All fibre laser source and specialty fibre for 2 μ m laser applications

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**NANYANG
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**All fibre laser source and specialty fibre for
2 μ m laser applications**

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Acronyms and abbreviations

BVP	Boundary value problem
CCD	Charge-coupled devices
Clad	Cladding
CR	Cross relaxation
CW	Continuous wave
DFB	Distributed feedback laser
DIAL	Differential adsorption Lidar systems
DTA	Differential thermal analysis
Er ³⁺	Erbium ion
Err	Error
FBG	Fibre Bragg grating
FT IR	Fourier transform infrared
Ge	Germanium
HiBi	High birefringence
HWP	Half wave plate
Ho ³⁺	Holmium ion
HR	High reflecting
IVP	Initial value problem
LIDAR	Light detection and ranging
Mid-IR	Mid-infrared
MOPA	Master Oscillator Power Amplifier
OC	Output coupler
P	Phosphorus
PBG	Lead-bismuth-gallium
PC	Polarization controller
PMF	Polarization maintaining fibre
QWP	Quarter wave plate
T _g	Glass transition temperature
T _p	Crystallization peak
Tm ³⁺	Thulium ion
Yb ³⁺	Ytterbium ion

Abstract

In military operations, soldiers often have to go through various challenging terrains. Thus, devices used in military applications have to be compact, lightweight and rugged. For example, the light detection and ranging (LIDAR) system which transmits light to precisely profile atmospheric cloud, aerosol scattering and air flow, is crucial for the weather forecasting, environmental monitoring and aircraft safety. With the development of high-speed data processing technique, the LIDAR performance and usage are ultimately constrained by the availability of an eye safe, compact laser source with widely tunable range. Different from the bulky free-space optics based laser source, our project aims to achieve an all fibre based laser source that is low cost, light and compact, alignment hassle free.

Thulium (Tm) doped fibre lasers have gained much interest in recent years because of its possible applications in the medical, defense, ranging and atmospheric sensing areas. However, most of these applications have very specific requirement for the wavelength of the laser source used. Thus, it is critical for the laser source to be wavelength-tunable, to correctly match each of the specific operating wavelengths. In our project, theoretical modeling of Tm-doped fibre laser was done based on the general rate equations for the energy levels of Tm^{3+} . Based on this theoretical modeling, we demonstrate experimentally a broadly wavelength-tunable, CW Tm-doped all fibre ring laser. The wavelength tunability in the fibre laser is enabled in the laser cavity using a fibre Sagnac loop filter constructed with a length of high birefringence (HiBi) fibre, a polarization controller and a 3 dB coupler. Tuning of the lasing wavelength can be realized by careful adjustment of the two polarization controllers in the fibre ring laser. We experimentally demonstrate a setup that can be tuned for 48nm from 1924.2 nm to 1972.2 nm. In addition, we also study on the effect and optimization of the HiBi fibre length with overall wavelength tuning range.

Laser sources in the 2 μm region and above also have great potential for industry applications such as spectroscopy, sensing, industry processing, medical diagnosis, surgery and various defence related applications. However, transmission and delivery of laser signal above the 2 μm region in convention silica based fibres is limited. Heavy metal oxide glasses exhibiting high transmission and high nonlinearity in the Mid-Infra-Red spectrum but are often difficult to manufacture in large sizes with optimized physical and optical properties. Lead-bismuth-gallium fibres have shown attractive properties such as high thermal stability, lower transmission losses, and broad transmission window. It is also suitable for achieving high nonlinearities for various applications. In this thesis, the author shows the design and fabrication of lead-bismuth-gallium optical fibres capable of transmission of light signal from 2 μm with the potential of extending even further into the mid infra-red spectrum.

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Appendix A – List of Publications

Chapter 1 Introduction

1.1 Background and literature review

Technological advancements in laser technology have created a plethora of applications in communication, medical, material processing and even in the military since the invention of the laser. Despite bulky setup and low efficiencies in the early days of lasers, tremendous improvements have been made in the simplicity, quality, and efficiency of lasers systems in the recent years. These improvements are made possible from the development of better components and also better knowledge of the lasing process in the gain medium. The development of efficient laser source operating around 2 μm has been an active area of research driven by applications in medicine, industry and military technologies.

Firstly, 2 μm corresponds to the eye-safe region in the infra-red spectrum. Its low atmospheric absorption makes the laser useful for material processing, range-finding, remote sensing, wind sensing, storm tracking, airline safety and other applications. In addition, the laser wavelength matches the absorption wavelength of atmospheric constituents such as H_2O , CO_2 and NO_2 [4]. The matching of adsorption lines in the spectrum is useful for the Differential adsorption Lidar systems (DIAL). Furthermore, there is a strong absorption peak in the wavelength region between 1.92 μm 1.94 μm by water, the main component in organic tissues, as shown in figure 1.1 [8]. Thus, it is attractive for the laser source to be used in laser surgery.

Figure 1.1. Optical absorption in water [8]

One of the past approaches to generate 2 μm laser radiation is the use of crystals co-doped with erbium (Er^{3+}), thulium (Tm^{3+}) and holmium (Ho^{3+}). In this approach, flash lamps are used to pump the crystal. In the crystal, it is the erbium ions that firstly absorb broad band radiation from the flash lamp. Following which, a series of excitation and cross-relaxation actions excite the thulium and holmium ions. Finally, lasing occurs from multiplets $^5\text{I}_7 \rightarrow ^5\text{I}_8$ generating radiation of around 2.06 μm . An improvement to this pumping scheme has been developed when the argon (Ar) gas lasers source was made available. The argon gas laser provides an output radiation at 488 nm which can be effectively absorbed by erbium ions and in turn excites the thulium and holmium ions for lasing operation. The improvement in the pumping and excitation provides a good promise in high quantum efficiency in theory. However, the high amount of loss and limited efficiency of the argon laser source substantially limit the operation of the system in low temperature.

The advancement of aluminum gallium arsenide (AlGaAs) laser diodes have brought us one step forward. These laser diodes have an output wavelength at 790 nm, showing an excellent match to the absorption spectrum of the thulium ions. Thus, erbium doping can be avoided in the medium. Furthermore, the good match between the pump wavelength of the laser diode pump and the thulium absorption greatly decreases the thermal effects in the material. Consequently the development of AlGaAs laser diodes has made a wider choices of host materials and in turn a more compact and rugged system possible.

The spectral window between 1.8 μm and 2 μm is a region of interest as it contains the absorption peaks of various substances like H_2O , CO_2 , H_2S and NO_2 . Enabling an effective laser source in this specific wavelength region will increase the prospect to perform high resolution spectroscopy and atmosphere remote sensing. In these specific applications mentioned above, there is a requirement for a steady wavelength laser output from the source. With this in mind, the most suitable choice is to have direct pumping of thulium ion and lasing of the $^3\text{F}_4 \rightarrow ^3\text{H}_6$ transition in thulium ion emitting an output at 2 μm region.

Apart from the application in spectroscopy and remote sensing, other applications such as in medical, surgical and the military have high requirements for the laser source. [7]. Besides the operating parameters like output wavelength and power, functional requirements are also critical for the laser source to be well received and accepted by the users. In particular for defense applications, wavelength and power stability, ruggedness and robustness, compactness and light weight are critical requirements to be met before the device can be used practically in large scale. Other characteristics such as the beam quality are important as it has effect in the tightness of the focus in some applications. Solid state lasers based on crystal lasing medium are less favored in applications which require a compact and light system with high ruggedness and robustness. Fibre lasers have become an alternative choice to replace crystal solid state lasers in these applications producing laser output at 2 μm wavelength region.

Progress in the research work on fibre lasers have shown the realization of kilowatts power output in both single and double cladding fibre lasers. High power fibre lasers are mainly enabled by active fibres doped with ytterbium (Yb^{3+}) as the gain medium. The output lasing spectrum is located in the region of 1080 nm. Laser radiation in this region has a big risk to the human eye. It is invisible thus poses risks in radiation into eyes which would harm a person's retina [6]. This will cause permanent scarring of the retina or loss of sight. This problem is a drawback of using such laser sources in applications. Looking into the eye safe region in the spectrum which is above 1400 nm, we can identify ytterbium–erbium system with the output lasing around 1550 nm and the thulium system with the output lasing around 2 μm to be good candidate for an eye safe laser source.

The first thulium doped fibre laser is considered to be reported in 1988. That year, Hanna et al. demonstrated a thulium doped fibre laser with output wavelength around 1.9 μm . The thulium gain fibre was pumped by a dye laser at 797 nm. The maximum extracted power

from this laser is 2.7 mW and the maximum slope efficiency is 13%. [11] It is until the invention and demonstration of double-clad fibre and the use of it in fibre laser that made high power thulium doped fibre laser possible. In 1998, Jackson demonstrated the first high power fibre laser the maximum output power achieved was 5.4 W and slope efficiency of 31%.[12] From then onwards, the power of thulium doped fibre laser has increased in a steady rate. Two years later in year 2000, Hayward et al. increased the output power of the thulium doped fibre laser to 14 W with a slope efficiency of 46%. [13] G. Frith et al. takes another five years to further improve the thulium doped fibre laser by achieving an output power of 85 W with a slope efficiency of 56% in 2005. [14] In 2009, the 2 μm output power from the TDFL was significantly enhanced by P. F. Moulton et al to 885W with a slope efficiency of 49.2% [6].

Figure 1.2 Schematic of fiber laser setup. [6]

The figure above shows the schematic diagram of the high power fibre laser setup. The development of thulium fibre laser has shown some systems with high output power as stated above. However, most of the systems require free space optics in the form of free space gratings and couplings using lens and mirrors. The presence of these free space components in the system make it difficult for us to tap on the great advantages of the fibre laser of the ability of rugged, robustness and stable design. As such, in this thesis, we will focus on the development and design of an all fibre configuration without any free space component being present in the laser source.

The mid-infrared (mid-IR) wavelength region above 2 μm has a great potential in spectroscopy, sensing, industry processing, medical diagnosis and surgery. Military related applications such as countermeasures, stand-off detection of explosion hazards, eye-safe seekers for smart munitions, and free-space communications systems are also possible applications of interest. If we want to reach even further into the infrared wavelength region, one option is the use of Raman fibre lasers. The maximum lasing wavelength region that the thulium fibre laser can cover is bounded by the spectrum bandwidth of the thulium ions. The limitation being inherited from the ion cannot be changed. Thus, the laser has a limited lasing wavelength span of 1.9 μm – 2.1 μm for thulium fibre lasers. The cascaded CW multiple-Stokes Raman fibre laser is another promising candidate to achieve the 2 μm lasers source using pumps of shorter wavelengths. The advantage is that in theory, we will be able to obtain any desirable lasing wavelength by changing the pump wavelength and the number of cascades in the Raman fibre laser. This means that we can obtain a wavelength tuning range even more than the thulium gain bandwidth.

Wavelength tunability is important for many applications in medical surgery and free space communication because we have to precisely control the medical laser's optical penetration depth in human tissue and match directly onto the narrow absorption peaks of the atmospheric gases. Rare –earth ions such as thulium doped into silica glass typically display broad absorption and emission spectrum.[34] These broad spectra makes thulium doped fibre laser an excellent gain media for broadly tunable laser source. In the year 2002, Clarkson et al. demonstrated a wavelength tunable thulium doped fibre laser using a free space external diffraction grating. [35]

Figure 1.3 Tunable thulium doped fibre laser setup. [35]

Figure 1.3 shows the tunable thulium doped fibre laser setup by Clarkson et al. Wavelength tuning was made possible by the extended cavity that comprised of a collimating lens and a diffraction grating to provide wavelength selective feedback. The tuning range obtained in this setup was 230 nm (1.86 to 2.09 μm) with a maximum power of 7 W. Building on this result, Sacks et al. attempts to push the wavelength tunable region further into longer wavelength in 2007 [36]. He demonstrated in a thulium doped fibre laser the tuning range of 220 nm (1.92 to 2.14 μm) with a maximum power of 1 W. This was done by optimizing Clarkson et al.'s setup changing the output coupler parameters. The wavelength tuning range in a thulium doped fibre laser was further improved by Tokurakawa et al. in 2013. [38]

Figure 1.4 Schematic diagram of tunable thulium fibre laser source [38]

Figure 1.4 above shows the tunable laser setup by Tokurakawa et al. In this setup two fibre gain stages were used, each of the stages were tailored to provide emission in complementary bands. One of the gain stages employed a relatively short length of a low thulium concentration single mode fibre pumped at 1565 nm to provide emission towards shorter wavelength. The other stage was employed with a longer length of highly doped thulium double-clad fibre pumped at 793 nm to provide emission towards the long wavelength. Similar to the previous setups, wavelength tuning was done by external cavity gratings. The tuning range demonstrated here was 330 nm (1.75 to 2.08 μm) with a maximum power of 0.5W.

We can notice that in the tunable thulium doped fibre laser setups shown above, wavelength tuning was all done by external diffraction grating. Free space optics was needed to realize the tunable thulium doped fibre lasers. All fibre laser source is a much more compact and

robust design configuration, making it highly desirable, especially for military applications. In 2013, Li et al. demonstrated a tunable thulium doped fibre laser as shown below. [37]

Figure 1.5 Schematic diagram of all fibre tunable thulium fibre laser [37]

Figure 1.5 shows the schematic diagram of the tunable thulium fibre laser by Li et al. The laser was built in a ring configuration. The tunable filter determines the operating wavelength of the laser output. The filter in this setup is fiberized grating based tunable filter. The tuning range obtained is 255 nm (1.82 to 2.075 μm). However, the maximum power is only 30 mW.

Modern communication systems rely on silica fibres as the transmission medium. Silica is inert and hence offers environmental stability over many years of service. It is easy to fabricate into a fibre in a manner offering good control over important fibre parameters. Low optical loss of silica fibres, which can be as low as 0.17 dBkm⁻¹ at a wavelength of 1.55 μm , is the most significant advantages over other materials. However, the opacity of silica in mid infra-red excludes its usage in this important spectral window and hence other materials with better transparency and transmission properties are demanded.

The transmission of optical signal of wavelength above 2 μm in conventional silica based optical fibre is limited because the material absorption of silica is too large. On the other hand, non-silica glass fibres have the advantage of lower phonon energy in mid-infrared regions (e.g. chalcogenide-based glasses: 300–450 cm⁻¹ and fluoride-based glass: 560 cm⁻¹) than the silica fibre (silica glass: 1100 cm⁻¹), thus providing a broader transparent window into mid-infrared region. Table 1 shows the refractive index, the third order nonlinear optical coefficient and nonlinear refractive index of various materials.

Material	$\lambda_{measured}$ (μm)	n_o	$n_2 (m^2/W)$	reference
Fused Silica	1.55	1.44	2.79×10^{-20}	[28]
Schott LLF1	1.55	1.53	6.0×10^{-20}	[31]
Schott SK2	1.24	1.59	2.1×10^{-20}	[32]
Schott F2	1.24	1.6	2.9×10^{-20}	[32]
Schott SF6	1.55	1.76	2.2×10^{-19}	[31]
Schott SF57	1.55	1.8	4.1×10^{-19}	[31]
Tellurite	1.06	2.03	5.1×10^{-19}	[27]
PBG	1.55	2.3	$\sim 10^{-18}$	[23]
GLSO	1.52	2.25	1.77×10^{-18}	[33]
GLS	1.52	2.41	2.16×10^{-18}	[33]
AsS	1.55	2.44	2.0×10^{-18}	[27][29]
AsSe	1.55	2.83	1.1×10^{-17}	[30]

Table 1.1 Comparison of nonlinear parameters of various materials

Another additional advantage of non-silica glass fibres are their high nonlinearity. Glasses with large optical nonlinearities have been obtained in glass systems such as fluoride [16], and chalcogenide glasses [17]. Comparatively low loss mid-infrared transmission in fluoride based fibre is achievable, but the nonlinear refractive index of such fibre is not considerably large. As such, in applications which require high nonlinearity, a long piece of fibre is necessary. Chalcogenide glasses exhibit high nonlinearity but it is difficult to find a suitable laser source close to its zero dispersion wavelength.

Heavy metal oxide glass systems with both high nonlinear refractive index and zero dispersion wavelengths close to conventional laser source such as tellurite or gallate glasses should be good candidates to achieve efficient nonlinear generation. Tellurite glass fibres were demonstrated for their high nonlinearity applications in the mid-infrared [18, 19].

The glass system of $PbO-Bi_2O_3-Ga_2O_3$ (PBG) is a made up of gallate glass containing lead and bismuth oxide. This heavy metal oxide glass is proposed by Dumbaugh et al. in 1984. [15] This glass system has good infra-red transmission characteristics and also has the highest χ^3 of other oxide glasses. Figure 1.6 below shows the glass forming region of PBG glass with different molar ratio of PbO , Bi_2O_3 , and Ga_2O_3 . Outside of this region, the chemical composition will not form a glass.

