

NPL REPORT OP 1

**The development of a
spectral scanning system
utilising controlled launch
conditions for the
characterisation of polymer
optical fibre (POF)**

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The development of a spectral scanning system utilising controlled launch conditions for the characterisation of polymer optical fibre (POF)

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Quality of Life Division

ABSTRACT

Characterising the spectral attenuation and bandwidth of plastic optical fibre (POF) inevitably requires an understanding of launch conditions and the subsequent effect upon the modal and energy distribution within the fibre. At the National Physical Laboratory (NPL), the development of a spectral scanning system that incorporates a flexible controlled launch system has provided a means to assess the effect of various launch conditions upon the attenuation and bandwidth of POF. In addition, the development process has enabled a deeper understanding of the issues involved.

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Approved on behalf of the Managing Director, NPL
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1 INTRODUCTION

1.1 Overview

Excitation of modes within any multimode (MM) fibre is dependant upon the way light is launched into the fibre. An understanding of launch criterion and the distribution of optical power are therefore essential in evaluating a fibre's spectral attenuation and the effects of intermodal coupling and bandwidth. The development of a spectral scanning system with a controlled launch system specifically intended for polymer optical fibre (POF) builds upon the work already established at NPL¹ and developed to provide controlled launch criteria for 62.5 and 50 µm core MM glass fibre. As well as requiring a wavelength range of approximately 500 nm to 900 nm, the significant increase in core size and numerical aperture (NA)² of POF presents new problems for the optical arrangement if larger spot sizes and launch NA 's are to be generated. In addition, the significantly larger attenuation levels associated with POF add to the problems of system design. As with silica-based fibre, attenuation in POF is both intrinsic and extrinsic. Intrinsic losses include electronic transitions at U-V wavelengths and molecular vibrations at I-R wavelengths in addition to Rayleigh scattering. In particular, are the losses associated with C-H molecules found in POF. Extrinsic losses are associated with absorption through impurities, dopants and variations in core geometry as well as imperfections at the core/cladding interface. Importantly, these material effects contribute to modal power re-distribution and mode coupling associated with POF. The launch of power into lower order modes can be transferred to higher order modes affecting both attenuation and bandwidth. These significant effects can occur over much shorter lengths than silica fibres (~20 m). Additionally, over longer fibre lengths effects such as mode conversion³, differential mode attenuation and mode mixing are also possible. Clearly, understanding the nature of the launch power (and modal) distribution is a powerful tool in assessing POF. In addition to the challenges of the system design, work has involved subsequent characterisation of spot size and NA along with a consideration of the quality of the fibre end face and the necessary overall system validation, traceable to national standards. This report discusses these issues with respect to the measurement of spectral attenuation using the established 'cutback' technique and bandwidth measurements made within the frequency and time domain.

1.2 General system arrangement

The system is based upon the established and commonly used cutback technique test method for measuring spectral attenuation⁴. The ratio of the power launched into the fibre to the power output provides the attenuation value. The use of a repeat measurement (without disturbing the launch conditions) through a short 'cut-back' length of fibre provides a practical solution in determining the reference launch power (P_i). Attenuation $A(\lambda)$, is defined as:

$$A(\lambda) = 10 \log [P_i(\lambda) / P_o(\lambda)] \text{ dB} \quad (1)$$

Where P_i is the power launched into the fibre and P_o is the output power of the fibre.

The system consists of a tungsten halogen lamp, a stepper controlled monochromator and bulk optics to image a pinhole aperture and provide control over the NA and spot

size. Figure 1 shows a schematic system for measuring fibre attenuation using the cutback technique. The optical arrangement that constitutes the launch module is positioned between a modulated reference signal arm and the front face of the fibre under test (FUT). The launch module comprises of two opposing infinity corrected objectives that image an interchangeable pinhole onto the fibre end face. The NA can be controlled with an iris aperture or simply dictated by the appropriate choice of objectives. Controlled micrometer stages allow precision alignment of the fibre end faces and a fibre guide plate facilitates controlled bend radii and/or mode scramblers to be applied to the FUT. In addition, the system makes use of a beamsplitter to allow direct viewing and measurement of the imaged spot on the end face of the fibre or indirectly using a suitable video camera and telephoto lens. Figure 2 shows the alternative launch module arrangements schematically.

Figure 1 Schematic showing established system used to measure the fibre attenuation using the cutback technique

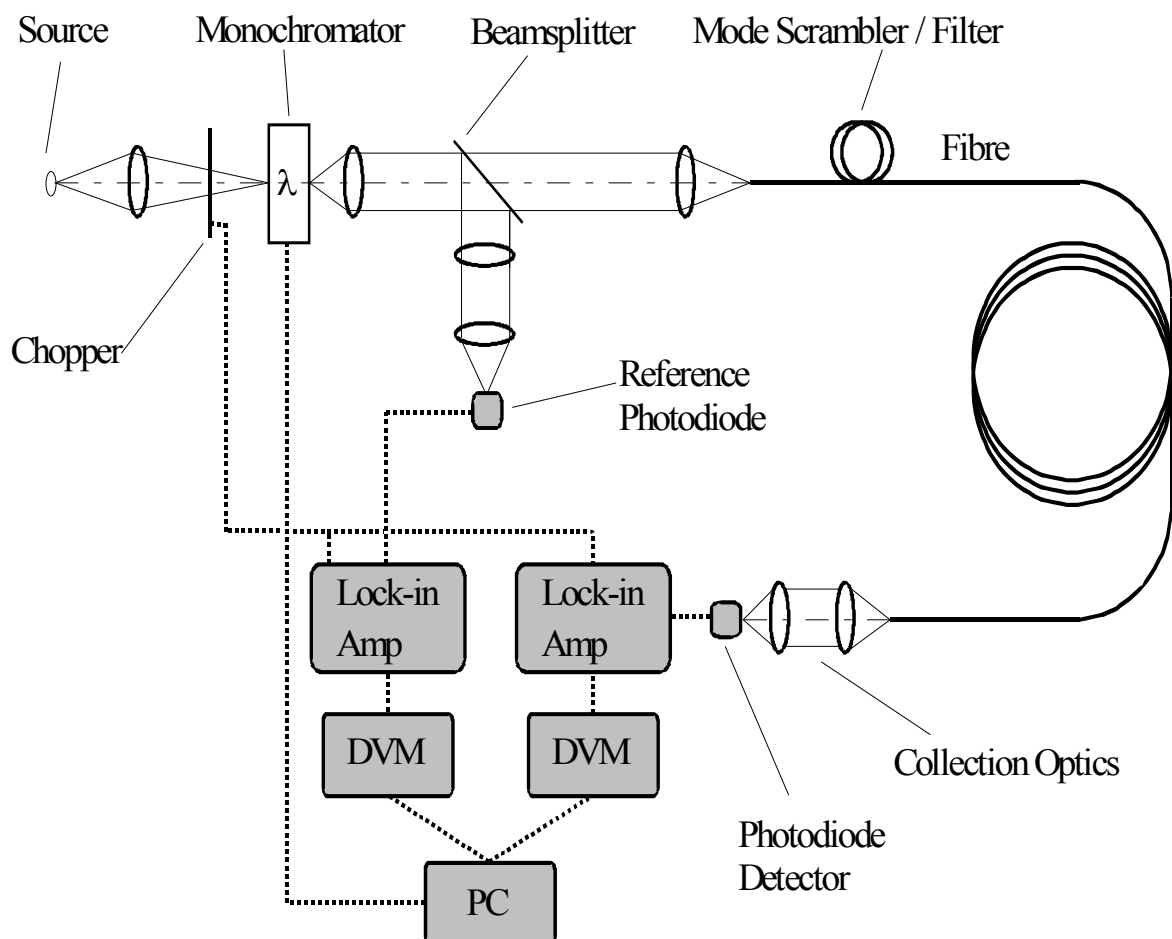
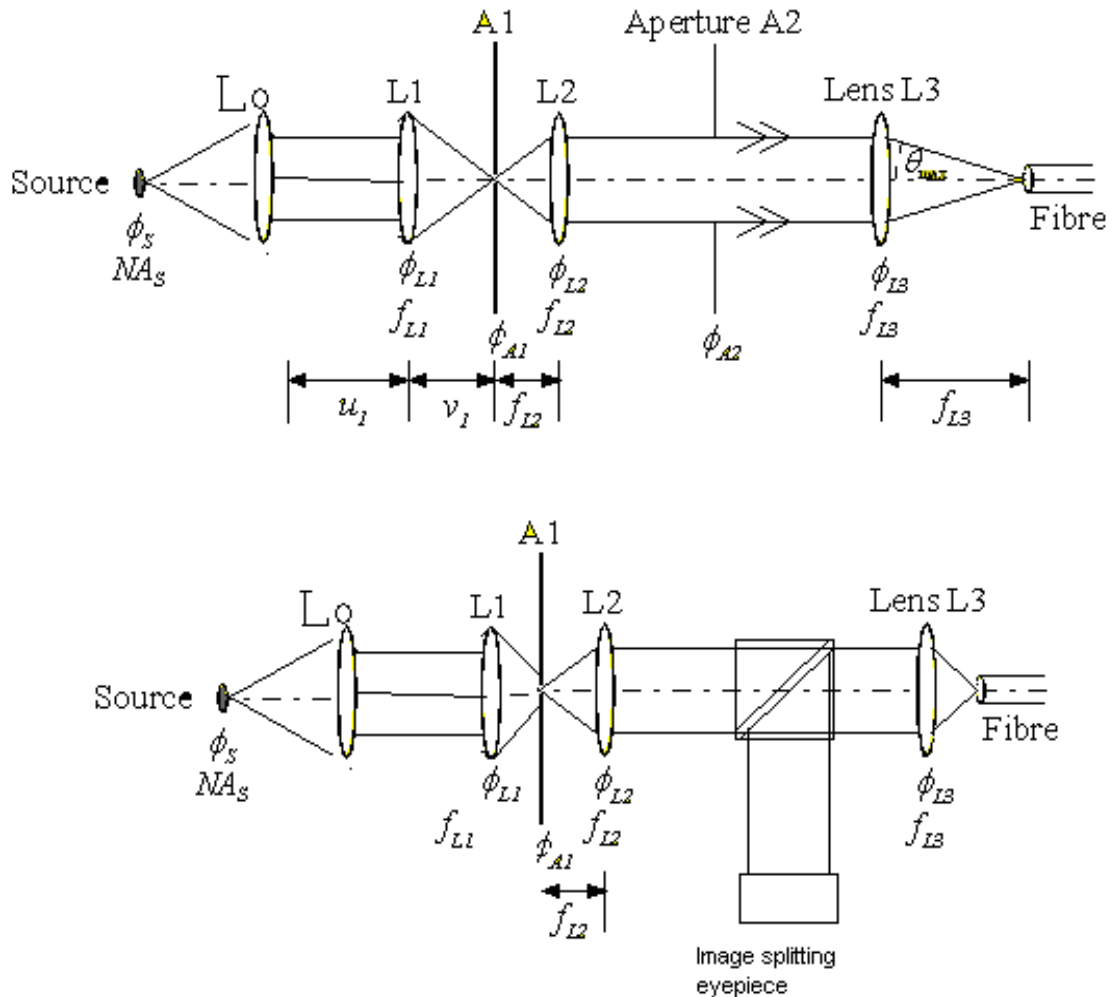
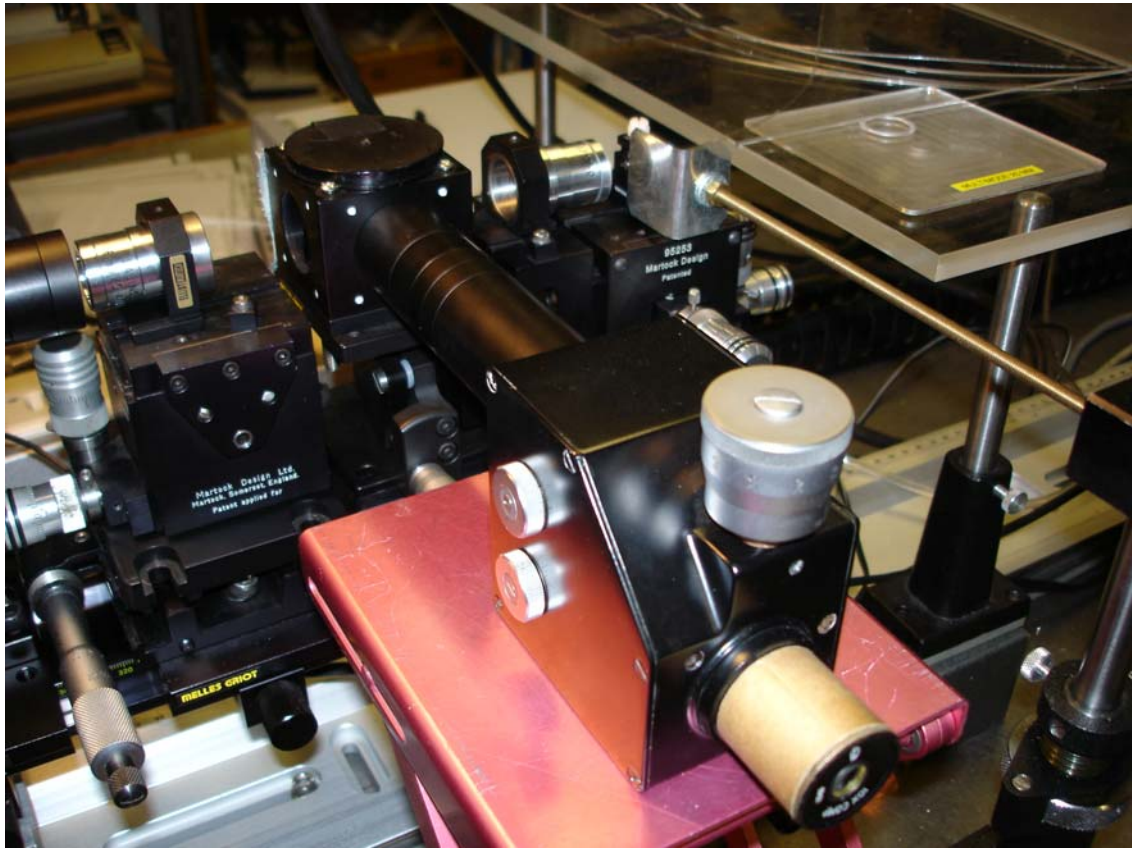


