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Towards the development of a thulium-doped all-fibre laser

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Declaration of Authorship

I, Mosima B. KGOMO, declare that this dissertation titled, “Towards the development of a thulium-doped all-fibre laser” and the work presented in it is my own. I confirm that:

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Abstract

Fibre based lasers have become a dominant laser architecture due to high output powers and efficiencies, compact form factors, and excellent beam quality. Double-clad large mode area fibres (DC-LMAF) are required to achieve high output power (up to kW level).

The performance and integrity of the thulium-doped all-fibre laser is critically dependent on the quality of splices between different components constituting the fibre laser. Power loss at the splice joints (splice loss) has a deleterious effect on the performance and long-term reliability of high power fibre lasers. Splice losses, caused by poor fusion splices, lead to a decrease in the optical-to-optical efficiency as well as degradation in the beam quality of fibre lasers.

The low-loss, wavelength-dependent fusion splices are required for the development of the high power thulium-doped all-fibre laser that is known to lase in the 2000 nm wavelength region. A spectral splice loss measurement technique was constructed to measure splice loss between two 25/400 μm passive DC-LMAF in the 2000 nm spectral region. The different types of aspects that can lead to splice loss measurement variations are investigated and mitigated. The 0.03% was the expected splice loss measurement variation.

The optimal parameter set points for fusion splicing two 25/400 μm passive DC-LMAF were found through conducting a splice loss optimization experiment. The fractional factorial design of experiment which enables the reduction of the required number of experiments by performing them at a certain specific combination of parameters was applied due to the seven large number of splice parameters that required to be optimized. A total of 18 experiments were conducted based on the fractional factorial design of experiment that followed the Taguchi orthogonal methodology.

The splice loss results were analysed by using a statistical technique, the analysis of variance (ANOVA). The Gap Distance and Arc Time 2 splice parameters were revealed to be the two most important parameters that have an impact on fusion splice quality by contributing 32% and 27% towards splice loss, respectively within the chosen splice parameter levels for this work.

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List of Symbols and Abbreviations

h	Planck's constant	LIDAR	Light Detection And Ranging
ν	Photon frequency	ANOVA	Analysis Of Variance
M^2	Beam Quality Factor	LMAF	Large Mode Area Fibre
cw	Continuous Wave	LDS	Large Diameter Splicer
CR	Cross-Relaxation	PCF	Photonic Crystal Fibre
Tm	Thulium	TIR	Total Internal Reflection
NA	Numerical Aperture	DOE	Design Of Experiment
DCF	Double-Clad Fibre	HOM	Higher Order Modes
SMF	Single Mode Fibre	FBG	Fibre Bragg Grating
SCF	Single-Clad Fibre	DOF	Degrees Of Freedom
ROF	Ring Of Fire	MFD	Mode Field Diameter
SRS	Stimulated Raman Scattering	SBS	Stimulated Brillouin Scattering
AS	Avantes Spectrometer	BBS	Broadband Light Source

Chapter 1: Introduction to Fibre Lasers

1.1 Introduction

Fibre-based lasers have become the dominant laser architecture due to their compact design form, high output power, excellent beam quality and exclusive physical features which distinguish them from other classes of lasers and differentiate them in terms of functionality, outstanding performance, and practicality. Inherent appealing advantages of fibre lasers over the bulk solid state lasers are listed in Table 1 [1]. These advantages have resulted in fibre lasers having a broad diversity of applications in many industries such as research, medicine, defence and materials processing (welding, cutting and marking).

Table 1: Comparison between fibre lasers and bulk solid state laser [1].

Characteristics	Fibre Laser	Bulk Solid State Laser
Laser mode	Single transverse mode in single mode fibres.	Thermally induced mode distortions.
Gain linewidth	Broad, up to 20 THz.	Narrow. However, glass can be utilized as the substrate to obtain a broad linewidth.
Gain	Higher gain which offers an option of master oscillator power amplifier (MOPA).	Lower gain. MOPA configurations used often.
Thermal lensing	Weak.	Strong.
Lasing threshold	Lower.	Higher.
Optics alignment	Hassle-free alignment when fibre components are used. Robust and compact configuration is created.	Misalignment issues may be encountered with free space components.
Cooling	Efficient cooling due to long lengths of fibre.	Uneven cooling due to bulk material.

Fully monolithic (all-fibre) laser architecture in Figure 1 is important for recognizing full potential of fibre lasers. This laser system requires optical fibres or fibre components such as pump combiners, fibre Bragg gratings, and mode adaptors to be joined on the system by process called fibre fusion splicing. Fusion splicing is a key element in the fabrication of rugged, robust, and reliable high power all-fibre lasers. Connection of fibres or fibre components generates a fusion splice which is associated with a splice loss. Poor fusion splices with high splice losses lead to power losses that can cause catastrophic damage to fibre components due to localized heat, a deterioration of beam quality as well as, a reduction in the optical-to-optical efficiency of the fibre laser. Obtaining low transmission loss fusion splices remains a challenge in the development of high power all-fibre lasers [2].

1.2 Objectives of the study

The objective of this research is to investigate and develop a procedure to conduct splicing experiments in order to find the best splice parameters set points that can produce quality fusion splices. The optimal splice parameter set points must generate quality fusion splices that are

characterised by low splice losses (<0.1 dB), for the purpose of ultimately building compact, robust and reliable high power thulium-doped all-fibre laser as presented in Figure 1..

The proposed thulium-doped all-fibre laser shown in Figure 1 is the actual fibre laser that is anticipated to be developed. However, this research project will focus on finding the best splice parameter set points that will be used to fabricate low loss fusion splices between two Nufern 25/400 μm passive double clad large mode area fibre (DC-LMAF) (see broken black arrows in Figure 1). This research can be viewed as a sub-component of the anticipated thulium-doped all-fibre laser. The proposed laser system comprises of a number of splices between passive to passive fibres, passive to active fibres: laser diode to pump combiners, pump combiners to fibre Bragg grating (FBG 1), FBG 2 to cladding mode stripper; FBG 1 to thulium-doped fibre, and thulium-doped fibre to FBG 2.

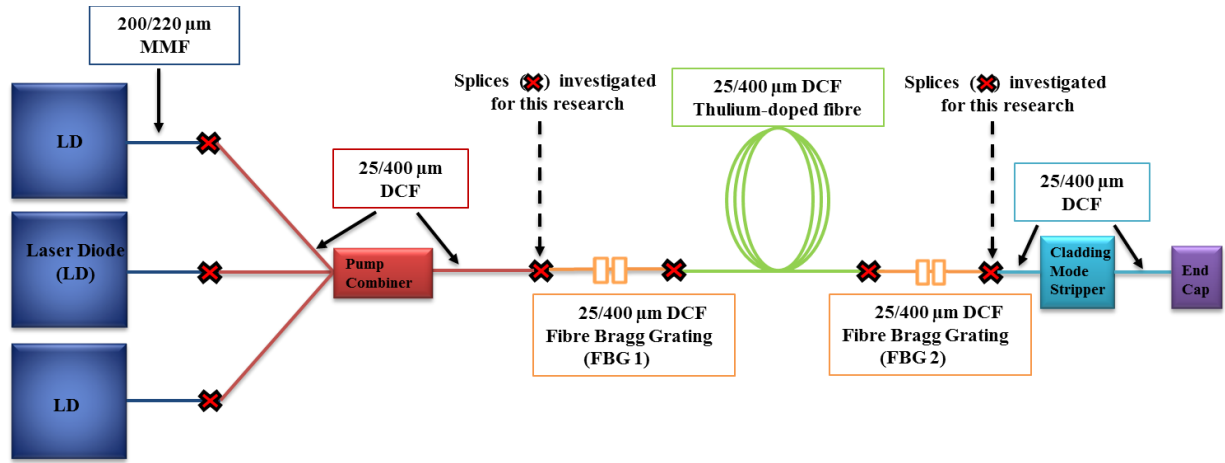


Figure 1: Thulium-doped all-fibre laser comprising of splices between laser diodes, pump combiner, two fibre Bragg gratings (FBG 1 and 2), cladding mode stripper and end cap.

This research will focus on finding the optimal splicing parameters between passive to passive fibres as indicated in Figure 1 by the broken black arrow. The passive fibres used in the optimization process for this work were Nufern double-clad large mode area fibres (DC-LMAF) with 25/400 μm core/cladding dimension. Due to the large core/cladding dimension of the passive DC-LMAF, a splicing experiment has to be made with a large diameter glass processing splicer (LDS) that can accommodate the dimensions of the passive DC-LMAF. Splice loss optimization between the passive to active fibres will not be considered for this study.

Chapter 1 (This chapter) introduces basic concepts behind fibre lasers and DC-LMAF. Chapter 2 will discuss the theory of fibre fusion splicing. The splice loss measurement approach used in this work is discussed in chapter 3. In chapter 4, the experimental design methodology as well as experimental results is discussed.

1.3 How a Laser Operates

In its fundamental form, a laser system comprises of three components, namely: gain medium, pump source, and optical resonator [3] (see Figure 2). A gain medium consists of group of atoms, molecules or ions which can either be in solid, liquid or gaseous form. For simplicity, consider a gain medium as an ensemble of atoms. Atoms are characterized into discrete energy levels from low and to high energy. The majority of atoms are at the lower energy state following a Boltzmann distribution at

thermal equilibrium. However, for a laser to be generated, a gain medium must be held under a state of population inversion, in which there is a much higher number of atoms in the higher energy level than the lower energy state. Population inversion can be achieved by applying pump sources such as laser diodes or flash lamps to pump the gain medium. Atoms in the gain medium will be excited to a higher energy state [3].

Once population inversion is achieved, electromagnetic radiation of particular frequencies can be amplified through stimulated emission as it passes through the gain medium. An incident photon with the appropriate frequency will interact with the gain medium in a population inversion state. An atom in the higher energy state will descend to a lower energy state while emitting a photon and when that emitted photon passes by another atom in the higher energy state it will stimulate the atom to decay and emit another photon. The two emitted photons can continue to stimulate two more atoms to emit two photons which leads to four photons to be released. Therefore a cascade of photons travelling in the same direction, which have same frequency, phase and polarization, will be produced. Photons are stimulating atoms to emit more photons, hence the process is called stimulated emission [3].

The population inverted gain medium must be continuously pumped to emit more photons. However, for larger number of photons to be emitted by the gain medium, photons must oscillate within the gain medium. The latter is achieved by placing and aligning a highly reflecting mirror at the one end of a gain medium and a partially transmitting mirror at other end of gain medium, thus forming an optical resonator. The two mirrors provide an optical feedback for amplification by reflecting and oscillating the light along a repeatable fixed path. Each round trip is amplified by stimulated emission as it passes through the gain medium and this is known as round trip gain. However, resonator losses such as scattering, reflectivity and fluorescence can be experienced by each round trip gain [4]. When the round trip gain is less than the resonator losses, optical power within the optical resonator will decrease until there is no optical power available. If the round trip gain is equal to the resonator losses, optical power will remain the same. If the round trip gain exceeds resonator losses, optical power within optical resonator will increase with each round trip. However, the increase in optical power will not persist endlessly because the intensity of the optical resonator will saturate the gain medium [5]. Therefore, a steady state oscillation will be reached within the optical resonator.

A steady state oscillation is a state in which the round trip gain is exactly equal to the resonator losses. This steady state represents continuous wave (CW) laser operation [4]. To extract CW laser beam from the optical resonator, a partially transmitting mirror is used to transmit a fraction of the laser beam.

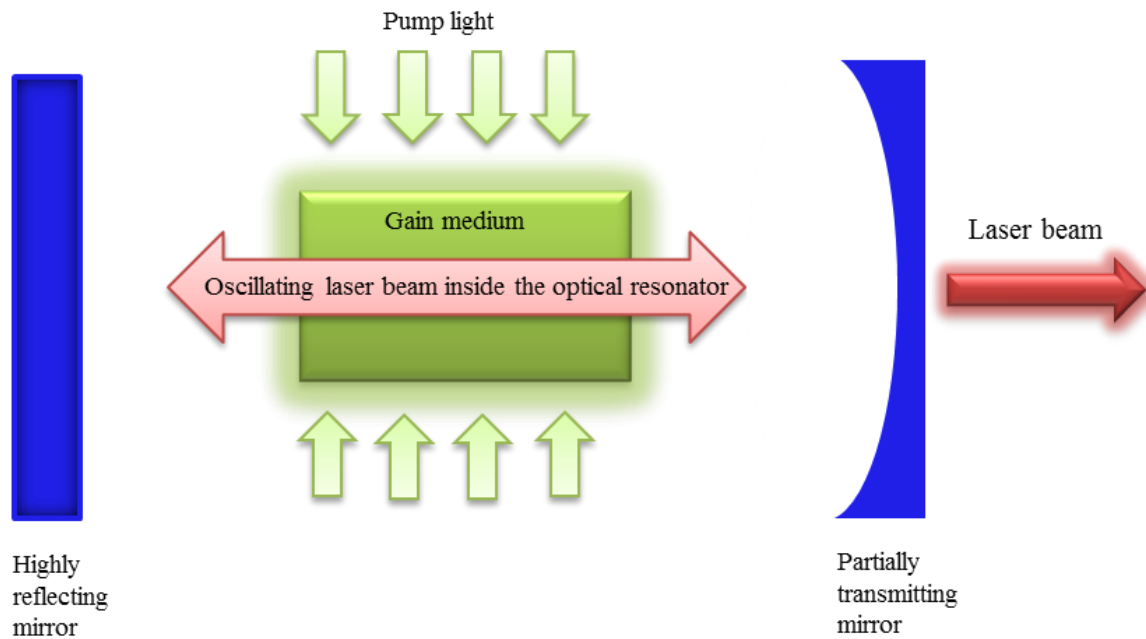


Figure 2: A simple diagram of a bulk solid-state laser [3].

1.3.1 Stimulated Emission

Albert Einstein described three distinct processes in which an atom can interact with electromagnetic radiation. The three processes are absorption, spontaneous and stimulated emission. In 1917, Albert Einstein used a two level system to demonstrate the three processes [6].

When an atom in the lower energy state (E_1) absorbs appropriate energy from a photon $E_P = h\nu$, the atom will be excited to a higher energy state (E_2) by a absorption process. Photon energy (E_P) is defined by Planck's constant h and frequency of photon ν . However, absorption will only occur when the photon energy is equal to the energy difference between higher energy and lower energy states, denoted by $E_P = E_2 - E_1$. The excited atom in the higher energy state can de-excite to a lower energy state by spontaneous and stimulated emission. In a spontaneous emission, the excited atom in the higher energy state will de-excite to a lower energy state and emit a photon in a random direction. The emitted photon consists of common incoherent light which can be obtained from ordinary light bulb or fluorescent lamp.

The acronym **LASER** stands for **L**ight **A**mplification through **S**timulated **E**mission of **R**adiation. Stimulated emission is the process that controls the operation of a laser and it can be explained by using Figure 3. As put by Albert Einstein in 1917 [6], stimulated emission is a process in which an incident photon with similar energy as the energy difference between higher and lower energy states $E_p = h\nu = E_2 - E_1$ interacts with an excited atom in the higher energy state. The excited atom will decay and two photons will be emitted; one photon is due to incident photon and the other photon is emitted by the atom in higher energy states which returns to lower energy state. Emitted photon will exhibit the same energy, frequency, direction and phase as the incoming photon. This process is the foundation upon which light amplification in lasers and amplifiers are accomplished.

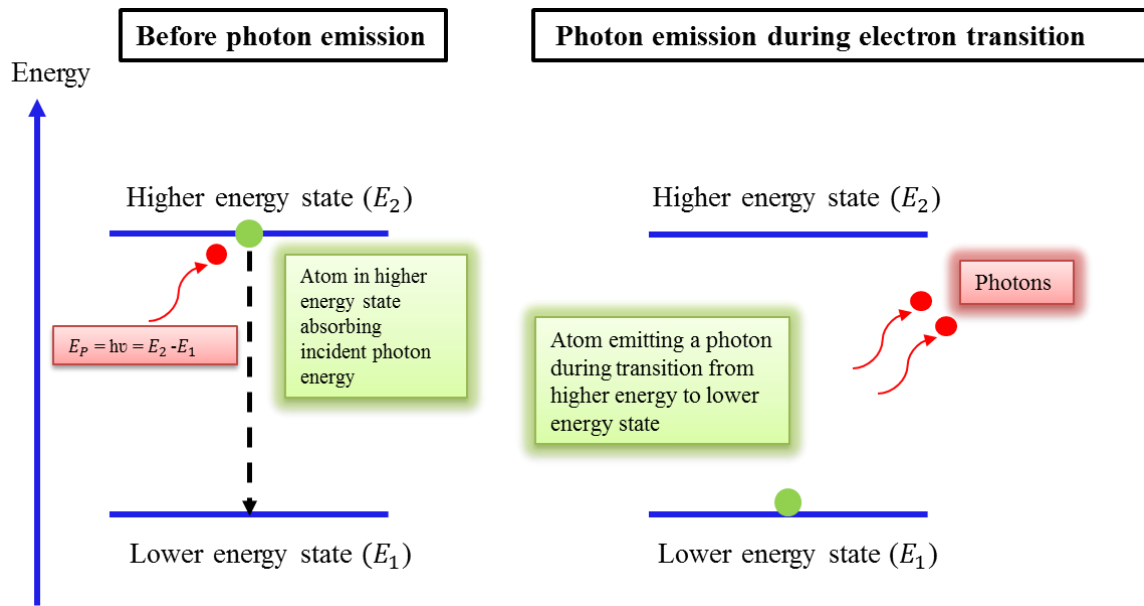


Figure 3: Illustration of stimulated emission process before photon emission (left) and after photon emission (right).

1.4 The Development of Double-Clad Fibres

In its simplest form, conventional optical fibres comprise of two layers namely, the core and the cladding (see Figure 4). The core has a higher index of refraction than the cladding and it serve to guide the light by total internal reflection (TIR). Considering $n_2 < n_1$ in Figure 4, when light is incident on a core-cladding interface at an angle greater than the critical angle Φ_c then all light will be reflected into the core by a process known as TIR [3] (see red arrows). However, when light is incident at the core-cladding interface at an angle less than the critical angle (see solid black arrows) then Fresnel reflection will be experienced at the core-cladding interface and some light will be transmitted, resulting in the attenuation of light as it propagates along the fibre (see dot-dash arrows). The cladding serves to enclose the core.

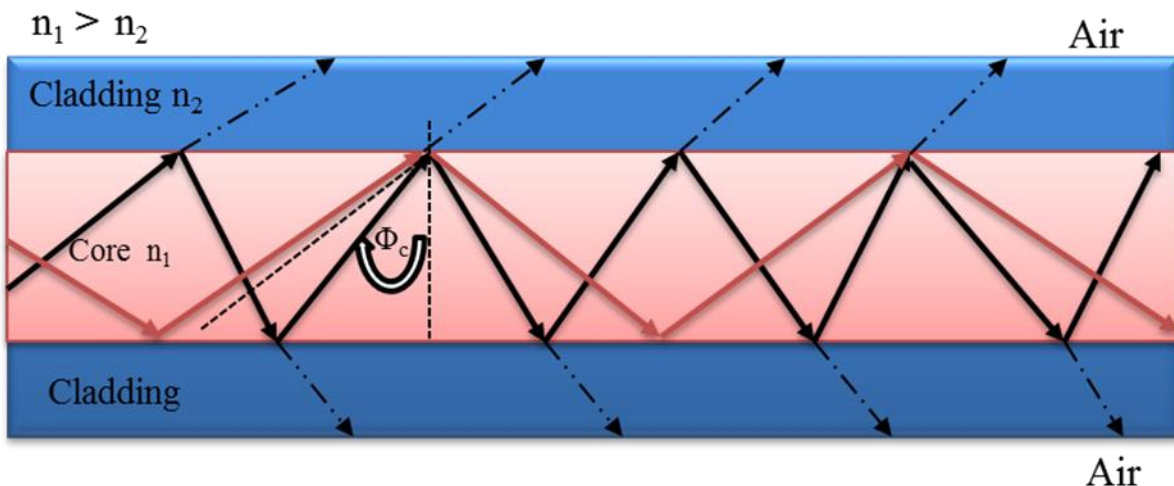


Figure 4 : Propagation of light through conventional optical fibre illustrating Fresnel reflection (black arrows) and total internal reflection (red arrows).

Single-clad fibres (SCF) comprises of acrylate coating that has a higher index of refraction than the cladding (See Figure 5(a)). Single-clad fibre lasers are pumped with single-mode pump diodes that are restricted to milliwatts in power. Therefore, single mode fibre lasers are limited to milliwatts output power [7]. Single mode fibre (SMF) has relatively 0.14 numerical aperture (NA) that requires low NA pump sources which are hard to manufacture and very costly.

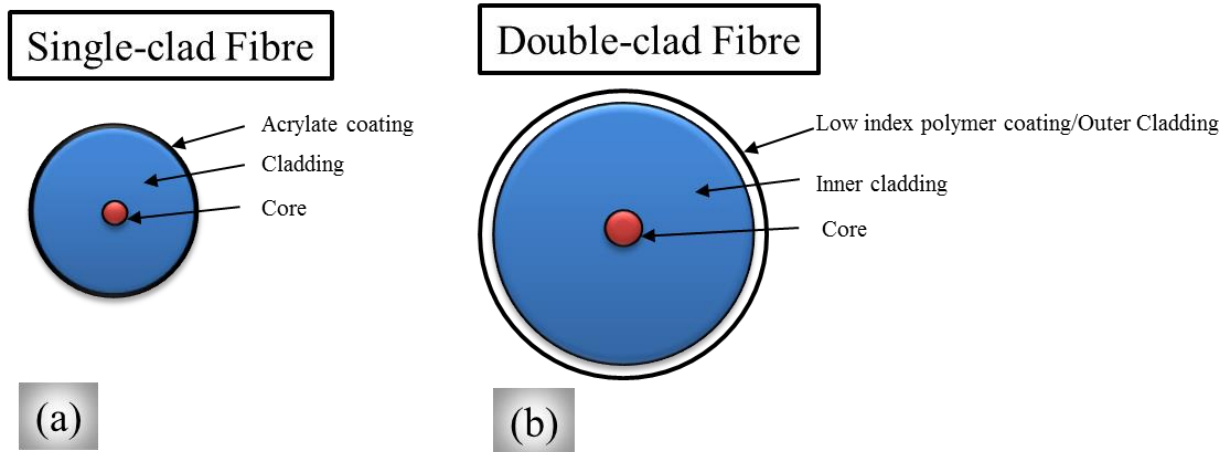


Figure 5 Representation of (a) Single-clad fibre (SCF); (b) Double-clad fibre (DCF).

However, the development of double-clad fibre (DCF) design by Elias Snitzer in 1988 overcame the shortcomings of single-clad fibre lasers [8]. Elias Snitzer's elegant innovation proposed that a fibre will consist of four layers and will operate on a cladding pump principle. The four layers of the DCF are the core, inner cladding, outer cladding and the polymer coating [9] (see Figure 5(b)). The core serves as a primary waveguide that guides the signal and is surrounded by an inner cladding with lower index of refraction. The distinction between SCF and DCF is the extra cladding of DCF. This inner cladding forms part of the core's secondary waveguide which guides the pump light and is highly multimode. The outer cladding with a lower index of refraction encloses the inner cladding and serves to promote waveguiding. The two cladding layers give rise to the name "double-clad fibre". The polymer coating serves as a protective layer. With the aid of Figure 6 below, the concept of pump cladding works as follows [10] :

- Pump light from a low brightness high power multimode diode laser is launched into the inner cladding (See green lines).
- The pump light remains confined in the inner cladding due to total internal reflection (see red arrows).
- The pump light will continuously be absorbed by the core as it propagates along the highly multimode inner cladding and will be transformed into high power laser radiation with high brightness.

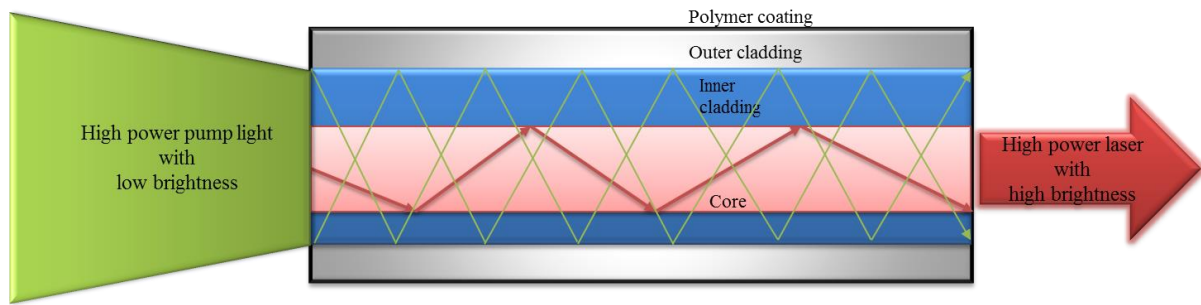


Figure 6 Operation of the cladding pumping principle in DCF [10].

The application of the cladding pump system has led to an increase in the output power of double-clad fibre lasers. In 1997 and 1998, output power increased as follows respectively: 20 W [11] to 30 W in 1.1 μm region, four ~ 915 nm fibre coupled diode bars was utilized and pumped at 55.4 W [12]; 55 W ultrahigh-power laser diode array used as a pump source for fibre lasers [11]. Additionally, cladding pump innovation became more phenomenal and revolutionised fibre lasers by increasing output power to over 100 W [13].

Dominic *et al.* [13] achieved the highest output power of 110 W CW by utilizing double-clad ytterbium doped fibre. The fibre laser consisted of ytterbium doped fibre which comprised of 170×330 μm rectangular shaped inner cladding. Four high brightness diode laser bars was applied and each diode laser had an output power of 45 W. Two diode lasers were placed on the input side of double-clad ytterbium fibre and the remaining two diode lasers were placed at the output side of the fibre. The sum of ~ 180 W of pump light was coupled into the two ends of double clad ytterbium fibre. With fibre lasers an optical resonator is created by applying either mirrors or fibre components such as fibre Bragg gratings (FBG). A high reflecting mirror was placed at the input side of the fibre and another dichroic mirror was placed at the polished output end of the fibre. One aspheric lens was placed behind the dichroic mirror on the input side and another aspheric lens was placed in front of the second dichroic mirror. The purpose of the lenses was to collimate the beam.

The greatest output power of 110 W was obtained at 90 A current which was record breaking output power to be generated by double-clad fibres. A 58% optical-to-optical efficiency, as well as a beam quality (M^2) value of 1.7 was achieved. The high M^2 value was accounted for thermal distortions in the aspheric lens placed in front of the second dichroic mirror on the output end of the fibre.

Furthermore, the work of Platonov *et al.* [14] and Limpert *et al.* [15] demonstrated and validated that cladding pumping fibre laser technology increases output power respectively: A 135 W CW ytterbium-doped fibre laser and 150 W neodymium-ytterbium dual doped fibre laser was demonstrated.

1.5 The Advent of Large Mode Area Fibres (LMAFs)

The development of DCF technology as previously discussed in section 1.3 made high power fibre lasers and amplifiers achievable. Nonetheless, the increase in laser output power due to DCF technology was hindered by the reduction of pump light absorption in the core. The latter is caused by intensity distribution in the inner cladding which contains no overlap with the core, thus leading to a

decrease in efficiency. In addition, the strong confinement of light in small fibre cores produces high power density within the fibre core which results in nonlinear effects [16]. Nonlinear effects originates from stimulated inelastic scattering processes known as stimulated Raman scattering (SRS) and stimulated Brillouin scattering (SBS). The aforementioned processes are caused when radiation transmits a certain amount of its own energy to the glass host in a form of excited vibrational modes [7], thus reducing the output power in fibre based lasers configuration. The above mentioned shortcomings of DCFs with small fibre core were overcome by innovative fibre design known as large mode area fibres (LMAF).

LMAF are designed to minimize nonlinear effects by means of an increase in fibre core diameter and reduction in the core's numerical aperture (NA). In Figure 7, the conventional DCF and the photonic crystal with 25 μm core diameter are examples of different types of LMAF. The low NA of the core decreases the quantity of fluorescence that is absorbed by fibre core therefore amplification of fluorescence will be reduced [17]. The advent of these fibre designs decreased nonlinear effects, thus resulting in scaling of output power of fibre lasers.

A 500 W CW high power fibre laser was demonstrated by Limpert *et al.* in 1.1 μm operating wavelength in 2003 [18]. A 25 μm core diameter of ytterbium and neodymium doped fibres with NA of 0.06 was used to build the fibre laser. The core diameter of these fibres is the same as the core diameter of fibres applied in this work but the NA is 0.11. Limpert *et al.* launched 700 W pump power which yielded 500 W output power and optical-optical efficiency of 72% was obtained. A beam quality M^2 -value of less than 1.5 was achieved. No evidence of nonlinear effects was observed at this high output power due to utilization of low numerical aperture LMAF which minimized the intensity. Demonstration of Limpert *et al.* validates that LMAFs increases output power of fibre based laser.

The reduction in the NA of the fibre core of LMAF makes these fibres susceptible to bend losses [19]. To prevent losses such fibres should not be tangled, kinked or bent through a tight radius [20]. Additionally, LMAF are susceptible to small angular misalignment that can often be experienced during fusion splicing process, thus inducing high splice loss. The larger core of LMAF often supports higher order modes (HOM) which can degrade beam quality of fibre laser.

This work used double-clad large mode area fibres because of their ability to scale output power of fibre lasers to kilowatt levels.

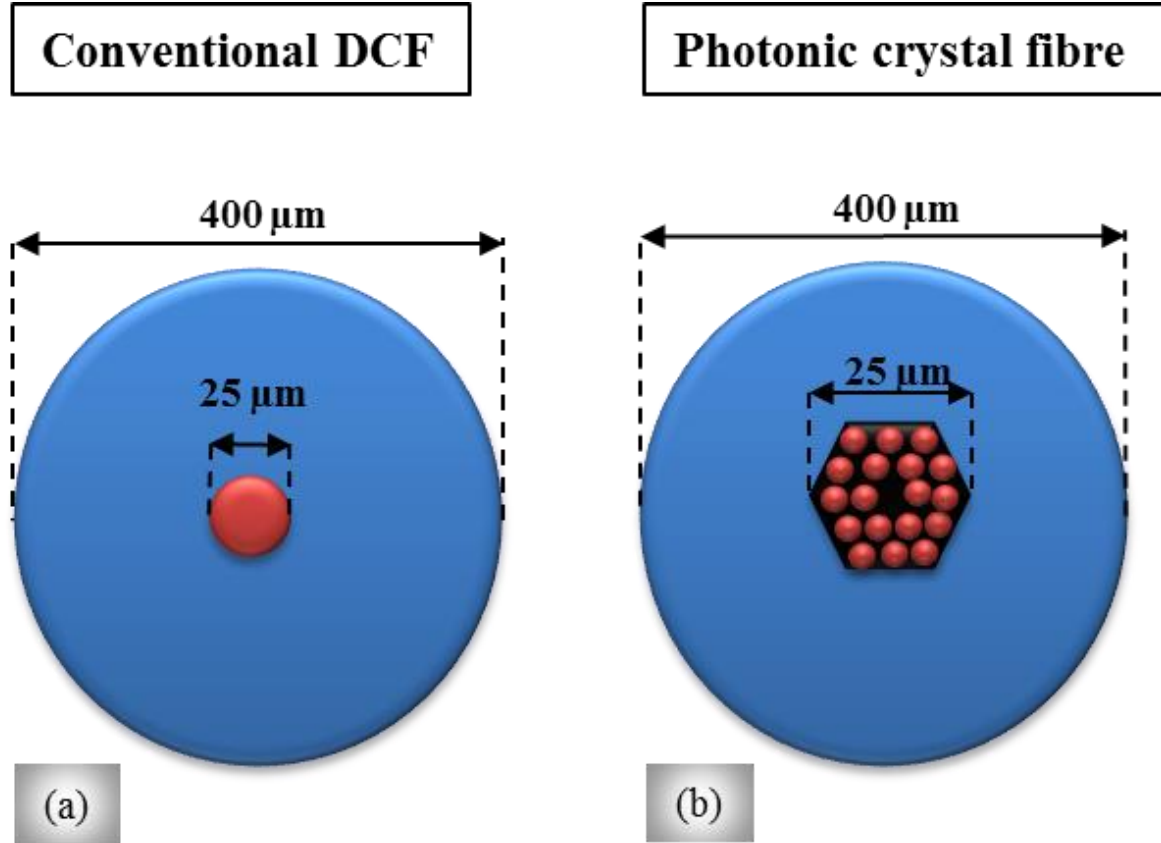


Figure 7: Representation of large mode area fibre (LMAF) without polymer coating: (a) conventional DCF with 25/400 μm core/cladding dimension and (b) photonic crystal fibre (PCF) with 25/400 μm core/cladding dimension.

