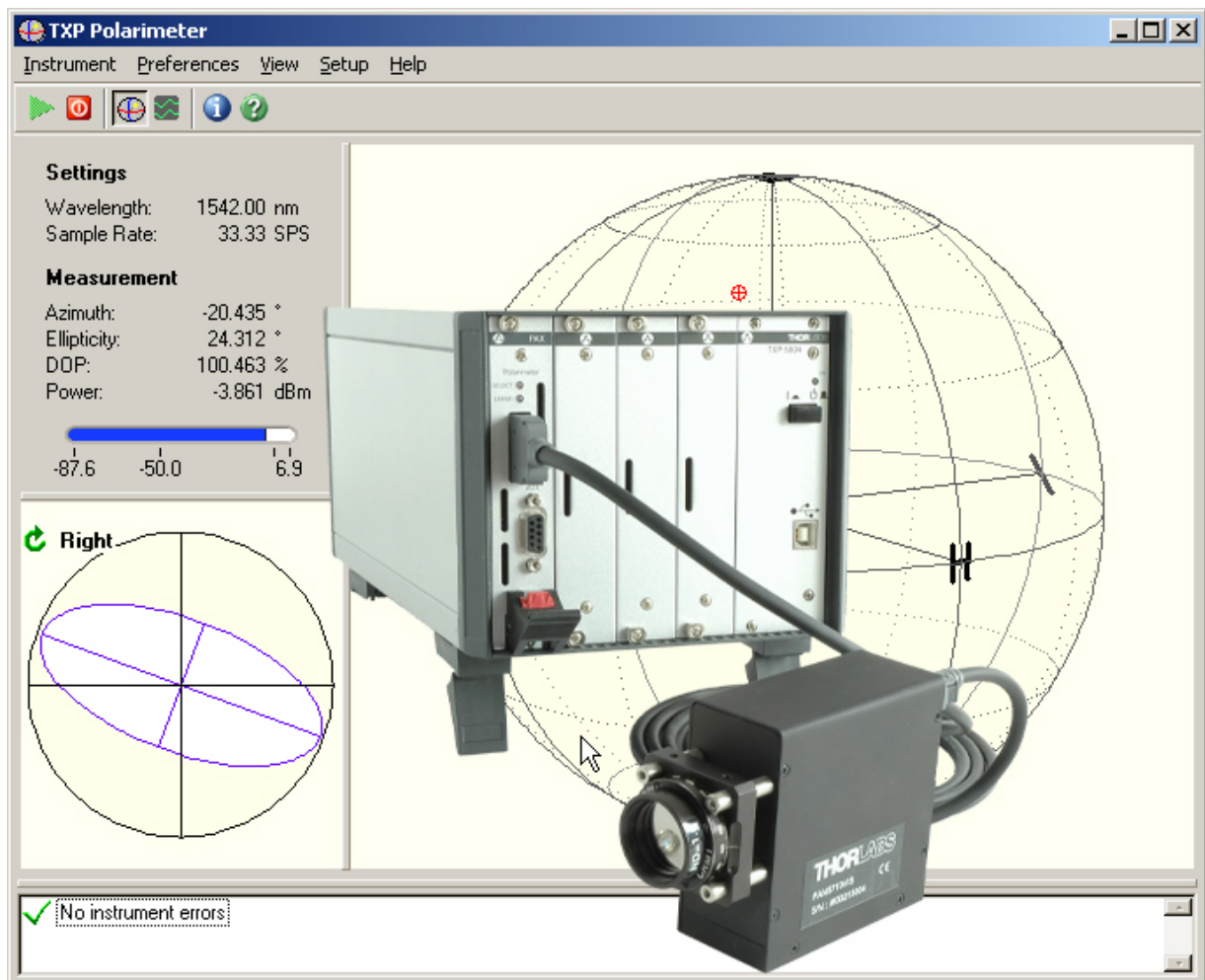# Operation Manual

Thorlabs Instrumentation

Polarization Analyzing System

PAX5710 / PAX5720
VIS / IR1 / IR2 / IR3

2008

THORLABS

Version: 1.5
Date: 05.03.2008

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We aim to develop and produce the best solution for your application in the field of optical measurement technique. To help us to come up to your expectations and develop our products permanently we need your ideas and suggestions. Therefore, please let us know about possible criticism or ideas. We and our international partners are looking forward to hearing from you.

Thorlabs GmbH

This part of the instruction manual contains every specific information on how to handle and use the PAX57xx Polarization analyzing system. A general description is followed by explanations of how to operate the unit remotely via the USB or Ethernet connection.

☞ Attention ☞

This manual contains "WARNINGS" and "ATTENTION" label in this form, to indicate danger for persons or possible damage of equipment.
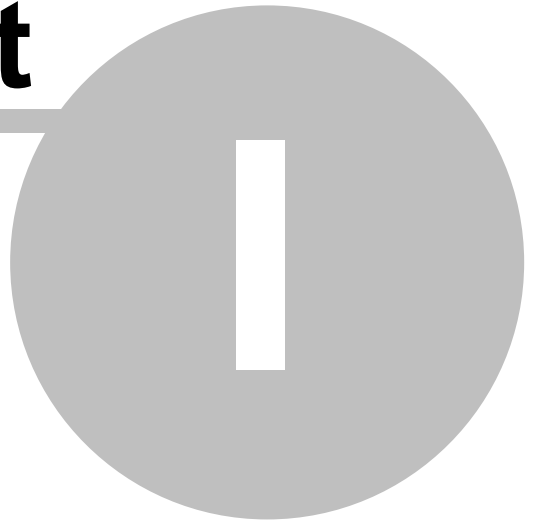
Please read these advises carefully!

NOTE

This manual also contains "NOTES" and "HINTS" written in this form.

General

PAX 57xx

Part I

1 General

1.1 Safety

<div align="center">

☝**Attention**☝

All statements regarding safety of operation and technical data in this instruction manual will only apply when the unit is operated correctly as it was designed for.

Before applying power to your TXP system, make sure that the protective conductor of the 3 conductor mains power cord is correctly connected to the protective earth (GROUND) contact of the socket outlet! Improper grounding can cause electric shock which may result in severe injury or even death!

All modules must be fixed with <u>all</u> provided screws provided for this purpose. Modules of the TXP5000 series must only be operated in mainframes of the TXP Series.

All modules must only be operated with proper shielded connection cables. Only with written consent from *Thorlabs* may changes to single components be carried out or components not supplied by *Thorlabs* be used.

This precision device is only serviceable if properly packed into the <u>complete</u> original packaging including the plastic foam sleeves. If necessary, ask for a replacement package.

</div>

1.2 Parts List - Accessories

A complete polarization analyzing system consist of a TXP mainframe, a PAX5710 card and a PAN5710xxx measurement head or a PAX5720 card with an internal measurement head. The polarimeter comes with different configuration depending on the order code:
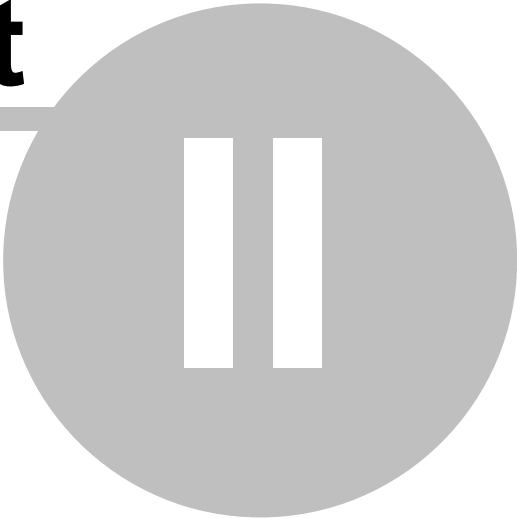
1. PAX5710xxx-T:
    *   TXP card for connecting an external measurement sensor
    *   Polarimeter measurement sensor for the specified wavelength range
    *   TXP5004 mainframe with USB interface
    *   I/O interface cable
    *   Collimation package appropriate to the wavelength range
    *   Hex key
    *   CD ROM with all software included

- Polarimeter and TXP operating manual
- USB cable

2. PAX5720xxx-T:
   - TXP card with an internal measurement sensor for the specified wavelength range
   - TXP5004 mainframe with USB interface
   - CD ROM with all software included
   - Polarimeter and TXP operating manual
   - USB cable

3. PAX5720xxx:
   - TXP card with an internal measurement sensor for the specified wavelength range
   - CD-ROM with all software included
   - Polarimeter operating manual

4. PAX5710xxx:
   - TXP card for connecting an external measurement sensor
   - Polarimeter measurement sensor for the specified wavelength range
   - I/O interface cable
   - Collimation package appropriate to the wavelength range
   - Hex key
   - CD-ROM with all software included
   - Polarimeter operating manual

5. PAX5710:
   - TXP card for connecting an external measurement sensor
   - CD-ROM with all software included
   - Polarimeter operating manual

6. PAN5710xxx:
   - Polarimeter measurement sensor for the specified wavelength range
   - I/O interface cable
   - Collimation package appropriate to the wavelength range
   - Hex key

7. TXP5004:
   - TXP5004 mainframe with USB interface
   - USB cable
   - TXP operating manual

8. There are four different wavelength ranges:
   - VIS: 400nm   -   700nm
   - IR1:   700nm   -   1000nm
   - IR2:   1000nm -   1350nm
   - IR3:   1300nm -   1700nm

Getting Started

PAX 57xx

Part

II

2 Getting Started

This section is provided for those interested in getting the polarimeter up and running quickly. The more detailed description and advanced features are described in the following sections.

2.1 PAX5710xxx-T Quick Start-up and Help Guide

1) Initial Software Installation

There are three different software components that must be properly installed and activated in order to allow USB control of your PAX5710xxx Polarimeter. All components must be installed prior to make any electrical connections between TXP mainframe and PC via USB interface.

A) Insert the "TXP 5000 Instrumentation CD " CD-ROM, included with your PAX5710xxx polarimeter. It automatically starts up and displays the installation start screen. Click on "Install TXP Series Software" button. The Windows Installer will guide you through the installation of the first two required components – the TXP PAX5710xxx GUI application and the TXP Server Control application. If an older TXP series version is detected on your computer, a dialog box will appear, informing you that you must remove the old application, before installing the new software. In this case, uninstall the old version (Control panel -> Software -> Remove) then restart the installation process.
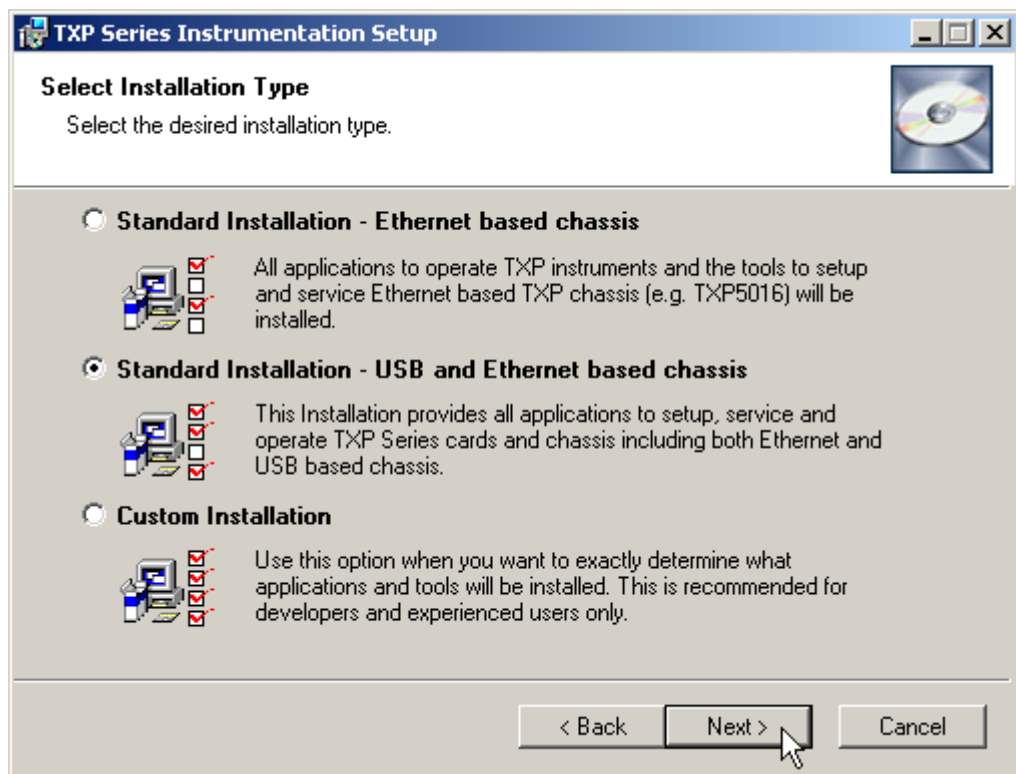
B) The following screen will appear:

Figure 1   TXP Installation Setup

Choose 'Standard Installation – USB and Ethernet based chassis' and click 'Next'.

C) During installation, the following screen may be appear:

Figure 2   **Windows Logo Message**

Ignore and click 'Continue Anyway'.

D) During the above installation you will be notified as to whether or not your computer already contains the required National Instruments' VISA files. If necessary you will have to install these files by clicking on the "Install NI VISA" button on the main installation screen.

2) Connect the PAX5710xxx-T to your computer using the USB cable provided with the unit, or a suitable USB cable and switch on the device. Now your computer should recognize the unit as "new hardware" and perform an initialization on the four USB slots available on the PAX5710xxx-T, even though you will be using only one. (For Windows XP: please press continue if a driver signature warning appears)

3) Connect the polarimeter head PAN57xxx to your PAX5710xxx card in the TXP5004 using the PAX cable provided with the PAN57xxx head.

4) Access the Programs List from START button and find the "TXP Series" listing. Click on this listing and then select "TXP Server Control". Follow the instructions while the TXP Server Control initializes and configures your computer to operate with your TXP based device. After completion, this application will run in the background on your computer. An icon will be placed on your task bar. Clicking on this icon various parameters of the TXP Server Control can be changed.

5) Access the Programs List from START button and find the "TXP Series" listing. Click on this listing and then select "TXP Polarimeter". The TXP

Polarimeter GUI will be started.

6) Please click the 'Green Arrow' in the toolbar.
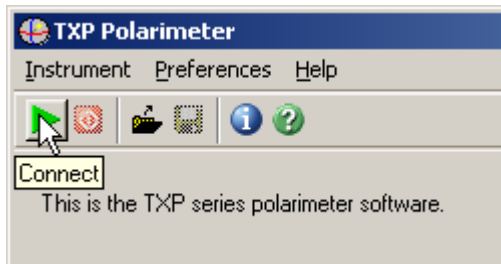
Figure 3   **Default Screen of the TXP Polarimeter GUI**

7) Choose 'This Computer' and click the 'Scan Cards <F5>' button. A list with available cards will appear. Select 'PAX5710 …' card and click the 'Select' button.
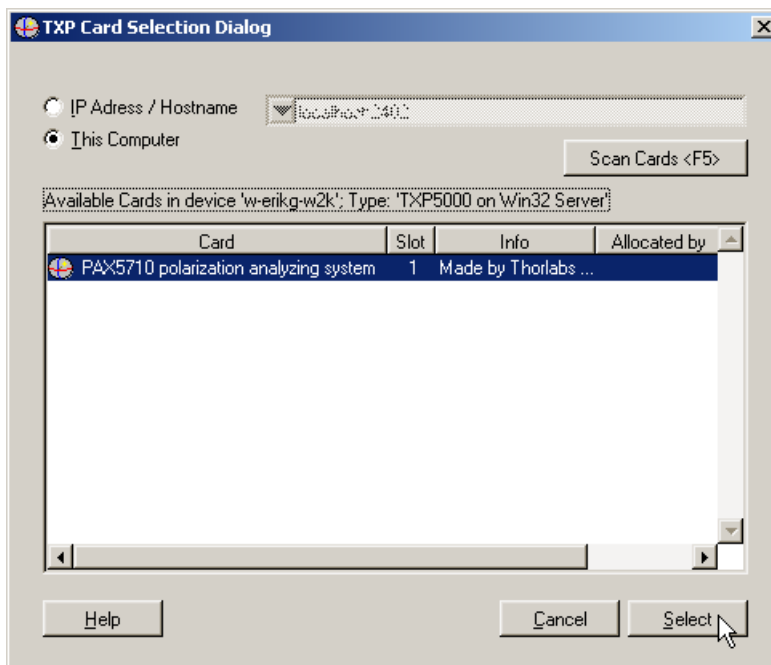
Figure 4   **TXP Card Selection Dialog**

8) The application will run.
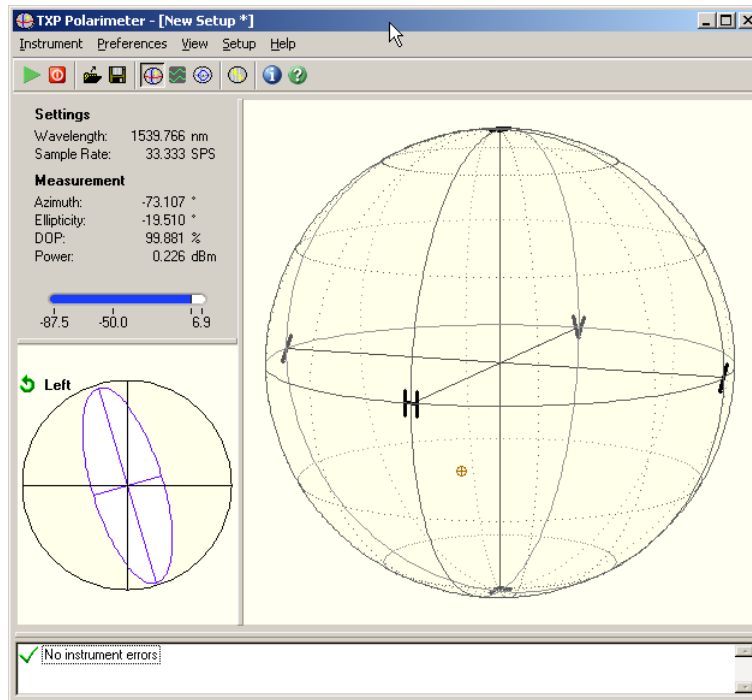
Figure 5   **PAX GUI**

9) General Comments

A) You can choose between Poincaré Sphere Mode, Scope Mode and ER
    Measurement Mode in the toolbar.

