

Measuring Polarisation Extinction Ratio for Optical Fibres and Components

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ABSTRACT

Polarisation extinction ratio (PER) is a power ratio measurement that is used to describe power exchange between polarisation states in optical fibres and components. It is particularly relevant to optical communication systems where increasing demand for higher data rates has focused attention on polarisation effects.

It has been shown there is an industrial need for traceability in such measurements and this report describes the development of a measurement service at NPL to verify the performance of commercially available PER meters. The work was carried out under contract to the NMS for milestone 2.2.3.2, “measurement system constructed and evaluated”.

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Approved on behalf of the Managing Director, NPL
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1. INTRODUCTION

The increasing demand for higher data rates in optical fibre communication systems has focused attention on the limitations arising from polarisation effects [1]. Polarisation extinction ratio (PER) is an important parameter and meters are available for making direct measurements of PER of light transmitted by optical fibre cables.

PER quantifies the ability of an optical fibre or other component to maintain an incident polarisation state. For example, if plane polarised light is launched into one axis of a birefringent fibre there will inevitably be a small amount of cross-coupling of power between the two polarisation modes and some light will emerge in the other axis. The polarisation extinction ratio quantifies the polarisation cross-talk. It is, however, a ratio of two power measurements and it ignores the relative phase of the polarisation components and the degree of polarisation. The measured value is highly dependent on:

- i) the alignment of the launched polarisation state with the polarisation axis of the device under test
- ii) the length of fibre
- iii) environmental conditions which lead to mode coupling

Other components for which PER is a useful parameter include multiplexers, modulators and pigtailed devices such as laser sources. PER meters are commercially available and this report describes a method for verifying the performance of such meters.

2. OPTICAL FIBRE AND PER

Polarisation extinction ratio (PER) is defined as the inverse ratio of optical power that is passed from the transmitted polarisation state into the orthogonal unexcited state. For a perfect optical system with no cross talk the PER value can be infinite. In practice PER values of 20-30 dB are observed for birefringent optical fibre and in many cases values of 10-20 dB are acceptable.

Refined manufacturing techniques are used to produce low loss monomode optical fibre but residual stresses will always creep in, either during manufacture or subsequent handling. The stresses induce birefringence and when linearly polarised light is launched into the fibre the effect of coupling between orthogonal components and random variations in the phase velocity will result in the state of polarisation varying along the length of fibre in an unpredictable way. The output polarisation is dependent on the length of fibre and the environmental conditions.

Polarisation maintaining fibres overcome this problem to a large extent by restraining linearly polarised light to principle axes defined by a controlled degree of birefringence introduced during manufacture. The PER at the fibre output is a strong function of the angular offset between the angle of polarisation of the launched light and the principle axis of the fibre.

If only one mode is launched the light remains linearly polarised along the length of the fibre because large differences in phase constants of the modes greatly reduce the coupling between them that might be caused by strain introduced by bending and other effects. However some of the original polarisation may couple into the orthogonal mode and continue to propagate in that mode.

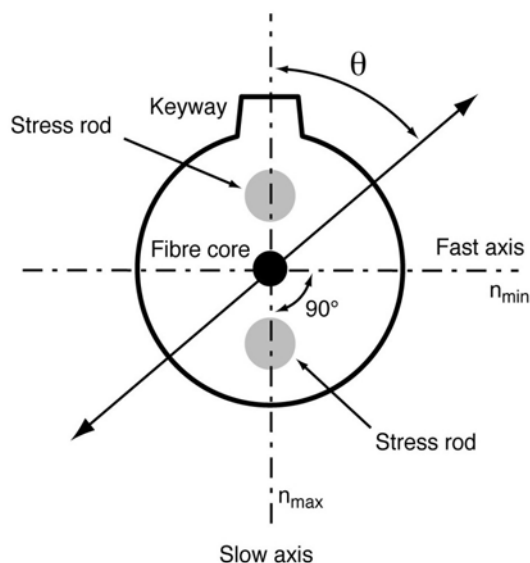


Figure 1. Birefringent fibre and polarisation axes

2.1 Launch alignment

How well a fibre maintains polarisation depends on the conditions under which the light is launched into the fibre. If linearly polarised light is launched into a Hi-Bi fibre at 45 degrees to the principle axes, the components travel at different speeds within the fibre and may emerge with a relative phase difference.

If that difference is finite the recombined light is elliptically polarised. If the phase difference is zero the components will recombine to produce linearly polarised light and the measured PER will have a high value. It is also possible to achieve a high PER value at the output by launching linearly polarised light aligned with one principal axis and this shows how ambiguities can arise when measuring PER.

In HiBi fibre the PER is the ratio between the optical power in the fast and slow axis:

$$\text{PER} = 10 \log_{10} (P_{\text{slow}}/P_{\text{fast}}) \text{ dB}$$

The importance of the angular alignment between the polarisation axis of the light with the slow axis of the fibre is illustrated here. If as in figure 1, the input beam is perfectly polarised

and misaligned by an angle θ with respect to the slow axis of the fibre, a small amount of light will be transmitted along the fast axis of the fibre. This will degrade the PER of the output beam. The maximum possible value of the output extinction ratio is thus limited by:

$$\text{PER} < 10 \log (\tan^2 \theta)$$

Figure 2 shows PER values calculated as a function of launch angle offset to the slow axis where $\text{PER} = 10 \log_{10} (P_{\text{slow}}/P_{\text{fast}})$. To achieve an extinction ratio above 20 dB in the output beam the launch alignment must be better than 6° . To achieve a 30 dB extinction ratio the launch alignment must be better than 1.8° .

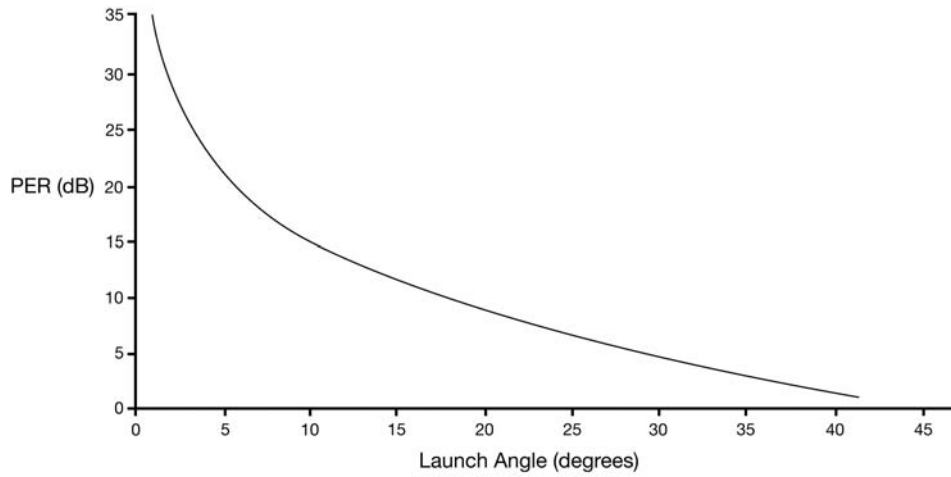


Figure 2. PER values calculated as a function of launch angle offset to the slow axis

2.2 Phase exploration

Because changes in the relative phase of the polarisation components in a fibre can alter the output state it is necessary to explore those effects so as to be able to specify a minimum value to the PER. As the fibre is used and stressed to varying degrees the phase relation will change and so will the output polarisation and the measured PER. Stress and microbends usually occur near fibre ends and if the microbend is at the output end of the fibre the polarisation may be rotated. If the microbend is at the input end the polarisation may be perturbed before travelling through the fibre so the polarisation will vary according to the way the fibre is used.