Figure 2 Schematic optical arrangements of launch module with pinhole position at A1 for spot size selection. An iris aperture A2 provides NA control at low NA . High NA requires selection of appropriate lenses L2 and L3. The use of a beamsplitter between L2 and L3 facilitates the viewing and measurement of the end face of the FUT.



The use of different pinhole apertures and lenses provides a reasonable degree of flexibility in achieving a range of NA and spot sizes. Various configurations were attempted in order to achieve a range of effective combinations. It is important to note that any changes to the launch module requires careful realignment of the system in order to ensure that the imaged spot is axially aligned to the end face of the fibre. Figure 3 shows the launch module with an image shearing optical head used for measuring spot size.

Figure 3 Photograph showing the launch module incorporating a beamsplitter viewing arrangement with image shearing optical head for measuring spot size.



2 LAUNCH DESIGN

The design of the launch module dictated that a high degree of flexibility was required in order to take the necessary combinations of objectives and pinholes as well as allowing complete removal for use in bandwidth measurements where a similar controlled launch is required. The system was constructed using commercially available Melles Griot and Martock equipment. The launch module can be adapted to take an adjustable diaphragm in order to control the NA or can be set up to take two opposing infinity-corrected objectives (where the NA is determined or limited by the design specification of the objective $L3$). Various approaches were used in order to achieve the high spot sizes and NA required. The use of infinity corrected objectives arranged to give a near 1:1 imaging system was achievable up to an NA limit of $\sim 0.4 NA$. The inclusion of the adjustable diaphragm is used to provide fine control of the launch NA providing flexibility throughout the given NA range. A range of commercial pinholes or apertures is used in order to provide the maximum possible range of spot size. The relationship between pinhole size and that of the imaged spot is given by the thin lens approximation:

$$d_2 = d_1 \left(\frac{f_2}{f_1} \right) \quad (2)$$

Where d_1 and d_2 are the diameters of the pinhole and image size respectively and f_1 and f_2 are the focal lengths of the imaging lenses. The arrangement allowed for the insertion of matched or unmatched infinity-corrected lenses in order to achieve specific spot sizes. Achieving both, a high spot size and large NA , proved difficult in practice due to limitations of the opto-mechanical arrangement and any chosen pairs involved a compromise position. In practice, high spot sizes ($\sim 1000 \mu\text{m}$) were found to be easier to achieve than a large NA .

3 CONSIDERATIONS REGARDING SPOT SIZE

In order to achieve the large spot diameters necessary to overfill the cores of typical graded index or step index POF, larger pinholes were necessary. However, for pinholes with diameters $> 500 \mu\text{m}$, edge definition of the illuminated spot image becomes degraded as the optical system ceases to image from a simple point source. The entry illumination underfilled pinholes with diameters $< 500 \mu\text{m}$ and it was necessary to increase the NA of the transmitted beam by introducing a scattering element at the pinhole aperture. This enabled the opposing objectives ($L2$ and $L3$) to be better illuminated over their design NA and thus generate a cone to overfill the FUT. This scattering element constituted a diffusing ‘Kodatrace’ screen placed over the pinhole. The optical system forms a real image of this screen enabling the rim of the pinhole aperture to be more clearly imaged and adjusted to be coincident with the face of the FUT.

3.1 Spot size measurement

Measuring the diameter of the imaged spot on the end face of the fibre was achieved by inserting a commercial image-shearing microscope head into the camera or viewing position (see Figure 1). By using the shearing head’s micrometer control, the outer diameter of the FUT can be used to provide a reference value in μm per division. This provides a scaling factor from which the imaged spot can be subsequently measured. This method provided an uncertainty of measurement of approximately $< \pm 5 \%$. Limitations of the method relate to the low image contrast and the need for careful alignment and observations as well as errors associated with the geometry of the end face of the FUT. The use of better viewing optics would certainly improve the image quality. Figure 4 shows a range of typical images of the end face of a FUT with coincident illuminated spots.

