VERSATILE INFRARED LASER SOURCE FOR LOW-COST ANALYSIS OF GAS EMISSIONS

DELIVERABLE D1.3

Thulium-doped fibres

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1. INTRODUCTION

The fibre design is a very important element in the overall Tm source design. There are a number of different options for the Tm source design and the fibre parameters must be tailored to satisfy the demands of the particular source architecture chosen. Our strategy was to minimise the number of gain elements to maximise the overall efficiency and reduce complexity. This is also important because of the lack of low-cost and low-loss fibre pigtailed components in the ~ 2 micron wavelength regime. Thus, scaling the output power from the DFB laser to reduce the number of fibre amplifier stages needed is a crucial element of this approach. Much of our fibre development work has focussed on addressing this requirement, since the Tm fibres required for the amplifier stages are much simpler to design and fabricate. The Tm fibre for the DFB lasers must be highly photosensitive to allow UV writing of the DFB structure and must have a relatively high Tm concentration so that pump light can be absorbed within the short length of fibre (5 – 8 cm) used for the DFB laser. A further requirement is that the fibre should be polarisation-maintaining to allow selection of a single (linearly-polarised) mode. This is also important for the amplifier fibre to preserve the linearly-polarised output as required for the nonlinear frequency conversion stage that follows the Tm source.

2. THULIUM-DOPED FIBRES FOR HIGH-POWER DFB LASERS

Tm-doped silica has a strong absorption band in the ~1.5-1.7µm regime which allows direct (in-band) pumping by a high-brightness Er,Yb cladding-pumped fibre laser. This results in very low quantum defect heating in the Tm fibre allowing a relatively high power pump source to be used, and allows the use of very short device lengths. All of the Tm fibres used in the Village project to date have been fabricated using the ORC's fibre fabrication facility. A number of fibre preforms and fibres have been fabricated and evaluated to allow further optimisation of the fibre design and core composition. The fibre design used in our best performing DFB fibre lasers to date has a Tm and Ge co-doped alumino-silicate core of diameter, 10µm and numerical aperture (NA), 0.17, surrounded by a pure silica inner-cladding of diameter, 125 µm. Germanium was also added to the core to produce the required photosensitivity for writing of in-fibre Bragg gratings. A relatively high Tm concentration of approximately 1% (by weight) was chosen to yield a very high pump absorption coefficient (~110dB/m) for pump light at 1565 nm and hence allow for short device lengths for core-pumped laser configurations. In contrast to conventional core-pumped fibres, the silica inner-cladding was coated with a low refractive index (n=1.375) outer-cladding so that any stray pump light not coupled into the core would be guided in the inner-cladding minimising the risk of damage at the relatively high power levels used in this work.

This fibre was initially tested in a simple, free-running laser configuration (as shown in figure 1) with pump light provided by a 10 W Er,Yb fibre laser at 1565nm and yielded 4.9 W of output at 1880-1885 nm for ~ 6.8W of absorbed pump power. The slope efficiency with respect to absorbed pump power (~78%) was very close to the theoretical limit of 83% confirming the spectroscopic properties of the core were not adversely affected by the high doping levels used. This fibre has also been used in the Tm DFB laser and MOPA configurations that have been delivered to HHUD (i.e. deliverables D1.1 and D1.2). Using this fibre we have successfully scaled the output power from a Tm-doped DFB laser (see figure 2) to a world-record power level of 900 mW. However, the photosensitivity (Δn) of this fibre is only ~ 5×10^{-5} and hence is on the lower limit of what is generally needed for a DFB fibre laser. Further preforms with higher germanium doping levels have been fabricated in an attempt to increase the photosensitivity, but with marginal success. Thus, the development of Tm fibres with enhanced photosensitivity remains as an ongoing activity.