One method of varying the relative phase of the polarisation components is to stress the fibre during measurement by wrapping it several turns round a mandrel 40–50 mm in diameter. Another technique is to heat the fibre with a lamp or a warming plate [2]. The measured value of PER will go through several values and the lowest reading is usually taken as the reference specification.

The phase exploration can also be accomplished by cooling part of the fibre with freezer spray and allowing the fibre to warm up to room temperature. The appendix to this report describes results obtained this way in an experiment to align a Hi-Bi fibre with the polarisation axis of a laser beam [3].

3 POLARISATION EXTINCTION RATIO METER

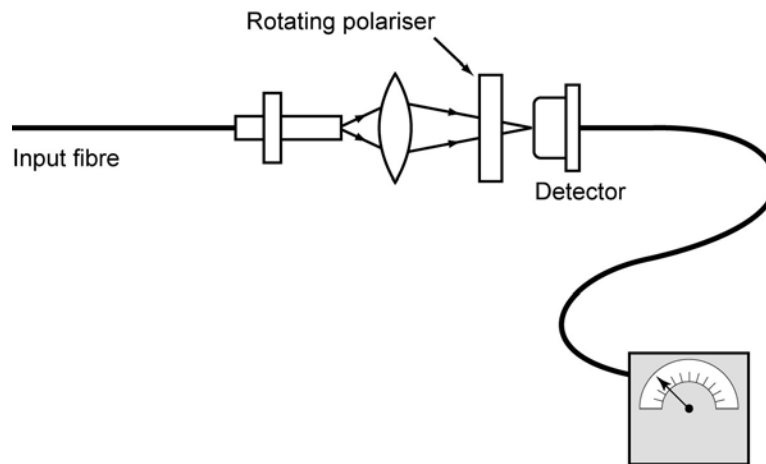


Figure 3. Polarisation extinction ratio meter in diagrammatic form

Figure 3 shows the simple layout of a polarisation extinction ratio meter. The meter uses a polariser as an analyser and a detector to measure the optical power. The PER is calculated from measurements of the amount of light in two orthogonal polarisation states. By continually rotating the polariser the maximum and minimum orthogonal power levels in the light can be measured. A sensor records senses the angular position at which the analyser transmits the maximum amount of light and the instrument then measures the amount of light in the orthogonal axis. It computes the ratio of the power measurements to give the extinction ratio.

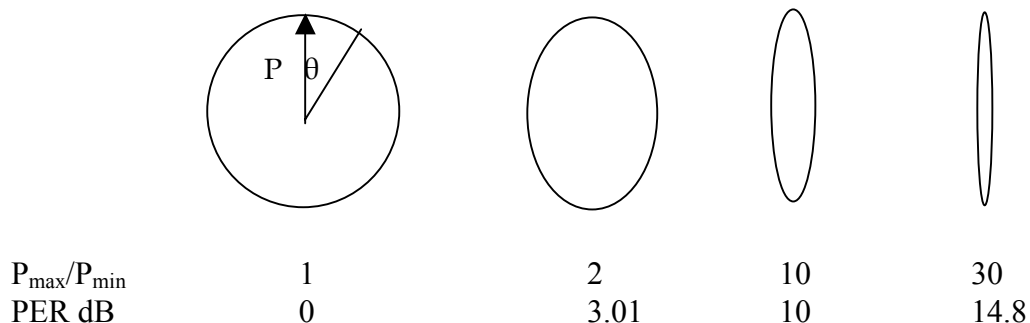


Figure 4. Geometrical representation showing variation of PER with angle of rotation of polarisation vector

Figure 4 shows a geometrical representation of the variation in optical power with angle of rotation of the polarisation vector. Randomly polarised light is represented by the circular figure. The ratio $P_{\max}/P_{\min}$ equals unity and the PER is 0. Polarised light with an extinction ratio of 3.01 dB is represented by an ellipse with an aspect ratio of 2:1. A PER of 14.8 dB is represented by an aspect ratio of 30.

4 EXPERIMENTAL

The aim of this work was to gain experience using a commercial PER meter and to explore an alternative system for measuring PER with a view to verifying the performance of the commercial meter. With this in mind a PER meter, polarised light source and optical fibre patchcord were purchased.

A separate measurement system was assembled on an optical bench and consisted of a high PER polariser to act as an analyser, an integrating sphere and detector with electronic amplifier and digital voltmeter. PER values are computed as a ratio of power measurements of orthogonal polarisation states.

The plan was to verify the PER of the light source, measure the PER of light transmitted by the patchcord and then to couple light of prescribed PER values to the meter to verify its response.

4.1 PER meter

At least two manufacturers supply PER meters specifically for use with optical fibres or components. The meter purchased for this work is based on the design shown in figure 3 and gives simultaneous readings of PER, polarisation angle and optical power. It accepts light directly from an optical fibre and is fitted with an FC/PC optical fibre connector.

4.2 Light Source

The light source used in these trials was a Fabry-Perot laser emitting 1 mW at a wavelength of 1550 nm. The manufacturer's specification for PER was 40 dB. The source was designed to be used with an optical fibre and light is focused to the end of the fibre when it is mounted in the FC/PC receptacle attached to the source housing. Without a fibre attached the light diverges from the receptacle.

The source has an adjustment to rotate the plane of polarisation of the output wavefront and align with the propagation axes of the optical fibre.

4.3 Optical fibre patchcord

As discussed in section 2, a highly birefringent fibre will tend to maintain the launched polarisation state and this is a convenient means for coupling polarised light from a source or

device under test into a PER meter. The polarisation maintaining patchcord used in these experiments was specified to maintain a PER of 30 dB and connected directly to the source and meter via the FC/PC receptacles.

4.4 Coupling source to meter

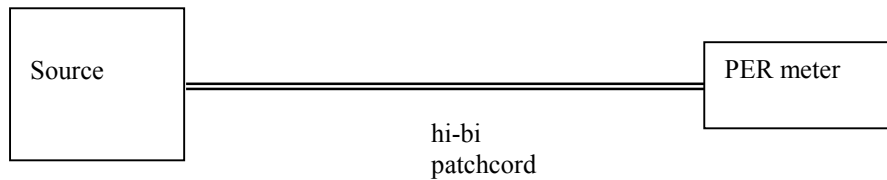


Figure 5a. Coupling source directly to PER meter with an optical fibre patchcord

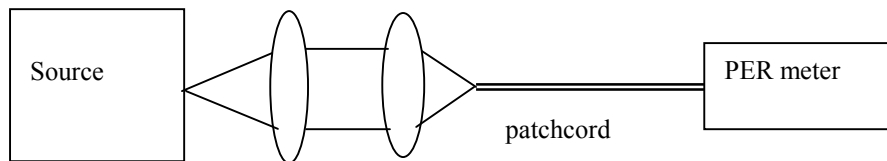


Figure 5b. Coupling light shaped by free space optics to PER meter via patchcord

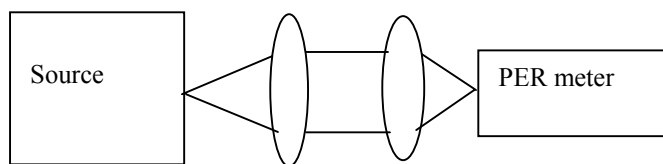


Figure 5c. Coupling light shaped by free space optics directly to PER meter

It is possible to couple light from the source directly into the fibre as shown in figure 5a or to use free space optics to focus the light to the patchcord as shown in figure 5b. The latter gives an opportunity to insert components such as waveplates and polarisers but the PER of the light reaching the meter will always be limited by the PER characteristics of the patchcord. To avoid such limitations trials were carried out with free space optics to couple light directly to the meter as shown in figure 5c.