Figure 6   **PAX Toolbar**
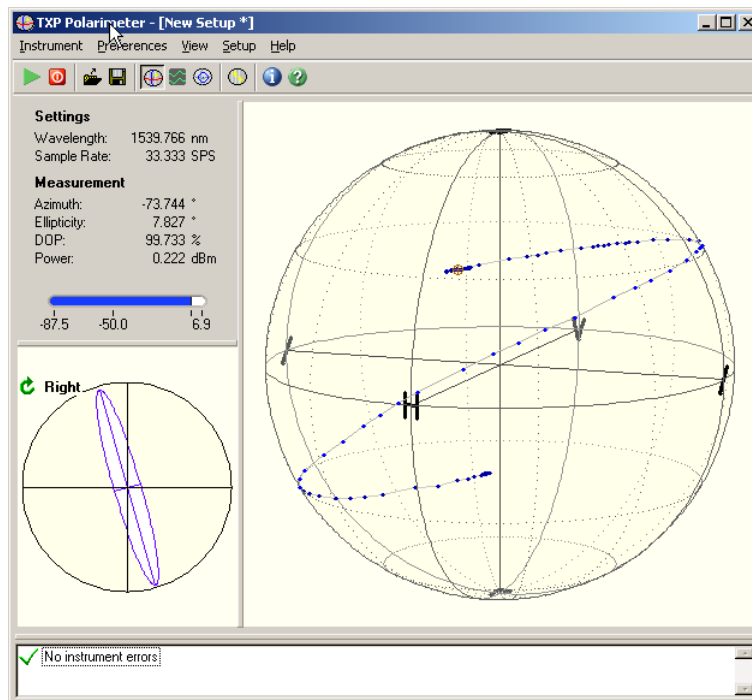
Figure 7 **Poincaré Sphere Mode**
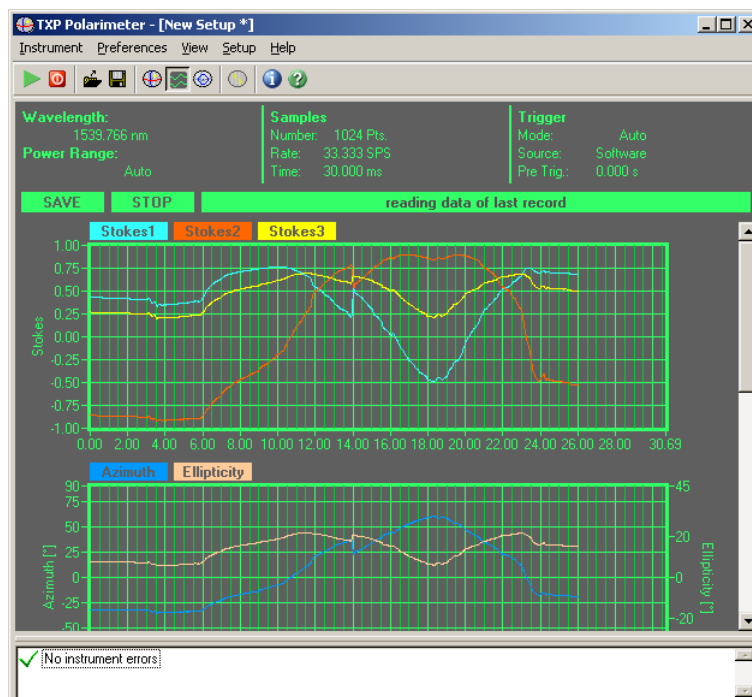
Figure 8 **Scope Mode**

B) Basic Measurement Setup
   Use this setup for:
   - Setting the Wavelength
   - Setting the Basic Sample Rate which corresponds to the waveplate rotation speed
   - Setting the Power Range
   - Azimuth Offset
   - SOP View Mode

C) Sphere Measurement Setup
Here you can choose different types of averaging.
D) Sphere Color Setup
Here you can set the colors and the appearance of the Poincaré Sphere.
E) Scope Measurement Setup
Here you can configure the scope mode.
F) Scope Color Setup
Here you can set the colors and the appearance of the Scope View.
G) Scope Scaling
Here you can change the scaling of the different graphs.

Please remark:

1) For accurate measurement results, you must enter the correct wavelength.
2) Align the laser beam right-angled to the front panel.

Hardware Description

PAX 57xx

Part III
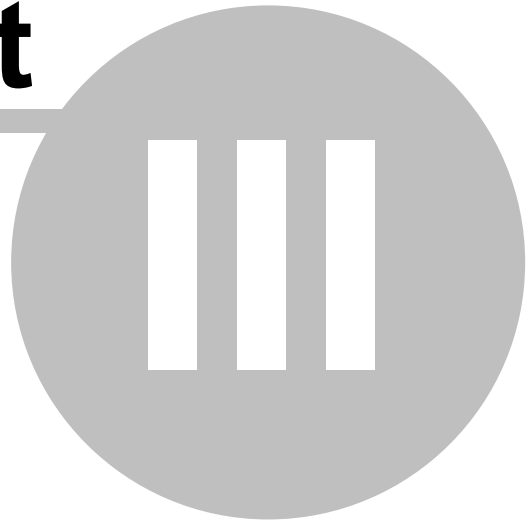
3   Hardware Description

The Thorlabs PAX5710 and 5720 Polarimeter system is a flexible and powerful polarization analyzing system based on the modular TXP platform. The polarimeter was designed for different applications ranging from classic polarization measurements, the determination of the Extinction Ratio of polarization maintaining fibers (PMF) and aligning of PMF to laser modules to complex tasks like evaluating of optical components with the Jones - or Mueller matrix algorithm.

Furthermore, in conjunction with the TXP modules DPC5500 and the ECL5000D, the PAX57xx enables a complete PMD and PDL measurement system to be built.

The PAX57xx is a rotating waveplate based polarimeter module for the TXP platform that enables measurements of the state of polarizations (SOP) for open beam and In-fiber applications. For more information about the rotating waveplate technique refer to the section Rotating Waveplate Technique. The external measurement head of the PAX5710 offers the possibility for easy integrating in an optical setup. All four Stokes values, which fully characterize a SOP, are provided either as analog output voltages or as digital values to the PC. The SOP measurement can be controlled via an external trigger function allowing the synchronization of the PAX5710 with other devices.

Designed for the Thorlabs TXP5000 modular Test & Measurement System the PAX5710 offers additional features like USB/Ethernet ports, 'plug and play' combination with other modules, flexible configuration via LabVIEW^{TM}, LabWindows/CVI^{TM}, MSVC and Borland C drivers, and easy to use graphical user interfaces.

3.1 Operating Elements

3.1.1 PAX5710

The PAX5710 is a polarimeter card with an external measurement sensor, and was designed for applications with an open beam. A removable collimation package allows fiber measurements to be performed.

LED's for:
- Module selected
- Error occured

I/O Connector for Polarization Measurement Sensor

9-Pin D-SUB Connector for analog Output and Trigger Input

Ejector Handle (Hot Plug Capability)

Mounting Screw

There are 4 holes to mount a 30mm cage system on the front panel. Optional an included fiber collimator can be used.

Mounting Screw

Polarization Measurement Sensor

Figure 9   PAX5710 Polarimeter with external Measurement Sensor

3.1.2 **PAX5720**

The PAX5720 was designed for fiber measurements only. The optical sensor is integrated into the polarimeter card and cannot be removed. The card is 2 slots wide and is ideal for measurements like extinction ratio (ER) measurements on polarization maintaining fibers (PMF) or polarization mode dispersion (PMD) or polarization dependent loss (PDL) measurements on fibers.

Figure 10   **PAX5720 Polarimeter with internal Measurement Sensor**

3.2   **The Auxiliary Connector**

Figure 11   **The Auxiliary Connector (D-SUB 9, female)**

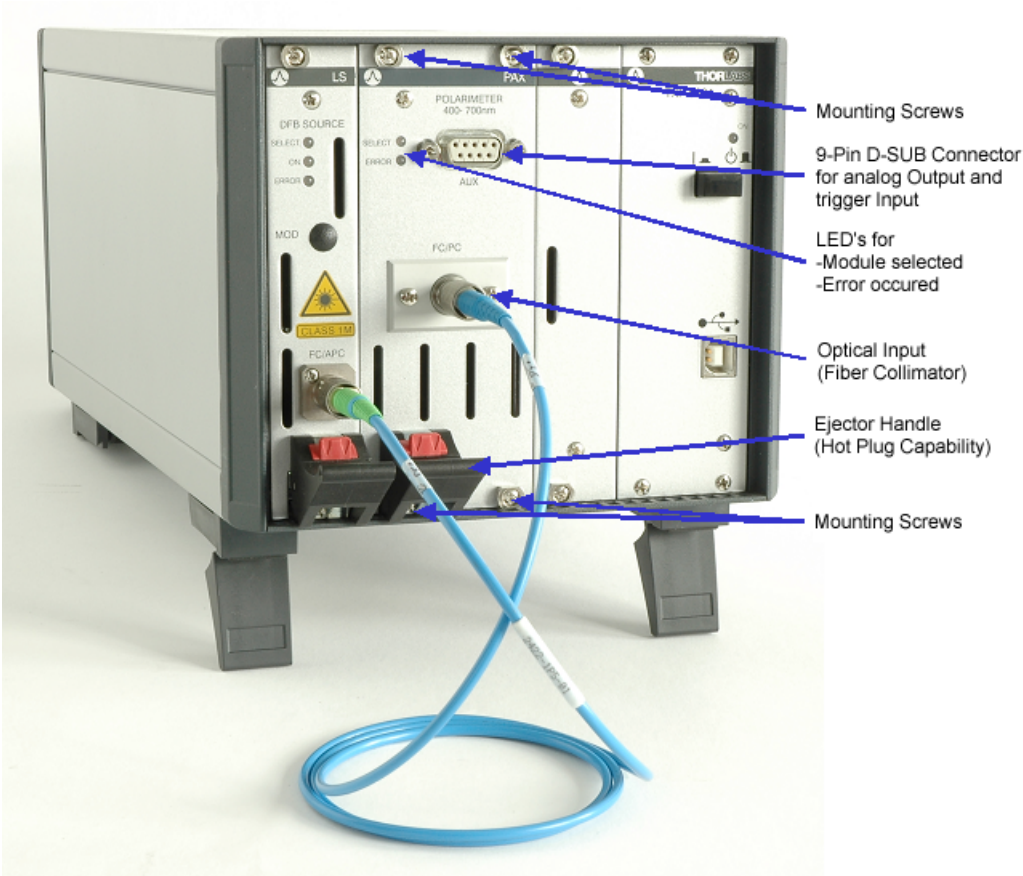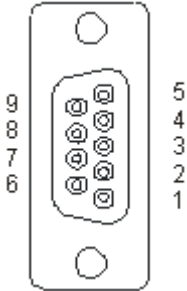| PIN	Name	I/O	Value	Function
1	Trigger	I	3.3/5V	External Trigger-signal (0V=L, 3.3 … 5V=H) (for array mode)
2	AGND			Analog ground
3	Power	O	-2.5 … +2.5V	Optical Power log. (-70dBm ... +30dBm)
4	s_3	O	-2.5 … +2.5V	Normalized Stokes Vector S_3 (-1 … +1)
5	s_1	O	-2.5 … +2.5V	Normalized Stokes Vector S_1 (-1 … +1)
6	DGND		-2.5 … +2.5V	Digital ground for Trigger
7	Analog In	I	-2.5 … +2.5V	Analog Control signal (not used here)
8	DOP	O	-2.5 … +2.5V	Degree of Polarization (0 ... 110%)
9	s_2	O	-2.5 … +2.5V	Normalized Stokes Vector S_2 (-1 … +1)

3.3 Installing and Removing Cards

The Thorlabs TXP series mainframes and cards are 'Hot-Swappable', which means you do not have to switch off the mainframe while exchanging cards:

- Loosen the two to four mounting screws on top and below the ejector handle
- Push the red button of the ejector handle and flip down the black ejector handle. This pulls out the card from its internal plug.

You can now remove the card. If you do not insert another card, please close the empty slot with a blind module to maintain a proper cooling air flow inside the unit. Tighten the two to four screws.

The external measurement head has also a hot-plug capability. The current setup, such as 'set wavelength', will be lost if you disconnect the measurement head from the card.

NOTE
All Slots of the TXP must be occupied, either by a card or by a blind module to maintain proper air flow for internal cooling!

Operating Instruction

PAX 57xx

Part

IV

4 Operating Instruction

This section gives an introduction to operating the PAX5710 / PAX5720.

4.1 Preconditions

1. You must install and initialize the connection between the TXP and your PC according to the manual of the corresponding TXP mainframe.
2. You must install the card specific software driver (normally installed together with the TXP Administrator and TXP Explorer). If this driver is not installed, proceed as follows:
   a) Insert the CD ROM delivered with the TXP / card into your CD-ROM drive.
   b) If the 'autorun' function is active on your PC, the installation program should start automatically. If not start the program 'TXP_Series_Instrumentation.exe' on the CD.
   c) The installation wizard leads you through the installation process. When prompted for the type of installation, select 'Custom Installation'. Then mark the components for the PAX modules and proceed with the installation.
3. Insert the PAX57xx card in your TXP mainframe (see Installing and Removing Cards).
4. Switch on the TXP if not yet done.
5. If you are using a TXP5004 mainframe you have to start the TXP Server Control before you can work with the application or the drivers.

The TXP system is now ready for operation and you can start the card specific graphics user interface (GUI).

4.2 The Graphics User Interface (GUI)

4.2.1 Start the GUI

The graphics user interface can be started by using the TXP Explorer, or by running the program: TXP_Polarimeter.exe

To start from the TXP Explorer:

1. Start the TXP-Explorer and connect to the desired mainframe .

   A system overview of the selected TXP mainframe is displayed (all TXP-Explorer details are explained in the mainframe manual):
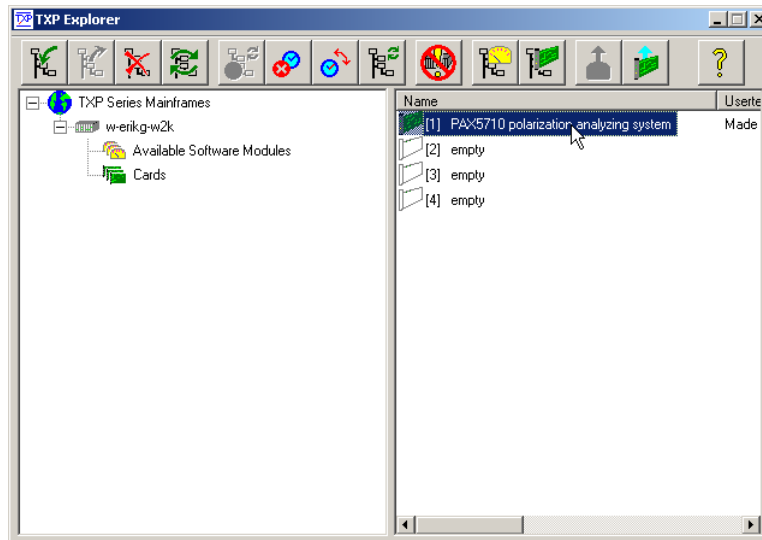
Figure 12   **The TXP Explorer Window**

2. Select the module you want to control (shown in slot [1] in the example above) and start the PAX specific operating program by clicking the button 'Launch card with its standard module' or by a left double click. The card specific operating software starts up (TXP_Polarimeter.exe):

To start the PAX application from the .exe file:

3. From the START menu, select 'Program Files / TXP Series / TXP Polarimeter / TXP_Polarimeter.exe'.

The following window appears.

Figure 13   **Default Screen of the TXP Polarimeter GUI**

Click the green arrow in order to establish a connection to the PAX card.

A 'TXP Card Selection Dialog' is displayed as shown below.
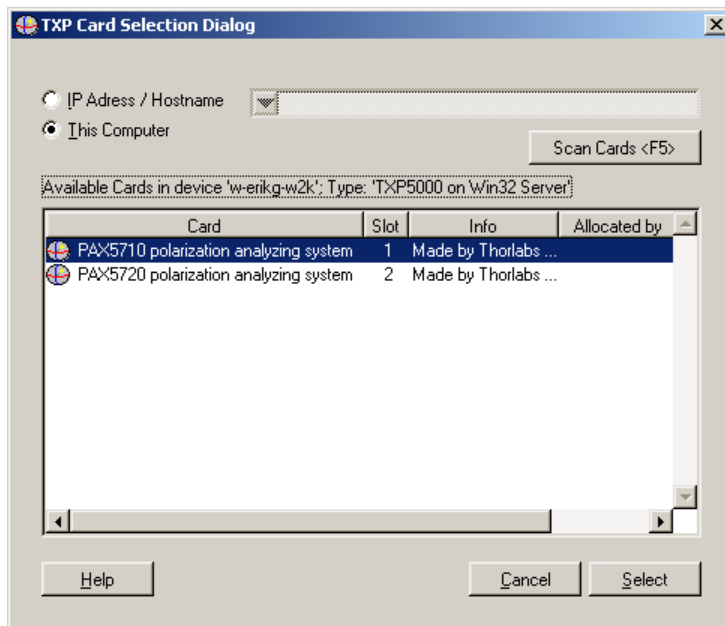
Figure 14   **TXP Card Selection Dialog**

4. TXP 5016 with Ethernet port only: you must enter the correct IP address or the hostname.

    TXP 5004 or 5001 with USB connection only: swap to 'This Computer' and click on the 'Scan Cards <F5>' button.

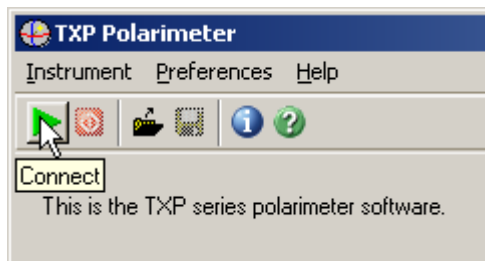   All available PAX cards will be shown.

5. Choose the PAX card and click the 'Select' button or double click on your choice. The TXP will initialize the PAX. This can last several seconds. During the initializing the message 'Card not ready (removed or initializing not yet finished)' appears. After a successful start up the motor of the polarimeter turns and measurement results are collected.

To start the PAX application from a setup (.txs) file:

6. From the START menu, select 'Program Files/TXP Series /TXP Polarimeter/TXP_Polarimeter.exe'.

    The default screen of the TXP polarimeter GUI appears. Click the folder symbol in order to open a file dialog. A 'File Dialog' is displayed as shown below.
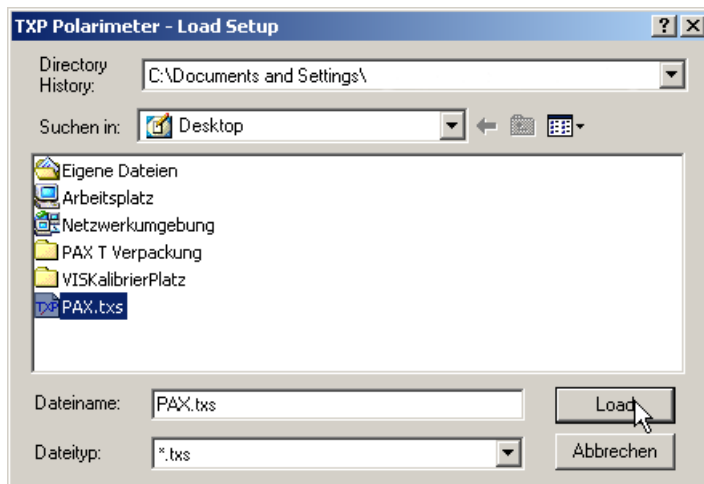
Figure 15   **Setup File Dialog**

7. Choose the desired setup file and click the 'Load' button or double click on your choice. The setup file is loaded. All necessary connection data are stored in this file.

