NPL REPORT CETM 41

March 2002

POLARISATION EXTINCTION RATIO – MEASUREMENT REQUIREMENTS FOR OPTICAL COMMUNICATION SYSTEMS

R F Stevens
Centre for Electrical and Time Metrology
National Physical Laboratory
Teddington, Middlesex

ABSTRACT

This report describes requirements for the measurement of polarisation extinction ratio (PER). PER is a parameter used to describe certain polarisation effects in optical fibres and components for optical fibre communication systems. The meaning of PER is discussed and methods for measuring it. Industrial specifications are considered and future work at NPL proposed.

National Physical Laboratory
Teddington, Middlesex, UK TW11 0LW

ISSN 1467-3932

Approved on behalf of the Managing Director, NPL
by S Pollitt, Head, Centre for Electrical and Time Metrology

EXECUTIVE SUMMARY

Polarisation extinction ratio is a power ratio measurement that is used to describe power exchange between polarisation states in optical fibres and components used in optical communication systems.

While the concept of PER is relatively simple, the parameter can be ambiguous and confusing to interpret because the resulting polarisation state is a function of the phase difference between the components that are measured to give the PER power ratio.

An example occurs with optical fibre. In theory, light guided within a perfectly formed monomode fibre will retain its polarisation state. In practice, the core shape varies with distance along the fibre and, for various reasons, non-uniform stresses are present. The result is a degree of birefringence which leads to arbitrary polarisation states for the transmitted light.

Strongly birefringent (Hi-Bi) fibre is designed to minimise the power exchange between polarisation modes and PER values greater than 35dB are typical. While it is possible to transmit linearly polarised light by launching into one axis of the Hi-Bi fibre it is also possible to launch at 45 degrees to the axes and achieve a linearly polarised output when there is zero phase difference between the polarisation components. A problem then occurs if the relative phase is disturbed by, for example, moving the fibre. The resultant polarisation can be cycled through linear, circular and elliptical polarisation states.

Other components for which PER is specified include emitters, couplers, splitters and modulators. Sometimes relatively low PER values have to be specified accurately. Optical engineers often build up a knowledge of a system by adding one component at a time and measuring PER. PER meters are commercially available and techniques for exploring the phase of the polarisation components are recommended but, despite this, repeatablity of measurement results is often a problem.

What appears to be lacking is a stable reference standard against which measurements can be compared. Monomode fibres with specifed values are available but are subject to the problems described above. It is proposed that NPL provides a reference artefact for the calibration of polarisation extinction ratio measurements.

TABLE OF CONTENTS

FIGURES

.

1. INTRODUCTION

An optical communication network consists of an optical source, a method of modulating the light from the source, optical fibre to guide the light and a detector to convert the optical information to electronic form. Various components such as amplifers, filters and connectors may be also be present in the system. The rate at which data can be transmitted is limited by optical effects that cause the individual light pulses to spread and eventually overlap. Some of these effects are due to polarisation variations and since most optical components in the network will have an effect on the polarisation of the transmitted signal, polarisation-related effects are an important issue.

A variety of parameters have been defined and measured to enable the optical properties of components to be deduced and the effect of changes to a system to be predicted. Examples of polarisation-related parameters are:

i) degree of polarisation (DOP) – the ratio of polarised light to non-polarised light
ii) polarisation dependent loss (PDL) – a measure of the dependency of the loss of a device on the input polarisation state.
iii) polarisation dependent response (PDR) – response of an instrument as a function of polarisation state
iv) polarisation dependent gain (PDG) – amplification that is dependent on polarisation state
v) polarisation mode dispersion (PMD) – in a single mode fibre, different polarisations arrive at different times leading to pulse broadening, bit errors and bandwidth limitations.
vi) differential group delay (DGD) - induced by polarisation variations, it is the instantaneous group delay difference between polarisations in a fibre.

Polarisation extinction ratio (PER) is the subject of this report. It describes 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. This is a polarisation cross-talk effect and can be quantified by the parameter, polarisation extinction ratio.