5 PER MEASUREMENTS

5.1 Source PER

When measuring the source PER, which is specified to better than 40 dB, the patchcord must be omitted. The source is designed to couple light directly into the patchcord and with it not in place light diverges from the connector. It is then necessary to collimate the light in order to pass it through an analyser and into the integrating sphere.

In these trials a 30 mm focal length doublet lens was used to collimate the beam and a polarising filter, specified to better than 45 dB, was used in a rotation mount as an analyser. The diameter of the integrating sphere was 50 mm and the light was accepted through a 5 mm diameter aperture. A digital voltmeter was used to measure the amplified signal from a photodetector in the sphere. The signal obtained was proportional to the intensity of the incident light.

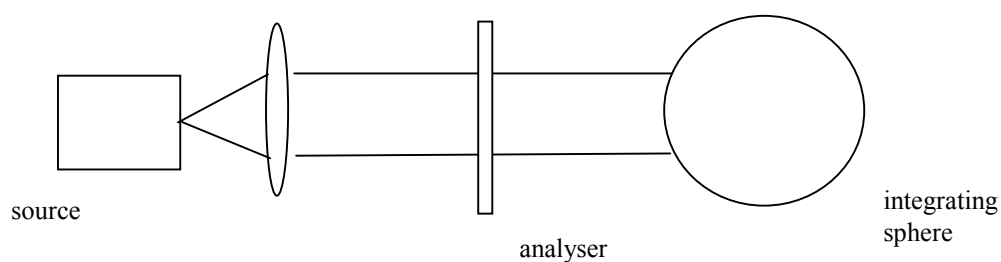


Figure 6. Measurement of polarisation extinction ratio of source

The angle of polarisation of the light from the source was adjusted until maximum intensity was transmitted by the analyser. The DVM signal was noted and the polarisation rotated 90° and another reading noted. The PER was calculated from the formula $PER = 10 \log_{10} (P_{\text{slow}}/P_{\text{fast}})$ and found to be better than 40dB.

5.2 PER of patchcord

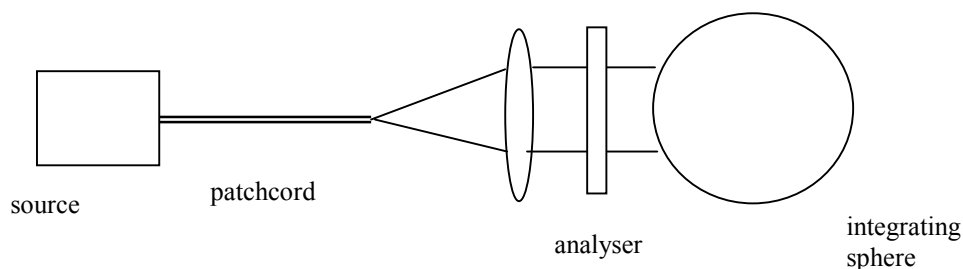


Figure 7. Measurement of polarisation extinction ratio of patchcord

PER measurements on light transmitted by the patchcord were made using the PER meter and again using the analyser and integrating sphere as shown in figure 7. Polarised light from the source was coupled into the fibre simply by plugging into the FC/PC connector. Light leaving the fibre was focused into the integrating sphere via the polariser using a collimating lens. For measurements with the PER meter the patchcord was simply plugged directly into the FC/PC connector.

Measurements made with the integrating sphere are compared in table 1 with those made with the PER meter.

PER meter (dB)	Integrating sphere (dB)
29.2	29.8
15	15.1
10	9.96
5 – 5.2	5.18

Table 1. PER measurements with the PER meter compared with the integrating sphere

The measured value of PER is a function of launch angle with respect to the fast/slow axes of the fibre and figure 8 shows values measured with the PER meter.

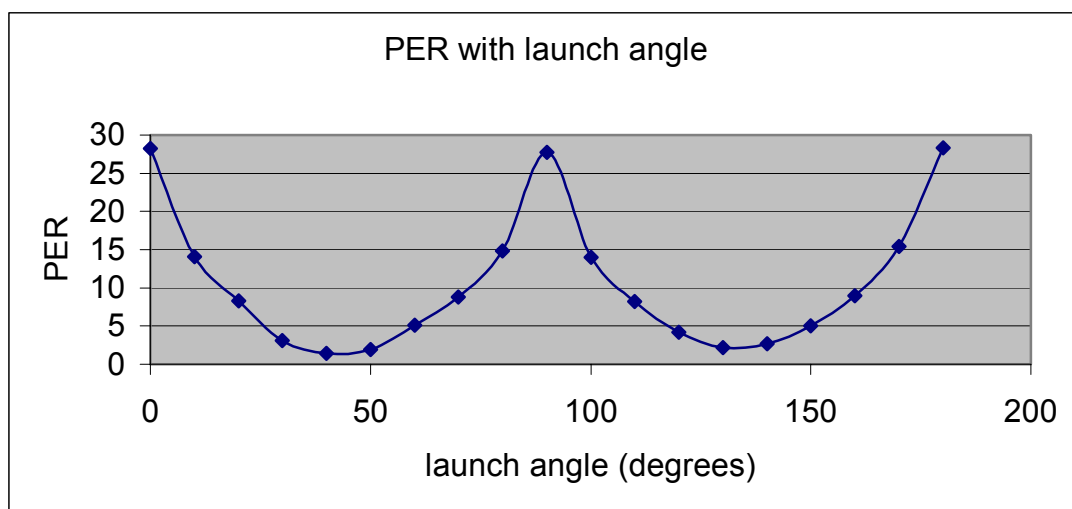


Figure 8. PER of light transmitted by patchcord, measured as a function of launch angle offset to the slow axis

Figure 9 shows PER values measured over a period approaching 30 seconds. Polarised light was launched at an angle of 20° to the slow axis of the hi-bi patchcord. The diode source had been left to stabilise and the instrument and patchcord were at a common stable temperature. It is unclear at this stage whether the 0.2 dB spread of readings is due to instrument or source noise.