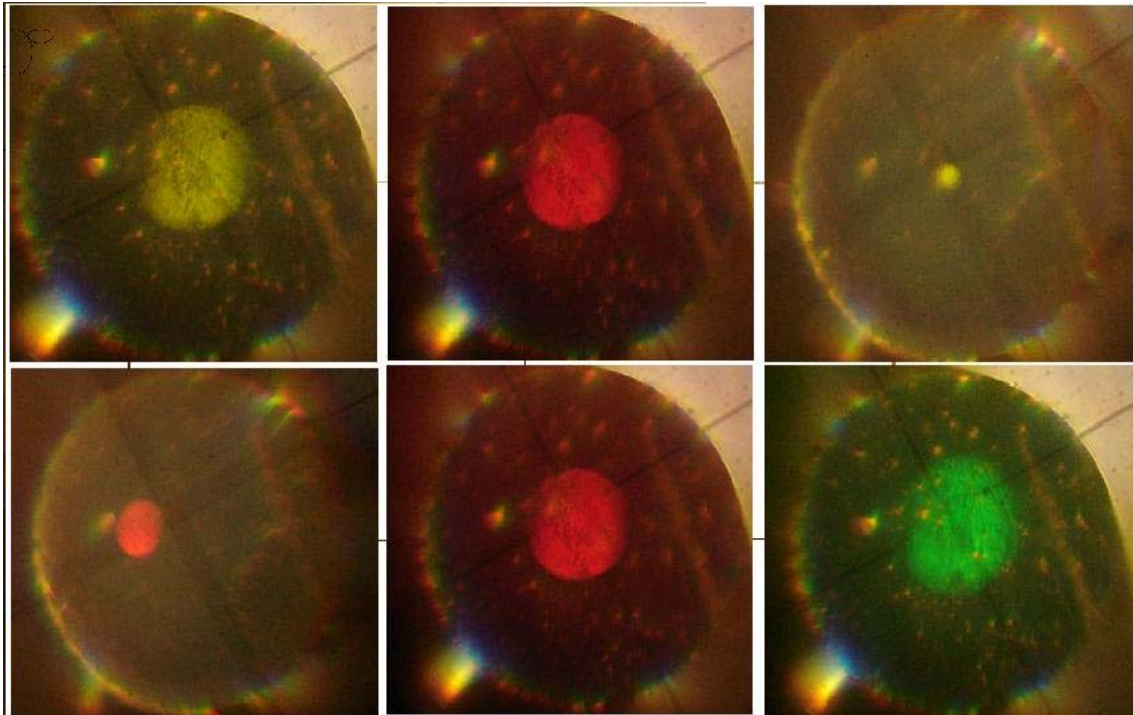
3.2 Spot size issues

It is important to note that no account is taken of any effects due to beam energy distribution of the imaged spot that may arise as a result of the wavelength distribution from the monochromator grating. This could well affect the modal power distribution within the FUT. The range of wavelengths emerging from the nominal slit size of 0.5 mm ($\sim 5 \text{ nm}$ bandwidth) could be diffused or a compensating double monochromator could be used. However, this would again result in significant signal

loss for a system that utilises a largely inefficient halogen lamp as its source. Further investigation is necessary in order to better understand these effects.

In addition, as spot size increased, the effects of the exit slit width on the monochromator affected the general illumination of the spot. Slightly lower illumination intensities can be seen along the edges of the spot in Figure 4. By defocusing and increasing the NA of the pinhole illumination lens L1 this could be improved.

Figure 4 A series of photographs showing various spots illuminating the end face of a section of OM-GIGA⁵ POF.



4 CONSIDERATIONS REGARDING NA

Launch NA values that approached the fibre's acceptance angle were sought. POF NA varies from 0.2 – 0.5 NA . Table 1 shows typical POF optical values including NA ⁶. The high NA values of POF give a significant advantage when considering low cost connection technologies. Information on modal or attenuation characterisation at these limits would therefore be advantageous. In practice, achieving high NA at the launch required various modifications to the opto-mechanical arrangement but is constrained by the monochromator exit slit NA and the pinhole illumination NA from lens L1 (even with the use of the scattering screen at the pinhole). The development work showed that although a large spot size of up to 900 - 1000 μm could be achieved with relative ease through the use of a near 1:1 imaging system, the NA was limited to $\sim 0.3 NA$. This applied even when objectives were used whose design NA was higher. A higher NA was possible but this noticeably affected the spot image definition and thus made quantifying the spot size difficult. Conversely, larger pinholes tended to produce lower NA values due to image formation ceasing to originate from a point source causing significant beam divergence.

Table 1 Typical POF optical properties.

Type	NA	Attenuation @ 650 nm (dB/km)	Core Diameter (μm)	Bandwidth (MHz) for 100 m	Remarks
SI-POF	0.47	120-160	50	50	Original type known as standard POF, low cost
SI-low NA	0.30	120-160	100	100	Requires low NA LED
DSI-POF	0.30	120-160	100	100	Lower bend losses than low NA
MC-POF	0.20	120-160	250	250	37-core, moderate cost 217-core
	0.50		60	60	
GI-POF	0.20	120-160	1000	1000	PMMA core base, various dopants, concerns about GI profile stability, more expensive than any non GI-POF
PF GI-POF	0.2	Extends to 1300 nm <50 dB	125-300	7500	PF polymer core 'CYTOP'. Probably most expensive of all POF
MSI-POF	0.30	120-160	700	250	May be 4-7 layers, possibly less expensive than GI-POF? More stable?

4.1 Measurement of NA

NA was measured by using a knife-edge controlled by appropriate X-Y translation stages arranged to cut the launched beam. The onset of signal loss at the detector determined the geometrical position of the launch beam. From these measured positions the NA was determined using the standard equation:

$$NA = \sin\left(\arctan\left(\frac{d_{BEAM}}{2f_2}\right)\right) \quad (3)$$

where f_2 is the focal length of the lens $L3$ and d is the effective beam diameter between $L2$ and $L3$. Measurements revealed a level of uncertainty of ± 0.015 NA for a single measurement. For a repeated sample a value of ± 0.005 NA could be achieved using this method.

4.2 Limitations of NA

The limitations associated with the NA of the launch were found to be due to several factors. These included beam divergence between the opposing objectives $L2$ and $L3$, the limiting apertures of the objectives themselves and the limitations imposed through the NA of the monochromator and lens $L1$. The rectangular aspect ratio of the exit slit of the monochromator necessarily dictates two different NA values, which influence the

NA received at the end face of the fibre. The difference was found to be as large as $\sim 0.1 NA$. This was overcome by the use of a circular aperture of diameter $500 \mu m$ that matched that of the width of the monochromator exit slit. However, this significantly reduced the net power able to be launched into the fibre. With the attenuation of POF anywhere between ~ 10 - 100 dB/km, system signal loss needs to be minimised and opportunities to maintain power in the beam constantly sought⁷.

5 FIBRE END FACE PREPARATIONS

5.1 Justification

Preparation and polishing the end faces of POF was found to be an important prerequisite of any measurement run leading to significant improvements in reproducibility. Investigations showed that signal losses associated with poorly prepared fibre were significantly higher than those that had undergone smoothing and polishing processes. Figure 5 shows repeatability measurements using attenuation scans for OM-GIGA POF whose end faces had been simply cleaved with a commercially available tool (this tended to crush and tear the material rather than cut cleanly). Figure 6 shows measurements in which the end faces had undergone smoothing and polishing stages. For each measurement run both fibre end faces were initially polished with the fibre face at the detector end being prepared a second time in order to measure the cutback length of fibre.

Figure 5 Attenuation scans of cleaved POF end faces.

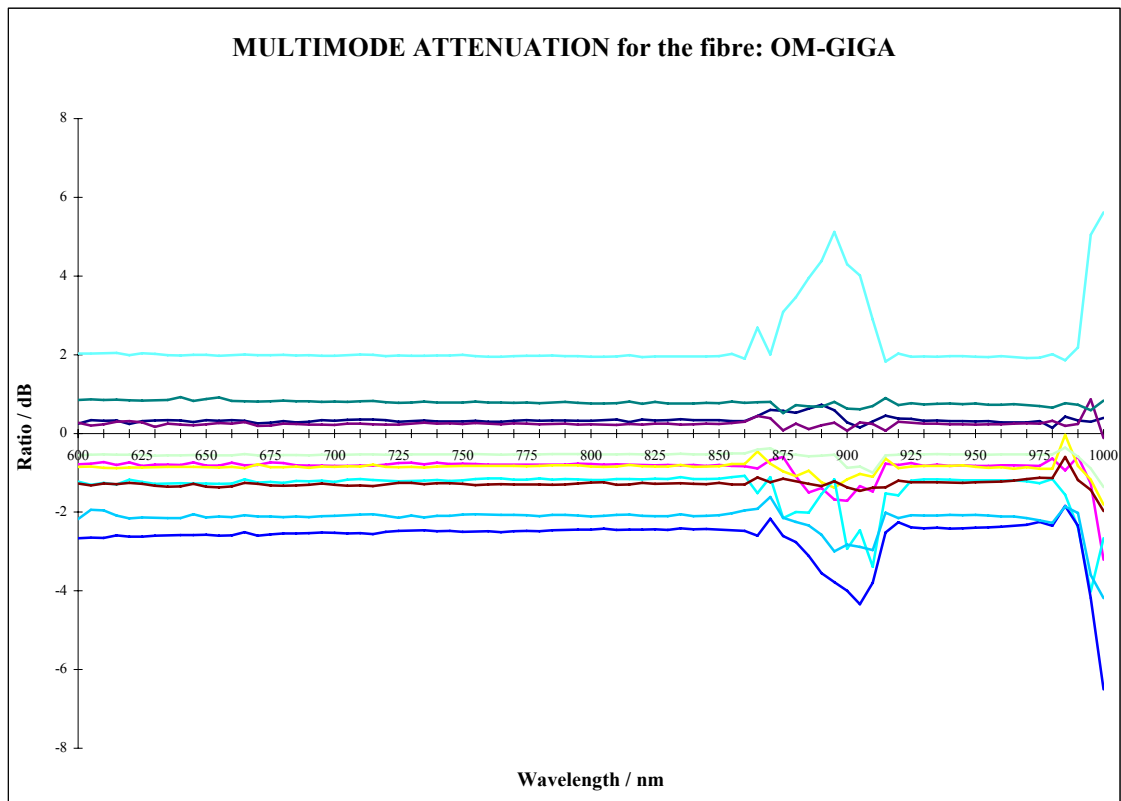
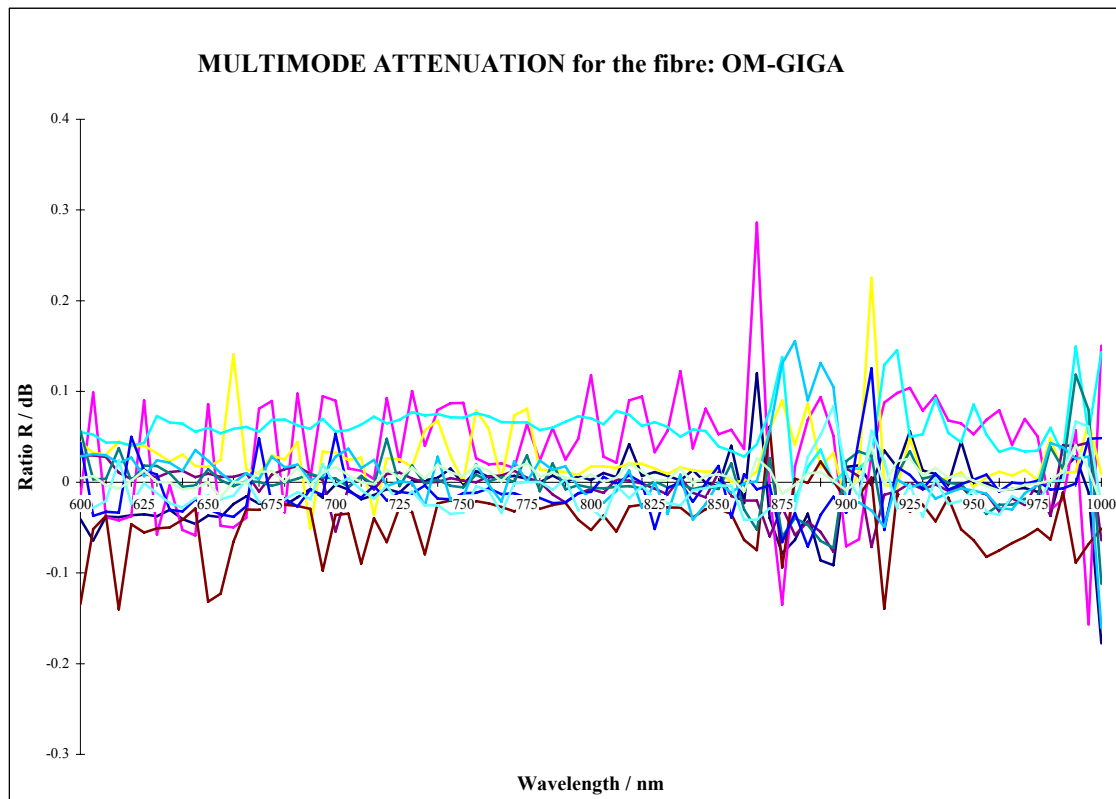