While this report is concerned with the measurement of PER for telecommunications applications it is noted that areas such as optical sensing make use of fibres and a knowledge of the polarisation characteristics is required.

2. POLARISED LIGHT

Light is electromagnetic radiation and linearly polarised light is light whose transverse vibration has a simple pattern [1]. For linearly polarised light the direction of the electric vector remains in a fixed plane as the light propagates whereas for unpolarised light, the magnitude and direction of the electric field vector changes rapidly and randomly with time.

In figure 1(1), a light wave is represented with vibrations of the electric vector in a horizontal plane and is said to be polarised linearly and horizontally. The diagram to the right of the figure represents a sectional pattern. In figure 1(2) the light is polarised linearly and vertically. In figures 1(3) and 1(4) the light is represented by a helix and the sectional pattern is a circle. The light is said to be polarised circularly and in fig 1(3) it is in a right hand state. Figure 1(4) represents light which is polarised circularly in a left hand state. Linear and circular polarisations are considered to be special cases of the general form of elliptical polarisation [2].

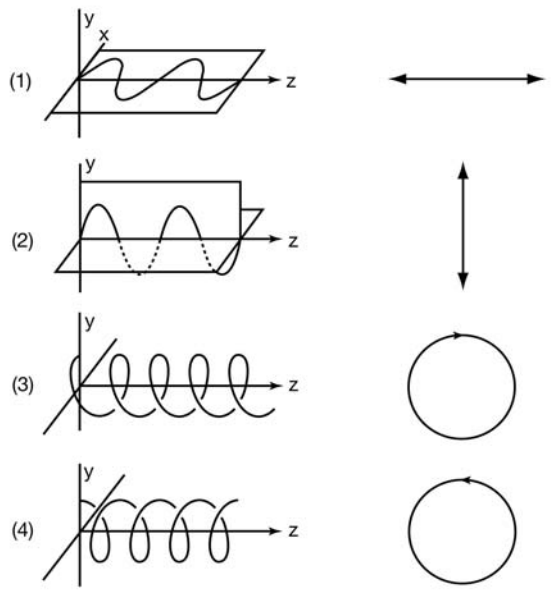

Figure 1. Diagrammatic representation of linear and circular polarisation states.

Mathematical descriptions of polarised light make use of vectors, matrices and calculus [3]. The Stokes vector was invented in 1852 and can be used to describe all states of polarisation for incoherent light, including mixtures of polarised and unpolarised light. It is used to predict the effect of combining two incoherent beams and the effect of adding a polariser or a retarder such as a half waveplate. The Stokes vector is based on intensity, not amplitude and has four components (I,M,C,S). The first parameter represents the intensity of the beam. M represents horizontal linear polarisation, C represents linear polarisation at 45 degrees and S right-handed circular polarisation. When the beam is completely polarised $I^2 = M^2 + C^2 + S^2$. When the beam is partially polarised $I^2 > M^2 + C^2 + S^2$. When passing a beam through several optical devices, each device can be represented by a Mueller matrix which acts on the input Stokes vector to give an output Stokes vector. In principle, the Stokes parameters for a beam can be measured using four ideal filters.

The Jones vector was invented in 1941 and can be used to describe completely polarised coherent light. It can predict the result of adding coherent beams but cannot cope with unpolarised or partially polarised light. Monochromatic light may be completely described by four quantities which specify the magnitude and phase of the electric field in two orthogonal directions. The relative magnitudes and phases of these components completely determine the polarisation ellipse.

The effect of adding polarisers and retarders to a polarised beam is calculated by multiplying the Jones vector of the incident beam by matrices that represent the components to give the Jones vector of the emerging beam. A 2 x 2 Jones matrix is used to represent each optical component and the Jones vector is multiplied by the Jones matrix to give a new vector that describes the transmitted light. This is repeated for subsequent components.

