Two Micron Tm Doped ZBLAN Double Clad Fibre Laser

By
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Declaration of Authorship

I, Md. Samiul Islam Sarker certify that this work contains no material which has been accepted for the award of any other degree or diploma in any other university or other tertiary institution and, to the best of my knowledge and belief contains no material previously published or written by another person, except where due reference has been made in the text.

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To My Parents

Abstract

Tm:ZBLAN fibre lasers have potential applications in many research areas, such as eye safe range detection, medical science and materials processing. In this thesis we investigate improving the laser performance of a thulium doped fluoride fibre (specifically ZBLAN) to generate laser output with wavelengths near 2 µm. Two approaches are demonstrated to investigate laser performance at 2 µm. One is 790 nm pumping in which the cross-relaxation mechanism is used for efficient operation by populating the upper laser level. Another is in-band pumping, where 1570 nm light is directly pumps the emitting laser level, reducing the quantum defect between the pump and lasing wavelengths, reducing the threshold and increasing the efficiency of the fibre laser. Tm:ZBLAN fibres fabricated in-house, we also characterized with the aim of processing towards the development of new classes of fibre laser.

A Tm:ZBLAN double clad fibre laser operating at 1.96 µm is demonstrated with a 1.53 W maximum output power and slope efficiency of 45% with respect to the launch pump power. Thereafter, the laser performance is analysed using cavity mirrors of various reflectivities.

A laser with an operating wavelength of 1.57 µm is demonstrated with 1 watt output power using an Er:Yb co-doped double clad fibre. The slope efficiency of this laser is measured to be 28.3% with respect to the diode pump power, with a measured beam quality (M^2) of 1.3. This 1.57 µm in-band pump source is then used to pump the 2 µm Tm:ZBLAN fibre laser.

In addition to the laser development, this thesis also analyses the pump absorption for different shaped double clad fibres numerically. Understanding of pump absorption is required to develop an efficient double clad fibre laser. The pump absorption is measured using cut-back method and compared with the modeled results.

Motivation and Thesis Outline

Thulium doped fibre lasers at 2 μm can be developed either using Tm:Silica or Tm:ZBLAN fibre. There have also been 2 μm lasers in other materials including tellurite [29]. The higher phonon energy of Tm:Silica ~1000 cm-^{1} limits the infrared transmission up to 2.2 μm. On the other hand ZBLAN is a heavy metal fluoride glass that offers a mid-infrared transparency out to 6 μm due its lower phonon energy of ~500 cm^{-1}. Singly charged fluoride ion and weaker bond strength of ZBLAN glass leads to greater mid-infrared transparency. Lower phonon energy and lower background loss around 2 μm of thulium fluoride fibre makes it is a suitable host material for an efficient operation of fibre laser at around 2 μm.

ZBLAN is therefore a promising glass material for the development of fibre lasers at 2 μm and in other infrared wavelengths. A thulium ion is chosen as a rare earth dopant due to the fact that, when using high thulium concentrations, cross-relaxation processes lead to highly efficient lasing at around 2 μm. As a result, Tm:ZBLAN fibre is considered for the development of the 2 μm laser in this research.

In band pumping approach is focused in this thesis due to the fact that laser active ions are pumped directly to the upper laser level from ground state. Using in-band pumping it is therefore possible to improve slope efficiency and threshold pump power by reducing quantum defects. To date the highest output power reported for a Tm:ZBLAN fibre laser at ~2 μm is only 53 mW [4], using in-band pumping, but had record slope efficiency of 74%. This low output power was believed to due to the unavailability of ~1.6 μm pump sources with sufficient power. It is now possible to develop a ~1.6 μm source with very good beam quality by using commercial components. Good beam quality source offers the potential to pump directly into the core of a Tm:ZBLAN double clad fibre and develop higher output powers at ~ 2 μm than before. The content of this thesis are:

Chapter 1: Chapter 1 contains a general overview of fibre lasers. The importance of thulium fibre laser operating around 2 μm and their applications. The importance of in-band pumping for the development of 2 μm Tm:ZBLAN fibre laser as well as review for the development of ~1.6 μm Er:Yb sources for in-band pumping are also summarised. In addition to the literature review, the author provides his own insights and deeper explanation of these systems.