Figure 1.6 Glass forming region of PBG glass. [15]

Glass systems with only lead and bismuth oxides are unstable with respect to crystallisation. Additional portion of Ga_2O_3 plays the role of the glass former, however too much percentage of it would degrade the glass refractive index. W.H. Dumbaugh completed a series of studies of PBG glass compositions [15,20,21] and reported good glass forming composition with high refractive index. Since the discovery, works on PBG bulk glass have been done to develop optoelectronics devices. [25,26] In 2000, Golis discussed the properties of PBG and the possibility of fabricating PBG optical [24]. However, PBG glass fibres have not yet been demonstrated. In 2010, Ducros et al. [22,23] demonstrated holey fibres based on $\text{PbO-Bi}_2\text{O}_3\text{-Ga}_2\text{O}_3\text{-SiO}_2\text{-CdO}$ glass compositions. Additional SiO_2 made the composition more stable against devitrification. However, SiO_2 has strong absorption at the wavelength around $3.0\text{ }\mu\text{m}$ and moves the multi-phonon absorption edge toward the shorter wavelength, thus the glass composition can only transmit up to $3\text{ }\mu\text{m}$ and have lower nonlinearity. Optical fibre that is fabricated with pure PBG glass without the addition of any SiO_2 has not been demonstrate to date. In this thesis, we focus in the glass forming system without any SiO_2 added to preserve the inherited the transmission and nonlinear properties.

1.2 Project Scope and motivation

From the review presented in section 1.1, we see that there is a lack of thulium doped fibre laser that has an all fibre configuration. This is especially so for tunable thulium doped fibre laser. Raman fibre laser has the potential to generate laser wavelength in the long wavelength but there is lack of an efficient to model multi-Stokes cascaded Raman laser. Comparing with other soft glass, PBG glass has very promising nonlinearity and properties in mid-infrared region, but SiO₂ free PBG fibre is not demonstrated yet.

In our work, we investigate on Tm-doped fibre lasers as an efficient, eye safe and compact laser source for applications in the 2 μm wavelength range. Theoretical modeling of Tm-doped fibre laser is carried out using the general rate equations for various energy levels of Tm³⁺. Based on this theoretical modeling, we experimentally demonstrate an all fibre CW Tm-doped fibre laser with a 3W output at wavelength of 1.93 μm . The contribution of this is to serve as a foundation for the development of all fibre wavelength tunable thulium doped fibre laser.

We also look into the modeling of Raman fibre laser as it has the potential to extend our laser source further into the infrared optical domain. In this part of our work, we develop a theoretical model based on the CW Raman laser rate equations. In this simulation, we propose, design and then demonstrate an effective and computationally compact Nelder-Mead simplex method which can be used to design and model a CW cascaded Raman fibre lasers. In our proposal, a linear cascaded Raman fibre laser with pump wavelength of 1064nm is modeled. The input pump power of the laser was 4W. The contribution here is that with our proposed model, we are able to simulate multi-Stokes cascaded Raman laser with ease and improve the computational speed of the tedious calculation.

Wavelength tunability of fibre Bragg grating in the all fibre laser cavity is investigated theoretically and experimentally. 12 nm tuning range for normal fibre Bragg grating is demonstrated by stretching the grating. Thermal tuning of FBG is also investigated and a tuning range of 1.2 nm is observed over 110°C temperature range. It possesses very good repeatability and has the potential for wavelength tunable high power fibre laser. In addition, we present a design and demonstration of an all fibre tunable 2 μm Tm-doped fibre laser experimentally. Broadband wavelength tunability is implemented by employing a high birefringence (Hi-Bi) fibre Sagnac loop acting as a comb filter in the laser ring cavity in 2 μm Tm-doped fibre lasers. Tuning is achieved by careful controlling of the two PCs in the setup.

Stable laser output was demonstrated at various wavelengths from 1924.3 nm to 1972.2 nm covering a total range of ~48 nm. Our contribution here is the demonstration of an all fibre thulium doped fibre laser without any external free space optics. The maximum power of our tunable laser is 340 mW, ten times higher than published result.

Last but not least, we discuss a heavy metal oxide glass of lead-bismuth-gallium for the fabrication of optical fibre with the aim for the delivery and nonlinear applications in the mid-IR region. Fabrication steps from glass melting, preform making and fibre drawing are covered in detail. The contribution here is our fabrication of PBG optical fibre without the addition of SiO₂ into the glass. Both step-index and suspended core fibre are fabricated. Supercontinuum generation results from PBG glass show it high nonlinearity for our application.

1.3 Objectives

- Demonstrate wavelength tunable all fibre thulium doped fibre laser with output power more than 100mW.
- Develop efficient modeling method that increases computation speed for the simulation of cascaded Raman fibre laser.
- Fabricate high quality PBG glass and optical fibre without the addition of SiO₂. Demonstrate its property for mid-IR application.

1.4 Thesis Organization

The report starts by looking at the motivation for developing a laser source in the 2 μ m range. An overview of bulk laser devices, their limitations and the need for a rugged all fibre laser source in the 2 μ m wavelength region is presented.

In Chapter 2, we develop a model for the analysis of thulium doped fibre lasers. The simulation results are verified with other published results. In addition, we propose an experimental setup of the all fibre solution and obtained laser output at 1.93 μ m.

In Chapter 3, we propose, design and demonstrate an effective and computationally compact Nelder-Mead simplex method for the design and modeling of CW cascaded Raman fibre lasers.

In Chapter 4, we show wavelength tunability using fibre Bragg gratings (FBG). Both mechanical and thermal tuning of the FBG is performed and verified with the calculation results. We also focus on tunable thulium doped fibre laser based on a Hi-Bi fibre Sagnac loop configuration.

In Chapter 5, we document the design and demonstration of a lead-bismuth-gallium optical fibre fabrication for the delivery and nonlinear applications in the mid-IR region. Fabrication steps from glass melting, preform making and fibre drawing are covered in detail.

Chapter 2 All fibre thulium Tm doped fibre laser

2.1 Introduction

In this chapter, we first introduce the thulium spectroscopic properties in section 2.2. In section 2.3, the theoretical model of thulium doped fibre laser is presented followed by its discussion. Simulation results from our model are verified with other published results. In section 2.4, the experimental setup is presented. We demonstrate a linear cavity thulium doped fibre laser with output power of 2.5 W.

2.2 Thulium Spectroscopic Properties

The absorption peak of the absorption spectrum of the Tm^{3+} ion doped in silica is displayed in figure 2.1 [41]. The earlier studies of lasing in a Tm doped silica fibre utilized the pump absorption $^3\text{H}_6 \rightarrow ^3\text{F}_2$ at around 670 nm [39] and $^3\text{H}_6 \rightarrow ^3\text{H}_4$ absorption at around 790 nm [11]. Pumping using the $^3\text{H}_6 \rightarrow ^3\text{H}_5$ transition with 1064 nm was also demonstrated [40].

Figure 2.2 displays the energy diagram for thulium doped fibre when pumping scheme of ~790 nm ($^3\text{H}_6 \rightarrow ^3\text{H}_4$) is used. The $^3\text{F}_4 \rightarrow ^3\text{H}_6$ transition of the Tm^{3+} ion is electronic transition that corresponds to the 2 μm radiations from the gain medium. In this transition, the lasing transition has a lower energy level at ground state and the emitted fluorescence is relatively broad. Pump wavelength used for this transition is 790nm radiation which pumps Tm^{3+} ion at the ground level of $^3\text{H}_6$ to the upper energy level of $^3\text{H}_4$. As shown in figure 2.1, there is a narrow peak at this pump wavelength which means that the absorption cross section for 790 nm pump radiation is large.

OSA-based attenuation measurements
04-B0200-00-3B-06
LMA-TDF-25/250

Figure 2.1 Absorption spectrum of Tm ion in silica

The narrow peak also implicates high requirement for the wavelength stability of the pump laser. A large shift of pump wavelength will see a great reduction in the pump absorption as the pump wavelength shifts off the absorption peak. With ${}^3\text{H}_4$ energy level pumped directly, CR_1 in the figure corresponds to the cross relaxation. This happens when a Tm ion change from a state of higher energy to that of a lower energy. The energy difference between the two energy levels is absorbed by an adjacent Tm^{3+} ion.

In this cross relaxation process, two adjacent Tm^{3+} ions (${}^3\text{H}_6$) at ground level can be excited to the upper lasing level (${}^3\text{F}_4$) by the absorption of only one photon of the pump at the wavelength of 790 nm. Thus, from one excited Tm^{3+} ion at the ${}^3\text{H}_4$ level, two Tm^{3+} ions at the upper lasing level (${}^3\text{F}_4$) is generated. [42,43]. This cross-relaxation depopulates the ${}^3\text{H}_4$ level. As this is a process involving two ions in the lattice, closer ion spacing increases the rate of energy transfer. The energy transfer processes occur faster than multi-phonon decay that depopulates the ${}^3\text{H}_4$ level. Therefore, more thulium ions are packed closer at higher Tm concentrations, lead to shorter observed ${}^3\text{H}_4$ lifetimes [1]. When thulium doped fibre lasers

are in operation, a faint blue fluorescence is often observed from the length of thulium doped fibre. The blue fluorescence is most likely caused by a two-photon avalanche up conversion process in a single thulium ion to the 1G_4 energy level. An alternate process involving energy transfer up conversion from $^3H_4 \rightarrow ^1G_4$ transition has also been proposed.

Figure 2.2 Energy diagram of thulium doped fibre laser system

2.3 The theoretical modeling of Tm-doped fibre laser

Figure 2.3 Configuration of a linear cavity CW Tm doped fibre laser

Figure 2.3 shows a typical linear cavity continuous wave (CW) Tm doped fibre laser. The pump power P_p is coupled into the thulium fibre using a wavelength division multiplexer

(WDM). The output P_s exits from both side of the fibre cavity, which is formed by two fibre Bragg gratings (FBG1 & FBG2) as the mirrors. In our model, we assume that Tm doped fibre is much longer than the rest of the signal-traveling region, thus the lengths of the rest of the cavity is negligible. In our model, all FBGs are assumed to be transparent at the pumping wavelength (λ_p).

The general rate equations in the model are of ${}^3\text{H}_6 \rightarrow {}^3\text{H}_4$ 790 nm pump scheme [2]. The four lowest energy levels of Tm^{3+} are displayed via the simplified energy level diagram in Figure.

2.4. For each of the four levels concerned in our model, we labeled them N_0 for ${}^3\text{H}_6$, N_1 for ${}^3\text{F}_4$, N_2 for ${}^3\text{H}_5$ and N_3 for ${}^3\text{H}_4$ respectively. N_3 here denotes the energy level to which the Tm ions are pumped to by the 790 nm pump radiation. N_1 is the upper level for laser transition while N_0 is the lower level for laser transition and the ground state for the ion.

Figure 2.4 Simplified Energy Level Diagram of Tm^{3+}

The general rate equations describe the rate of change in population in each of the levels and the equations are listed as follows. The model describe the theoretical modeling for Tm-doped fibre lasers based on the energy population equations and general rate equations stated by S. D. Jackson et al. [2] This paper is well cited for modeling of thulium doped fibre laser. It describes the pumping scheme of ${}^3\text{H}_6 \rightarrow {}^3\text{H}_4$ (790 nm) and laser transition happens ${}^3\text{F}_4 \rightarrow {}^3\text{H}_6$ ($\sim 2 \mu\text{m}$). The only difference of our model is the addition of the confinement factor ($\mathcal{L}_p$ and $\mathcal{L}_s$) which assumes that the power is pumped through fiber cladding and the lasing wavelength is out through fiber core. This improvement to the model will take into account the confinement of pump and signal wavelength in the fibre. Also, please note that the energy

level labelling of our model is as shown below following the new norm for naming the levels.

In the reference [2], the energy labelling still follows the old way of naming.

Symbol Notation	Description	Formula (if applicable)
$N_0, N_1, N_2 \dots$	Population at energy levels	
A_{ij}	Spontaneous transition rates of Tm^{3+} when doped into silica glass.	
$\sigma_e(\lambda_s)$	Stimulated emission cross-section of laser transition at output wavelength λ_s	
$\sigma_e(\lambda_p)$	Emission cross section at the pump wavelength	
c	Speed of light	
$\sigma_a(\lambda_s), \sigma_a(\lambda_p)$	Absorption cross-section at laser (signal) and pump wavelength respectively	
Γ_i	Nonradiative transmission rate, i.e. energy that will be released as phonons or lost as heat	
CR	Cross-relaxation, i.e. when an atom moves from a state of higher energy to that of a lower energy, the energy difference between the 2 levels is absorbed by another atom.	$CR_1 = k_{3101} N_3 N_0 - k_{1310} N_1^2$, cross relaxation: ${}^3H_4, {}^3H_6 \rightarrow {}^3F_4, {}^3F_4$ $CR_2 = k_{2101} N_2 N_0 - k_{1012} N_1^2$, (cross relaxation: ${}^3H_5, {}^3H_6 \rightarrow {}^3F_4, {}^3F_4$)
$P_{f,r}(z)$	Forward and reverse propagating pump fields along the length of the fibre	$dP_{f,r}(z)/dz = -(\pm P_{f,r}(z))[\sigma_a(\lambda_p)N_0(z) + \delta_p]$ -ve sign: forward (+z) direction +ve sign: reverse (-z) direction
δ_p	Intrinsic absorption of the host glass at pump wavelength	
$S_{f,r}(z)$	Forward and reverse propagating laser radiation field along the length of the fibre	$dS_{f,r}(z)/dz = \pm S_{f,r}(z)[\sigma_e(\lambda_s)N_1(z) - \sigma_a(\lambda_s)N_0(z) - \delta_a]$ +ve sign: forward (+z) direction -ve sign: reverse (-z) direction
δ_s	Intrinsic absorption by host glass at the laser wavelength	
R_1, R_2	Input and output mirror reflectivities	
W_{03}	Local pump absorption rate	$W_{03} = \sigma_a(\lambda_p)[P_f(z) + P_r(z)] N_0$
L	Length of the fibre	
P_{launched}	Launched pump power in fibre core	
W_{10} [$N_0 \rightarrow N_1$]	Deexcitation of the 3H_4 energy level	$W_{10} = \sigma_e(\lambda_p)[P_f(z) + P_r(z)] N_1$ [${}^3H_6 \rightarrow {}^3H_4$ or 3F_4]

Table 2.1 A list of the descriptions of symbol notations

$$\frac{dN_0}{dt} = \sum_{i=1}^3 A_{i0} N_i + \Gamma_1 N_1 - W_{03} - CR_1 - CR_2 + W_{10} \quad (2.1)$$

$$\frac{dN_1}{dt} = \sum_{i=2}^3 A_{i1} N_i + \Gamma_2 N_2 - [A_{10} + \Gamma_1] N_1 + 2CR_1 + 2CR_2 - W_{10} \quad (2.2)$$

$$\frac{dN_2}{dt} = A_{32} N_3 + \Gamma_3 N_3 - \left[\sum_{j=0}^1 A_{2j} + \Gamma_2 \right] N_2 - CR_2 \quad (2.3)$$

$$\frac{dN_3}{dt} = W_{03} - \left[\sum_{j=0}^2 A_{3j} + \Gamma_3 \right] N_3 - CR_1 \quad (2.4)$$

W_{03} is the local pump absorption rate, from N_0 to N_3 , given by the equation:

$$W_{03} = \sigma_a(\lambda_p) \left[\frac{P_f(z) + P_r(z)}{\left(\frac{hc}{\lambda_p}\right) A_{core}} \right] N_0 \quad (2.5)$$

and the lasing rate from N_1 to N_0 , W_{10} , given by the equation

$$W_{10} = [\sigma_e(\lambda_s) N_1 - \sigma_a(\lambda_s) N_0] \left[\frac{S_f(z) + S_r(z)}{\left(\frac{hc}{\lambda_s}\right) * A_{core}} \right] \quad (2.6)$$

In (1)-(6), A_{ij} represents the spontaneous transition rates relating to Tm^{3+} doped into silica glass, $\sigma_e(\lambda_s)$ is the simulated emission cross-section of the laser transition at an output wavelength λ_s and, $\sigma_a(\lambda_p)$ and $\sigma_a(\lambda_s)$ are the absorption cross-sections for ${}^3H_6 \rightarrow {}^3H_4$ and ${}^3H_6 \rightarrow {}^3F_4$, respectively. Γ_i is the radiative transition rate.

The cross relaxation mechanisms operating when the 3F_4 energy level is pumped directly are given by

$$CR_1 = k_{3101} N_3 N_0 - k_{1310} N_1^2 \quad (2.7)$$

(cross relaxation: ${}^3H_4, {}^3H_6 \rightarrow {}^3F_4, {}^3F_4$)

$$CR_2 = k_{2101} N_2 N_0 - k_{1012} N_1^2 \quad (2.8)$$

(cross relaxation: ${}^3H_5, {}^3H_6 \rightarrow {}^3F_4, {}^3F_4$)

The forward and reverse propagating pump fields are denoted by $P_{f,r}(z)$ with the subscripts f and r indicating the forward and backward reverse directions. Pump fields propagating in the two directions are described by the following power propagation equations:

$$\frac{dP_{f,r}(z)}{dz} = \mp \mathcal{L}_p P_{f,r}(z) [\sigma_a(\lambda_p) N_0(z) + \delta_p] \quad (2.9)$$

$$\text{Where } \mathcal{L}_p = \frac{A_{Core}}{A_{Cladding}}$$

Here $\mathcal{L}_p$ is the confinement factor for pump power; δ_p is the intrinsic absorption of the host glass at the pump wavelength.