2.1. Poincaré Sphere

The Poincaré sphere is a convenient three-dimensional aid for representing different polarisation states. It is used as a map to plot the effect on a polarised beam of adding a polarisation sensitive component such as a retarder. A point representing the initial polarisation state is located on the sphere and an arc drawn on the sphere surface to locate another point that represents the new polarisation state.

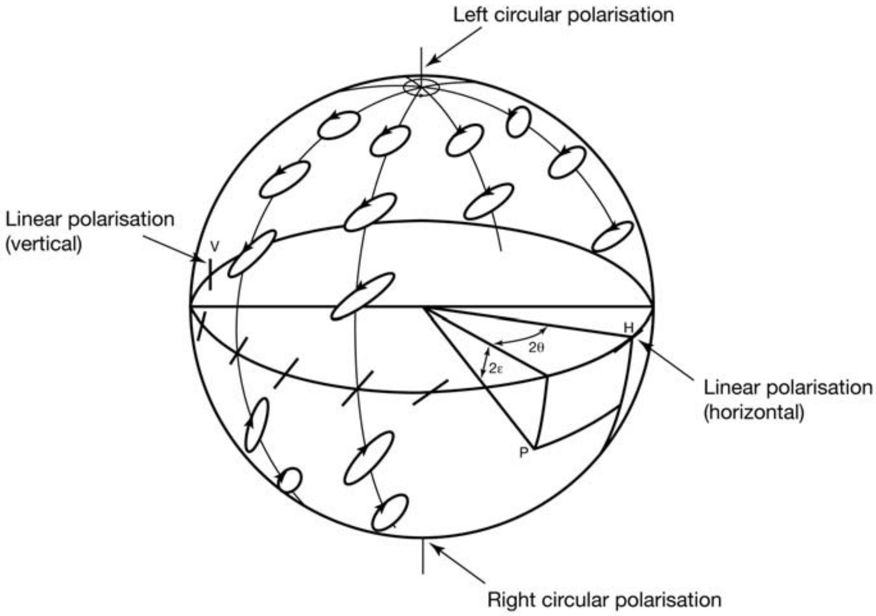

Figure 2. The Poincaré sphere is a three-dimensional surface on which all polarisation states are represented.

For polarised monochromatic light the polarisation state can be represented on a sphere of radius I, which for convenience is taken as unity. The x, y, z coordinates of a point on the surface of this sphere are (M,C,S). Points on the equator represent linearly polarised light.

The north pole represents right-hand circularly polarised light and the south pole represents left-hand circularly polarised light. Other points represent elliptically polarised light. The effect of a component or retarder on a polarised beam is found by locating the input polarisation P on the sphere. The retarder is identified by another point R corresponding to the polarisation state which is unchanged passing through it. The input state is then "rotated" about the radius of the sphere through an angle equal to the retardance to obtain the output polarisation state P'.

3. POLARISATION EFFECTS IN FIBRES

Light guided by optical fibre is constrained to the fibre core by total internal reflection (TIR) at the fibre walls. This is a process that introduces phase changes that are a function of the polarisation state of the incident light [4]. Linearly polarised light guided within a perfectly symmetrical monomode fibre will retain its polarisation state. In practice however, it is not possible to form a perfectly cylindrical fibre or to keep it in a straight line and it is inevitable that there will be some asymmetry, due to noncircularity of the fibre core or as a result of strain in the fibre. Fibre packaging also introduces stresses and special consideration is given to the packaging design [5]. Bending the fibre will induce linear strain, twisting will induce circular strain and strained fibre will exhibit birefringence.

Linearly polarised light can be resolved into orthogonal components and when launched into the fibre these components will have different phase velocities. Coupling between components and random variations in the phase velocity will have the effect of varying the state of polarisation along the length of fibre in an unpredictable way.