Chapter 2: The introduction of this Chapter describes the motivation for conducting the pump absorption calculation of a double clad fibre. The result of the simulation for different outer cladding shapes of Tm:ZBLAN double clad fibre are provided along with impact of offsetting core and varying the core diameter. Apart from this a pump absorption measurement of Tm:ZBLAN double clad fibre using cut-back technique is compared to the modeled result.

Chapter 3: This chapter comprises three sections. The first section is about the experimental demonstration of ~2 µm 790 nm pumping Tm:ZBLAN fibre laser, results and discussions. It also includes the characterization of homemade Tm:ZBLAN double clad fibre. Second section is about the development of Er:Yb in-band pump source at 1.57 µm, where high reflective Fibre Bragg grating (FBG) and 4% Fresnel reflection formed the resonator cavity including a critical discussion. The third section represents the in-band pumping approach i.e. towards the development of an in-band pumped Tm:ZBLAN fibre laser.

Chapter 4: This chapter concludes the thesis with a general discussion and a description of possible promising future work.

List of Publications

Conference paper

H. Ebendorff-Heidepriem, D.G. Lancaster, K. Kuan, R.C. Moore, M.S.I. Sarker, T.M. Monro, "Extruded fluoride fiber for 2.3µm laser application", accepted for oral presentation at CLEO PACRIM, 2011.

Acknowledgements

I would like to express gratitude from the very core of my heart to my supervisor Prof. Tanya Monro for giving opportunity to perform this research in a world class research environment. Her direction and guidance helps me to learn many things which were very essential for me. This research would not be possible to finish without her constant support and co-operation.

I also want to express my cordial gratitude to my co supervisor Associate Prof. David G. Lancaster. I discussed about many valuable things with him and got ideas to perform the experiment.

I would also like to thank to the rest of Institute for Photonics & Advanced Sensing (IPAS) people specially Heike Ebendorff-Heidepriem, Ori Henderson-Sapir, Michael Oermann, Richard White, Matt Henderson, H. Tilanka Munasinghe, Krishtopher Rowland, Sebastian Ng, and Chris Kalnins. They helped me in different ways and I am really grateful to them all.

I would like to acknowledge Dr. Ioannis Dritas, School of Engineering & Mathematical Science, City University London, who provide me the simulation code for calculation of pump absorption of a double clad fibre. I am very grateful to him for his kind cooperation.

Thanks also Dr Selim Mahbub for his support during the time I stayed in Adelaide.

Finally but most importantly, I would like to thank my wife Saki Farhana Noor for her support, encouragement and willingly offered sacrifice during the time I spent in Adelaide.

Contents

Chapter1. Literature Review

Chapter 2. Double Clad Fibre: Comparison of Predicted and Measured Pump Absorption

Chapter 3. Development of 2 μm Tm:ZBLAN Fibre Laser

<u>Amendment of thesis</u>

This document provides the answer on comments of referee 1 and referee 2.

Answer on comments of referee 1

Chapter 1

Section 1.3

- The near-IR spectral region, i.e. from 1.4 to 1.8 μm is called eye safe region, where optical absorption by water in the eye prevents power from reaching to the retina.
- For cross relaxation and resonant pumping process reference diagram has given. Energy level diagram for resonant pumping process has moved earlier in the chapter.

Section 1.3.1

- Suitable plot for tuning range of Tm fibre laser has been added.
- Reference has given to the 1^{st} sentence of last paragraph.

Section 1.5

- Figure 1.4 (b) is fixed as a rectangular inner cladding.

Section 1.6

- Corrected sentence is: Single mode guidance can be done either by increasing the core diameter or by decreasing the numerical aperture (NA) at a certain V value.
- Corrected sentence is: For a multimode fibre the intensity distribution function often approximated as a top-hat function of radius a, with uniform intensity distribution along the core of the fibre.

Section 1.8

- Energy level diagrams have given to the first paragraph.
- In 1998, when diode pump power began to available, a 5.4 W output power was achieved from a double clad fibre laser at wavelength near 2 μm.
- References added to the last sentence.