Figure 6 Attenuation scans of polished POF end faces.



Improvements are shown to be of the order of a factor of ten. The need to conserve power within the system, coupled with the high attenuation of POF, requires that end preparation forms an integral part of the measurement process.

5.2 Polishing Equipment

Initial investigations utilised commercially available fibre holding pucks and abrasive papers of varying grades. These proved unsatisfactory as the reliance on a manual technique revealed a difficulty in achieving a repeatable quality of finish and consistently low 'cleave' angles. Cutting the POF with heated blades was also attempted. Although producing a highly polished surface, the heat seriously distorts the refractive index profile of the fibre with adverse consequences for any assessment of launch criteria. The use of a commercially available machine tool proved the best approach with consistent surface finishes and 'cleave' angles. Modifications were made to a Beuhler 'Fibremet' optical fibre polishing machine tool in order to accept the large diameters associated with POF.

5.3 Methodology

Traditional optical glass working skills and established methods of polishing glass fibres informed the polishing of POF. The processes of plastic polishing combines localised heating and melting (without significantly disrupting the refractive index profile) with the cutting action of abrasive grains embedded within a suitable matrix. A two stage process was used that smoothed and then polished the mounted end face using pads embedded with 3 μm and 0.3 μm diamond abrasive. Building upon the work carried out at the University of Applied Science (Nuremburg) by Stäber, Poisel and

Ziemann⁸ a methodology was developed that established a compromise between surface quality, ‘cleave’ angle and polishing time. The last of these is of considerable importance given the need for end preparation during attenuation measurements using the cutback technique. Figure 7 shows a craftsman preparing and mounting a section of POF prior to polishing on the machine tool.

Figure 7 Machine tooling used for polishing POF



5.4 Inspection of end faces

The quality of the end faces was assessed by manual inspection during the polishing process using a suitable eyeglass. Final inspection was provided by a Norland microinterferometer, together with a suitable objective. The instrument provides a view of any surface damage such as cuts and scratches and provides information on surface flatness and wedge angle through the interferometric fringe pattern. Figure 8 shows the interferogram of an end face of POF that has undergone a polishing process. Typical flatnesses obtainable were of the order of few fringes (up to $\sim 0.5 \mu\text{m}$ peak to valley over a central $\sim 90\%$ aperture) and wedge angles of up to $\sim 0.5^\circ$. In practice, it proved unnecessary to measure the wedge angle after each polishing stage and this would be used as an occasional quality check. The working of end faces was kept to a minimum in order to reduce the turnaround times for any series of measurement runs.

Figure 8 Photograph showing polishing machine tooling and interferogram of end face of a sample of POF using a 'Norland Microinterferometer'.



6 SYSTEM VERIFICATION

6.1 Overview

An assessment of the system's performance required a series of test measurements that were traceable to national standards. Several key areas of the measurement system were identified and their uncertainty contributions determined and combined within an appropriate uncertainty budget. Further refinement of the uncertainty contributions would be necessary in the future.

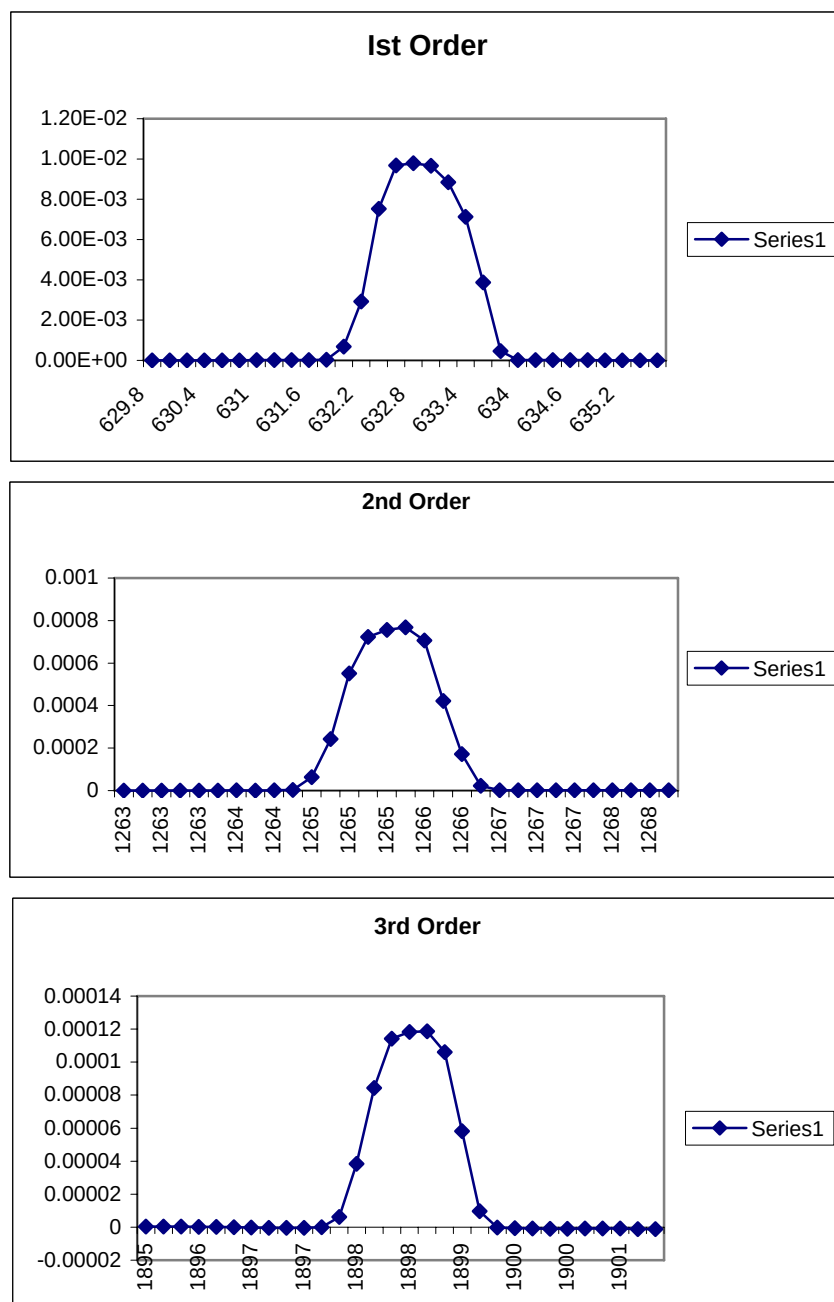
6.2 Type A contribution – Repeatability

A repeatability component provided an uncertainty of measurement due to such things as fibre end face positioning and alignment with respect to the mounts and end face variation in terms of quality of finish and angle. Ten runs were carried out using a ~2 m length of OM-GIGA POF over the wavelength range 600-1000 nm. Each measurement involved removing, re-polishing and re-optimising the fibre thus simulating an attenuation measurement using the cutback technique. Spot size was optimised at 1 mm using two opposing 0.4 *NA* objectives. The standard deviation of the mean (SDOM) of these measurements was found to be 0.014 dB, which was rounded to 0.02 dB.