8. If a different hardware, e.g. a different measurement sensor, is used a warning message appears. In this case some parameters like the wavelength may be modified.
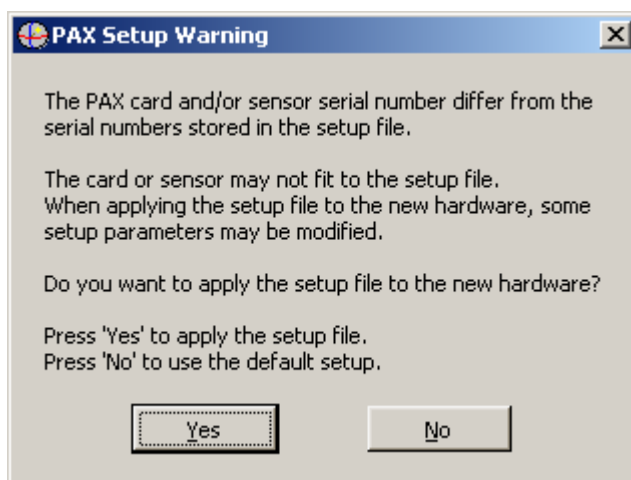
Figure 16   **Warning Message**

9. The TXP will initialize the PAX. This can last several seconds. During the initializing the message 'Card not ready (removed or initializing not yet finished)' appears. After a successful start up the motor of the polarimeter turns and measurement results are collected.

4.2.2   Starting the GUI from the Command Prompt

The graphical user interface for the PAX can also be started using the Command Prompt. This is convenient if the procedure to start the GUI as described in the Start the GUI section needs too long. Furthermore a shortcut can be created so that just a click is necessary to connect to a TXP card.

The following command line parameters has to be used to start the GUI quickly.

Command line syntax:
TXP_Polarimeter.exe [<setup file>] [/N<hostname> /P<port> [/S<slot> /M<module>]] [/T<timeout>]

<setup file>	Path and name of the setup file to load.
/N<hostname>	Hostname or IP-Address of a TXP-Mainframe to connect.
/P<port>	Port number of host.
/M<module>	Module to open (e.g. PAX)
/S<slot>	Slot number (range is 0 ... 63).
/T<timeout>	Timeout for the TCP/IP connection in ms.

Example (1): "TXP_Polarimeter.exe" /N10.10.1.102 /P2402 /S0 /MPAX /T2000

Example (2): "C:\Program Files\TXP Series\TXP polarimeter\TXP_Polarimeter.exe" /Nlocalhost /P2402 /S1 /MPAX /T10000

To create a shortcut on the desktop of your computer right click with the mouse on the desktop. Choose 'New' from the menu and then 'Shortcut'. Now you can browse for the TXP_Polarimeter.exe and add the command line parameters to the link.

NOTE
The TXP Server Control has to be started before you can connect to a card within a TXP5004.

4.2.3 Measurement Modes

There are three operating modes for the PAX.

1. **Poincaré Sphere Mode:** The PAX polarimeter measures one state of polarization after the other (Single Measurement Mode). The time for one measurement result depends on several settings such as revolution speed of the waveplate and the averaging.

   In the GUI, the update rate of the measurement results is independent of the sample rate. The program requests one data set after another. The PAX itself measures continuously. A request for a new single measurement provides only the latest data set.

   The polarization measurement results are displayed in three ways: numerically, graphically on the Poincaré sphere, and as polarization ellipse. The measurement results are also available as analog signals at the auxiliary output.

2. **Scope Mode:** You can analyze the input polarization and show the results in a linear diagram, plotted against time. The PAX collects up to 1024 measurement results continuously (Array Mode).

   The measurement results are transferred asynchronously to the GUI, i.e. the

first of n measurement points is displayed before the complete measurement is finished. This mode provides a defined time scale for the measurements. There is also the option to define a hardware trigger or to register pre-trigger samples.

3. **Extinction Ratio Measurement on Polarization Maintaining Fibers:** The PAX polarimeter offers this optional mode to analyze polarization maintaining fibers. Primarily the aligning of a laser diode and a PMF can be verified during the manufacturing. Furthermore also PMF can be characterized regarding the crosstalk.

4.2.4   Changing the Basic Measurement Settings

The basic measurement setup can be changed by selecting 'Setup' / 'Basic Measurement Setup' from the menu bar. These settings are valid for all measurement modes.
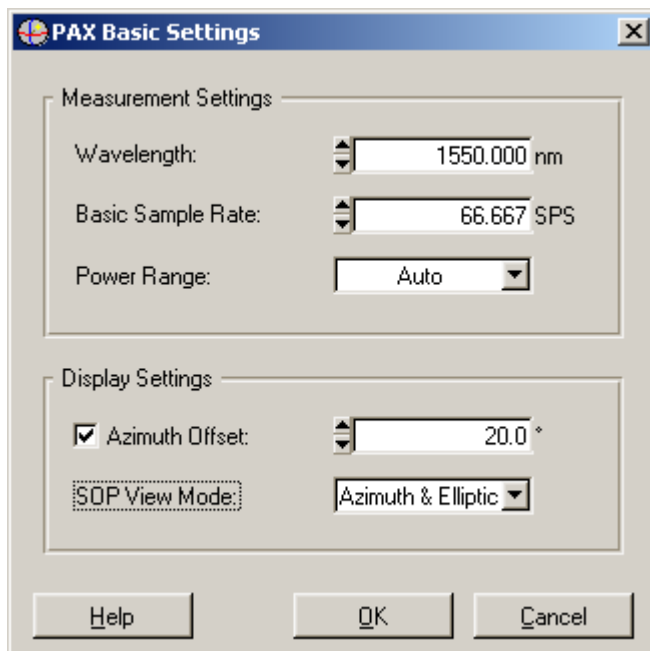
Figure 17   PAX Basic Settings

The 'PAX Basic Settings' window appears, where you can set the actual wavelength, the basic sample rate and the power range.

Wavelength - specified in nm. Depending on the measurement sensor used, the wavelength range can cover the visible area from 400nm to 700nm or three different infrared regions from 700nm to 1000nm, 1000nm to 1350nm or 1350nm to 1700nm.

Basic Sample Rate - specified in samples per seconds (from 66.667 to 333.333 SPS). One basic period is captured during a half turn of the waveplate. The basic sample rate is directly related to the rotation frequency of the motor. For more information about sample rate and averaging see the Rotating Waveplate Technique section.

Power Range – The measurement sensor has 5 gain settings and the corresponding power range depends on the wavelength selected. The maximum power setting for each range (at the selected wavelength) is displayed. The recommended and default setting is 'auto', whereby the optimum power range will be set automatically.

Azimuth Offset – specified in degrees. The azimuth is shifted by the azimuth offset. This parameter enables a user defined reference plane. To activate the offset click the check box.

SOP View Mode – The ellipse can be expressed by azimuth and ellipticity, by power split ratio and phase difference, or by the 3 normalized Stokes Parameters. See the Polarization Ellipse and Poincaré Sphere sections for definitions. The selection will effect the display of all measurement modes.

4.2.5   Poincaré Sphere Mode

The Poincaré sphere mode of the PAX polarimeter has been designed as a classical polarization application. The polarization is presented by a Poincaré sphere, an ellipse and as numerical values, which includes azimuth, ellipticity, power split ratio, phase difference, normalized Stokes Parameter, degree of polarization (DOP) and power. The individual windows for the numerical values, the ellipse and the Poincaré sphere can be resized by the customer. Individual graphs and parameters are described in the following sections.
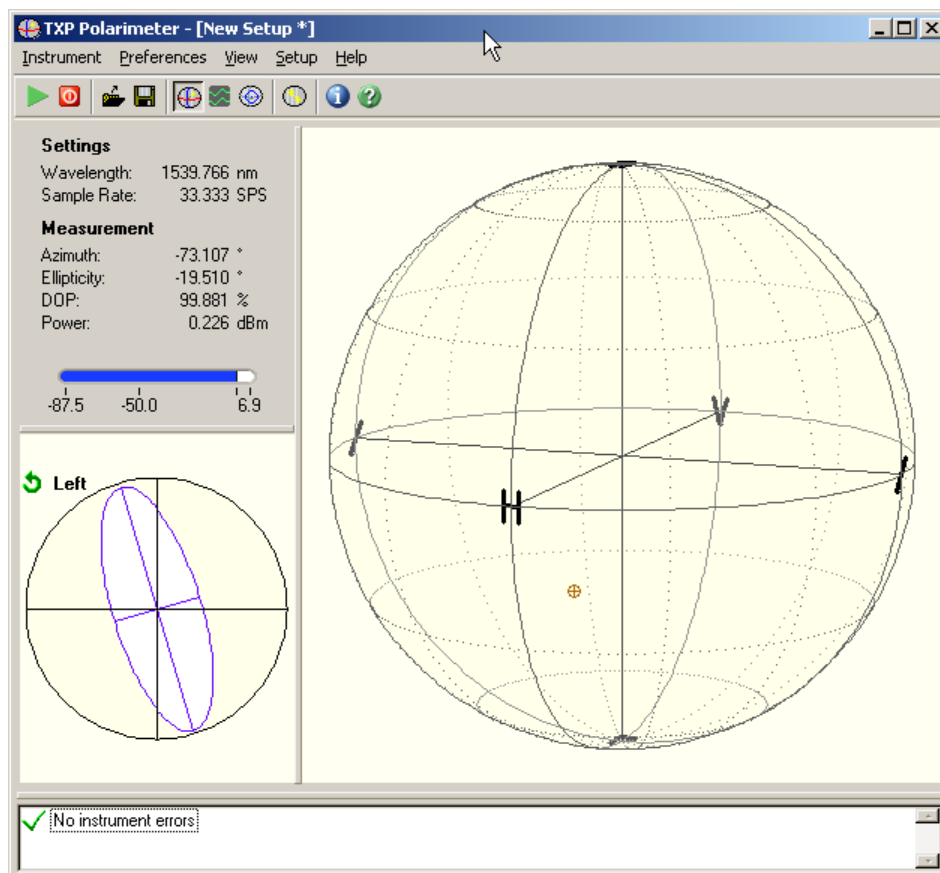

Figure 18   **Poincaré Sphere Mode**

4.2.5.1   **Poincaré Sphere**
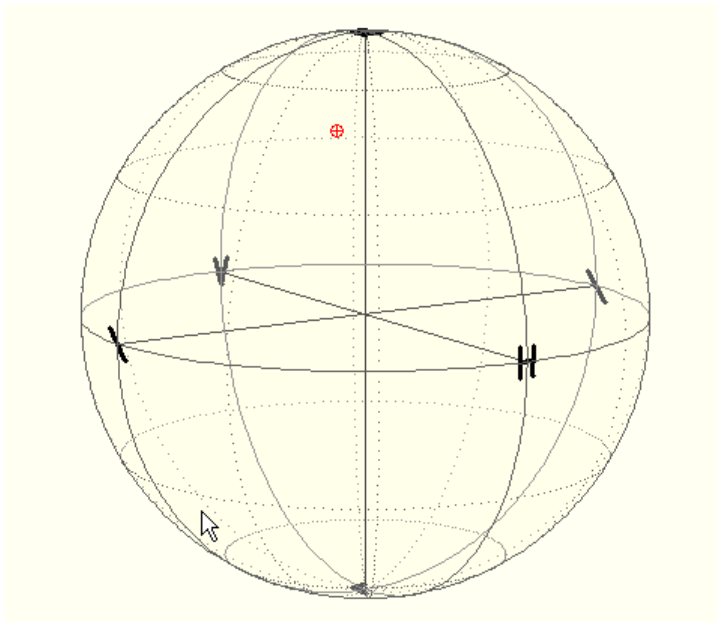

Figure 19   **The Poincaré Sphere**

The window 'Poincaré Sphere' shows the actual status of the output polarization on the sphere. The red marker represents the actual output polarization.

To rotate the sphere to a convenient viewing position, click the sphere and drag to a new position.

To zoom in or out of the sphere, press <Shift> then click and drag.

Polarization states on the front side of the sphere are shown in a preselected color. The default color is orange. If the polarization state is on the rear side the cursor's color is a little darker or brighter.
For details to change the Poincaré Sphere view settings see:
Poincaré View Preferences

4.2.5.2   **Ellipse**

The polarization status can also be viewed as a polarization ellipse. 'Right' or 'Left' handed polarization is shown on upper corner of the display. To change the appearance, see: Poincaré View Preferences
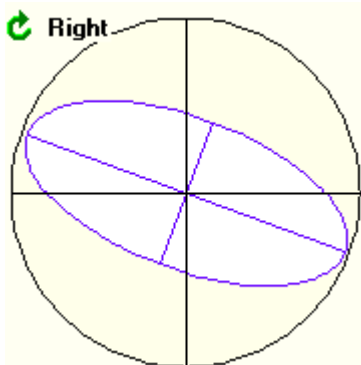
Figure 20   **The Ellipse**

4.2.5.3 Numerical Values

The numerical values of the current measurement are shown in the upper left corner of the main 'Poincaré Sphere Mode' display. The current wavelength and the resulting sample rate are shown, together with the polarization data: azimuth, ellipticity, degree of polarization (DOP) and the power (also shown as a graph). Instead of azimuth and ellipticity the parameters power split ratio and phase difference or the Stokes Parameter can be displayed.

Figure 21   Numerical Values in the Poincaré Sphere Mode

4.2.5.4 Differential SOP Measurements

The measurement of a differential SOP (dSOP) can be easily performed by using the dSOP measurement feature. Select from the menu 'View' / 'dSOP Measurement' or click on the button 🕐 'dSOP Measurement' from the toolbar to open the 'dSOP Measurement' panel.

Figure 22   dSOP Measurement Panel

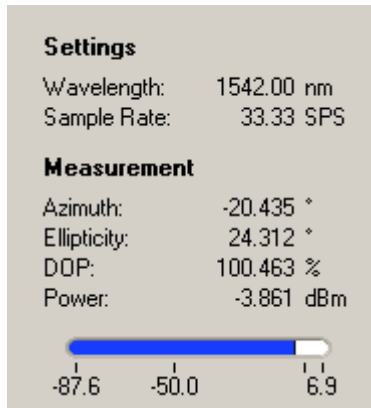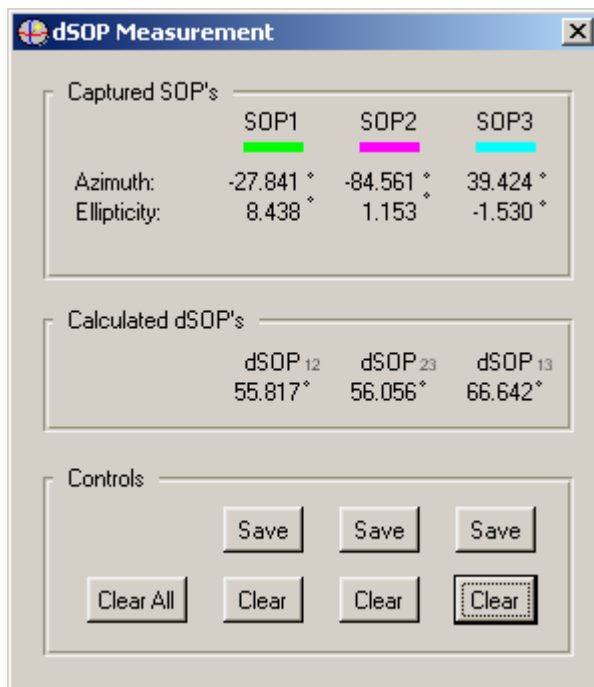The upper part of this panel shows the captured state of polarization. The representation of the SOPs depends on the settings of the 'SOP View Mode'. You can choose the parameter azimuth and ellipticity, power split ratio and phase difference, or the 3 normalized Stokes Parameters. See section Changing the Basic Measurement Settings.

The middle part displays the calculated differential SOPs. $dSOP_{12}$ indicates the dSOP between SOP1 and SOP2. Analogous $dSOP_{23}$ and $dSOP_{13}$ represent the differential SOP between SOP2 and SOP3 and between SOP1 and SOP3, respectively.

The lower part contains the control elements. The 'Save' button assigns the current measured SOP to the specified column. Only if more than one SOP was captured a dSOP can be calculated. In the case that no dSOP can be calculated a value of zero will be displayed.

A captured SOP will also be shown as a cursor on the Poincaré sphere. The color of the cursor is indicated in the 'dSOP measurement' panel and can be changed in the 'Sphere Color Setup'. See section Poincaré View Preferences.
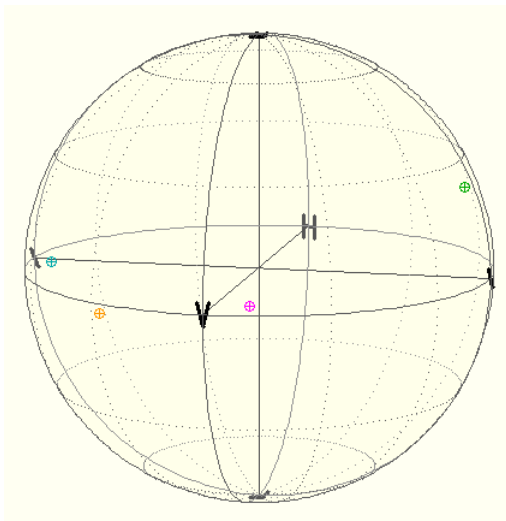
Figure 23   Poincaré Sphere with captured SOPs

4.2.5.5 Poincaré Sphere Measurement Settings

NOTE
The polarization measurement with the rotating waveplate technique is complex and offers several averaging possibilities. This section deals only with the Poincaré Sphere Measurement Settings. For more detailed information about the measurement technique see the Rotating Waveplate Technique section!