Instead of trying to produce a perfectly symmetrical fibre that will maintain the polarisation state, an alternative approach is to deliberately introduce a significant amount of birefringence. If n_x and n_y are the refractive indices for orthogonally polarised modes in the fibre, the degree of birefringence is defined by

$$B = n_x - n_y$$

High birefringence may be achieved by forming an elliptical core or by doping the cladding in an asymmetric manner. Asymmetric stresses may be induced by surrounding the circular core of a single-mode fibre by zones having cross-sections in the shape of a bow tie. Fibres with two circular zones are often called "panda" fibres and a typical cross-section is drawn in figure 3. Where the birefringence is large the phase velocity differences are large and the coupling between modes is difficult. Fibre with phase velocity of the order of 10^{-3} of the light velocity is known as "hi-bi" and light launched into one of the axes will tend to stay there.

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.

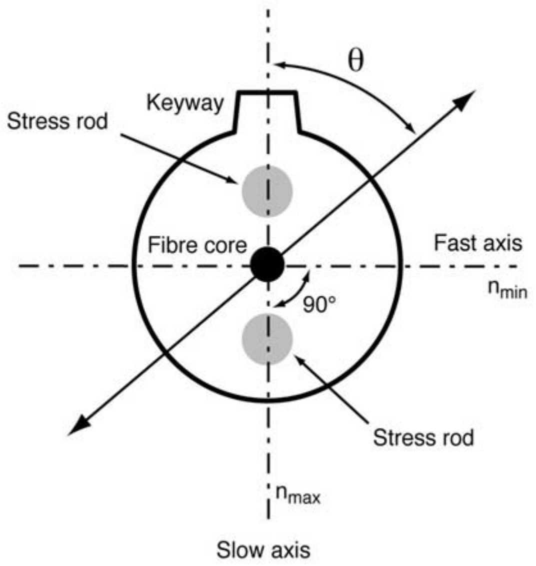

Figure 3. Birefringent fibre and polarisation axes.

Highly birefringent fibres are used to guide linearly polarised light and to maintain the polarisation state. A typical application is use as polarisation-maintaining patchcords to guide light from a source to a system over a few metres in a laboratory.

3.1 Polarisation Extinction Ratio

For polarised light incident on a polarising filter and analyser, the polarisation extinction ratio (PER) is defined as the ratio of power transmitted by the device when the polarisation axes are aligned compared with the condition when the axes are crossed.

$$\text{PER (dB)} = 10 \log_{10} (P_{\text{pass axis}} / P_{\text{crossed axis}})$$

As discussed earlier, if plane polarised light is launched into one axis of a birefringent fibre, usually the slow axis, 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. This is a polarisation cross-talk effect and can be quantified by the polarisation extinction ratio. PER is defined here as the inverse ratio of optical power that is passed from the transmitted polarisation state into the orthogonal unexcited state.

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

For a perfect system with no cross talk the PER value is infinite. In practice PER values of 20-30 dB are typical for birefringent fibre and 10-20 dB is acceptable in many cases. The PER value is a strong function of the angular offset between the angle of polarisation of the launched light and the principle axis of the fibre. It is also dependent on the length of fibre and environmental conditions.

Other components for which PER is a useful parameter include multiplexers, modulators and pigtailed devices such as laser sources.

3.2 Phase Effects in Birefringent Fibre

As we have seen the final polarisation state of the light emergent from "hi-bi" fibre is a function of the phase relationship between the two orthogonal polarisation components. For example, linearly polarised light launched at 45 degrees to the principal axes will excite both states equally which will then travel at different speeds in the fibre. A typical value for the speed difference is 1-2 picoseconds per metre.

If the phase difference between the emerging states is a quarter wavelength, the light will be circularly polarised and the measured PER will be zero. In between these states the light will be elliptically polarised. If the phase difference between the emerging states is zero then the light will be linearly polarised and at 45 degrees. A high PER value will be measured.

If there is no cross coupling in the fibre it is also possible to achieve a high PER value by launching linearly polarised light aligned with one principal axis.

