20 dB GAIN THULIUM-DOPED FLUOROZIRCONATE FIBRE AMPLIFIER OPERATING AT AROUND 0·8 μm

Indexing terms: Optical fibres, Amplifiers

A thulium-doped fluorozirconate fibre amplifier pumped at 785 nm is described. Amplification is observed from 800 nm to 830 nm, with a small signal gain in excess of 20 dB at 806 nm.

Introduction: To date, most research on optical fibre amplifiers in fluorozirconate glass has been directed towards erbium-doped and neodymium-doped fibres for communications systems operating at 1·53 μm[1] and 1·3 μm,[2] respectively. However, as recently pointed out by Whitley *et al*.,[3] amplifiers operating near 850 nm in the first telecommunications window may also be expected to find applications for short distance distribution and local area networks. The attraction of devices operating in this wavelength region is that the AlGaAs transmitters and silicon receivers required are significantly less expensive than devices operating at longer wavelengths. In a previous letter[4] we have reported the operation of a thulium-doped fluorozirconate fibre laser operating on the $^3F_4$–$^3H_6$ transition producing in excess of 100 mW output at 803 nm when pumped at 780 nm, and have suggested the use of this fibre as an amplifier. Amplification and laser oscillation via this transition was expected to be efficient because of the lack of excited state absorption for both pump and signal, high branching ratio for the $^3F_4$–$^3H_6$ transition,[5] good overlap between pump and signal modes and small energy defect between pump and signal photons. We report results confirming that thulium-doped fluorozirconate fibres offer high gain amplification at signal wavelengths available from AlGaAs diode lasers. Furthermore, we show that efficient AlGaAs diode pumping of these devices should be possible in monomode fibres.

Experimental: The fibre used in these experiments was of the standard fluorozirconate ZBLANP composition and fabricated by a casting technique. The Tm^{3+} concentration was ~500 *ppm* (by weight) with a core diameter of ~10 μm and a numerical aperture 0·15 implying that the fibre was multimode at both pump and signal wavelengths.

The experimental arrangement used for the measurements described in this Letter is shown in Fig. 1. A Ti : sapphire laser operating at 785 nm was used as a pump source to excite ions from the $^3H_6$ ground state to the $^3F_4$ excited state. A second Ti : sapphire laser, the output of which was attenuated by neutral density filters, was used to provide the signal and

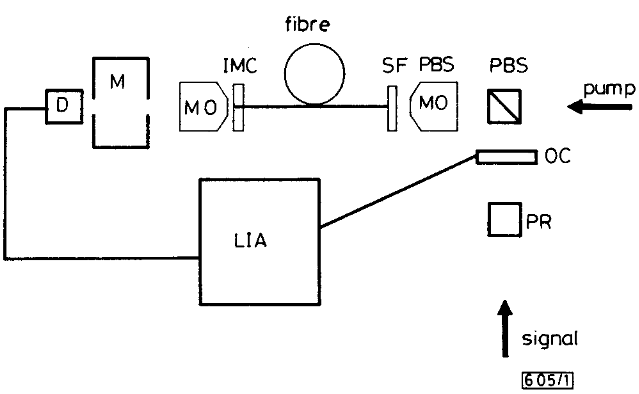

Fig. 1 *Experimental arrangement used for investigating amplification in thulium-doped fluorozirconate fibre*

PR = polarisation rotator
OC = optical chopper
PBS = polarising beam splitter
MO = microscope objective
SF = silica flat
IMC = index matching cell
M = monochromator
D = silicon detector
LIA = lock-in amplifier