1. From the menu bar, select 'Setup' / 'Sphere Measurement Setup'. The window shown below is displayed.
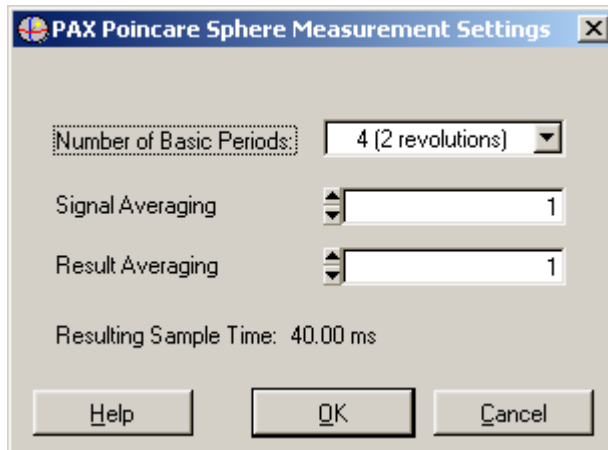
Figure 24　　　　**PAX Poincaré Sphere Measurement Settings**

The polarization data is calculated from a Fourier transformation of a photodiode current, measured over a preselected number of basic periods, 1 basic period = half a turn of the waveplate. This basic period is represented by a periodic sinusoidal current, and contains all information to calculate the polarization information.

Since the waveplate itself can have slight imperfections, subsequent turns of the waveplate can often yield different polarization results compared to the first turn. Therefore if the number of basic periods is higher, this will result in more frequencies being obtained by the Fourier Transformation.

NOTE
Only two frequencies are used to calculate the polarization data. If only one basic period is used for the Fourier transformation, the single and double rotation frequencies (or sample rate) of the waveplate are used. Using two or four basic periods the frequencies are the double and quadruple or quadruple and octuple, respectively.

2.　*Number of Basic Periods* – The number of basic periods (turns of the waveplate) over which the photo-diode current is measured. The default setting is two basic periods.

　The basic sample rate, together with the number of basic periods, resulting in the sample rate can be used to filter out unwanted modulation frequencies (noise).
　– see Measurement Settings Example.

3.　*Signal Averaging* – The photo-diode current is measured over the Number of Basic Periods selected previously. When measuring light of a low power, it may be advantageous to take an average of several photo-diode current measurements **before** the Fourier Analysis is performed, thereby reducing the effects of noise or signal fluctuations. The *Signal Averaging* parameter specifies how many measurements should be averaged.

4.　*Result Averaging* – On some occasions, e.g. when the PAX is integrated in a complex measurement system to measure PMD or PDL, it may be advantageous to take an average of the polarization data from several Fourier

Analyses. The Result Averaging parameter details the number of data sets over which the polarization data is averaged.

4.2.5.5.1 Measurement Settings Example

If the measurement task requires an open beam, noise and scatter from fluorescent lighting can corrupt the data acquisition. However the 'Sample Rate' and 'Number of Basic Periods' settings can be adjusted to suppress the noise signal.

The fluorescent light generates a noise signal at harmonic frequencies of the supply frequency, e.g. 120 Hz, 240 Hz, 480 Hz etc. for a 60Hz supply. If the sample rate is set to 80SPS and the number of periods is set to 1 the harmonic frequency of the fluorescent light with 240Hz is described by the 3rd frequency of the Fourier transformation. It will not influence the calculation since only the 2nd and 4th frequency are used to calculate the polarization data. However, the harmonic frequency with 120Hz yield error of the calculation. It is no integer number of the frequency of the Fourier transformation..
Therefore, it is recommended to set the number of periods to 2. The resulting sample rate is 40SPS and the harmonic frequency of the noise signal with 120Hz corresponds to the 3rd frequency of the Fourier transformation. All the other harmonic frequencies of the noise signal will be at multiple integer values of this frequency. That means they have no effect on the polarization data calculation.

The following table gives different configuration setups:

Noise Frequency (Power Frequency)	Number of Basic Periods	Basic Sample Rate
50Hz	2	66.67 SPS
50Hz	4	66.67 / 80.0 / 133.33 SPS
60Hz	2	80 SPS
60Hz	4	68.57 / 80.0 / 96.0 / 160.0 SPS

4.2.5.6 Poincaré View Preferences

The colors and appearance of the Poincaré sphere and the ellipse can be customized.

1. From the main menu bar, select 'Setup/Sphere Color Setup' or double click on the Poincaré sphere.

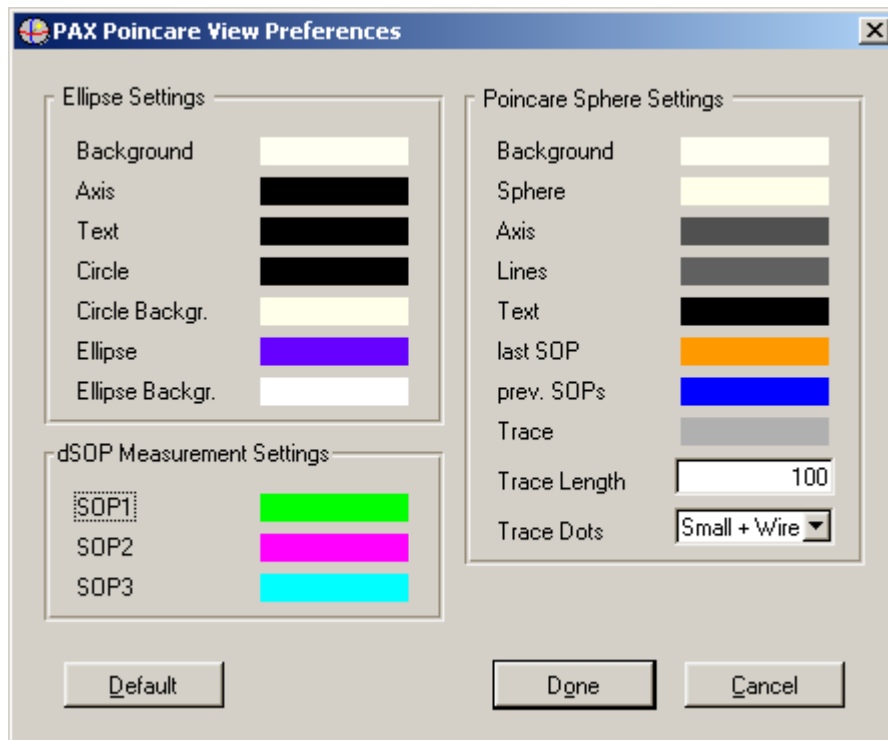   The 'Poincaré View Preferences' window is displayed.

Figure 25   Poincaré View Preferences

2. To change the color of the specified item, click on the color bar adjacent to the parameter description.
3. *Trace Length* - specifies the number of measurement points shown on the sphere. If '0' is selected, only the newest captured state of polarization (SOP) is displayed. If 'n' is selected, then the last 'n' SOPs are drawn.
4. *Trace Dots* – Sets the layout of the measurement points.
5. Click 'Done' to confirm your selection, 'Cancel' to discard the changes or 'Default' to reset all settings to the default state.

4.2.6 Scope Mode

The scope mode of the PAX polarimeter is similar to an oscilloscope view. Normalized Stokes vector parameters s1, s2 and s3, Azimuth and Ellipticity, (Power Split Ratio and Phase Difference), Degree of Polarization, and Power, are each shown in a separate diagram.
The PAX collects up to 1024 measurement results continuously (Array Mode). The measurement results are transferred asynchronously to the GUI, i.e. the first of n measurement points is displayed before the complete measurement is finished. This mode provides a defined time scale for the measurements. There is also an option to set a hardware trigger and to collect pre-trigger samples.
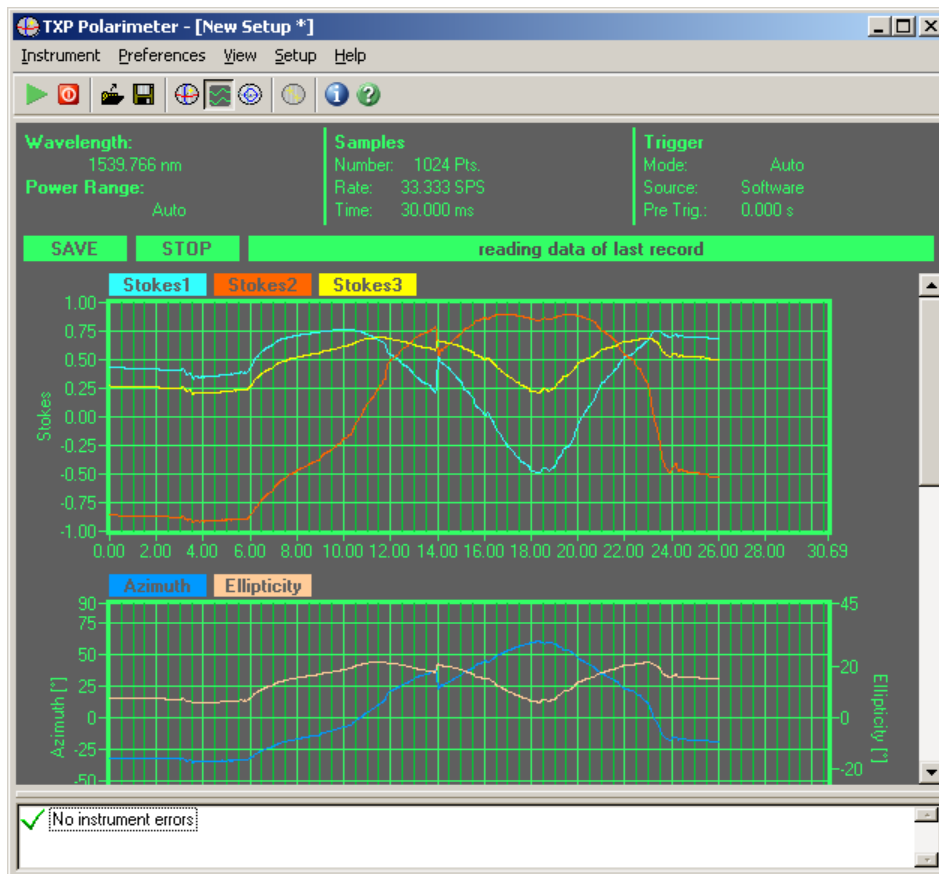
Figure 26   Scope View

There are two buttons and a status display on the screen.

The button 'Save' will open a wizard to save the current data into a comma separated value (*.csv) file. It is not necessary to wait until a measurement is finished to save the already captured data.

The second button will change its description depending on the current trigger mode and the current state. You can start or stop a measurement. If a measurement is stopped it will finish the actual measurement. That means if the numbers of measurement is 200 and the measurement is stopped after 100 points the missing 100 data points will be still collected. This is convenient in the trigger mode 'Auto' or with hardware trigger.

The status display will give information about the current state.

4.2.6.1   Numerical Values

The upper part of the scope view shows the current settings, including Wavelength and Power Range, Sample settings, and Trigger settings. For further details on the trigger settings, see the Trigger Modes section. For more information on the other settings see the Scope Measurement Settings section.
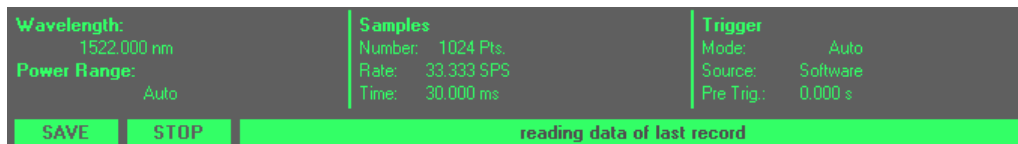
Figure 27 **Settings for the Scope Mode**

4.2.6.2 **Diagrams**

Normalized Stokes Parameters
The normalized Stokes parameters s1, s2 and s3 are displayed in the first diagram. The domain ranges from -1 to +1. The shown range cannot be changed to a higher resolution.
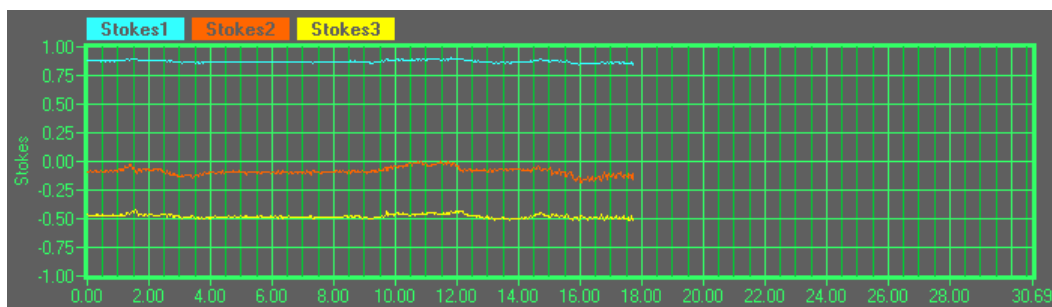

Figure 28 **Stokes Parameter Diagram**

Azimuth and Ellipticity / Power Split Ratio and Phase Difference
In the second diagram polarization is shown as Azimuth and Ellipticity. A definition of Azimuth and Ellipticity can be found in Part VII, The Nature of Polarization. The diagram has two axes of ordinates. The left axis of ordinates specifies the Azimuth and has a total range from -90° to +90°. The displayed range can be customized by right clicking on the diagram to open the setup window, see the Scope Measurement Preferences section for further details.
The right y-axis characterizes the Ellipticity. The domain ranges from -45° to +45° but can also be customized by right clicking on the diagram to open the setup window.
If you swap to Power Split Ratio and Phase Difference this diagram will show these measurement values instead of Azimuth and Ellipticity.
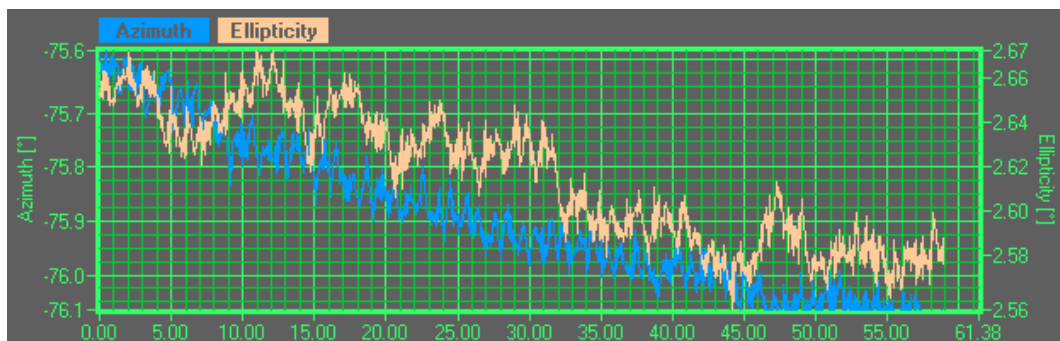

Figure 29 **Azimuth and Ellipticity Diagram**

Degree of Polarization (DOP)

The third diagram displays the DOP, measured over time. The display values can range from 0% to 200%. In theory, DOP is defined to be between 0% and 100% including the limits, and a value greater than 100% is not possible. However, measurement errors, calibration data tolerances or an incorrect wavelength setting can yield DOP values greater than 100%.

If DOP values greater than 100% are measured, check the wavelength setting. For continuative information refer to Troubleshooting. The preferences can be customized by right clicking on the diagram to open the setup window, see the Scope Measurement Preferences section for further details.
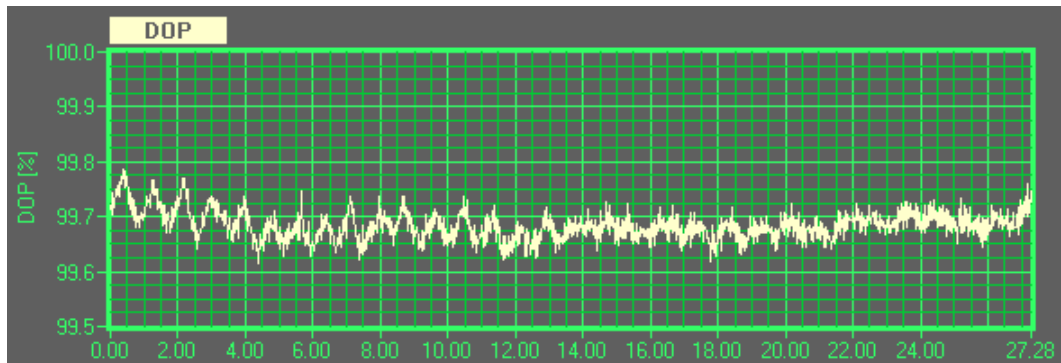
Figure 30   **DOP Diagram**

Power

The fourth diagram displays the power. The preferences can be customized by right clicking on the diagram to open the setup window, see the Scope Measurement Preferences section for further details.
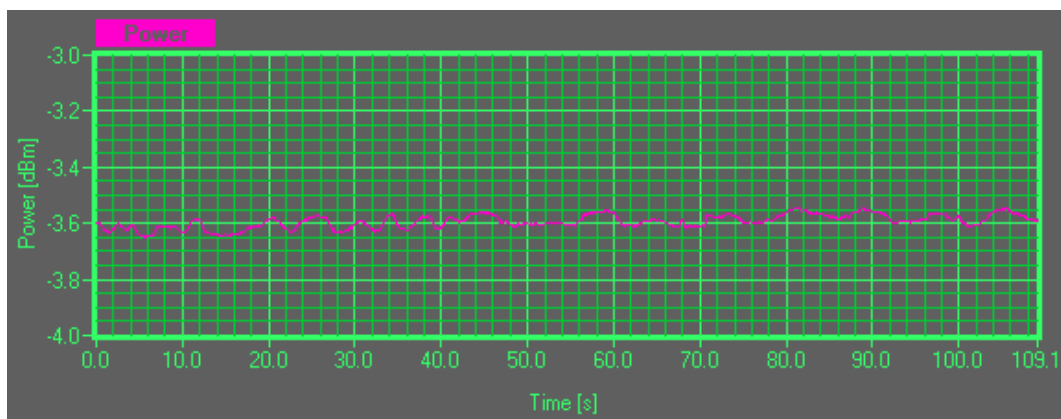
Figure 31   **Power Diagram**

4.2.6.3 Trigger Modes

Scope mode offers several trigger modes which are described in the following section. It is also possible to use pretriggers, see the Scope Measurement Settings section for further details.

Auto Mode

The measurement data is collected continuously. After a complete record (measurement cycle) is transferred to the application and displayed in the diagrams it is discarded and the diagrams cleared. The next measurement starts

immediately and the new data is displayed. The trigger source is 'Software'. The status display shows 'reading data of last record'. If the 'STOP' or 'Save' button is pressed the current scan will be captured and displayed. No further scans will be started until the 'RUN' button is clicked.

Falling Edge
In this mode the GUI-application prepares the PAX to be triggered by the falling edge of an external hardware trigger signal. While waiting for the trigger, the status display shows 'waiting for pre trigger time to elapse' resp. 'waiting for trigger'. Once the trigger signal is received, the status line displays 'reading data of last record' and the collected data is shown on the screen. When all data is read the GUI will arm the PAX again and the cycle restarts. If 'STOP' or 'SAVE' is activated a new trigger pulse will not start a new scan automatically.

Rising Edge
Similar to the Falling Edge mode, but the PAX is triggered by the rising edge of an external hardware trigger signal.