Section 1.9

- Dichroic mirror act as an input coupler for pump light in Fig 1.7(a).

Section 1.11

- Corrected sentence is: The energy transfers for laser materials are mainly through radiative and nonradiative process. In case of radiative energy transfer process, the emission of photon by one ion causes the absorption of that photon by another ion.

Section 1.12

- Corrected sentence is: The short-infrared wavelength range effectively covered by Tm^{3+} doped lasers can pump directly with ~800 nm diodes.
- Moreover, it also observed from Figure 1.11 and 1.12 that the absorption wavelength range spanning from ~1550 nm to ~1850 nm, which is near to laser emitting wavelength at ~ 2 µm.
- Corrected sentence is: A smaller efficiency of the cross relaxation process has the effect of raising the laser threshold
- The $^3F_4$ lifetime is shortened through multiphonon decay. This shortening the life time of the $^3F_4$ manifold due to multiphonon decay will reduce the $^3F_4 \rightarrow {}^3H_6$ quantum efficiency. The lower quantum efficiency would reduce the slope efficiency.

Section 1.14

- Corrected sentence is: The effective absorption coefficient for pump light launched into the cladding of Er:Yb fibre as a function of pump wavelength is shown in Figure 1.18. In this case the core diameter of an Er:Yb fibre was 30 µm having numerical aperture 0.22 and the core was surrounded by a pure silica D-shaped inner-cladding of 400 µm diameter (~360 µm along the short axis) and the numerical aperture was 0.4. The doping concentration to the core of Er:Yb fibre was respectively Yb^{3+} ion (~8.7×10^{20} cm^{-3}) and Er^{3+} ion (~5.1×10^{19} cm^{-3}).

Chapter 2

Section 2.1

- The first paragraph has deleted as it was repetition of material in Chapter 1.
- For consistency "outer core" replaced as "inner cladding" in everywhere.
- Corrected sentence is: For small inner cladding area, fibre losses are reduced at laser wavelength due to the reduction of absorption length.
- Corrected sentence is: The core area and numerical aperture should be high enough to allow a high absorption efficiency of pump power in the single mode core as well as be able to excite single mode oscillation at laser wavelength.

Section 2.2

- Corrected sentence is: A beam propagation method (BPM) can be approximated by the effective index method to reduce a 3D problem to a 2D one, and still it suffers from the need to discretize paraxial wave equation throughout dense grids over realistic propagation distances, especially when large and complex geometries are involved.
- Corrected sentence is: They have demonstrated that the absorption is influenced by the bend radius for circular fibre, but in fibre design with offset core and rectangular inner cladding the bend effect is negligible.

Section 2.3 (model verification) now in Appendix

- Model verification has moved to appendix (as with other referee comments). In model verification 1000 container used.
- Corrected sentence is: Pump absorption for circular shape becomes saturated with increasing fibre length due to the non absorption of skew rays.
- Figure 2.1 now becomes Figure A1: the caption changed to square shape

Section 2.4 is now 2.3

- Corrected sentence is: The interface between inner and outer cladding is an ideal surface, has no reflective aberration and uniform step refractive index distribution. Under these conditions the propagated rays in model strictly follow the geometrical optics domain. Regarding the geometrical boundary condition, it is also assumed that there are no losses when a pump ray is scattered by a dielectric interface and that during total internal reflection the refracted energy is negligible compare to the reflected energy when refraction takes place [92]. Moreover, it is assumed that all rays propagate in the fibres are independent of each other and have no mode coupling.

Section 2.4.1 now 2.4

- Corrected sentence is: The incident points i.e. the spot centre of incident pump photons are generated on to equally distant co eccentric circumferences (see Figure 2.1) which are centred on the fibre axis and cover a circular area defined by the pump delivering core.
- Corrected sentence is: The incident points are shown Figure 2.1(previously it was Figure 2.2) as blue star marks at the input end of the fibe.
- Figure 2.3 now becomes 2.2 and axes labels have fixed.
- Figure 2.3 caption also changed to become understandable.

Section 2.5

- ρ is density of ions and recalculated after each time step.
- Model verification part transferred to the Appendix section.