6.3 Type B contribution – Monochromator grating

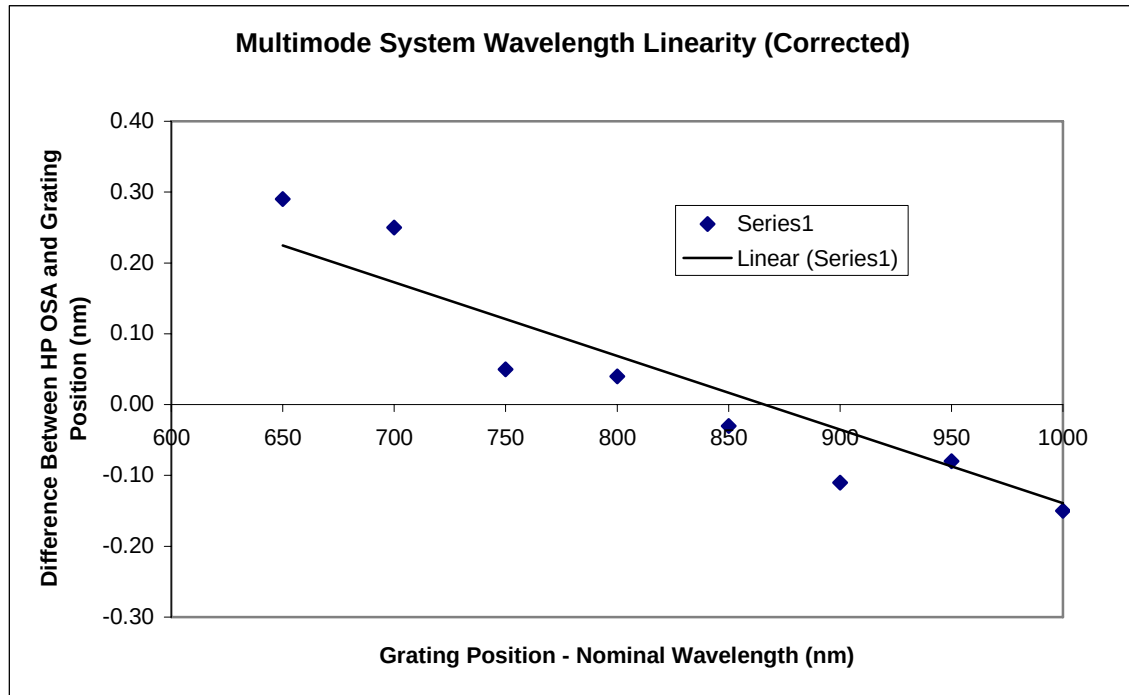
The uncertainty contribution due to the monochromator was assessed using a combination of HeNe spot wavelength measurements (corresponding to the first, second and third order lines) and a wavelength linearity measurement using an optical spectrum analyser. A frequency stabilised HeNe laser was connected to a faceplate attached to the entrance slit of the monochromator. A program scanned a wavelength range around the three orders. The maximum offset from the orders combined with setting errors of the faceplate provided this part of the wavelength linearity contribution and was found to ± 0.5 nm.

Figure 9 Plots showing monochromator spot wavelengths at 1st, 2nd and 3rd order positions using a frequency stabilised HeNe laser.



An optical spectrum analyser (OSA) was calibrated using known spectral atomic lines⁹ obtained from a gas discharge HeNe laser. Once calibrated, the grating position was set to appropriate intervals and the output launched into a 50/125 μm patchcord connected to the OSA. Results showed a variation of ± 0.4 nm over the wavelength range 600 – 1100 nm.

Figure 10 Plot showing wavelength linearity of monochromator grating with respect to calibrated optical spectrum analyser

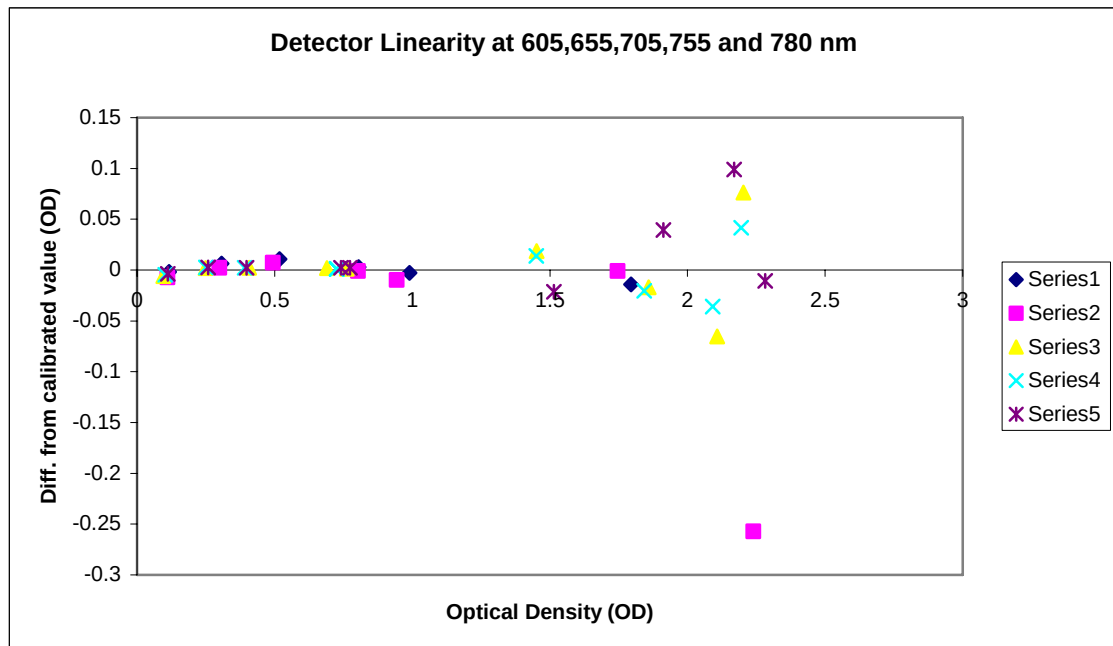


The two uncertainty contributions of spot wavelengths and wavelength linearity are combined in quadrature and rounded up to give ± 0.7 nm. This is subsequently applied to the slope of the attenuation spectrum to obtain the corresponding uncertainty in the attenuation for each measurement point. The slope in this case corresponded to a typical OM-GIGA POF over the wavelength windows of 600-700 nm and 750-800 nm. The smallest variation of attenuation with wavelength for these windows is less than 0.07 dB/nm.

6.4 Type B contribution – Detector linearity

Determining the performance of the detector linearity proved difficult due to the wide signal ranges required and the lack of available traceable reference standards needed to cover the lower wavelength range associated with POF. A method was adopted that utilised calibrated neutral density (ND) filters placed in and out of the beam with the signal attenuation levels compared. The calibration range of the ND filters was ~ 600 – 800 nm and covered densities ranging from $\sim 10\%$ to $\sim 80\%$. These were also used in combination in order to get as close to the dynamic range associated with measuring POF as possible. Adjusting the sensitivities of the lock in amplifiers increased the measurable dynamic range and the effects of the sensitivity changes were included in the uncertainty contribution.

Figure 11 Plotted data showing linearity of detector by comparison with calibrated ND filters at various wavelengths.



The results showed a range of uncertainty contributions depending upon the dynamic range in operation. The uncertainty associated with the detector linearity and the effects of changing the lock in amplifier's sensitivity settings were combined in quadrature and gave values of:

Dynamic Range (dB)	Uncertainty of measurement (+/- dB)
0-10	0.25
10-20	0.44
20-30	1.66

These are considered preliminary values and are subject to improving the methodology associated with measuring the detector linearity, particularly with respect to the wavelength and dynamic ranges. This aspect of system verification also highlighted the need to incorporate gain switching within the control program.

6.5 Other systematic contributions

6.5.1 Voltmeters

The Keithley 2000 voltmeters provide an uncertainty contribution of 0.004 dB

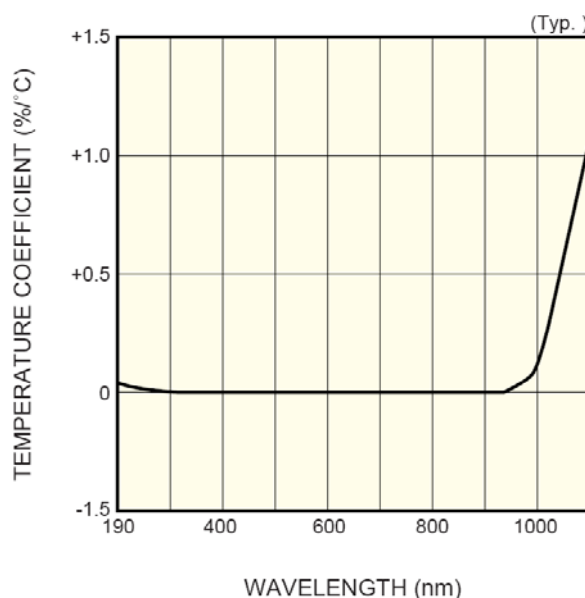
6.5.2 Temperature effects - detection system

A potential source of uncertainty of the detection system with respect to temperature

effects concerns the spectral responsivity of the silicon detectors. Information provided by the manufacturers of the silicon detectors (Hamamatsu Si Photodiode S1337 series)¹⁰ shows that the photosensitivity of the detector changes with temperature coefficient beyond around 950 nm (See Figure 12). As the upper spectral scan limit of the multimode variable launch system is 1000 nm it can be seen that the maximum temperature coefficient is $\sim 0.1\text{ }^{\circ}\text{C}$. The maximum temperature range for the laboratory is $\pm 2\text{ }^{\circ}\text{C}$, therefore, an uncertainty contribution of $\sim \pm 0.2\%$ can be expected between 950 – 1000 nm. For a total attenuation or dynamic range of $\sim 25\text{ dB}$ (for a length of $> 70\text{ m}$) this amounts to a worst-case error of $\pm 0.1\text{ dB}$.