1.6 Thulium-doped Fibre Lasers

Thulium-doped fibre lasers have captivated much consideration due to their operation in a wavelength range from 1700 to 2100 nm. In the aforementioned wavelengths, the laser has variety of applications in medicine, materials processing, gas sensing and Light Detection And Ranging (LIDAR) [21]. The strong absorption features of water in this spectral range make Tm lasers useful for medical applications such as ablation of urinary tissue [22], the vaporization of prostate tissue, and treatment of melasma [23]. Tm-doped fibre lasers have numerous applications in processing of non-metal materials such as plastics which are highly transparent in the 1 μm region [24]. The moderate absorption of plastic materials in the 2000 nm spectral range enables plastic cutting, welding and drilling through the use of high power Tm-doped fibre lasers [25]. Green-house gases such as carbon dioxide and nitrous oxide can also be detected in this wavelength region [26].

In Figure 8, the absorption bands of thulium (Tm) which are ~ 793 nm, ~ 1200 nm and 1550-1750 nm are shown [1]. The strong absorption band is at ~ 793 nm, where a high power GaAlAs laser diode can be applied as efficient and cost effective pump source [25]. The ~ 793 nm absorption band is important due to cross-relaxation (CR) process.

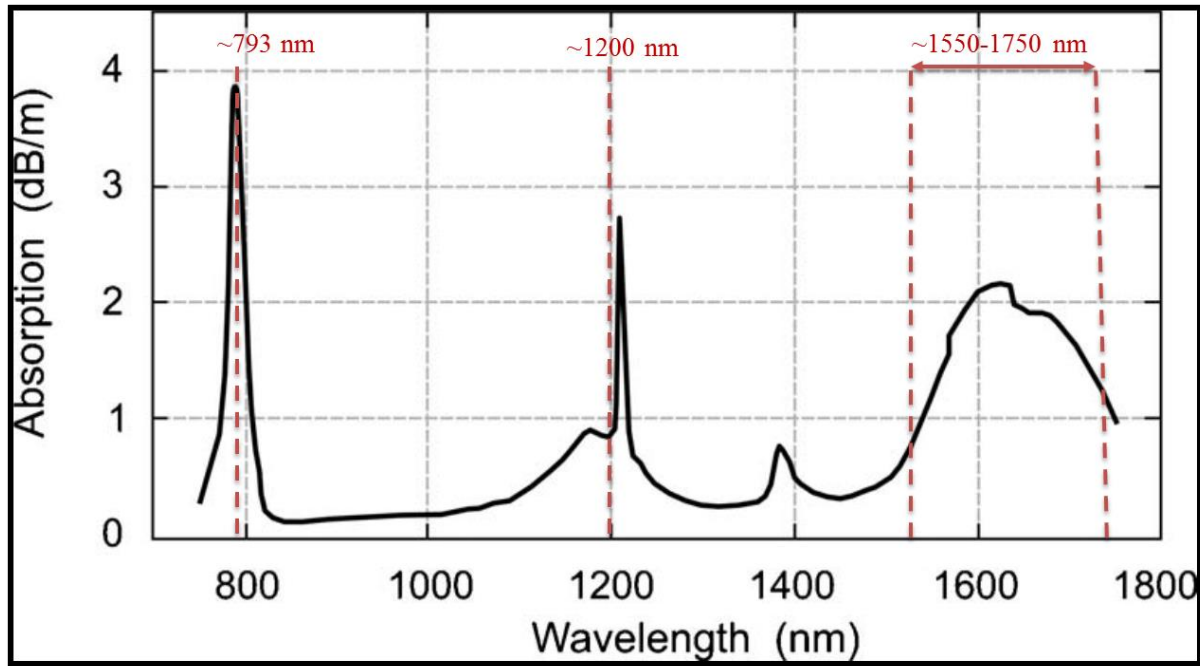


Figure 8 : Absorption spectrum of Tm^{3+} ion in silica glass [1].

The CR process occurs when pumping Tm-doped fibre lasers with 793 nm laser diode. This process furnishes Tm-doped fibre with another interesting feature known as “two for one” excitation of the upper laser level which improves quantum efficiency of high power Tm-doped fibre laser [27]. The “two for one” optical conversion produced by cross relaxation is illustrated in Figure 9 below and it takes place as follows [28]:

- One Tm^{3+} ion in the ground state ($^3\text{H}_6$), is excited to upper laser level ($^3\text{H}_4$).
- This ion in $^3\text{H}_4$ will decay to $^3\text{F}_4$ state and release energy as it decays.
- The energy will be absorbed by another Tm^{3+} ion in the ground state.
- This Tm^{3+} ion in the ground state will move to $^3\text{F}_4$ state.
- Thus, two Tm^{3+} ions in the ground state can be excited to $^3\text{F}_4$ state by absorbing only one pump photon at ~793 nm.

Hence, the ~793 nm strong absorption band and the “two for one” optical conversion makes Tm doped fibre a very appealing gain medium for pursuing and achieving high power fibre lasers

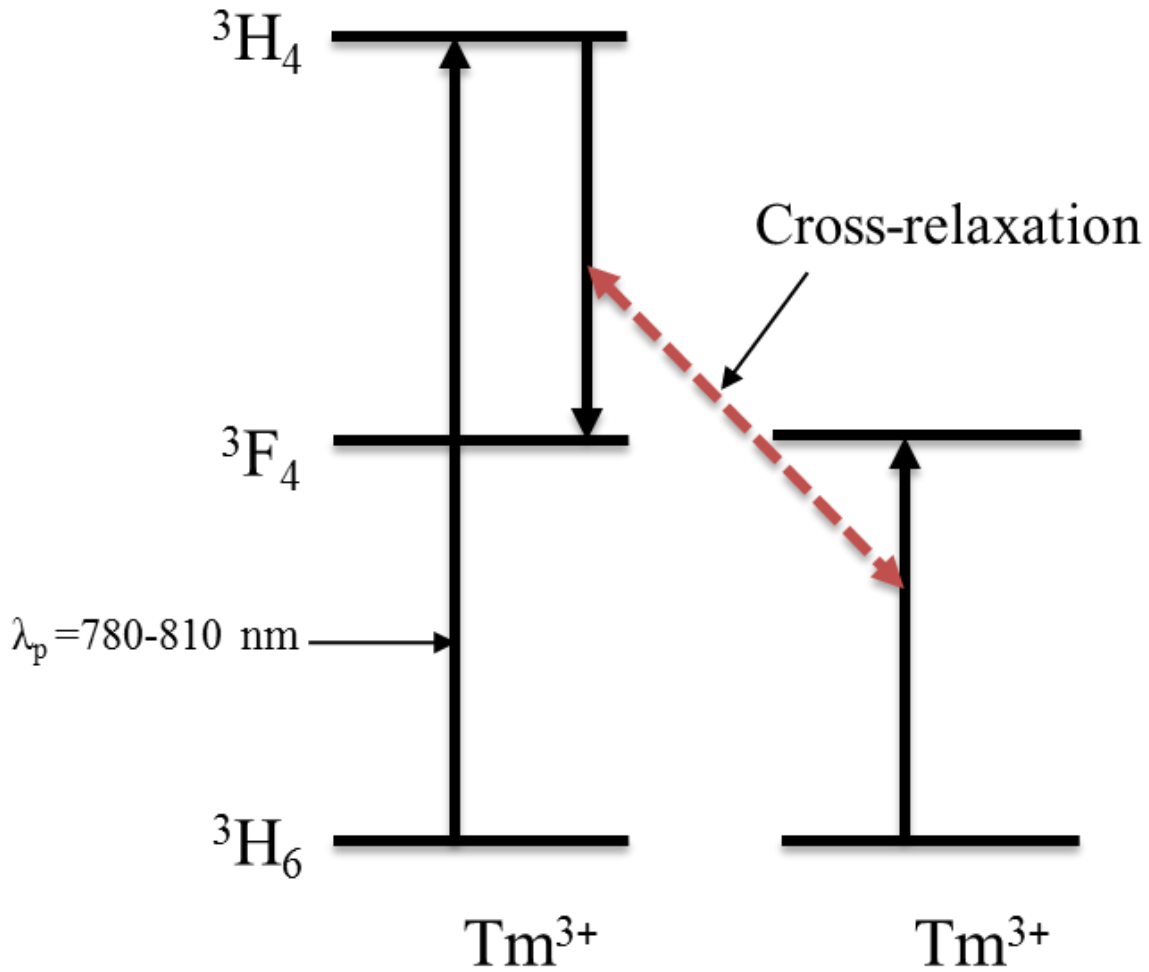


Figure 9 Energy level diagram of Tm-doped silica [28].

The following work aims to address research that has been conducted on free space thulium-doped fibre laser:

The first operation of a continuous wave monomode of Tm-doped fibre laser was reported by Hanna *et al*, in 1988 [29]. A $\sim 800 \text{ nm}$ dye laser was used as a pump source. The incident pump threshold was 30 mW, of which 21 mW was absorbed. The maximum output power was 2.7 mW and a slope efficiency of 13% with respect to the absorbed power was measured. It was concluded from this research that diode-pumped operation is feasible, due to the results of threshold power and absorption wavelength band.

The first high power diode cladding-pumped Tm-doped silica fibre laser operating near $2 \mu\text{m}$ was reported by Stuart Jackson and Terence King in 1998 [30]. Sixteen 2 W laser diodes which produced 25 W of output power at a wavelength of 790 nm were used as a pump source. A maximum output power of 5.4 W and slope efficiency of 31% was obtained from using a double cladding pumping arrangement. Confirmation of ion clustering effects in the form of self-pulsing was observed from the fibre laser output.

In 2000, Hayward *et al*. demonstrated CW operation of a double-cladding Tm-doped silica fibre laser at $2 \mu\text{m}$ [31]. The maximum output power of 14 W in single-mode beam and slope efficiency of

~46% for 36.5 W launched pump power was obtained. This laser was pumped by two beam shaped diode bars to increase output power. Efficient pump absorption was ensured by the use of a 4.5 m long fibre. One dichroic mirror placed at one end of the fibre and the 3.5% Fresnel reflection from the opposite cleaved fibre end was used as resonator.

High power and highly efficient operation of a Tm-doped silica fibre laser was reported in 2005 by Shen *et al* [32]. A double-clad Tm-doped silica fibre laser pumped with 793 nm laser diodes that yielded output power of 30.8 W for a launched pump power of 58.5 W. A high slope efficiency of 61% with respect to 65% of pump power was measured. These results illustrated the important role of cross relaxation processes which increases the pump quantum efficiency. An aspheric focusing lens was used to couple the pump light into the output end of Tm-doped fibre and a dichroic mirror was used for the production of 2 μ m fibre laser. Pump power was increased by using a third diode which led to an increase in output power. The pump power from the third diode was shaped by two mirrors so that coupling into a multimode delivery fibre was possible.

1.6.1 Thulium-doped All-Fibre Lasers

Thulium-doped fibre lasers with an all-fibre design (see Figure 1) have various advantages when compared to lasers that contain free space components. A good beam quality can be maintained by using fibre components instead of using bulk optics. An all-fibre laser configuration is simple, robust and resistant to external factors such as contamination and vibration. Passive fibre components permit efficient integration of pump power into the active double-cladding fibre and they create a robust, hassle-free alignment laser configuration. In this section, previous work on the development of thulium doped all-fibre laser is discussed.

A study implementing high power pump combiners in Tm-doped fibre laser was published by Stachowiak *et al.* in 2015 [26]. The input and output of the 3 m 10/128 μ m Tm-doped fibre was spliced to two FBGs, which served as a resonator. A 3SAE large diameter splicer (LDS) with tri-electrode technology was utilized for the fabrication of the two fusion splices. This LDS is the same equipment that is used for the fabrication of all fusion splices in this work. 20 W pump power in total was launched into the laser system by five ~790 nm laser diodes. The fabricated pump combiner was able to combine pump power with 80-85% transmission efficiency. The laser system produced 6.42 W output power with 32.1% slope efficiency. The low slope efficiency was suggested to be as a result of splice losses associated with the two fabricated fusion splices. This study aims to mitigate such kind of flaws found by Stachowiak *et al* by finding best splicing parameters that will yield low splice losses with the intention of developing a high power all-fibre laser. The work of Stachowiak *et al* demonstrated that an all-fibre pumping scheme is an attractive option compared to free space coupling.

Tang *et al.* reported in 2012 on a high power narrow bandwidth Tm-doped all-fibre laser in the 2 μ m regime [27]. An optical-to-optical slope efficiency of 62% with respect to incident 793 nm diode pump power and a maximum output power of 137 W were measured. The all-fibre laser configuration employed a fibre component called the fibre Bragg grating (FBG) which was used to obtain a narrow linewidth. The FBG also enhance the robustness of the laser system and no misalignment setbacks are encountered.

A single-mode cw Tm-doped all-fibre laser emitting in the 2 μ m region was reported in 2007 by Meleshkevich *et al* [33]. The double clad Tm fibre laser was end pumped by a 720 W Er-doped fibre

laser. The maximum CW power obtained was ~415 W with a slope efficiency of ~60%. Some part of Er pump power was not absorbed in Tm fibre but filtered out and this led to the lower output power.

Thulium fibre laser output power has increased from 14 W in the year 2000 [31] to 85 W in 2005 [34], 415 W in 2007 [33], 885 W in 2008 [35], and for single-frequency operation : 608 W in 2009 [21] ; 1kW in 2010 [36]. The increase in output power was due to multiple stage oscillator (MOPA) laser configurations.

Chapter summary:

- The basic components, principles and the operation of a laser were discussed. Stimulated emission is the fundamental process on the light amplification in lasers and amplifiers.
- The basic concepts of fibre lasers which include the propagation of light in an optical fibre and the operation of cladding pumping principle in DCF were discussed.
- The motivation for the selection of DC-LMAF for the splice loss optimization experiment was discussed. These fibres are known to scale output power to kW level.
- Previous research on the comparison between the thulium-doped fibre laser that utilized free space components and the thulium-doped all-fibre laser that used fibre components was reviewed. Thulium-doped all-fibre laser has more attractive pumping scheme, robust laser system, free of misalignment issues, can scale output power through the use of MOPA configuration than the thulium doped fibre laser with free space components.

High splice losses have a deleterious impact on the performance and long-time reliability of fibre lasers. The purpose of this study is to find optimal splice parameter set points that can be used to fabricate fusion splices that are associated with low splice losses (< 0.1 dB).

Chapter 2 will discuss the theory of fibre fusion splicing, the design of experiment for splicing and the previous work conducted on the optimization of fusion splices.

Chapter 2: Introduction to Fibre Fusion Splicing

2.1 Introduction

Fibre fusion splicing is a critical process that is required in the development of fibre lasers. The process involves the connection of optical fibres and fibre components such as passive and active fibres, fibre Bragg gratings (FBG) and pump combiners, for the purpose of producing high strength and permanent splice joints (fusion splices). The objective of this chapter is to:

- Motivate the choice of splicing technique that is used in this study.
- Describe the basic mechanics and optics of fusion splicing.
- Describe the design of experiment and data analysis for splicing.
- Review the research conducted on the optimization of fusion splices.

2.2 Fusion Splicing Techniques

There are different types of fusion splicing techniques that use distinct heat sources for splicing fibres. These fusion splicing techniques are: flame, laser, filament and arc fusion splicing [20]. Only laser, filament and arc fusion splicing have been implemented in commercial equipment.

In the flame splicing technique [19], propane or oxy-hydrogen is applied as a heat source. The flame serves as a crucible that encloses the fibre to ensure the heat zone is confined and gas flow disturbance is reduced. Telecom fibre couplers can be fabricated by means of flame splicing. This technique is not commercially available due its unstable heat zone which is difficult to control. The heat zone produces low quality fusion splices with rounded fibre end facets.

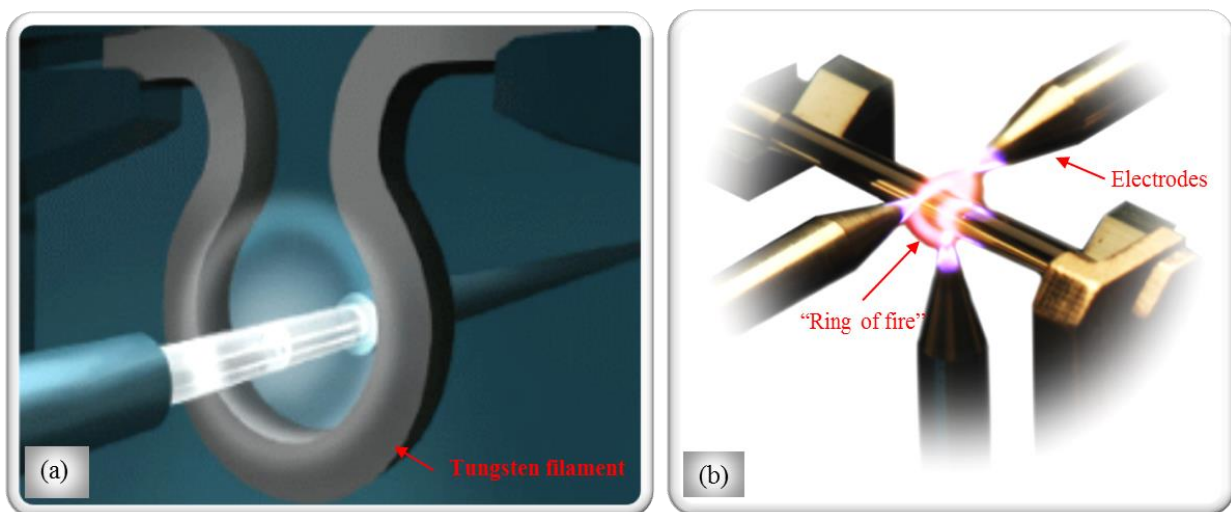


Figure 10: (a) Vytran filament fusion splicer uses a tungsten filament as a heat source [37]; (b) 3SAE large diameter splicer (LDS) with electrode heat source that generates a “ring of fire” [38].

The laser fusion splicing technique [19] uses carbon dioxide (CO₂) - based lasers as a heat source because silica has a good absorption at 10 μm lasing wavelength. The basic heating method of laser fusion splicing is through radiation.

The filament fusion splicers [39] by Vytran utilize a resistively heated filament which consists of tungsten metal that acts as a heat source (see Figure 10(a)), graphite and iridium can also be applied as a heat source for these splicers. The filament has a ribbon inverted omega Ω shape, which serves to enclose the inserted fibre and to provide a homogeneous heat zone around the fibre. A noble gas such as argon surrounds the filament to prevent the reaction of filament with oxygen at high temperatures. The enclosed fibre is heated by conduction from the surrounding environment which ultimately forms a fusion splice. The heat generated can be regulated continuously over a broad temperature range. The utilization of distinct filaments furnishes filament fusion splicer with the flexibility of permitting different fibres such as large mode area (LMA), polarization maintaining (PM) and microstructured fibres to be used. However, filament splicing is not appropriate for field splicing application due to its dependence on the supply of a noble gas.

A conventional arc fusion splicer [19] is equipped with two alloy electrodes which are separated by an air gap. The electrodes serve to generate a high voltage glow discharge, which is referred to as an arc heat source. A current will travel across the electrode gaps and heat up the neighbouring air. The fibre will be heated through conduction, leading to the formation of a fusion splice. The heat source provided by the two electrode system of a conventional arc fusion splicer is a narrow and single dimensional arc plasma heat zone. The aforementioned heat source is insufficient for fibres with a larger cladding diameter ($> 250 \mu\text{m}$) because of the failure to heat all sides of the fibre uniformly. Only standard telecom silica fibres with cladding diameters ranging from 125-250 μm can be accommodated by the heat source. Therefore, conventional arc fusion splicer that uses two electrodes cannot accommodate the Nufern 25/400 μm passive DC-LMAF that are utilized in this research. The “ArcMaster” fibre fusion splicer [40] by Fujikura which is also equipped with two electrodes offers an innovative technology in the splicing area. These splicers are capable of regulating the plasma zone for fusion splicing by means of the so called “electrode swinging” which creates a wider plasma zone. Fibres with cladding diameters that ranges from 60-1200 μm can be accommodated by these fusion splicers.

A recent ground-breaking arc discharge splicer furnished with three electrodes has been developed by 3SAE to eliminate the fibre dimension limitation and to generate improved heat zone uniformity [38]. The three electrodes provide an extensive plasma arc discharge field that effectively encloses the splice zone, forming a “ring of fire” (ROF) or triangular-two dimensional plane (see Figure 10 (b)). The addition of the third electrode results in plasma arc discharge to be 100 times greater than that of the conventional two electrode arc fusion splicer. The advantage of three electrodes results in an isothermic plasma arc discharge around the fibre which maintains its narrow shape. The three electrode arc fusion splicer system can process fibres with cladding diameters from 125 μm to up to large diameter of 2500 μm .

In this work, a 3SAE large diameter glass processing fusion splicer (LDS) was used to fabricate fusion splices between two Nufern 25/400 μm passive DC-LMAF, because it is capable of handling the dimensions of the fibres used in this study. The LDS allows rapid operation, flexible control and sophisticated software package that permits an operator to view the live splicing process.

2.3 Mechanics of Fusion Splicing

2.3.1 Viscosity and Surface Tension

Fusion splicing involves the joining of two optical fibre ends that are firstly softened by localized heat and then pushed together to form a fusion splice. There are mechanical forces such as viscosity and surface tension that occurs during the fusion splicing process [20]. For silica-based fibres, fusion splicing process will take place when the viscosity is reduced to 10^5 Poise, which is achieved when the heating from the splicer is above 2000 °C. When the aforementioned viscosity state is reached, surface tension will cause a flow of softened glass, forming a fusion joint with a smooth and homogeneous external surface [41]. Surface tension develops from the molecular structure difference between the surface interface material and inside bulk material. It can either be advantageous or deleterious during the fusion splicing process. Surface tension will cause accurate self-aligning of the cladding of two fibres relative to each other during the fusion splicing process, regardless if the claddings were originally offset [42]. The self-alignment aspect is called the surface tension effect which enhances fibre core alignment, thus minimizing splice loss [43]. However, fibre ends may be deliberately offset to align non-concentric fibre cores. Surface tension on the cladding will annihilate the offset; hence fibre cores will be misaligned thus increasing splice loss. Another disadvantage of surface tension is that when fusion splicing takes place at elevated fusion power and extended times, surface tension effect can cause fibre cladding to be non-uniform and more rounded (see Figure 11(a)) resulting in balling up of fibre end facets (see Figure 11(b)) or can generate a fibre core radial offset which will result in maximum splice loss [19]. The fibre core radial offset that is produced by surface tension effect can induce a shear force across fibre end facet which can deform fibre core during fusion splicing [44].

During fusion splicing process, surface tension is a dominant and important mechanical force that is experienced by fibre end facet because it causes flow of molten glass and is responsible for the formation of a fusion splice.

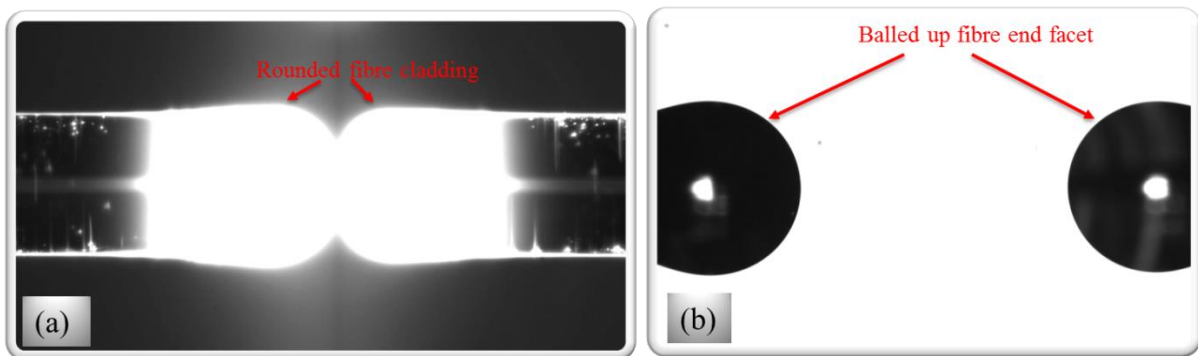


Figure 11: Surface tension producing, (a) non-uniform or rounded fibre cladding during fusion splicing; (b) balling up fibre end facets outcome from non-optimal fusion splicing process.

2.3.2 Dopant Diffusion

When two fibre ends are heated at an elevated temperature or at splicing temperature (2000 °C for silica based fibres) during fusion splicing, impurities or dopants residing in the fibre core will begin to diffuse [20]. Dopant diffusion will cause the mechanical properties of the fibre to change. Mechanical

properties such as the thermal expansion of the fibre core diameter in Figure 12, will decrease the refractive index resulting in an increase in the mode field diameter (MFD) [19]. MFD is the attribute of fibre that describes the bounding of light or mode in the fibre core [45]. Splice loss is minimized by the dopant diffusion in the fibre core when the mode field distribution between the two fibres becomes better matched [39]. The principle of dopant diffusion is associated with heating the expanded splice region to a specific temperature and maintaining the splice region in that temperature zone for some time. The degree of dopant diffusion in the fibre core of both fibres will increase towards the splice joint until the optical difference between the fibres is no longer visible at the splice joint [46].

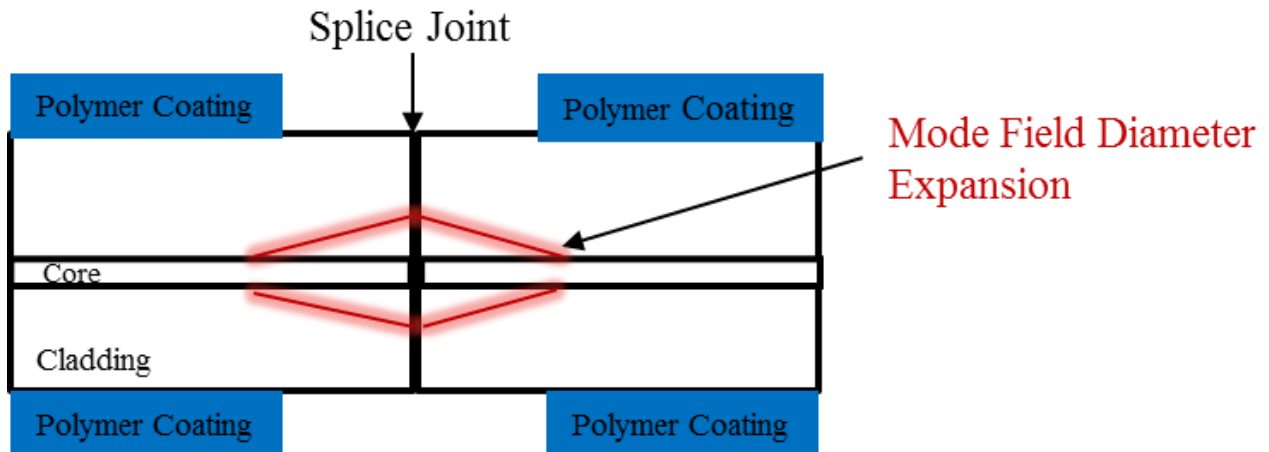


Figure 12: Mode field diameter (MFD) expansion during fusion splicing.

2.4 Optics of Fusion Splice

2.4.1 Splice Loss Definition

A fusion splice (splice joint) is formed between two fibres by fibre fusion splicing technique previously discussed in section 2.2. In a spliced fibre, an optical signal propagating from a launch fibre into receiving fibre through the splice joint in Figure 13, can be [20]:

- Reflected back into the launch fibre.
- Transmitted into identical mode and/or another mode of the receiving fibre.
- Radiated out of the receiving fibre.

Splice loss and splice return loss are optical characteristics of a fusion splice. The return loss is the amount of optical signal power that is reflected at the splice joint and splice loss is the fraction of optical signal power that has radiated from the fibre core at the splice joint. This study will measure splice losses between two fusion spliced Nufern 25/400 μm passive DC-LMAF.

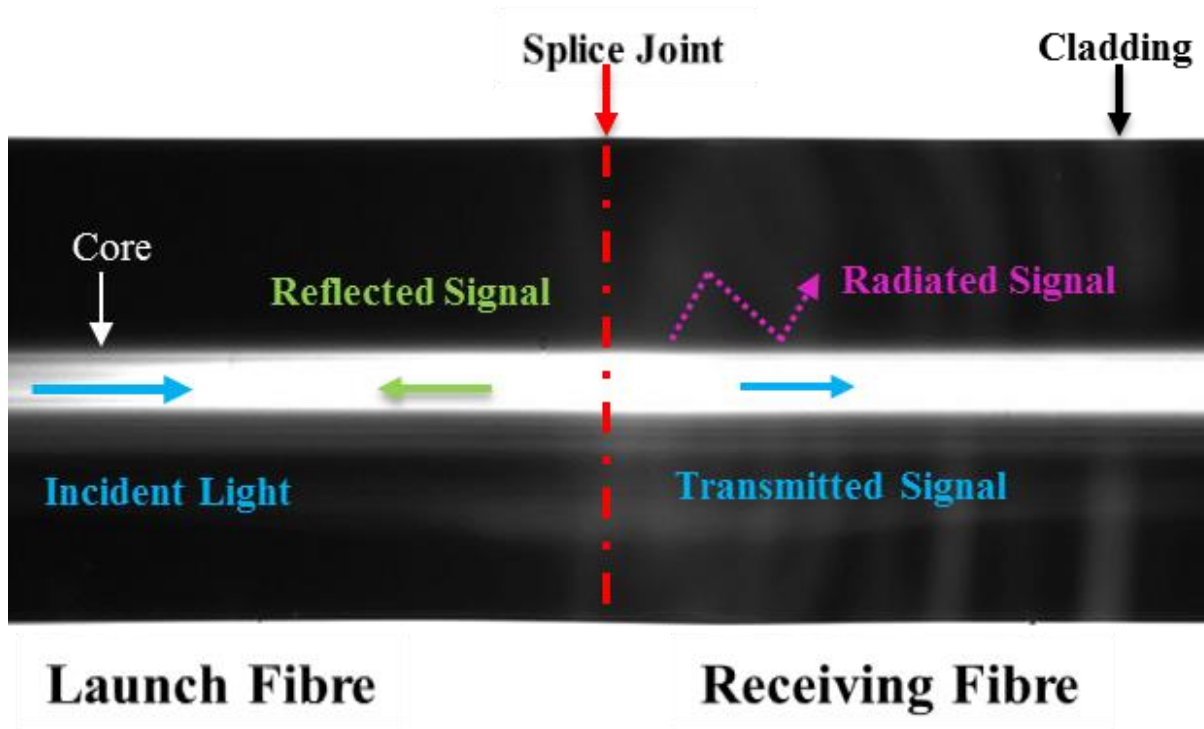


Figure 13: Impact of fusion splice joint on optical signals propagating from the launch fibre into the receiving fibre [2].