Section 2.6

- Concentration is fixed as 20000 ppm by weight.
- Figure 2.5 is now as 2.4 and explanation as follows:

  It is observed in Figure 2.4 (a), that the magnitude of core optical path for circular inner cladding is levelled around 0.6 mm, also shows the wider groups of bars and bigger valleys observed in the patterns of optical paths when it compared to Figure 2.4(b). This pattern supports that for circular inner cladding there is a strong overlap between core volume and meridional rays. On the other hand in figure 2.4 (b) the magnitude of core optical path in square shape cross-section is levelled at around 0.5 mm and more noisy bar groups emerging above the base line. Therefore, the propagation of skew rays contributes more strongly in parallelogram shape. Moreover, in case of circular inner cladding, it is observed in Figure 2.4(a) that longer ray paths are recorded inside the core containers, they correspond mainly to a small population of meridional lines which become completely absorbed during the first few tens of centimetres. In case of square inner cladding Figure 2.4(b), the total ray spatial paths are generally shorter inside each container but they represent the contribution of a larger population of rays more sporadically interacting with the core volume and thus being able to transfer their energy along longer propagation lengths.

- Chaotically propagated rays changes to skew rays.
- For circular shape, the pump absorption tends to saturation along with the increasing of length. At the beginning the absorption increases with length sharply. After a certain distance the increasing becomes smaller and smaller due to the non-absorbtion of skew rays to the core of a fibre.

Section 2.6.2

- Figure 2.8(d) now as 2.7(d): The horizontal axis as well as legend has been fixed.

Section 2.7

- "In conclusion" changes to appropriate word.
- Corrected sentence is: The presence of higher order modes lead to degradation in the output beam quality, but most of the application requires diffraction limited beam quality.

Section 2.8.1 is now as A2 in Appendix

- "100 μm" is a core diameter of a fibre
- In Figure A2 the units of efficiency η corrected as W/A
- Table is deleted according to other referee comments and also standard deviation is omitted from the graph as the fluctuations are mostly due to a drift rather than normally distributed random fluctuations

Section 2.8.2 is now 2.8.1

- The pump light coupled from the patch fibre to Tm:ZBLAN fibre using the optical system in section A2.

- Corrected sentence is: The cleaving ends have been tested every time by placing fibre ends under microscope throughout the experiment to ensure the nice cleaving end.
- $P_p(Z_o)$ is defined for $A(Z_i)$ as: $P_p(Z_o)$ is pump power measured for smallest fibre length Zo, very close to the input end of the fibre.
- Corrected sentence is: In an optically active fibre the pump wave absorption rate at a certain point depends on the local population inversion and consequently on the local flurescence. However, to avoid the flurescence effect, the launched power should be kept resonably low so that the population inversion remains negligible.
- The label on vertical axis of Figure 2.12 is now 2.9 changes to 10log10(P).

Section 2.9

- Absorption efficiency is calculated as follows:
  Firstly, cutback data is fitted and extrapolated to zero length of a fibre, which gives the launch pump power at input end. Therefore, with the help of launch pump input and the transmitted output for every cutback length, absorption efficiency is calculated.
- Further explanation of model calculation differ from experimental valuesas follows: There might be two other possibilities to differ experimental result from model calculation. Firstly in model calculation effect of fibre bending was not considered for pump absorption calculation. Secondly for cut-back measurement we measured absorption at 10 metre and below 1 metre length only. For more accuracy of measurement it could be performed the cut back experiment repeatedly througout the whole length of fibre. But we had limited length of commercial fibre and also needed to perform fibre laser experiment.

Chapter 3

Section 3.1.2

- As it is evident from the microscopic view of the end facet of the fibre that the fibre is 5 μm offset. Considering that we used pump absorption 0.76 dB/m (measured for 10 m length of fibre) to calculate the pump absorption for 5 m fibre.

- Explanation for launch efficiency measurement: After collimating and focusing, 790 nm light has been coupled to Tm:ZBLAN fibre and optimised for maximum coupling. After optimisation output power is recorded. Therefore the launch efficiency to the fibre was calculated by measuring the difference of input power and transmitted output power with power absorbed to the fibre, which is 92%. It is noted that absorbed power is calculated by using cut-back absorption.
- Output coupler having 0% reflectivity at 2000 nm butted to the output end of fibre to examine fibre laser spectrum at ~2 μm laser. It is noted that we didn't used any index matching gel to mitigate against Fresnel reflection.