Figure 12

■ Photo sensitivity temperature characteristic



The temperature coefficients of the amplifiers, digital voltmeters (DVM's), monochromator wavelength calibration are considered negligible for this temperature range and therefore do not contribute to the uncertainty budget.

6.5.3 Temperature effects - attenuation of POF

The high coefficient of expansion of POF and fundamental material difference from silica fibre is a possible cause of uncertainty in attenuation. However, as the laboratory temperature range is expected to be within $\pm 2\text{ }^{\circ}\text{C}$ any increase in attenuation due to temperature change is likely to be small. It has been shown that the effects of temperature upon attenuation occur at much higher temperatures than are likely to be encountered within the laboratory¹¹.

6.5.4 Attenuation coefficient as a function of length

Shorter lengths of fibre where the launch conditions do not produce equilibrium mode distribution (EMD) within the fibre are liable to suffer from length dependent attenuation coefficient values. In practice, experimentation with different launch conditions will necessarily involve different degrees of mode distribution over the initial length of the fibre producing a wide range of values. Investigations of these

effects are described here. Initial measurements of the attenuation coefficient as a function of length were made on OM-GIGA fibre. The source used was a Firecomms VCSEL¹² at 665 nm (at 5 mA) with a FWHM of 1 nm. The output was modulated through the use of a chopped signal and lock-in amplifiers. The transmitted power was recorded at 1 m intervals, being successively reduced from an initial 24 m roll of fibre. The launch was fixed with insulating tape for the whole run. The reading from the final 2 m length of fibre was taken as the reference measurement for all the other measurements (representing the cut-back run). It was discovered that the best way to avoid severe kinks in the fibre is to wind off the main reel, directly onto a second reel. The launch was optimised using the Arden Photonic's MPX-1 Modal Explorer¹³. The fibre was cleaved using a razor blade, but not polished. No mode scrambler was used. The calculated attenuation coefficient took into consideration the cut back length and is shown in Figure 13.

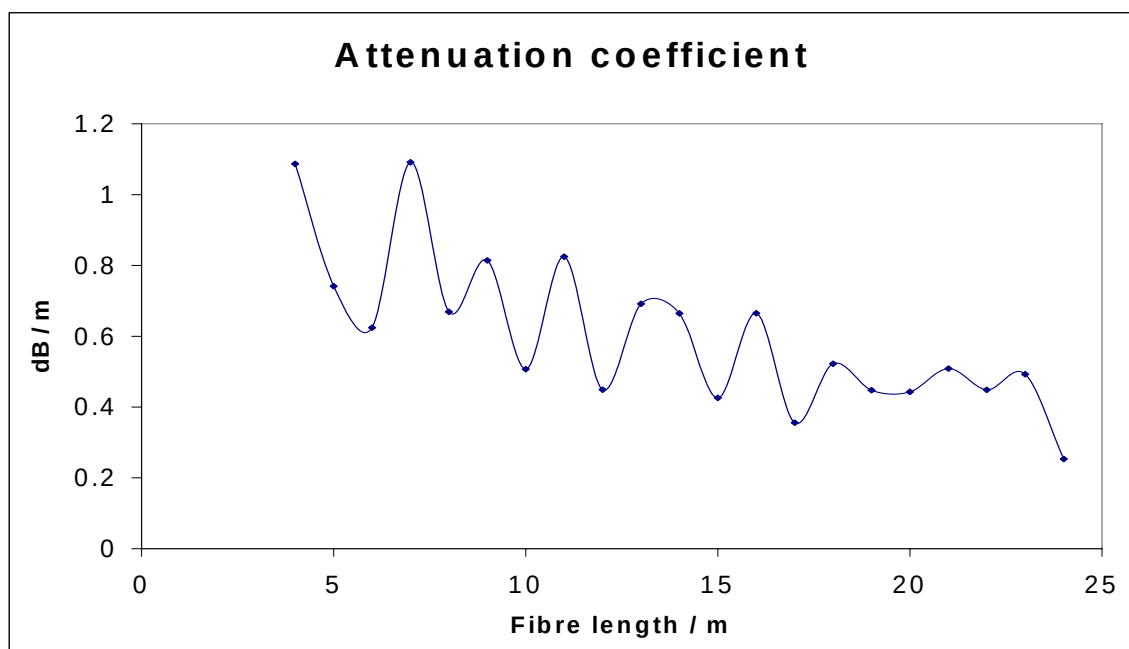


Figure 13 The calculated attenuation coefficient as a function of fibre length. There is a clear trend for the attenuation coefficient to decrease with increasing fibre length. This indicates that higher order modes are linearly filtered out at short fibre lengths.

There are several possible explanations as to why the fall is not smooth:

- 1) Cleave quality was uncertain.
- 2) Alignment not optimised.
- 3) Bend losses due to kinks in the fibre resulting from poor winding.
- 4) Stability of VCSEL power output not monitored due to lack of reference channel.
- 5) Interference losses due to phase matching introduced by bends in the fibre.

This experiment highlighted the need to ensure polished end faces with repeatable quality. Noise on the signal could possibly be due to non-linearity of the VCSEL signal output, particularly since there was no reference signal for the lock in amplifiers. A more thorough investigation of the attenuation coefficient as a function of fibre length

was carried out using the multimode variable launch system with the monochromator to provide a suitable wavelength range. This was performed for a low and a high NA launch. To maximise the light incident on the fibre the NA was selected by the microscope objective used, rather than a limiting aperture. The fibre was reeled into lengths of 15, 30, 50, 70 and 100m. The spot size was larger than the core. The results for a low NA launch are presented in Figure 14. The behaviour at three wavelengths is highlighted in Figure 15. The results for a high NA launch are presented in Figure 16 and all of the results are shown for comparison in Figure 17.

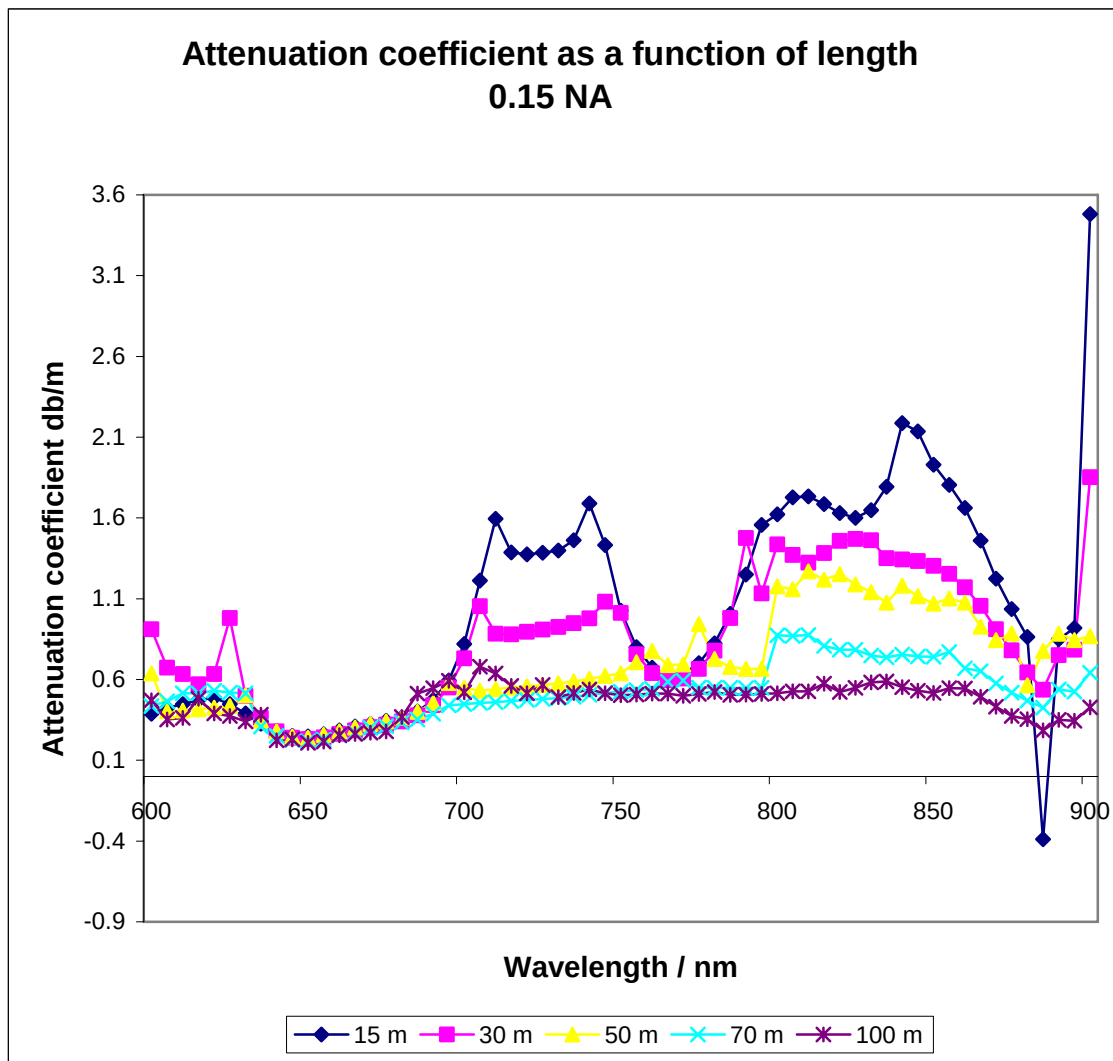


Figure 14 The calculated attenuation coefficient for a launch from a 0.15 NA microscope objective. The coefficient is practically independent of fibre length around the design wavelength of 650 nm. Over the rest of the spectral range the coefficient is seen to change dramatically with length, until the fibre reaches about 50m, after which there is little change. This is most likely due to a combination of reaching the limit of the dynamic range of the system and also having a little stray light propagating through the system.

