition occurs at around 780–785nm, where the ratio between the absorption and emission cross-sections reaches a maximum, [2].

Using various doped fibre lengths between 3.5 and 9m a series of gain measurements were made as a function of launched pump power for various input signal levels. Gain was measured under conditions of CW pumping by comparing the signal input level at the input connector with that at the output connector using an optical spectrum analyser. Taking account of signal losses at the input and output the intrinsic gain was determined. For a 3.5m length of fibre 13mW of launched pump power was sufficient to produce a saturated gain of around 16dB for a launched signal power of –27dBm at 805nm. In this case transparency was reached for 2.5mW, and by 3.7mW of launched pump power, the gain had risen to around 9dB indicating a maximum gain efficiency of 2.4dB/mW. However the output characteristic for this length was limited due to the large amount of unabsorbed pump, around 14mW for 31mW launched, emerging from the pump port of the output WDM device. At this point the doped fibre length was increased to ~9m and the gain against launched pump power results were repeated at various signal levels at around 806nm. These results, which are illustrated in Fig. 2, show that for all input signal levels transparency was reached for around 5–6mW of launched pump power, and that for an input signal level of –31 dBm a maximum gain of around 26dB was achieved for 17mW of

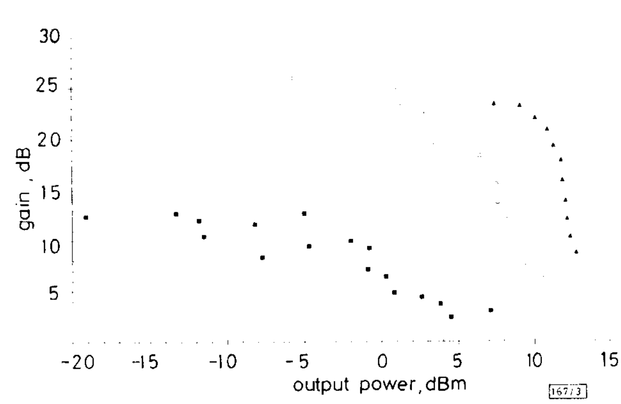

Fig. 3 *Gain against output power for 9m length of doped fibre, at 806nm for launched pump power of 7.5, 15, and 31mW*

■ 7.5mW
○ 15mW
▲ 31mW

launched pump power. However beyond this point oscillation caused by reflection from the output connector prevented any further measurements from being taken. It is also worth noting that for input signal levels of 0dBm more than 10dB of gain was possible for less than 20mW of launched pump power. As further confirmation a series of measurements were taken of gain against output power at three different levels of launched pump power, 7.5, 15 and 31mW, these results are depicted in Fig. 3. As can be seen, gain values ranged from a maximum of 12–13dB for the lowest pump power used to around 25–26dB. The output powers obtained show a similar variation with a maximum of nearly 13 dBm achieved for around 31mW of launched pump power. For each characteristic illustrated in Fig. 3 the conversion of launched pump power to signal output power occurs with an efficiency of ~65%. The theoretical quantum limit, excluding any parasitic effects, should be 97%. Although some upconversion into the visible was observed this effect was so weak that its effect is probably negligible. However it has long been known that ~11% of the population residing in the $^3F_4$ manifold decays through two radiative routes into the $^3H_4$ manifold which has a lifetime of ~7ms, i.e. between 4 and 5 times the $^3F_4$ level lifetime thus a significant fraction of the ground state population could become trapped in this level and therefore be unable to contribute to the signal output. This would be particularly noticeable at high input signal levels when the inversion is being depleted.

Conclusion: Results have been presented, for the first time under diode pumping, of a fully connectorised thulium doped fluoride fibre amplifier. The results indicate that for a 9m length of doped fibre transparency occurs for around 5–6mW and that maximum small signal gains of 25–26dB are possible for relatively modest launched pump power levels of ~20mW. In addition a maximum signal output power of nearly +13dBm was achieved for a signal input power of +4dBm. By going to shorter fibre lengths of ~3.5 m, transparency was achieved for a minimum launched pump power of 2.5mW, and gain efficiencies of 2.4dB/mW were possible.

Although the results reported here are the best ever and clearly demonstrate the strong potential of the 800nm transition in thulium to act as an in-line amplifier, or power booster, for a first window system, there are number of improvements that can still be made; back reflections in particular need to be reduced to at least around –40dB if lasing is to be avoided.

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