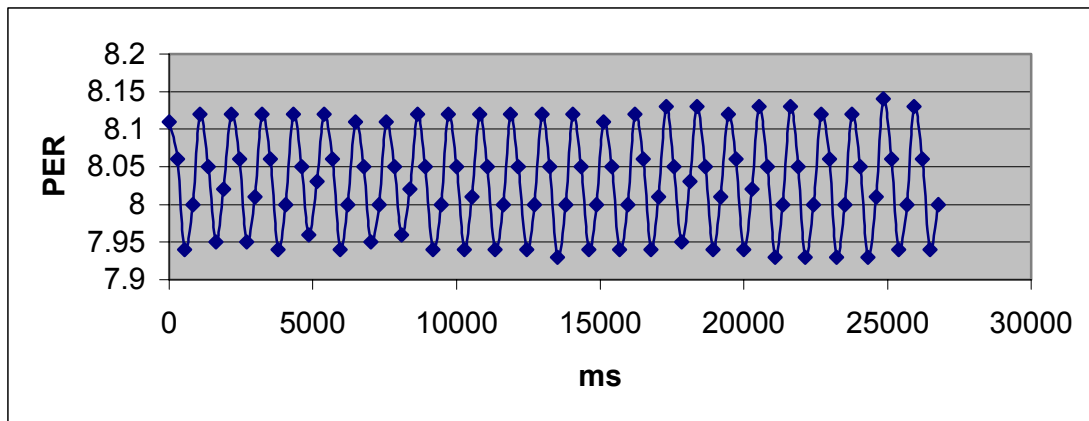


Figure 9. PER measurements made with PER meter, showing periodic variation. Light launched at 20° to the slow axis of patchcord.

The phase relationship between the principle polarisation states in the fibre was explored by gently heating with a reading lamp placed in close proximity. Figures 10a,b,c show how the measured PER is affected by the temperature induced variations of phase between the polarisation states for launch angles of 45, 20 and 10 degrees respectively.

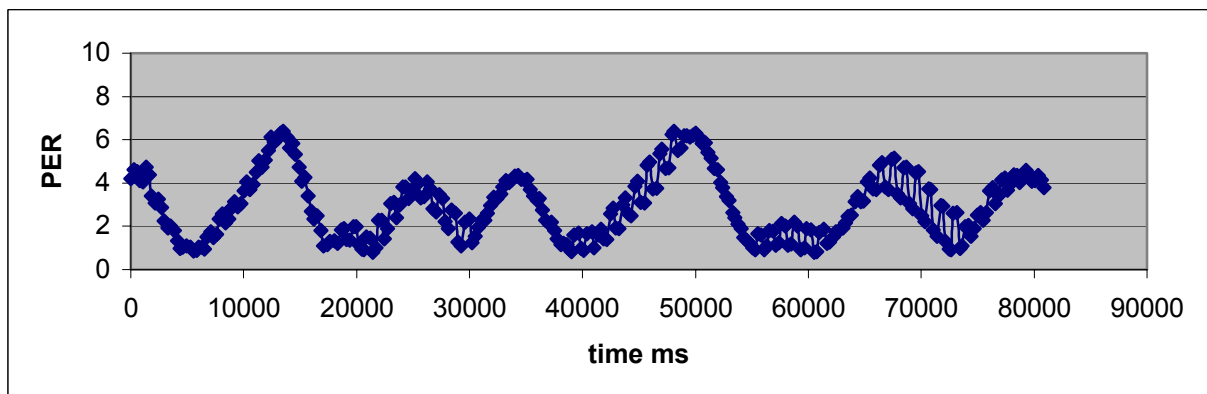


Figure 10a. PER measurements made with PER meter. Light launched at 45° to the slow axis of patchcord. The fibre is gently heated with a reading lamp.

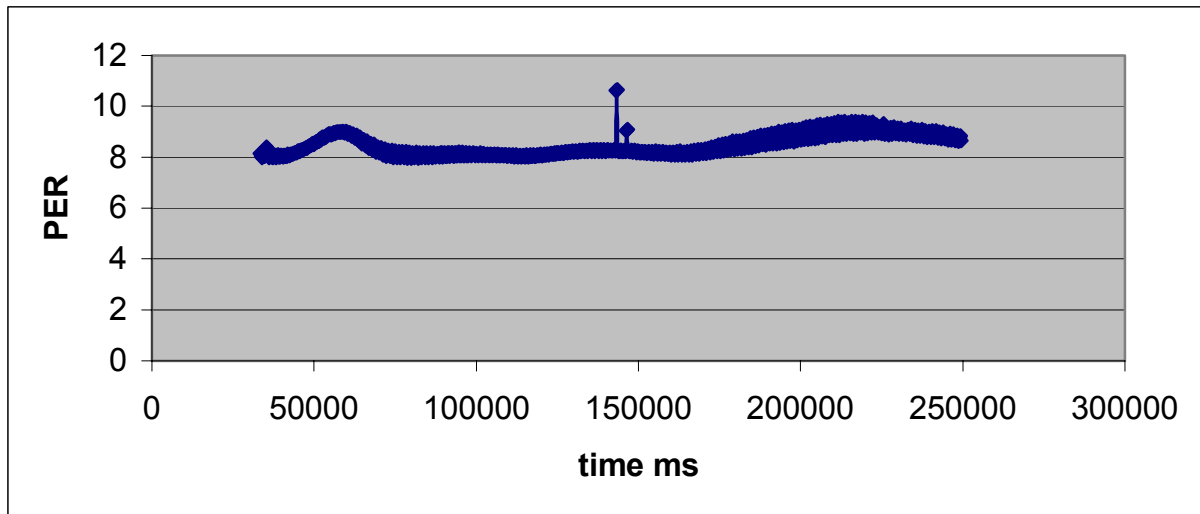


Figure 10b. PER measurements made with PER meter. Light launched at 20° to the slow axis of patchcord. The fibre is gently heated with a reading lamp.

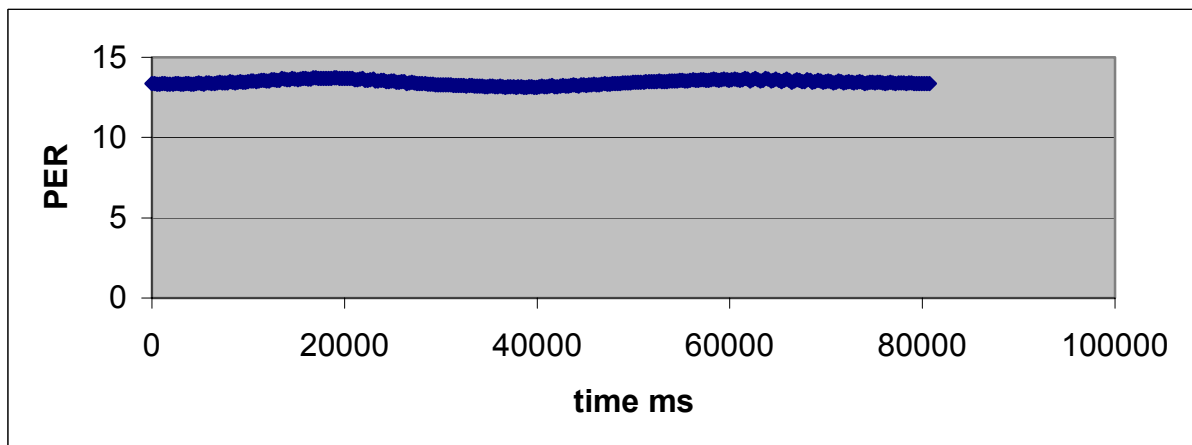


Figure 10c. PER measurements made with PER meter. Light launched at 10° to the slow axis of patchcord. The fibre is gently heated with a reading lamp.