On the other hand, $S_{f,r}(z)$ are the forward and backward reverse propagation of the lasing radiation along the fibre cavity.

$$\frac{dS_{f,r}(z)}{dz} = \pm \mathcal{L}_s S_{f,r}(z) [\sigma_e(\lambda_s) N_1(z) - \sigma_a(\lambda_s) N_0(z) - \delta_s] \quad (2.10)$$

$$\text{Where } \mathcal{L}_s = \frac{A_{Core}}{A_{eff}} = 1$$

Similarly, $\mathcal{L}_s$ is the confinement factor for lasing power, and δ_s is the intrinsic absorption by the host glass at the laser wavelength.

Two boundary conditions of the pump radiation field:

$$P_r(L) = R_2 P_f(L) \quad (2.11)$$

$$P_f(0) = R_1 P_r(0) + P_{\text{launched}} \quad (2.12)$$

Two boundary conditions of the laser field:

$$S_r(L) = R_2 S_f(L) \quad (2.13)$$

$$S_f(0) = R_1 S_r(0) \quad (2.14)$$

Where R_1 and R_2 represent the reflectivity of the FBGs, and P_{launched} is the input pump power into the core of the fibre.

To solve the coupled rate equations, we first simplified the rate equations through some assumptions listed as follows:

- 1) The population equations of equation (2.2 – 2.4) are set to be 0 considering the steady state case
- 2) Using total radiation rate γ_i is used in replacement for the sum of spontaneous transition rate A_{ij} cross relaxation rate and irradiative transition rate I_i for equation (2.1 – 2.4); where $\gamma_i = \frac{1}{\text{Total life time}}$

Secondly, using the principle of conservation of total thulium ion population (N_t), one more equation can be obtained:

$$N_t = N_0 + N_1 + N_2 + N_3 \quad (2.15)$$

Finally, the following equations are used in the simulation with the boundary conditions for the lasing field,

$$0 = \frac{dN_3}{dt} = -\gamma_3 N_3 + \left[\frac{P_f(z)}{\left(\frac{hc}{\lambda_p}\right) A_{core}} \right] \mathcal{E}_p \quad (2.16)$$

$$0 = \frac{dN_2}{dt} = \gamma_3 N_3 - \gamma_2 N_2 \quad (2.17)$$

$$0 = \frac{dN_1}{dt} = \gamma_2 N_2 - \gamma_1 N_1 - [\sigma_e(\lambda_s) N_1 - \sigma_a(\lambda_s) N_0] \left[\frac{S_f(z) + S_r(z)}{\left(\frac{hc}{\lambda_s}\right) * A_{core}} \right] \mathcal{E}_s \quad (2.18)$$

$$\frac{dP_f(z)}{dz} = -\mathcal{E}_p P_f(z) [\sigma_a(\lambda_p) N_0(z) + \delta_p] \quad (2.19)$$

$$\frac{dS_{f,r}(z)}{dz} = \pm \mathcal{E}_s S_{f,r}(z) [\sigma_e(\lambda_s) N_1(z) - \sigma_a(\lambda_s) N_0(z) - \delta_s] \quad (2.20)$$

To verify our simulation model, we compare our simulation results on the calculation of slope efficiency with respect to pump wavelength and fibre length to that of the reference [2]. The table 2.2 shows the parameters used in the simulation.

Symbol	Description	Value	Remarks
h	Planck's constant	6.63×10^{-34}	
c	Light Speed	2.998×10^8	
τ_1	Level 1 total life time	$334.7 \mu s$	Data from [2]
τ_2	Level 2 total life time	$0.007 \mu s$	Data from [2]
τ_3	Level 3 total life time	$14.2 \mu s$	Data from [2]
λ_s	Lasing Wavelength	1945nm	Set according to [2]
$\sigma_e(\lambda_s)$	Emission cross-section at lasing wavelength	$4.1 \times 10^{-25} m^2$	Data from [2]
$\sigma_a(\lambda_s)$	Absorption cross-section at lasing wavelength	$0.01 \times 10^{-25} m^2$	Data from [2]
$\sigma_e(\lambda_p)$	Emission cross-section at pump wavelength	$0.001 \times 10^{-25} m^2$	Data from [2]
δ_p	Scattering loss at pump wavelength	$12 \times 10^{-3}/m$	Data from [2]
δ_s	Scattering loss at lasing wavelength	$23 \times 10^{-3}/m$	Data from [2]
r_{core}	Radius of core	$11 \mu m$	Data from [2]
R_1	Reflectivity at pump input end	1	Assumption
N_t	Total population density / Tm concentration	$2.35 \times 10^{25} /m^3$	Data from [2]

Table 2.2 A list of parameters and values used

Table 2.3 below shows the set of values of absorption cross section with respect to the pump wavelength that we used in the simulation for figure 2.5.

Pump Wavelength λ_p (nm)	Absorption Cross Section $\sigma_a(\lambda_p) (10^{-25} \text{m}^2)$	Pump Wavelength λ_p (nm)	Absorption Cross Section $\sigma_a(\lambda_p) (10^{-25} \text{m}^2)$
760	1.0	798	8.0
763	1.3	800	5.6
765	1.5	803	4.5
768	1.7	805	3.8
770	1.9	808	3.3
773	2.6	810	2.9
775	3.5	813	2.2
778	4.5	815	1.8
780	5.3	818	1.5
783	7.8	820	1.2
785	8.4	823	0.9
788	8.4	825	0.7
790	8.5	828	0.5
793	8.4	830	0.3
795	8.4		

Table 2.3 A list of the absorption cross section values at different wavelengths [2]

Figure 2.5 Simulation results for the slope efficiency against pump wavelength

The simulation results are compared with the results from [2] in figure 2.5.

After verifying our model, we simulated thulium doped fibre laser with two different doping concentrations. The result is shown in figure 2.6 below. The output coupler is set to be 10% reflective. The highly doped thulium gain fibre of 6000 ppm requires shorter fiber length to reach high efficiency. However at long fibre length, the slope efficiency is almost the same for both cases. This result is also supported in the reference. [2]

Figure 2.6 Simulation results for the slope efficiency of different doping concentration against fibre length

2.4 All fibre CW Thulium doped fibre laser

Figure 2.7 Schematic diagram of the experimental setup of the linear cavity CW thulium doped fibre laser

The experiment design is shown in figure 2.7. A 5-meter thulium gain spool is deployed as the gain medium fibre in the fibre laser setup. Two Apollo 790 nm pump laser diodes with 18W maximum output power each are spliced onto the pump fibre ends of the thulium gain spool. The backward pump fibre of the thulium gain spool is spliced together to act as a highly reflective fibre mirror for the pump radiation not absorbed at the right hand side of the gain fibre. FBG written onto 13/125 fibre is fusion spliced to each end of the signal fibre of the thulium gain spool with a peak reflectivity at 1930nm. The left hand side FBG is of high reflectivity of 99% while the right hand side FBG is of 10% reflectivity. Both ends of the FBGs are angle cleaved of 8° to prevent any reflections from the fibre ends that may form multi-cavities in the fibre laser.

The two pump laser diodes are products of Apollo. Figure 2.8 shows the optical spectrum obtained from an optical spectrum analyzer (OSA). The center wavelength of the laser diodes is 784.07 nm. As the absorption peak of thulium at wavelength around 790 nm is very narrow, we are concerned with the wavelength variation of the 790nm Apollo laser diode used with regards to the electric current applied. Figure 2.9 displays the reading of the wavelength variation and it is verified that in the operating region of the laser diodes, the pump wavelength output is well within the absorption peak of the thulium ions.

Figure 2.8 Optical spectrum of the 790nm Apollo laser diode

Figure 2.9 Wavelength variation of the 790nm Apollo laser diode

The experiment is performed in laboratory conditions. The cover of the thulium gain spool is cooled by the use of water chiller. For this experiment, the pump diodes and the gain spools are cooled in series pipes connected to a chiller with temperature set to 18°C. The output spectrum is observed using an OSA from ocean optics. The spectrum is displayed in figure 2.10 below. Output wavelength of our laser is centered at 1931.11 nm. The output wavelength matches with the center wavelength of the FBGs used to form the laser cavity.

Figure 2.10 Optical spectrum of the laser output

Two sets of experiment were conducted. One with a straight cleave only at the right hand side of our linear laser setup that provide a 4% reflection and form a cavity with the high reflectivity FBG at the left hand side of the laser; The other with a FBG that has 10% reflectivity at the right hand output end of the laser to form a cavity with the high reflectivity FBG. The resulting laser output and efficiencies are displayed in figure 2.11. From the figure, we observed the output power is higher on the condition of lower output coupling FBG reflectivity. The highest slope efficiency of 15.56% was also achieved with the lowest output coupling FBG reflectivity of 0.04. Laser cavity with a high output coupling FBG reflectivity will confine a large portion of the radiation inside the laser cavity, leaving only a small portion of radiation to be coupled out of the cavity as laser output. However, the high confinement of laser radiation inside of laser cavity will lower the threshold for fibre laser to start lasing. A long-pass filter that filters out any pump radiations is deployed at the fibre output end of the laser to block off any pump radiation that is not absorbed and managed to appear with the signal wavelength at the setup output end. Power meter is used to determine the signal output wavelength power at the right hand side of the fibre laser. The power stability of the laser output is measured for 30 minutes with the input pump power at 17 W. Table 2.4 shows the conditions for the stability experiment. The stability plot is shown in figure 2.12.

Figure 2.11 Laser efficiency of a) 4% output coupling b) 10% output coupling

Pump wavelength	784.07 nm
Length of gain fibre	5 m
High reflectivity FBG	99 %
Output coupler FBG	10 %
Output lasing wavelength	1931.11 nm
Slope efficiency	15.56%

Table 2.4 Characteristics of the experiment setup

Figure 2.12 Power stability of the laser output

The theoretical model of thulium doped fibre laser rate equations described in section 2.3 is used to compare with our experimental setup. The model is used to calculate the output power and slope efficiency of the laser setup. Output coupling of 4% is chosen for the comparison. The result is summarized in figure 2.13 below. The simulated slope efficiency is 21%, with maximum power reaching 3.5 W.

Figure 2.13 Comparison of experiment and simulation results

The simulation results exhibit a slope efficiency of 21%, which is 5.44% higher than that of the experimental data at 15.56%.

This could be due to losses in the cavity that were unaccounted for in the simulation program such as splicing loss, coupling loss and insertion loss contributed by the components in the setup. Also, the simulation program for the oscillator was simplified by negating the effects of cross-relaxation, which otherwise would complicate the computational process. Therefore, these factors might have contributed to the discrepancies between the simulation results and the actual experimental data.

As seen from chapter 1.1, the slope efficiency of published results ranges from 13% [11], to 31% [12], 46% [13] and 56% [14]. Both the experimental and simulated slope efficiencies seem relatively low compared to some of the published results. Possible reasons for the low slope efficiency in the employed laser setup could be attributed to the doping ratio between Tm^{3+} and Al^{3+} [44] as some of the published results could have used customized fibers with special doping ratios, which would increase the absorption cross section and thereby enhancing the laser performance.

2.5 Chapter Summary

In this chapter, we numerically investigate thulium doped fibre lasers. The simulation results of the slope efficiencies from our model are verified with published results. Experimental setup producing 2.5 W at 1.93 μm is implemented. The output efficiency and power stability of the laser are also presented.

Chapter 3 Modeling of cascaded continuous wave (CW) multiple-Stokes Raman fibre lasers

3.1 Introduction

This chapter is based on a publication [Optical Engineering 49(9),091009(2010)] by Tse et al.

The maximum wavelength range that the thulium fibre laser can cover is limited by the gain spectrum bandwidth of the thulium ions. This limitation is inherited and cannot be changed. Thus, the laser has a limited wavelength range of $1.9\ \mu\text{m} - 2.1\ \mu\text{m}$ for thulium fibre lasers. The cascaded CW multiple-Stokes Raman fibre laser is another promising candidate to achieve the $2\ \mu\text{m}$ lasers source using pumps of shorter wavelengths. The advantage is that in theory, we will be able to obtain any wavelength we want by changing the pump wavelength and the number of cascades in the Raman fibre laser. This means that we can obtain a wavelength tuning range even more than the thulium gain bandwidth. In addition, lasers in the longer wavelengths such as $3\ \mu\text{m}$ process some advantages. For example, in medical applications, the water present in organic tissues absorbs the $3\ \mu\text{m}$ wavelength radiation better and therefore it ablates more efficiently and produce smaller tissue crater as compared to the $2\ \mu\text{m}$ lasers. If we want to reach even further into the infrared wavelength region, one option is the use of Raman fibre lasers.

In optical fibres, Stimulated Raman scattering (SRS) can convert the radiation of a source which is of a shorter wavelength to longer wavelength. Raman fibre laser based on FBGs was demonstrated in 1988 [45] and since then Raman fibre lasers have been extensively studied. As a laser source, a main attraction of Raman fibre laser is that essentially any output laser wavelength can be achieved with a suitable choice of the pump wavelength. Given that all wavelengths in the cavity are within the transparency region of the fibre material and the optical intensity has reached the Raman threshold.

In addition, the development of diode lasers and FBGs with high reflectivity made it possible for them to be employed as the pump laser and feedback element in the Raman fibre laser, respectively. Thus, nested cavities in which multiply Stokes wavelengths resonate simultaneously can be realized [46]. The continuous-wave (CW) cascaded Raman fibre laser

is an efficient configuration to achieve high power multiple Stokes wavelength output. With the use of FBGs to resonate the Stokes light, the pump wavelength can be efficiently down converted to single transverse mode laser radiation. CW cascaded Raman fibre lasers can be modeled with the coupled ordinary differential equations. At the input and output end of the laser cavity formed by the FBGs, we are able to set the boundary conditions.

Because numerous Stokes wavelengths is propagating in CW cascaded Raman fibre lasers, numerical investigation of the pump and intra-cavity Stokes becomes important for us to design a CW cascaded Raman fibre laser. Like many problems in applied science and engineering, CW cascaded Raman fibre lasers can be treated as two-point boundary value problems (BVPs). A few numerical and analytic methods have been extensively studied for BVPs of single Stokes Raman fibre lasers [47-50]. Generally, the exact analytical solutions of such problems do not exist. Thus, the numerical solution is highly desired. Presently, the shooting method is frequently used for solving single Stokes Raman fibre laser equations. The shooting method is done by assuming initial values that would have been given if the ordinary differential equation were an initial value problem. From each initial assumption, we will be able to calculate the boundary values. These calculated boundary values are then compared with the actual boundary value. Using trial and error or some other approach, we tries to get as close to the boundary value as possible. However, the simple shooting method is not efficient for modeling the cascaded multi-Stokes Raman fibre lasers as convergence of the coupled rate equations will be a multi-dimensional problem. Unlike single Stokes Raman fibre lasers, multiple Stokes Raman fibre lasers are operated at numerous wavelengths causing it to be difficult to determine the analytical solutions. Numerical models for investigating cascaded multiple Stokes Raman fibre lasers based on variable substitution [51], differential evolution algorithm [52] and genetic algorithm [53] have been reported. In such multi-dimensional problems, convergence of the solution is very sensitive to the guessed values of the initial conditions as convergence direction is difficult to determine for the multi-dimensional problem. The results for the BVPs of multiple-Stokes Raman fibre lasers are usually found numerically. One method is to solve the equation using the shooting method with some guess arbitrary initial values. However, this approach has poor stability and has the possibility that results the calculation to divergence. As the cascaded Raman rate equations are coupled together, convergence direction is difficult to determine as all the boundary conditions have to be satisfied simultaneously.

In this chapter, considering the excellent multi-dimensional searching ability of Nelder-Mead simplex optimization algorithm and utilizing the advantage of fast converging speed in shooting method, we propose a novel and efficient numerical algorithm to solve the multi-dimensional problem of multiple-Stokes Raman fibre lasers. We use the proposed algorithm to evaluate a three wavelength all fibre Raman fibre laser with the intra-cavity Stokes wavelengths at $\lambda_1=1117$ nm and $\lambda_2=1175$ nm, when a 1064 nm laser diode with an output power of 4W is used to pump input. An output power of 2.5857W at 1175 nm is obtained based on the proposed model. The simulation results are comparable to that of published simulation and experimental results in [47][58]. Our proposed method has been verified with the features of good convergence and fast converging speed. Moreover, it is shown that the solution of rate equation is not sensitive to the choice of initial guessed conditions.

3.2 Numerical simulations of Coupled Raman Rate Equations

Figure - 3.1. Schematic diagram of an n^{th} -order CW cascaded Raman fibre lasers. HR represents a highly reflecting FBG ($\sim 100\%$ reflectivity) and OC represents an output FBG ($< 100\%$ reflectivity).