In highly birefringent fibre the degree of birefringence can be be seen by observing the light that is scattered from the fibre when the input is linearly polarised at 45 degrees to the principal transverse axes. The different phase constants cause the polarisation modes to run in and out of phase at a rate determined by the birefringence, producing periodic variations in the transmitted polarisation states from linear to circular and back again. The period, known as the beat length L_B, is given by

$$L_B = \lambda/B$$

B is the degree of birefringence and λ is the wavelength of the light. The radially scattered light is a function of the polarisation and the ability of hi-bi fibre to maintain the linear polarisation state is limited by Rayleigh scattering which feeds a small amount of power into the unwanted polarisation.

All this illustrates the need for the phase relationship of the two principle polarisation states to be known in order to put a full meaning to the PER value. The problem lies in choosing an appropriate method for exploring the phase relationship and this is discussed by Haigh [6].

4. POLARIMETRY

Polarimeters are instruments that have been developed in many forms, some for measuring optical rotation and others for determining the complete polarisation state of light [7].

4.1 Optical Rotation

When linearly polarised light travels through certain materials the vibration direction changes but the type of polarisation remains unchanged. The increment in polarisation angle can be measured with a polarimeter. A simple polarimeter uses a fixed polariser, and an adjustable polariser as an analyser which is rotated until minimum transmission is observed. The sample is introduced and the adjustable polariser rotated again until another minimum is achieved. In some polarimeters a half wave plate is rotated to align the linearly polarised light.

The light flux transmitted by two linear polarisers aligned at angle θ is proportional to $\cos^2 \theta$. If the second polariser is rotated once through 360^0 the transmitted light flux will alternate through extreme values in succesive positions of the polariser differing by 90^0. The values will be maxima at $\theta = 0^0$ and 180^0 and minima at $\theta = 90^0$ and 270^0.

If the first polariser transmits linear polarisation there will be complete absorbance at $\theta = 90^0$ and 270^0. If for any reason the polariser polarises elliptically there will be only partial absorbance. The same effect occurs when the analyser is kept steady and the polariser is rotated. For light without any preferred direction of polarisation no change at all in the light flux will be found.

To enable the minimum transmission settings to be determined more precisely, split-field polarisers are used and a balance obtained between the intensity in two halves of the field. While high precision can be achieved with visual settings, photoelectric detection increases the consistency of measurement and the spectral range. A precision of 0.001 degrees is typical.

In electronic polarimeters the split-field principle is realised by a light intensity variation method. Faraday discovered that when a magnetic field is applied to certain substances they become optically active and rotation of the polarisation vector with distance travelled can be observed. In the polarimeter, a Faraday modulator is placed between the test object and the analyser, or polariser, and an alternating magnetic field imparts an optical rotation to a glass core that transmits the test beam.

Optical rotation is circular birefringence. An incident beam which is linearly polarised is divided into right and left-hand circularly polarised components which travel at different speeds through the test medium. When recombined the resultant plane of polarisation has a different orientation. If the two refractive indices and path lengths are known the retardance value can be calculated.

When light is reflected back to retrace its path through an optically active medium, such as a sugar solution, the rotation cancels. The oppposite occurs where the optical activity is induced by the Faraday effect. In this case, if the light is reflected back along its path the rotation is additive and does not cancel.

Ambiguities can occur when measuring optical rotation and it is necessary to consider whether the polarisation has rotated by an angle θ or mutiples of θ and whether the plane of vibration was rotated clockwise or anticlockwise.

4.2 State of Polarisation Measurements

An instrument that measures all four Stokes parameters or all three normalised Stokes parameters to derive the state of polarisation may be called a complete polarimeter. This is distinct from an instrument that measures, for example, optical rotation.