A more interesting analysis is gained by plotting the polarisation angle recorded by the meter as a function of PER [2]. Figures 11a,b show U charts for light launched at 20° and 10° respectively. In figure 11a the minimum PER value is in the region of 8 dB and reference to figure 2 indicates a theoretical PER of 9 dB for a 20° offset.

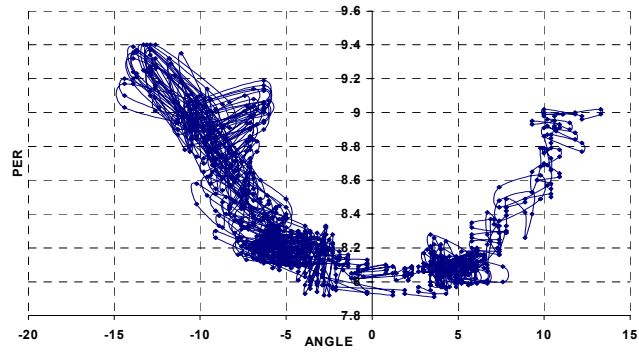


Figure 11a. PER values plotted against polarisation angles recorded with PER meter as the fibre is gently heated. Launch angle = 20° .

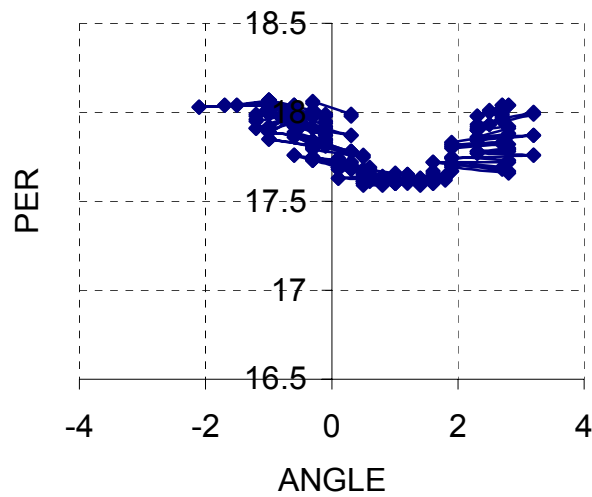


Figure 11b. PER values plotted against polarisation angles recorded with PER meter as the fibre is gently heated. Launch angle = 5° .

5.2.1 PER measurements with polarisation state analyser

Another method for calculating PER is to make measurements with a polarisation state analyser. The PER meter makes relatively simple measurements of power transmitted by a rotating polariser. The polarisation state analyser uses a rotating quarter wave plate and makes more detailed measurements of the Jones and Stokes parameters and the result of a polarisation measurement is represented by a point on the surface of the Poincare sphere.

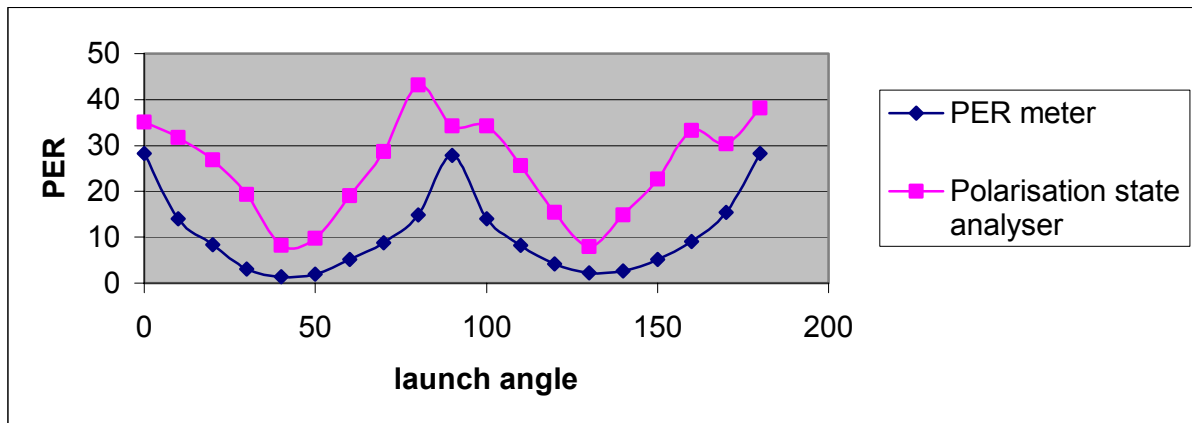


Figure 12. PER values as a function of launch angle, measured using:
a) PER meter, b) polarisation state analyser

Figure 12 shows PER values as a function of launch angle, measured with the PER meter and with a polarisation state analyser. There is an obvious discrepancy between the results and this is thought to be largely due to the polarisation state analyser being more selective than the PER meter in the polarisation states that are included in the calculation of PER.

5.3 Coupling source to meter without a patchcord

The limitations imposed by the patchcord on the measurement range have already been described. Although the PER of the light leaving the source is 40 dB it was only possible to couple light with a PER of less than 30 dB with the patchcord. Various attempts were made to preserve the 40 dB PER and couple light from the source to the meter with free field optics instead.

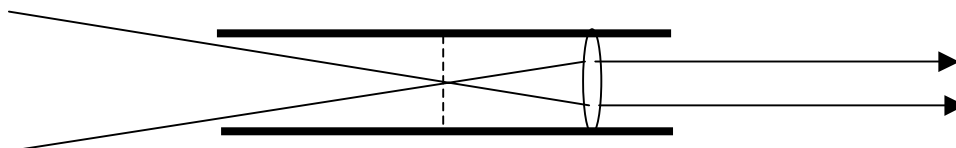


Figure 13. Schematic diagram of fibre connector and coupling lens

At the base of the FC/PC connector in the PER meter lies a small collimating lens and when an optical fibre is inserted the tip locates in the focal plane of this lens. It is necessary to focus light into the 8 mm deep aperture of the connector, avoiding reflections from the sides and vignetting at the entrance as in figure 13.

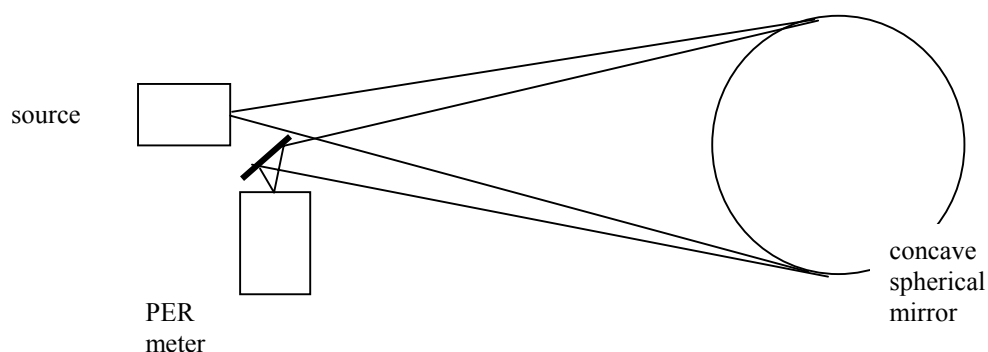


Figure 14. Coupling source and meter with a concave mirror

A variety of optical systems were tried including a concave spherical mirror imaging at unit magnification as shown in figure 14. The attraction of mirror optics is the lack of chromatic aberration. This meant the system could be aligned using visible light such as a helium-neon laser and the infrared source substituted. The difficulty arises in extracting the reflected light from the incident light. If a spherical mirror is used it is best used on axis but that means a beamsplitter must be incorporated and this will inevitably affect the polarisation properties.