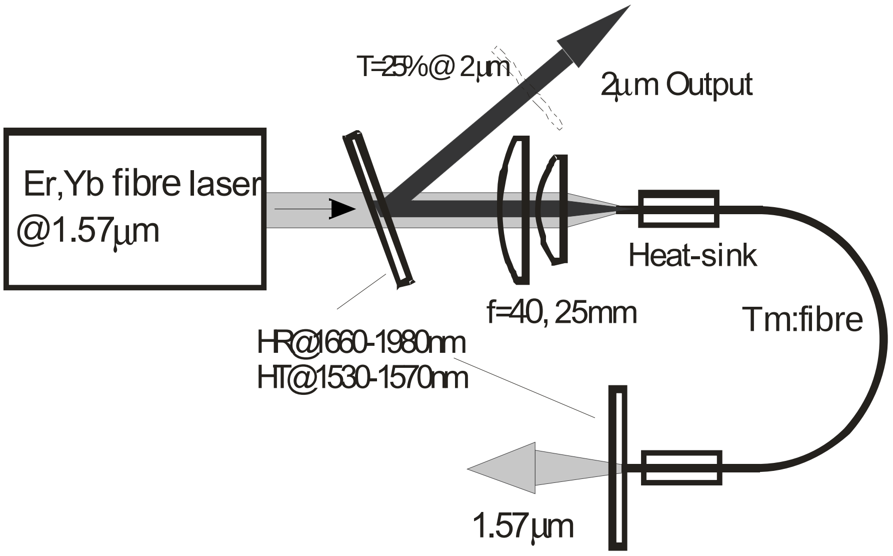

Figure 1: Free-running Tm fibre laser.

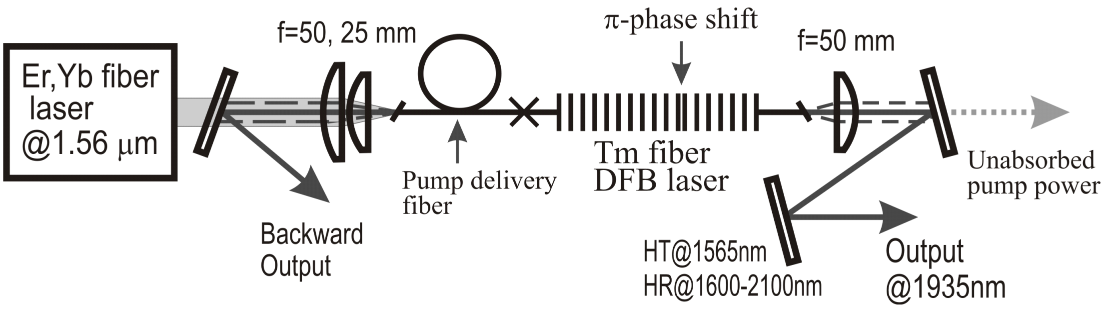

Figure 2: Tm DFB laser set-up.

3. POLARISATION-MAINTAINING THULIUM-DOPED

The Tm-doped DFB fibre lasers demonstrated so far have all operated on two orthogonally-polarised modes with a frequency spacing of ~600MHz determined by residual birefringence in the fibre. Only one of these modes can be used due to the linewidth constraint set by the final application. Thus, one mode is removed by a polariser prior to entering the power amplifier stage. This leads to a reduction in overall efficiency. However, a more serious problem is the output power fluctuation (for a given mode) that results from mode competition. This can be reduced by starting with a lower power DFB laser and extracting more power from the amplifier stages. However, a more elegant solution is to force the DFB laser to oscillate on a single (linearly-polarised) mode.

This requires polarization-maintaining (PM) Tm-fibre. PM fibres are more difficult to fabricate than conventional fibres since the boron-doped stress rods used produce the birefringence required are prone to shattering. Thus, a great deal of extra care is needed when fabricating PM fibres and the success rate is somewhat lower than for conventional (non-PM) fibres.

Figure 3 shows the PM fibre fabricated to explore the possibility of a truly single-frequency fibre DFB laser. A PANDA design was employed with dimensions as shown and using similar Tm and Ge co-doping parameters as for the non-PM fibre described in the previous. The birefringence of the fabricated PM fibre was measured to be ~1.6×10^{-4}. The fibre was originally designed to have a birefringence of ~3.0×10^{-4} but, due to a problem encountered with shattering of the boron-doped stress-rods when these were being etched, the distance from the centre of the fibre-core was increased to ~4a, which resulted in the slightly reduced value of the birefringence. Since the new PM Tm-fibre had a similar level of germanium in the core, the photosensitivity was also similar and hence it was possible to generate a similar level of index modulation to form Bragg gratings in the fibre. As a result DFB lasers of similar grating design could be fabricated in this PM fibre. As shown in figure 4, two polarization modes still exist in this PM fibre laser output despite the increased birefringence. This is attributed to the relatively low level of photosensitivity of the fibre which despite the enhanced birefringence still does not allow for a sufficient difference in the grating strength between the slow and fast axis of the fibre to be formed. Future fabrication effort on PM Tm fibres will therefore concentrate as its first priority on enhancing the photosensitivity through an increase of the Ge concentration in the fibre.