Single Shot
In this mode the GUI-application arms the hardware to be ready for a single shot record. When the pretrigger time has elapsed the PAX is ready ('armed') to record a single shot. During this process, the status display in the GUI changes from 'waiting for pretrigger time to elapse' to 'armed for single shot'. The PAX then waits for the user to click the trigger button. After the button is pressed, data is collected and shown on the screen. The PAX immediately starts again to collect data for the next trigger period. See the Scope Measurement Settings section for more details on setting the pretrigger parameter.

Single Shot Falling Edge
This mode is similar to the Falling Edge mode but re-arming of the trigger is not performed automatically. The user must press the 'RUN' button, then the PAX waits for the next trigger signal.

Single Shot Rising Edge
This mode is similar to the Rising Edge mode but re-arming of the trigger is not performed automatically. The user must press the 'RUN' button, then the PAX waits for the next trigger signal.

4.2.6.4 Save Measurement Data

To save the current measurement data click on the button 'Save'. A window pops up and a wizard helps to configure the output file.

Separator - specifies the character between two consecutive measurement values in the data file. You can choose between comma(,), semicolon(;), tabulator and pipe(|).

Include Header information - The header contains date and time as well as the serial number of the card and the sensor and the current configuration like wavelength, sample rate, averaging etc. To disable the insertion of the header uncheck the box.

Include Comment Text - To add a comment check the box. The comment input will be enabled and you can enter your comment.
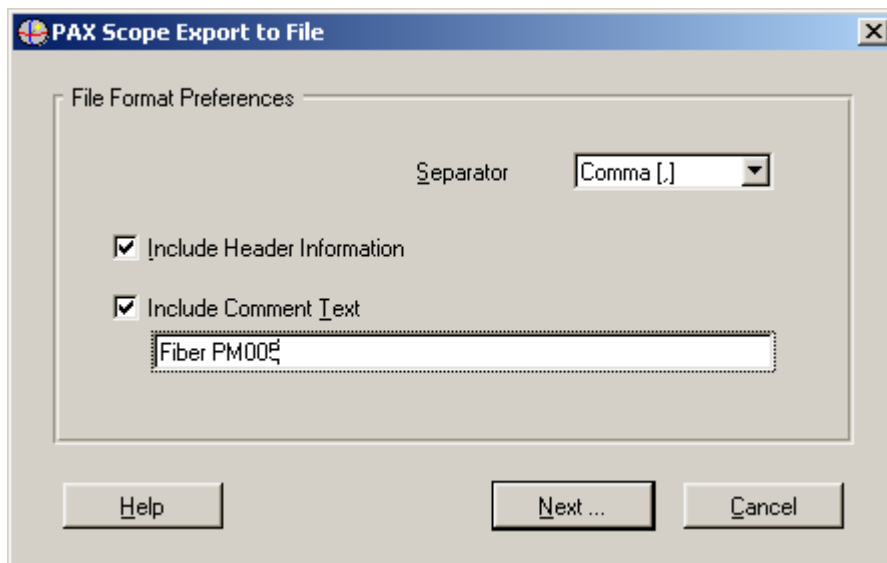
Figure 32   **Export to File**

After all settings are done click next and a file dialog box appears. Select a file name and save the data.

It is not necessary to wait until a measurement is finish to click on the save button. All measurement data which are captured when you exit the save wizard are stored in the file.

4.2.6.5   **Scope Measurement Settings**

1. To access the settings for the Scope Mode, select 'Setup' / 'Scope Measurement Setup' from the menu bar. The following window is displayed.

Figure 33   **PAX Scope Measurement Settings**

The polarization data is calculated from a Fourier transformation of a photodiode current, measured over a preselected number of basic periods, 1 basic period = half a turn of the waveplate. This basic period is represented by a periodic sinusoidal current, and contains all information to calculate the polarization information.
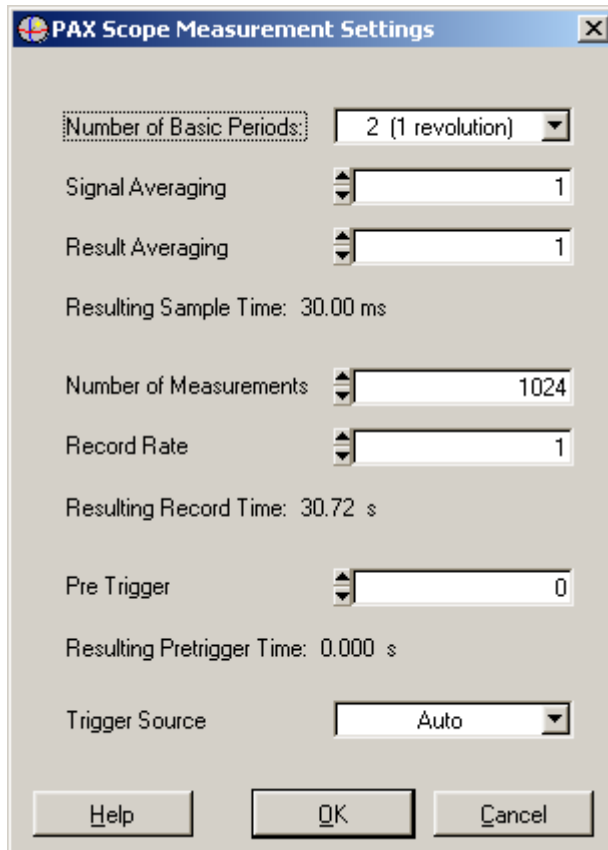
Since the waveplate itself can have slight imperfections, subsequent turns of the waveplate can often yield different polarization results compared to the first turn. Therefore if the number of basic periods is higher, this will result in more frequencies being obtained by the Fourier Transformation.

NOTE
Only two frequencies are used to calculate the polarization data. If only one basic period is used for the Fourier transformation, the single and double rotation frequencies (or sample rate) of the waveplate are used. Using two or four basic periods the frequencies are the double and quadruple or quadruple and octuple, respectively.

2. *Number of Basic Periods* – The number of basic periods (turns of the waveplate) over which the photo-diode current is measured. The default setting is two basic periods.

The basic sample rate, together with the number of basic periods, resulting in the sample rate can be used to filter out unwanted modulation frequencies (noise).

– see Poincaré Sphere Measurement Settings / Measurement Settings Example.

3. *Signal Averaging* – The photo-diode current is measured over the Number of Basic Periods selected previously. When measuring light of a low power, it may be advantageous to take an average of several photo-diode current measurements **before** the Fourier Analysis is performed, thereby reducing the effects of noise or signal fluctuations. The *Signal Averaging* parameter specifies how many measurements should be averaged.

4. *Result Averaging* – On some occasions, e.g. when the PAX is integrated in a complex measurement system to measure PMD or PDL, it may be advantageous to take an average of the polarization data from several Fourier Analyses. The Result Averaging parameter details the number of data sets over which the polarization data is averaged.

5. *Number of Measurements* - specifies the length of the record which will be collected. The maximum number is 1024.

6. *Record Rate* - defines the number measurement which will add to the record.
   1: each measurement data set is added to the record
   5: each fifth measurement data set is added to the record

   The time taken to display the records is dependent upon the selected Record Rate and the resulting sample time. The '*Resulting Record Time'*, is displayed below the *Record Rate* selection window.

7. In all trigger modes but the Auto mode, the application collects data before the trigger is applied. The *Pretrigger* parameter determines the number of polarization data sets which are collected before the measurement is started (independent from the trigger source, hardware or software). The trigger button shows if the trigger is armed. The measurement can be started only if the number of samples, specified in the '*Pretrigger'* parameter has been collected.

   NOTE
   The maximum data record can contain 1024 data sets. Any 'Pretrigger' data samples are deducted from this figure. For example if 100 pretriggers are collected only 924 data sets can be acquired after the trigger pulse.

   The time taken to collect the pretriggers samples depends upon the value set in the Pretrigger parameter. The *Resulting Pretrigger Time* is displayed below the *Pretrigger* selection window.

8. *Trigger Source* - specifies the trigger mode. Refer to the Trigger Modes section for the further details.

4.2.6.6 Scope Measurement Preferences

All diagrams except the SOP (Stokes parameters) diagram can be customized. To open the 'Scope Measurement Preferences' window, either right click on the diagram or select 'Setup' / 'Scope Scaling' from the menu bar.
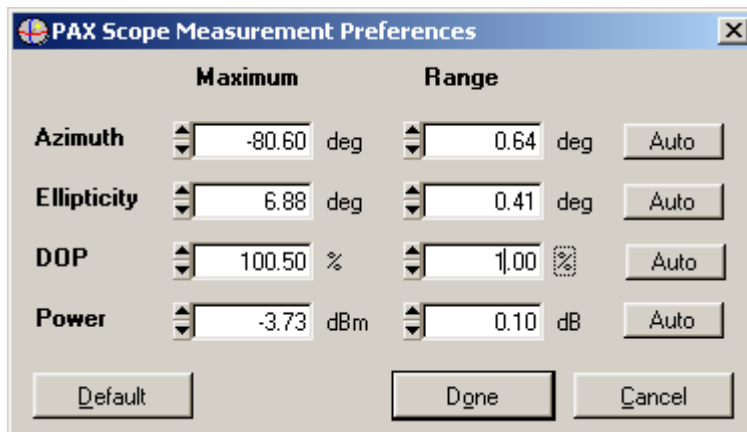
Figure 34 **Scope Measurement Preferences**

The Maximum and Range parameters can be selected. Together, these two parameters infer the minimum value (Maximum minus Range), e.g. for the DOP shown above, with a maximum of 100.5% and a Range of 1.00%, the minimum value is 99.5%.
To set the parameter automatically to the correct values with the best resolution, click the 'Auto' button.
To set all parameters to default values click the 'Default' button.
To save the settings click 'Done', to exit without saving click 'Cancel'.

4.2.6.7 Scope View Preferences

The colors and appearance of the Scope view can be customized.

1. From the main menu bar, select 'Setup / Scope Color Setup' or double click on the diagram area.

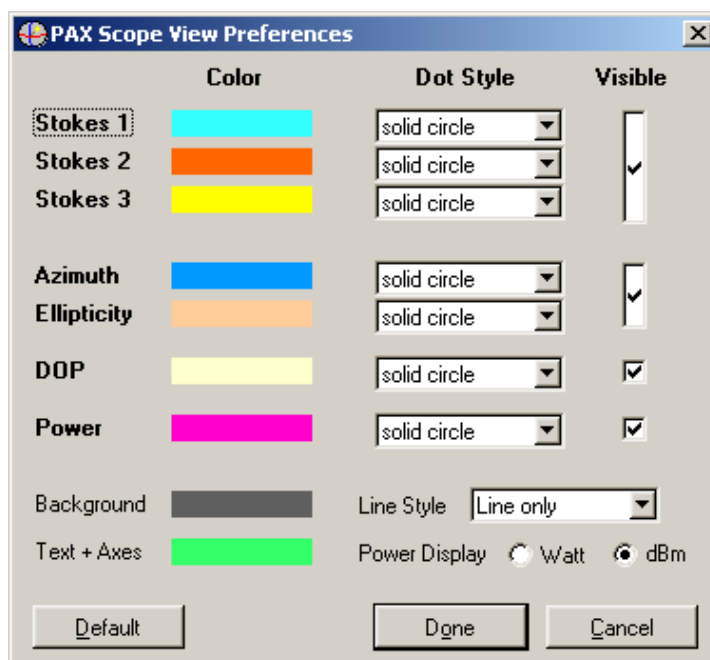   The 'PAX Scope View Preferences' window is displayed.

Figure 35 **Scope View Preferences**

2. To change the color of the specified item, click on the color bar adjacent to the parameter description
3. To change the style of the specific measurement points, click on the drop down menu in the 'Dot Style' column.
4. To apply the dot style chosen above, set the applicable line style.
5. To select which diagrams are displayed, click the check box in the 'Visible' column.
6. To change the units for displayed power, select 'Watts' or 'dBm'.
7. Click 'Done' to confirm your selection, 'Cancel' to discard the changes or 'Default' to reset all settings to the default state.

4.2.7 Extinction Ratio of PMF

A Polarization Maintaining Fiber (PMF) is only effective if linear polarized light is launched parallel to a main axis. A dimension for the quality of this coupling is the ratio in dB, of the powers in the two main axes of the PMF, the so called extinction ratio (ER).

4.2.7.1 Definition of Terms

The term extinction ratio (ER) can have two different meanings depending on the context: polarization ellipse and/or combination with PMF. The extinction ratio of a polarization state expresses the ratio of the length of the minor axis of the current polarization ellipse to the length of the major axis, in dB. Sometimes the reverse ratio is taken also.

At the exit of a PMF, the size of polarization ellipse depends on the phase difference between the x and y component, and this in turn, results from the length of the PMF. The form of the ellipse will of course change when the measurement plane is shifted back or forth. However, the specific polarization state is only of interest where the ellipse is maximally elliptic (maximally expanded in the direction of the minor axis). At this point, the calculated ratio (of the length of the axes) is referred to as the Extinction Ratio (ER).

$$ER = 10\log\frac{P_{MainAxis\,1}}{P_{MainAxis\,2}} = 20\log\frac{Halfaxis_{LargeEllipse}}{Halfaxis_{SmallEllipse}} = 20\log\frac{1}{\tan|\eta|}\bigg|_{max}$$

NOTE
ER is also used to characterize the modulation depth of lasers.
There is no relation to the ER in PMF.

The ER expresses the ability of a PMF to maintain the launched linear polarization state when optimally aligned with one of the main axes, without cross coupling to the other orthogonal main axis, i.e. it is a crosstalk specification. If the ER is poor then either the PMF has a poor polarization preserving capability (or enhanced mode coupling) or the alignment into the PMF is not optimal.

A PMF preserves the linear polarization state of the input only if the polarization state at the input is linearly polarized and perfectly aligned with one of the principal PM axes (polarization eigenstates). If both principal axes are excited with some light, they propagate independently through the fiber, each keeping it's

linear polarization state when measured individually and always staying orthogonal to each other. However, due to the birefringence of the PMF the phase shift between the two axes continuously changes. This phase shift yields different polarization ellipses at each measurement location along the fiber. The accumulated phase shift at the fiber exit point depends on the wavelength of the light source, the length of the PMF and the fiber birefringence. The polarization ellipse will be affected by a change in any of these parameters. This is the basis for the optimal alignment of a PMF to a laser chip or to a second PMF.

4.2.7.2   Measuring Method

For ER measurement the fiber must be "stressed" during data acquisition by
- either mechanically "pulling" the fiber
- or heating or cooling the fiber
- or changing the wavelength.

During the stress application the polarization at the exit of the fiber is recorded with the polarimeter sensor PAN57xx. If there is a non-optimal launch condition (misalignment) or a poor fiber the polarization will trace a circle on the Poincaré sphere due to the stress. The diameter of the circle is obviously a measure for the extinction ratio. The smaller the circle the higher is the ER.

An intermediate non polarization maintaining optical element like a patchcord will normally map the expected linear output polarization state to an elliptical polarization state off the equatorial plane in the Poincaré sphere. However this is not an obstacle for the measurement since the circle is only repositioned but not resized.
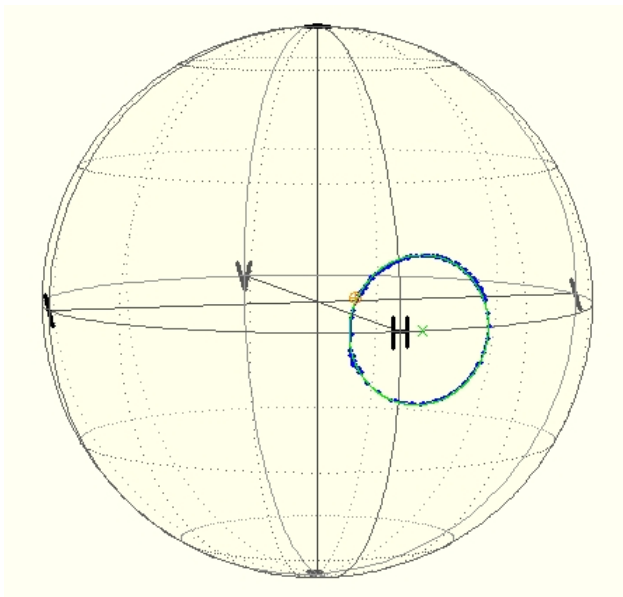

Figure 36   **Polarization States at the End of a stressed PMF**

The smaller the circle the better the polarization preserving capability of the fiber.

4.2.7.3   Possible Error Sources

If linear polarized light is fed in the PMF not coinciding with a main axis or slightly elliptical light, the polarization at the output will be elliptical even in case of an ideal fiber. The diameter of the circle measured while stressing the fiber will then

be too large - the fiber is rated worse than it is.

If the launched light does not have a high degree of polarization then always both principal axes are excited and there is a limit to the ER which is due to the degree of polarization. Improve your set up in this case by inserting a high quality linear polarizer.

If the fiber under test has on both ends a connector with a perpendicular surface like FC/PC a Fabry Perot resonator can occur. This will result in a power variation which generates a polarization variation. To prevent this a laser source with a lower coherence length should be used. Another possibility is a FP laser with several laser lines. This kind of laser has also a shorter coherence length. A DFB laser with coherence control will also work.

If the created circle has collapsed to a point on the Poincaré sphere or to a small circle the calculated ER will be quite high. That doesn't mean that the center of the circle lies on the equator. The only criteria for the ER calculation is the radius of the generated circle. As smaller the circle as better the linear polarized light is adjusted to one of the main axes of the PMF.

During the assembling of the connector to the fiber stress can be applied and this may change the behavior of the birefringence fiber. Even if the linear polarized light is guided in one main axis this stress can transform the linear polarization into an elliptical polarization. The result is an elliptical output polarization although the linear input polarization is parallel to the main axis.

4.2.7.4 Measurement Setup

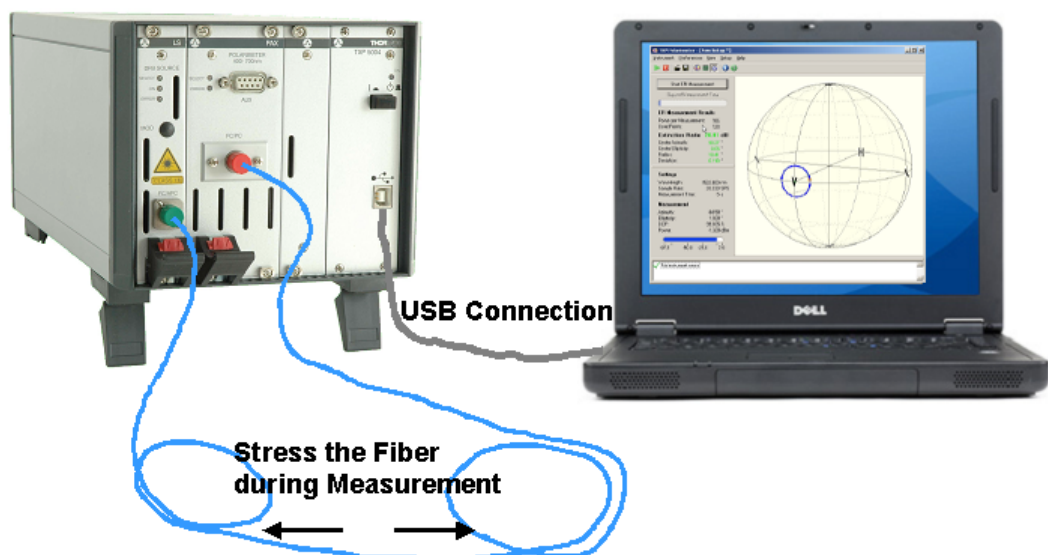The measurement setup is shown in following picture.