was tuned between 800 nm and 830 nm. Pump and signal beams were combined using a polarisation rotator and polarising beam splitter and launched copropagating into the fibre by a × 10 microscope objective. The launch efficiency of pump light into the fibre core was measured to be ~75%. Index matching fluid was used to prevent laser oscillation which otherwise was caused by the Fresnel reflections resulting from the fibre/air interface. At the launch end the fibre was butted against a silica flat and at the output it was inserted into an index matching cell. The signal beam was chopped so that lock-in detection techniques could be used to distinguish the amplified signal from spontaneous emission. The ratio of the detected signal values with the pump beam blocked and unblocked was measured. The host absorption consisting of ground state absorption and a small scattering loss (measured by a cut-back technique) was subtracted from this value to yield the true small signal gain. A signal of ~10 μW was used to determine the small signal gain. Measurements were carried out for a 6·5 m length of fibre. This length was chosen as a compromise between ensuring efficient absorption of the pump light, and minimising signal absorption losses due to the $^3H_6$–$^3F_4$ transition.

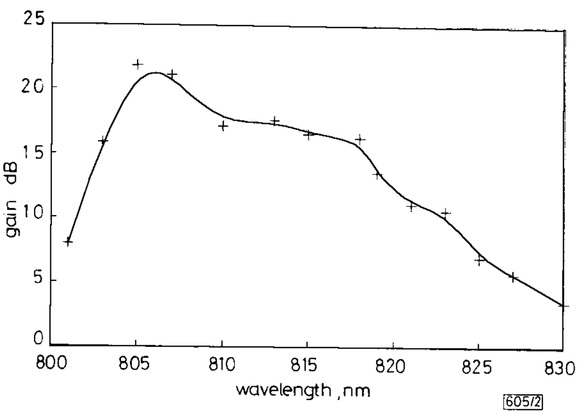

Fig. 2 *Small signal gain as function of signal wavelength for 6·5 m length of thulium-doped fluorozirconate fibre*

Pump wavelength = 785 nm
Launched pump power = 350 mW

A plot of the value of the true small signal gain as a function of signal wavelength is shown in Fig. 2. These data are for a pump wavelength of 785 nm and a power of 500 mW from the Ti : sapphire laser (375 mW launched into the fibre of which ~320 mW was absorbed). It should be noted that the value of gain at each wavelength is subjected to an estimated error of ~±2 dB arising from the determination of the host absorption via the cut back. From Fig. 2 it can be seen that gain was observed between 800 nm and 830 nm, with the peak in the gain spectrum being ~22 dB at 806 nm. This result, together with that reported by Whitley *et al.* for an Er^{3+} amplifier at 850 nm shows that gain from fibre amplifiers is available over most of the wavelength range covered by AlGaAs laser diodes. Incidentally, it should be noted that without index matching the fibre ends, the threshold for laser oscillation was ~300 mW launched pump power. This cavity has a singlepass loss of ~14 dB, and hence this value is in reasonable agreement with the results shown in Fig. 3.

A graph of the small signal gain at 806 nm as a function of pump power is shown in Fig. 3. From this Figure it can be seen that gain only occurs when the launched pump power is greater than ~130 mW. This is a result of the three-level nature of the amplifier transition. Hence for lower pump powers, a shorter length will prove to be optimum and a theoretical model dealing with this aspect will be described elsewhere.* At high levels of pump power gains greater than 20 dB were achieved. This value of gain is clearly useful and is comparable to that demonstrated by Whitley *et al.* for an 801 nm pumped erbium-doped fluorozirconate fibre amplifier operating at around 850 nm.[3]

* CARTER, J. N., SMART, R. G., TROPPER, A. C., HANNA, D. C., CARTER, S. F., and SZEBESTA, D.: 'Theoretical and experimental investigation of a resonantly pumped thulium doped fluorozirconate fibre amplifier at around 810 nm', to be submitted to *J. Lightwave Technol.*

Discussion: The results reported here show that thulium-doped fluorozirconate fibres offer high gains over a wide range of wavelengths near 800 nm. In the present arrangement, the pump power required to achieve high (20 dB) gain is rather high, as a result of the larger than optimum core diameter (10 μm). With a monomode fibre of core diameter $\sim 3\,\mu$m, the pump requirements for producing 20 dB gain should be reduced by an order of magnitude. Because fibres of this core size have already been successfully fabricated in fluorozirconate glass,[6] and singlemode high brightness AlGaAs diodes with 100 mW output power are commercially available, a diode-pumped thulium-doped fluorozirconate fibre amplifier with 20 dB gain near 800 nm now appears feasible. In addition to applications in the telecommunications field, this amplifier may be useful for the amplification of the output of single longitudinal mode or mode-locked AlGaAs laser diodes.