In these trials the spherical mirror was used off-axis and a small plane mirror was used to fold the beam close to the source and reduce the off-axis angle. It was not found to be possible to measure, with the PER meter, values larger than 18dB. It was suspected that this was due to astigmatism in the spot focused at the PER meter even though the off-axis angle was kept as small as possible.

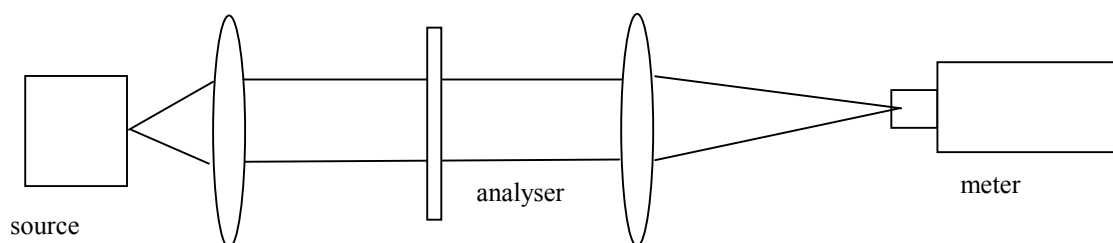


Figure 15. Coupling light from source to PER meter with lenses.

Figure 15 shows doublet lenses used to collimate the light from the source and refocus into the PER meter fibre receptacle. PER values larger than 30 dB were recorded but not reproducible, being highly dependent on alignment.

Much smaller lenses were tried, placed close to the fibre receptacles. Figure 16 shows small convex lenses at the entrance to the receptacles. Graded index (GRIN) lenses were also tried placed inside the receptacles. The highest PER values recorded were in the region of 30 dB and the measurements were again highly dependent on alignment. It is possible that GRIN lenses degrade the PER by scattering.

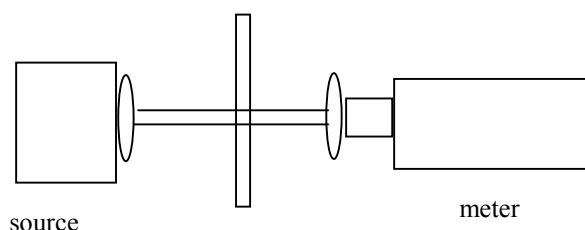


Figure 16. Coupling light from source to PER meter with small lenses mounted on the fibre receptacles.

These experiments showed that although it was possible to use doublet lenses to couple light with a PER value greater than the 30 dB value obtained using the hi-bi fibre patchcord the process was not repeatable. It depended on very careful transverse and angular alignment of the focused spot with respect to the small lens at the rear of the fibre receptacle. Strain in the lenses may also be responsible for a degree of depolarisation. Trials with the small lenses and the concave mirror showed a maximum value for the PER of the coupled light to be less than the 30 dB obtained with the patchcord.

6 PROPOSED MEASUREMENT SERVICE

The work described in this report has shown the difficulty of coupling light into the PER meter using free space optics. Repeatable measurements were only obtained using the patchcord to couple to the meter and this placed an upper limit of 30 dB on the PER of light reaching the meter. Independent measurements on the light leaving the patchcord, using a polariser and integrating sphere, yield results comparable with those obtained with the PER meter. It is proposed to establish a measurement service using the polarised light source, free space optics to generate a variety of polarisation states and the patchcord to deliver light to the meter under test.

Figure 17 shows a diagram of the optical layout. The source provides linearly polarised light which is aligned with the fibre axes by adjustment at the source or by rotation of a halfwave plate in the beam. Further adjustment enables the light to be launched into the patchcord at specific angles to the axes to obtain specific PER values at the output. To generate elliptically polarised light for launch into the fibre a quarter wave plate is inserted in the beam.

Measurements on light leaving the patchcord are made with the meter under test and are compared with measurements made with the integrating sphere and polariser.

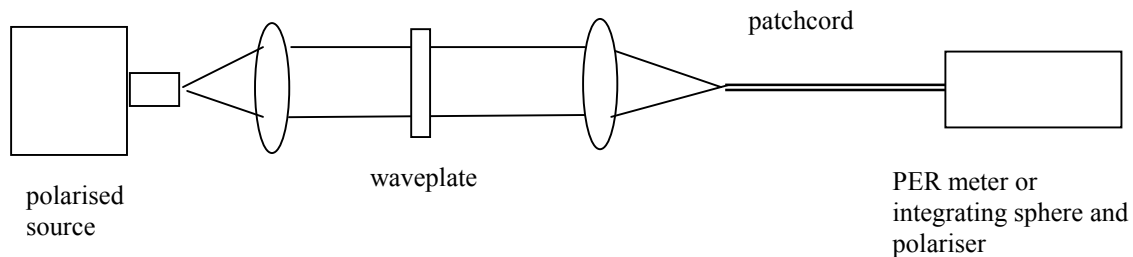


Figure 17. Arrangement for comparing PER meter readings and integrating sphere measurements for light transmitted by fibre in various polarisation states.

Figures 18-20 show photographs of parts of the test rig. The light from the source is plane polarised to a high PER value. A quarter-wave plate is included to enable the linearly polarised light to be converted to elliptically polarised light and hence generate a range of PER values.

Figure 18 shows free space optics used to couple the source to the fibre. Figure 19 shows the arrangement for collimating the output from the fibre, the polariser and integrating sphere. Figure 20 shows the fibre coupled directly to the PER meter.

The next step is to make a careful analysis of the uncertainties and establish procedures. Particular points are the exploration of phase effects in the fibre and the linearity of the integrating sphere detector and associated electronics.