Figure 37   ER Measurement on PMF

The linear polarized light is fed into the PMF. This may be (as in the drawing) a feeding optic, the focusing optic of a laser with PM pigtail or a connection between two PMF.

The measured parameter ER refers to the PMF directly connected to the

polarimeter input.
The most simple measurement technique is to find the maximum expansion of the polarization ellipse compared to the ideal linear state. Since this expansion is depending on the fiber stress, a lot of values have to be recorded while the fiber is "stressed" (pulled or a wavelength scan is performed).

This technique requires highest accuracy in the measurement of the ellipticity angle.
With a very high ER (>30 dB corresponding to almost linear states) the setup is prone to measurement inaccuracies.

To mitigate this issue the PAX57xx uses an optimized algorithm. The recorded values during fiber stressing are used to fit a circle on the Poincaré sphere. The radius of the circle expressed in degrees is representative for the maximum expansion of the polarization ellipse.

Only the relative polarization measurement accuracy determines the ER measurement error since the shift of the circle to any position on the Poincaré sphere is irrelevant as long as the size of the circle remains unchanged. Errors resulting e.g. from poorly or angle polished fibers have no influence. ER measurements of up to more than 45 dB are thus possible.

Only the ER of the stressed fiber segment is measured. Even a non PMF connected in series, do not influence the result.

As mentioned tuning the wavelength would also lead to a circle on the Poincaré sphere if there is non ideal alignment or a poor PMF. However, often a very large tuning range is required to get a full circle.

4.2.7.5   **Measurement Procedure**

Select the menu item 'View' / 'ER Measurement'. The following window appears.
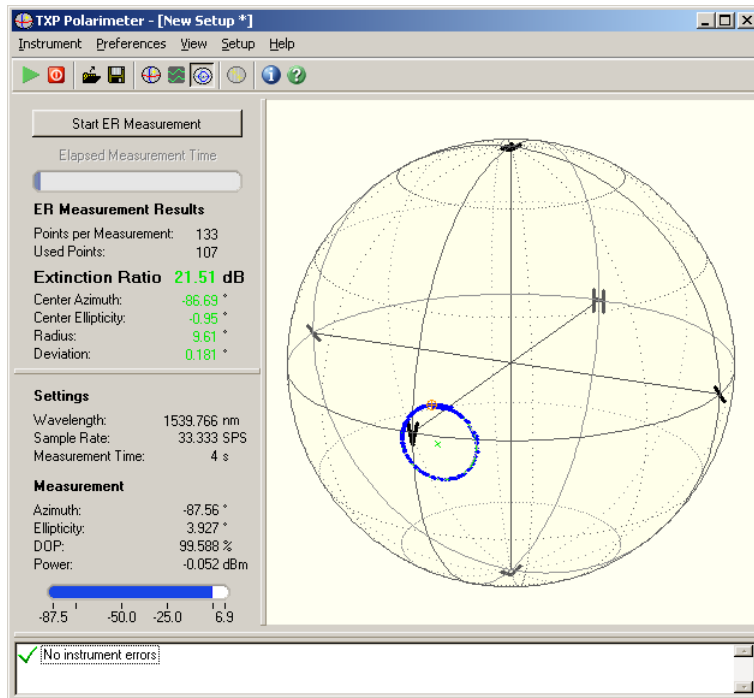

Figure 38   **ER Measurement View**

The PMF has to be stressed during the measurement time. As explained in the Measuring Method section there are different techniques. The simplest on is to pull the fiber manually. No additional equipment is necessary. On the other hand it needs experience to pull the fiber with constantly increasing force. The successive measured polarization data can vary too less or too much and an approximation of a circle will highly deviate from these measurement points. An accurate calculation is not possible in this case. However the circle fit will be done and error or warning messages will pop up if the deviation is too high or the measurement is too noisy. The circle with its center is drawn in the color green if the circle fit could be done with small variance to the measurement points. The color yellow is used if small deviation occur and red if the measurement points do not result in a circle.

Start the ER measurement by clicking on the button 'Start ER measurement'. During the measurement time the fiber has to be stressed with a constantly increasing force. As described above this can be done by pulling the fiber. There are different method like warming up the PMF. Coil the PMF around cage with a halogen bulb lamp inside. If the lamb is switched on it will heat up the cage and the PMF. This will stress the fiber and a circle on the Poincaré sphere will be drawn. The measurement results are shown in the left upper corner.
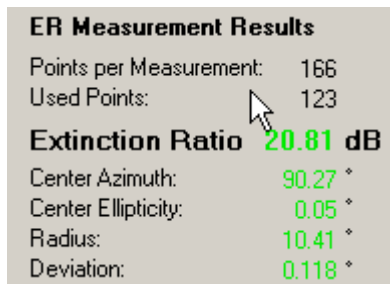
ER Measurement Results

Points per Measurement:	166
Used Points:	123
Extinction Ratio	**20.81 dB**
Center Azimuth:	90.27 °
Center Ellipticity:	0.05 °
Radius:	10.41 °
Deviation:	0.118 °

Figure 39   ER Measurement Results

There is a difference between the 'Measured Points' and the 'Used Points' for the calculation. The points which lie close to each other are not used for the calculation to avoid a weighting of a measurement cluster. This may happen if the applied stress did not begin with the measurement start, stopped before the measurement was finished or was not continuously increased during the measurement. All points which have a smaller distance to each other than the half average distance are discarded.

The extinction ratio (ER) is a measure for the coupling of linear light into one of the main axes of the PMF or/and the cross coupling of the PMF, respectively.

The center point describes the center of the approximated circle in terms of azimuth and ellipticity on the Poincaré sphere. The radius in degree specifies the distance from center to the circle. The last value is the standard deviation of the measurement points to the fit circle.

4.2.7.6 ER Measurement Settings

The measurement time can be changed by selecting 'Setup' / 'ER Measurement' from the menu bar. A window pops up and the time can be set in the range from 1 to 30 seconds. A short measurement time results in few measurement points where a long measurement time produces many measurement points. Values between 5 and 10 seconds are recommended for common measurements. If the ER is expect to be small a longer time should be used. If the applied stress is slowly increased also a long measurement time is suggested.
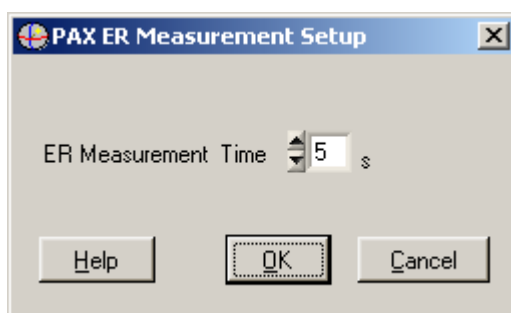

Figure 40   ER Measurement Setup

4.2.7.7 ER View Preferences

The colors and appearance of the Poincaré sphere can be customized. Either one selects in the menu bar 'Setup' / 'ER Color Setup' or double clicks on the Poincaré sphere with the left mouse button. The window 'ER View Preferences'
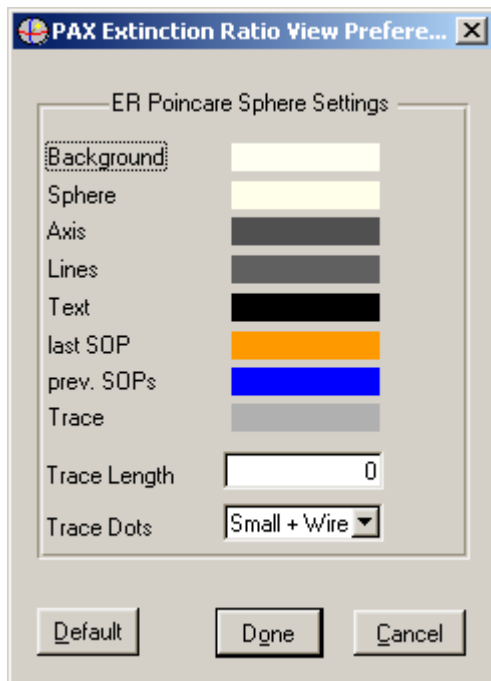
appears.

Figure 41   **ER View Setup**

The color is changed by a mouse click on the color bar. A window pops up and the wanted color can be chosen.

The trace length only effects the continuously measurement display and not the ER measurement which starts with a click on the Start button. Increase this value to check for example the stress inducing force or the position of the circle. All displayed measurements will be cleared if the an ER measurement is started.

The style of the measurement points can be modified by the 'Trace Dots' selection. This will be applied to the current and ER measurement displays.

All ER view preferences changes can be reset with the 'Default' button.

4.2.8 Save Settings

The actual settings of a setup can be saved in a file. This is convenient if a system is used with in the same configuration for example in a manufacturing process.

The connection data like the polarimeter type, the hostname, port slot number, and timeout are saved and it is not necessary to go through the complete log on.

The serial number of the polarimeter card and sensor are also stored.

The basic settings contains the wavelength, the basic sample rate, the power range, and the azimuth offset.

Furthermore there are the data for the Poincaré sphere mode (number of basic periods, signal and result averaging) as well as for the scope mode (number of basic periods, signal and result averaging, number of measurements, record rate, number of pretriggers and the trigger mode) and for the ER measurement mode

(measurement time).

To save or load a setup select 'Instrument'/'Save Setup as ...' or 'Instrument'/'Load Setup ...' respectively. To reset the setup to default values choose 'Instrument'/'Reset to Default Setup'. the default values are stored in the nonvolatile memory of the measurement sensor.
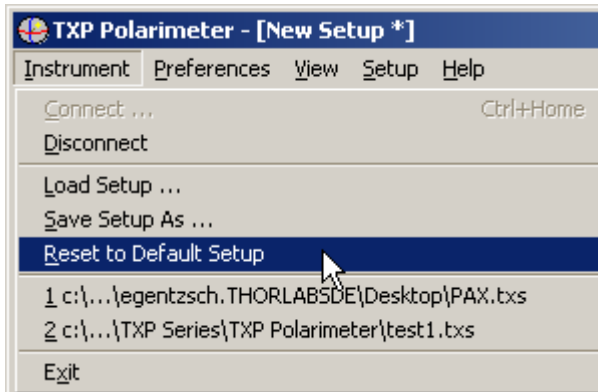

Figure 42   Setup Menu

The last 10 used setup files are listed in a file history under 'Instrument' in the menu bar.

4.2.9   Display Refresh Rate

The display refresh rate can be set choosing 'Preferences / Connection' from the menu bar. A window appears where the frames per seconds can be set. As smaller the number of frames per second as less the display will be refreshed. Especially if the laptop has a low performance a low refresh rate is recommended.

4.3   Write your own Application

The PAX57xx is a card for the TXP mainframe. To control the polarimeter a PC is always necessary. The connection from the TXP mainframe to the PC depends on the mainframe model. A TXP5004 is equipped with an USB connection whereas the TXP5016 offers an Ethernet connection.
These models are different in their operating. The TXP5004 requires always the 'TXP Server Control'. Before you can establish a connection to the TXP5004 you have to start the server. You will find it clicking on the 'START' button and choose 'Programs / TXP Series / TXP Server Control'.
The TXP5016 do not need this server. You simply have to connect it to your network and enter the correct address.

The PAX / TXP system comes together with an installation CD. You need to install the PAX driver if you want to write your own application. Click on the button 'Driver...'.
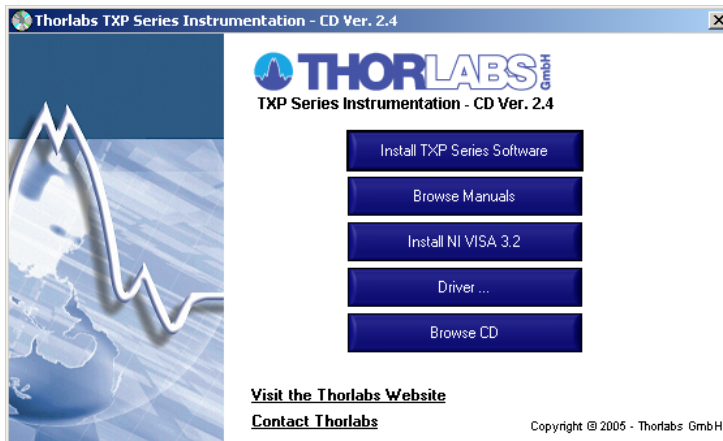
Figure 43   TXP Installation Menu

A file explorer window pops up. Select the folder 'TXP_PAX' and open it.
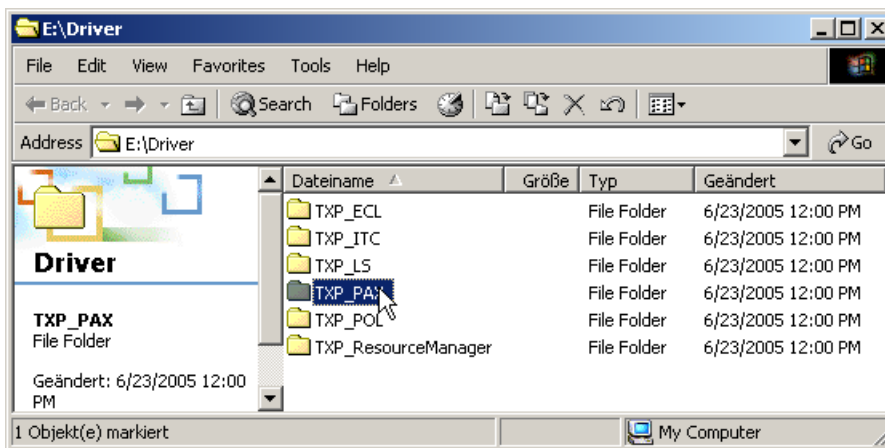

Figure 44   TXP Installation File Explorer

Another file explorer window appears. Select the setup.exe and start it by a double mouse click. Follow the installation instructions.
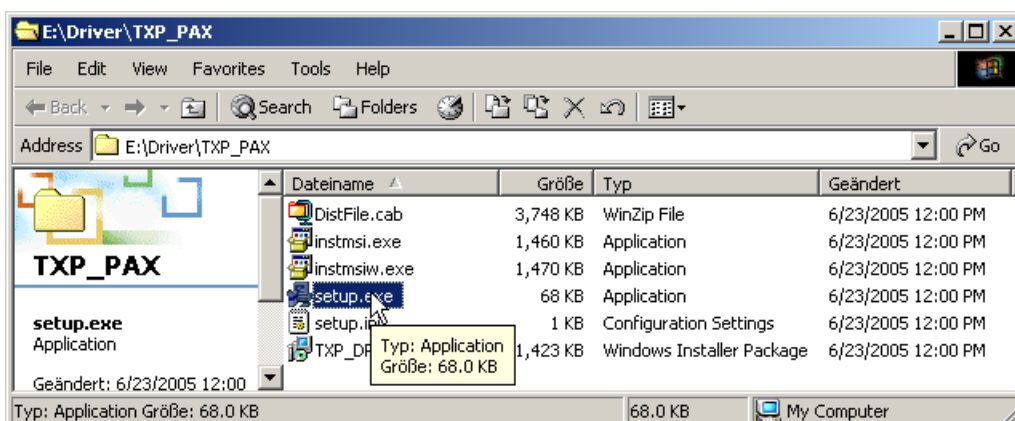

Figure 45   TXP Installation File Explorer

The default path for the PAX driver is
C:\VXIpnp\WinNT\Thorlabs_TXP_Series\PAX_Driver or C:\Programme\IVI
Foundation\VISA\WinNT\Thorlabs_TXP_Series\PAX_Driver. The part 'WinNT'

depends on the PC's actual operating system and can differ from this example. In this folder you will find the LabWindows Instrument Driver. Furthermore there is a help file 'TXP_DRV_PAX.hlp'. It contains the description for each function. An additional subdirectory is also within this folder. It contains some example applications.

There is a convenient way to import the driver direct to LabVIEW. Choose in LabVIEW Tools → Instrumentation → Import CVI Instrument Driver... ! A Window appears and you have to select the file TXP_DRV_PAX.fp from the folder C:\VXIpnp\WinNT\Thorlabs_TXP_Series\PAX_Driver. LabVIEW automatically convert the CVI driver and you will find all the drivers in the function palette → Instrument I/O → Instrument Driver → TXPPAX. Use the TXPPAX Initialize.vi to open a session and the TXPPAX Close.vi always to disconnect the session.

For LabView 8.0 or higher you need the LabView Interface Generator for LabWindows/CVI Instrument Drivers. It can be downloaded from the National Instruments website.

Service and Maintenance

PAX 57xx

Part

V

5 Service and Maintenance

5.1 Troubleshooting

- Card does not work at all :

    - Look if the card is inserted properly into the TXP mainframe and the ejector handle has snapped into its position.
    - Look if the mainframe is powered up (the LED light is on).
    - Try to insert the card in another slot. Maybe the internal fuse of the slot has opened (refer to the mainframe manual for changing the fuses).

- The PAX application cannot be started :

    - If you work with a TXP 5004 make sure the TXP server control is running.

- The degree of polarization (DOP) is greater than 100% :

    - The degree of polarization can range from 0 to 100% by theory. However since several parameter influence the calculation the DOP can exceed 100%. This is an evidence that the measurement results are wrong. Check if the wavelength is set accurately.

- The measurement of Extinction Ratio (ER) of PMF is noisy:

    - The fiber under test can operate as Fabry Perot (FP) especially if both fiber ends have a perpendicular surface. A laser source with a short coherence length will eliminate this problem. See also the Possible Error Sources section for more information.

- The center of the circle of an ER measurement of PMF is not linear:

    - Even if the linear polarized input light is ideal aligned to one of the main axis of the PMF the output light can be elliptical. Due to stress induced during the connector assembly the property of a birefringent fiber can be changed. Try to change the input and the output of the fiber. Then it can be arranged that the polarization of the input light is transformed into linear polarization travelling along one of the main axis. If the output fiber connector does not distort the polarization due to stress the output polarization is linear.