Splice loss is denoted by Γ_{splice} and defined by convention in decibel [20] as:

$$\Gamma_{splice} = 10 \log_{10} \frac{P_{in}}{P_{tran}} \dots \dots \dots \text{Equation 1}$$

where P_{in} is the total optical power incident upon the fusion splice and P_{tran} is the amount of optical power that is transmitted across the fusion splice. Splice loss will be a positive number due to $P_{in} > P_{tran}$.

Generally, splice loss can be categorized into intrinsic and extrinsic splice loss [47]. Intrinsic splice loss is associated with the two fibre ends having distinct propagating characteristics. Extrinsic splice loss refers to losses caused by the geometric deformation at the splice joint. Factors that produce intrinsic and extrinsic splice losses are shown in Table 2.

Table 2: Intrinsic and extrinsic splice loss factors [47].

Intrinsic Factors	Extrinsic Factors
Mode field mismatch	Poor fibre-end quality
Core diameter mismatch	Axis misalignment
Core eccentricity	Physical deformation of fibre-end
Cross-section irregular shape	Fibre-end separation

Splice loss optimization and special splicing strategies such as splice tapering can be applied to reduce intrinsic splice loss. Extrinsic splice losses can be mitigated by paying proper attention to producing good quality cleaves prior to splicing.

2.4.2 Influence of Splice Loss on the Performance of Fibre Lasers

Splice loss plays a significant role on the performance and reliability of high power fibre lasers. The quality of fusion splices influences the output power and beam quality of a fibre laser.

A 20/400 μm ytterbium-doped high power fibre laser with a master oscillator power amplifier (MOPA) configuration was simulated by Yin *et al.* [2] in 2011 with the purpose of investigating the impact of fusion splice on the laser system. Yin *et al.* used 10 kW output power level as an example and simulated three distinct fibre lasers. The fibre lasers which were labelled fibre laser #1, #2 and #3 which constituted of six, three, and two booster amplifier stages with the pump capacity of 1, 2, and 3 kW, respectively.

The total power loss as well as decrease in optical-to-optical efficiency for each of the fibre lasers was calculated as a function of splice loss. Many fibre laser manufacturers have revealed the average splice loss of DCF to be 0.1 dB [48], thus the work Yin *et al.* presented total power loss of 475, 213.7 and 111 W as well as a corresponding reduction in slope efficiency of 4.0%, 1.7% and 0.9%, respectively at 0.1 dB level (See Figure 14). Additionally, fibre laser #1 with six amplifier stages has the highest power loss and lowest optical-to-optical efficiency even at other splice losses when compared with fibre laser #2 and #3. This could likely be due the six splices that constitute fibre laser #1 which induces high splice losses on the laser system. Fibre laser # 2 and # 3 demonstrated the lowest power loss which could possibly be due to fewer (three and two) amplifier stages found on the laser system

Slope efficiency is defined as the slope of the curve for the output power against the input power of a laser system [49]. In Figure 14, the increase in the splice loss from the three laser systems resulted in an increase in the power loss, as well as a decrease in the slope efficiency. The work of Yin *et al.* revealed that fusion splice (splice loss) produces power loss as well as a decrease in optical-to-optical efficiency which can consequently reduce the functional reliability of the laser system.

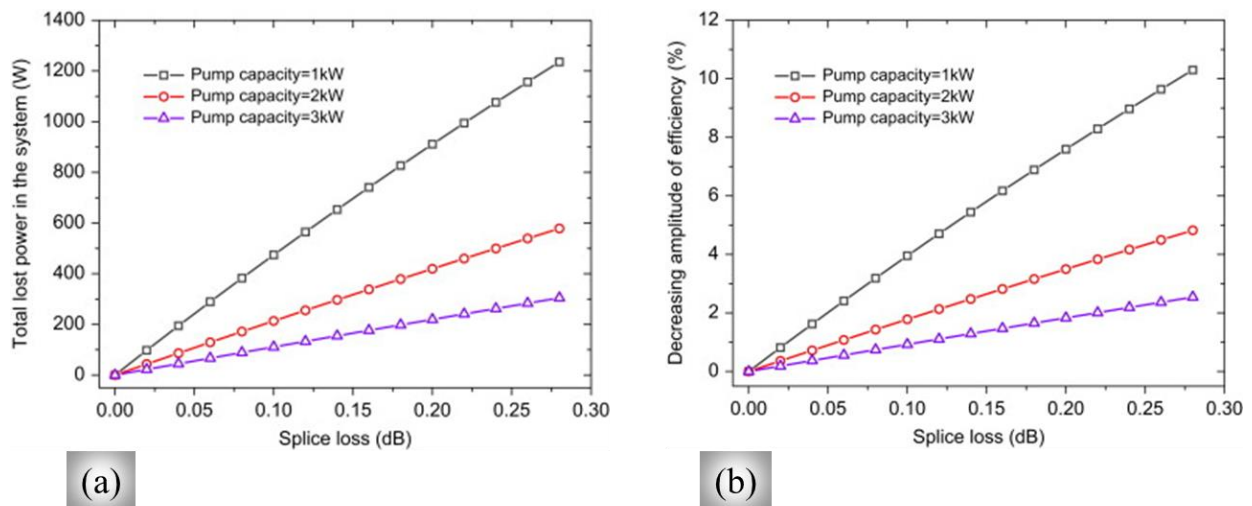


Figure 14: Demonstration of (a) total lost power; (b) decrease in optical-to-optical efficiency of fibre laser #1, #2, #3 with MOPA structure pumped at 1kW, 2kW and 3kW, respectively [2].

In 2013, Yan *et al.* [50] demonstrated that fibre fusion splicing does not only affect the output power but also affects the beam quality of a fibre laser. Spatial deviations namely, splice shifting and tilting which occurs during fusion splicing was investigated through simulation and experiment with the intention of analysing its effect on beam quality. Five passive fibres were used in the simulation and the 25/400 μm passive DC-LMAF used in this dissertation has similar properties to one of the passive fibres used by Yan *et al.* (see passive fibre #2 in Table 3). The only difference is that the passive fibres used in this dissertation has a larger core NA=0.11.

Table 3: Five passive fibres used in the simulation of Yan *et al* [50].

Passive Fibre #	Core diameter (μm)	Cladding diameter (μm)	Core NA	Cladding NA
1	20	400	0.06	0.46
2	25	400	0.06	0.46
3	30	400	0.06	0.46
4	20	400	0.065	0.46
5	20	130	0.08	0.46

In Yan *et al*'s simulations, splice shifting (see Figure 15(a)) was defined into one and two dimensional shifting. When a fibre is spliced to a second fibre with a shift in the x- or y- axis at the splice joint, it is defined as one dimensional splice shifting and when there is a shift in both x and y axis it is described as two dimensional splice shifting. Passive fibre # 1, # 2 and # 3 (see Table 3 above) were examined under two dimensional splice shifting in the range of $0 \mu\text{m} \leq x \leq 5 \mu\text{m}$ and $0 \mu\text{m} \leq y \leq 5 \mu\text{m}$. The simulation results showed that an increase in splice shifting generates an increase in the beam quality factor from the ideal $M^2=1$. The passive fibre # 2 had the largest beam quality factors $M_x^2=1.68$ and $M_y^2=1.67$ at a maximum splice shift of $5 \mu\text{m}$. The beam quality factor of passive # 2 increased more rapidly with an increase in splice shifting indicating it to be more susceptible to splice shifting during fusion splicing process. The increase in beam quality factor of passive fibre # 2 was attributed to the four intrinsic modes. Light in low order modes will couple into higher order modes during splice shifting and the power distribution of two high-order modes will increase, resulting in the degradation of the beam quality.

Simulation for splice tilting was performed for passive fibre # 1, # 2 and # 3. Splice tilting in Figure 15(b) below is defined as splicing two fibres in which an angle exists between the two fibre axes. The simulation showed that an increase in tilting angle resulted in an increase in beam quality factor, which implied degradation of the beam quality. Passive fibre # 2 had a beam quality factor of $M_x^2=1.2$ and $M_y^2=1.29$ at a maximum tilting angle of 5° .

Comparing simulations of the beam quality factor for splice shifting and tilting of passive fibre # 2, it was found that splice shifting deteriorates the beam quality much more than splice tilting. Therefore, Yan *et al.* concluded that it is more significant to prevent splice shifting than splice tilting to minimize deterioration of beam quality during fusion splicing process.

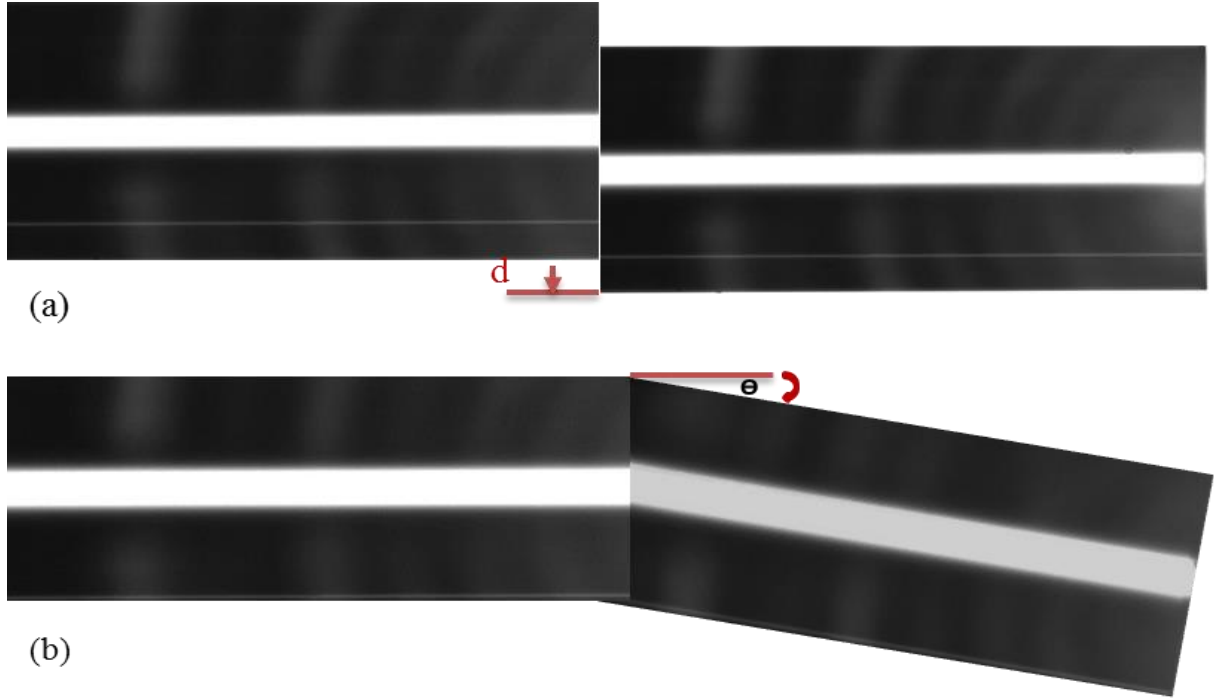


Figure 15: Representation of (a) splice shifting (b) splice tilting between two optical fibres [50].

In Yan *et al.*'s experimental work, the 20/400 μm ytterbium doped fibre laser was used to investigate one and two dimensional splice shifting, with the Spiricon M2-200s utilized to measure the beam quality. The output end of ytterbium doped fibre was spliced to another 20/400 μm ytterbium doped fibre, with 2 μm and 5 μm shift in one dimension as well as 1 μm and 3 μm shift in two dimension. Beam quality values of 1 μm and 3 μm shift in two dimension were $M^2_x=1.24$ and $M^2_y=1.37$; $M^2_x=1.27$ and $M^2_y=1.45$ respectively. The results revealed that the beam quality factor increased with an increase in splice shifting, leading to the deterioration of beam quality of the ytterbium doped fibre laser. The experimental results validated the simulation results.

2.5 Design of Experiment and Data Analysis for Splicing

The fibre fusion splicing process is associated with many distinct splice parameters that are required for the fabrication of a good quality fusion splice. The many splice parameters and the hidden physical interaction amongst these parameters, as well as the distinct variation in the fusion splice quality makes splice loss optimization a difficult duty to perform [20]. This work requires seven splice parameters to be optimized for the purpose of achieving low splice losses. The solution to the optimization of these seven parameters is to conduct experiments that are well designed, in a way that significant fusion splicing parameters are efficiently elucidated such that their optimal set points can be achieved. The aforementioned solution is achieved with the design of experiment (DOE) approach.

Design of experiment (DOE) is a systematic approach that is used for data collection [51]. Optimization is one of the problem areas in which DOE is applicable. In the interest of this work, there are seven splice parameters that have to be optimized. The DOE is applied to investigate the response of two fusion spliced passive fibres to different splicing parameters. In this work, the DOE is

needed to determine the level of each splice parameter that will optimize splice losses between two Nufern 25/400 μ m passive DC- LMAF. The main objective with DOE is to obtain parameter set points that will yield low splice loss that is critical to development of high performance and reliable thulium-doped all-fibre lasers.

There are different types of DOE that can be used for the optimization process (see appendix 1). This dissertation utilised a mixed level fractional factorial design that followed the Taguchi orthogonal array methodology (see appendix 1 for Taguchi methodology guidelines). The L_{18} Taguchi orthogonal array in Table 1 of appendix 1 which can accommodate a maximum of eight factors that can be evaluated over mixed levels was used for this work. The implementation of Taguchi methodology guideline for this work is executed in chapter 4.

The analysis of variance (ANOVA) defined in Appendix 1, is applied to determine the contribution and importance that each splice parameter has towards splice loss. The implementation of the ANOVA is demonstrated in chapter 4.

2.6 Previous Work on Optimization of Fusion Splices

Fusion splicing of single mode fibres (SMF) is well established and is mainly applied in telecommunication. However, there are limited published papers on fusion splicing of large mode area fibres (LMAF) and large diameter specialty fibres due to their applications in the splicing field being relatively new and still in progress. This section reviews the few published works on the optimization of fusion splicing of LMAF.

Fusion splicing of large mode area 10/125 μ m photonic crystal fibre (LMA-PCF) with standard 9/125 μ m single mode fibre (SMF) was reported by Shaymaa *et al.* in 2014 [45]. The methodology applied in achieving optimal splice parameter conditions was through controlling arc power and arc time splice parameters of conventional electric arc fusion splicer which is equipped with two electrodes. A PCF was spliced in between two SMF by choosing distinct fusion time with a constant value of fusion power. Transmission power measurements in SMF-PCF-SMF was obtained and splice loss of SMF and PCF joint was calculated. The fusion power was kept constant at STD+ 10 (bit) and fusion times were varied in the range of 500 ms from 1000 to 4000 ms. A minimal splice loss of 0.07 dB was obtained when the arc time was 3500 ms.

Likewise, PCF was spliced between SMF by selecting different fusion power at a constant value of fusion time and similar transmission and splice loss measurements were obtained. The fusion time was fixed at 3500 ms and the fusion power was varied from STD (-50 to -10) bit. A minimal splice loss of 0.065 dB was obtained when arc power was STD-10 bit

The low splice losses resulted from an increase in temperature which decreased the viscosity of SMF-PCF splice joint. The decrease in viscosity during fusion splicing led to a collapse of PCF air holes (see Figure 16) by expanding the PCF MFD, thus generating a better mode field match between the fibres.

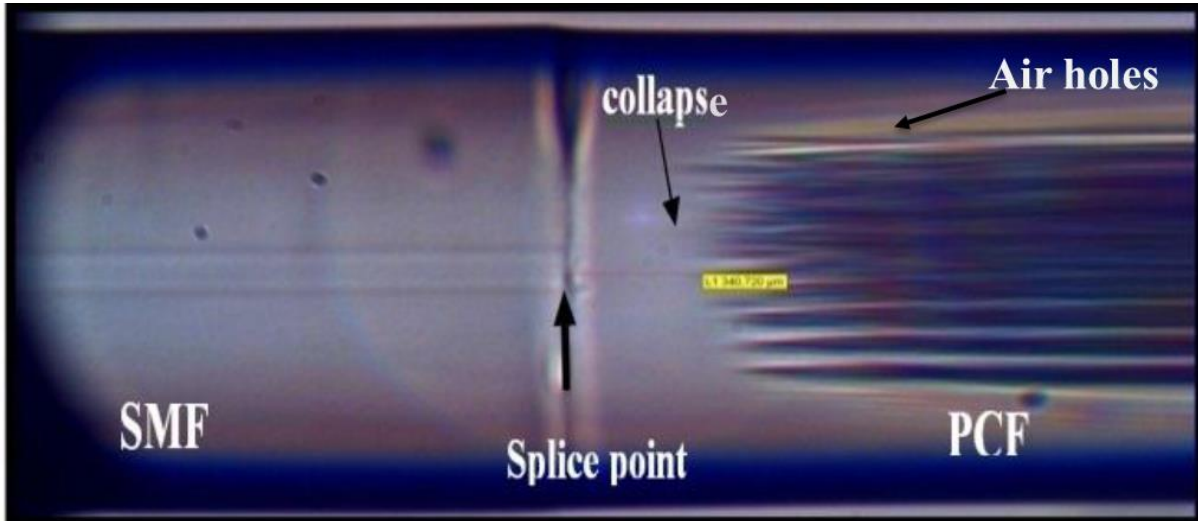


Figure 16: Collapse of air holes from PCF during fusion splicing of SMF and PCF [45].

In 2013, Michalska *et al.* [52] used the 4/125 μm erbium doped fibre (EDF) and the 8/125 μm single mode fibre (SMF) (see Figure 17(a)) to show that dopant diffusion has the ability to enlarge the MFD of a fibre during fusion splicing. The dopant diffusion was observed in the EDF spliced to the SMF through filament fusion splicing. The aluminium dopant diffusion in the EDF doubled the fibre core diameter which resulted in a reduction of the MFD mismatch (see Figure 17(b)), leading to minimal splice loss of 0.12 dB. Additionally, Michalska *et al.* also showed that the dominant mechanical force known as surface tension can deform the shape of a fibre during fusion splicing. An erbium and ytterbium co-doped double clad fibre was used in the high power all-fibre laser which experienced inner clad shape deformation, changing from octagonal to cylindrical shape after splicing (see Figure 18(a) and Figure 18(b)). The inner clad deformation was due to excessive arc power which caused the surface tension to make the corners of the inner clad to be more rounded during fusion splicing.

In this work, the fusion splices with rounded fibre cladding are fabricated at high arc power. Surface tension is the suspected cause of the rounded fibre cladding and this is discussed in chapter 4.

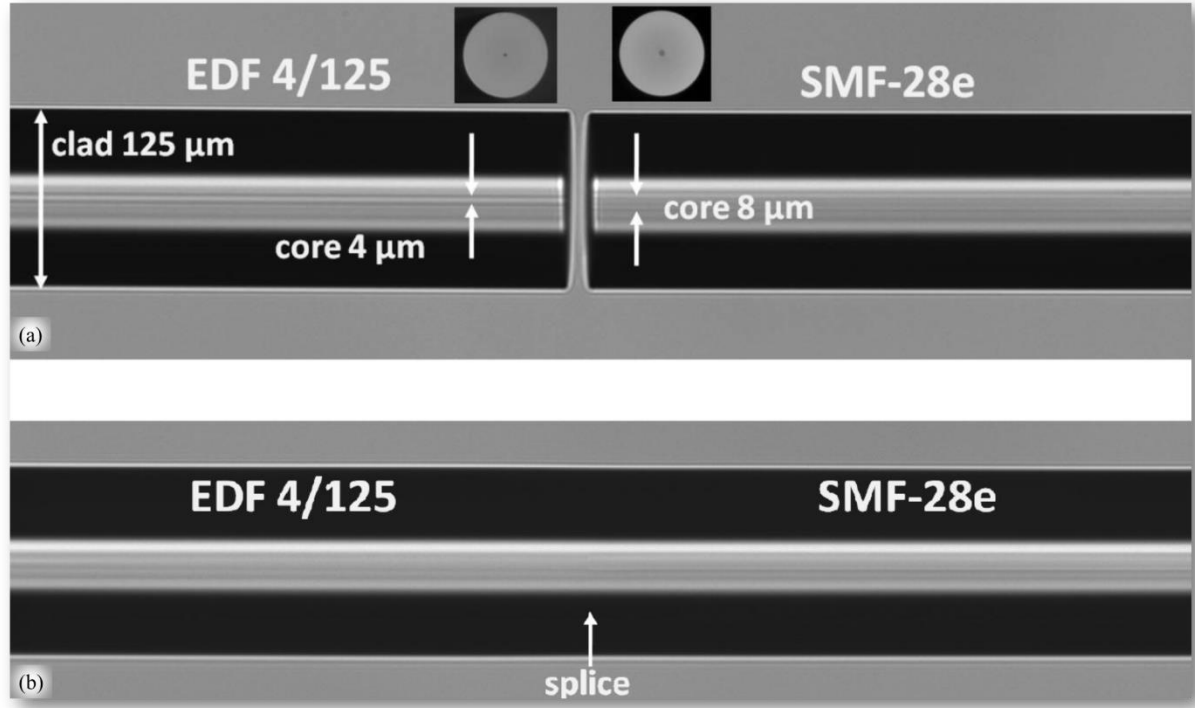
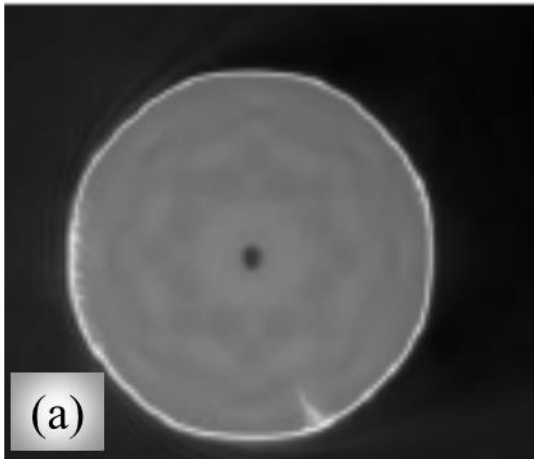


Figure 17: The EDF and SMF (a) before fusion splicing; (b) after fusion splicing [52].

Octagonal Fibre Clad



Cylindrical Fibre Clad

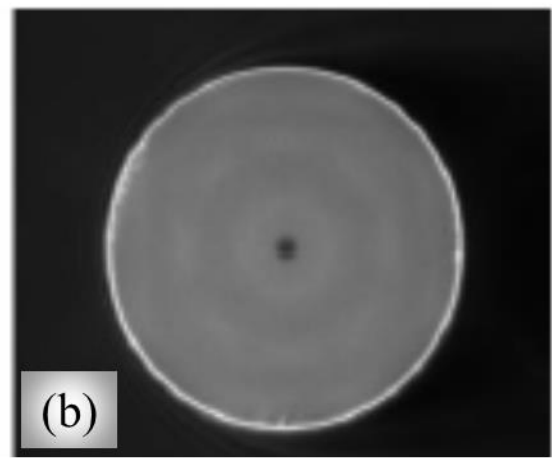


Figure 18: (a) Octagonal fibre clad before filament splicing; (b) same fibre after filament splicing, which has become cylindrical [52].

In 2011, Shen *et al.*[47] developed a method for fabricating large mode area fibre (LMAF) passive components. The best splicing parameters between 20/80 μm LMAF and 6/125 μm single mode fibre (SMF) were determined by adjusting parameters on the conventional fusion splicer with two electrodes. Splice parameters for the conventional splicer are fusion current, fusion time and prefusion parameter (prefusion time, prefusion current, gap and overlap). The optimal splicing parameters were found by changing fusion current or fusion time or prefusion parameters within reasonable range. The research showed that when fibres are pushed together during fusion splicing, the overlap splice parameter can induce a bending misalignment which can result in high splice losses. This overlap

splice parameter is defined as additional distance provided to fibres beyond the original gap spacing during fusion splicing and it is one of the splice parameter that will be optimized in this work.

In 2003, Pradhan *et al.*[53] conducted a splice loss optimization experiment between 9/125 μm single mode fibre (SMF) and 4/125 μm erbium doped fibre (EDF), with the purpose of creating an erbium doped fibre amplifier (EDFA) that would amplify an optical signal. The EDFA configuration comprised of two fusion splices (SMF to EDF and EDF to SMF). A full factorial design of experiment consisting of five parameters varied over two levels and the ANOVA was applied to find optimal splicing parameters that would generate the minimum splice loss. Splice loss was optimized by decreasing the mode field mismatch that occurs during fusion splicing process between the two fibres. The aforementioned drawback was mitigated by expanding the MFD of EDF. The splice parameters that controlled the extension of the EDF MFD during fusion splicing process were the gap distance, push distance and overlap distance and a minimal splice loss of 0.04 dB was achieved. The approach of applying full factorial design of experiment resulted in $2^k=2^5=32$ experiments to be conducted, whereas if fractional factorial experimental design were considered only 8 experiments (L_8 Taguchi orthogonal array) would need to be performed and would yield the same results. The above mentioned splice parameters are some of the parameters that are used in this study and they influence the MFD expansion during fusion splicing which can limit the splice loss.

In 1990, Singh *et al.* [54] obtained 0.47 dB splice loss between standard 9/125 μm single mode fibre (SMF) and 7/80 μm erbium doped fibre (EDF) through optimization process that utilized arc splicing machine equipped with power monitoring method. The minimal splice loss between the two fibres was achieved by examining the reliance of splice loss on the fusion time. A fusion time of 1.2 s generated the lowest splice loss and a fusion time longer than 1.2 s resulted in an increase in splice loss to 0.95 dB between the two fibres. The increase in splice loss was due to core distortion induced by surface tension, while the minimal splice loss at fusion time 1.2 s was due to self-alignment of molten fibre ends induced by surface tension during arc fusion splicing. This demonstration shows that surface tension can be deleterious or useful during arc fusion splicing, depending on the splicing condition.

Chapter summary:

- The different types of fusion splicing techniques were reviewed. In this work, the arc fusion splicing technique which utilizes the 3SAE LDS equipped with three electrodes will be used. The 3SAE LDS fabricated all the fusion splices discussed in this work.
- Viscosity and surface tension plays a major role in the fusion splicing process. Surface tension is the dominant force that shapes the joint formation of a fusion splice. It can either be advantageous or deleterious during fusion splicing process.
- The 2000 °C splicing temperature for silica based fibres can result in substantial dopant diffusion. This dopant diffusion can change the mechanical properties of a fibre, in the vicinity of a fusion splice.
- Splice losses can negatively impact fibre lasers by degrading the beam quality, as well as producing power losses which can furthermore decrease the slope efficiency.
- Fractional factorial design of experiment was briefly discussed. It is used to optimize the seven distinct splice parameters that are required for the fabrication of the fusion splices between the two Nufern 25/400 μm passive DC-LMAF. The fractional factorial experimental design allows the execution of fewer, well-designed experiments such that the optimal set points of each parameters can ultimately be revealed.

Chapter 3 will encompass the setting up of the measurement system to determine splice loss. The splice loss analysis will be discussed in chapter 4.

Chapter 3: Splice Loss Measurement System

3.1 Introduction

To obtain quality fusion splices, there are technical procedures that should be performed on the fibre before fabricating a fusion splice. These technical procedures are discussed in section 3.2 which is titled fibre end preparations. In section 3.3, the operation and parameters of the 3SAE large diameter glass processing splicer (LDS) are discussed to show the implementation of arc fusion splicing and the fabrication fusion splices. The fusion splices that are fabricated in this research are wavelength dependent, and will be utilized in the development of thulium-doped all-fibre laser operating in the 2000 nm region. The spectral splice loss measurement system is constructed in section 3.4 to obtain splice losses between two fusion spliced 25/400 μm passive DC-LMAF. In the construction of the spectral splice loss measurement system, the possible drawbacks which can hinder accurate splice loss measurements are investigated and solutions are suggested to mitigate the drawbacks.

3.2 Fibre End Preparations

In this research, multi-mode fibres (MMF) and double-clad fibres (DCF) in Table 4 are the two types of fibres chosen for constructing the splice loss experiment. MMF is an optical fibre that is designed to carry multiple modes concurrently inside the fibre core. DCF is designed to allow the propagation of single mode light in the fibre core and multimode light in the cladding. Therefore, DCF can be fusion spliced to either single-mode fibre or multi-mode fibre.

Table 4: Fibres applied for constructing splice loss measurement setup.

Fibre Name	Fibre Type	Core/Cladding Dimension (μm)	Connector	Manufacturer	Model No
MMF1	Multi-mode fibre optic patch cable	400/425	SMA	Thorlabs	FT400EMT
MMF2	Multi-mode fibre optic patch cable	400/425	SMA	Thorlabs	FT400EMT
MMF3	Multi-mode fibre optic patch cable	400/425	FC/PC	Thorlabs	FT400EMT
MMF4	Multi-mode fibre optic patch cable	400/425	FC/PC	Thorlabs	FT400EMT
Fibre Under Test (FUT)	Passive DC-LMAF	25/400	None	Nufern	FUD-3793: MM-GDF-11 FA Optical Fibre

Table 5: 25/400 μm passive DC-LMAF parameters.

Fibre Type	Operating Wavelength	Core Numerical Aperture (NA)	Cladding Numerical Aperture (NA)	Cladding Attenuation at 1095 nm
Passive DC-LMAF	800-2000 nm	0.1-0.12	0.46	0.15 dB/km

There are certain fibre end preparation procedures that should take place prior to performing a fusion splice, namely stripping and cleaving of optical fibres. Fibre preparations are very important to the fabrication of a splice, as they contribute towards the quality of a fusion splice.

Silica-based double-clad large mode area fibre (DC-LMAF) and multi-mode optical fibres (MMF) comprises of core, cladding and a protective outer coating. The first step taken in fibre preparation is the removal of the outer coating by process called stripping. Stripping has to be executed to avoid burning of the outer coating and damage to the cladding (glass) that can be experienced due to heat generated during joint formation between two optical fibres. The techniques that can be used for stripping the outer coating include mechanical, chemical and vaporization stripping techniques [20].

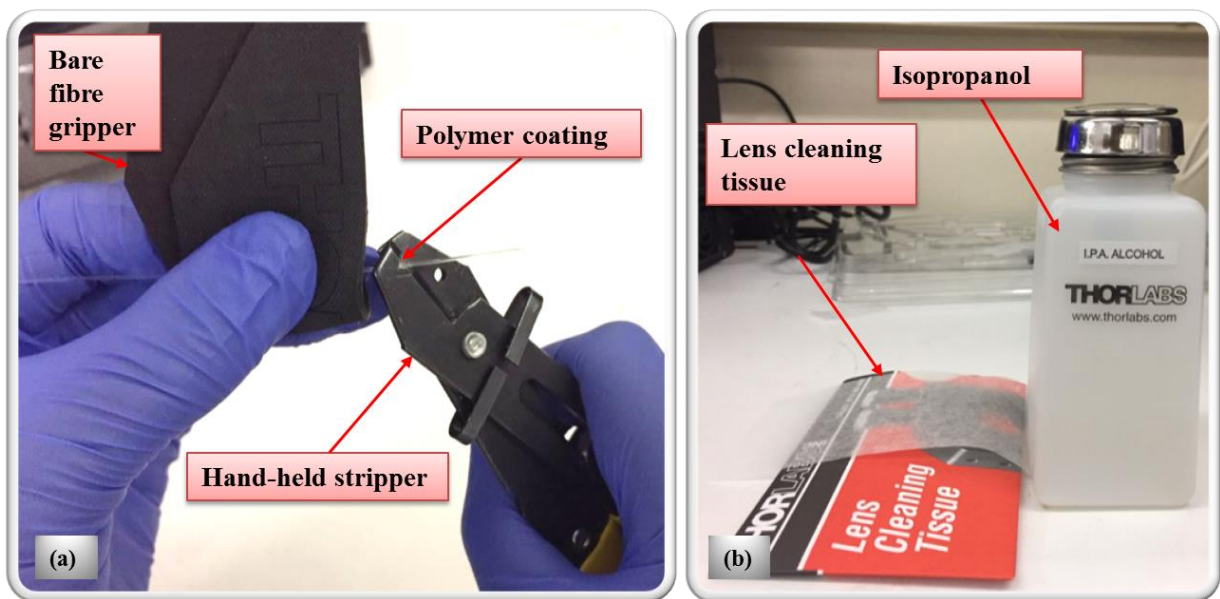


Figure 19: (a) Mechanical stripping applied to 25/400 μm Nufern passive DC-LMAF with 570 μm diameter outer coating; (b) Lens cleaning tissue and isopropanol.