Figure 3.1 shows the schematic diagram of the n^{th} -order cascaded Raman fibre laser. It is an all fibre configuration that comprise of a length of Ge- or P- doped silica fibre as the Raman gain medium and pairs of fibre Bragg gratings (FBGs) forming the laser cavity. A pair of wavelength matching FBGs is placed at the two ends of the gain medium in order to form resonators for the intra-cavity Stokes fields [47]. The Raman fibre laser in our model is pumped at the wavelength of $\lambda_0=1064\text{nm}$, the Stokes wavelengths λ_i (where $i = 1$ to n) are separated from each other by 14.1 THz [48].

$$\pm \frac{dP_0^\pm(z)}{dz} = \left[-\alpha_0 - g \frac{\lambda_1}{\lambda_0} (P_1^+ + P_1^-) \right] P_0^\pm(z) \quad (3.1)$$

$$\pm \frac{dP_i^\pm(z)}{dz} = \left[-\alpha_i + g_i (P_{i-1}^+ + P_{i-1}^-) - \frac{\lambda_{i+1}}{\lambda_i} g_{i+1} (P_{i+1}^+ + P_{i+1}^-) \right] P_i^\pm(z) \quad (3.2)$$

$$\pm \frac{dP_n^\pm(z)}{dz} = \left[-\alpha_n + g_n (P_{n-1}^+ + P_{n-1}^-) \right] P_n^\pm(z) \quad (3.3)$$

where $i = 1$ to $n-1$,

and the boundary conditions :

$$P_0^+(0) = P_0 \quad (3.4)$$

$$P_i^+(0) = R_{li} \cdot P_i^-(0) \quad \text{for } i=1 \text{ to } n \quad (3.5)$$

$$P_i^-(L) = R_{ri} \cdot P_i^+(L) \quad \text{for } i=0 \text{ to } (n-1) \quad (3.6)$$

$$P_n^-(L) = R_n \cdot P_n^+(L) \quad (3.7)$$

In this chapter, the cascaded Raman fibre laser is modeled by the classical differential equations (3.1) – (3.3). In the equations, z represents the position along the fibre, L is the fibre length, R_{li} and R_{ri} are the respective FBGs' reflectivity at the left ($z = 0$) and right hand end ($z = L$) of the Raman fibre, P_0 is the input pump power at $z = 0$ in a unit of Watts. Positive and negative superscripts in the rate equations (3.1) – (3.3) represent the forward (+) and backward (-) propagation direction of the pump and Stokes wavelengths in the z direction. The coefficient α_i , is the intrinsic loss of fibre at individual wavelength. Raman gain coefficient is denoted by g_i in the equations. In the single-cavity non-cascaded Raman fibre laser (when there is only one Stokes wavelength in the cavity), the BVP can be well solved numerically by a simple shooting method [54]. However, when we are solving for n^{th} -order cascaded Raman fibre lasers, a simple shooting method will not be effective to solve the BVP as it is necessary to satisfy boundary conditions of all the Stokes wavelength simultaneously. When there are more than one Stokes wavelengths in the cavity, solving the coupled laser rate equations will become a multi-dimensional problem. Thus, we have to choose the initial values for each of the Stokes wavelengths that fulfill each of their boundary conditions, respectively. In this chapter, we propose an effective and computationally compact Nelder-Mead simplex algorithm to solve the difficulty in designing an n^{th} -order cascaded Raman fibre laser.

3.3 Proposed Nelder-Mead Simplex Method

A simplex method for finding a local minimum of a function with several variables has been proposed by Nelder and Mead in 1965. Then, it has been applied to many areas of economics, engineering and medicine as an effective algorithm to solve nonlinear unconstrained optimization problems [55]. The algorithm is a classical and very powerful local descent algorithm, without making use of the objective function derivatives. In order to solve the n^{th} -order cascaded Raman fibre laser model, guessed initial value is generated at $z = 0$ for each of the Stokes wavelengths. With the guessed sets of initial conditions, the Boundary value problems (BVPs) are transformed to initial value problems (IVPs) and their numerical solutions can be found using methods such as the Runge-Kutta algorithm. In our modeling, we define an error term (err), as shown in equation (3.8), which will be calculated at the end of every iterations.

$$err = \sum_{i=1}^n \left| \frac{R_{ri} \text{ of numerical calculated solution} - R_{ri} \text{ of boundary conditions}}{R_{ri} \text{ of boundary conditions}} \right| \quad (3.8)$$

The initial values for next iteration are determined by our proposed Nelder-Mead algorithm on the principle of finding the converging direction that minimizes the value of err . In the case of two variables, a simplex is a triangle. In the algorithm, a pattern search is conducted to compare the function values at the three vertices of the triangle. The ‘worst’ vertex is the one with a greatest err value, is determined and written over by a new vertex found by our proposed Nelder-Mead algorithm. A new triangle is created with this new vertex, and the search continues. The algorithm is a process to generate a progression of triangles, with the function values (err in our model) at each of the vertices reducing after each cycle. Every iteration of the algorithm will reduce the size of triangle and converge to local minima. In our model, the minimum error point corresponds to the solution of the coupled Raman fibre laser rate equations. Our algorithm can be generalized for triangle in N dimensions. Finally, the minimum of a function of N variables can be found. The replacement process of our method consists of this four basic operations to the vertex namely: reflection, expansion, contraction, and multi-contraction [56][57], as shown in figure 3.2.

Figure - 3.2. The four basic operations of the Nelder–Mead method. (a) Reflection using the point R ; (b) Expansion using the point E ; (c) Contraction using the point C ; (d) Multi-contraction towards B .

At the start of the algorithm, we input three sets of initial values and the rate equations are solved using 4th order Runge-Kutta method. Using equation (3.8), the err term of the rate equations for each of the initial value sets are calculated. The initial value sets and their respective err term calculated will form the three vertices of a triangle. These vertexes are ranked according to the value of the err term and slotted in order such that B is the best vertex, G is good (next to best), and W is the worst vertex ($err_B < err_G < err_W$). After the ranking of the vertices, our algorithm will start to replace the vertex W with a better one. Figure 3.3 shows the schematic decision flowchart of the proposed Nelder-Mead method. The tolerance (tol) of the program is defined as the maximum overall error that we can accept in the numerical solution. This tolerance will determine the computational time and accuracy of the program. At the end of every iteration, the three vertices are ranked again and the err term of the best vertex, err_B , will be compared with the pre-determined tol value. If $err_B \leq tol$, the algorithm will terminate with the rate equation solution found. In contrary, if err_B is still not in the tolerance range, the next iteration will start with the three new vertices as the new initial values.

Figure 3.3 Schematic decision flowchart of the proposed Nelder-Mead method.

3.4 Results and discussions

We assume $\alpha_0 = 0.8\text{dB/km}$ and $\alpha_i = 0.66\text{dB/km}$ [59]. The pump wavelength (λ_0) is 1064nm with a power of 4W. The Stokes wavelengths are $\lambda_1=1117\text{nm}$, $\lambda_2=1175\text{nm}$, etc; separated from each other by 14.1THz. We assume that the Raman gain coefficient $g_i = 1.2(\text{W}\cdot\text{km})^{-1}$. The length of Ge-doped fibre used in the cavity is 1000 meters. Reflectivity of the output coupler FBG at the highest Stokes wavelength R_n is 0.1 or 10%. The tolerance tol is set to be 0.002. The convergence of the proposed Nelder-Mead method is shown in figure 3.4. The three convergence plots in figure 3.4 correspond to three different initial guessed conditions used in our model.

Intrinsic loss of fibre at pump wavelength	α_0	0.8dB/km
Intrinsic loss of fibre at Stokes wavelength	α_i	0.66dB/km
Input wavelength	λ_0	1064 nm
Input power	P_0	4 W
Raman gain coefficient	g_i	$1.2(\text{W}\cdot\text{km})^{-1}$
Output FBG coupler reflectivity	R_n	10%
Calculation tolerance	tol	0.002
Length of fibre in cavity	z	1000 m

Table 3.1 Parameters used in the simulation.

Figure 3.4 Convergence of the Nelder-Mead method.

The Nelder-Mead algorithm in our model determined with great efficiency the convergence direction of the multi-dimensional problem. We observed great reduction of the *err* term just after the first two iterations. From our simulation, it is noted that solution of the rate equation we calculated is not sensitive to the choice of the initial guessed conditions, meaning all three calculations converge to the same solution. However, the closer the initial guessed values are to the exact values, the less computational time is required for the simulation. Although the three sets of initial guessed conditions are of different proximity to the true solution, all of them converge to the same final solution. Our method is effective and computationally compact. A relative error of less than 0.005 is achieved at the 41th iteration for all of our calculations with different initial guessed values. The convergence graphs clearly show the improvement of the relative error after each iteration. It is noted that the relative error reduced drastically after three iterations. These convergence figures show that our proposed method is very effective in locating the convergence direction in this multi-dimensional problem. However, the simple shooting method, on the other hand, is not able to determine this multi-dimensional converging direction effectively.

Figure 3.5 (a) Calculated values of the intra-cavity power (W) of Pump wavelength

Figure 3.5 (b) Calculated values of the intra-cavity power (W) of 1st Stokes shift wavelength

Figure 3.5 (c) Calculated values of the intra-cavity power (W) of 2nd Stokes Shift wavelength

The calculated intra-cavity fields of the pump and all Stokes wavelengths are plotted with respect to the distance along the Raman fibre as shown in figure 3.5. From figure 3.5(a), we observed that the forward propagating pump radiation (1064 nm) is gradually absorbed and emitted as first Stokes wavelength (1117 nm) as it propagates along the fibre. As the pump radiation reached the end of the fibre ($z = 1000$ m), the highly reflective FBG with the Bragg wavelength of 1064 nm reflects all the remaining pump radiation back in the backward direction. Similar to the forward propagating pump, the backward propagating pump radiation gradually decrease and is converted to the first Stokes radiation. At the expense of the pump radiation, the first Stokes radiation experienced amplification. For the first Stokes field, both the forward and reverse propagating radiation are equal at the ends of the Raman gain fibre, as shown in figure 3.5(b). This is a result of the boundary conditions imposed on the first Stokes radiation by the highly reflective FBG (1117 nm) at both end of the Raman gain fibre. Together with the reduction of the pump radiation along the fibre, the first Stokes

cavity mode is shaped into a fundamental standing wave with the nodes at the two ends and the maximum of the first Stokes radiation near the midpoint of the fibre length. Similarly, the second Stokes radiation at 1175 nm experienced the boundary conditions imposed by a highly reflective FBG at the input and a 10% output coupler FBG at the output. The output of the Raman fibre laser with a wavelength of 1175 nm was calculated to be $(2.873\text{W} \times (1 - 0.1)) = 2.5857\text{W}$).

Figure 3.6 Output power of Raman fibre laser versus launched pump power of various output mirror reflectivity

The output power of the Raman fibre laser was plotted against the launched pump power for various output coupling (OC) FBG reflectivity ranging from 0.1 to 0.9, as shown in figure 3.6. The length of the Raman gain fibre in this comparison was set to be 600 m. From the figure, we observed that the output power (1175 nm) is higher on the condition of lower output coupling FBG reflectivity. The highest slope efficiency of 72.5% was also achieved with the lowest output coupling FBG reflectivity of 0.1. Laser cavity with a high output coupling FBG reflectivity will confine a large portion of the radiation inside the laser cavity, leaving only a small portion of radiation to be coupled out of the cavity as laser output. However, the high

confinement of laser radiation inside the cavity will lower the threshold for the Raman fibre laser to start lasing.

To verify that our method of modeling cascaded Raman fibre laser is accurate and agree well with experimental results, we use our Nelder-Mead simplex model to simulate the experimental results from Kurukitkoson et al. [62]. The experimental results are obtained from a two –stage cascaded Raman fibre laser based on phosphosilicate core fibre. This Raman fibre laser is pumped by a ytterbium laser at 1061 nm.

Figure 3.7 Schematic diagram of experimental setup [62]

Figure 3.7 above shows the schematic diagram of experimental setup. The P_2O_5 doping level of the phosphosilicate-core single mode fibre is 13mol%. The parameters of the fibre are shown in the table below.

Wavelength	Intrinsic loss α	Raman gain coefficient g
$\lambda_0=1061$ nm	1.55 dB/km	$1.29 \text{ (W}\cdot\text{km)}^{-1}$
$\lambda_1=1240$ nm	0.92 dB/km	$0.94 \text{ (W}\cdot\text{km)}^{-1}$
$\lambda_2=1480$ nm	0.75 dB/km	-

Table 3.2 Parameters of P_2O_5 fibre in experiment setup [62].

Figure 3.8 Comparison of experimental results from [62] with our simulation method

In this setup, the output coupling (OC) FBG have 15% reflectivity at 1480nm. The length of fibre used in the cavity is 500m. Each of the input power conditions of the experiment is calculated using our method and the results are compared in the figure 3.8 below. There is good agreement between our simulation results and the published experiment results.

3.5 Modeling of cascaded Raman fibre laser at 1.9 μ m

The cascaded CW multiple-Stokes Raman fibre laser is a promising candidate to achieve the $\sim 2\mu$ m lasers source using pumps of shorter wavelengths. However in this wavelength region, the loss of the bulk silica imposes a limit on long wavelength operation in conventional silica fibers. Increasing the doping concentration of GeO_2 in optical fibre will shift the intrinsic infrared absorption to longer wavelengths as compared to silica glass because germanium atoms have a greater mass than silicon atoms, making heavily doped GeO_2 a better candidate for Raman generation in the infrared. [60] To achieve laser output around 2μ m pumping by the 1064 nm radiation will be difficult and can only be achieved by using at least a ten-stage cascaded Raman laser. For this reason, we used in our study here pumping at longer

wavelengths of 1625nm. Various parameters of the cascaded Raman fibre laser is obtained and shown in the table below: [61]

Intrinsic loss of fibre at pump wavelength	α_0	0.8dB/km
Intrinsic loss of fibre at Stokes wavelength	α_i	21dB/km
Input wavelength	λ_0	1625 nm
1 st stoke wavelength	λ_1	1753 nm
2 nd stoke wavelength	λ_2	1902 nm
Input power	P_0	4 W
Raman gain coefficient	g_i	$3.7(\text{W}\cdot\text{km})^{-1}$
Output FBG coupler reflectivity	R_n	10%
Calculation tolerance	tol	0.002
Length of fibre in cavity	z	45 m

Table 3.3 List of parameters for modeling of cascaded Raman fibre laser at 1.9 μm

Using our simulation algorithm based on Nelder-Mead Simplex Method, the calculated intra-cavity fields of the pump and all Stokes wavelengths are plotted with respect to the distance along the Raman fibre as shown in figure 3.9. The forward propagating pump radiation (1625nm) is gradually absorbed and emitted as first and second Stokes wavelength (1753nm and 1902nm) as it propagates along the fibre. Optical fibre heavily doped with GeO_2 has increased the Raman gain as compared to the normal silica fibre. Thus, we are able to use a shorter length of Raman gain fibre in this modeling. The final output power is 1.4W at the wavelength of 1902nm.

Figure 3.9 (a) Calculated values of the intra-cavity power (W) of Pump wavelength

Figure 3.9 (b) Calculated values of the intra-cavity power (W) of 1st Stokes shift wavelength

Figure 3.9 (c) Calculated values of the intra-cavity power (W) of 2nd Stokes Shift wavelength

3.6 Chapter Summary

In this chapter, we have proposed an effective and computationally compact Nelder-Mead algorithm. The proposed method have good convergence in the modeling of CW cascaded Raman fibre lasers. We have also presented and discussed the convergence of the method in solving the rate equations with boundary conditions. Our results have shown that the proposed method has good computational speed and will be useful in the design and simulation of multi-Stokes cascaded Raman fibre lasers.

Chapter 4 All fibre wavelength tunable thulium doped fibre laser

4.1 Introduction

In the chapter 2, we designed and demonstrated an all fibre thulium doped fibre laser. However, for our 2 μm fibre laser source to be attractive to practical applications, our laser source must be made wavelength tunable.

Wavelength tunability is important for many applications in medical surgery and free space communication because we have to precisely control the medical laser's optical penetration depth in human tissue and match directly onto the narrow absorption peaks of the atmospheric gases. For years, Tm or Ho doped crystal lasers have been used in these applications [63]. However, their free-spaced cavity design limits their potential in real life applications. All fibre laser source is a much more compact and robust design configuration, making it highly desirable, especially for military applications. The maximum tuning range of thulium ion in silica host stretches from 1.7 μm to 2.1 μm , the widest of all rare-earth ions in various host materials [35]. It is possible for thulium doped fibre lasers to be effectively wavelength tuned over a broad region enabling them to be employed in various applications. Recently, there are quite a few works on various tunable Thulium-doped fibre lasers by using gold coated reflection grating on rotation stage [64], volume Bragg gratings [65] and master oscillator power amplifier (MOPA) seeded by a distributed feedback laser (DFB) [66].

In this chapter, we establish experimentally a broadly wavelength-tunable, CW Tm doped all fibre ring laser. In our setup, we utilize a Sagnac loop filter in the laser cavity to achieve broad wavelength tunability in a Tm-doped all fibre laser. The wavelength tunability in the fibre laser is enabled in the laser cavity using a fibre Sagnac loop filter consisting of a length of high birefringence (Hi-Bi) fibre, a polarization controller (PC) and a 3 dB coupler.