5.2 Service

In normal operation the PAX57xx card does not need any service. For highest precision of the measurement it is recommended to recalibrate the PAX57xx every two years. You can see the due date of calibration in the card info-menu of the card driver to determine the recalibration date.

Appendix

PAX 57xx

Part

VI

6   Appendix

6.1   Warranty

Thorlabs warrants material and production of the PAX5700 for a period of 24 months starting with the date of shipment. During this warranty period *Thorlabs* will see to defaults by repair or by exchange if these are entitled to warranty.
For warranty repairs or service the unit must be sent back to *Thorlabs* or to a place determined by *Thorlabs*. The customer will carry the shipping costs to *Thorlabs,* in case of warranty repairs *Thorlabs* will carry the shipping costs back to the customer.
If no warranty repair is applicable the customer will be responsible for the costs for return shipment.
In case of shipment from outside the EU, any duties, taxes etc. which should arise have to be carried by the customer.

Thorlabs warrants the hardware and software determined by *Thorlabs* for this unit to operate fault-free provided that they are handled according to the requirements of *Thorlabs*. However, *Thorlabs* does not warrant a faulty free and uninterrupted operation of the unit, of the software or firmware for special applications nor this instruction manual to be error free. *Thorlabs* is not liable for consequential damages.

Restriction of warranty

The warranty mentioned before does not cover errors and defects being the result of improper treatment, software or interface not supplied by *Thorlabs*, modification, misuse or operation outside the defined ambient conditions stated by *Thorlabs* or unauthorized maintenance.

Further claims will not be consented to and will not be acknowledged. *Thorlabs* does explicitly not warrant the usability or the economical use for certain cases of application.

Thorlabs reserves the right to change this instruction manual or the technical data of the described unit at any time.

6.2   Technical Data

All technical data are valid at 23 ± 5°C and 45 ± 15% rel. humidity

General technical data

Operating Temperature:	5 ... +40 °C
Storage Temperature:	-40 ... +70 °C
Width:	PAX5710xxx:1 TXP slot
	PAX5720xxx:2 TXP slots
Warm-up time for rated accuracy	15 min
Analog monitor output	-2.5 V … + 2.5 V

Optical Parameters [1]

Wavelength Range	VIS:	400nm -	700nm
	IR1:	700nm -	1000nm
	IR2:	1000nm -	1350nm
	IR3:	1300nm -	1700nm
Dynamic Range [2]			-60dBm to +10dBm

Sampling Rate
    Maximum   333S/s
    Default   33S/s
Measurable SOP States   full Poincaré Sphere

Azimuth Accuracy [3]   ±0.25°

Ellipticity Accuracy   ±0.25°

DOP Accuracy   ±0.5%

Rel. Power meas. Accuracy   ±0.3 dB

Abs. Power meas. Accuracy   ±1.0 dB
(P_{input} > -40 dBm)
Parameter Resolution
    DOP   0.01%
    SOP angles   0.01°
    s1, s2, s3   0.0001
Input Fiber Connector   FC/PC

Free space aperture $\varnothing$ 3mm

1) All polarization specifications are valid for power range from -40dBm to 0dBm
2) Absolute power range depends on the current wavelength
3) For any SOP with -30° < ellipticity < 30°

6.3 WEEE

As required by the WEEE (Waste Electrical and Electronic Equipment Directive) of the European Community and the corresponding national laws, Thorlabs offers all end users in the EC the possibility to return "end-of-life" units without incurring disposal charges.

This offer is valid for Thorlabs electrical and electronic equipment
- sold after August 13, 2005
- marked correspondingly with the crossed out "wheelie bin" logo (see fig. 62)
- sold to a company or institute within the EC
- currently owned by a company or institute within the EC
- still complete, not disassembled and not contaminated

As the WEEE Directive applies to self-contained operational electrical and electronic products, this "end-of-life" take back service does not refer to other Thorlabs products, such as
- pure OEM products, that means assemblies to be built into a unit by the user (e. g. OEM laser driver cards)

- components
- mechanics and optics
- left over parts of units disassembled by the user (PCBs, housings etc.)

If you wish to return a Thorlabs unit for waste recovery, please contact Thorlabs or your nearest dealer for further information.

6.3.1 Waste Treatment on your own Responsibility

If you do not return an "end-of-life" unit to Thorlabs, you must hand it to a company specialized in waste recovery. Do not dispose of the unit in a litter bin or at a public waste disposal site.

6.3.2 Ecological Background

It is well known that WEEE pollutes the environment by releasing toxic products during decomposition. The aim of the European RoHS Directive is to reduce the content of toxic substances in electronic products in the future.
The intent of the WEEE Directive is to enforce the recycling of WEEE. A controlled recycling of end-of-life products will thereby avoid negative impacts on the environment.

Figure 46   **Crossed out "Wheelie Bin" Symbol**

6.4 Listings

6.4.1 List of Acronyms

The following acronyms and abbreviations are used in this manual:

AGND	Analog Ground
DC	Direct Current
DFB	Distributed Feedback (Laser)
DGND	Digital Ground
DPC	Deterministic Polarization Controller
DOP	Degree of Polarization
dSOP	Differential State of Polarization
EC	European Community
ECL	External Cavity Laser
ER	Extinction Ratio
FBG	Fiber Bragg Grating
GUI	Graphical User Interface

IPM	Inline Polarimeter
LED	Light Emitting Diode
MMF	Multi Mode Fiber
OEM	Original Equipment Manufacturer
PAX	Polarization Analyser
PC	Personal Computer
PCB	Printed Circuit Board
PDL	Polarization Depending Loss
PMD	Polarization Mode Dispersion
PM	Polarization Maintaining
PMF	Polarization Maintaining Fiber
RoHS	Restriction of the use of certain hazardous substances in electrical and electronic equipment
SMF	Single Mode Fiber
SOP	State of Polarization
SPS	Samples per Second
TXP	Thorlabs Extended Platform
USB	Universal Serial Bus
WEEE	Waste Electrical and Electronic Equipment Directive

6.4.2   List of Figures

6.4.3   Addresses

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Our company is also represented by several distributors and sales offices throughout the world.
Please call our hotline, send an Email to ask for your nearest distributor or just visit our homepage **http://www.thorlabs.com**

Application Notes

PAX 57xx

Part VII

7   Application Notes

7.1   Polarization of Light

7.1.1   The Nature of Polarization

Light is an electromagnetic wave. It oscillates perpendicular (transverse) to the direction of the propagation of the light beam. Such a transverse electromagnetic wave can be divided into unpolarized and polarized. The plane of polarization of unpolarized light also called as natural light fluctuates arbitrarily around the direction of propagation, so that in average no direction is favoured.
All field components of polarized light have a fixed phase difference to each other. Each state of polarization (SOP) can be split into any two orthogonal states. There are different SOP's shown in the following picture.
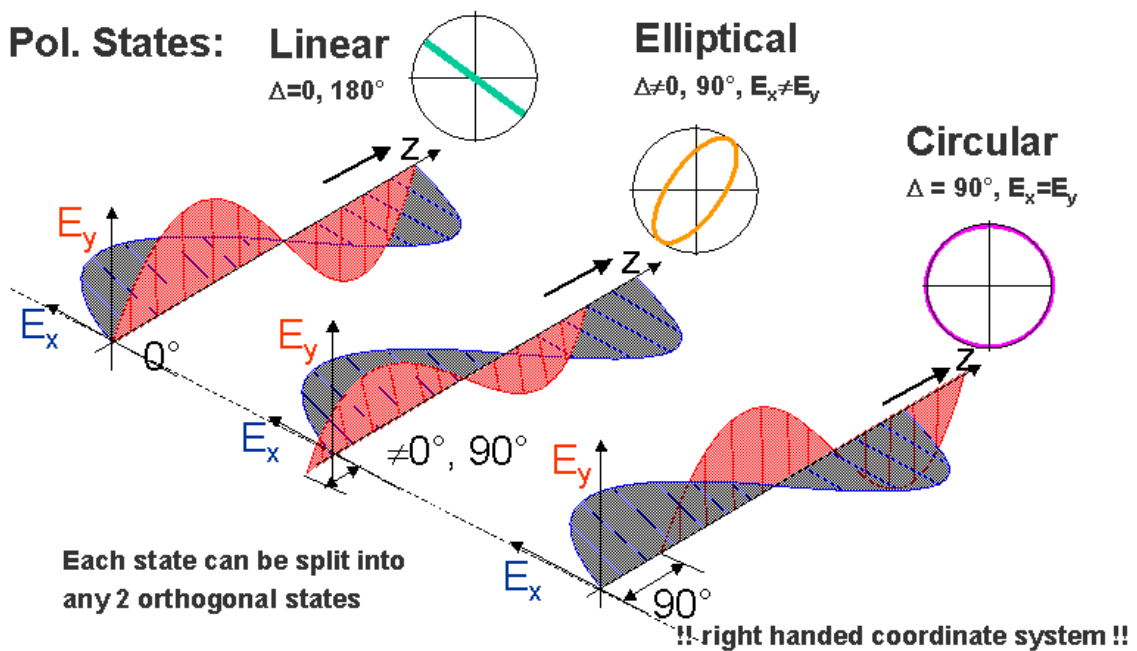

Figure   **Polarization States**

In the first diagram there is linear light displayed. The superposition of both orthogonal states is oriented in only one direction of the transverse plane. The projection of the field vectors to the plane results in a line.
The second diagram shows an elliptical polarization state. Both orthogonal states have a fixed phase between 0 and 90°. The projection results in a ellipse with a right or left direction of rotation. A special case is the circular polarization where the phase difference is 90°. Then the electric field vector rotates by 360° within one wavelength.

The handedness describes the direction of rotation of the electric field vector. The representation of the polarization with the PAX software refer to a right handed coordinate system.
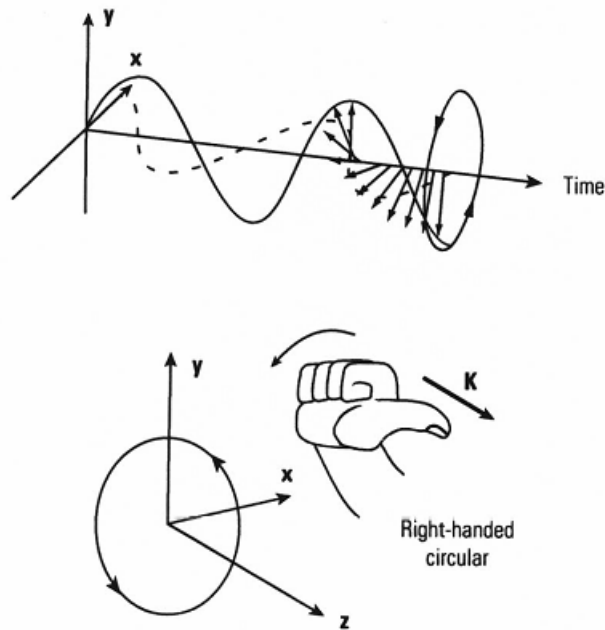
Figure   Handedness

Common light sources except lasers emit natural light. Helium Neon lasers or DFB laser diodes normally feature linear polarization. However if this laser light is launched into a single mode standard fiber the linear polarization is transformed into an arbitrary polarization. Even if a polarization maintaining fiber is used the linear polarization has to be coupled into one of the main axes to prevent the loss of linearity. A multimode fiber allows a propagation of numerous modes. The state of polarization at the end of the fiber is totally arbitrary.

The spectral width of the emitted light has also be considered. If the emission has a spectral width of zero the light must be polarized since the field vectors can be superposed to a resulting vector. A DFB laser diode with a linewidth of about 3MHz is one example. Lightsources with a broad spectrum like LEDs are generally unpolarized. A polarizer can be used to polarize light with a large spectral width.

7.1.2   **Mathematical Representation**

A monochromatic plane wave of frequency ν traveling in the z direction has its polarization vector in the x-y plane. Any location of the polarization vector at different times t can be written by superposition of the x- and y- vector components:

$$E(t) = \hat{E}_x \cos(\omega t + \delta_x) + \hat{E}_y \cos(\omega t + \delta_y) = E_x(t) + E_y(t)$$

with:

$\hat{E}_x$, $\hat{E}_y$ amplitude of the electric field intensity in x- or y-direction
E_x, E_y electrical field intensity in x- or y-direction
δ_x, δ_y phase of the electric field intensity in x- or y-direction
ω angular frequency

The phase difference is:

$$\delta = \delta_y - \delta_x$$

Another convenient representation is the Jones vector formalism. It is an analytical description of the state of polarization. The usual time dependence, exp(jωt), is omitted. The same monochromatic wave is completely characterized by the complex envelopes:

$$A_x = a_x \exp\left(j\varphi_x\right)$$

and

$$A_y = a_y \exp\left(j\varphi_y\right)$$

of the x and y components of the electric field. It is convenient to write these complex quantities in the form of a column matrix:

$$J = \begin{bmatrix} A_x \\ A_y \end{bmatrix} = \begin{bmatrix} \cos\chi \\ \sin\chi \exp(j\varphi) \end{bmatrix}$$

The first vector is known as Jones vector and the last is the normalized Jones vector.

The following figure shows spatially the curves of the x- and y-components of he electric field intensity as a function of time.
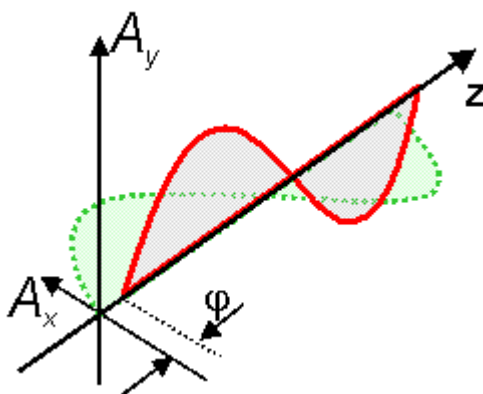

Figure   Electric Field Intensity as a Function of Time

The vector of the electric field intensity E (t) is determined by the superposition of the x- and y-component. At a fixed time it points to a defined direction and has a defined magnitude.
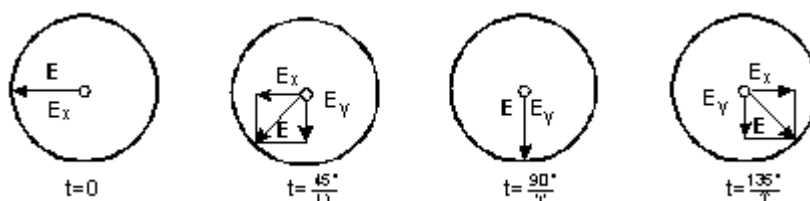
Figure   **Origin of a circularly polarized Wave**

Hypothesis: $\hat{E}_x = \hat{E}_y$, $\delta_x = 180°$, $\delta_y = 90°$. If the times stated in figure above are inserted in equation E(t), E_x and E_y can be calculated. Summed up we get the vector of the electric field intensity E. In our example the head of the vector is moving anti-clockwise on the periphery of a circle if the wave is propagating towards the spectator.

To be $\hat{E}_x \neq \hat{E}_y$ the top of the vector, it is moving on an ellipse. If the phase difference is not 90° but 0°, the ellipse or the circle becomes a line. We get linear polarized light.

7.1.3   Polarization Ellipse

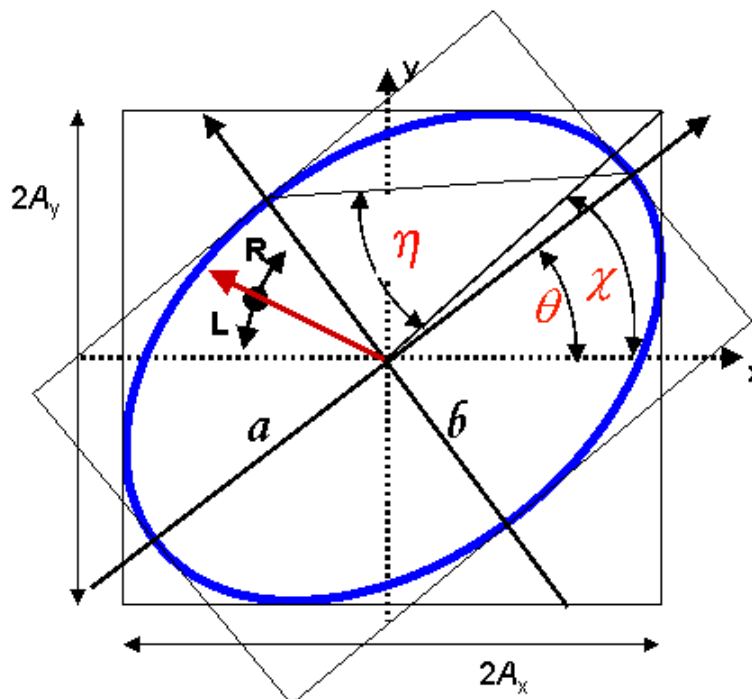The state of polarization can be represented by an ellipse:

Figure   **Ellipse View represented by Azimuth and Ellipticity**

The (virtual) observer looks towards the light source.
Definition of right and left handed polarization: In a right handed coordinate system x, y and z where the light wave propagates in the z direction the helical motion of the tip of electrical field vector can be visualized with a right hand whose thumb is showing in the propagation direction and whose finger curl into the same direction as the rotation of the field. This definition yields a clockwise rotation of the field vector tip through the ellipse when viewed from a position looking into the light beam. For left handed light the left hand must be used and the rotation is counter clockwise on the ellipse.

The parameters ellipticity (η) and azimuth (θ) as well as the handedness (right and left which corresponds to the sign of η) are necessary to describe the polarization completely. The azimuth angle θ is the angular deviation of the ellipse

from the x-axis. The angle η is calculated from the ratio of the semi-minor (b) to the semi-major (a) axis according to the following equation:

$$\tan \eta = \frac{b}{a}$$

$\eta > 0$: The light is right-handed polarized.
$\eta = 0$: The light is linear polarized.
$\eta < 0$: The light is left-handed polarized.

An ellipse can also be described by the parameters angle χ and phase φ. The handedness is defined by the sign of φ.