In this study, mechanical stripping was used to remove the optical fibre coating (see above Figure 19(a)). Mechanical stripping entails the removal of outer coating by means of bare fibre gripper which was used to hold fibre tightly and hand-held fibre stripper that fractured and cut into the coating. The 5 cm fractured coating was pulled along the fibre and removed from the fibre end. Any residual coating on the fibre was removed using a lint free tissue soaked in isopropanol (see above Figure 19(b)). The drawback with mechanical stripping is that if not performed carefully, the pristine fibre

surface can be damaged. The aforementioned damage results in poor tensile strength of the fibre surface which ultimately leads to short term reliability of a splice. However, when mechanical stripping is implemented carefully, the fibre will maintain its mechanical strength.

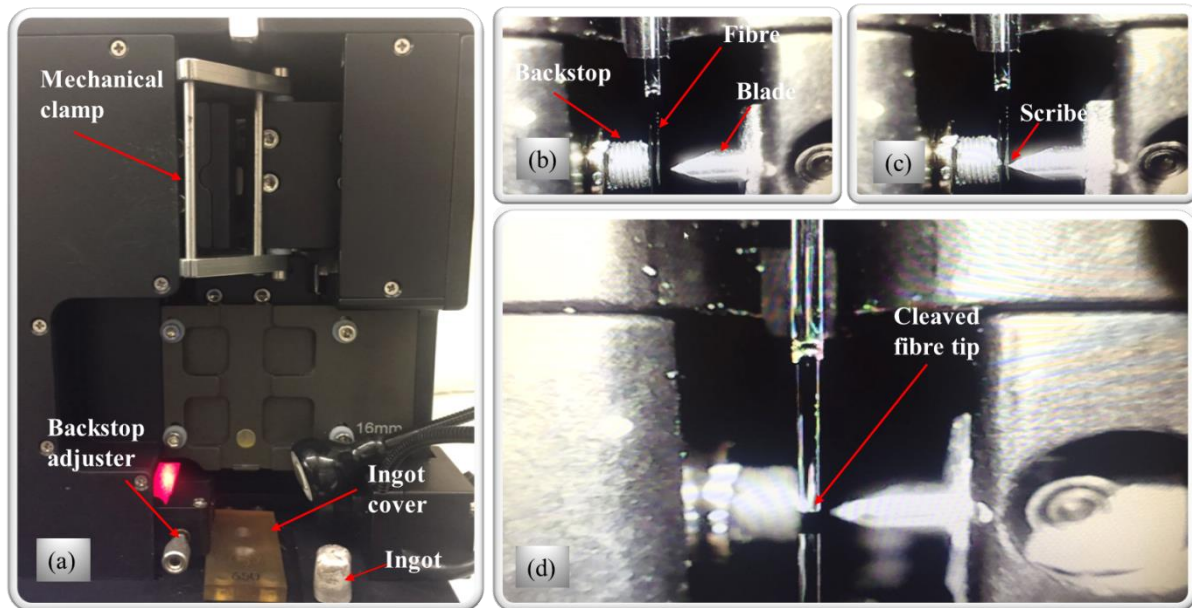


Figure 20: (a) LCC II cleaver assembly; (b) backstop, blade and fibre in position for cleaving; (c) Scribing of fibre surface; (d) Cleaved fibre tip.

The second step required in fibre preparation is the cleaving of the optical fibre. Cleaving is the process in which the optical fibre is fractured in a controlled manner for the purpose of obtaining smooth mirror-end faces on the fibre tips. A 3SAE liquid clamp cleaver (LCC II) in Figure 20 (a) was utilized to execute the cleaving process; the parameter settings are listed in appendix 2. The LCC II consists of two clamps namely, ingot and mechanical. As illustrated in Figure 20 (b)-(d), a cleave process occurs as follows [55]:

- The metal alloy ingot is heated and liquefies so that the fibre tip can be inserted into the ingot.
- A mechanical clamp is applied to the fibre above the ingot.
- Heat is removed and the ingot solidifies firmly around the fibre resulting in a torque-free clamp around the fibre tip.
- The backstop is adjusted to prevent fibre movement during the cleave process.
- The LCC II then introduces the pre-set tension on the fibre. A vibrating (piezo driven) diamond blade scribing tool moves towards the fibre surface to scribe the fibre, resulting in a cleaved fibre tip.

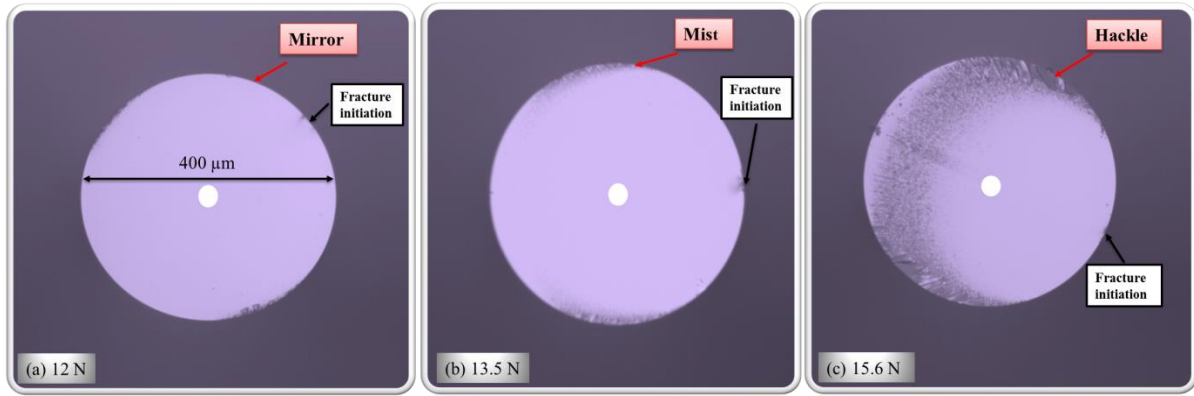


Figure 21: Three Nufern 25/400 μm passive DC-LMAF fibre faces cleaved at various tensions and viewed with Zeiss Axiocam microscope.

The cleave quality influences the geometric formation of the resulting fusion splice. In Figure 21 fracture regions created by cleave are categorised into the mirror, mist and hackle regions [56]. The mist region comprise of slightly speckled fractured surfaces caused by medium cleave tension; while the hackle region consist of coarse surface where fracture has been separated due to excessive cleave tension. The presence of the mist and hackle regions leads to propagating light to either be reflected or diffused at a splice joint, resulting in high splice loss.

A mirror region is smooth, planar clean area that is adjacent to origin of the fracture and is achieved when proper cleave tension is set. The mirror finish is desirable for splicing as it allows two fibre ends to fuse properly, permitting maximum transmission of light to propagate from one fibre end to another, thus resulting in minimal splice loss to be obtained.

It was established experimentally that 12 N of cleave tension generated a mirror finish region on the Nufern 25/400 μm passive DC-LMAF. This setting was used for all cleaves generated in this research study.

3.3 Operation of Large Diameter Splicer (LDS) System

This work utilized 3SAE Large Diameter glass processing Splicer (LDS) shown in Figure 22(a) to execute arc fusion splicing process previously discussed in chapter 2. The LDS is equipped with three electrodes (see below Figure 22(b)) that generate a plasma arc discharge which forms a “ring of fire” (ROF) around the fibre. The plasma arc discharge will melt and fuse two optical fibre ends homogeneously. The LDS contains two orthogonal cameras (see Figure 22(a)) to provide top view and side view images, which furnishes live visualization of the splicing process.

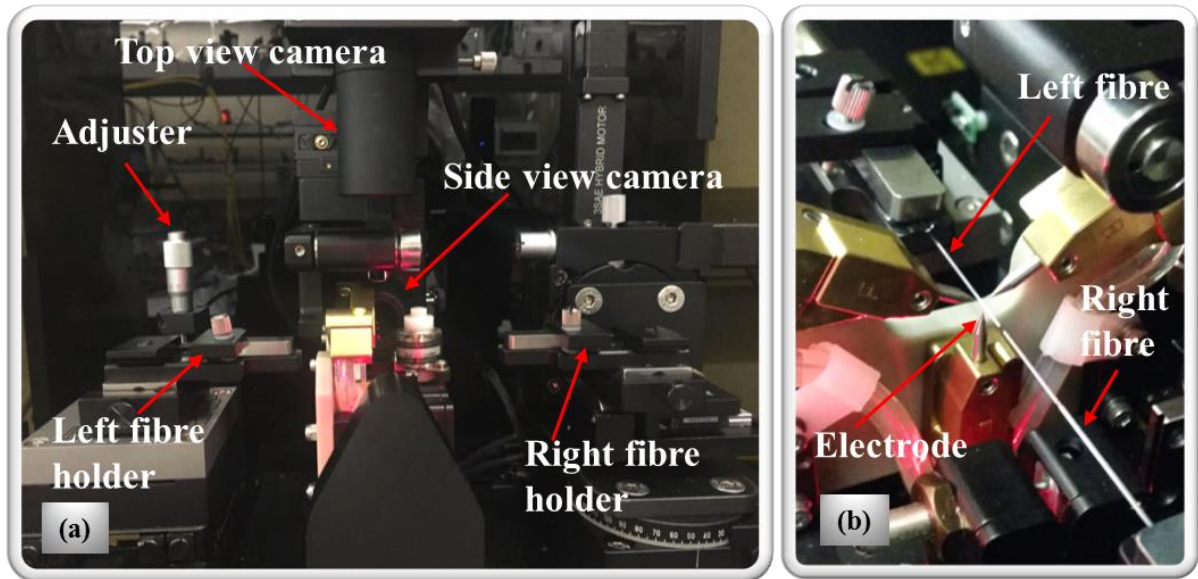


Figure 22: (a) Components of LDS (b) two aligned fibres in LDS with three electrodes in place.

With reference to Figure 22(a) and Figure 23, the following series of steps is followed before splicing fibres together:

- Firstly, the left fibre previously prepared in accordance with section 3.2 through stripping and cleaving processes is placed in the left fibre holder. The fibre is positioned by microadjusters in such a way to centre the fibre along the red horizontal line on both the top and side view screens, and to the left of the red vertical line.
- Secondly, the right fibre prepared according to section 3.2 is then loaded into the right fibre holder. The LDS software then aligns the right fibre with respect to the left fibre. Therefore, it is very important to properly centre the left fibre first.

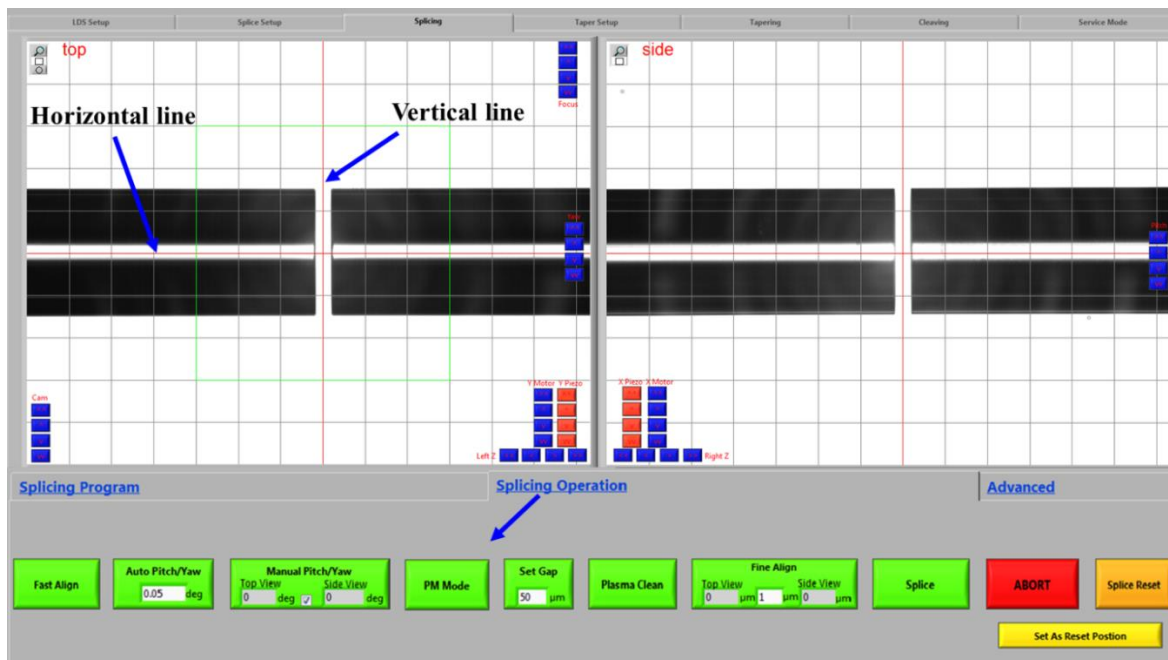


Figure 23: A screenshot of splicer programme after “Fine Align” operator.

With both fibres loaded inside the LDS, the following splicing operations are followed in Figure 23 in sequence:

- “Fast Align” adjusts and aligns the left and right fibre to be within a distance of 200 μm .
- “Auto Pitch/Yaw” operator adjusts the pitch and yaw of the right fibre to align with the left fibre.
- “Set Gap” moves the left and right fibre ends to at the specified distance in microns (μm) within the textbox.
- “Plasma Clean” activates the arc to decompose and vaporize any residual polymer coating and other impurities on the fibre tips. Arc power of plasma cleaning is 20 [a.u], which is lower than the arc power for splicing and will not melt fibre or cause dopant diffusion. A debris on the fibre tips will cause contamination, resulting in a poor splice that has bubbles.
- “Fine Align” operator activates the x and y stepper motors at the same time. The simultaneous activation of x and y stepper motors, adjusts the right fibre with left fibre to align to within the accuracy of the value specified in the textbox. The example of two fibres adjusted until “Fine Align” operator is presented in Figure 23.
- The “Splice” operator executes the splice programme pre-set in splice setup tab (see below
-
- Figure 24) and the splicing sequence in Figure 25 will be initiated.



Figure 24: Splice programme in splice setup tab.

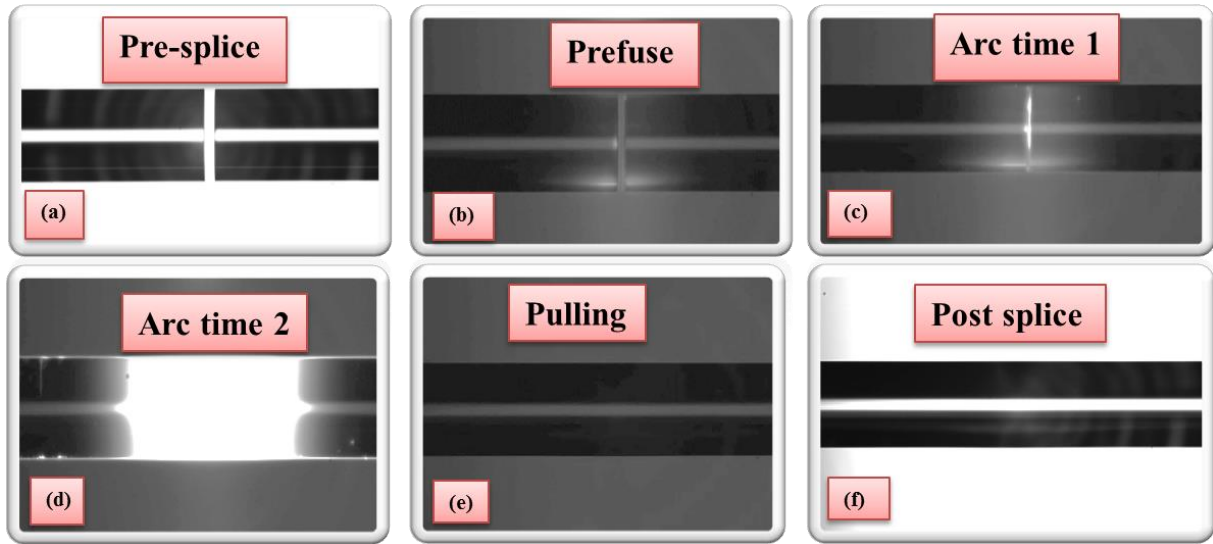


Figure 25: Images of the splicing sequence (a)-(f) corresponding to splice programme in figure 24 for splicing the two 25/400 μm passive DC-LMAF.

The splicing sequence in Figure 25 occurs as follows:

- The two aligned fibre tips in Figure 25 (a) will experience prefusion, which is heat generated from an arc prior to fibre tips being pushed together. The heat is applied to fibre tips for given Prefuse Time in seconds (s) and Prefuse Power in arbitrary unit (a.u.) (see Figure 25 (b)).
- The left fibre will subsequently push against right fibre for given travel distance, regarded as Push Distance which is measured in microns (μm). In the interim of this process, the arc will induce heat for given time in seconds and power and this is called Arc Time 1 and Arc Power 1 (see Figure 25 (c)).
- Subsequent to fibre tips being pushed against each other, the arc will induce heat around the pushed fibre tips for given Arc Power 2 (a.u.) and longer Arc Time 2 (s) (see Figure 25 (d)) as compared to Arc Time 1. Furthermore, the two fibres are fused together.
- Following fusion of two fibre tips, the fibre will be pulled for given Pull Distance (μm), Pull Time (s) and Pull Power (a.u.) (see Figure 25 (e)). In the interest of this work, the Pull Distance, Pull Power and Pull Time were set to zero because it is not required for fabrication of fusion splice but for tapered fibres.
- Once a fusion splice is fabricated (see Figure 25 (f)), it must be protected from external stress in the environment by means of proper packaging. The fusion splice was mounted on a 7 cm cardboard and was fixed on either side of the fusion splice with a sticky tape (see Figure 26).

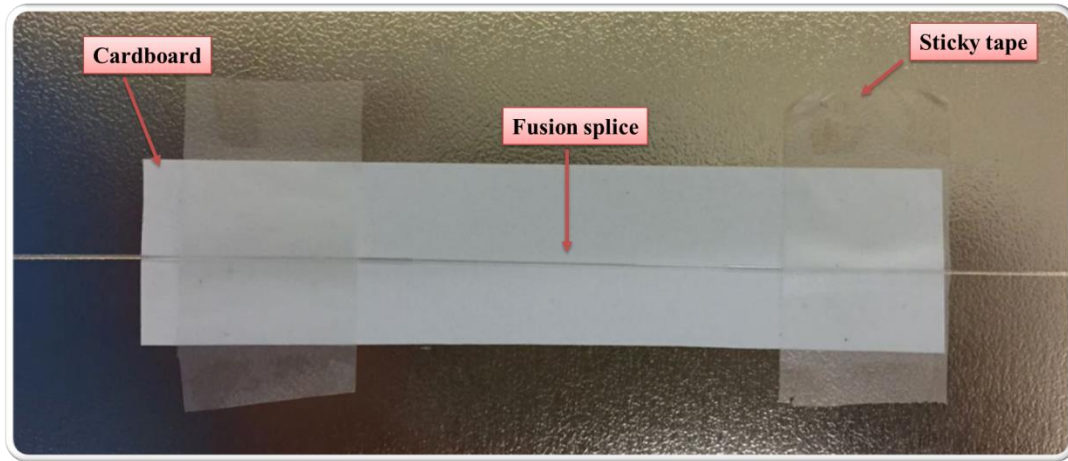


Figure 26: Packaging of a fusion splice.

3.4 Splice Loss Measurement Approach

This section aims to:

- Illustrate and explain different splice loss measurement techniques.
- Investigate different splice loss measurement approaches which resulted in the final construction of splice loss experimental setup for this study.
- Establish and mitigate the extent of measurement errors associated with different splice loss measurement approaches taken in this research study.

The purpose of this section is to investigate and construct an experimental measurement system that can be applied to accurately determine splice loss measurements for this study.

3.4.1 Splice Loss Measurement Techniques

There are different techniques that can be used to measure splice loss. These techniques are, pre-splice, double-splice and spectral splice loss measurement techniques [20]. The pre-splice technique is used to counteract signal attenuation generated by a transmission fibre in the near infrared telecommunications region. The approach is also applied to transmission fibre that is situated a far distance from the fusion splice which occurs during installation of optical fibre cable. The pre-splice approach works as follows:

The calibration setup in Figure 27 (a) is applied to obtain transmitted power, denoted by $P_{cal\ 1}$ which is measured after Fibre 1. A temporary splice namely, a pre-splice fabricated between Fibre 1 and Fibre 2 in Figure 27 (b) for the purpose of measuring the total transmitted power, denoted by $P_{cal\ 2}$. Thereafter, Fibre 2 is physically broken a short distance after the pre-splice. The transmitted power $P_{cal\ 2}$ which is emitted after Fibre 2, is measured after fabrication of pre-splice. Fibre 2 is severed a short distance from the pre-splice, after measurement of $P_{cal\ 2}$ is obtained. In Figure 27 (c), the transmitted power denoted by $P_{cal\ 3}$ is obtained after breaking Fibre 2 a short distance from the pre-splice. The pre-splice is broken after measurement of $P_{cal\ 3}$ which results in removal of Fibre 2 section that is spliced to the pre-splice. The pre-splice is broken to permanently fusion splice Fibre 1 to the main portion of Fibre 2. The final transmitted power denoted by $P_{cal\ 4}$, is measured after fabrication of final fusion

splice between Fibre 1 and the main section of Fibre 2 in Figure 27 (d). Splice loss, measured in decibel (dB) is computed by $r = 10 \log_{10} \left(\frac{P_{Cal1} P_{Cal2}}{P_{Cal3} P_{Cal4}} \right)$ and the optical attenuation caused by Fibre 2 is eliminated.

The pre-splice technique can generate reliable splice loss measurements to fibres that have unknown attenuation. This approach is not applicable for this study as it requires transmission fibre to be located a distance away from fusion splice. The connecting and reconnecting of Power Meter 1 and 2 observed in Figure 27 (b-d) can produce to splice loss measurement errors. The introduction of double-splice technique aims to provide an alternative method to mitigate errors that can be generated by the pre-splice technique.

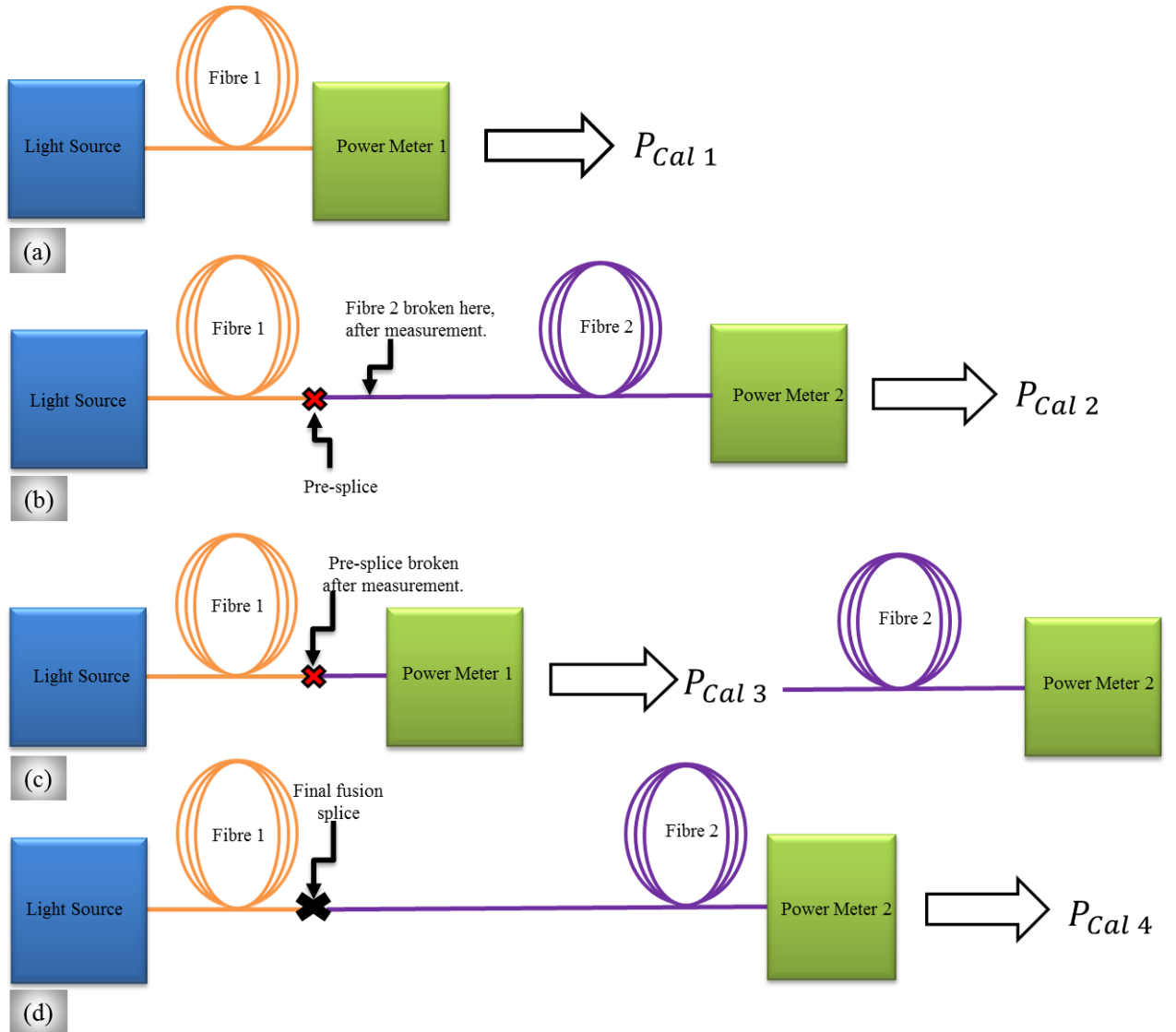


Figure 27: Demonstration of the pre-splice technique to measure splice loss [20] (a) Calibration setup consisting of light source, Fibre 1 and Power Meter 1; (b) Fabrication of the pre-splice between Fibre 1 and Fibre 2; (c) Measurement of transmitted power $P_{Cal 3}$ after Fibre 2 is broken a short distance from the pre-splice and (d) Measurement of transmitted power $P_{Cal 4}$ after fabrication of the final fusion splice.

The double splice technique operates as follows:

Firstly, calibration power likewise in the pre-splice technique is measured (see below Figure 28 (a)). The Fibre 1 in the calibration setup is severed in the middlemost section. In Figure 28 (b), the Fibre 2 is inserted between broken Fibre 1 ends by fusion splicing process, resulting in the fabrication of two fusion splices. The splice loss generated by fusion splice 1 and fusion splice 2 are assumed to be identical. The transmitted power measurement is measured after Fibre 1 which is connected to Power Meter. The technique avoids the measurement errors that are introduced by reconnecting the Power Meter as observed in Pre-splice technique or having differently calibrated multiple power meters.

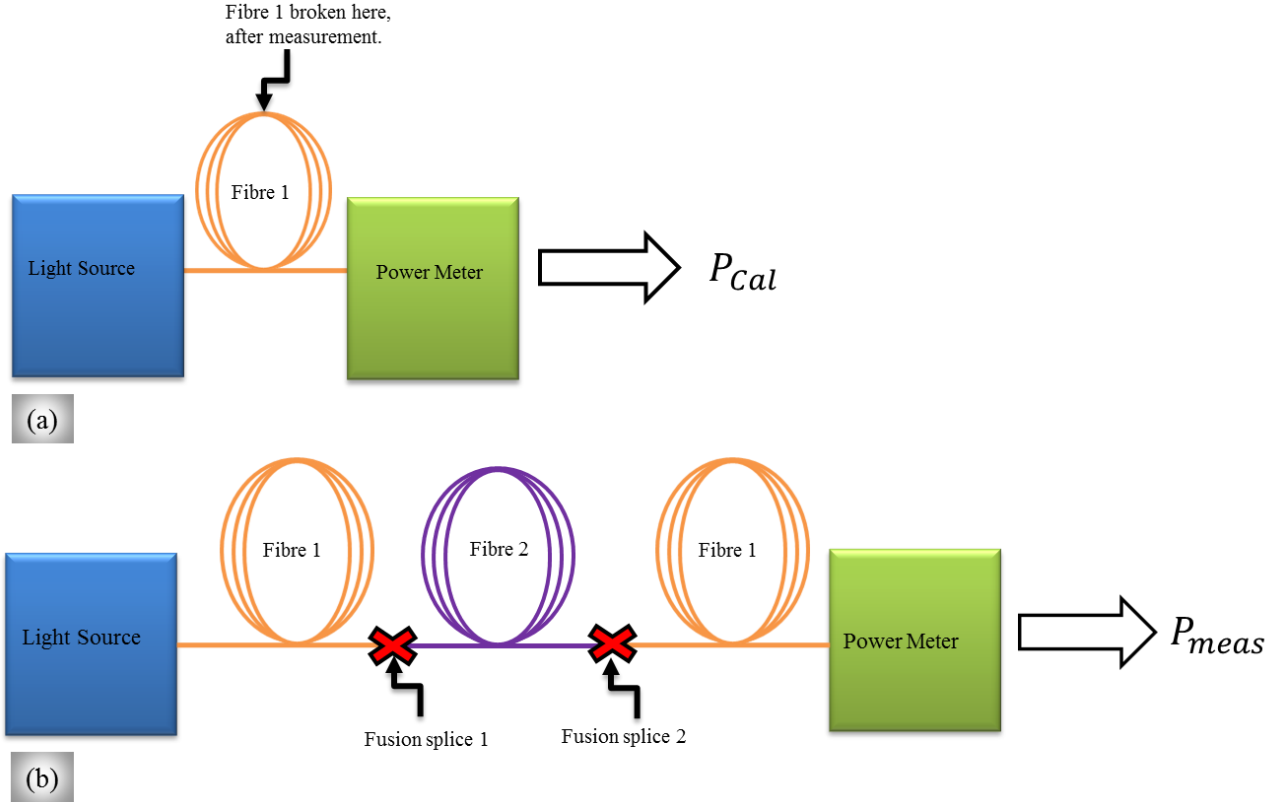


Figure 28: Demonstration of the double-splice technique to measure splice loss [20] (a) Calibration setup to measure power transmitted through fibre 1, denoted by P_{cal} (b) Transmitted power, denoted by P_{meas} measured after the fabrication of fusion splice 1 and fusion splice 2.

The spectral splice loss measurement technique is applied to fusion splices that are wavelength dependent. This technique works similar to the double splice technique. In the spectral splice loss measurement system, the double splice technique is applied by fabricating two fusion splices. The difference between the two techniques is that the spectral splice loss measurement technique utilizes a wavelength sensitive detector such as a spectrometer (see below Figure 29).