Section 3.1.3

- Figures are rearranged
- The figure 3.2 (a) for 0% reflective output coupler. The data showed in table 3.2 but all the data tables have been deleted according to other referee comments.
- Resonator layout has explained.
- In initial configuration 4% Fresnel reflection used to form the resonator. For 0% reflective output coupler, mirror butted to the output end.
- Here forward direction refers to the increment of input power from zero to maximum value used in this experiment and backward direction refers to the decrement of input power started from forward directions maximum value.
- Corrected sentence is: Further scaling the output is possible by increasing the launch pump power as well as by maintaining proper cooling system to protect from thermal damage of the fibre.

Section 3.1.5.1 is now 3.1.5.2

- Fibre fabrication section is now as 3.1.5.1
- To increase the core refractive index of ZBLAN fibre part of BaF_2 replaced with the PbF_2.

Section 3.1.5.2 is now 3.1.5.3

- The variation of NA values might be due the defect of interface between core and cladding.

- Assuming a refractive index of Tm:ZBLAN glass 1.495 at 790 nm, the core refractive index is 1.4954 ± 0.0001,
- Δn, the index difference between core and cladding is 0.0004 ± 0.0001.

Section 3.1.5.3 is now 3.1.5.1

Section 3.1.5.5

- To reduce the loss of the fibre the outer and inner surface of the tube should be etched prior to fibre drawing to achieve a pristine surface. A defect free interface between the core and cladding glass is prerequisite to achieve low fibre loss. Therefore future work will focus on further reducing the fibre loss through optimization of fibre drawing conditions and demonstration of lasing at 2.3 μm.

Section 3.2.5 is now 3.2.4

- Corrected sentence is: By pressing the fusion button fibre becomes spliced and the splicing loss was observed 0.02 dB in Ericsson splicer.
- A pump mirror which has HR (900-990 nm) >99.9% and HT (1500-1650 nm) >98% butted to the rear side of the fibre to separate the lasing signal from pump laser wavelength.

Section 3.2.6 is now 3.2.5

- Corrected sentence is: To verify the accuracy of measurement of a monochromator it was calibrated for 2nd order wavelength using HeNe source.
- Table 3.8 has deleted according to other referee comment.
- The length of the fibre was 3.85 m for 1570 nm laser output.

Section 3.2.7 is now 3.2.6

- “xx” software changes to LabVIEW software.

Section 3.2.8 is now 3.2.7

- For core pumping approach absorption coefficient is very high. Therefore relatively short length of fibre can be used to form the fibre resonator. That's why we chose double clad fibre in our case.

Section 3.3.1

- Reference has given for 2nd sentence of 2nd paragraph.
- Laser reported by [63] now becomes [2] was single mode.

Section 3.3.2

- First the absorption is calculated at 1570 nm from absorption spectra (chapter 1 Fig. 1.11) of a Tm doped ZBLAN glass. As the graph was given absorption (cm^{-1}) as a function wavelength, so the absorption (cm-^{1}) at 1570 nm was calculated by deducing the value from base line to 1570 nm. Therefore, the absorption coefficient at 1570 nm becomes 0.03 cm^{-1} and the corresponding absorption is 0.13 dB/cm. The data in Table 3.10 was calculated using Beer Lamberts law(data is deleted now).

Section 3.3.3

- Initially 1570 nm light is collimated and focused using 18.4 mm and 15.29 mm aspheric lenses to coupled the light to the core of a Tm:ZBLAN fibre . As the light was not coupled to the core, therefore 4.5 and 4.51 mm aspheric lenses used to collimate and focus the light to the core of a Tm:ZBLAN fibre.
- The length of fibre 30cm chosen and the absorption at 1570 nm is 60.84% as evident from figure 3.19.