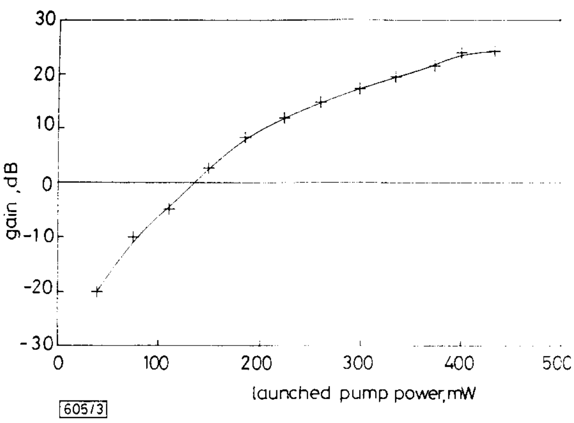

Fig. 3 *Gain/loss at 806 nm as function of launched pump power*

By combining the thulium-doped amplifier described here with an erbium-doped 850 nm amplifier similar to that described by Whitley *et al.* it should be possible to demonstrate gain over the wavelength range 800 nm to 860 nm, and hence cover most of the wavelength range available from AlGaAs diode lasers. Hence it may be possible to construct a very broadband amplifier for local area networks.

Conclusions: We have demonstrated that thulium-doped fluorozirconate fibres offer gain from 800 nm to 830 nm when pumped at 785 nm. Gains in excess of 20 dB have been demonstrated for 350 mW launched pump power in a fibre of 10 μm core diameter. By using a monomode fibre of $\sim 3\,\mu$m diameter it should be possible to demonstrate high gains with AlGaAs diode laser pumping. Further characterisation of this amplifier with regard to signal saturation and the dependence of gain with pump wavelength will be published elsewhere* together with a comprehensive model which gives a full quantitative description of the behaviour of this amplifier.

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References

1 MILLAR, C. A., and FRANCE, P. W.: 'Diode-laser pumped erbium-doped fluorozirconate fibre amplifier for the 1530 nm communications window', *Electron. Lett.*, 1990, **26**, pp. 634–635

2 PEDERSEN, J. E., BRIERLEY, M. C., CARTER, S. F., and FRANCE, P. W.: 'Amplification in the 1300 nm telecommunications window in an Nd-doped fluoride fibre', *Electron. Lett.*, 1990, **26**, pp. 329–330

3 WHITLEY, T. J., MILLAR, C. A., BRIERLEY, M. C., and CARTER, S. F.: '23 dB gain up-conversion pumped doped fibre amplifier operating at 850 nm', *Electron. Lett.*, 1991, **27**, pp. 184–186

4 CARTER, J. N., SMART, R. G., HANNA, D. C., and TROPPER, A. C.: 'Lasing and amplification in the 0·8 μm region in thulium-doped fluorozirconate fibres', *Electron. Lett.*, 1990, **26**, pp. 1759–1761

5 SMART, R. G., CARTER, J. N., TROPPER, A. C., and HANNA, D. C.: 'Continuous-wave oscillation of Tm^{3+}-doped fluorozirconate fibre lasers operating at around 1·47 μm, 1·9 μm and 2·3 μm when pumped at 790 nm', to be published in *Opt. Commun.*, 1991

6 ALLAIN, J. Y., MONERIE, M., and POIGNANT, H.: 'Room temperature CW tunable green upconversion holmium fibre laser', *Electron. Lett.*, 1990, **26**, pp. 261–262