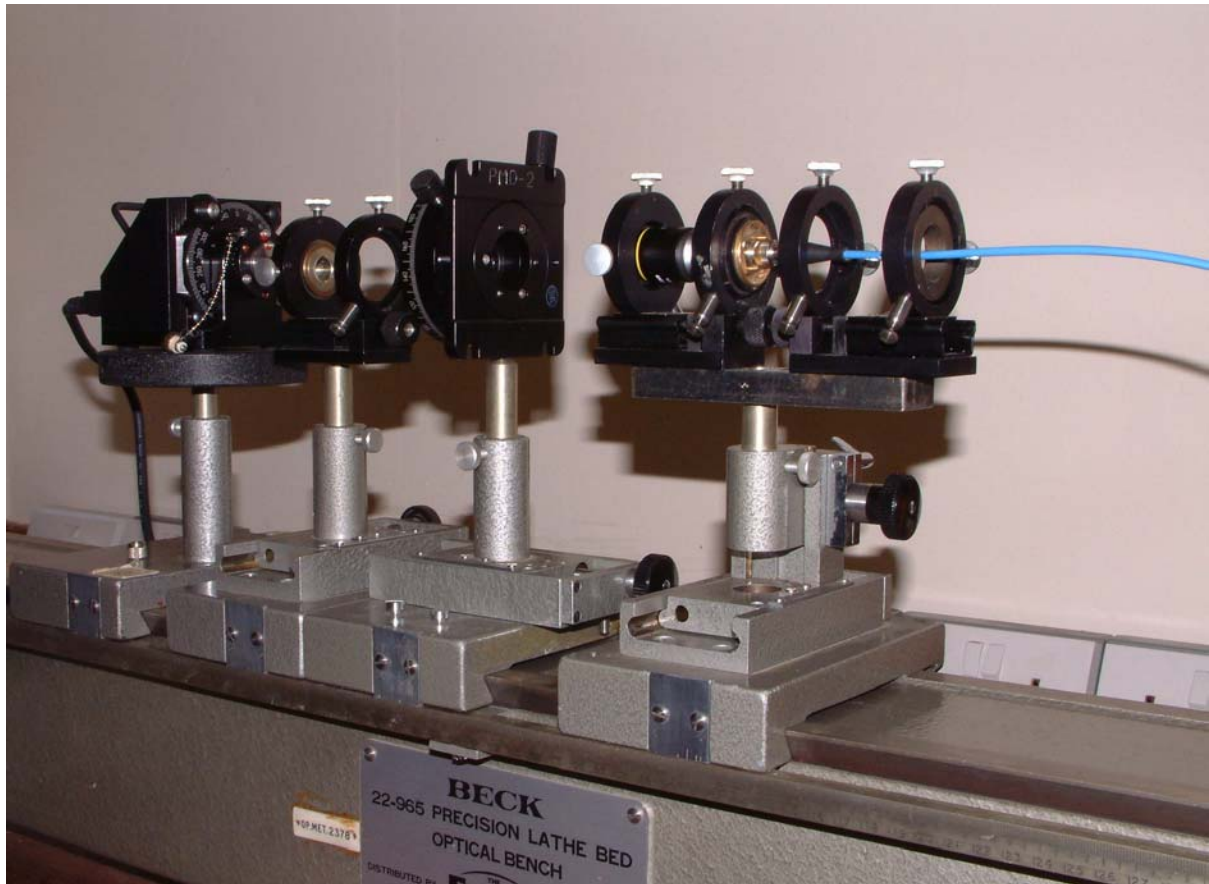


Figure 18. Stabilised source, collimator, waveplate and fibre launch optics.

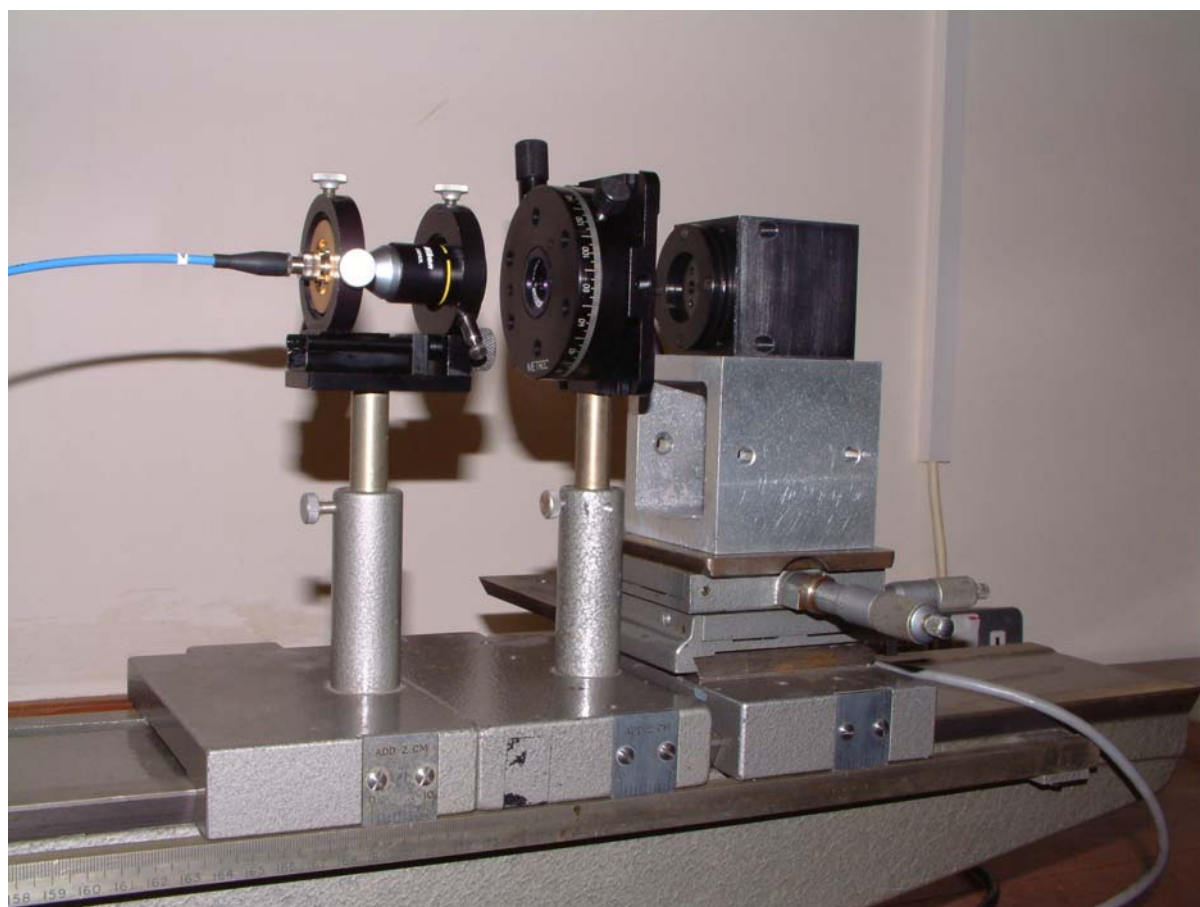


Figure 19. Fibre feed to collimator, polariser and integrating sphere with detector.



Figure 20. Stabilised source feeding optical fibre connected directly to PER meter

7. CONCLUSIONS

Experience has been gained in the measurement of polarisation extinction ratio using a polarised light source, patchcord and commercial PER meter. Measurements have also been made using a high quality polariser, integrating sphere and detector and amplifier. Because the meter will only reliably accept light coupled with a patchcord it has only been possible to measure PER values less than the 30 dB transmission limit of the patchcord.

Specific PER values can be generated by rotating the polarisation vector or using a waveplate before the light is launched into the patchcord and the proposed measurement service will verify PER meter readings at specific points using power ratio measurements made with the analyser and integrating sphere.

The next step is to make a careful analysis of the uncertainties and establish procedures. Particular points are the exploration of phase effects in the fibre and the linearity of the integrating sphere detector and associated electronics.

8. ACKNOWLEDGEMENT

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APPENDIX I.

ALIGNING FIBRE AXIS TO PLANE OF POLARISATION

Another application is described here. A hi-bi fibre is used to deliver linearly polarised light to an interferometer where it is required to align the fibre axes to a linearly polarised wavefront from a helium-neon laser.