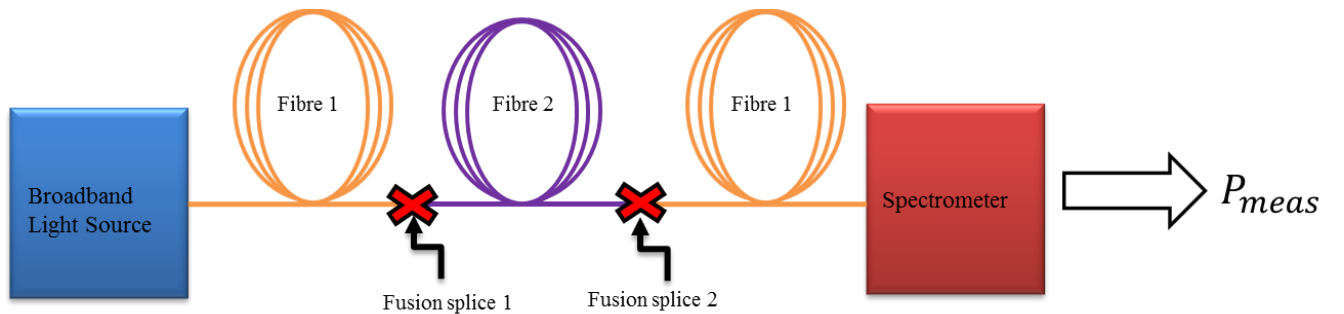


Figure 29: Demonstration of spectral splice loss measurement technique that utilizes a spectrometer [20].

This work utilized the spectral splice loss measurement technique which is discussed in detail in section 3.4.2.

3.4.2 Spectral Splice Loss Measurement Setup: First Iteration

This study aims to fabricate quality fusion splices that will yield low splice loss for the purpose of ultimately building the thulium-doped all-fibre laser. Spectral feature of splice loss is significant for most applications and has an effect on noise figure, gain, tunability and efficiency characteristics of a laser. This research implemented the spectral splice loss measurement technique and transmission measurements were taken at 2000 nm wavelength to determine splice loss as experienced by thulium-doped all-fibre laser, which lases around aforementioned wavelength region.

The purpose of the preliminary spectral splice loss experimental setup is to:

- Obtain preliminary transmission spectrum and transmission measurement at 2000 nm after the Thorlabs broadband light (BBS) is launched through MMF 1 (SMA) - Passive DC-LMAF-MMF 1 (SMA) fibres.
- Identify and mitigate any variation in transmission that may be generated on the splice losses before conducting the splice loss optimization experiment.
- Outline different approaches that led to final spectral splice loss measurement configuration.

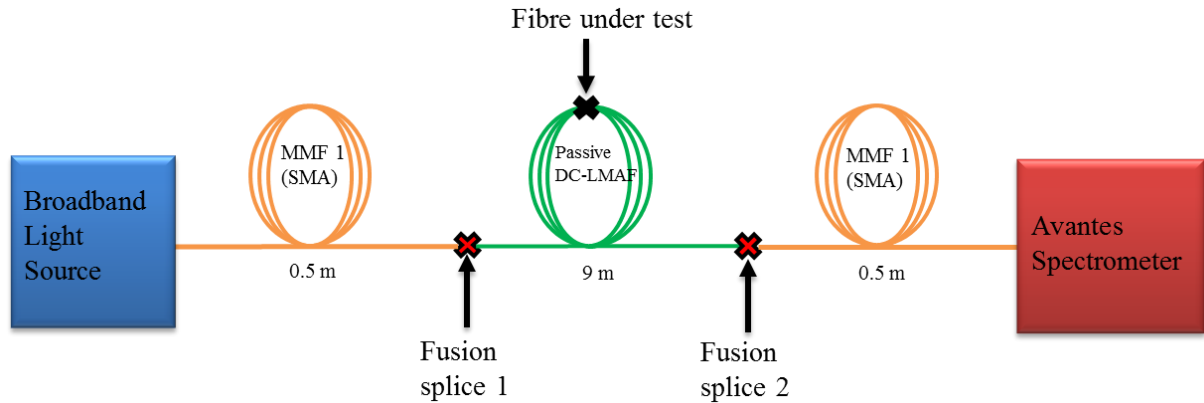


Figure 30: Preliminary spectral splice loss experimental setup; Thorlabs broadband light source (BBS) with wavelength range (360-2600 nm), 1 m MMF 1 with SMA connectors with core and cladding diameter of 400/425 μm , ✕ splice joint, 9 m Nufern passive DC-LMAF with core and cladding diameter of 25/400 μm and a numerical aperture of 0.1, ✕ different splices fabricated at this position, Avaspec Avantes spectrometer (AS) with wavelength range (1000-2500 nm).

The spectral splice loss measurement system is setup as follows (see Figure 30):

A 1 m Thorlabs multi-mode fibre (MMF) patch cable with SMA connector with a core/cladding diameter of 400/425 μm was broken at 0.5 m so that the 9 m length of Nufern 25/400 μm passive DC-LMAF can be inserted into it with two fusion splices. These two fusion splices are considered as references splice that are not part of spectral splice loss measurement for this work. The splices fabricated on the passive DC-LMAF are the splices that are of interest for this study and the passive fibre is regarded as “fibre under test” (FUT). The MMF 1 fibre ends, as well as fibre ends of 9 m FUT were prepared through stripping, cleaving and observed under Axiocam microscope as discussed in section 3.2. The two fusion splices in Figure 30 were fabricated between MMF 1 and passive DC-

LMAF by using non-optimal parameter set points of the 3SAE LDS. A Thorlabs broadband light source (BBS) was connected to the input of the first MMF 1 to launch broadband light through fibres in Figure 30 . The Avaspec Avantes NIR256-2.5 TEC spectrometer (AS) was connected to output of the second MMF 1 for transmission spectra to be obtained.

The transmission spectrum of broadband light launched through MMF 1 (SMA) - Passive DC-LMAF-MMF 1 (SMA) fibres is shown in Figure 31. The transmission is taken at 2000 nm and is indicated by the broken red line.

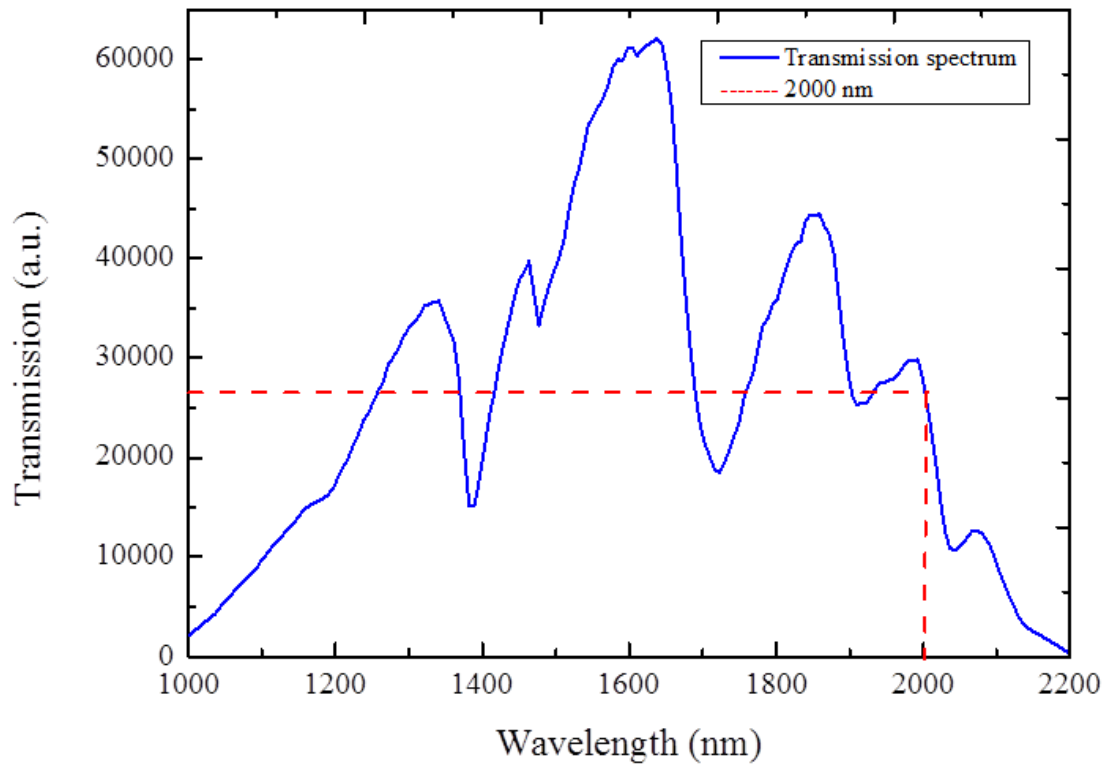


Figure 31: Transmission spectrum of BBS launched through MMF 1(SMA)-Passive DC-LMAF-MMF 1 (SMA) fibres. The transmission intensity taken at 2000 nm by AS is 25608 (a.u.).

The preliminary experiments were conducted to investigate possible factors that can cause splice loss measurement errors and to give guidance in constructing a proper final spectral splice loss measurement setup. The main objective is to identify measurement errors that can be encountered and to minimise those errors in the final spectral splice loss measurement experiment.

The factors identified that could impact the accuracy of splice losses include:

- Thorlabs broadband light source (BBS) stability.
- Measurement variations caused by using different types of connector ends.
- Measurement variation produced by slight movement of reference fibre system, which includes splices.

3.4.2.1 Thorlabs Broadband Light Source (BBS) Stability Experiment

The purpose of the broadband light source stability experiment is to check the amount of time it takes the Thorlabs broadband light source (BBS) to be stable after initial switch on. The experiment was performed by connecting the BBS, a second multi-mode fibre (MMF 2) with Sub Miniature Assembly (SMA) connector and Avaspec Avantes spectrometer (AS).

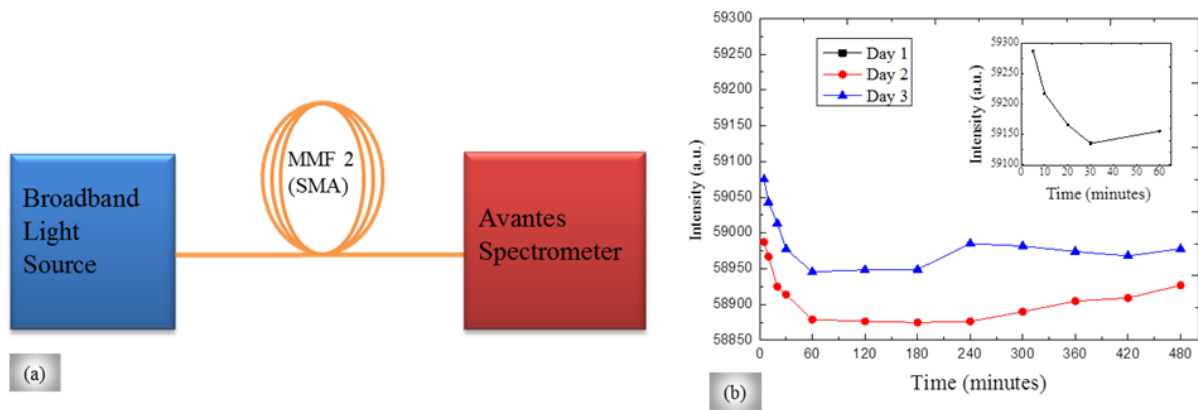


Figure 32: (a) Power stability experimental setup performed by 1 m Thorlabs FT400EMT MMF 2 (SMA) with 400/425 μm core/cladding diameter and 0,39 numerical aperture connected to BBS and AS; (b) power stability graphs over one day for an hour and two days for 8 hours. The insert in (b) shows the intensity change over time 60 minutes timescale.

The stability of the BBS was inspected by monitoring the intensity of the light source over three consecutive days which were the approximated days required to conduct the complete design of experiment (DOE) for this work (see chapter 4, Table 12). A second multi-mode fibre with SMA connector MMF 2 (SMA) was connected to BBS and AS (see above Figure 32). The BBS was firstly monitored for an hour, thereafter switched off and was further monitored for 8 hours each for the following two days. The intensity measurements were monitored at 2000 nm, with the application of the AS. A rapid decrease in intensity was observed after 30 minutes for the experiment performed on the first day, however experiments conducted over two days displayed intensity drift after 4 hours (240 minutes), which remained approximately constant for the remaining 4 hours.

The starting intensities for all three days (59286, 58987 and 59075) after switching on BBS are different.

It was concluded that the BBS should be turned on for at least 8 hours for stability to be obtained, before performing final spectral splice loss measurements and should not be turned off in between each splice experiment.

3.4.2.2 Reconnection Variation of MMF 2 (SMA) to Thorlabs Broadband Light Source and Avaspec Avantes Spectrometer

The BBS and AS have output SMA connectors therefore a multi-mode fibre path cable with SMA connectors is required for connecting the BBS and AS. The amount of measurement error that can be produced at the BBS and AS output connectors through connecting and reconnecting multi-mode fibre patch cable from the BBS and AS can cause splice loss measurement errors. The objective of the experiment in this subsection is to determine the amount variation caused by the reconnection of

MMF 2 (SMA) from BBS and AS under free space connection. The experiment was conducted by applying experimental setup in Figure 32.

In Figure 32 the BBS was used to launch broadband light into MMF 2 (SMA) fibre and AS was applied to obtain transmission measurements. The input of MMF 2 (SMA) was connected and reconnected into BBS, afterwards transmission measurement were obtained at 2000 nm. The aforementioned procedure was repeated seven times. Likewise, similar procedure was performed for output MMF 2 (SMA) connected to AS. Calculations such as average, variance, and standard deviation were obtained to account for variation induced by reconnection of MMF 2 (SMA) from the BBS and AS (see appendix 2, table 20 for actual sample measurements and calculations).

Table 6: Variation produced from experimental setup in Figure 32 by reconnecting MMF 2 SMA from BBS and AS.

Left	Right	Sample Measurement							Average	Standard deviation	% SD
BBS	MMF 2 (SMA)	26873	25992	25961	25943	25919	25969	24253	25844	780	3
MMF 2 (SMA)	AS	26873	25992	25961	25943	25919	25969	27029	26241	487	2

The measurement variation produced by the reconnection of the input of MMF 2 (SMA) to BBS and output of MMF 2 (SMA) to AS are shown in Table 6. The input of MMF 2 (SMA) reconnected from BBS and output of MMF 2 (SMA) reconnected from AS generated 3 % and 2 % measurement variation, respectively. The variation implies that transmission measurement that will be obtained from splice loss experiment will have measurement inaccuracies of 3% and 2 % contributed at BBS and AS with SMA connector, respectively. The results demonstrated that MMF 2 (SMA) has a high insertion loss and that it is incapable of reproducing fibre alignment in its optimal position during reconnection.

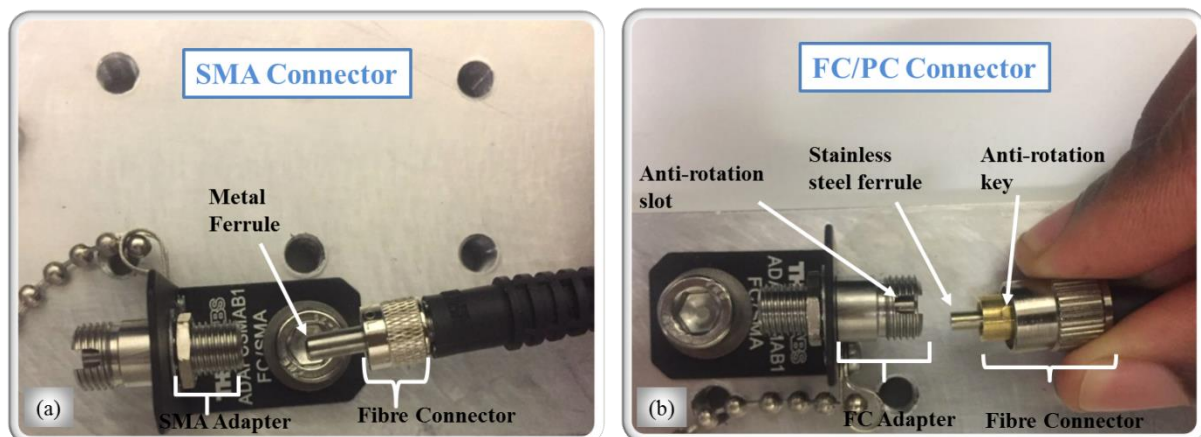


Figure 33: Images of (a) SMA connector and (b) FC/PC connectors; and SMA/FC/PC adaptor.

The aforementioned disadvantage of multi-mode patch cable with Sub Miniature Assembly Connector MMF (SMA) was mitigated by utilizing multi-mode patch cable with ferrule connector that has physical contact endface MMF (FC/PC). These fibres have high precision 2.5 mm diameter stainless

steel ferrule that is furnished with alignment key known as anti-rotation key (see Figure 33(b)). The latter as well as a matching anti-rotation slot on its adapter, serves to minimize fibre's endface deterioration, as well as its rotational alignment responsiveness. Additionally, the anti-rotation key aids to obtain reproducible fibre alignment in the minimal loss location [57]. The 3.14 mm diameter metal ferrule of MMF (SMA) has no anti-rotation key and it aligns fibre endfaces by its threaded barrel adapter which consist of smooth inner wall (see Figure 33(a)) [58]. Therefore optimal loss position cannot be repeated when connecting and reconnecting the fibre from BBS and AS, thus high insertion loss will be generated.

The inspection measurement variation of MMF (FC/PC) is demonstrated in the following section below.

3.4.2.3 Measurement Variation Produced by Multimode Fibre with Ferrule Connector with Physical Contact Endface (MMF 3 FC/PC)

The purpose of this experiment is to determine the amount of variation produced on transmission measurements by repeatedly inserting and removing MMF 3 (FC/PC) from SMA/FC and FC/SMA adapter. Due to the input SMA connectors of the BBS and AS, the MMF 3 (FC/PC) cannot be directly connected to the BBS and AS. Therefore, MMF (SMA) as well as adapters are utilized to be able to connect MMF (FC) on the experimental setup in Figure 34.

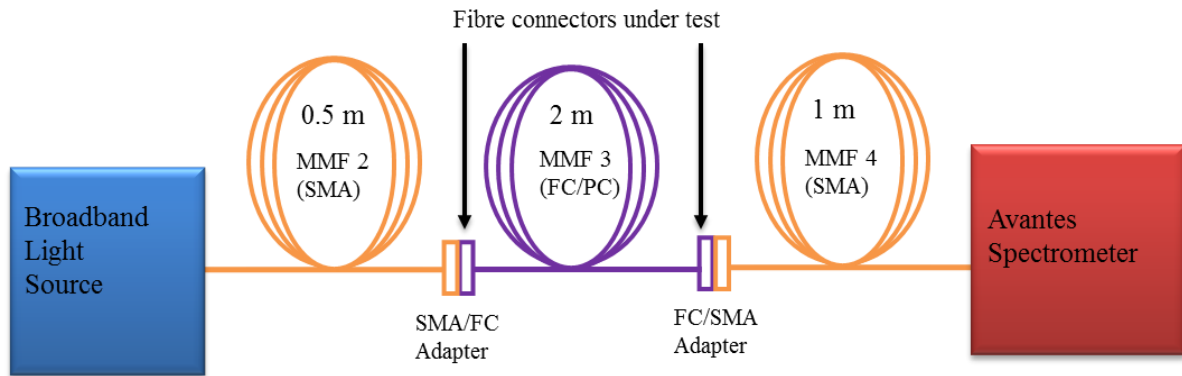


Figure 34: Experimental setup for determination of variation produced by the 2 m Thorlabs FT400EMT multi-mode fibre with FC/PC connector with core/cladding dimension of 400/425 μm , 0.39 numerical aperture connected to 0.5 m and 1 m Thorlabs FT400EMT MMF 2 and MMF 4 with SMA connectors, respectively.

In Figure 34, broadband light from BBS is launched into MMF 2 (SMA) through MMF 3 (FC/PC) and MMF 4 (SMA) fibres. The different patch cable with different connector MMF 3 (FC/PC) was joined by SMA/FC adapter. Likewise in section 3.4.2.2, the input of MMF 3 (FC/PC) was seven times repeatedly connected and disconnected from the SMA/FC adapter, and transmission measurements were taken at 2000 nm. Similar operation was performed on the output of MMF 3 (FC/PC) that is connected to FC/SMA adapter. Calculations likewise in section 3.4.2.2 were made in Table 7 (see appendix 2, table 21 for actual sample measurements and calculations).

Table 7: Variation calculations of MMF with FC/PC and SMA connectors, obtained from Figure 34.

Left	Right	Sample Intensity							Average	Standard deviation	% SD
MMF 2 (SMA)	MMF 3 (FC/PC)	31403	31356	31400	31329	31667	31429	31526	31436	115	0.4
MMF 3 (FC/PC)	MMF 4 (SMA)	31837	31711	31743	31619	31766	31715	31579	31710	87	0.3

In Table 7, the insertion and removal of input of MMF3 (FC/PC) from SMA/FC adapter and the output of MMF3 (FC/PC) from FC/SMA adapter generated a measurement inaccuracies of 0.4% and 0.3%, respectively. The aforementioned results imply that splice loss results will have measurement errors of 0.4% and 0.3%. The input of MMF3 (FC/PC) has a higher measurement error than the output of MMF3 (FC/PC). The latter is due to the closer position of the MMF 2 (SMA) to the BBS. The higher order modes propagating in the MMF 2 (SMA) are easily decoupled because multimode fibre permits higher order modes to propagate from the BBS. Since MMF 2 (SMA) and MMF 3 (FC/PC) are in physical contact at the SMA/FC adapter then higher order modes have decoupled into MMF 3 (FC/PC), therefore 0.4% measurement inaccuracy was obtained.

The measurement inaccuracies produced by MMF 3 (FC/PC) are lower than measurement errors generated by MMF 2 (SMA) in Table 6. Therefore, multi-mode patch cables with FC/PC connectors were employed in the second iteration of the spectral splice loss measurement setup in section 3.4.3.

3.4.3 Spectral Splice Loss Measurement Setup: Second Iteration

This second iteration of spectral splice loss measurement system improves upon the spectral splice loss measurement system previously constructed in Figure 30 of section 3.4.2, by taking into consideration the outcomes from section 3.4.2 to obtain splice loss measurements with minimum inaccuracies. The objective was to validate whether 0.4% and 0.3% measurement variation of MMF (FC/PC) connectors generated previously in Table 7 of section of 3.4.2.3 can be achieved with 25/400 μm passive DC-LMAF spliced between the two MMF (FC/PC).

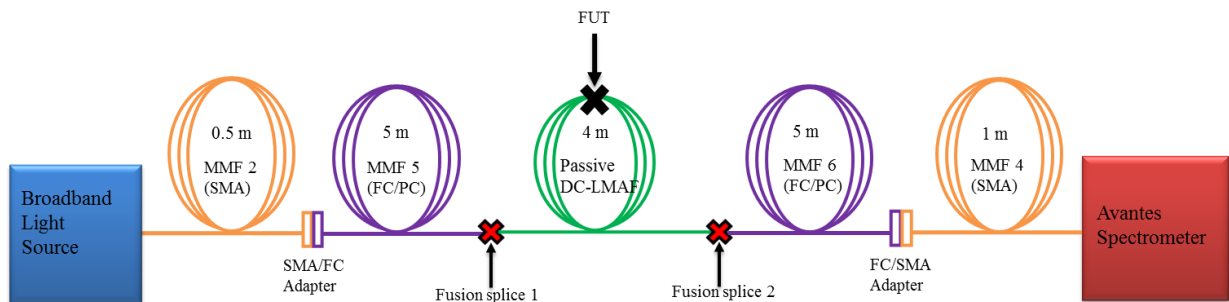


Figure 35: Second iteration on the spectral splice loss measurement setup, with the 4 m Nufern 25/400 μm passive DC-LMAF fusion spliced between the two 5 m Thorlabs FT400EMT MMF (FC/PC) with 400/425 μm core/cladding dimension.

A 4 m Nufern 25/400 μm passive DC-LMAF was spliced between two 5 m Thorlabs FT400 MMF (FC/PC) through arc fusion splicing by using non-optimal splicing parameters, resulting in fabrication of fusion splice 1 and 2 in Figure 35. A 0.5 m MMF 2 (SMA) was used, with its input and output end connected to BBS and SMA/FC adapter, respectively. The input and output end of 1 m MMF 4 (SMA) was connected to FC/SMA adapter and AS. The broadband light was launched in sequence into MMF 2 (SMA), MMF 5 (FC/PC), passive DC-LMAF, MMF 6 (FC/PC) and MMF 4 (SMA) fibres and through the AS.

Similar method of inserting and removing of fibres executed previously in section 3.4.2.2 and 3.4.2.3 was performed on input end of MMF 5 (FC/PC) connected to SMA/FC adapter and output end of MMF 6 (FC/PC) connected to FC/SMA adapter in Figure 35. Additionally, Fusion splice 1 and 2 were slightly moved and with each movement a transmission measurement was taken at 2000 nm. The lattermost procedure was conducted to account for measurement inaccuracies generated by two fusion splices on splice loss measurements. Calculations were made likewise in Table 6 and Table 7 (see appendix 2, table 22 for actual sample measurements and calculations).

Table 8: Measurement variation produced by MMF 5 (FC/PC), MMF 6 (FC/PC), and fusion splice 1 and 2 on the second iteration on the spectral splice loss setup in Figure 35.

Left	Right	Sample Intensity							Average	Standard deviation	% SD
MMF 2 (SMA)	MMF 5 (FC/PC)	8024	8043	8113	8130	8096	8190	8216	8116	70	1.0
MMF 6 (FC/PC)	MMF 4 (SMA)	7788	7795	7795	7796	7801	7804	7802	7797	5	0.1
Fusion splice 1		3106	3104	3093	3087	3102	3095	3096	3098	7	0.2
	Fusion splice 2	3117	3116	3118	3116	3113	3114	3113	3115	2	0.1

A 0.2%, 0.1%, 1% and 0.1 % measurement error generated by Fusion splice 1 and 2, MMF 5 (FC/PC) and MMF 6 (FC/PC) is presented in Table 8 respectively. The measurement variation of fusion splice 1 and 2 are as a result of slight movement of fusion splices which might have perturbed propagation of light at the splice joint. The 1 % measurement variation of MMF 5 (FC/PC) was possibly due to the closer location MMF 2 (SMA) and MMF 5 (FC/PC) to the BBS. The BBS resulted in the decoupling of unstable higher order modes (HOM). The MMF 2 (SMA) permitted HOM to propagate from BBS, resulting in HOM to be coupled into MMF 5 (FC/PC) at the SMA/FC adapter interface, thus generating a 1% measurement variation. Due to the distant location of MMF 6 (FC/PC) from BBS, the HOM from BBS would have radiated into cladding of fibres and ultimately lost into the environment, therefore minimal HOM at MMF 6 (FC/PC) is experienced, thus 0.1% in measurement variation is obtained.

Results in Table 8 signify that splice loss measurements will have measurement inaccuracies of 0.2%, 0.1% if fusion splice 1 and 2 is slightly moved and 1% and 0.1% if MMF 5 (FC/PC) and MMF 6

(FC/PC) are connected and reconnected into its adapter during spectral splice loss measurement experiment.

Since connecting and reconnecting of MMF (FC/PC) and slight movement of Fusion splice 1 and 2 generated a certain amount of measurement error as observed in Table 8 , it was suggested to execute the final spectral splice loss measurement experiment by avoiding the reconnection of all MMF (SMA), MMF (FC/PC) and slight movement of the two fusion splices. The final spectral splice loss measurement system is inspected in section 3.4.4 below.

3.4.4 Final Spectral Splice Loss Measurement Experimental System

The final approach of executing the splice loss measurement experiment was implemented in this section after taking into account all the lessons learnt from the experiment conducted in section 3.4.2 and 3.4.3. The approach limits physical contact to the “splice loss measurement region” in Figure 36 only and avoiding the reconnection of all MMF (SMA) and MMF (FC/PC) and slight movement of the fusion splices. The splice loss measurement region which consist of 25/400 μm passive DC-LMAF would be the movable active region whereby stripping, cleaving procedures are performed and ultimately fabricating multiple fusion splices.

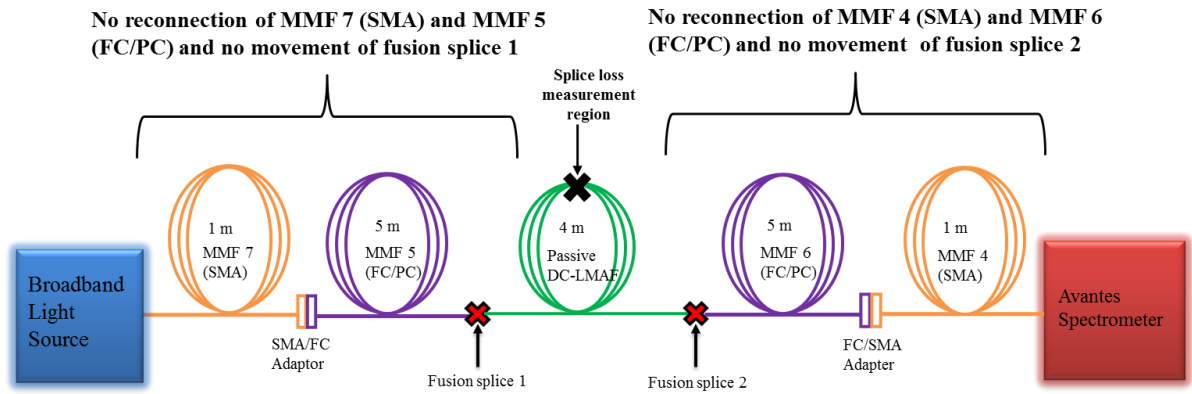


Figure 36: The final spectral splice loss measurement experimental setup two 1 m Thorlabs FT400EMT MMF (SMA), two 5 m Thorlabs FT400EMT MMF (FC/PC) spliced to 4m Nufern 25/400 μm DC-LMA passive fibre.

The objective of the approach was to:

- Avoid measurement variation associated with reconnecting of multi-mode fibre with FC/PC and SMA connectors as previously obtained in subsection 3.4.2.2, 3.4.2.3, and section 3.4.3,
- Limit any discrepancies that may be induced by a slight movement of multi-mode fibre with FC/PC and SMA connectors and fusion splice 1 and 2.

Prior to executing multiple fusion splice in the splice loss measurement region on the final spectral splice loss measurement system in Figure 36 , measurement variation generated by the no reconnection of multimode fibres with FC/PC and SMA connectors and no movement of fusion splice 1 and 2 was examined.

In Figure 36, the BBS was switched on for 8 hours to obtain power stability and broadband light was launched through MMF 7 (SMA) - MMF 5 (FC/PC) - Passive DC-LMAF- MMF 6 (FC/PC) - MMF 4

(SMA) fibres. After 8 hours from switch on , seven transmission measurements were taken at 2000 nm and calculations of average, variance, and standard deviation likewise in Table 6, Table 7 and Table 8 was computed in Table 9 for the final spectral splice loss experimental setup constructed in Figure 36.

Table 9: The splice loss measurement variation for the no reconnection of multi-mode fibres with FC/PC and SMA connectors and no slight movement of fusion splice 1 and 2 obtained from Figure 36.