We are able to design the properties of the filter by using different lengths of the Hi-Bi fibre. Wavelength tuning of the laser is realized when careful adjusting the two PCs within the cavity. In the experiment, the effect of the Hi-Bi fibre length on the wavelength tuning range is investigated. With an optimized Hi-Bi fibre length, the lasing wavelength can be continuously tuned for $\sim 48\text{nm}$ from 1924.3 nm to 1972.2 nm. It is noted that the range of wavelength tunable using this method is smaller if compared to systems that uses active

elements and free space filters. However, with our all fibre configuration for the application in mind, it is still a favored design in our tunable Tm doped fibre laser source.

The second part of this chapter, we demonstrate experimentally a CW Tm doped all fibre ring laser with fine wavelength-tunability. The wavelength tunability in the fibre laser is enabled by strain and temperature tuning of the Fibre Bragg Grating (FBG). Tuning of the lasing wavelength can be realized by introducing strain or changing the temperature of the FBG in the cavity. We experimentally demonstrated a setup that can be continuously tuned for more than 1.7nm (from 1931.17nm to 1932.89nm) for temperature tuning and more than 16nm (1931.17nm to 1947.19nm).

4.2 Wavelength tunability in Thulium doped fibre laser

Figure 4.1 A tunable fibre laser configuration

Figure 4.1 shows a typical double cladding tunable high power fibre laser configuration. In this configuration, laser output from a high power laser diode source is coupled into a thulium doped gain fibre by the use of a focusing lens. The required tunable wavelength selective feedback is provided by the free space diffraction grating fixed on a rotation stage and intermediate collimating lens.

Figure 4.2 Typical tunable thulium doped fibre laser setup. [35]

An example of thulium doped fibre laser employing such a configuration is shown in figure 4.2 [35]. The tuning range obtained in this setup was 230 nm (1.86 to 2.09 μm) with a maximum power of 7 W. Wavelength tuning was made possible by the extended cavity that comprised of a collimating lens and a diffraction grating to provide wavelength selective feedback. This method offers a wide tuning range by rotating the diffraction grating. However, substantial loss is experienced when signal radiation propagates out of the gain fibre then coupled back from a fibre end in free space. In addition, the configuration cannot be considered to be an all fibre solution because of the presence of free space optics at the dichroic mirror and the diffraction grating. Thus, this configuration is not suitable for applications that require rugged operation conditions such as in defense applications.

Figure 4.3 Four Stage Tm fibre MOPA layout [66]

Figure 4.3[66] shows another thulium doped fibre laser with wavelength tuning capability. The setup consists of a DFB single frequency diode laser with center wavelength at 2040nm as the seeder. The seed laser output is amplified by a three stage pre-amplifier chain, then a MOPA setup with 790nm pump free space coupled. The final laser output can reach up to

608 W. However, the wavelength tuning range is limited by the tuning range of the seeder DFB laser.

These laser sources require free space optics in the form of reflection gratings or dichroic beam splitters which combines the pump and the signal beam. An all fibre solution design is critical as the lasing wavelength stability and tuning range is not restricted by the free space optics, thus making the device compact, flexible and rugged.

4.3 Wavelength-Tunable Tm-doped All fibre Laser Using Hi-Bi Fibre Sagnac Loop Filter

All fibre comb filters, based on a Sagnac loop interferometer, have been employed in multi-wavelength and tunable fibre lasers because it is cheap, low loss, easily implementable, and easy handling [67]. The role of the loop in the laser cavity is to select the wavelength as a band selective filter. In a Sagnac loop filter, the transmission pass band depends on the length and the birefringence of the Hi-Bi fibre [68]. However, it is not practical to vary these parameters during the operation of the system as changing these parameters usually mean we have to remove and replace the Hi-Bi fibre in the cavity. Alternatively an all fibre polarization controller (PC), made from a half-wave plate and two quarter-wave plates, can be used to tune the periodic multichannel spectrum of the filter [69].

Birefringence refers to the phenomenon in which a material exhibits different refractive indices in different directions. It can be an intrinsic property of a material or induced by applying a force (electric field or mechanical stress) on the material.

Due to imperfections in fabrication and external influences such as fibre bending, mechanical stress, vibrations and temperature fluctuations, random birefringent effects occur along the fibre. This then results in random coupling between the two polarization directions and hence random polarization changes along the fibre length. Therefore, polarization maintaining fibres (PMFs) help to create consistent birefringence patterns along its length, preventing coupling between the two orthogonal polarization direction.

For the Sagnac loop filter, a high birefringence (Hi-Bi) PMF is used. The Hi-Bi fibre introduce an even stronger linear birefringence in order to negate the random birefringence effects so that no coupling will occur and the state of polarization would be unchanged and hence maintained throughout the fibre length.

When a linearly polarized light is launched into a Hi-Bi fibre at an angle of 45° to the principle axis, it splits into two components with equal power each travelling along one of the principle axis. The component along the axis with the higher refractive index (also known as the slow axis – represented arbitrarily by the blue arrow in figure 4.4 below) travels slower than the component along the axis with the lower refractive index (the fast axis – red arrow in figure 4.4). This introduces a phase retardation $\Delta\phi$ between the two components which is dependent on the fibre length. Therefore, we will establish the required length of the Hi-Bi PMF fibre to achieve the desired wavelength spacing.

Figure 4.4 Schematic drawing of the Hi-Bi fibre and the Sagnac loop filter

The schematic diagram of the experimental setup is shown in figure 4.5. In our experiment, a 5-m-long Thulium-doped fibre in GTwave (SPI, UK) configuration is used as the gain fibre to maintain the all fibre configuration. Two 790 nm pump laser diodes (Apollo Instrument, USA) with 18 W maximum output power each are spliced onto the pump fibre ends of the Thulium gain spool. Pump wavelength of 790 nm corresponds to the $^3\text{H}_6 \rightarrow ^3\text{H}_4$ pumping scheme. A 30/70 fibre coupler with 30% output is used for light extraction from the laser cavity. A fibre-based polarization-independent isolator is spliced into the cavity to ensure unidirectional operation of the laser. A fibre-based PC in the cavity controls the state of polarization of the propagating wave.

Figure 4.5 Experimental setup of the wavelength-tunable Tm-doped fibre laser

The novelty of our work in the Sagnac loop based tunable thulium doped fibre laser is its all fibre configuration without any external free space optics and packaged gratings. The output power of our laser is above 340 mW, more than 10 times more than the results shown by Li et al. [37] which used a packaged fiberized grating filter in the cavity.

The Hi-Bi fibre (Nufern, USA) Sagnac loop is constructed with a 3-dB coupler, a length of Hi-Bi fibre and a fibre-based PC. When the optical field in the laser cavity reaches the 3dB-coupler, it splits into two fields with equal power each propagating in one of the output arms of the 3-dB coupler. When the fields travel through the Hi-Bi fibre, the slow and fast axes introduce a phase difference $\Delta\phi$ between the two components which is dependent on the fibre length. The two counter-propagating fields interfere back after the propagation through the Sagnac loop at the 3-dB coupler. The calculations below determine the Length of Hi-Bi fibre to be used in the setup:

Wavelength shift (or peak spacing),

$$\Delta\lambda = \frac{\lambda^2}{BL} \quad (4.1)$$

where λ = Wavelength

B = Birefringence

L = Length of Hi-Bi PMF fibre

Based on the data sheet of the Hi-Bi PMF used in the project,

$$B = 1.5 \times 10^{-4}$$

Rearranging Equation (5.1),

$$L = \frac{\lambda^2}{B\Delta\lambda} \quad (4.2)$$

For a 5 nm wavelength shift (i.e. $\Delta\lambda = 5$ nm),

$$\begin{aligned} L &= \frac{(1930 \times 10^{-9})^2}{1.5 \times 10^{-4} \times 5 \times 10^{-9}} \\ &= 4.97 \text{ m} \end{aligned} \quad (4.3)$$

Similarly, the subsequent Hi-Bi fibre lengths for the wavelength shifts is calculated and shown in table 4.1.

Wavelength spacing, $\Delta\lambda/\text{nm}$	Length of PMF, L/m
5	4.97
10	2.48
15	1.66
20	1.24

Table 4.1 Wavelength shift and the corresponding Hi-Bi PMF fibre length required

Figure 4.6 Diagrammatic representation of a fibre polarization controller [70]

The purpose of a polarization controller (PC) is to convert an input polarization to any other output polarization state. As shown schematically by figure 4.6 above, the PC consists of 3 plates, namely a quarter wave plate (QWP), a half wave plate (HWP) followed by another quarter wave plate. The first QWP converts any arbitrary input polarization to a linearly polarized form. The HWP then rotates the linearly polarized light to a desired angle based on

the angle of tilt. Lastly, the second QWP then translates the linearly polarized light to a desired polarization state, thereby converting the input polarization to the polarization state of one's choice.

A certain loop diameter in the PC for a given wavelength will generate a phase retardation of 90° or $\pi/2$ radian, similar to the effect of a quarter-wave plate for classical optics. Similarly, a half wave plate can be designed with twice the number of loops wound on the same paddle, thereby generating a 180° phase retardation. The paddles can be tilted to alter the relative direction of the fast and slow axes, achieving the same effect as the rotation of the conventional optical wave plate.

Bending of a normal silica fibre introduces stress in the fibre and makes it linearly birefringent with the fast and slow axes of the orthogonal planes in the fibre loop.

Bending-induced birefringence of the single mode fibre [71],

$$\Delta n_{eff} = n_{ex} - n_{ey} = -C \left(\frac{b}{R} \right)^2 \quad (4.4)$$

Where n_{ex} and n_{ey} = Effective indices in the fundamental modes polarized in the fast and slow axes of the bend respectively

b = Radius of the fibre cladding

R = Radius of the polarization controller loop

C = Constant that depends on the fibre material and the elasto-optic properties of the fibre, $C \approx 0.133$ at 633 nm

The bend-induced phase difference between the two polarizations,

$$\begin{aligned} \Delta\phi &= \frac{2\pi}{\lambda_0} \Delta n_{eff} 2\pi R N \\ &= \frac{4\pi^2}{\lambda_0} C \frac{b^2}{R} N \end{aligned} \quad (4.5)$$

where λ_0 = Lasing wavelength

Δn_{eff} = Bending-induced birefringence

N = Number of loops of radius R (to coil in the grooves of the polarization controller)

Because most of the PCs were made for laser wavelengths centered around 1550 nm and 1310 nm and not for the lasing wavelength of thulium doped fibre lasers. Below shows the calculations of the number of loops of fibre to be wound in order to form the QWPs and HWP for the PC.

To achieve phase difference of π , coil radius corresponding to a half wave plate (HWP),

$$R(\Delta\phi = \pi) = \frac{4\pi C b^2 N}{\lambda_0} \quad (4.6)$$

Similarly, for a quarter wave plate (QWP) coil radius with phase difference of $\pi/2$,

$$R\left(\Delta\phi = \frac{\pi}{2}\right) = \frac{8\pi C b^2 N}{\lambda_0} = 2 R(\Delta\phi = \pi) \quad (4.7)$$

Using equation (4.6) for the QWP,

$$R = \frac{8\pi C b^2 N}{\lambda_0}$$

Rearranging and making N the subject of the formula,

$$N_{QWP} = \frac{\lambda_0 R}{8\pi C b^2} \quad (4.8)$$

Similarly for the HWP, using equation (4.5),

$$R = \frac{4\pi C b^2 N}{\lambda_0}$$

$$N_{HWP} = \frac{\lambda_0 R}{4\pi C b^2} = 2N_{QWP} \quad (4.9)$$

For the ThorLabs PC,

$$R = \frac{1}{2} \times 5.7 \times 10^{-2} = 0.0285 \text{ m}$$

$$N_{QWP} = \frac{\lambda_0 R}{8\pi C b^2}$$

$$= \frac{1930 \times 10^{-9} \times 0.0285}{[8\pi \times 0.133 \times (62.5 \times 10^{-6})^2]}$$

$$= 4.213$$

$$\approx 4 \text{ rounds}$$

$$N_{HWP} = 8 \text{ rounds} \tag{4.10}$$

The Sagnac loop produces a comb spectrum and the comb spectral spacing is controlled by varying the Hi-Bi fibre length by making use of equation (4.1). The peak spacing is inversely proportional to the Hi-Bi fibre length, i.e. a closely spaced peak to peak transmission spectrum of around 5 nm can be obtained by using a 5m long Hi-Bi fibre.

The filtering bandwidth can be controlled by choosing an appropriate length of the Hi-Bi fibre and the filtering transmission wavelength can be altered by adjusting the paddles of the PC in the fibre loop. The PC outside the fibre loop (PC2) controls the polarization state of the circulating light in the ring cavity. Its variation controls the signal to noise contrast ratio. The laser power output is monitored using a power meter placed at the free output fibre end of the coupler.

The Sagnac loop filter produces a comb spectrum and the comb spectral spacing can be controlled by varying the Hi-Bi fibre length. When using a 5m long Hi-Bi fibre, a 5nm spaced peak to peak transmission spectrum can be obtained. The drive current of the two pump diodes was slowly increased so that the input power reached the threshold of the fibre laser. Figure 4.7 shows the laser output power as a function of the launched pump power. With the input pump power of 4 W, the laser output power obtained was 0.34 W at the wavelength of 1930nm

Figure 4.7 Output power of the fibre ring laser against the launched pump power

To allow us to observe the wavelength tunability of the fibre laser with Sagnac loop interferometer in the experiment, we used an optical spectrum analyzer (NIR256, from Ocean Optics, USA) which is able to examine the wavelength range from 862.2nm to 2607.3nm. Both the PCs in the ring cavity and Sagnac loop were carefully adjusted to obtain the wavelength shifting. The tilting the PC in the ring cavity will in turn alters the overall gain spectrum. This adjusts the overall birefringence in the laser cavity and controls the effective gain bandwidth. On the other hand, the PC in the Sagnac loop governs the state of polarization of the signal propagating in the loop. In addition, adjusting this PC in the Sagnac loop affects the contrast ratio of the comb filter transmission spectrum. Figure 4.8 shows that the laser output could be tuned continuously in the range of 1924.3nm to 1972.2nm covering a total of ~48nm.

Figure 4.8 Spectrum of the laser output tuned from 1924.3nm to 1972.2nm

The Hi-Bi fibre Sagnac loop filter Tm-doped fibre laser can be broadly tuned by careful selection of the Hi-Bi fibre length. This allows us to optimize the laser operation and tuning range. Stable laser operation and wavelength tuning can be observed when 0.5m to 5.08m of Hi-Bi fibre was used in the Sagnac loop filter. Comparing our setup to other 2 μ m laser source [35,64-66], our setup has the advantage of low cost, easy handling and stable operation.

4.4 All fibre thulium doped fibre laser based on Fibre Bragg Gratings (FBGs)

4.4.1 Strain tuning of FBG to achieve wavelength tunability

Figure 4.9 Fibre Grating-based all fibre typed tunable high power fibre laser

With the rugged requirements of the defense applications in mind, another all fibre structure tunable fibre laser is shown in figure 4.9. In this all fibre solution, a tunable fibre Bragg grating with high reflection is adopted inside the fibre cavity as the cavity mirror. The other

mirror is formed by perpendicularly cleaving of the fibre end to provide 4% reflection for the cavity oscillation. This all fibre structure tunable fibre laser is attractive due to its superior all fibre structure, low loss, good repeatability and reliability [72,73]. However, its tuning range is limited by the mechanical characteristics of the fibre grating.

As we know, FBG is basically an optical fibre for which the refractive index of the core is altered to a periodic or quasi-periodic index modulation profile. The reflected wavelength (Bragg wavelength) is given by [79]

$$\lambda_B = 2n_{eff}\Lambda \quad (4.11)$$

where Λ is the grating pitch and n_{eff} is the effective index of the fibre core, both of which is changed with the ambient temperature and the applied strain. And so the corresponding shift in Bragg wavelength with temperature change ΔT and applied strain ε can be expressed using [79]

$$\begin{aligned} \Delta\lambda_B &= \Delta\lambda_{BT} + \Delta\lambda_{B\varepsilon} \\ &= 2\left(\Lambda \frac{\partial n_{eff}}{\partial t} + n_{eff} \frac{d\Lambda}{dt}\right)\Delta T + 2\left(\Lambda \frac{\partial n_{eff}}{\partial L} + n_{eff} \frac{d\Lambda}{dL}\right)\Delta L \end{aligned} \quad (4.12)$$

Where ΔT is the change in grating temperature, and ΔL is the change in grating length. For FBG wavelength tuning, the method of adding some strain on FBG is preferred because of the fast tuning speed compared with thermal tuning.

Axial strain sensitivity of an FBG is given by the following equation,

$$\frac{\Delta\lambda}{\lambda_B} = (1 - P_e)\varepsilon_{ax} \quad (4.13)$$

P_e being the effective photo-elastic coefficient of the fibre glass, and ε_{ax} is the axial strain (tensile or compressive) experienced by the FBG. The average value of P_e is about 0.22 [81-83].