The axes are located by exploring the phase differences between the components in the fast and slow axes of the fibre and in this case phase changes are induced by cooling part of the fibre with a freezer spray and then allowing the fibre to warm up to room temperature. The intensity of light transmitted by an analyser may vary as shown in figure 21. The modulation is measured and the variation of this modulation with launch angle is recorded.

The modulation can be described using the visibility function that is used to describe intensity variations in interference patterns.

$$V = (I_{\max} - I_{\min}) / (I_{\max} + I_{\min})$$

where $I_{\max}$, $I_{\min}$ are maximum and minimum intensities respectively.

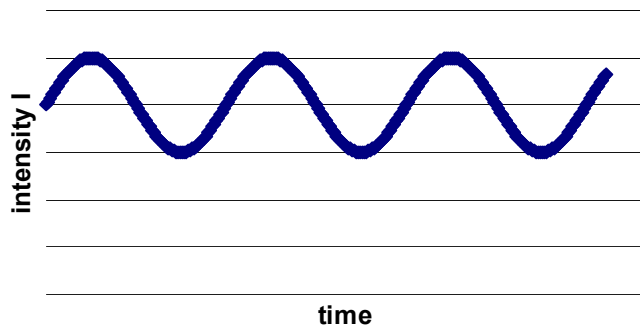


Figure 21. Intensity modulation of light transmitted by polariser as fibre is warmed.

The visibility $V = 0$ when $I_{\max} = I_{\min}$ and this corresponds to the light being aligned along a fibre axis at input, assuming no cross-talk occurs during transmission. The visibility $V = 1$ if $I_{\min} = 0$. The intensity of the light transmitted by the analyser will only go to zero if the light leaving the fibre is linearly polarised and perpendicular to the analyser axis.

If we define α = the angle between the input polarisation and the fibre axis and β = the alignment of the polariser axis and the fibre axis, for each value of α there are two values of β for which $V = 1$. By locating these and rotating the input angle by $\alpha = \pm(\beta_1 - \beta_2)/2$ the visibility will drop to zero when the temperature is cycled and the plane of polarisation is aligned with the fibre.

E_x and E_y are the x and y components of the electric vector. In general there are two plane polarised output states corresponding to components E_x and E_y being in phase or out of phase. The two linear states can be drawn as shown in figure 22, for an input angle α relative to the fibre axis x. The input angle $\alpha = (\beta_1 - \beta_2)/2$ and rotation of the input polarisation plane should align with a fibre axis ($\alpha = 0$). Figure 23 shows a polar plot of the experimental results indicating the alignment of the fibre axes with respect to the distribution.

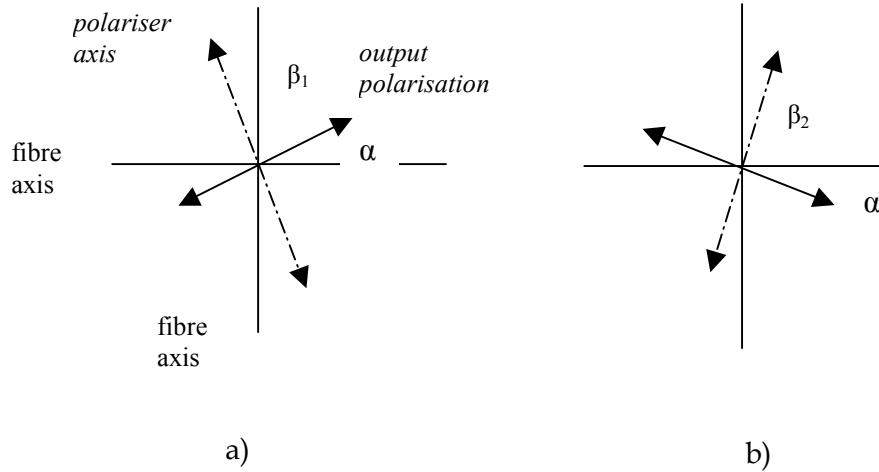


Figure 22. Diagram showing a) E_x E_y in phase b) E_x E_y out of phase

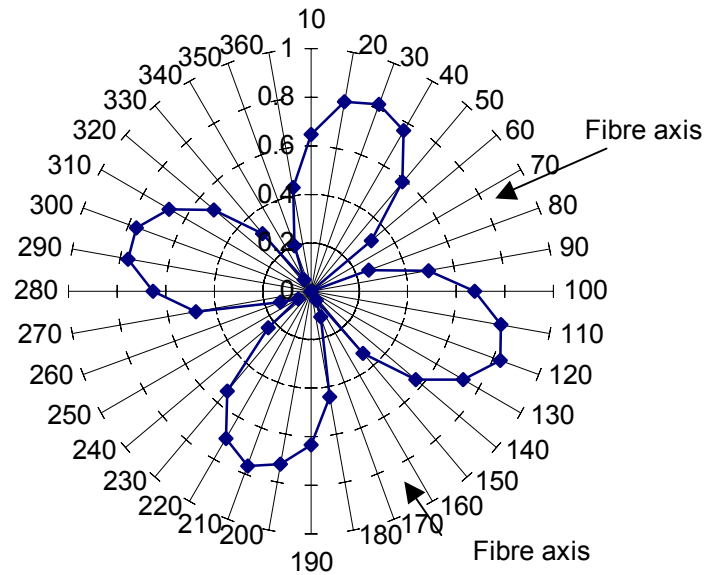


Figure 23. Polar plot of output visibility versus analyser position.

APPENDIX II

COUPLING LIGHT TO FIBRES

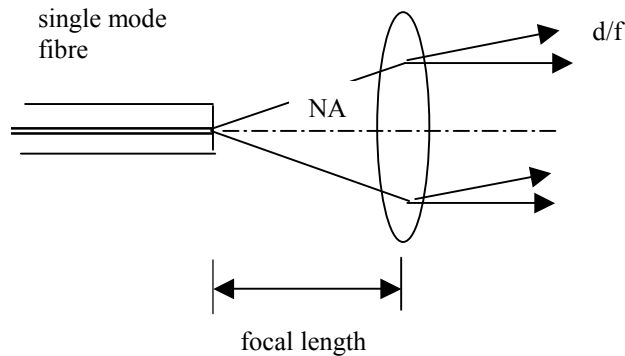


Figure 24. Matching fibre illumination to free space optics.

When coupling light into and out of optical fibres it is necessary to consider the mode field diameter of the light within the fibre and the numerical apertures of the optical fibre and the coupling lens.

Consider a fibre, shown in figure 24, with a mode field diameter d emitting light diverging at a specific numerical aperture (NA) to illuminate a collimating lens of focal length f . The finite size of the fibre core, the apparent source of the diverging beam, will limit the collimation to a divergence angle of d/f . When a 100 mm focal length lens is used in conjunction with a fibre core diameter of 8 μm the divergence angle is 80 microradians. If a 5 mm focal length lens is used the divergence is 1.6 milliradians.

In order to collect the light the lens must obviously subtend an NA larger than that of the diverging light. The NA of light leaving the single mode fibre can be defined as $\text{NA} = 2\lambda / \pi d$. For a fibre with an 8 μm mode field diameter at a wavelength of 1550 nm the NA is calculated to be 0.12. The same principles hold in reverse when illuminating the fibre. To produce a focused spot 8 μm in diameter the NA of the illuminating cone must be larger than 0.12.