No reconnection of MMF with FC/PC and SMA connectors and no movement of fusion splice 1 and 2			
Average	Variance	Standard deviation	%
12489	18	2	0.03

A minimal variation of 0.03% was obtained under the no reconnection of multimode fibres with FC/PC and SMA connectors and no slight movement of fusion splice 1 and 2 approach. The result implies that splice loss measurements that will be taken in Figure 36 under the no reconnection of multimode fibres with FC/PC and SMA connectors and no movement of fusion 1 and 2 will have a measurement variation of 0.03 %. This measurement variation is lower than the measurement variation obtained by the reconnection of multimode fibres and the slight movement of fusion splices as observed in Table 8 of section 3.4.3. Therefore, the results in Table 9 was considered as the reference transmission intensity measurement for the final spectral splice loss measurement experiment.

Chapter summary:

- Fibre end preparations namely, stripping and cleaving are required before arc fusion splicing process can occur. The two preparations have an impact on the long term reliability of the fusion splice and the resulting splice loss [20]. Stripping is necessary to prevent the burning of the polymer coating which can be generated by the heat during the fusion splice formation. In this study, mechanical stripping was implemented on the 25/400 μm passive DC-LMAF by hand-held stripper. Cleaving of an optical fibre is required to obtain mirror finish fibre end facet for the purpose of forming a high quality fusion splice. The high quality fusion splice will allow the maximum transmission of light to propagate from one fibre end to another; therefore low splice loss will be achieved.
- The 3SAE LDS was utilized to fabricate all the fusion splices in this work. The LDS parameters and operating procedures are defined and discussed.
- The spectral splice loss measurement approach was applied to obtain transmission intensity measurements in the 2000 nm spectral range. Different spectral splice loss configurations were investigated to determine and mitigate the possible factors that can yield inaccurate splice losses.
- The final spectral splice loss measurement setup was implemented by avoiding the reconnection of all multi-mode fibres with SMA and FC/PC connectors from the setup. The approach limited physical contact to the “splice loss measurement region” only. This approach yielded the 0.03% expected measurement variation on the splice losses.

Chapter 4 will optimize splice loss between two 25/400 μm passive DC-LMAF through the implementation of the Taguchi experimental design methodology guidelines set out in appendix 1 and analysis of the splice loss results through statistical technique, the analysis of variance (ANOVA).

Chapter 4: Splice Loss Optimization of Double Clad Large Mode Area Passive Fibres

4.1 Introduction

The objective of Chapter 4 is to optimize the splice loss between two Nufern 25/400 μm passive DC-LMAF by showing the procedures that was followed in arriving at the optimal set points. The implementation of the fractional factorial design of experiment and the Taguchi experimental design methodology for the splice loss optimization is executed in section 4.2 and 4.3, respectively. Section 4.4 will discuss the splice loss experimental data. The negative splice losses obtained in this study are discussed in section 4.5. The fusion splice analysis is conducted in section 4.6 with respect to the different level of Arc Power 2 in which the fusion splices were fabricated. In section 4.7, the analysis of variance (ANOVA) is applied on the splice loss data to demonstrate the statistical significance of each splice parameter towards the splice loss. The optimal splice parameter set points are found and discussed in section 4.8.

4.2 Fractional Factorial Design

The factors that constitute a design of experiment or optimization process control the quality of the output product. In this study, the splice parameters are the factors that control the quality of a fusion splice. Many splice parameters require numerous experiments to be conducted for the optimization process. This work has seven splice parameters varied over three levels that have to be optimized.

For seven parameters that are varied over three levels, a full factorial design described in appendix 1 will require $3^k=3^7=2187$ experiments to be conducted as well as one experiment to be executed for every addition of splice parameters. The numerous experiments required by full factorial design can be very tedious, difficult and time consuming. However, to avoid the difficulty of full factorial design this work applied fractional factorial design which will require 18 experiments to be executed.

In a fractional factorial design, all splice parameters are varied concurrently during a collection of experiments, as a substitute of executing a series of experiments in which one splice parameter is changed at a time. The shortcoming of this experimental design is that the interaction between two splice parameters can be hidden. The advantage of using fractional factorial experimental design is that splice parameters that are of major importance, in conjunction with their impact on the splice quality, can be efficiently established [20].

Taguchi experimental design methodology described in appendix 1 developed by Dr Genichi Taguchi, is a type of fractional factorial design that was followed in this work. The methodology comprises of an orthogonal array of splice parameters with their respective levels and each distinct splice parameter level appears an equivalent number of times. The Taguchi orthogonal array methodology is implemented in section 4.3 for this work

4.3 Taguchi Experimental Design Methodology for Splice Loss Optimization

The work in this dissertation followed the Taguchi experimental design methodology. The objective of this methodology is to improve the quality of a fusion splice by establishing the optimum parameter set points that will generate minimum splice loss. The optimization process of this methodology followed guidelines that are stated in appendix 1 and are applied in the subsections below [59].

4.3.1 System Design for Splice Parameters Selections

A system design involves the identification of splice parameters that plays a role towards fabrication of a fusion splice. In this research, seven splice parameters were identified from the 3SAE large diameter glass processing splicer (LDS). The LDS, previously described in chapter 3 is the machine that is used for fabrication of all fusion splices that are generated in this research.

The seven splice parameters are the Gap Distance, Prefuse Time, Arc Time 1, Arc Power 1, Arc Time 2, Arc Power 2, and Overlap Distance. The aforementioned splice parameters are defined in the splicing sequence previously discussed in chapter 3, section 3.3. The Gap Distance splice parameter is the same as the “Set Gap” that is found on the splicing operation in Figure 23.

4.3.2 Splice Parameter Design

The splice parameter design comprises of the above-mentioned seven parameters and their respective levels (see Table 10). It makes the pursuit of optimal parameter set points more comprehensible, by allowing discrete values of each parameter level to be chosen in the vicinity of the near optimal known fusion splice condition (see Table 10, level 2). This known fusion splice condition decreases the number of choices of each parameter by enabling the selection of distinct set points that are approximately within the vicinity of the near optimal known fusion splice condition (see Table 10, level 1 and 3).

The set points of the known fusion splice conditions for the Gap Distance, Prefuse Time, Arc Time 1, Arc Time 2 and Overlap splice parameters were recommended by the supplier. However, the set points for Arc Power 1, Arc Power 2 and Prefuse Power were determined by performing a rough preliminary splice optimization between two Nufern 25/400 μm passive DC-LMAF.

Table 10: Parameter design consisting of seven parameters varied over three levels.

Level	Gap Distance (μm)	Prefuse Time (s)	Arc Time 1 (s)	Arc Time 2 (s)	Arc Power 1 (a.u.)	Arc Power 2 (a.u.)	Overlap Distance (μm)
1	40	0.8	0.2	5.5	69	69	10
2	50	1	0.3	6	71	71	15
3	60	1.2	0.4	6.5	73	73	20

The preliminary optimization involved the adjustment of arc power set points of the Prefuse Power and Arc Power 1 and 2 splice parameters only. The arc power set points of the above mentioned splice parameters were kept equal to each other. The set points were increased in an increment of two,

starting from 71 (a.u.) until 73 (a.u.). Ten fusion splices were fabricated at each set point 71 (a.u.) and 73 (a.u.), and the arc intensity as a function of time monitored during the splicing process.

The comparison of arc intensity measurements in the Arc Time 2 region and the visual inspection of deformities on the fusion splices between the two set points in Figure 37 were the criteria applied to determine the acceptable arc power set point.

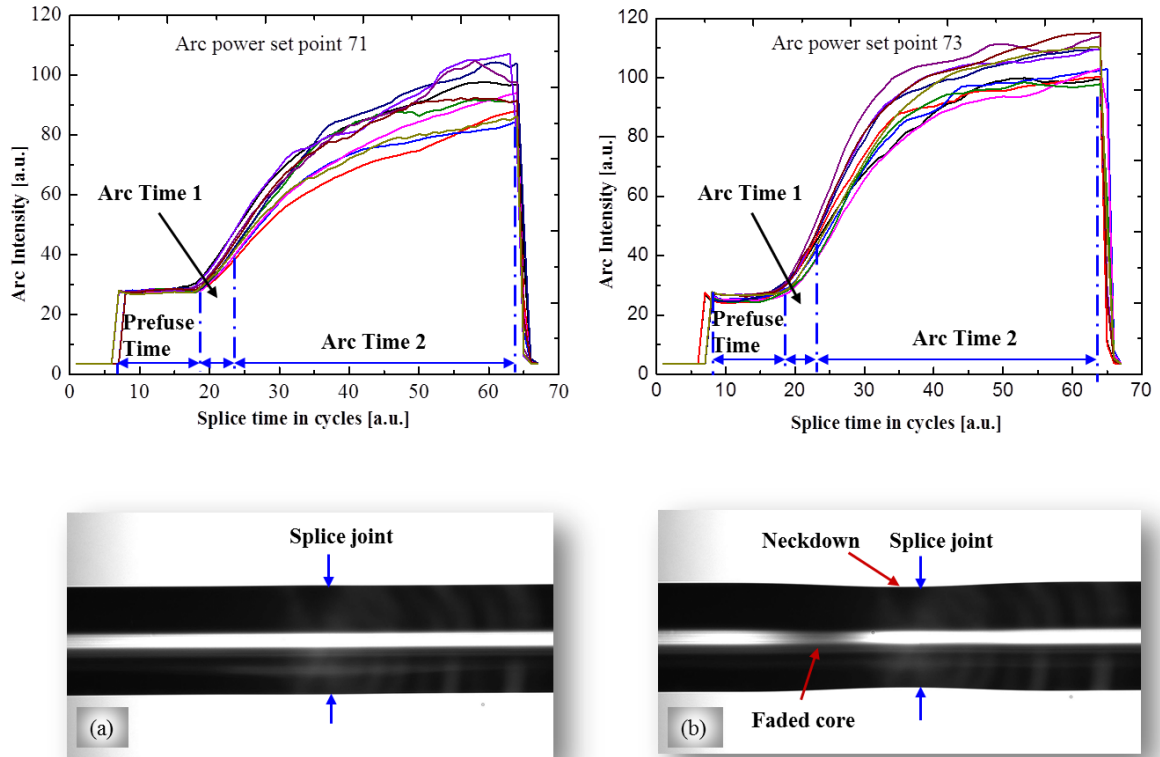


Figure 37: Arc intensity measurements for ten fusion splices fabricated at arc power set point 71 (a.u) (left) and 73 (a.u) (right).

In Figure 37 above, plots of arc intensity counts is made against splice time in cycles. The LDS has 12 frequency of a cycle, thus 1 second (s) is equivalent to 12 cycles. Each plot is divided into Prefuse Time, Arc Time 1 and Arc Time 2. In both plots, the arc begin heating fibre tips at 7 cycle until 19 cycle within the Prefuse Time region, for the purpose of softening fibre tips before fusion splicing occurs. The arc intensity begin to increase at the end of Prefuse Time region (19 cycle) as fibres are pushed against each other and are getting hotter from 19 to 24 cycle in Arc Time 1 region. The arc finally discharge an actual plasma arc from 24 until 64 cycles thus fabricating a fusion splice for longer time in Arc Time 2 region. The arc cease at 64 cycles. Arc Power set point 73 (a.u.) in the Arc Time 2 region displays intensity measurement graphs that has more variation than graphs in Arc Power set point 71 (a.u.). Furthermore, total integrated arc intensity measurement across the Arc Time 2 region for Arc Power set point 73 (a.u.) and 71(a.u.) is 8032 a.u. and 3408 a.u., respectively. The aforementioned integrated arc intensity implies that Arc Power set point 73 more intense, provides more heat than Arc Power set point 71 (a.u.) over the same time period.

In the fabricated fusion splices depicted in Figure 37, Arc Power set point 73 (a.u.) causes a neckdown fusion splice that contains a deformed fibre core [20]. When a fusion splice is subjected to excessive arc discharge for longer time duration, surface tension will decrease the fibre diameter in the splice area by pinching the molten glass from the vicinity of the splice, thus forming a neckdown fusion splice. The faded appearance of the fibre core was possibly produced by germanium dopant diffusion that occurred during the excessive arc discharge during fusion splicing. During the formation of the fusion splice, the germanium dopant diffusion from the core may have likely diffused outward into the cladding at the splice joint. Therefore, set point 73 (a.u.) resulted in unacceptable visual fusion splice. However, set point 71(a.u.) generated ten visually good reproducible splices which depicted no deformities, which implying that the plasma arc discharge is stable and controlled.

Due to the less intense integrated arc intensity of Arc Time 2 region of set point 71 (a.u.), as well as no visual presentation of any deformities on the ten fabricated fusion splices, therefore arc power set point 71 (a.u.) was chosen as the more acceptable set point when compared to set point 73 (a.u.).

4.3.3 Selection of Taguchi Orthogonal Array

Selection of orthogonal array was made through determining the degrees of freedom (DOF) of the seven splice parameters. Each splice parameter is varied over three levels and has $n-1=3-1=2$ DOF. The total $DOF = 14+1= 15$. Therefore, the Taguchi orthogonal array that must be selected should have at least 15 experiments. By using table 1 in appendix 1 then L_{16} , L_{16} and L_{18} are the possible orthogonal arrays that can be utilized. However, L_{16} permits factors that are varied over two levels only and this work requires the evaluation of factors over three levels and L_{16} accommodates maximum five factors which are evaluated over four levels but this work has seven parameters that have to be evaluated over three levels. Furthermore, L_{18} Taguchi orthogonal array in Table 11, denoted by $L_{18}(2^1 \times 3^7)$ and also known as mixed level orthogonal array, is applicable for this study due to its ability to accommodate a maximum of eight factors and to evaluate one factor over two levels and seven factors over three levels. Full factorial experimental design would requires a total of $3^k=3^7=2187$ experiments to be executed; however Taguchi orthogonal array only requires a total of 18 experiments to be conducted.

Table 11: $L_{18}(2^1 \times 3^7)$ Taguchi orthogonal array with 18 experiments, showing the different level combinations for each experiment. Taguchi orthogonal arrays are well balanced and the arrangement of levels within a factor cannot be changed. The different levels are obtained from table 10 that comprises of the parameter design consisting of seven parameters varied over three levels..

Experiment No	Independent Factors							
	A	B	C	D	E	F	G	H
1	1	1	1	1	1	1	1	1
2	1	1	2	2	2	2	2	2
3	1	1	3	3	3	3	3	3
4	1	2	1	1	2	2	3	3
5	1	2	2	2	3	3	1	1
6	1	2	3	3	1	1	2	2
7	1	3	1	2	1	3	2	3
8	1	3	2	3	2	1	3	1
9	1	3	3	1	3	2	1	2
10	2	1	1	3	3	2	2	1
11	2	1	2	1	1	3	3	2
12	2	1	3	2	2	1	1	3
13	2	2	1	2	3	1	3	2
14	2	2	2	3	1	2	1	3
15	2	2	3	1	2	3	2	1
16	2	3	1	3	2	3	1	2
17	2	3	2	1	3	1	2	3
18	2	3	3	2	1	2	3	1

4.3.4 Assigning the Splice Parameters to L_{18} ($2^1 \times 3^7$) Taguchi Orthogonal Array

The splice parameters and their respective set points stated in Table 10 must be assigned to the relevant columns of L_{18} Taguchi orthogonal array (see below Table 12). All experiments must be conducted according to combination of levels in the orthogonal array. However, experiments were performed randomly and not conducted in sequence as tabulated in Table 12 to prevent potential preference or experimental bias that may be generated by the LDS

The remaining analysis of data guideline by the ANOVA technique for this work is discussed in section 4.7.

Table 12: L_{18} Taguchi orthogonal array with splice parameters and actual set points values.

Experiment No	Splice Parameters						
	Gap Distance	Prefuse Time	Arc Time 1	Arc Time 2	Arc Power1	Arc Power 2	Overlap
1	40	0.8	0.2	5.5	69	69	10
2	40	0.8	0.3	6	71	71	15
3	40	0.8	0.4	6.5	73	73	20
4	40	1	0.2	5.5	71	71	20
5	40	1	0.3	6	73	73	10
6	40	1	0.4	6.5	69	69	15
7	40	1.2	0.2	6	69	73	15
8	40	1.2	0.3	6.5	71	69	20
9	40	3	0.4	5.5	73	71	10
10	50	0.8	0.2	6.5	73	71	15
11	50	0.8	0.3	5.5	69	73	20
12	50	0.8	0.4	6	71	69	10
13	50	1	0.2	6	73	69	20
14	50	1	0.3	6.5	69	71	10
15	50	1	0.4	5.5	71	73	15
16	50	1.2	0.2	6.5	71	73	10
17	50	1.2	0.3	5.5	73	69	15
18	50	1.2	0.4	6	69	71	20

4.4 Splice Loss Experimental Data

The final spectral splice loss measurement system in Figure 36 was constructed previously in section 3.4.4, after considering the power stability of BBS, measurement variation produced by the reconnection of multimode fibres and the slight movement of two reference fusion splices as previously discussed in chapter 3.

Before beginning the splice loss optimization experiment, the BBS was switched on for 8 hours to obtain power stability, there was no reconnection of any multimode fibres from the BBS, AS and adapters and no slight movement of reference fusion splices and no movement of the passive DC-LMAF which is within “splice loss measurement region”. The 4 m passive DC-LMAF is continuous and does not contain any fusion splices. The aforementioned procedure was performed to obtain baseline spectrum that will be used to compare with the spectra that are generated after the commencement of the splice loss optimization experiments.

The baseline spectrum in Figure 38 was obtained after 8 hours from switch on of the BBS.

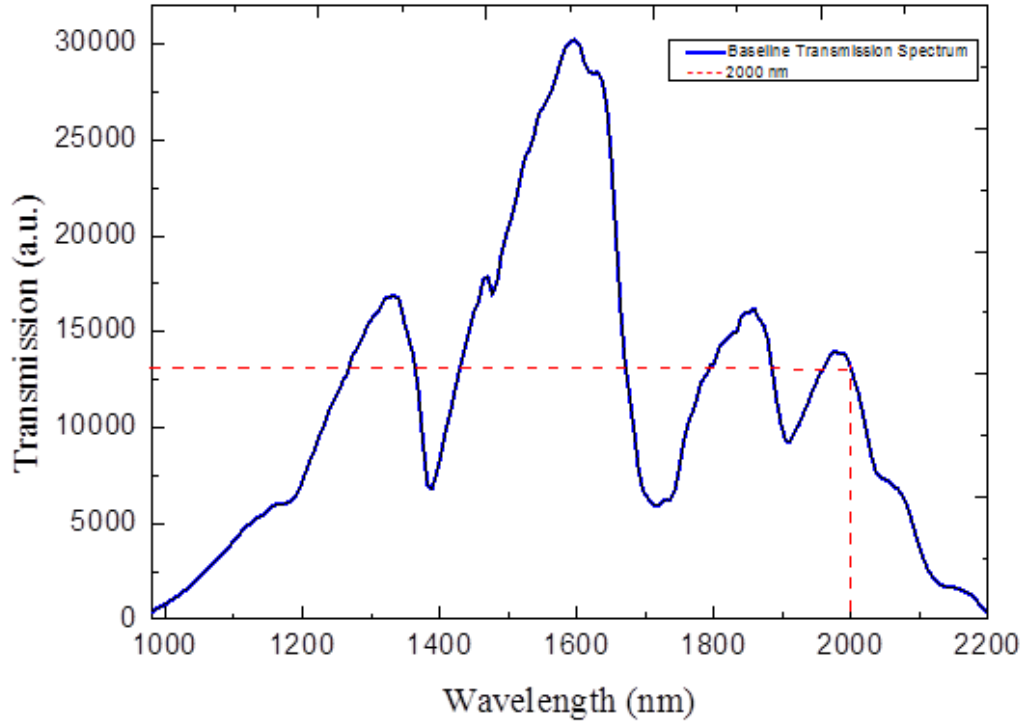


Figure 38: Baseline transmission spectrum for the splice loss optimization experiment. The transmission at 2000 nm is indicated by the red dotted lines.

The actual experiments comprise of cutting and splicing the 25/400 μm passive DC-LMAF in Figure 36 in the middlemost section. The 4 m passive fibre is cut and the two divided fibre ends prepared following the procedures previously described in section 3.2. They were spliced according to the splicing process in section 3.3 using different combinations of splice parameter settings as set out in the Taguchi $L_{18}(2^1 \times 3^7)$ orthogonal array (see Table 12). Each combination of splice parameters is considered as a unique experiment on its own. Ultimately, 18 different splicing experiments were executed within the splice loss measurement region in Figure 36.

Table 13: The splice losses and transmission intensities from the randomised 18 experiments arranged in the order of experiment execution. The baseline transmission intensity for the splice loss optimization experiment obtained after 8 hours from switch on of the BBS.

Baseline transmission intensity (a.u.)		
12489		
Experiment No	Transmission intensity (a.u.)	Splice loss (dB)
9	12272	0.07
18	12413	0.02
4	12488	-0.0013
15	12585	-0.037
14	12590	-0.038
11	12598	-0.138
16	13652	-0.387
2	13446	-0.319
10	14288	-0.581
3	5690	3.41
5	9607	1.13
1	Unsuccessful fusion splice	Unsuccessful fusion splice
8	8066	1.90
13	11650	0.31
7	5093	3.89
6	5824	3.31
17	8197	1.83
12	12978	-0.174

In this work, the splice optimisation process comprising the 18 experiments was only conducted once. Ideally, repetition of at least one other time is required to take into consideration the variations in the splice preparation (cleaning and cleaving) and splicing process (atmospheric pressure and ambient temperature). It is also necessary to check for consistency in the transmission measurements and to calculate the measurement variation for each experiment.

In Table 13, the splice losses, transmission intensities for the randomised 18 experiments are arranged in the order of experiment execution and the baseline transmission intensity for the splice loss optimization is shown. Only 17 splice losses and transmission intensities are shown in Table 13.

The 18 experiments in Table 13 were randomised to avoid the possibly preference or experimental bias that may be generated by the 3SAE large diameter glass processing splicer (LDS). The baseline transmission intensity was obtained for calculating the splice losses according to Equation 2 for each experiment. Due to the particular splice parameter combination of Experiment 1 (discussed in section 4.6) the unsuccessful fusion splice was obtained, resulting in no splice loss and transmission intensity to be measured. Therefore only 17 splice losses and transmission intensities were obtained from the splice loss optimization experiment.

In the 17 splice loss measurements found in Table 13, 8 of the experiments, namely Exp 4,15,14,11,12,2,16,10, showed negative splice loss. These results implies $P_{trans} > P_{inc}$, according to the splice loss definition in Equation 3 that is power transmitted across a fusion splice is greater than the total power incident upon a fusion splice, and P_{inc} with respect to this study is the baseline transmission intensity measurement. Therefore, the results are unrealistic and the implications of the results are discussed in section 4.5.

4.5 The Negative Splice Losses

This section addresses the transmission spectra obtained from the 17 experiments and the reasoning for the negative splice losses obtained in Table 13 from Exp 4,15,14,11,12,2,16,10.

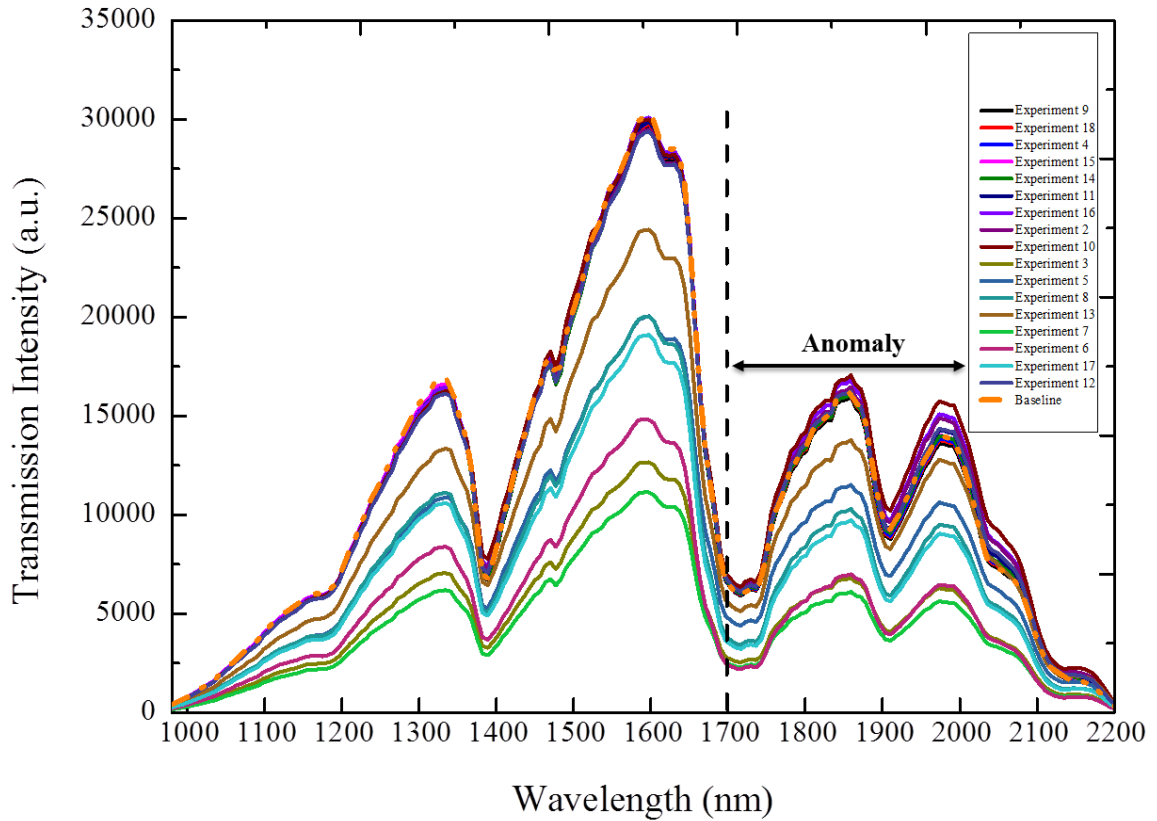


Figure 39: Transmission intensity spectra for the 17 experiments and the baseline transmission spectrum represented by the orange dash dot line.

In Figure 39 the baseline transmission intensity spectrum (represented by orange dash-dot line) and the 17 transmission intensity spectra for the 17 experiments are shown. The shorter wavelength ranges from (1000-1700 nm) and the longer wavelength ranges from (1700-2200 nm). The 1700 nm in Figure 39 can be regarded as the cut-off wavelength. In the longer wavelength, an anomaly is observed however this anomaly is not evident in the shorter wavelength (see Figure 39). In this work, the transmission intensities used to determine splice losses are obtained in the 2000 nm and an anomaly was observed for certain experiments.

The above mentioned 8 experiments giving rise to the 8 negative splice loss is visually represented by the anomaly in the 1700-2200 nm (see Figure 39). The transmission intensity of the 8 experiments appears to be higher than the transmission intensity for the baseline. However, such anomaly is not observed in the shorter wavelength (1000-1700 nm) (see Figure 39). This anomaly in the longer wavelength range was suspected to be generated by the propagation of higher order modes (HOM) in the cladding of the receiving passive fibre, at the splice joint.

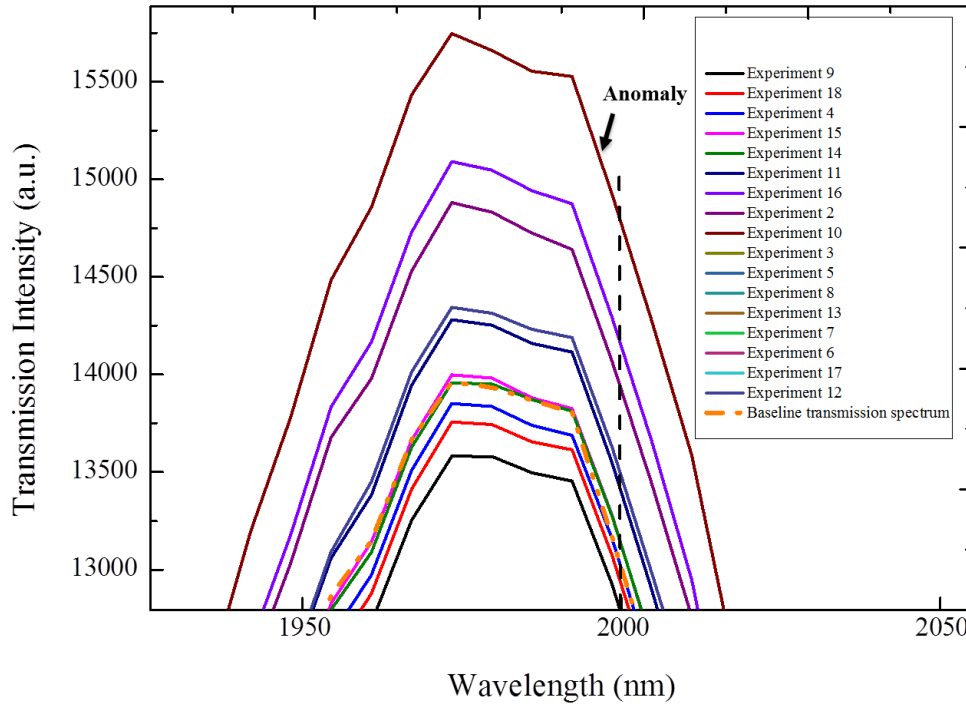


Figure 40: Zoomed in spectra for transmission measurements obtained in the 2000 nm region showing anomalous data.

In Figure 40, the zoomed in transmission spectra in the 2000 nm region is shown. The transmission intensity through two fusion spliced passive DC-LMAF is higher than the baseline, resulting in the negative splice losses for Exp 4,15,14,11,12,2,16,10.

The observation of the anomaly can be explained by looking at the V number of an optical fibre [60]. The V number is an indication of the number of supported modes which can propagate through the fibre, expressed as:

$$V = \frac{2\pi a}{\lambda} NA \dots \dots \dots \text{Equation 2}$$

where a is the radius of the fibre core, λ is the wavelength of the light propagating in the fibre core and NA is the numerical aperture. In Equation 2, it can be noted that the wavelength is inversely proportional to the V number, that is the longer the wavelength the fewer the number of guided modes. Conversely, the shorter the wavelength the higher the number of guided modes.

Consider the final spectral splice loss measurement setup in Figure 36. The 400 μm core multi-mode fibre MMF 7 (SMA) connected to the BBS will couple in many higher order modes, some of which will eventually decouple out of the fibre into the surrounding environment due to sufficiently long propagation distance in the cladding. The guided modes from the 400 μm core of MMF 7 (SMA) will couple into the 400 μm core of the MMF 5 (FC/PC). Perturbation such as bending, twisting of MMF 5(FC/PC) and the mode field diameter mismatch at Fusion Splice 1 between the 400 μm core of MMF 5(FC/PC) and 25 μm core of passive DC-LMAF and the fusion splice between the two 25/400 μm passive DC-LMAF may cause the light at high angles to the fibre axis to dissatisfy the critical

angle condition, leading to the light to not be totally internally reflected. The power associated with this light will couple into the 400 μm cladding of the receiving passive DC-LMAF, thus generating the propagation of higher order modes (HOM) in the cladding.

Consider the splice joint between the 400 μm core of MMF 5(FC/PC) and 25 μm core of passive DC-LMAF and the splice joint between the two 25/400 μm passive DC-LMAF in figure 36.

For shorter wavelengths, the HOM at the two fusion splices will propagate for a moderate distance and the power associated with these modes will dissipate into the surrounding environment. At the two splice joint, the guided modes from the launching MMF 5(FC/PC) and 25 μm core of passive DC-LMAF will be transmitted into the 25 μm core of the receiving passive fibre. Therefore no HOM are present, thus no anomaly is observed in this region.

For longer wavelengths, the HOM at the two fusion splices will propagate for a longer distance in the 400 μm cladding of the receiving passive DC-LMAF. These HOM will eventually become trapped by the 570 μm low-index polymer coating of the passive DC-LMAF. The HOM will reach the AS thus yielding the false increase in transmission intensity which creates an anomaly.