Section 3.3.4.1

- Schematic figure is added to understand the knife edge measurement. 15.29 mm lens was the same as used in section 3.3.3
- Corrected sentence is: the beam cut into micron distance along the x direction as shown in figure 3.21
- The number of significant figures in the spot size in Figure 3.22(a) has changed.
- The explanation for overfilling the beam as follows:

The table below provides the relative picture of beam diameter for different lenses used to collimate and focus 1570 nm light. The diameter of a beam is calculated using the relation, Beam diameter=2*E.F.L*NA, where, E.F.L is the effective focal length of a lens and NA is the numerical aperture of the source

Table 3.2. Calculation of a beam diameter of a beam coming out from 6 µm core having NA 0.18 of Er:Yb fibre

Focal length (mm)	NA of lens	Acceptance angle(deg)	Diametre of a lens(mm)	Beam diameter(mm)
4.50	0.42	24.83	3.70	1.62
4.51	0.54	32.68	4.95	1.62
15.29	0.16	18.41	5.0	5.50
18.4	0.15	17.25	5.5	6.62

It is clear from above calculation that the beam is overfilling for longer focal length lens. Therefore the next step was to use shorter aspherics to collimate and focus the light into the core and to measure the core absorption using cut-back method.

- Due to the shortage of time knife edge spot size measurement for shorter aspherics did not perform.
- As Er:Yb fibre laser output offers very good beam quality, which is suitable for core pumping. Moreover for high absorption coefficient shorter length of fibre needed for fibre laser experiment. Therefore, we chose core pumping approach although the fibre is double clad.

Section 3.3.4.2

- Careful adjustment was required to couple the pump light to the core.
- To measure the core absorption of pump light, initially output power was recorded when light was not coupled to the core. Then, light into the core has been ascertained through optimisation and by observing the fluorescence through IR viewer. After observing the light coupled into the core, it has been optimised and input end of the fibre kept unchanged. A power metre head was fixed in position and the transmitted output was recorded for every cut-back measurement. As the transmitted output is composed of core and cladding light, therefore the core absorption for every cutback

is considered here as the difference between the output power when pump light coupled only to the cladding and when coupled both to the core and cladding. Symbolically one can write core absorption = $P_{inner\ cladding}$ - $P_{core\ \&\ innercladding}$. Where, $P_{inner\ cladding}$ is the output power for pump light passing through cladding and $P_{core\ \&\ innercladding}$ is the output power passing through both the core and inner cladding.

- Figure 3.23 vertical axis change to 10log10(P)
- α value calculated from 0.05 dB/cm.
- We assumed the data in Figure 3.23 for core absorption, but there might be error in measurement as the light from cladding was not possible to remove.
- From Figure 3.23 the output extrapolated to zero length is 10log10(P)=17.68, i.e. 58.6 mW and the input power was 185 mW. Therefore, it is assumed that the coupling efficiency to the core of a fibre was estimated at 31.6%.
- Text has re written for logical argument. For explanation of suitabality of 30 cm fibre than 56 cm Please see the explanation in page 105.
- Most of the pump light should couple to the core. As Er:Yb fibre laser output offers very good beam quality, which is suitable for core pumping. Moreover for high absorption coefficient shorter length of fibre needed for fibre laser experiment. Therefore, we chose core pumping approach although the fibre is double clad

Answer on comments of reffere report 2

- Page 20, 2^{nd} paragraph: repititive part of second paragraph has been deleted.
- Page 20, Fig 1.2 has deleted.
- Page 22, 2^{nd} paragraph corrected the word from confirm to confined
- Page 24, 1^{st} paragraph: Figure 1.4(b) is corrected as a representative of a offset fibre.
- Page 25: V number has linked linked to normalised frequency as well as weak guiding regime. Please see page 25. Core refractive index n_c used ingeneral. Poulain's unexpected discovery of fluorozirconate glasses.
- Page 31: K changed to k for Boltzman constant. The value for K also followed by standard SI table.
- Page 34: Figure becomes visible.
- Page 38: In band ZBLAN results are plotted with a muliplier factor.
- Page 45: 1st paragraph has deleted as it was contained repetition material of chapter 1.
- Page 46: Double clad fibre consists of three different layer having step index refractive index profile from core to outer cladding. The detail has been discussed in previous chapter.