A variety of methods can be used to measure the state of polarisation [8]. They include adjustable combinations of retarder and analyser, continuously moving elements, polarisation-modulating elements and interferometry. Some are designed specifically for use with optical fibres. One such instrument measures the four Stokes parameters using a retarder (quarter wave plate), polariser and photodetector. Several measurements of intensity are made with the compensator and analyser in prescribed relative positions. In practice the analyser is fixed and the compensator rotated constantly to generate a sinusoidal variation of intensity at the detector in the form of a base sine wave with a superimposed harmonic component. The Stokes parameters are determined using a discrete fourier transform. The properties of the retarder will vary with the illumination wavelength, which must be known precisely.

In a different version of the instrument the compensator is removed and the analyzer continuosly rotated instead. The intensity variation measured by the detector is then a pure sine wave without any harmonic components. Although the measurement is independent of spectral bandwidth and wavelength it fails to determine one of the Stokes parameters and the method cannot differentiate between the circular components and non-polarised components of the radiation.

5. POLARISATION EXTINCTION RATIO METER

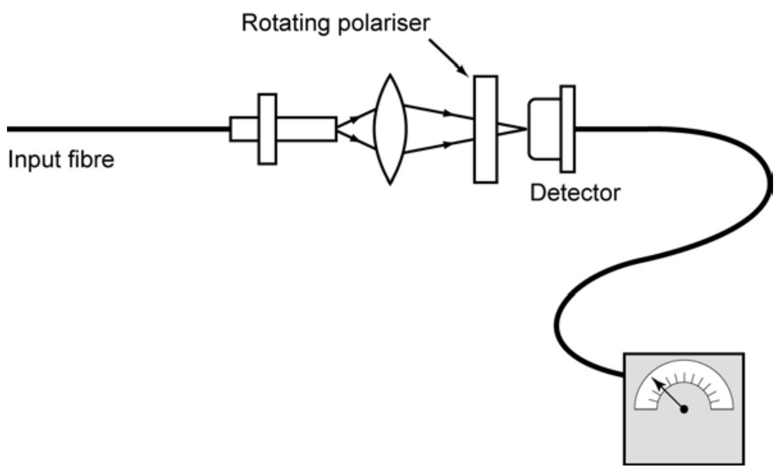

Figure 4. Polarisation extinction ratio meter in diagrammatic form.

A polarisation extinction ratio meter calculates the PER value from measurements of the amount of light in two orthogonal polarisation states. A simple system uses an adjustable polariser as an analyser and a detector to measure the optical power. By continually rotating the polariser the maximum and minimum orthogonal power levels in the light can be measured to give simultaneous readings of PER, polarisation angle and optical power. At least two manufacturers supply PER meters specifically for use with optical fibres or components [9,10].

It is not necessary to know the orientation of the principal axes of the fibre under test relative to the principle axis of the measurement optics in order to make the PER measurement. However, where the orientation of the polarisation axis is required it can be measured with respect to a fiducial mark, usually the connector keyway, and reference patchcords can be purchased to check these measurements. A typical specification is for the polarisation to be maintained to better than 30dB and the fibre aligned to within ± 1.5 degrees.

5.1 Phase Exploration

The relative phase of the two polarisation components is an important factor. If the two components are in phase they will recombine to form linearly polarised light. If not they will form elliptically polarised light. 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.

One way to explore this is to measure the PER and stress the fibre during by wrapping the fibre several turns round a mandrel 40–50 mm in diameter. Another technique is to heat the fibre with a lamp or a warming plate. The measured value of PER will go through several values and the lowest reading is usually taken as the reference specification. It is important to match the rate of heating to the response rate of the PER meter otherwise rapid changes may not be recorded. It is also useful to have a knowledge of the stress history of the fibre to understand the effectiveness of the stress introduced for the analysis.

By measuring the polarisation extinction ratios of light entering and leaving a polarisation maintaining fibre one can measure how well the fibre maintains polarisation. In most cases the output polarisation is limited by the fibre properties. A one-metre long connectorised patchcord constructed with PM fibre can maintain polarisation to at least 30 dB at a wavelength of 1300 nanometres.