The propagation of the HOM in the cladding is likely caused by the low-index polymer coating of the 25/400 μm passive DC-LMAF. An experiment was setup to support this theory (see section 4.51). Simultaneously, this experiment also provided a solution to remove the anomaly observed.

In the 400 μm core MMF 5 (FC/PC), all the light is guided in the shorter and longer wavelength region. However

4.5.1 High Refractive Index (RI) Liquid Experiment

This sub-section discusses the 570 μm low-index polymer coating of the 25/400 μm passive DC-LMAF which is suspected to be the possible reason for the generation of the 8 negative splice losses obtained in Table 13. The sub-section also discusses and demonstrates the proposed solution to the 8 negative splice loss measurements by means of executing the high RI liquid experiment.

The presence of the low-index polymer coating of the passive DC-LMAF can trap a fraction of optical signal that escaped from the core at the fusion splice into the cladding [20] (see Figure 41). In this work, the higher order modes of the longer wavelengths propagate for longer optical paths and it becomes trapped by the low-index polymer coating of the passive DC-LMAF. Consequently, the higher order mode of the longer wavelength propagates in the cladding until it reaches the AS, thereby yielding false transmission intensities which results in the negative splice losses.

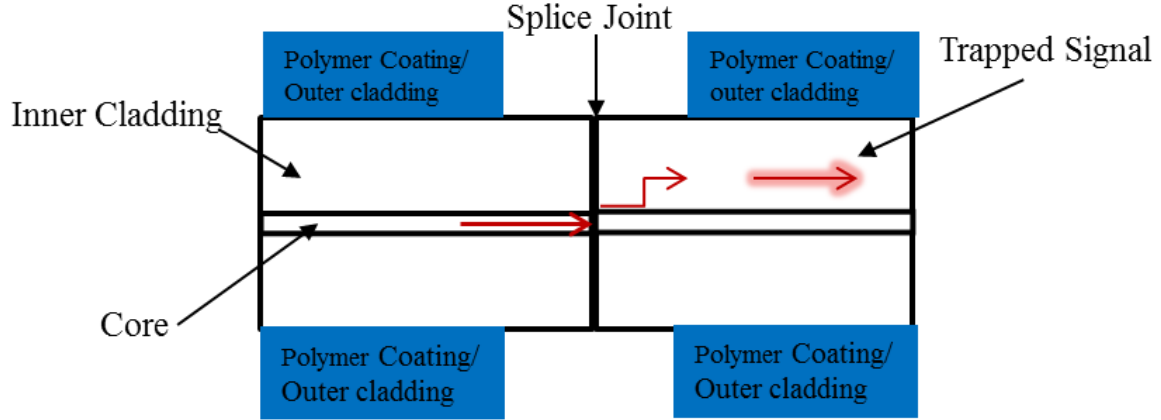


Figure 41: 25/400 μm passive DC-LMAF with a low- index polymer coating that traps optical signal into the fibre cladding.

An experimental setup was developed to validate the theory of the low-index polymer coating of the passive DC-LMAF. The experiment applies the high RI liquid on the fusion splice that yielded false transmission intensity. The objective is to remove the trapped optical signal propagating in the cladding, with the expectation of obtaining the realistic transmission intensity measurement.

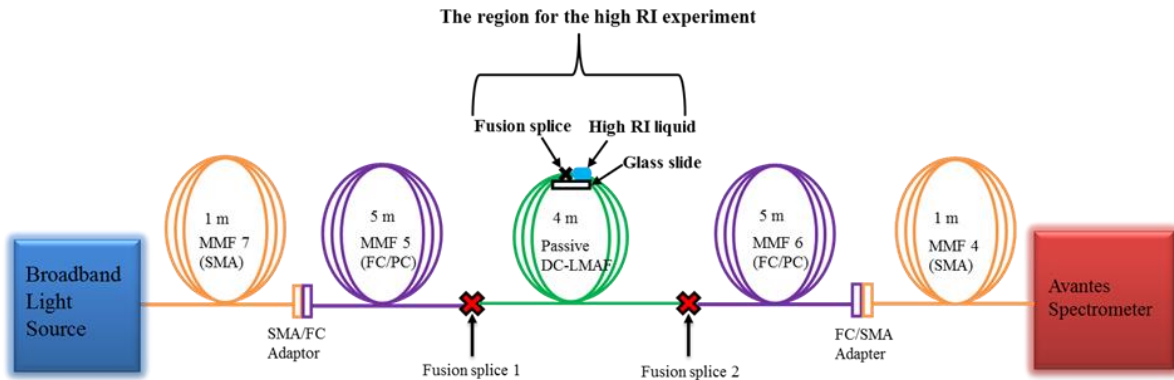


Figure 42: The high RI liquid experimental setup.

In Figure 42, the region for the high RI experiment is indicated within the final spectral splice loss measurement setup previously constructed in Figure 36. The experiment in Figure 42 required the high RI liquid and the glass slide to hold the fusion splice and the liquid.

The fusion splice represented by the black cross in Figure 42 is the fusion splice previously fabricated by Experiment 12 which yielded the false increase in transmission intensity of 12978 (a.u.). The fusion splice was placed under the glass slide and the high RI liquid was poured on the cladding of the receiving 25/400 μm passive DC-LMAF, downstream the fusion splice (see Figure 42).

The transmission intensity measurement of 10818 (a.u.) was obtained at 2000 nm from the AS, after the liquid had settled on the cladding of the receiving 25/400 μm passive DC-LMAF. This transmission intensity is lower than the baseline transmission intensity 12489 (a.u.). Considering that the cladding of the receiving 25/400 μm passive DC-LMAF has a low refractive index and the liquid has a high refractive index. The higher order mode propagating in the cladding is suspected to have refracted away from the cladding-liquid interface, resulting in the higher order mode to be transmitted into the high refractive index liquid medium. The removal of the higher order mode results in the

absence of the false increase in transmission intensity. Therefore, the guided modes propagating in the fibre core will yield realistic transmission intensity measurement as obtained from the high refractive index experiment.

The transmission intensity obtained from the high RI experiment confirms the theory of the low-index polymer coating of the 25/400 μm passive DC-LMAF. The higher order mode from the receiving 25/400 μm passive DC-LMAF of the fusion splice can be trapped in the cladding by the polymer coating. This result in the false increase of transmission intensity measurement which leads to negative splice losses as obtained from the splice loss optimization experiment (see Table 13). The obtained lower transmission intensity than the baseline transmission intensity validates that the trapped optical signal was effectively removed from the cladding of the receiving 25/400 μm passive DC-LMAF. Therefore, the obtained transmission intensity is in agreement with the predicted expectation of achieving the realistic transmission intensity measurement.

The low-index polymer coating is the possible cause of the negative splice losses obtained from the 8 experiments. This low-index polymer coating predicament can be mitigated by the utilization of the high RI liquid.

The negative splice losses in Table 13 affects the accuracy of trusting the final set points that will be determined in section 4.8 to be the optimal set point for the 7 splice parameters. Therefore, the level of confidence of the splice loss that will be produced by the optimal set point of the 7 splice parameters will be low.

4.6 Fusion Splice Analysis

This section categorises and compares the fabricated fusion splices according to the different levels of the main fusion Arc Power 2 and its respective Arc Time 2. Arc Power 2 generates the main plasma arc discharge that fabricates a fusion splice. The different levels of the main fusion Arc Power 2 are 69 a.u., 73 a.u. and 71 a.u. and are categorised into the low, high and moderate main fusion Arc Power 2, respectively. The shortcoming with this analysis is that the remaining splice parameters are not taken into consideration and the analysis applies the visual inspections of the fabricated fusion splices. The experiments referred in this section are the experiments set out from the Taguchi orthogonal array in Table 12.

4.6.1 Fusion Splices Fabricated at Low Main Fusion Arc Power 2 (69 a.u.)

In Figure 43, fusion splices that were fabricated at the low main fusion Arc Power 2 with set point 69 (a.u.) are shown. The different fusion splices presents the unsuccessful splice joint, weak splice joint, seam and the vertical line.

Fusion splices fabricated in Experiment 1 and Experiment 6 presented the unsuccessful splice joint and the weak splice joint, respectively (see Figure 43(a)-(b)). Only Experiment 1 and Experiment 6 had a splice parameter combination that comprised of low 69 a.u. for Arc Power 1 and Arc Power 2. During fusion splicing, fibre tips experienced a low plasma arc discharge which was produced by Arc Power 1, leading to fibre tips to be insufficiently soft. The inadequate heating of the fibre tips implies that viscosity at the fibre tips is not sufficiently reduced to below 10^5 Poise [20]. The high viscosity and the high surface tension experienced at the fibre tips prevented the flow of glass material.

Additionally, the low main plasma arc discharge generated by Arc Power 2 resulted in the formation of the weak splice joint (see Figure 43(b)), as well as the unsuccessful splice joint as observed in Figure 43(a).

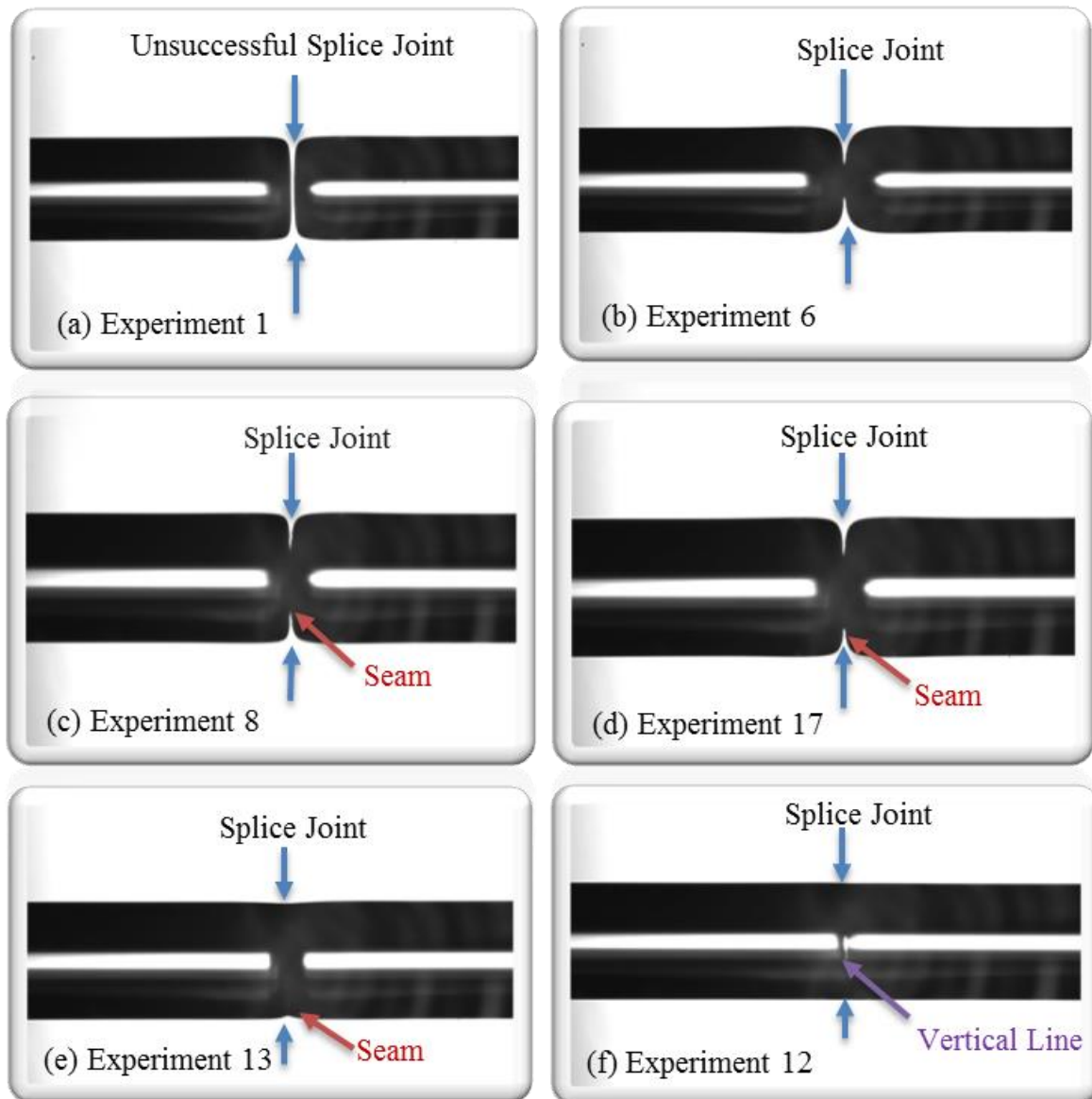


Figure 43: Fusion splices fabricated at low arc discharge fusion power, 69 (a.u.).

A seam is commonly associated with low temperature fusion splices and can suggest a reduction in the strength and reliability of a fusion splice [20]. In Figure 43(c)-(f), the seam is present in all four of the fusion splices that were fabricated where Arc Power 2 is set to 69 a.u. When a seam is formed between two fibres during fusion splicing, the surface tension will act to smooth the seam [20]. Due to the low plasma arc discharge experienced by fibre tips, the surface tension process of smoothing the seam was likely unaccomplished. Furthermore, the splice joint will exhibit a deformed fibre cladding which can refract light, resulting in the observation of a vertical line at the splice joint (see Figure 43 (f)). The vertical line and the seam indicate the formation of the weak splice joints which are associated with high splice losses.

4.6.2 Fusion Splices Fabricated at High Main Fusion Arc Power 2

The fusion splices in Figure 44 were fabricated at an elevated Arc Power 2 set to 73 (a.u). There are different fusion splices displayed, with rounded fibre tips, core deformation and continuous well-formed splice joints.

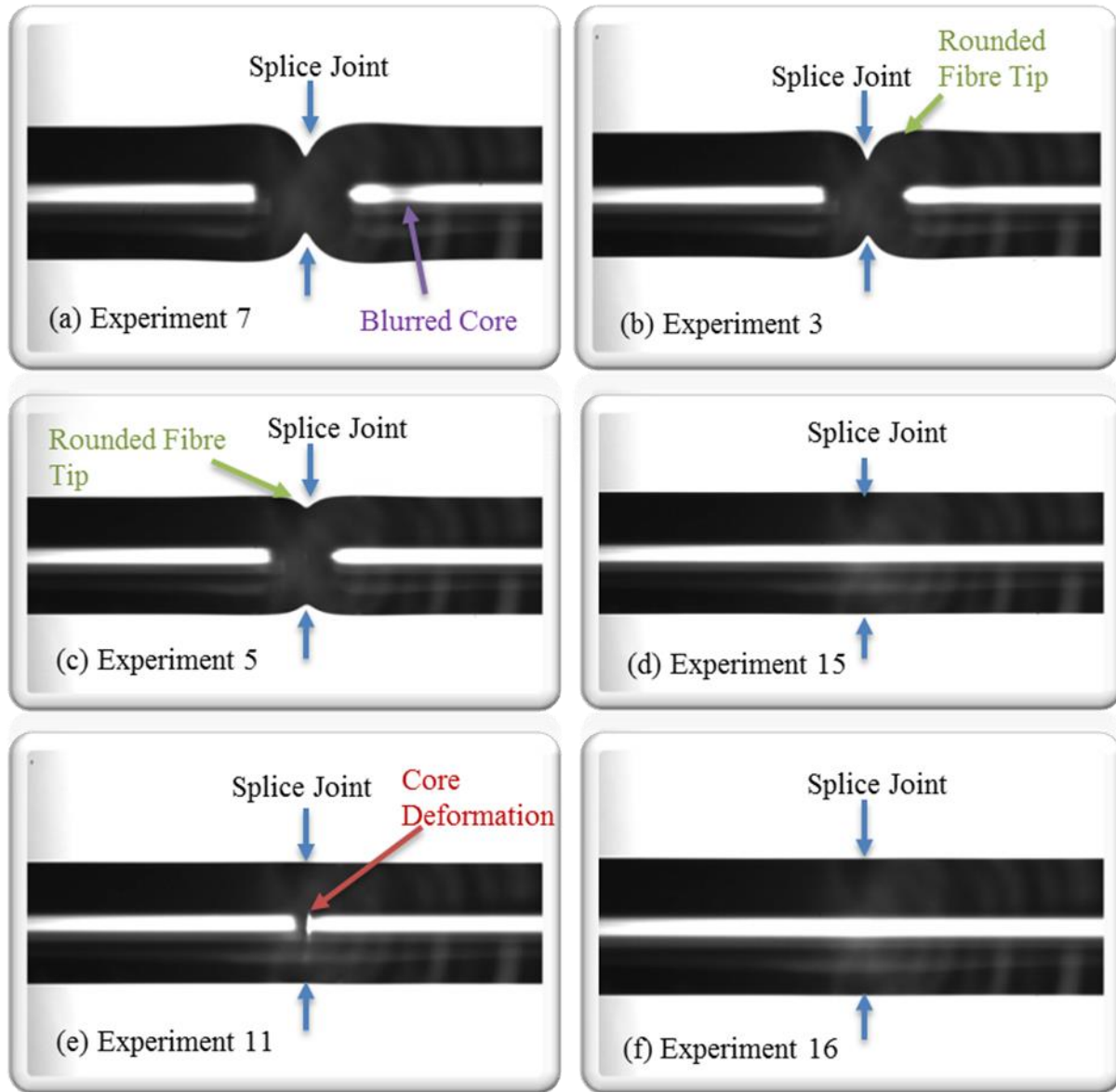


Figure 44 : High arc power fusion splices, 73 (a.u.).

In Figure 44(a)-(c), the fusion splices with the rounded fibre tips are shown. The rounded fibre tips are most likely generated due to the high main plasma arc discharge which is produced by Arc Power 2 with set point 73 (a.u.). During fusion splicing, the high heat and low viscosity ($>10^5$ Poise) experienced at the fibre tips suggest that lower surface tension may have pinched the molten glass away from the splice joint until the fibre tips became rounded. If the fibre tips were held at an extended time > 6.5 s for this study, the fibre tips would be pulled apart and appear more rounded or balled up. The blurred fibre core in Figure 44 (a) is likely due to the substantial dopant diffusion.

In Figure 44 (e), core deformation of a fusion splice is shown. The core deformation is likely generated by the fibre core radial offset which is produced by surface tension effect during the push distance. A joint is created when the fibre tips are pushed against each other; however the fibre core radial offset will produce a shear force across the two fibre tips [20]. The shear force will deteriorate the fibre core, resulting in core deformation.

Furthermore, deformation of the core implies that less power will be transmitted through the fusion splice, resulting in a high splice loss.

The well-formed, good visual fusion splices with no deformities are shown in Figure 44 (d)-(f). Experiment 15 and Experiments 16 are the two experiments that had a splice parameter combination with set point 71 (a.u.) for Arc Power 1 and set point 73 (a.u) for Arc Power 2. During fusion splicing, the fibre tips were sufficiently heated and softened by the moderate arc plasma discharge generated by Arc Power 1 with set point 71 (a.u), thereby the lower surface tension allowed a flow of molten glass. Furthermore, the main plasma arc discharge with set point 73 (a.u.) fabricated the continuous, well-formed splice joints. Hence, the guided optical signal will propagate from one fibre into the receiving fibre, thus low splice losses will be achieved.

4.6.3 Fusion Splices Fabricated at Moderate Main Fusion Arc Power 2

The six fusion splices in Figure 45 are fabricated with the main Arc Power 2 having set point 71 (a.u.) which is considered as moderate arc plasma discharge. Only one fusion splice presented a splice joint with core deformation. The remaining five fusion splices exhibited continuous well-formed splice joints with no evidence of visual defects.

The core deformation is evident in the fusion splice in Figure 45(e). This geometric deformation likewise in Figure 44(e) may likely have been caused by high surface tension which induces lateral misalignment of the fibre cores. The fibre tips will shear across each other during joint formation, resulting in core deformation. Therefore, the core distortion will hinder the guided optical signal to propagate through the fibre, thus high splice loss will be generated.

The fusion splices in Figure 45 (a)-(d) and (f) shows well-formed splice joints with the absence of deformities. These fusion splices were likely fabricated due to the sufficient reduction of the viscosity (below 10^5 Poise) at the fibre tips. The low viscosity and low surface tension experienced at the fibre tips allows the flow of molten glass, during fusion splicing. Therefore, the continuous splice joint will be formed during the moderate plasma arc discharge released by Arc Power 2 with set point 71 (a.u.). Hence, the well-formed splice joints suggest that the guided optical beam can easily propagate through the fibre, thus minimal splice loss can be attained.

The moderate Arc Power 2 generates well-formed fusion splices in comparison with the fusion splices fabricated at low and high Arc Power 2. The continuous, well-formed fusion splices contain no evidence of any visual deformities at the moderate Arc Power 2, which suggests that the set point 71 (a.u.) may be one of the optimal set point for Arc Power 2. This is confirmed in the following section 4.8.

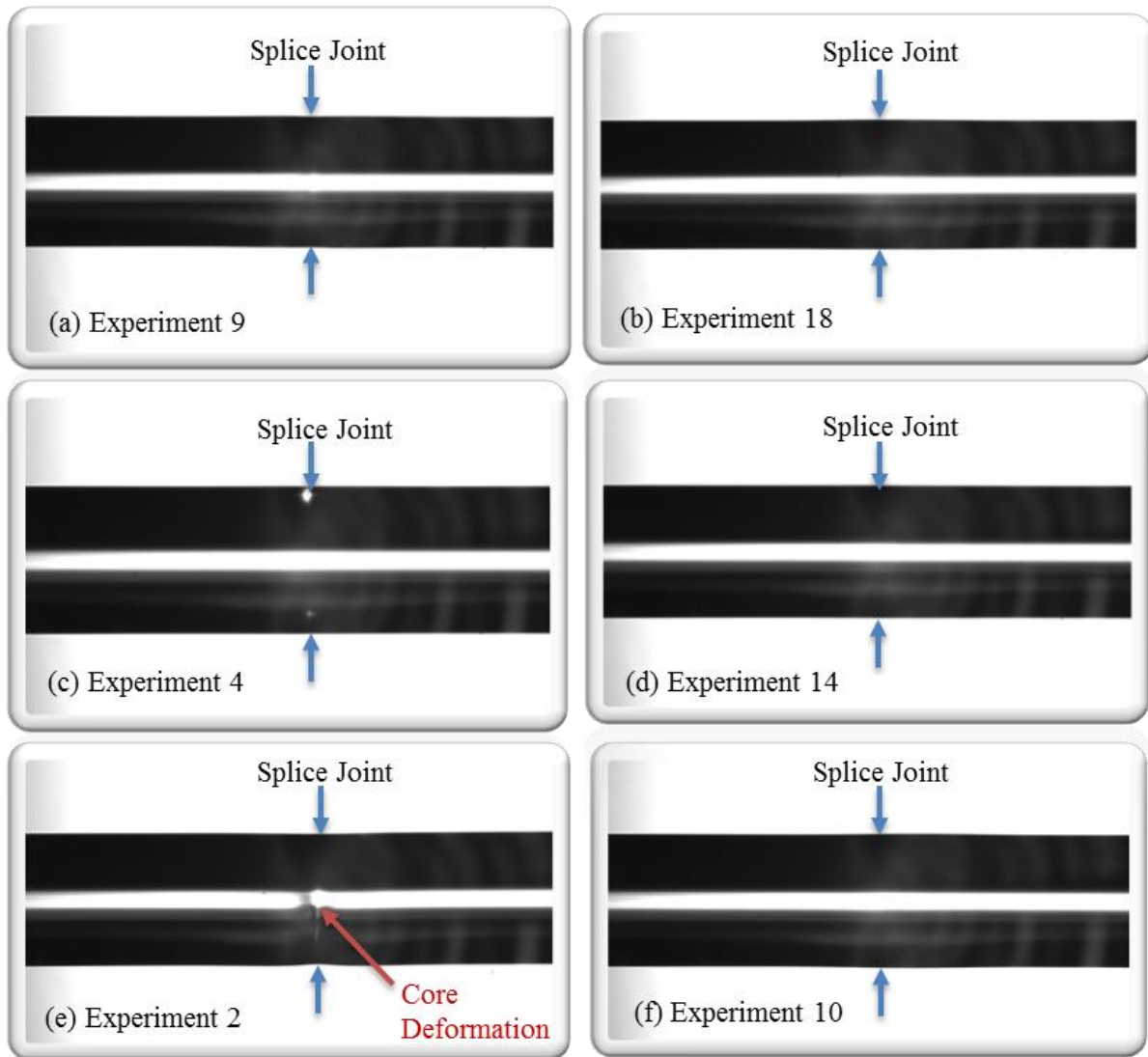


Figure 45: Fusion splices fabricated at moderate main fusion Arc Power 2 set to 71 (a.u.)

4.7 Analysis of Variance (ANOVA)

The ANOVA is applied to the transmission intensity measurements in Table 13 by using equations set out in appendix 1. ANOVA is a statistical technique that is applied in this work to determine the significant effect that each splice parameter has on the quality of the fusion splice. The technique involved separating the total variation of each splice parameter from the total mean of splice parameters through determining the following:

- Sum of squares
- Percentage contribution
- Fisher's F-ratio test

This section will implement the ANOVA technique and discuss the statistical and physical implications of the technique.

4.7.1 Overall Mean

The overall mean is the reference point that each parameter's splice loss is calculated. The overall mean for the splice losses in Table 13 was calculated as:

$$\begin{aligned}\bar{Y} &= \frac{1}{N} \times \sum_{i=1}^{N_{17}} Y_i \\ &= 0.83 \text{ dB}\end{aligned}$$

4.7.2 Sum of Squares

The sums of squares quantify the variation that is produced by each splice parameter around the overall experimental mean. As an example, the sum of square of the Gap Distance splice parameter, represented by the symbol A found in Table 12, is calculated as follows:

$$\begin{aligned}SS_A &= N_{A1=40} \times (\bar{Y}_{A1=40} - \bar{Y})^2 + N_{A2=50} \times (\bar{Y}_{A2=50} - \bar{Y})^2 \\ &= 8 \times (1.678 - 0.83)^2 + 9 \times (-0.091 - 0.83)^2 \\ &= 10.672 \text{ (dB)}^2\end{aligned}$$

Similar sum of squares calculations for the other splice parameters in Table 12 are listed in Table 14.

Total sum of squares for all seven splice parameters was calculated by:

$$\begin{aligned}SS_{\text{total}} &= SS_A + SS_B + SS_C + SS_D + SS_E + SS_F + SS_G \\ &= 10.672 + 1.701 + 0.672 + 2.338 + 4.608 + 8.898 + 4.173 \\ &= 33.062 \text{ (dB)}^2\end{aligned}$$

4.7.3 Percentage Contribution

The relative contribution of each splice parameter on the splice loss is calculated by taking the ratio of each splice parameter's sum of squares to the total sum of squares

The percentage contribution for the Gap Distance splice parameter is then:

$$\begin{aligned}\% \text{ contribution} &= (10.672 / 33.062) \times 100 \\ &= 32\%\end{aligned}$$

Similar calculations were made for the remaining six splice parameters and are tabulated in Table 14.

4.7.4 Fisher's F-ratio Test

F-test is a variance ratio used to test the overall significance of each splice parameter.

The F-test value for the Gap Distance splice parameter was calculated as follows:

- Applying equation 7, $MST = \frac{10.7}{2-1} = 10.7$
- Applying equation 8, $MSE = \frac{24.2}{17-2} = 1.6$
- Applying equation 6 which is F-test formula, $F = \frac{10.7}{1.6} = 6.6$

The F critical is calculated by using the degrees of freedom from the F-test equation as follows:

- $MST = \frac{SST}{2-1} = \frac{SST}{1}$ which is 1 numerator degrees of freedom
- $MSE = \frac{SSE}{17-2} = \frac{SSE}{15}$ which is 15 denominator degrees of freedom

The significance level that was chosen was 0.100. The significance level implies there is 10% probability that the mean of groups are different even when there is no actual difference. The aforementioned statement is the null hypothesis for the F-ratio test. Using the degrees of freedom for numerator, $k-1 = 1$ and denominator, $n-k=15$ which leads to $F_{critical} = 3.0$ (see appendix 1 Table 18, for table of F critical values).

For the Gap Distance parameter, $F \geq F_{critical}$, $6.6 \geq 3.0$, the null hypothesis is rejected and it is concluded that there is a difference in the mean of the groups within the parameter. Additionally, the Gap Distance splice parameter is statistically significant and similar observations were made for Arc Power 2 splice parameter. However for Arc Power 2, $F < F_{critical}$, $2.3 < 2.7$, thus Arc Power 2 is statistically insignificant.

The remaining five parameters generated F-test value that was smaller than F-critical value, implying that the splice parameters are statistically insignificant.

The results of the ANOVA calculations for this study are shown in Table 14.

Table 14: ANOVA results for the splice loss optimization experiment.

Symbol	Splice Parameter	Sum of squares	Degrees of freedom	Mean square	Mean square error	F-ratio	F _{critical} (0.10)	Percentage contribution
A	Gap distance	10.6	1	10.6	1.6	6.6	3.0	32
B	Prefuse time	1.7	2	0.8	2.3	0.3	2.7	5
C	Arc time 1	0.6	2	0.3	2.4	0.1	2.7	2
D	Arc time 2	2.3	2	1.1	2.3	0.5	2.7	7
E	Arc power 1	4.6	2	2.3	2.1	1.0	2.7	14
F	Arc power 2	8.8	2	4.4	1.8	2.3	2.7	27
G	Overlap	4.1	2	2.0	2.1	0.9	2.7	13
Error		1.8	4					
Total		34.9	17					100

The results of ANOVA indicate that:

- The Gap Distance has the largest sum of squares, followed by Arc Power 2. The results imply that the two parameters have a stronger influence in controlling the measured quality of a fusion splice.
- The Gap Distance contributes 32% of observed variation in splice quality, whereas Arc Power 2 provides 27%. Therefore, Gap Distance and Arc Power 2 have the most important impact on fusion splice quality and are the main splice parameters that controls splice loss (see Figure 46 below).
- The hypothesis test used to compare the results statistically revealed that the Gap Distance has a $F_{\text{ratio}} > F_{\text{critical}}$ and Arc Power 2 has $F_{\text{ratio}} = F_{\text{critical}}$ at 90% confidence level ($\alpha=0.10$). The results suggests that at 90 % confidence level, Gap distance and Arc Power 2 are statistically significant and are the most important splice parameters that contribute towards the quality of a fusion splice, whereas the remaining splice parameters have an insignificant effect towards fusion splice quality based on the chosen level settings.