  Explanation for second sentence as follows:

  For non circular shape of DCFs, the symmetry of light rays is broken and the absorption efficiency is improved by blending of the pumping waves [76, 82]. This is because for non circular shape of inner cladding the symmetry of pumping wave is broken as well.

  Although various cross-sectional shapes have been employed, in practice, only a few researchers have focused on the influence of cross-sectional shape on the absorption characteristics of DCF lasers. The reason can be explained as follows.

  In order to calculate the absorption characteristics by solving the wave propagation equation in DCFs it is necessary to calculate the eigen modes. Generally typical double clad fibre having NA 0.5 and 100 μm inner cladding will support more than 10^4 eigen modes. It will require a very large amount of computing time and cumbersome to include all these modes in the calculation.
- Page 47: Model verification moved to Appendix.

For circular shape, the pump absorption tends to saturation along with the increasing of length. At the beginning the absorption increases with length sharply. After a certain distance the increasing becomes smaller and smaller due to the non-absorbtion of skew rays to the core of a fibre.

- Page 50: Labels become visible now.
- Page 52: This sentence moved to the result section.
- Page 52: Fig 2.3 Labels have been modified
- Page 53: Fig 2.4 labels have been modified
- Page 55: ppm by volume changes to ppm by weight. Also explained more explicitly the reason for only meridional rays contribution for circular shape and logical flow is maintained.
- Page 58: The sentence is corrected. Please see page 58.
- Page 61: Horizontal axis label is corrected. Also the pump absorption explanation is changed according to comment.
- Page 62: Corrcted as advised.
- Page 63: Table 64,65 as well as other tables have been deleted where the graph represents the data.
- Page 64,65: Pump laser scaling and fluctuation has moved to Appendix.
- Page 66: Extra value of 10 in the equation has been deleted.
- Page 69 now page 66: Fig 2.13 becomes 2.10, label has changed.
- Page 70 becomes page 67: Further explanation of model values differe from experimental values as follows:

  There might be two other possibilities to differ experimental result from model calculation. Firstly in model calculation effect of fibre bending was not considered for pump absorption calculation. Secondly for cut-back measurement we measured absorption at 10 metre and below 1 metre length only. For more accuracy of measurement it could be performed the cut back experiment repeatedly througout the whole length of fibre. But we had limited length of commercial fibre and was needed to perform fibre laser experiment.
- Page 72: Repetitions contains in indroduction and motivation section has deleted.
- Page 73: V number of 1.88 at 2 μm wavelength.
- Page 74: Figures are rearranged accordingly. Also Fig 3.3 (a), (b), (c) plotted seperately. Please see section 3.1.3, page 71.

- Page 76: Modified accordingly as comments. For 0% output coupler we did not use index matching gel.
  Upward direction changes to forward direction.
  Increasing the output coupler reflectivity's causes the decrease of slope efficiency of Tm:ZBLAN fibre laser.
- Page 79: Labels are modified
- Page 80: Modified according to comments.
- Page 82: The trerm dag is replaced to to unabsorptive surface coating every where.
- Page 83: Refractive index of Tm:ZBLAN 1.495 used as supplied by commercial Tm:ZBLAN fibre data sheet. In the future, we will measure the refractive index of our core and cladding glasses to provide insight into the predicted NA.
- Page 89: The calculation is for only the cladding absorption. Please see page 85 for detail
- Page 92 now page 87: Fig 3.13 is now 3.12, axis label has been fixed.
- Page 93: It has been confirmed from the transmission measurement graph (Figure 3.12) that the reflectivity of FBG is around 1570 nm.
  Second sentence is corrected as: By pressing the fusion button fibre becomes spliced and the splicing loss was observed 0.02 dB in Ericsson splicer.
- Page 96: Additional explanation added for the purpose of transmission measurement.
- Page 97: horizontal axis fixed to match with other figures.
- Page 100: xx softaware changes to LabVIEW software .
- Page 106: M2 value changes to 1.3
- Page 107: Initially 100% output is recorded. Therefore data is recorded from above 90% to below 10%. The label of of 90% and 10% indicated in graph.
- Page 109: Number of significant figure has modified.
- Page 108: Convention for molar weight has chnged to MW
- Page 116: Journal for ref 29 now ref 28 has been added.

List of Figures

List of Tables