A distinct difference between the frequency spectrum of the PM and non-PM fibre DFB laser is the frequency spacing of their two oscillation modes. For the non-PM DFB fibre laser the mode spacing was typically ~ 600 MHz, while for the PM DFB fibre laser the mode spacing (shown in figure 4) was much larger and determined directly by the higher birefringence of this fibre. By use of an optical spectrum analyzer, the wavelength spacing between the two oscillation modes in this PM fibre DFB laser was measured to be ~0.19nm (~15GHz) (see figure 5). A potential advantage of DFB lasers with PM fibre over that with non-PM fibre is that the competition between the two polarization modes will be relatively weaker, and as a result, the power stability of a single polarization is significantly better.

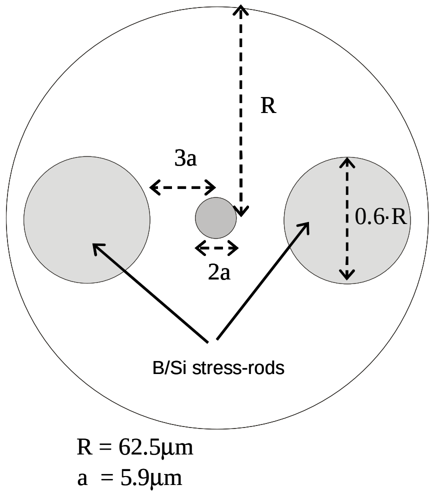

Figure 3: Polarisation-maintaining Tm fibre design.

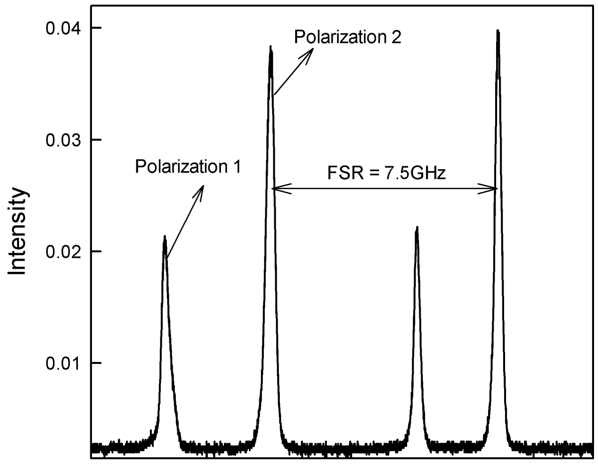

Figure 4: Scanning Fabry-Perot interferometer trace of PM fibre DFB laser output.

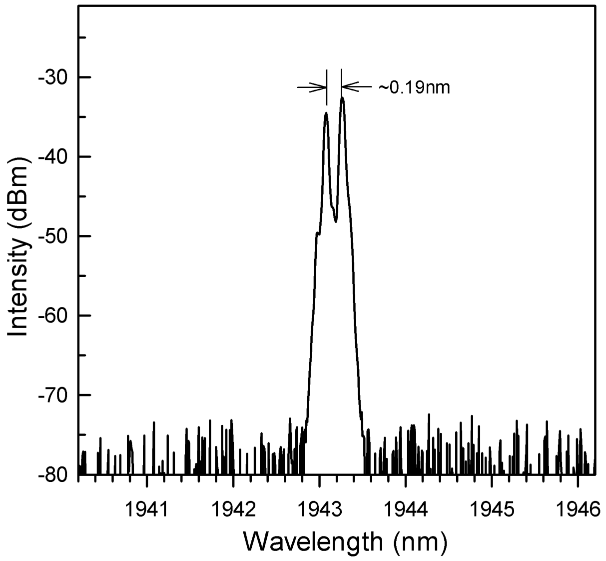

Figure 5: Optical spectrum of the PM fibre DFB laser output.

4. FUTURE FIBRE DEVELOPMENT WORK

The Tm fibres fabricated so far during this project have allowed impressive levels of performance to be achieved in terms of output power and efficiency from both DFB laser configurations and amplifiers. Nevertheless, there still remain a number of issues relating to single (linearly-polarised) mode selection and the impact of thermal loading on wavelength tuning which need to be solved to bring the Tm laser source operating characteristics in-line with the requirements for the intended application. Thus, the remaining fabrication effort will focus on developing PM Tm fibres with enhanced photosensitivity, higher birefringence and reduced thermal loading density. This will involve the fabrication of a number of new preforms with lower Tm doping concentration to reduce the thermal loading density and higher germanium concentration to increase photosensitivity, and then, following optimisation of the core design, polarisation-maintaining fibres will be fabricated to facilitate selection of a single (linearly-polarised) mode in the DFB laser and linearly-polarised propagation in the amplifier stages.