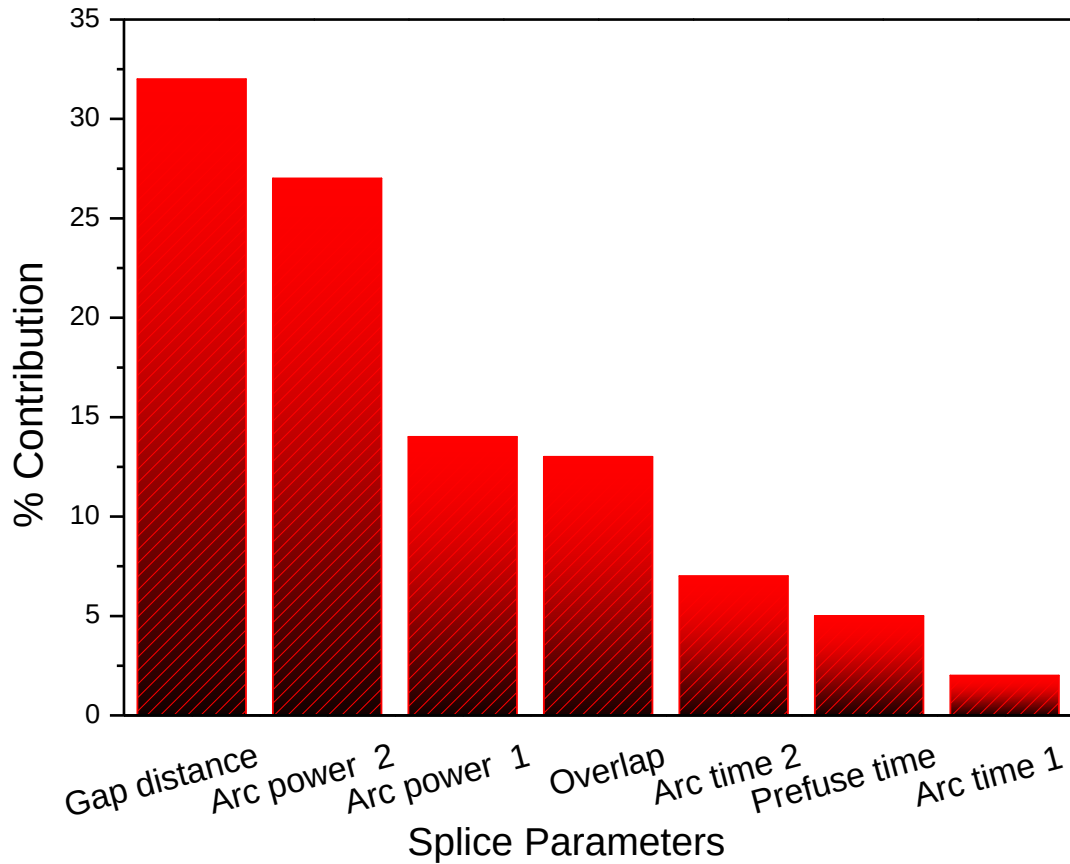


Figure 46: Percentage contribution of each splice parameter towards splice loss.

The physical implications of the ANOVA:

- Mode field diameter (MFD) expansion defined in section 2.3.2 of the two 25/400 μm passive DC-LMAF during fusion splicing have most significant effect, with the highest impact on fusion splice quality and control towards splice loss. The expansion of MFD is influenced by Gap Distance, push distance and Overlap Distance splice parameters. The mathematical representation of these parameters is given by $\text{Overlap Distance} = \text{Push Distance} - \text{Gap Distance}$. The Gap Distance indicates the gap between two 25/400 μm passive DC-LMAF ends before fusion splicing process begins. The left fibre will push against the right fibre for given push distance, which represents position of two fibre ends during the actual arc discharge (Arc Power 2). The two fibres will be subjected to additional travel distance beyond original gap spacing, namely the Overlap Distance. Furthermore, an increase in overlap creates an increase in extension of the physical contact of the two fibres, resulting in the expansion of mode field diameters [53]. Hence mode field distribution between the two spliced passive fibres will be exceptionally matched. Moreover, a good quality fusion splice will be fabricated; permitting optical signal to be transmitted into guided modes of the receiving passive fibre and a good quality of a fusion splice will be fabricated resulting in minimal splice loss to be obtained.

- Arc Power 2 is the second splice parameter that has the highest contribution and control towards fabrication of a fusion splice. This splice parameter provides the main plasma arc discharge that fabricates a fusion splice after push and overlap movement of the two fibres. Surface tension is responsible for fabrication of fusion splice during Arc Power 2. During the main arc plasma discharge, surface tension will adjust cladding of the two passive fibres and enhance alignment of the fibre cores. The heat provided by Arc Power 2 will lower the surface tension to allow for the flow of sufficiently viscous molten glass, thereby fabricating a smooth, homogenous fusion splice. Therefore, more optical signal will be transmitted into the receiving passive fibre, resulting minimum splice loss to be obtained. It should be noted that surface tension can either be advantageous or deleterious during fusion splicing process.
- The third and fourth splice parameter that has an impact on the quality of fusion splice is Arc Power 1 followed by Overlap in Figure 46. Arc Power 1 generates plasma arc discharge during push movement of the left fibre against right fibre and overlap movement, so that thermal expansion of the two mode field diameters of the fibres can occur.
- Arc Time 2, Prefuse Time and Arc Time 1 have a minor influence on splice quality and control towards splice loss. The 7% contribution of Arc Time 2 serves as a duration time for the main plasma arc discharge (Arc Power 2) during the fabrication a fusion splice. The 5% of Prefuse Time provides time duration of the initial plasma arc discharge (Prefuse Power) that pre-heats the two fibre ends to soften fibre ends before initiating the fusion splicing process. Arc Time 1 contributes 2% towards fabrication of a fusion splice by generating time duration of Arc Power 1 that applied during push and overlap movement of two fibres.

The ANOVA technique was applied by Pradhan *et al.* [53] to find significant parameters that controls the splice loss. This technique was implemented on splice losses obtained between two 9/125 μm single mode fibres (SMF). Arc Power, Arc Time, Prefuse Power and Prefuse Time were the chosen four splice parameters. A full factorial design of experiment was designed which required $2^k = 16$ experiments varied over 2 levels to be conducted. Arc Power and Arc Time were the statistically significant parameters that contribute towards the splice loss. The best splicing set points yielded 0.03 dB lowest splice loss. Likewise in this work Arc Power 2 was found to be statistically significant.

It should be noted that there are limited published work on the splice loss optimization of large mode area fibres (LMAF) and large diameter specialty fibres due to their applications in the splicing field being new and still in progress.

4.8 The Optimal Splice Parameter Set Points for the Splice Loss Optimization Experiment

This section present the optimal splice parameter settings that will provide strong welded quality fusion fusion splices between two 25/400 μm passive DC-LMAF with minimum splice loss.

The average splice loss at distinct level setting for each splice parameters and the overall splice loss mean for the entire splice loss optimization experiment are graphically represented in Figure 47. The average splice loss and the overall mean were calculated during the implementation of the ANOVA technique. The two are used to graphically present the optimal set points for each splice parameter.

The plots in Figure 47 are made to obtain optimal set points for each splice parameter. The optimal set points and the lowest average splice losses for each splice parameter obtained from Figure 47, are shown in Table 15. The Arc Power 2 splice parameter with set point 71 (a.u.), is the only splice parameter that presents a contradictory average splice loss (see Table 15).

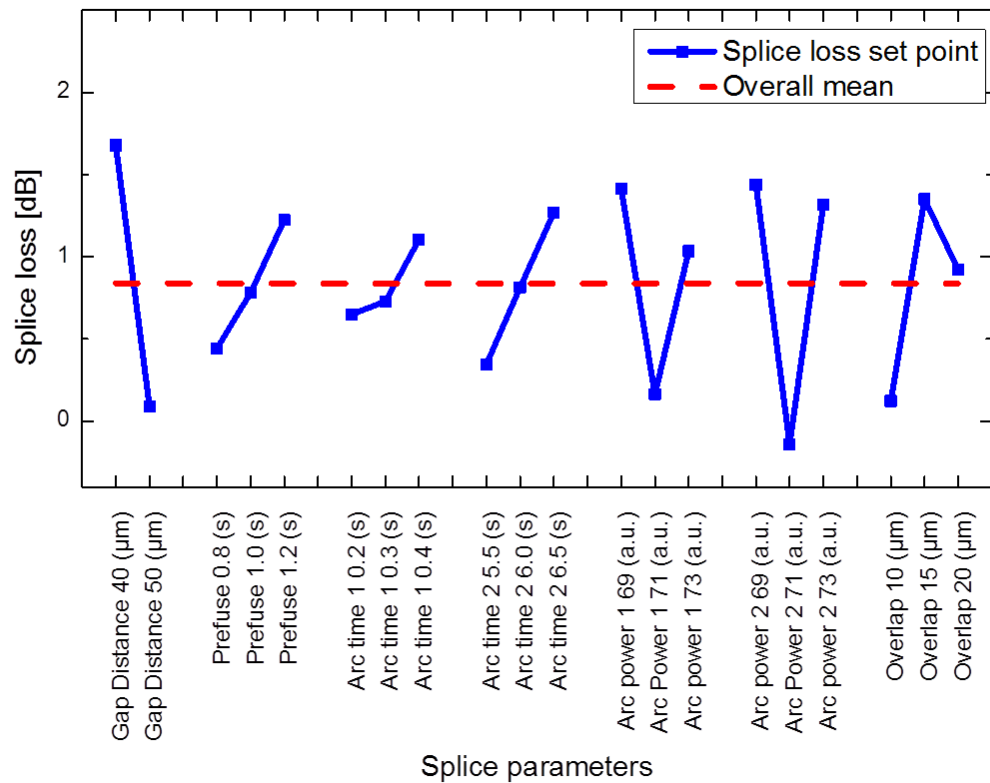


Figure 47: Plots of splice parameter set points and splice loss.

Table 15: Optimal splice parameter set points.

Splice parameters	Gap Distance	Prefuse Time	Arc Time 1	Arc Time 2	Arc Power 1	Arc Power 2	Overlap
Optimal parameter set points	50	0.8	0.2	5.5	71	71	10
Average Splice loss (dB)	0.091	0.441	0.649	0.346	0.163	-0.139	0.123

In Table 15, the Gap Distance has the lowest average splice loss of 0.091dB at set point 50 µm, followed by Arc Power 2 with the average splice loss of -0.139 dB at set point 71 (a.u.). The lowest average splice losses for the two splice parameters validates the ANOVA results which implied that

the two splice parameters are statistically significant and they have a stronger contribution towards the splice loss as compared to the rest of the splice parameters. The Gap Distance at set point 50 μm will promote mode field diameter expansion of the two 25/400 μm during fusion splicing process, resulting in better matched mode fields distribution.

Arc Power 2 with the average splice loss of -0.139 dB was unrealistic. Splice loss cannot be a negative value, based on standard definition of splice loss (see chapter 2) where splice loss will always be a positive number. The splice losses of the experiments conducted at Arc Power 2 with set point 71 (a.u.) form part of the experiments that generated the anomalous transmission intensity measurements which yielded negative splice losses. The anomaly was possibly due to the propagation of the HOM for longer wavelength in the cladding of the receiving fibre, from the splice joint. This anomaly is suspected to be due to the 570 μm low-index polymer coating of the 25/400 μm passive DC-LMAF. This polymer coating has the ability to trap optical signal that has escaped from fusion splice core into the cladding (see Figure 41), thereby enforcing TIR at the 400 μm cladding-570 μm polymer coating interface, thus giving false high transmission intensity readings. Therefore, the negative splice losses affects the accuracy of the set point 71 (a.u.) in being the optimal setting for Arc Power 2. Contrary to the unrealistic average splice loss of set point 71 (a.u.) and the negative splice losses, the visual inspection of the fusion splices fabricated at this set point in sub-section 4.6.3 confirms this as the optimal Arc Power 2 value. The continuous, well-formed fusion splices with minimal to no evidence of deformities are fabricated at this set point. Hence, the optimal set point for the splice parameter, as well as the respective average splice losses in Table 15 are still trustworthy by virtue of incorporating visual inspection the fabricated fusion splices.

The graphical presentation of lowest splice loss of the Gap Distance, Prefuse Time, Arc Time 1, Arc Time 2 and the Overlap suggest that their optimal parameter set points, lie near the boundary of parameter space stated in Table 10 for the experimental design. The remaining optimal set points of Arc Power 1 and Arc Power 2 lie in the middlemost of the parameter space. Therefore, a smaller splice loss optimization experiment enclosing only optimal parameter set points of significant and more influential parameters which are the Gap Distance and Arc Power 2 for this study may yield further improved parameter set points that can generate more desirable fusion splices with lower average splice losses. The lower the splice loss of each splice parameter, the greater and improved process of fabricating good quality fusion splices.

The optimal splice parameter set points with lowest average splice losses listed in Table 15 were found to be the best parameters for fusion splicing process, based on the obtained splice losses from the splice loss optimization experiment and the graphical presentation of the average splice loss for each splice parameter in Figure 47 for this study.

The optimal splice parameter set points in Table 15 are yet to be implemented in an experiment and to have the lowest splice loss confirmed experimentally. Several problems encountered with the 3SAE large diameter glass processing splicer (LDS) means that it was not possible to complete this within the allocated time frame.

Chapter summary:

- The fractional factorial design of experiment required a total of 18 experiments to be executed for the splice loss optimization of seven splice parameters.
- The Taguchi experimental design methodology was implemented for the splice loss optimization of the 25/400 μm passive DC-LMAF.

- The baseline transmission spectrum for the splice loss optimization experiment was obtained after implementing all the lessons learnt in chapter 3.
- The 570 μm low index polymer coating of the 25/400 μm passive DC-LMAF causes unrealistic splice losses by trapping the optical signal in the 400 μm cladding of the receiving passive DC-LMAF by total internal reflection at the cladding-polymer coating interface. This optical signal can be removed from the cladding by the high refractive index liquid.
- The fusion splices characterized by moderate Arc Power 2 with set point 71 (a.u) presented well-formed fusion splices with no deformities. These fusion splices confirms that 71 (a.u) is the optimal set point for Arc Power 2 for this work.
- The analysis of variance (ANOVA) revealed the Gap Distance and Arc Power 2 have the significant impact on the quality of the fusion splice. The Gap Distance and Arc Power 2 contribute 32% and 27 % , respectively towards the splice loss for the chosen parameter space in this work. The Gap Distance influences the mode field diameter expansion between the two 25/400 μm passive DC-LMAF during fusion splicing. Therefore a continuous fusion splice that allows the optical signal to be transmitted into the guided mode of the receiving fibre will be formed. Arc Power 2 generates the main plasma arc discharge that fabricates a fusion splice during splicing.
- The optimal parameter set points for splicing two Nufern 25/400 μm passive DC-LMAF are found by making the graphical presentation of the average splices for the seven splice parameters.

CHAPTER 5: Conclusions and Future Work

The objective of this section is to give highlights on the important points found in the Chapter 3 and Chapter 4 and to give recommendations on future work.

The purpose of this work was to investigate and develop a procedure to optimise splice parameters to achieve low splice losses (<0.1 dB). The two Nufern 25/400 μm passive DC-LMAF were selected for the purpose of developing the high power, compact and robust thulium-doped all-fibre laser.

A spectral splice loss measurement system was setup to execute the splice loss optimization experiment between two Nufern 25/400 μm passive DC-LMAF. Two iterations on the spectral splice loss measurement system were conducted with the intention of investigating and mitigating the factors that could generate measurement variations. In the two iterations, it was discovered that the reconnection of multimode fibre patch cables with SMA and FC/PC connectors produces splice loss measurement variations. These variations were mitigated by conducting the splice loss optimization experiment without the reconnection of both the multimode fibre patch cables from the spectral splice loss measurement system. The area that consisted of 25/400 μm passive DC-LMAF was considered to be the only movable regions, whereby the 18 experiments set out from the Taguchi orthogonal array was conducted. The calculated expected splice loss measurement error was 0.03% for the final spectral splice loss measurement setup.

The statistical technique, analysis of variance (ANOVA), was applied to identify splice parameters that were statistically significant and to identify the parameter set points that will yield lowest splice loss between two fusion spliced 25/400 μm passive DC-LMAF. The technique revealed that within the selected parameter space, the Gap Distance and Arc Power 2 are the two most significant splice parameters that have the greatest impact on the quality of the fusion splice and the remaining five splice parameters are statistically insignificant. The Gap Distance controls the quality of a fusion splice through expanding the MFD of two 25/400 μm passive DC-LMAF during fusion splicing, thereby allowing most of the optical signal to be transmitted into fundamental guided mode of the receiving 25/400 μm passive DC-LMAF. The Arc Power 2 was the second significant splice parameter that had an influence towards fabrication of a strong welded quality of a fusion splice by generating the main plasma arc discharge that fabricates a fusion splice.

The optimal splice parameter set points was established by making the graphical presentation of the seven splice parameters with their respective average splice losses extracted from statistical analysis. The Gap Distance at set point 50 μm and Arc Power 2 with set point 71 (a.u.) had the lowest average splice loss. However, the average splice loss value of (-0.139 dB) for Arc Power 2 at set point 71 (a.u.) was illogical. The value contradicts the splice loss definition by implying that the power transmitted across the fusion splice is greater than the total power incident upon the fusion splice. This splice loss contradiction is possibly due to the higher order modes of the longer wavelength propagating in the cladding of the receiving 25/400 μm passive DC-LMAF. This anomaly was suspected to have been generated by the 570 μm low-index polymer coating of the 25/400 μm passive DC-LMAF. This low index polymer coating was suspected to have promoted total internal reflection on the 400 μm cladding-570 μm polymer coating interface. The polymer coating has the potential to trap the optical signal that has radiated from core of fusion splice into the cladding of the receiving 25/400 μm passive DC-LMAF, thus generating false increase in transmission intensities. This flaw does not negate this work since the set point 71 (a.u.) for Arc Power 2 is the set point that generated

good visual symmetrical and well-connected fusion splices that depicted minimal deformities in Figure 45. The high refractive index liquid can be utilized on the fusion splices that generate negative splice losses in order to overcome shortcoming induced by the low index polymer coating.

The lowest average splice loss of the Gap Distance, Prefuse Time, Arc Time 1, Arc Time 2 and the Overlap suggest that the optimal parameter set points, lie near the boundary of the chosen parameter space. The lowest average splice loss of Arc Power 1 and Arc Power 2 indicates that the optimal set points lie in the middlemost of the parameter space. The ANOVA suggested optimal set points for each splice parameter. The optimal set points found in this study can be verified by fabricating a fusion splice on the LDS. The fusion splice should present no deformities and the transmission intensity measurement generated by this fusion splice should yield a splice loss that is < 0.1 dB.

Based on the ANOVA results and the graphical representation of the optimal parameter set points of each splice parameter, a smaller splice loss optimization experiment will be designed by enclosing the optimal set points of the Gap Distance and Arc Power 2 and searching within their vicinity. The optimal set points for the insignificant splice parameters will be maintained fixed. This smaller splice loss optimization experiment will further optimise the splice parameters by yielding set points that will generate lower splice loss as compared to this study.

The fusion splicing process can be made more repeatable by the proper cleaning of electrodes and avoiding contaminants. The splice loss optimization process can be improved by replicating the experiments to obtain the measurement variation and to check for consistency in measurement of each experiment. The change in surrounding environment such temperature and humidity may perturb the plasma zone, thus leading to a change in the quality of fusion splices.

The optimal set points found for this work are the set points that will be used for fusion splicing passive fibres and passive fibre components on the proposed thulium doped all-fibre laser illustrated in Figure 1 which are:

- 25/400 μm DCF pump combiner and 25/400 μm DCF FBG 1.
- 25/400 μm DCF FBG 2 and 25/400 μm DCF cladding mode stripper.

To develop the all-fiberized thulium-doped fibre laser that is stated in Figure 1, a splice loss optimization experiment should be executed between two passive fibres with different fibre dimensions, and passive fibre and active fibre. The different fibre dimensions of the two passive fibres can cause MFD mismatch, which can cause high splice losses. The arc fusion splicing of passive to active could be challenging due to the dopant diffusion of the different elements constituting each fibre which can likely cause MFD mismatch, which can yield poor quality fusion splices, thereby generating high splice losses.

The next splice loss optimization that needs to take place will fabricate fusion splices, with respect to the thulium-doped all-fibre laser in Figure 1 between:

Passive to passive fibres

- 200/220 μm MMF Laser diode and 25/400 μm DCF pump combiner.

Passive- Active fibres

- 25/400 μm DCF FBG 1 and 25/400 μm DCF thulium doped fibre.
- 25/400 μm DCF thulium doped fibre and 25/400 μm DCF FBG 2.

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Appendix 1

Types of Design of Experiments (DOE)

Design of Experiment (DOE) is a systematic methodology that is used to represent the relationship between input factors and output measured responses. The relationship is used to manage the input factors for the purpose of optimizing the output measured responses. Experiments are arranged systematically and data analysis is performed by using analysis of variance (ANOVA) technique which combines the synergy between mathematical and statistical methods to find optimal output measured responses [61].

Response surface methodology (RSM) and factorial designs, such as full factorial and fractional factorial designs, are some of the commonly used DOE. RSM is used in tuning of input factors which are known to be close to the optimal settings. It models the output measured response as a Taylor series function of input factors and the local gradient of output measured response is employed to direct the search for best input factors. RSM disregard the global gradient of output measured response which makes RSM DOE a flawed technique [20].

A full factorial design is a design in which a single experiment is executed for every combination of factors and levels [51]. There are two types of full factorial design namely, two level design and a general design that consists of more than two levels. The number of trials in a two level design is denoted by 2^k , where k is the number of factors. For example, a two level full factorial design that comprises of 3 factors will require $2^3 = 8$ trials and a design with 6 factors will need 64 trials. It can be noted that in a two level full factorial design, an increase in the number of factors increases the total number of experiments exponentially, and likewise for a general design with more than two levels. Therefore, full factorial designs require many experiments to be conducted, which can be very tedious and time consuming especially when there are many factors that have to be considered in the design. The aforementioned drawback of full factorial design is resolved by applying a design called fractional factorial design.

Fractional factorial design is an experimental design in which all factors are varied concurrently at certain specific combinations of factors, during a collection of experiments [20]. The experimental design generates sufficient information that exposes significant factors of the problem study by only conducting fewer experimental trials. These fewer experimental trials are considered as a subset or fraction of experimental trials that one would find in a full factorial design [51]. Fractional factorial design is not only utilized for two level factorial design but is applied on factors that have more than two levels as well as factors that have mixed levels. The disadvantage with fractional factorial design is the capability to hide the interaction between two factors. Interaction is when the impact of one factor on the results is dependent on the level of another factor. The experimental design is preferred due to its ability to efficiently establish factors that are of major importance, as well as their impact on the output response.

Taguchi Design Experimental Methodology

Developed by Dr Genichi Taguchi, the Taguchi method is a type of fractional factorial design that applies a set of orthogonal arrays comprising of factors and their respective levels. The orthogonal arrays provide a way of performing the minimal number of experiments which generates sufficient knowledge on the effects of all factors on the output response. In a Taguchi orthogonal array, the different levels of each factor will appear an equal amount of times and the arrangement of each level within each factor is mutually orthogonal to the sequence of levels of another factor. Therefore, Taguchi orthogonal arrays are well balanced and the arrangement of levels within a factor cannot be changed. The Taguchi method makes an assumption that there is no interaction between two factors, therefore each factor is independent. The uncertainty with Taguchi method is that the selection of each parameter to be optimized is chosen according to the experience or literature review which can be uncertain. The Taguchi process is repeatable by following the Taguchi orthogonal array guidelines. The Taguchi experimental design methodology follows well defined guidelines which are [62]:

- 1) **System design:** Firstly, information on the process/product that must be optimized must be known, followed by the identification of independent factors that are anticipated to have influence on the output response.
- 2) **Parameter design:** The identified independent factors must be assigned to levels. The choice of levels is dependent on the performance characteristics of each independent factor at different level settings. When an independent factor has a linear function performance characteristics or no definite relation, then it is assigned to level 2 setting. However, when an independent factor has quadratic, cubic or higher order relation performance characteristics then it is assigned to 3, 4 or higher levels.
- 3) **Selection of orthogonal array:** The total degrees of freedom (DOF) are used to select the relevant Taguchi orthogonal array for implementation. Consider three independent factors A, B and C each having two levels. The guidelines to the calculation of degrees of freedom work as follows:
 - Each independent factor has a degree of freedom that is one less than the number of levels for that factor. If the number of levels is denoted by n_A , n_B and n_C , then the degrees of freedom for factor A, B and C are $DOF_A = n_A - 1 = 2 - 1 = 1$, $DOF_B = n_B - 1 = 2 - 1 = 1$ and $DOF_C = n_C - 1 = 2 - 1 = 1$. The total degrees of freedom for the three factors are $DOF_{(A,B,C)} = DOF_A + DOF_B + DOF_C = 1 + 1 + 1 = 3$.
 - The overall mean of the output response always has one degree of freedom, $DOF_{(Overall\ mean)} = 1$.
 - The minimum number of experiments in an orthogonal array must be greater or equal to the total DOF. For example, given three independent factors with each having two levels. The total degrees of freedom for this example is $DOF = DOF_{(A,B,C)} + DOF_{(Overall\ mean)} = 3 + 1 = 4$, therefore the Taguchi orthogonal array that must be selected should have at least 4 experiments. Thus, according to Table 16, listing the Taguchi arrays, the L_4 Taguchi orthogonal array with a total of four experiments will be chosen for this example.

Table 16: Table of Taguchi orthogonal arrays based on degrees of freedom (DOF).

Orthogonal Array	Number of Experiments	Maximum Factors	Maximum columns at these levels			
			2 level	3 level	4 level	5 level
L ₄	4	3	3			
L ₈	8	7	7			
L ₉	9	4		4		
L ₁₂	12	11	11			
L ₁₆	16	15	15			
L ₁₆	16	5			5	
L ₁₈	18	8	1	7		
L ₂₅	25	6				6
L ₂₇	27	13		13		
L ₃₂	32	31	31			
L ₃₂	32	10	1		9	
L ₃₆	36	23	11	12		
L ₃₆	36	16	3	13		
L ₅₀	50	12	1			11
L ₅₄	54	26	1	25		
L ₆₄	64	63	63			
L ₆₄	64	21			21	
L ₈₁	81	40		40		

The Taguchi orthogonal array is denoted by $L_a b^c$ [61], L_a represents design matrix or orthogonal array of experiments, b is number of levels of factors and c is the number of factors. The aforementioned example would have $L_4(2^3)$ orthogonal array (see Table 17 below). The number of experiments generated by Taguchi method can be viewed as a subset of experiments of the full factorial design. A full factorial design will require the aforementioned example to conduct a total of $2^k=2^3=8$ experiments, while the Taguchi or fractional factorial design will require only 4 experiments.

Table 17: Example of a $L_4(2^3)$ orthogonal array [63] , with 3 independent factors A, B and C and two levels.

Experiment No	Independent Factors		
	A	B	C
1	1	1	1
2	1	2	2
3	2	1	2
4	2	2	1

- 4) **Assigning independent factors to columns:** Each independent factor must be assigned to the relevant column on the Taguchi orthogonal array with its actual level value. Each combination of independent factors is contemplated as a unique experiment on its own.
- 5) **Performing Taguchi orthogonal array experiment:** All experiments must be executed according to the way the levels are combined on the orthogonal array.
- 6) **Analysis of data:** A measurement obtained from each experiment is a combination of different factor levels. It is essential to separate the effect of an individual independent factor which is executed through the application of a statistical tool called analysis of variance

(ANOVA). Furthermore, optimal set points for each factor are found from graphical presentation factors.

- 7) **Verification experiment:** A confirmation experiment has to be conducted in order to validate the optimal set points generated by the ANOVA.

Analysis of Variance (ANOVA)

The analysis of variance denoted by ANOVA and developed by Sir Ronald Fisher in 1930s is an objective statistically-based tool that reveals the strongest contributing parameters and their significance for the purpose of ultimately establishing optimum parameter set points [63]. The beauty of the ANOVA arises from application of a mathematical technique known as sum of the squares. The sum of squares quantitatively investigates the deviation of each parameter's average from the overall experimental mean. Sum of squares due to variation about the mean for each parameter is calculated which further allows relative percentage contribution of each parameter to be calculated. Furthermore, the variance ratio which is called the F-test, named in honor of Sir Ronald Fisher, is calculated so that the significance of each parameter can be determined. Hence, the ANOVA can be viewed as a procedure that uses variance to quantify the strength and importance of each parameter so that optimal parameter set points can be obtained. The calculations that are taken in ANOVA are as follows:

The overall mean is the reference point from which variance of each parameter will be calculated. The overall mean is:

$$\bar{Y} = \frac{1}{N} \sum_{i=1}^{N_{\text{exp}}} Y_i \dots \dots \dots \text{Equation 3}$$

Where $\bar{Y}$ is the overall mean.
 N is total the number of experiments in the orthogonal array.
 Y_i is measured splice loss for each experiment i.

The objective sum of squares is to quantify the variation that is produced by each parameter around the overall experimental mean hence the name, analysis of variance. The values of the sum of squares elucidate a measure of the relative importance and strength of each parameter in controlling the measured quality of the output response.

Sum of squares due to variation about the overall mean is calculated by

$$SS_p = \sum_k N_{p=k} (\bar{Y}_{p=k} - \bar{Y})^2 \dots \dots \dots \text{Equation 4}$$

Where SS_p is sum of squares resulting from individual parameter.

$\sum_k$ is summation that occurs over parameter combinations in which parameter p was set to level k.
 $N_{p=k}$ is the number of experiments that were performed at parameter combination in which parameters were set to level k.
 $\bar{Y}_{p=k}$ is the average of a parameter combination that was set to level k.
 $\bar{Y}$ is the overall mean of all experiment in the orthogonal array.

Total sum of squares is calculated by

$$SS_{\text{total}} = \sum_p SS_p \dots \dots \dots \text{Equation 5}$$

Where SS_p is sum of square of an individual parameter p.

The relative contribution of an individual parameter on the output response is calculated by taking the ratio of each parameter's sum of squares and total sum of squares below equation 5.

Percentage contribution is calculated by

$$\text{Percentage contribution} = \left(\frac{SS_p}{\text{Total SS}} \right) \times 100 \dots \dots \dots \text{Equation 6}$$

Fisher (F)-Test

F-test is a variance ratio used to test the overall significance of an individual parameter [64]. Two F-values, namely the calculated F-value and the critical value, denoted by F_{critical} are used. F_{critical} value is a function of degrees of freedom in the numerator and denominator of F-test formula (see equation 8). The F-test applies a significant level, null and alternative hypothesis to determine the overall significance of a given parameter. The null hypothesis is denoted by H_0 and expressed by $H_0: \mu_1 = \mu_2 = \mu_3$ is an assumption that all mean of experiments performed at different groups or levels (k) within a parameter are equal. Alternative hypothesis, denoted by H_k and expressed as $H_k: \mu_1 \neq \mu_2 \neq \mu_3$ state that the mean of experiments executed at miscellaneous levels within a parameter are not equal and that there is at least two group's means that are different and statistically significant. The significance level expressed by α , is the probability of rejecting the null hypothesis even when it is true. If $F \geq F_{\text{critical}}$ then the null hypothesis is rejected resulting in the alternative hypothesis to be accepted, furthermore overall parameter is statistically significant. The flaw with F-test is that the groups within a parameter which are statistically significant and different from each other cannot be specified.

The formula of F-test is given by [64]:

$$F = \frac{MST}{MSE} \dots \dots \dots \text{Equation 7}$$

Where MST is mean square of the treatment

MSE is Mean square of the error

$$MST = \frac{SST}{K-1} \dots \dots \dots \text{Equation 8}$$

Where SST is sum of squares of the treatment

K = is the number of groups/level

$$MSE = \frac{SSE}{n-K} \dots \dots \dots \text{Equation 9}$$

Where SSE is sum of the squares of the error

n is the number of observation/experiment within a group

Table 18: Example of F_{critical} values for different significant levels

Denominator degrees of freedom (DOF)	Numerator degrees of freedom (DOF)						
	α	1	2	3	4	5	6
15	.100	3.07	2.70	2.49	2.36	2.27	2.21
	.050	4.54	3.68	3.39	3.06	2.90	2.79
	.025	6.20	4.77	4.15	3.80	3.58	3.41
	.010	8.68	6.36	5.42	4.89	4.56	4.32
	.005	10.80	7.70	6.48	5.80	5.37	5.07

Appendix 2

3SAE Liquid Clamp Cleaver (II) Parameter Settings

Table 19: 3SAE LCC II cleaver parameter settings.

Cleave Parameters					
Tension (N)	Twist (deg)	Clamp Force (N)	Blade Speed	Vibration (Hz)	Pause for anvil (s)
12	0	100	5	5	1