It is possible that the behaviour of a device is not the same in both directions. 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 at the input end the polarisation may be perturbed before travelling through the fibre so the polarisation will vary.

5.2 Launch Alignment

How well a fibre maintains polarisation depends on the conditions under which the light is launched into the fibre. In a HiBi fibre PER is the ratio between the optical power in the fast and slow axis:

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

An important factor is the angular alignment between the polarisation axis of the light with the slow axis of the fibre (see figure 3). If 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:

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

Figure 5 shows PER values calculated as a function of launch angle offset to the slow axis. To achieve extinction ratios greater than 20 dB the angular misalignment must be less than 6 degrees. For a 30 dB extinction ratio the angular misalignment must be less than 1.8 degrees.

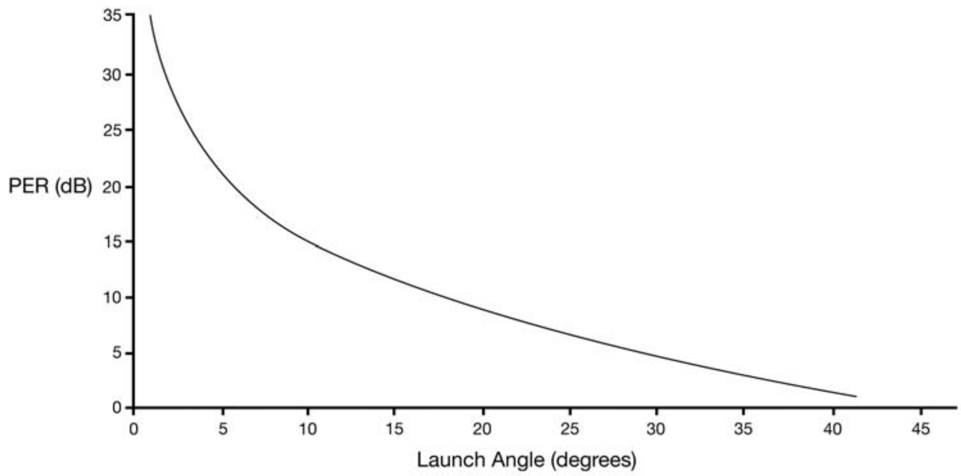

Figure 5. PER values calculated as a function of launch angle offset to the slow axis**.**

5.3 PER Analysis

Haigh reports a comparison of measurements taken with a polarimeter and a PER meter for polarised light launched into a polarisation maintaining fibre [5]. In one trial he plotted the measured PER values against polarisation angle to give a series of U-shaped plots. Some of the U-shaped plots so obtained were asymmetrical and he attributed this to an inability to smoothly stress all the polarisation states.

In another analysis a comparison was made with results obtained using a polarimeter and the U-chart figures were compared with the equivalent trace on a Poincaré sphere. It was concluded that the information obtained was similar but the U-charts revealed information that might be more easily overlooked during an analysis of the Poincaré arc.

6. INDUSTRIAL SPECIFICATIONS

PER values are specified for a range of components including optical fibre. Polarisation maintaining fibre is a particular example. Some manufacturers refer to PER as crosstalk A typical value is 30 dB at a wavelength of 1550 nm [11]. Other components for which PER is specified include modulators, laser sources, fibre-coupled (pigtailed) devices, polarisers, splitters and combiners. A typical extinction ratio value for a planar splitter with polarisation maintaining properties is 18 dB for an 8 way splitter and 16 dB for a 32 way splitter.

Lithium niobate modulators are highly birefringent and must be carefully aligned with respect to the polarisation axes of the incident light to obtain maximum modulation in the transmitted light. If the alignment is incorrect then some of the incident light fails to be modulated and is transmitted as background noise. PER values of 20 dB are specified.

Fibre-coupled (pigtailed) devices include laser diodes emitting in the visible and near infrared wavelengths. They are permanently connected to the optical fibre and sometimes include collimating optics with the package. PER values in the region of 15 dB are typical.