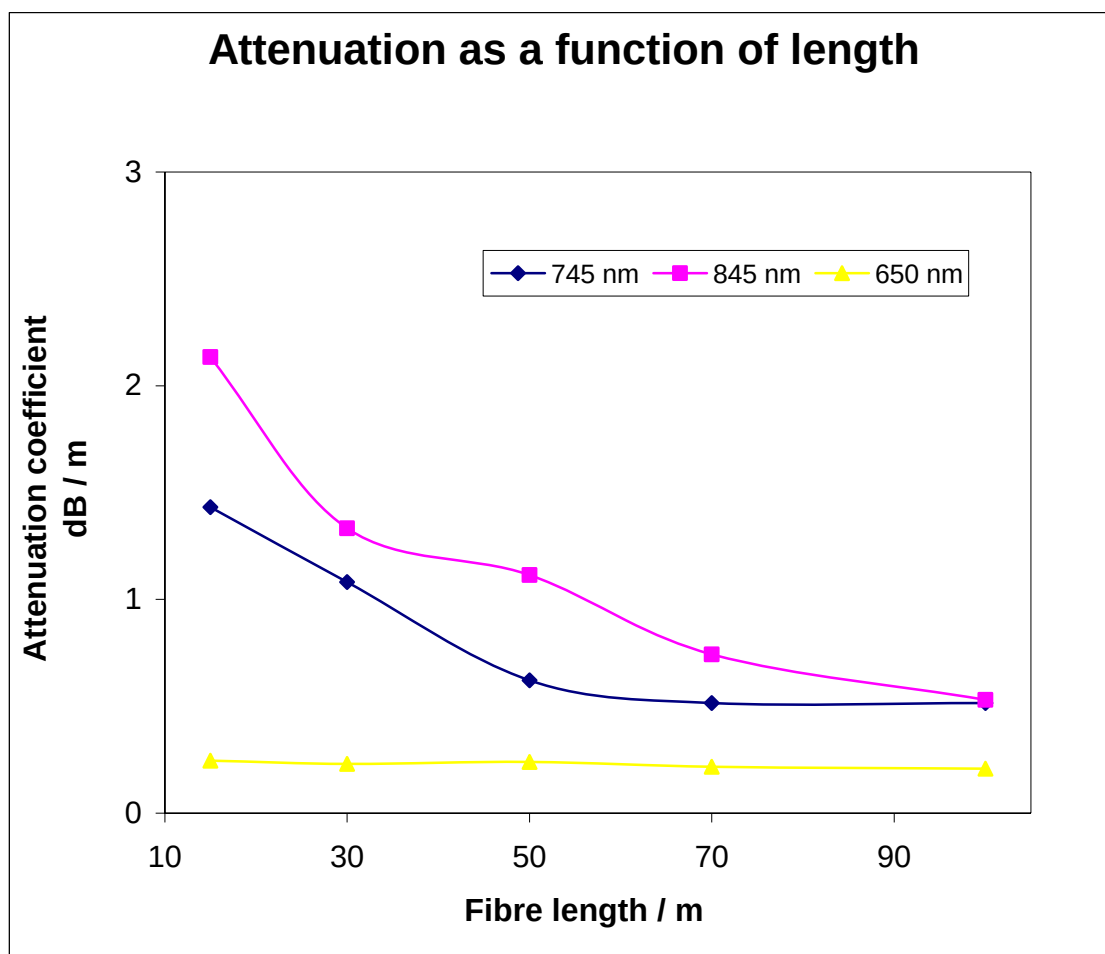


Figure 15 At 650 nm the attenuation coefficient appears independent of length. At the other wavelengths the attenuation coefficient decreases with length, approaching a constant value for longer fibre lengths. This general trend may suggest length dependent mode filtering which is roughly inversely proportional to the length of the fibre, away from the design wavelength range. However, it is more likely that it is dependant upon the relatively low dynamic range of the system.

The reduced signal to noise at longer fibre lengths combined with the fact that the coefficient is averaged for a longer length of fibre may explain why the attenuation coefficient is flattening out to a constant value across all wavelengths. These measurements were carried out prior to the modification to the program that enabled gain switching of the lock-in amplifiers and limited end face preparation. Gain settings can be independently optimised for the long and short fibre lengths, in order to measure the exact profile at long fibre lengths. Further measurements are required in order to determine the exact length where the EMD attenuation spectrum can be identified.

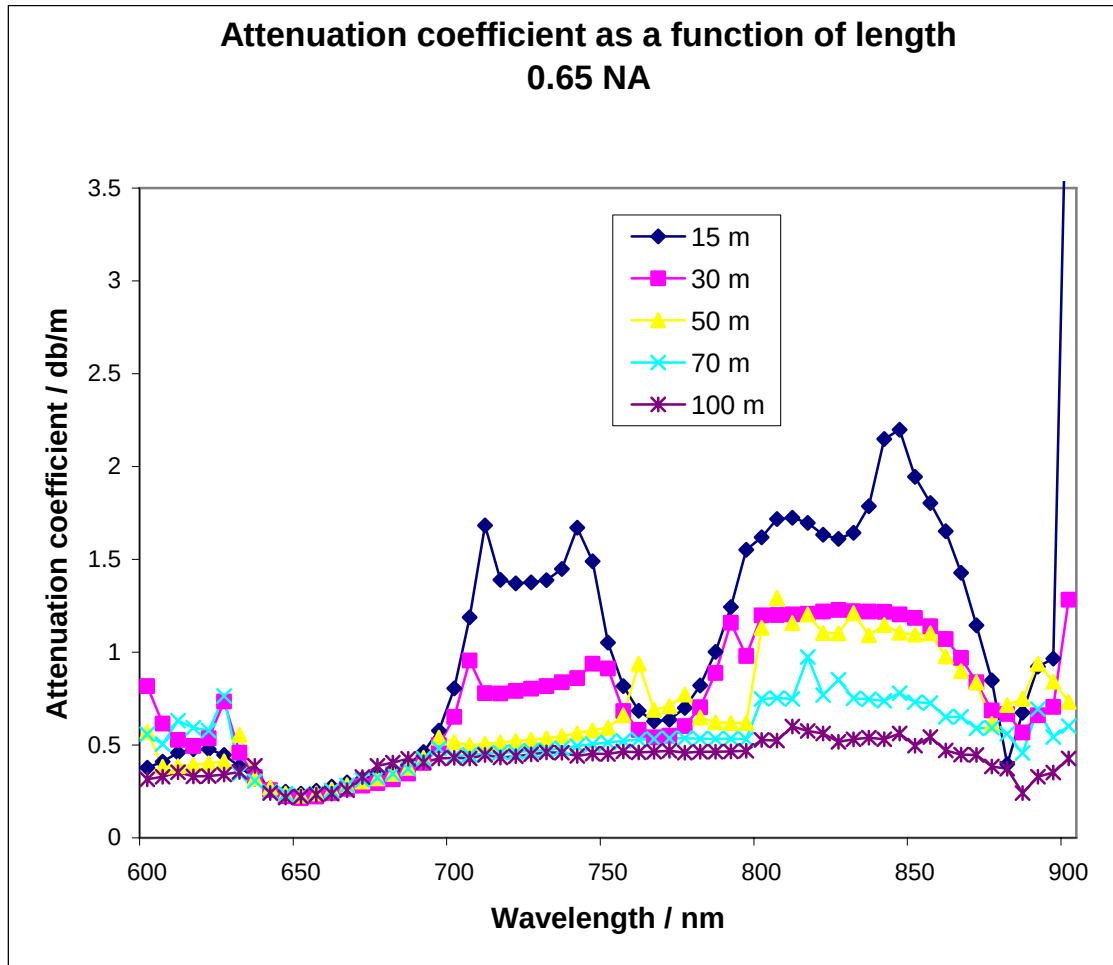


Figure 16 The attenuation coefficient for a launch from a 0.65 NA microscope objective. The values measured appear almost identical for those measured with a low NA launch indicating little evidence for NA dependence beyond ~ 15 m. This could suggest that the re-distribution of power from the lower order modes to the higher order modes is complete after 15 m of fibre. However, more detailed investigations of the attenuation coefficient length dependence for fibre lengths of 15 m and less will help to understand mode power re-distribution. This could be achieved through the use of mode scramblers.