The value of λ_B in our setup is 1931.1764 nm. To measure and verify the strain coefficients, strain is applied to the FBG by fixing both ends of the grating with temperature Epoxy and stretched with a translation stage. During the strain testing, the FBG was maintained at room

temperature. The measured wavelength shift versus the applied strain on FBG is presented in figure 4.10. It shows a very good repeatability for FBG wavelength tuning with 16nm tuning range that corresponds to about 1.2% applied strain. During this 16 nm shift range, the peak reflection change is less than 0.1 dB, which presents neglectable spectrum deformation. And, the wavelength shift is linear to the applied strain. Compared with theoretical calculations, the wavelength shift slope is a little bit of lower for the experimental result. This discrimination is mainly caused by the elastic expansion and the deformation of the epoxy we used here.

Figure 4.10 Wavelength tuning of the laser output with strain applied on FBG.

4.4.2 Thermal tuning of Fibre Bragg Gratings

As compared to strain tuning, thermal tuning of the FBG has a smaller tuning range and the response time is slower. However, in FBG strain tuning usually require the FBG to be fixed permanently on the translation stage. It is very easy for the FBG to be damaged during the tuning process or when we try to remove the FBG from the stage. Thermal FBG tuning on the

other hand does not face the same problem. Thus, thermal FBG tuning can be an alternative for small wavelength range tuning of around 1 nm [84].

From the equations (4.11) and (4.12), the shift in the Bragg wavelength ($\Delta\lambda_B$) is dependent on temperature changes.

Using a ceramic heater oven, the heating temperature was varied from 40°C to 150°C. The transmission spectrum was then observed on the OSA at 10°C intervals starting at 40°C. The shift in the Bragg wavelength ($\Delta\lambda_B$) is dependent on temperature changes. Assuming that the temperature of the fibre (T_F) is equivalent to the temperature of the surroundings (T_0), i.e. $T_F \approx T_0$.

Temperature change of the FBG,

$$\Delta T_{FBG} = T_H - T_0 \quad (4.14)$$

Where ΔT_{FBG} = temperature change of FBG

T_H = heating temperature

T_0 = temperature of the surroundings

Differentiating equation (4.12) with respect to temperature,

$$\frac{\Delta\lambda_B}{\Delta T_{FBG}} = 2 \left[n_{eff} \frac{d\Lambda}{dT} + \Lambda \frac{dn_{eff}}{dT} \right] \quad (4.15)$$

Simplifying equation (4.15),

$$\begin{aligned} \Delta\lambda_B &= 2 \left[n_{eff} \frac{d\Lambda}{dT} + \Lambda \frac{dn_{eff}}{dT} \right] \Delta T_{FBG} \\ &= 2 n_{eff} \Lambda \left[\frac{1}{\Lambda} \frac{d\Lambda}{dT} + \frac{1}{n_{eff}} \frac{dn_{eff}}{dT} \right] \Delta T_{FBG} \\ &= \lambda_{B0} (\alpha_\Lambda + \alpha_n) \Delta T_{FBG} \end{aligned} \quad (4.16)$$

Where λ_{B0} = FBG Bragg wavelength at initial temperature T_0

α_Λ = thermal expansion coefficient

α_n = thermo-optic coefficient

FBG Thermal Sensitivity (S_{FBG})

$$S_{FBG} = \frac{\Delta\lambda_B}{\Delta T_{FBG}} = \lambda_{B0}(\alpha_\Lambda + \alpha_n) \quad (4.17)$$

Thus,

$$\begin{aligned} \lambda_B &= \lambda_{B0} + \Delta\lambda_B \\ &= \lambda_{B0} + S_{FBG}\Delta T_{FBG} \\ &= \lambda_{B0} + S_{FBG}(T_H - T_0) \end{aligned} \quad (4.18)$$

Parameters used for calculations as constants,

$$\begin{aligned} \text{Thermal Coefficient, } \alpha_\Lambda &= \frac{1}{\Lambda} \frac{d\Lambda}{dT} \\ &= 0.55 \times 10^{-6} \text{ (}^\circ\text{C}^{-1}\text{)} \text{ (obtained from [84])} \end{aligned} \quad (4.19)$$

$$\begin{aligned} \text{Thermo-optic Coefficient, } \alpha_n &= \frac{1}{n_{eff}} \frac{dn_{eff}}{dT} \\ &= 8.6 \times 10^{-6} \text{ (}^\circ\text{C}^{-1}\text{)} \text{ (obtained from [84])} \end{aligned} \quad (4.20)$$

Hence, the equation can be simplified to

$$\begin{aligned} \lambda_B &= \lambda_{B0}[1 + \Delta T_{FBG}(0.55 \times 10^{-6} + 8.6 \times 10^{-6})] \\ &= \lambda_{B0}[1 + 9.15 \times 10^{-6} \times (T_H - T_0)] \end{aligned} \quad (4.21)$$

Assuming that the FBG has thermal and thermo-optic coefficients as stated in Equations (4.19 and 4.20), substituting the appropriate values for λ_{B0} , T_H and T_0 into equation (4.21), and the respective λ_B values can thus be easily calculated.

FBG temperature was achieved by incorporating a ceramic heater over the FBG illustrated by the red dotted box in figure 4.11. By varying the temperature using a temperature controller, measurement readings for the laser emission wavelength were recorded at the diode pump current value of 25A.

Figure 4.11 Diagrammatic representation of laser setup with FBG in heating oven

At Diode Pump Current, $I_{\text{pump}} = 25\text{A}$,

Reference wavelength, $\lambda_{B0} = 1931.1764\text{ nm}$,

Reference temperature, $T_0 = 28^\circ\text{C}$,

$T/^\circ\text{C}$	Experimental Data		Theoretical Data	
	Centre wavelength, λ_c / nm	Wavelength shift, $\Delta\lambda / \text{nm}$	Centre wavelength, λ_c / nm	Wavelength shift, $\Delta\lambda / \text{nm}$
38	1931.3736	0.1972	1931.353103	0.176702641
67	1931.7663	0.5899	1931.86554	0.689140298
78	1932.1232	0.9468	1932.059913	0.883513203
110	1932.4518	1.2754	1932.625362	1.448961653
125	1932.7297	1.5533	1932.890416	1.714015614
135	1932.8908	1.7144	1933.067118	1.890718254

Table 4.2 FBG tuning at different temperatures on laser setup for $I_{\text{pump}} = 25\text{ A}$

Figure 4.12 Spectrum of the laser output thermal tuned by FBG

Figure 4.13 Spectrum of the laser output thermal tuned by FBG

Generally, the wavelength shift obtained from experimental results using the FBG temperature tuning was limited. The wavelength shift and the temperature increase have a linear relationship as described by the mathematical model represented in Equation (4.21) as well as the experimental results shown in figure 4.12. However, the heating temperature is largely limited by how heat resistant the FBG coating. Figure 4.13 shows the spectrum of the laser output thermal tuned by FBG. The wavelength spectrum corresponding to different temperature applied to the FBG is shown. As we increase the FBG temperature from 28 °C to 135 °C, we observe the centre wavelength of the laser being tuned towards the long wavelength. The total tuning range shown is 1.7144 nm limited by the heating stage used. For this tunable laser setup, the laser linewidth is of 0.067 nm or 5.38 GHz. The laser extinction ratio ranges from 7 dB to 8dB depending on lasing wavelength. The tunable spectral width of this setup is 1.7144 nm. The output power of this laser is 1 W. To protect the OSA used to measure the spectrum, we added attenuation at the output of the laser before allowing the radiation to reach the detector of the OSA. This explains why the plot in figure 4.7 shows power less than 12 nW.

4.5 Chapter Summary

In summary, an all fibre tunable 2 μm Tm-doped fibre laser was experimentally demonstrated in this chapter. Broadband wavelength tunability was achieved by employing a Hi-Bi fibre Sagnac loop acting as a comb filter in the laser ring cavity in 2 μm Tm-doped fibre lasers. Tuning was carried out by careful controlling of the two PCs in the setup. Our design enables all fibre tunable laser as there was no external free-space optics required. Stable laser output was demonstrated at various wavelengths from 1924.3 nm to 1972.2 nm covering a total range of ~48 nm.

In addition, we investigate FBG-based tunable fibre laser. Both mechanical strain and thermal tuning mechanism of FBG was analyzed in detail. Respective experiment setups on tunable FBG were done to verify the calculations. Strain tuning shows a 16 nm tuning range in which there isn't degradation and wavelength shift. On the other hand, thermal tuning showed consistent results yielding a maximum wavelength shift of 1.7 nm over the 97°C range.

Chapter 5 Lead-Bismuth-Gallium glass preform and optical fibre fabrication

5.1 Introduction

Heavy metal oxide glasses are soft glass systems that are based on heavy metal oxides and do not have the content of silica. This class of glass system in theory can obtain high transmission in the Mid Infrared region. However, they are not easy to fabricate. The physical and optical characteristics are critical to produce large quantity in large sizes. Lead-bismuth-gallium (PBG) is a non-silica based glass used in the fabrication of optical fibre with high nonlinearity, low transmission loss, high transition temperature, and a broad transparency window. With a nonlinearity two orders higher than that of the fluoride based fibres, it has attracted much attention worldwide for its potential applications in the mid-infrared regime, particularly for applications such as supercontinuum generation. The fabrication process of lead-bismuth-gallium optical fibre is still not mature, leading to relative high transmission loss. However its intrinsic advantages such as high nonlinearity, high transition temperature, and low transmission loss provide a huge potential to achieve a higher output power by further improving the fibre fabrication processes. In this chapter, we document the design and demonstration of a glass system of PBG optical fibre fabrication aimed for the delivery and nonlinear applications in the wavelength region of 2 μm and above.

5.2 Lead-Bismuth-Gallium glass system

Gallate glass containing lead and Bismuth oxide (PBG) was reported to have the highest χ^3 of other oxide glasses. Only lead and bismuth oxides glasses are unstable with respect to crystallisation. Additional portion of Ga_2O_3 plays the role of the glass former, however too much percentage of it would degrade the glass refractive index. W.H. Dumbaugh has done a series of studies of PBG glass compositions [15, 20, 21] and reported good glass forming composition with high refractive index. However, PBG glass fibres have not yet being demonstrated. Ducros et al. [22, 23] demonstrated holey fibres based on $\text{PbO-Bi}_2\text{O}_3\text{-Ga}_2\text{O}_3\text{-SiO}_2\text{-CdO}$ glass compositions. Additional SiO_2 made the composition more stable against devitrification. However, SiO_2 has strong absorption at the wavelength around 3.0 μm and move the multi-phonon absorption edge toward the shorter wavelength. Thus in this chapter, we focus in the glass forming system without any SiO_2 added.

5.3 Glass melting of Lead-Bismuth-Gallium glasses

Various glass compositions each with different ratio of PbO, Ga₂O₃ and Bi₂O₃ were chosen to test out their transmission and physical properties. PbO, Ga₂O₃ and Bi₂O₃ are powders obtained from chemical suppliers with purity of 99.999%. The chemical powders are carefully weighted separately and are batched in a glove-box controlled environment. The batched samples are then mixed for at least 2 hours using a roller mixer. The mixed sample is checked visually for homogeneity and the content is loaded into a chosen crucible. In our glass melts, we used either alumina crucibles or platinum crucibles. The crucible loaded with sample is then melted at 1050°C for one hour under 3 l/min oxygen-nitrogen premix gas purging. During the push out from the melt furnace, the melted glass is either poured into cast for casting or left in the crucible to quench to room temperature. Table 5.1 below shows the complete list of PBG glass melts performed in related to this project.

<i>Glass Code</i>	<i>Composition</i>	<i>Furnace</i>	<i>Crucible used</i>	<i>Purpose</i>	<i>Date Scheduled</i>	<i>Comments</i>	
PBG 1	Bi ₂ O ₃ 50, Ga ₂ O ₃ 25, PbO 25	F1 L2	Pt 1	Trial melt	18/04/2013	Glass complete
PBG 2	Bi ₂ O ₃ 50, Ga ₂ O ₃ 25, PbO 25	HF L1	Pt 1	Trial melt with 24hr Ar purge	22/04/2013	Glass failed	
PBG 3	Bi ₂ O ₃ 50, Ga ₂ O ₃ 25, PbO 25	F1 L2	Alumina	Trial melt in Al ₂ O ₃	26/04/2013	Glass formed but attached firmly to crucible
PBG 4	Bi ₂ O ₃ 50, Ga ₂ O ₃ 25, PbO 25	Annealing F2 L2	Pt 2	Test of new chemicals (testbourne) and slow quenching	07/06/2013	Glass complete
PBG 5	Bi ₂ O ₃ 50, Ga ₂ O ₃ 25, PbO 25	F1 L2	Pt 2	Experiment on the effect of purging of chemicals	15/06/2013	Glass complete

PBG 6	Bi ₂ O ₃ 45, Ga ₂ O ₃ 30, PbO 25	Annealing F2 L2	Pt 3	Determine the effect of Ga ₂ O ₃ on mid-IR transmission	07/06/2013	Glass complete
PBG 7	Bi ₂ O ₃ 55, Ga ₂ O ₃ 15, PbO 30	F1 L2	Pt 3	Determine the effect of Ga ₂ O ₃ on glass formation	14/06/2013	Glass crystallised during annealing
PBG 8	Bi ₂ O ₃ 55, Ga ₂ O ₃ 15, PbO 30	F1 L2	Pt 3	Re-melt of PBG 7	18/06/2013	Glassy sample formed but cracked to pieces when removed from crucible
PBG 9	Bi ₂ O ₃ 45, Ga ₂ S ₃ 30, PbO 25	VF L1	Carbon	Trial melt with Ga ₂ S ₃	20/06/2013	Glass fail	
PBG 10	Bi ₂ O ₃ 50, Ga ₂ O ₃ 25, PbO 25	VF L1	Carbon	Trial melt in Carbon crucible in VF	20/06/2013	Glass fail	
PBG 11	Bi ₂ O ₃ 50, Ga ₂ O ₃ 25, PbO 25	F1 L2	Pt2 Pt 3	Trial melt for 120g melt size	10/07/2013	Content of two crucibles tipped into single one. Glass formed but fail to remove from crucible	
PBG 12	Bi ₂ O ₃ 50, Ga ₂ O ₃ 25, PbO 25	F1 L2	Pt2	Re-melt of PBG 11 and trial casting into extrusion die	12/07/2013	Glass formed and casted into extrusion die
PBG 13	Bi ₂ O ₃ 50, Ga ₂ O ₃ 25, PbO 25	F1 L2	Pt boat 1	Trial for Pt boat and glass casting for extrusion	15/07/2013	Glass formed and casted into extrusion die
PBG 14	Bi ₂ O ₃ 50, Ga ₂ O ₃ 25, PbO 25	F1 L2	Pt boat 1/ Cast in Pt boat 2	Trial casting for in Pt boat for longer pre-form (60g)	16/07/2013	Glass formed and removed in the shape of Pt boat. (5mm thickness)
PBG 15	Bi ₂ O ₃ 50, Ga ₂ O ₃ 25, PbO 25	F1 L2	Pt boat 1/ Cast in Pt boat 2	Casting in Pt boat for pre-form (100g)	17/07/2013	Glass formed but cracked open when removed (8mm thickness)

PBG 16	Bi2O3 45, Ga2O3 30, PbO 25	F1 L2	Pt 1	Trial for rod insertion	11/09/2013	Glass failed	
PBG 17	Bi2O3 50, Ga2O3 25, PbO 25 ; GeO2 10*	F1 L2	Pt 1	Trial for adding GeO2 to lower index	16/09/2013	Glass failed	
PBG 18	Bi2O3 50, Ga2O3 25, PbO 25	F1 L2	Alumina	Determine failure of PBG16 & 17	16/09/2013	Glass complete
PBG 19	Bi2O3 25.11, Ga2O3 17.75, PbO 57.14	F1 L2	Alumina	New glass composition	16/09/2013	Glass complete
PBG 20	Bi2O3 50, Ga2O3 25, PbO 25	F1 L2	Alumina	New chemical from Alfa Aesar	18/09/2013	Glass complete
PBG 21	Bi2O3 25.11, Ga2O3 17.75, PbO 57.14	F1 L2	Alumina	New composition with Alfa Aesar	20/09/2013	Glass complete
PBG 22	Bi2O3 25.11, Ga2O3 17.75, PbO 57.14	F1 L2	Alumina	Change of PBO batch	23/09/2013	Glass Complete
PBG 23	Bi2O3 25.11, Ga2O3 17.75, PbO 57.14	F1 L2	Alumina	120g melt for extrusion	24/09/2013	Glass failed as spillage during casting
PBG 24	Bi2O3 22.60, Ga2O3 15.98, PbO 51.42; GeO2 10	F1 L2	Alumina	120g for extrusion with GeO2 (Clad)	24/09/2013	Glass complete. Some opaque specks found in glass.