In-line polarisers are used to polarise and couple light to an output fibre. The polariser produces a linear polarisation state and a typical figure for the extinction ratio is 25 dB. They are designed to have a low insertion loss, typically 0.4 dB.

Polarisation controllers are used to create a range of polarisation states. The output is polarised to better than than 40 dB. PER meters are available commercially and a typical quoted accuracy of PER measurement is ± 1dB with a resolution of 0.1 dB. Polarisation angle resolution is of the order of 0.5 degrees.

Optical engineers often build up a knowledge of a system by adding one component at a time and measuring PER. While techniques for exploring the phase of the polarisation components are recommended by manufacturers of PER meters, repeatablity of measurement results is often a problem. Some is this is due to the variable transmission of the patchcords. Some engineers only need to know whether a component has a PER value greater than say 35 dB and high accuracy is not a requirement. Others need to measure to ± 0.5 dB at 35 dB and even more precisely at 15 dB. Feedback from industry has indicated that if a stable reference artefact were available that would assist in these measurements.

7. CONCLUSIONS

Polarisation extinction ratio is a parameter that is relatively simple in concept but sometimes ambiguous and confusing to interpret. It is a ratio of two power measurements that 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) length of fibre
iii) environmental conditions which lead to mode coupling

For linearly polarised light launched at 45 degrees to the axes of a hi-bi fibre, the emerging light can be linearly or elliptically polarised depending on the relative phase changes that occur in the fibre. It is also possible to achieve a high PER value by launching linearly polarised light aligned with one principal axis. Thus a high PER result is ambiguous unless the phase relationship is explored. This problem appears to be understood by engineers in the telecommunication industry and the manufacturers of PER meters supply test procedures.

There does not appear to be a great demand for traceablity of measurements of high values of PER. It is often sufficient to know that a fibre has a PER value greater than say 35 dB rather than the exact value. However a precise knowledge of the polarisation angle is important because PER is strongly affected by misalignment of the polarisation axes. The angular orientation of the connectors can be checked using calibrated patchcords.

With components such as splitters with lower PER values it becomes more important to have an accurate figure.

Suggested areas for future National Measurement System (NMS) involvement are:

i) Development of reference artefact for PER
ii) Calibration of polarisation maintaining patchcords

8. ACKNOWLEDGEMENT

This document has been produced for the Department of Trade and Industry's National Measurement System Policy Unit (NMSPU) under contract number GBBK/C/011/00005.

9. REFERENCES

[1] SHURCLIFF W A and BALLARD S S. *Polarized Light*. D. Van Nostrand Company, Inc. 1964.

[2] HECHT E and ZAJAC, A. *Optics*. 1974, Addison-Wesley Publishing Company.

[3] HUARD S. *Polarization of Light*. 1997, John Wiley & Sons.

[4] DAKIN J. *Optical Fibre Sensors: Principles and Components*. 1988, Artech House.

[5] YUZHONG DAI. Relation between external stresses and the degradation of extinction ratio of polarization maintaining fibers. *Proc. 16th National Fiber Optics Engineers Conf.* Denver, Aug 2000. **1**, 480-487.

[6] HAIGH N R and KEMSLEY S. Aspects of polarisation extinction ratio measurement. *Proc. 6th Optical Fibre Measurement Conference,* Cambridge, Sept. 2001. ISBN 0 946754 40 3, National Physical Laboratory

[7] CLARKE D and GRAINGER J F. *Polarized Light and Optical Measurement*. 1971 Pergamon Press.

[8] HAUGE P S. Survey of methods for the complete determination of a state of polarisation. *Proc SPIE meeting on Polarized Light,* San Diego 1976, **88,** 3-10,

[9] Santec Europe Ltd, Oxford OX4 4GA

[10] OZ Optics Ltd, Ontario Canada K0A 1L0

[11] SEZERMAN, O. and BEST, G. Accurate alignment preserves polarisation. *Laser Focus World* Dec. 1997, 27-30.