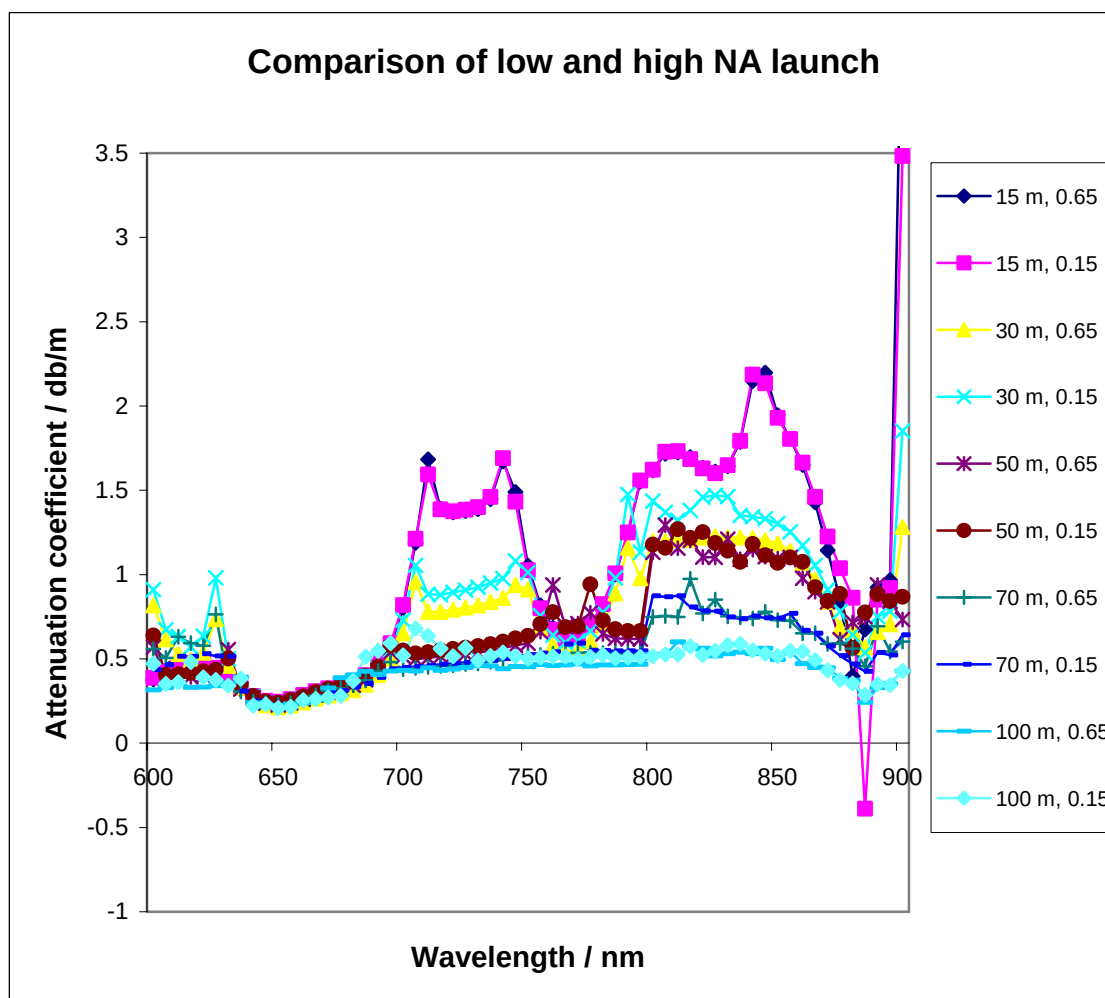


Figure 17 All results for comparison. There is close agreement between the results for the two launches at all fibre lengths. Again, the signal to noise ratio could be improved by allowing re-optimisation of the gain between the long and short lengths of fibre in order to increase the available dynamic range.

It was only after these measurements were made that the imaging telescope was installed and the spot size could be validated.

In summary, the graphs provide limited information regarding the attenuation coefficient as a function of length due to the insufficient dynamic range of the system. A more thorough analysis is required with a larger dynamic range achievable through gain switching and the implementation of end face polishing. The use of mode scramblers could also help in the determination of EMD with respect to fibre length. Further knowledge would enable a final length for a fibre to be defined after a series of measurement runs that include the removal of the cutback section. This value will depend upon the particular fibre and it is hoped that further characterisation of leading POF samples will be useful in determining this. In addition, the lengths of fibre should be recorded for each measurement run in order to assess the possible impact of this effect. This is especially the case if the supplied sample is of limited length.

6.6 Verification summary

A more thorough analysis and refinement of the uncertainty budget will be required as work progresses but a preliminary calculation of the expanded uncertainty is shown in Table 2. It is hoped that the contributions will be reduced as more measurements are processed and knowledge of the system is increased. A significant reduction in overall uncertainty is anticipated through the effects of including the gain switching capability of the program. This should have a marked effect upon the linearity contribution.

Table 2 The table below shows preliminary results of the uncertainty contributions for the system and the method of calculating the measurement uncertainty using the best measurement capability parameters. The actual measurement uncertainty is calculated by the results processing macro at the time of measurement for each wavelength point.

Source of uncertainty	Value $\pm$ dB		Probability distribution	Divisor	c_i	u_i $\pm$ dB		v_i or v_{eff}
Wavelength	0.070		Rectangular	$\sqrt{3}$	0.4	0.016		∞
Linearity	Dynamic Range	Value	Normal	1	1	Dynamic Range	Value	∞
	0-10 dB	0.25				0-10 dB	0.25	
	10-20 dB	0.44				10-20 dB	0.44	
	20-30 dB	1.82				20-30 dB	1.66	
Temperature (Detectors)	0.1		Rectangular	$\sqrt{3}$	1	0.06		∞
Voltmeter	0.004		Normal	1	1	0.004		≥ 10
Repeatability	0.020		Normal	1	1	0.020		∞
Combined uncertainty			Normal			Dynamic Range	Value	356
						0-10 dB	0.26	
						10-20 dB	0.45	
						20-30 dB	1.67	
Expanded uncertainty			Normal ($k=2$)			Dynamic Range	Value (Rounded)	356
						0-10 dB	0.6	
						10-20 dB	1.0	
						20-30 dB	3.4	

7 CONCLUSIONS

7.1 Progress

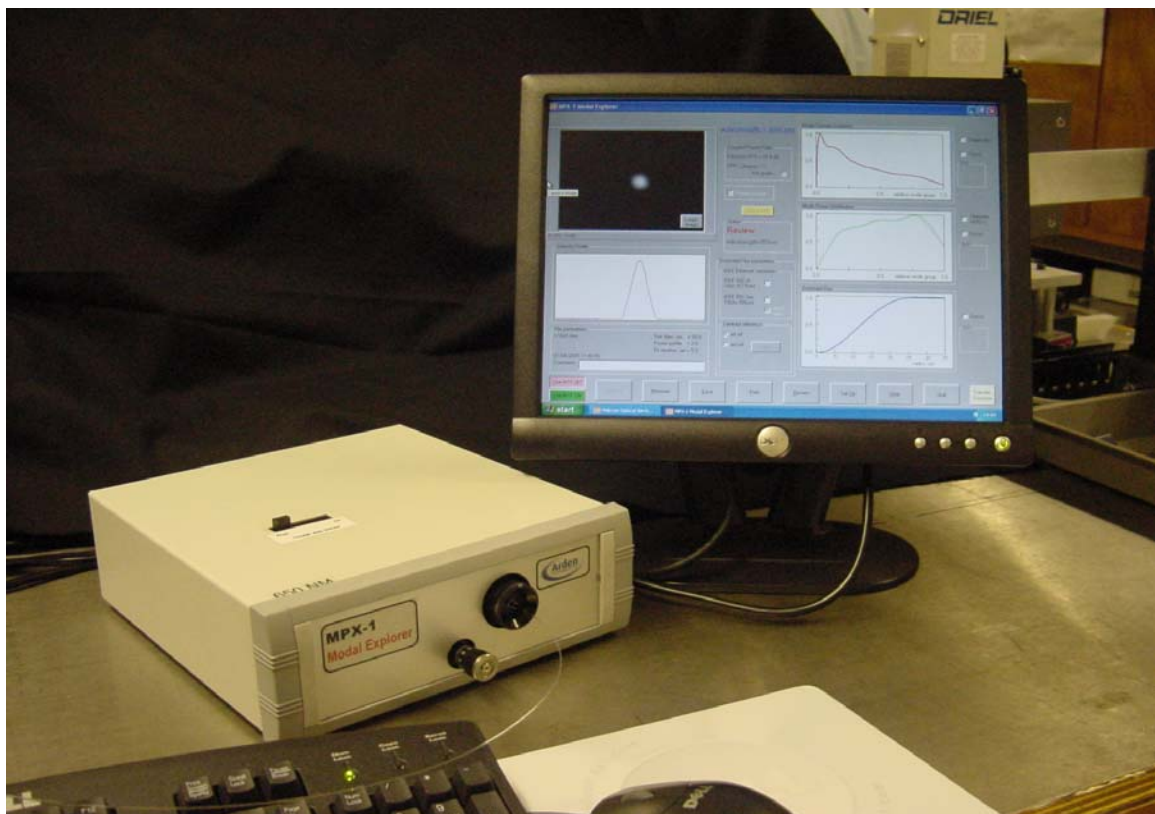
A working system to provide a range of controlled and quantifiable launch conditions has been developed in order to measure spectral attenuation and bandwidth of various types of POF. The launch module has been shown to be capable of producing spot sizes in excess of 1000 μ m with NA 's up to ~ 0.4 . The flexibility and range of the achievable

launch conditions and the portability of the launch module as a whole are notable successes of the work undertaken. Knowledge gained through understanding the system uncertainty contributions ensures future confidence in measurements.

7.2 Future planning

A more radical approach to the optical arrangement may allow for greater NA values to be achieved while maintaining an evenly illuminated spot size. However, this may require the use of expensive, novel optics. The possible use of tuneable lasers instead of the monochromator arrangement would provide much greater power as well as a circular, better-collimated beam. Even if possible the cost could again, prove prohibitive. However, as the requirements of manufactures and end users become clear, the need to measure over a continuous wavelength range may be supplanted by a series of optimal spot wavelengths. Although limitations exist, the variable launch system can be employed to assess a range of POF types under user specified launch conditions and used in conjunction with the Arden Photonic's MPX-1 Modal Explorer. This instrument measures the mode distribution of any connected fibre source. It is capable of quantifying parameters associated with IEC/TIA standards such as mode transfer function (MTF), mode power distribution (MPD), encircled flux and coupled power ratio (CPR). It is hoped that this powerful tool will be used in conjunction with the developed controlled launch conditions thereby providing a more complete analysis and evaluation of the light transfer throughout the fibre medium.

Figure 12 MPX-1 Modal Explorer supplied by Arden Photonics Ltd.



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