PBG 25	Bi2O3 25.11, Ga2O3 17.75, PbO 57.14	F2 L2	Alumina	For Extrusion of core glass	27/09/2013	Glass complete
PBG 26	Bi2O3 22.60, Ga2O3 15.98, PbO 51.42; GeO2 10	F2 L2	Alumina	Change of Bi2O3	30/09/2013	Glass Complete
PBG 27	Bi2O3 22.60, Ga2O3 15.98, PbO 51.42; GeO2 10	F2 L2	Alumina	180g for extrusion with GeO2 (Clad)	01/10/2013	Glass Complete
PBG 28	Bi2O3 50, Ga2O3 25, PbO 25	F2 L2	Alumina	160g billet for extrusion of core glass	14/10/2013	Glass complete. Opaque in appearance.
PBG 29	Bi2O3 25.11, Ga2O3 17.75, PbO 57.14	F2 L2	Alumina	Melt to test chemicals as particles are found in PBG 28	16/10/2013	Glass complete
PBG 30	Bi2O3 49.65, Ga2O3 17.12, PbO 33.23	F2 L2	Alumina	Glass melt for test glass with index n=2.25.	17/10/2013	Glass complete. Opaque.
PBG 31	Bi2O3 25.11, Ga2O3 17.75, PbO 57.14	F2 L2	Alumina	Testbourne chemicals. New batch of 500g PbO.	23/10/2013	Glass complete
PBG 32	Bi2O3 50, Ga2O3 25, PbO 25	F1 L2	Alumina	Testbourne chemicals. New batch of 500g PbO.	23/10/2013	Glass complete
PBG 33	Bi2O3 25.11, Ga2O3 17.75, PbO 57.14	Clean room L-shape glove box	Alumina	First melt in cleanroom glovebox.	25/10/2013	Glass complete

PBG 34	Bi ₂ O ₃ 22.60, Ga ₂ O ₃ 15.98, PbO 51.42; GeO ₂ 10	F2 L2	Alumina	Melt for extrusion of cladding glass	29/10/2013	Glass complete. Specks of opaque particles found in glass.
PBG 35	Bi ₂ O ₃ 22.60, Ga ₂ O ₃ 15.98, PbO 51.42; GeO ₂ 10	F2 L2	Alumina	Melt for extrusion of cladding glass. Trial for longer melt time	31/10/2013	Glass complete. Glass is opaque with particles.
PBG 36	Bi ₂ O ₃ 22.60, Ga ₂ O ₃ 15.98, PbO 51.42; GeO ₂ 10	F2 L2	Alumina	Test melt for a short time (20mins) two separate crucibles.	13/11/2013	Glass complete
PBG 37	Bi ₂ O ₃ 22.60, Ga ₂ O ₃ 15.98, PbO 51.42; GeO ₂ 10	F2 L2	Alumina	Melt for extrusion of cladding glass	14/11/2013	Glass complete
PBG 38	Bi ₂ O ₃ 22.60, Ga ₂ O ₃ 15.98, PbO 51.42; GeO ₂ 10	F2 L2	Alumina	Melt for extrusion of cladding glass	15/11/2013	Glass complete
PBG 39	Bi ₂ O ₃ 22.60, Ga ₂ O ₃ 15.98, PbO 51.42; GeO ₂ 10	Clean room L-shape glove box	Pt 2	Large volume melt in glovebox. n=2.16	10/12/2013	Glass complete
PBG 40	Bi ₂ O ₃ 25.11, Ga ₂ O ₃ 17.75, PbO 57.14	Clean room L-shape glove box	Pt 3	Large volume melt in glovebox. n=2.22	10/12/2013	Glass complete
PBG 41	Bi ₂ O ₃ 25.11, Ga ₂ O ₃ 17.75, PbO 57.14	Clean room L-shape glove box	Pt 3	Large volume melt in glovebox. Cast in extrusion die. n=2.22	12/12/2013	Glass complete

PBG 42	Bi₂O₃ 22.60, Ga₂O₃ 15.98, PbO 51.42; GeO₂ 10	F2 L2	Alumina	Melt for crystallization experiment when annealed at 500°C.	15/01/2014	Glass complete
PBG 43	Bi₂O₃ 20.09, Ga₂O₃ 14.20, PbO 45.71; GeO₂ 20.00	F2 L2	Alumina	First trial with 20% GeO₂ added.	17/01/2014	Glass complete
PBG 44	Bi₂O₃ 22.60, Ga₂O₃ 15.98, PbO 51.42; GeO₂ 10	Clean room L-shape glove box	Pt 3	Large volume melt in glove box.	20/01/2014	Glass complete
PBG 45	Bi₂O₃ 20.09, Ga₂O₃ 14.20, PbO 45.71; GeO₂ 20.00	Clean room L-shape glove box	Pt 3	Large volume melt in glove box.	22/01/2014	Glass complete
PBG 46	Bi₂O₃ 22.60, Ga₂O₃ 15.98, PbO 51.42; GeO₂ 10	Clean room L-shape glove box	Pt 3	Large volume melt in glove box. Cast in the shape of a square rod.	21/01/2014	Glass complete

Table 5.1 List of PBG glass melts done for the development of the fibre.

From the resultant glass obtained from the list above, we can see that glass melt in platinum crucibles have the characteristic orange appearance while glass melt done in alumina crucibles have the characteristic yellowish appearance. This colour difference is caused by reactions of the glass melts at the molten temperature with the crucible material. This is the reason why we try to keep the glass melting time to a minimum.

It is very important for us to know the thermal properties of the glass we produced. Different from very stable silica glass systems, soft glass such as our lead-bismuth-gallium glass is easily crystallised. Glasses that we melted will need to go through various heat treatment processes such as extrusion, preform canning and fibre drawing. To obtain the thermal properties of our glass samples, we allow our samples to go through the differential thermal analysis (DTA) system. Figure 5.1 below shows the DTA result of glass sample PBG 19. From the analysis, we can find out the region of glass formation, crystallization and melting

points. This is useful to determine the annealing temperature furnace temperature for future melts, determine the temperatures of processes such as annealing, extrusion, preform canning and fibre drawing.

Figure 5.1 DTA result of PBG 19

The glass has a glass transition temperature (T_g) around 330 $^{\circ}\text{C}$ and crystallization peak (T_p) presented at 500 $^{\circ}\text{C}$. When the glass is heated to the transition temperature, there is a chance that crystals will start to form in the sample. Above the transition temperature, the rate of crystal growth will increase to the crystallization peak. Thus during all these heat treatment fabrication processes, we have to ensure that the glass sample stays a minimum duration above the glass transition temperature.

The measurement of glass refractive index was carried out using ellipsometry at the wavelength range from the visible to 1600 nm. The result is shown in figure 5.2 below. The glass disc samples have one side fine polished to 1 μm finish and the other side roughed. A high linear refractive index is obtained from this glass, e.g. 2.25 and 2.22 at the wavelength of 1060 and 1550 nm, respectively.

Figure 5.2 Refractive index analysis of PBG 19

To achieve the step index profile of the fibre design, we need to identify glass compositions that give different refractive index for the core and the cladding. We also have to take into consideration of the physical properties of the chosen composition as the glass have to go through a series of heat treatment processes (Casting, extrusion, canning and fibre drawing) that may cause crystallization in the glass preform of resultant fibre.

We have identified two possible PBG glass compositions for the fibre core structure.

Component	% molar
PbO	25%
Ga ₂ O ₃	25%
Bi ₂ O ₃	50%

Table 5.2 Core glass composition 1

Component	% molar
PbO	57.14%
Ga ₂ O ₃	17.75%
Bi ₂ O ₃	25.11%

Table 5.3 Core glass composition 2

Both these glass composition have the refractive index of 2.22.

As for the cladding glass composition, we added a 10 mole % of GeO₂ to glass composition 2. The addition of GeO₂ to the composition will lower the refractive index and also give better physical and thermal stability. However, GeO₂ added will also reduce the infra-red transmission window of the resultant glass. Thus, we will only add GeO₂ to the cladding glass, not limiting the light transmission in the infra-red region in the core. The cladding glass composition has refractive index of 2.16.

Component	% molar
PbO	51.426%
Ga ₂ O ₃	15.975%
Bi ₂ O ₃	22.60%
GeO ₂	10.0%

Table 5.4: Cladding glass composition

5.4 Reduction of OH content of glass melts

Apart from thermal and refractive index analysis, we also need to investigate the optical transmission properties of the glass samples. To measure the infrared spectrum of transmission of the glass samples, we used a fourier transform infrared (FT IR) spectrometer to perform analysis on the glass samples. Figure 5.3 below shows a measurement result of two of the samples melt in different conditions; PBG 21 is melt in open atmosphere while PBG 33 is melt in a controlled glove box environment. All chemical batching are done in the same environment in the glove box. However, when glass melts are done in open atmosphere, moisture in the room atmosphere increases the OH content in the resultant glass. We can observe the OH absorption peak at around 3.2 μm on the transmission spectrum. Melting in the high purity glove box environment also reduces the amount of impurities present in the atmosphere that causes transmission loss in the glass samples.

Figure 5.3 FT IR spectrum of PBG 21 (bottom) and PBG 33 (top)

The OH level of the glass melts can be further reduced by treating the batched and mixed chemicals in hot and dry purging gas. Before starting glass melting, a step of pre-drying of the chemical powders is introduced. The chemical after being mixed is allowed to dry at 100°C in the glove box furnace. The whole furnace is purged in dry N₂ gas for a period of time. The FT IR spectrum of PBG 41 in figure 5.4 shows the reduction of OH content affecting the transmission spectrum. From this analysis, we notice that we need to dry the chemicals for at least 4 hours for sample size of 100 grams. For larger melts, longer drying time is used.

Figure 5.4 FT IR spectrum of PBG 41 with different drying times

5.5 Preform fabrication

The method used for preform fabrication is the rod-in-tube method to obtain the core-clad structure of the step indexed fibre. At the push out temperature, the molten glasses from glass melts are casted into pre-heated stainless-steel casting mold. The design of one of the mold is shown below in figure 5.5.

Figure 5.5 (a) 31mm Billet cast; (b) PBG glass quenching in cast

The stainless steel cast cleaned and preheated to 230°C in an annealing furnace. At push out, the molten glass is poured into the cast and allowed to quench, glass annealing is done immediately after casting. The annealing is programmed as follows:

- Ramp 5°C/min to 230°C and dwell for 1 hour.
- Ramp 1°C/min to 310°C and dwell for 16 hours.
- Ramp 1°C/min to room temperature.
-

Below shows an example of glass billet removed from the stainless steel cast after quenching and annealing.

Figure 5.6 Example of a glass billet casted for extrusion (PBG 27)

Through the extrusion process, we can produce PBG rods and tubes of various diameters for our rod in tube fibre drawing method. Below shows PBG glass in an extrusion die and the schematic diagram of extrusion system.

Figure 5.7 PBG 12 casted in die

Figure 5.8 Schematic diagram of extrusion system

Some examples of the results of tube and rod extrusion are shown below.

Figure 5.9 PBG 12 after rod extrusion

Figure 5.10 PBG 27 after tube extrusion

Figure 5.11 - PBG 27 after tube extrusion

Apart from fabricating lead-bismuth-gallium glass rods and tubes for the rod-in-tube method in fibre drawing, a suspended core preform design is also implemented to produce lead-bismuth-gallium suspended core fibres.

(a)

(b)

(c)

Figure 5.12 (a) Extrusion die for suspended core preform; (b) Extrusion die after extrusion run; (c) Cross section of extruded preform

Figure 5.13 Extruded suspended core preform

Because of the more complex design as compared to the rod and the tube, the extrusion speed of the suspended core is set to a much lower speed of 0.06mm/min. The slow extrusion speed will help to maintain the shape and structures of the resultant preform.

5.6 Drawing of lead-bismuth-gallium optical fibre

5.6.1 Step indexed fibre

The PBG glass preform is setup as in the picture below. (core $n=2.22$; clad $n=2.16$)

Figure 5.14 Rod-in-tube preform setup

Figure 5.15 Top tip of rod is rounded

The condition of the draw is as follows:

Gas flow	50% N ₂ / O ₂ mix
Drop-down temperature	530 °C (gas flow of 3 l/min)
Fibre drawing temperature	530 °C (gas flow of 4.5 l/min)
Feed rate	1.0 mm/min
Capstan speed	5.5 m/min

Table 5.5 Fibre drawing condition

Figure 5.16 Cross-section of the fibre drawn

The fibre of this draw has the cladding diameter of around 160 µm and core diameter of around 35 µm. We noticed the shape of the core is now round; this could be because the fibre drawing temperature is too high.

To observe the light guiding in the core, we launched 1550 nm of laser into a 50 cm length of fibre and used a CCD detector to observe guidance of light in the core.

Figure 5.17 CCD image of the fibre cross-section with 1550nm

To determine the loss of this fibre at 1550 nm, we used the cut-back method to estimate the fibre attenuation. The loss is determined to be around 32 dB/m.

Figure 5.18 Fibre loss measurements via cut-back method

The novelty of this part of the thesis is the ability to fabricate structured optical fibre from PBG glass composition that is SiO_2 free. PBG optical fibres demonstrated before this requires addition of SiO_2 to stabilize the composition against devitrification. However, SiO_2 has strong absorption at the wavelength around $3.0 \mu\text{m}$ and moves the multi-phonon absorption edge toward the shorter wavelength, thus the glass composition can only transmit up to $3 \mu\text{m}$ and have lower nonlinearity. Optical fibre that is fabricated with pure PBG glass without the addition of any SiO_2 has not been demonstrate to date. We are able to fabricate pure low loss PBG fibre is mainly due to the pre-melt drying and purification steps done during the process. Before glass melting, the batched powers are heated to 300°C with dry Oxygen/Nitrogen mix gas for at least 24 hours. During the melt process, it was enforced that the sample will not come into contact with the outside atmosphere. The samples done this way will reduce the amount of impurities in the glass significantly. Such impurities will form centers of nucleation sites for facilitating crystal growth. The effect of impurities present is especially significant during processes when glass samples have to through high temperature. That is the reason why crystallization normally occurs during fabrication steps such as preform cast, extrusion and fibre drawing when the glass is heated to a high temperature.

5.6.2 *Suspended core fibre*

The step index fibre design shown in the previous section is simple and easy for us to produce the preform using the rod-in-tube method using two slightly different glass compositions to obtain the difference in refractive index. However, we found that this method has its own disadvantages.

The first disadvantage is the fact that we have to use two different glass compositions to form the core and cladding structures. In the rod-in-tube method for the step indexed fibre preform, the rod is made up of a glass composition with a higher refractive index but lower softening and crystallization temperature. On the other hand, the cladding tube is made up of a glass composition with a lower refractive index but higher softening and crystallization temperature. This gives rise to a possible problem during the fibre drawing process. For the assembled core-clad preform to be drawn down to the size of a fibre, the drawing temperature used will have to be close to the fibre drawing temperature of the cladding glass. Thus during the fibre drawing process, the core glass will have to experience a higher temperature necessary, increasing the likelihood to crystallization occurring in the fibre core during the fibre drawing process.

Apart from the danger of causing crystallization during the fibre drawing process, it will also be difficult to produce fibres of very small core size using the rod-in-tube method. This is due to the difficulty in producing a tube with very small inner diameter. In section 5.6.1, the preform consists of a core rod of diameter 2mm and cladding tube of outer diameter of 10 mm. The resultant fibre of the fibre drawing process has a core diameter of 35 μm and a cladding diameter of around 160 μm . The overall fibre nonlinearity is directly related to the cross section area of the core. A smaller core will allow higher nonlinearity experienced for applications. However, if we want to produce a fibre with core diameter of 3 μm and cladding diameter of around 125 μm , the core rod glass of the preform will have to be scaled down to 0.24 mm accordingly. Although not impossible, it will be difficult to produce such a small core rod for the preform and the additional processes will require extra heat treatments that increase the likelihood of the core experiencing crystallization.

The wagon wheel suspended core design is formed with the fibre core suspended in an air space in the fibre by only three glass arms attached and evenly spaced apart. The light in the core is guided by the air-core interface. Using this suspended core fibre design, we will be

able to eliminate the necessity to have two different glass compositions in the fibre preform for fibre drawing, allowing us to use a more optimized condition for the core glass during the process. The suspended core structure preform can be fabricated by the extrusion process as documented in section 5.4. This fibre design will also allow us to have a much smaller core diameter without additional heat treatment process. Careful control of the parameters during extrusion allows us to produce the fine structures of the small core preform.

The setup for fibre drawing of the suspended core PBG fibre is similar to the step indexed fibre. The extruded suspended core preform is reduced to the size of around 2mm outer diameter by cane pulling on the fibre drawing tower. The cane is then in turn inserted into an extruded tube of PBG glass of the same composition. The preform combination is then drawn down to fibre size of 100 – 200 μm .

Figure 5.19 below shows the resultant fibre cross section. In this fibre draw, a gas pressure is applied to the center air holes to maintain the structural shape during the drawing process. A separate vacuum of 20 mbar is applied to the gap between the cane and the tube to collapse the gap during the fibre draw. The resultant fibre has an outer diameter of 250 μm and a core diameter of 3 μm .

Figure 5.19 Examples of PBG suspended core fibre cross section with deformed structure

The shape and size of the air holes in the fibre is noticed to have deformed. This is caused by both the uneven gas pressure being applied to the air holes during the process and the preform being uneven heated due preform not maintaining at the center of the heat zone throughout the fibre draw.

To observe the light guiding in the core, we also launched 1550 nm laser into a 50 cm length of fibre and used a CCD detector to observe guidance of light in the core.

Figure 5.20 CCD image of suspended core fibre cross section

To improve on the uniformity of the air hole structures of the fibre, separate fibre draws are done to improve on the process. The setup of the preform remains the same as previous one. However, no gas is being applied to the air holes during the fibre draw. Two ends of the cane are fused before the draw such that air is being trapped inside the air holes during the whole fibre drawing process. Vacuum of 20 mbar is still applied between the cane and the glass jacket during the draw. The resultant fibre has an outer diameter of 150 μm and the core size is measured to be 1.5 μm .

Figure 5.21 Cross section of PBG suspended core fibre.

5.6.3 Loss reduction for Suspended core fibre draw

The fibre draws shown in the figure 5.19 and 5.21 above show this possible to produce micro structures in the form of suspended core using our chosen glass composition, preform fabrication techniques and fibre drawing conditions. However, the loss of the fibre was found to be very high during characterization. There are a few causes for the high loss and the first is that there are crystals forming in the glass in one of the melting, preform fabrication and fibre drawing process. Crystals formed will act as scattering centers for the transmitting light lowering transmission. The second cause for the high loss is the high OH content of the glass melts. The third cause is the core size of the above mentioned suspended core fibre draws is too small.

With the aim to produce a suspended core fibre with low loss, we planned the next fibre fabrication with the following improvements.

Firstly, we increased the germanium oxide content for a more stable glass to reduce the chances to crystallization occurring. Table 5.6 shows the composition of the glass melt done for suspended core fibre preform.

Component	% molar
PbO	45.712%
Ga ₂ O ₃	14.200%
Bi ₂ O ₃	20.088%
GeO ₂	20.0%

Table 5.6: Glass composition for final suspended core fibre preform

In addition, all the glass melts are done in a low moisture glovebox environment to ensure minimum water is introduced into the glass during the melting process. The oxide powder raw materials are also being dried over night at 100 °C to drive off moisture already present in the powder mixture. Last but not least, changes are also made to the suspended core fibre design to a larger core dimension.

Figure 5.22 Resultant fibre of PBG suspended core fibre draw.

For this fibre fabrication, the setup for fibre drawing is similar to one described above. The extruded suspended core preform is reduced to the size of around 2 mm outer diameter by cane pulling on the fibre drawing tower. The cane is then in turn inserted into an extruded tube of PBG glass of the same composition. The preform combination is then drawn down to fibre size of 100 – 200 µm.

Figure 5.22 shows the resultant fibre cross section. Similar to the previous draw, a gas pressure is applied to the center air holes to maintain the structural shape during the drawing process. A separate vacuum of 20 mbar is applied to the gap between the cane and the tube to collapse the gap during the fibre draw. The resultant fibre has an outer diameter of 170 µm and a core diameter of 6 µm.

To observe the light guiding in the core, we launched 1550 nm of laser into a 50 cm length of fibre and used a CCD detector to observe guidance of light in the core.

Figure 5.23 CCD image of the fibre cross-section with 1550nm

To determine the loss of this fibre at 1550 nm, we used the cut-back method to estimate the fibre attenuation. The loss is determined to be around 4.8 dB/m.

Figure 5.24 Fibre loss measurements via cut-back method

5.7 Supercontinuum generation using lead-bismuth-gallium glass

To test and demonstrate the effect of nonlinearity of the PBG glass fabricated, we used a femtosecond laser source to inject optical power into PBG glass canes with the aim of generating supercontinuum. The parameters of the laser system is shown in the table below

Output wavelength	1550 nm
Repetition rate	1 kHz
Pulse duration	100 fs
Peak power	~MW

Table 5.7 Parameters of laser system for supercontinuum generation

Figure 5.25 Schematic diagram of the supercontinuum generation setup

Figure 5.25 shows the schematic diagram of the setup we used for PBG supercontinuum generation. The laser is generated from a Ti: sapphire laser with a wavelength centered at 808nm. The pulse duration and repetition rate is 100 fs and 1 kHz respectively. To shift the laser wavelength to the proximity of PBG glass's zero dispersion wavelength of 1.43 μm , an optical parametric oscillator (OPO) is used to shift the output laser wavelength to 1.5 μm . With the help of optical lens, we couple the laser into a PBG glass cane. The PBG cane used in this setup is of 600 μm in diameter with a refractive index of 2.16. The length of the PBG cane used in the setup is just 5 cm long.

The spectrum of femtosecond laser is shown in figure 5.26 below. The laser wavelength is centered at 1.5 μm . Optical lens and translate stage are used to align and couple the laser energy into the PBG sample. The final output supercontinuum spectrum is observed using an optical spectrum analyzer (OSA).

Figure 5.26 Spectrum of the laser before injecting into PBG glass

Figure 5.27 Spectrum of the laser after injecting into PBG glass

A spectrum broadening from 1.2 μm to 2.4 μm is observed from the output of the PBG sample. The spectrum broadening allows us to demonstrate the high nonlinearity of the PBG glass we have fabricated.

5.8 Physical and nonlinear parameters of fabricated PBG fibre

Figure 5.27 in the previous section shows the experimental result of PBG supercontinuum generation. To estimate the nonlinear refractive index (n_2) of our fabricated fibre, we simulated the supercontinuum generation and compare it with the experimental result. The simulation of supercontinuum generation by PBG is based on solving the nonlinear Schrödinger equation using split-step Fourier method. The simulation is written in Matlab. A series of simulation is done and the figure below shows a comparison of the experimental and a simulation result. From our comparison, we can estimate the nonlinear refractive index n_2 to be in the range of $1.7 \times 10^{-18} \text{ m}^2/\text{W}$.

Figure 5.28 Comparison of experimental and simulation result of PBG supercontinuum generation with n_2 value of $1.7 \times 10^{-18} \text{ m}^2/\text{W}$

The nonlinear coefficient gamma (γ) is calculated from the equation below

$$\gamma = \frac{2\pi n_2}{\lambda A_{eff}} \quad (5.1)[93]$$

Equation 5.1 shows the equation for γ , n_2 is the nonlinear refractive index of the glass, λ is the wavelength and A_{eff} is the effective mode area of the fibre. Figure 5.29 below shows the simulated PBG fibre fundamental mode based on 1.55 μm radiation. The fundamental mode and mode area are calculated by Lumerical MODE solution by using the Finite Difference Method. According to the experimental cross-section of the fabricated fibres, the mode propagating inside the fiber is analyzed and calculated.

Figure 5.29 Simulated fibre fundamental mode at 1.55 μm

From equation 5.1, we are able to calculate the value of the nonlinear coefficient gamma (γ) using the estimated n_2 value of our PBG glass fibre and the effective mode area of the fibres obtained above.

PBG fibre cross-section	Simulated mode area @ 1.55 μm	Fibre diameter (μm)	Mode Area (μm^2)	γ ($\text{km}^{-1}\text{W}^{-1}$)
230	116.07	59.34
140	3.79	1817.35
130	8.58	802.77
180	32.92	209.23

Table 5.8 Estimated physical and nonlinear parameters of various PBG fibres fabricated

The table above gives a summary of the calculated mode area and γ value for some of the PBG fibre we fabricated. Calculations are based on the nonlinear refractive index n_2 value of $1.7 \times 10^{-18} \text{ m}^2/\text{W}$. From these results, we can estimate the γ values of our PBG fibre ranging from 59.34 to 1817.35 $\text{km}^{-1}\text{W}^{-1}$ depending on the fibre mode area.

5.9 Chapter Summary

In conclusion, we have successfully designed and fabricated both the step indexed and the suspended core Lead-Bismuth-Gallium glass fibres. The fabricated fibres have been tested and shown to guide light with reasonably low loss. It is found that the addition of germanium oxide to the glass system will stabilize the glass formed with better mechanical strength, making it possible to perform all the preform fabrication steps and fibre drawing without crystallization. It is because of this more stable glass formed that we are able to produce the highly defined structures in the suspended core fibre which allows us to produce fibre with very small core suitable for nonlinear applications.

In the process of glass making, we looked into the glass forming region of the glass system and singled out the glass composition that suits our requirement of physical and thermal stability; and at the same time giving us the high reflective index and nonlinearity. Various parameters of the glass melting conditions are also tested out for us to successfully produce quality glass bulks for the fabrication of fibre preforms.

With ability to produce glass with different refractive index, we performed various processes on the glass melts to form the fibre preform we require. Of which, the extrusion process allows us to shape glass melts into the shape of rods, tubes and even microstructure designs. Casting is another method for preform fabrications. With the various parts of the preform made to shape, we are able to attach them together forming the core-clad structure of the step-indexed fibre preform and the suspended core fibre design preform. The constructed fibre preform is drawn down to optical fibre using the fibre drawing tower. A wide range of fibre drawing parameters are used and tested out before we are able to successfully draw fibres from our preform.

Chapter 6 Conclusion and further works

This thesis has covered a diverse range of subjects, spanning aspects of generation and transmission of laser around 2 μm . One of the initial aims of the work is to produce a laser source in the 2 μm wavelength region suitable for military applications. With the importance of the laser source to be compact and rugged to withstand the harsh operating environment, we started off the thesis with the design and demonstration of an all fibre thulium doped fibre laser, and then moved onto simulation methods of Raman fibre laser for possible 2 μm laser generation; the thesis then focused on the tunability of the all fibre thulium doped fibre laser in chapter 4 and finally ends off with the design and fabrication of a novel heavy metal oxide glass system optical fibre with high nonlinearity capable of transmission at 2 μm . The original intentions of this work were, to produce an all fibre laser source capable of wavelength tunability and fabrication of an optical fibre with high nonlinearity to allow the demonstration of mid-infrared supercontinuum generation in future. This section summarizes the major achievements, evaluates the success of this work in the light of the original intentions, and suggests areas of further study.

6.1 Conclusion

In this thesis, initial work was devoted to the construction of an all fibre configuration of the thulium doped fibre laser as a source to produce an output of close to 2 μm . In addition, for the laser source to be of real practical use, we realized that the laser source needs to be wavelength tunable. That is the motivation for use to design and implement the capability of wavelength tunability as documented in chapter 4. We also explored a simulation method which would help in Raman fibre laser modeling, with is a potential method of generating 2 μm output. The final part of the thesis is then devoted to the design and fabrication of lead-bismuth-gallium oxide glass fibre for the possible nonlinear applications in the mid-IR wavelength region.

The initial design and modeling of the thulium doped fibre laser setup was a high significant step towards the understanding of the thulium lasing system and also optimization of the laser cavity. This all fibre configuration setup also forms the basis of the wavelength tunable 2 μm fibre laser. Before looking into the design of the laser source setup, we looked into the

spectroscopic properties of thulium, and its use as the gain medium of bulk and fibre lasers. A numerical model of the thulium doped fibre laser is constructed and used to help in the optimization of the laser cavity. The simulation results of the slope efficiencies from our model are verified with other published results. With reference to the simulation results, we built an experimental setup and demonstrated a output producing 2.5 W at 1.93 μm . The output efficiency and power stability of the laser is also presented accordingly.

Another possible candidate for 2 μm fibre laser is the Raman laser. In chapter 3, considering the excellent multi-dimensional searching ability of Nelder-Mead simplex optimization algorithm and the fast converging speed of shooting method, we propose a novel and efficient numerical algorithm for solving the multi-dimensional problem of multiply-Stokes Raman fibre lasers.

An all fibre tunable 2 μm Tm-doped fibre laser was experimentally demonstrated in this chapter. Broadband wavelength tunability was achieved by employing a Hi-Bi fibre Sagnac loop acting as a comb filter in the laser ring cavity in 2 μm Tm-doped fibre lasers. Tuning was carried out by careful controlling of the two PCs in the setup. Our design enables all fibre tunable laser as there was no external free-space optics required. Stable laser output was demonstrated at various wavelengths from 1924.3 nm to 1972.2 nm covering a total range of ~48 nm.

In addition, we investigated FBG-based tunable fibre laser. Both mechanical strain and thermal tuning mechanism of FBG were analyzed in detail. Respective experiment setups on tunable FBG were done to verify the calculations. Strain tuning shows a 16 nm tuning range in which there isn't degradation and wavelength shift. On the other hand, thermal tuning showed consistent results yielding a maximum wavelength shift of 1.7 nm over the 97 $^{\circ}\text{C}$ range.

One very promising application of the 2 μm fibre laser is that it can serve as a pump to achieve even higher wavelength output into the mid-IR region. An optical fibre capable to transmission and high nonlinearity in the mid-IR region is very useful for applications such as super continuum generation in this wavelength region. To fabricate this heavy metal oxide glass fibre, we looked into and performed various fabrication steps from glass melting, making of the preform, and finally fibre drawing of the optical fibre.

In terms of soft glass fibre production, we have successfully designed and fabricated both the step indexed and suspended core Lead-Bismuth-Gallium glass fibres. The fabricated fibres have been tested and shown to guide light with reasonably low loss. It is found that the addition of germanium oxide to the glass system will stabilize the glass formed with better mechanical strength, making it possible to perform all the preform fabrication steps and fibre drawing without crystallization. It is because of this more stable glass formed that we are able to produce the highly defined structures in the suspended core fibre which allows us to produce fibre with very small core suitable for nonlinear applications.

6.2 Further work

Despite the results achieved in this work to date, there exist some areas to further advance the work. Listed below are some suggestions which would help to further advance the work described.

6.2.1 Amplify the all fibre thulium fibre laser using a MOPA

Increasing the output power of the all fibre laser source of both the linear cavity and the wavelength tunable setup up can increase the range of applications of the 2 μm laser source. One way of doing it is to use a MOPA setup to amplify the laser output of the laser source we developed. As an all fibre configuration of the MOPA amplifier is possible, we can still retain the advantage of the all fibre laser setup by fusion splicing of output of our laser source to the amplifier input. However, with the increase in power output, other issues such as the thermal management, back reflection and nonlinear effects have to be carefully considered and dealt with.

6.2.2 Purification of the rare materials of PBG glass and Scale up production of the drawing tower

From the characterization of the glass melts and fibre fabricated, we notice that the OH absorption peak is still present. To reduce this absorption peak and hence reduce the loss of the glass in general, further purification methods can be implemented into the glass making process. One example is the use of reactive drying process to further reduce the water content in the raw materials powders. Chemical reagents such as chlorine gas actively react with the water present in the raw materials and produce a by-product that can be easily removed from the raw material itself. Another approach is to produce our own oxide powders from chemical reactions in a controlled environment with low moisture. By scaling up the length of perform

that the drawing tower could take (currently ~15 cm), and the lengths of extruded preforms, the available glass and time to achieve a good draw would be similarly increased. This could allow significant improvements to the final quality of the fibre, and would facilitate giving the fibre a polymer coating to improve its strength. The steps described above will improve the fibre optical and mechanical properties but will need a greater in depth study into the chemical reactions for moisture reduction and oxide production. In addition, an upgrade to the existing equipment will be needed for us to perform these tasks efficiently.

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Appendix A – List of Publications

- [1] **C. H. Tse**, X. H. Li, Q. J. Wang, "Supercontinuum Generation in Lead-Bismuth-Gallium (PBG) Glass," *International Conference on Material for Advanced Technologies*, 2015
- [2] **C. H. Tse**, Z. G. Lian, P. Bastock, C. Craig, D. Hewak, F. Poletti, Q. J. Wang, "Fabrication of lead-gallium-bismuth (PGB) optical fibre for mid-infrared nonlinearity applications," *Sixth International Conference on Optical, Optoelectronic and Photonic Materials and Applications, Leeds, UK*, 2014
- [3] **C. H. Tse**, C. M. Ouyang, P. Shum "Tm-doped All-fiber Laser with Wavelength Tunability," *Photonics Global Conference, 2nd Postgraduate Student Conference*, 2012
- [4] **C. H. Tse**, L. Y. Hong, R. F. Wu, C. M. Ouyang, P. Shum, "Wavelength-tunable, Tm-doped fiber laser using HiBi fiber Sagnac loop filter," *International Conference on Information Photonics & Optical Communications*, 2011.
- [5] **C. H. Tse**, M. Tang, P. Shum, R. F. Wu, "Nelder-Mead simplex method for modeling of cascaded continuous-wave multiple-Stokes Raman fiber lasers," *Optical Engineering*, vol. 49, pp. 091009-6, 2010. (*Best Student Paper Award organized by IEEE photonics society Singapore chapter, Jan 2010*)
- [6] **C. H. Tse**, N. N. Jie, R. F. Wu, P. Shum , "Numerical Simulation of Thulium doped fiber laser," *International Conference On Advanced Infocomm Technology*, 2010.
- [7] **C. H. Tse**, L. K. Lim, P. Shum, G. Wang, "Stokes and Anti-stokes Raman Fiber Laser," *Symposium P, Optical Fiber Devices & Applications, International Conference on Materials for Advanced Technologies*, 2009.
- [8] **C. H. Tse**, M. Tang and P. Shum, "Nelder-Mead Simplex Method for nth-order cascaded CW Raman fiber lasers," *International Conference On Advanced Infocomm Technology*, 2009.