Another way to determine an ellipse is to use the power split ratio a and the phase difference Δ. The powersplit ratio is defined between $0 \le a \le 1$ and the phase difference can take valuse between -180° $\le \Delta \le$ 180°.
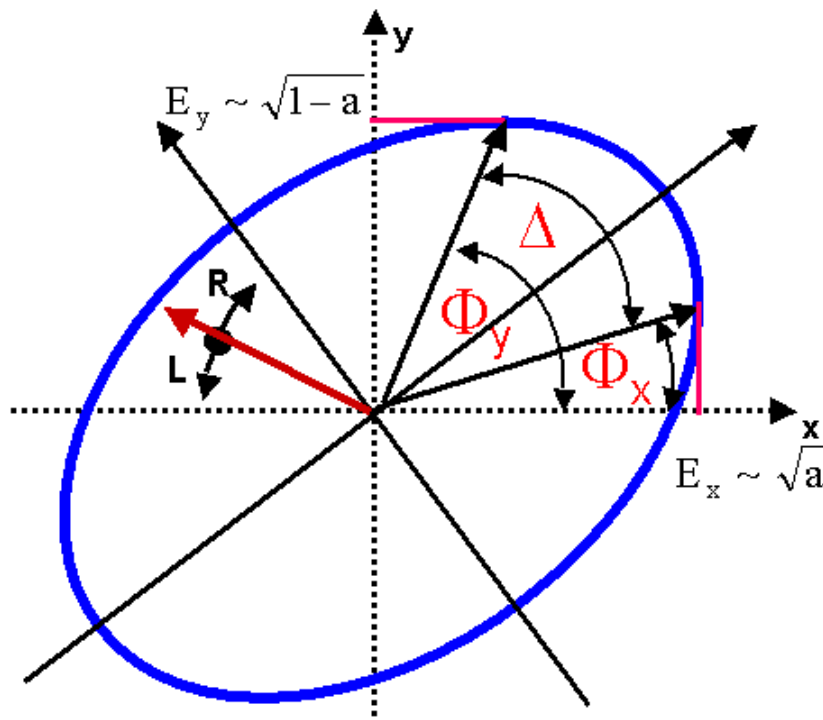

Figure   **Ellipse View represented by Power Split Ratio and Phase Difference**

The power split ratio and the phase difference can be calculated from azimuth and ellipticity by the following formulas:

$$a = \frac{1}{2}\left(1 + \cos 2\theta \cos 2\eta\right)$$

$$\Delta = \arctan\left(\tan\theta \tan\eta\right) + \arctan\frac{\tan\eta}{\tan\theta}\begin{pmatrix} +180° & \theta < 0, \eta > 0 \\ -180° & \theta < 0, \eta < 0 \end{pmatrix}$$

7.1.4   Poincaré Sphere

An appropriate way to display the state of polarization is the representation via the Poincaré sphere. The center of the Poincaré sphere is located in the origin of the Cartesian coordinate system. The Cartesian coordinates of any point on the Poincaré sphere represent the corresponding 3 normalized Stokes Parameters s_1, s_2 and s_3.

The azimuth and ellipticity angles of the polarization ellipse can be mapped uniquely onto spherical coordinates with 2θ to the latitude and 2η to the altitude position. Please note the factor of 2 involved in the mapping. Each point on the Poincaré sphere describes a defined state of polarization.

The equator plane represents all linear states of polarization. The two poles represent the states of circular polarization (right/left). All other points on the upper (lower) half sphere correspond to elliptical Polarization's with right (left) handed rotation.
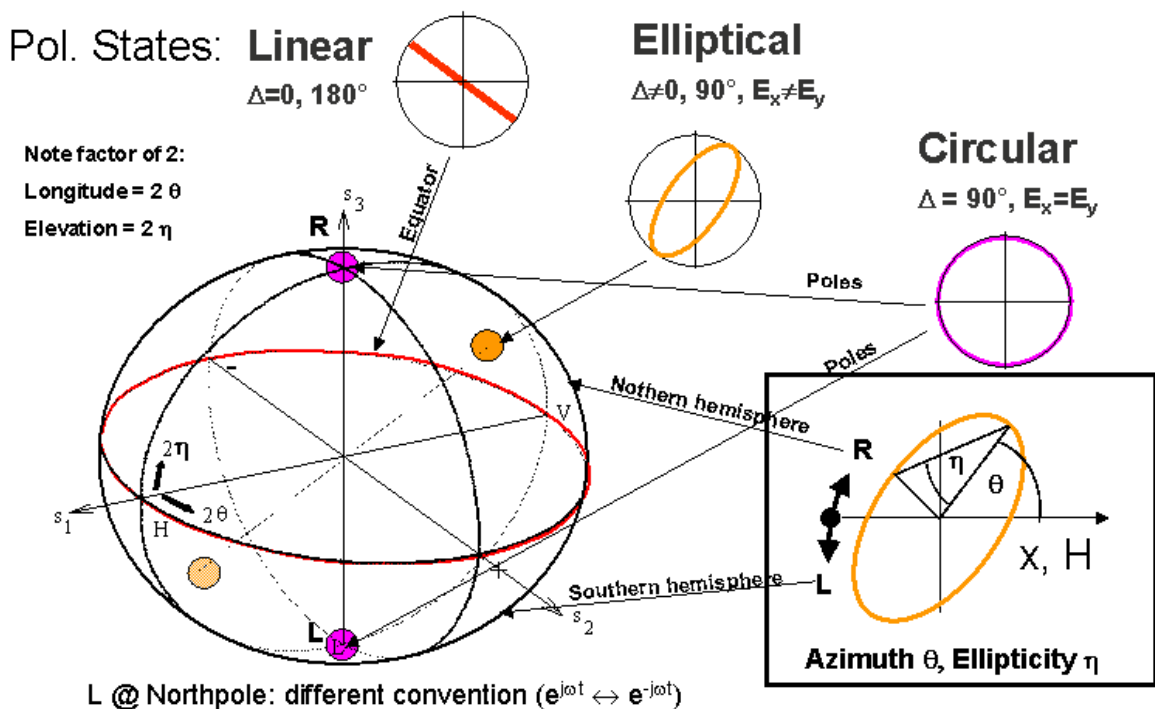

Figure   **Poincaré Sphere**

Short Polarization		θ	η
H	linear, horizontal	0°	0°
+	linear +45°	45°	0°
V	linear, vertical	±90°	0°
-	linear -45°	-45°	0°
R	right circular	-	+45°
L	left circular	-	-45°

Changes of the state of polarization as a function of time can be displayed as a trace on the Poincaré sphere.

7.1.5 Polarization in Fibers

There are different kind of fibers and they influence the polarization differently. A multi mode fiber (MMF) allows the propagation of up to several hundreds of modes. The polarization at the end of the fiber is totally arbitrary.

Only one mode, the fundamental mode, can propagate in a single mode fiber (SMF). Due to imperfections of the cylindrical structure and to stress inducing bends birefringence is generated. The input polarization is transformed into an arbitrary output polarization.

For example changes in the dimensions of the fiber cross section from a circular to an elliptic symmetry result in different refractive indices for the x- and y-direction, i.e. $n_x \neq n_y$. Both field components then propagate with different speeds. This effect is called birefringence.

Birefringence can also occur in fibers with symmetrically circular stress birefringence core due to mechanical stress. One distinguishes linear, elliptical and circular birefringence.

The changes in the phase difference δ result in a change of the state of polarization. See the following figure! Depending on the magnitude of the phase difference δ we are talking about linear, elliptical or circular polarizations.
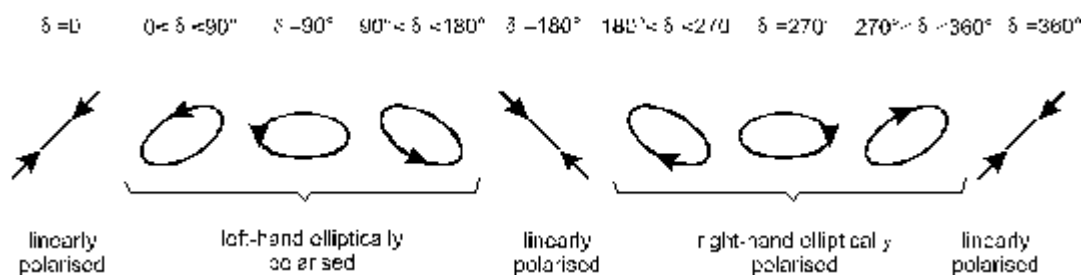

Figure   **States of Polarization**

Although the deviations of two refractive indices from each other are low, the birefringence cannot be neglected if long transmission distances must be realized.

The phase difference of the two field components in x- and y-direction depends on the propagation speeds in x- and y-direction. The phase difference δ cycles through 0° to 360° and the resulting state of polarization goes through a complete cycle, as shown in the figure above. The beat length is a measure of the different propagation velocities. It is the fiber length between two planes of identical polarization states. The wave in the slow axis is delayed by exactly one optical wavelength after one beat length which results in the original polarization state.

Since the birefringence of single mode fibers fluctuates statistically, the beat length fluctuates as well. The measurement values must be evaluated statistically. Refer to polarization mode dispersion (PMD) measurements for more information.

Polarization maintaining fibers (PMF) are manufactured with intentionally induced stress (PANDA fiber, Bow-tie fiber) or with an elliptic core. In these fibers, the difference of the effective refractive indices for the two orthogonal field components is that high, that small statistical changes of the refractive indices can be neglected compared to the high difference that was intentionally introduced during the manufacturing process.

But it is important that the light is launched into the PMF with linear polarization in correct azimuth orientation. If this is not guaranteed, an extremely short beat length of few millimeters will be the result. The large difference of the refractive indices will then cause the opposite of polarization maintenance: frequent changes in the state of polarization along the fiber will be the result.
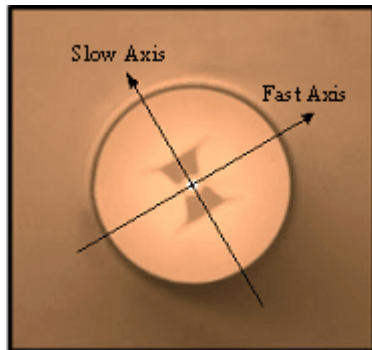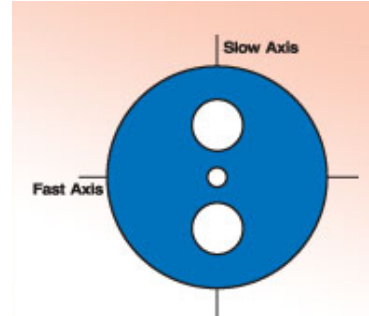

Figure   Bowtie Fiber

Figure   PANDA Fiber

7.2   Polarization Controller and Transformation

The polarization of light can be manipulated by retarders, polarizers and other polarization optics. Even single mode fiber will change the polarization of the inserted light wave. The control of the state of polarization is important since many optical components require a well defined polarization state. In many applications a polarization controller is a key component. In the following chapters a short summary of polarization controllers are given.

7.2.1   Bulk Optics

Polarizers are also helpful devices, to make the state of polarization measurable. A polarizer is an optical component that allows only one polarization of light to pass. All other polarizations are filtered. Depending on its location in the set-up the polarizer can also be called analyser. At the beginning of the transmission path we are talking about a polarizer, at the end about an analyser.

Retardation plates can be used to control the polarization. In general a retarder is an birefringence element and has two main axes with different refractive indices, $n_x \neq n_y$. A waveplate divides the incoming polarization in two parts for their direction is stated by the both main axes (linear self polarizations). The birefringence causes that a part of the light is delayed to the other for a certain time (90° = $\lambda/4$, 180° = $\lambda/2$).

If you place a quarter waveplate, a half waveplate and a quarter waveplate in order into the optical path any output polarization can be adjusted from an arbitrary input polarization.
The first quarter waveplate is used to adjust a linear polarization by rotating the retarder. Now the half waveplate acts as rotator. The desired azimuth angle can be adjusted. The second quarter waveplate transforms the linear into any elliptical polarization. If a main axis is parallel to the azimuth angle of the linear polarization no transformation is applied. If the main axis and the azimuth angle span an angle of 45° circular polarization is generated.

7.2.2   Fiber Optics

With a fiber optic polarization controller the state of polarization of light in a singlemode fiber can be set accurately. These polarization controllers follow the principle of a plane waveplate as described in the <u>Bulk Optics</u> section. In the fiber optic polarization controller the singlemode fiber is spooled on several paddles. The bending of the fiber causes a linear birefringence, similar to a bulk optical waveplate. The electro-magnetic wave disintegrates into two orthogonally oscillating waves. This stress-induced birefringence is low compared to the crystal birefringence. However, since it is integrated along a certain fiber length, a distinct effect is noticeable. Thus, by spooling the fiber to a paddle with a suitable radius phase shifts of 180°, 90° or 45° can be realised.
The fiber polarization controller operates according to the same principle . In general these polarization controllers features two $\lambda/4$-paddles and one $\lambda/2$-paddle that can be twisted. The diameters of the paddles are chosen in such a way that, with 1/2/1 or 2/4/2 turns (depending on the wavelength range) all states

of polarization can be set. A rotation of a paddle causes a rotation of the fast and slow axes the fiber spool with respect to the incoming electric field, even though the field is in the same fiber.

The so-called fiber squeezer can also be used to influence the state of polarization. It puts a sideway pressure on the fiber which also results in stress birefringence. By setting up three independent fiber squeezers in series with each of them inclined to each other with 45°, any desired transformation of polarization can be realized. A big disadvantage of a fiber squeezer is, however, the strong stress it puts to the fiber.

7.2.3 Deterministic Polarization Controller

The deterministic polarization controller DPC5500 is an inline deterministic polarization controller that combines deterministic state of polarization control, high speed, low loss and high accuracy in a unique and unprecedented way. This polarization controller is comprised of our high speed, low loss inline polarimeter technology and a non-deterministic state of polarization (SOP) controller.
It facilitates the SOP control at a user-defined location in the optical system such that the SOP can be varied to accurately and precisely follow a prescribed path on the Poincaré sphere. Compared to existing systems the DPC5500 eliminates the inadequacies of most commercially available SOP controllers, which do not control the output SOP. The DPC5500 does not suffer from drift and hysteresis effects like most other commercial high speed SOP controllers. The new all-fiber technology of the DPC5500 provides true deterministic control with very low insertion loss. The desired SOP may either be defined via its azimuth/ellipticity parameters or its corresponding Stokes values which are graphically defined by a point on the Poincaré-sphere or electronically by supplying a feedback signal from a control loop. Software modules for electronic SOP control, SOP tracing on the Poincaré-sphere and SOP scrambling are available for specific application.

Figure **Deterministic Polarization Controller**

7.2.4 Polarization Scrambler

Polarization scramblers convert highly polarized light into light with arbitrary states of polarization. Piezo-electric components affect a fast modulation of the state of polarization by a time depending change of the birefringence in the fiber. Thus it is possible to reduce polarization dependent effects in optical transmission systems, for example, polarization dependent losses or gain. Polarization scramblers should have a low insertion loss and operate in a wide wavelength range.
The deterministic polarization controller offers different scrambler modes ranging from uniformly distributed states of polarization across the Poincaré sphere to complete random states of polarization.

7.3 Polarization Measurement Techniques

There are different methods to measure the state of polarization. The 4 detector method is a well known technique. A similar technique can be used to measure the polarization in fibers. Pairs of special fiber Bragg grating (FBG) couple out a portion of light. The polarization can be calculated from the ratio of the powers. The inline polarimeter IPM5300 from Thorlabs is a product which uses this technique to measure the polarization with a up to 1MS/s.
The rotating quarter waveplate technique is in detail described in the following section Rotating Waveplate Technique.

7.3.1 Rotating Waveplate Technique

The optical unit of the PAX57xx measurement sensor consists of a rotating quarter waveplate, a fixed linear polarizer and a photodiode. The waveplate transforms the input polarization. The polarizer only transmits the portion of light which is parallel to the transmission axis. The photodiode acts as powermeter.
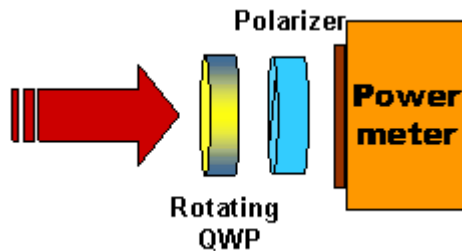
Figure   **Rotating Waveplate Technique**

The incoming polarization is manipulated by the rotating waveplate and the corresponding polarization depends on the angle of the waveplate. So if linear polarization is assumed to be the input state of polarization and the starting point of the quarter waveplate is the fast axis. The linear polarized light travels along the fast axis and is not changed. After the waveplates rotates 45° the transformed polarization is circular right. Another 45° gives again linear polarization since the slow axis is parallel to the incoming linear polarization. A rotation of 135° yield circular left polarization and a half turn corresponding to 180° results in the original linear polarization. The following picture of the Poincaré sphere points up the change of the polarization. An eight is drawn on the sphere after a half revolution of the quarter waveplate.
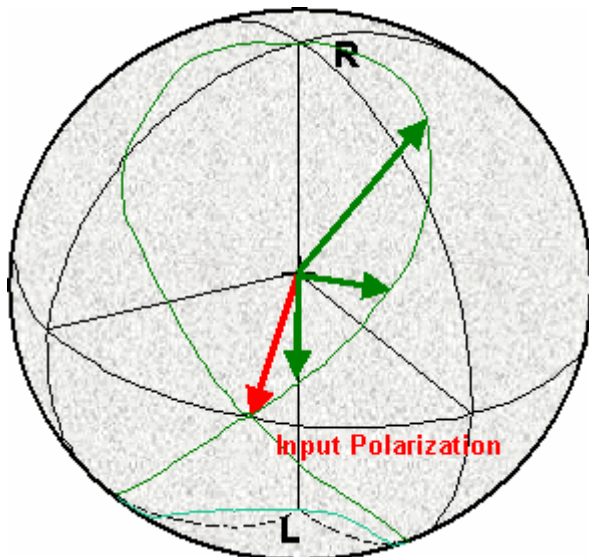
Figure **Polarization during a half turn of the λ/4 Waveplate**

The polarizer transforms the polarization modulation into an amplitude modulation. The detector supplies a current that is proportional to the optical power and to the square of the electric field intensity. The photo current consists of three parts. A DC part, a part with the double quarter waveplate rotation frequency and a part with the quadruple rotation frequency with a phase shift.
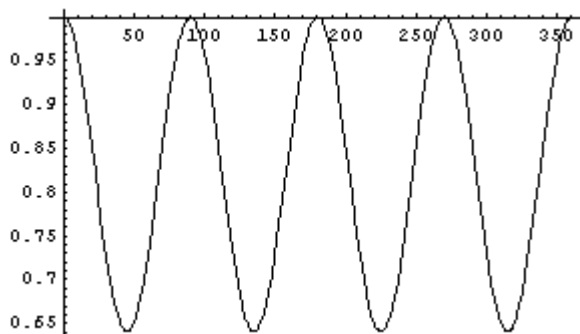

Figure **Photocurrent over one Waveplate Revolution for linear Polarization**

The photo diode current I(t) is proportional to the quadruple rotation frequency in the case of linear polarization. The phase shift reflects the azimuth angle.

$$I(t) \approx \hat{I}_4 \cos\left(4\omega_{QWP}t + \varphi_4\right)$$

Now let us consider the case of circular right polarization. Circular polarization will be transformed into linear polarization by a quarter waveplate. A revolution of the waveplate will change the azimuth angle of the generated linear polarization. The polarization coming out of the waveplate will travel on the equator of the Poincaré sphere. After a full revolution of the waveplate two turns around the Poincaré sphere have been done.
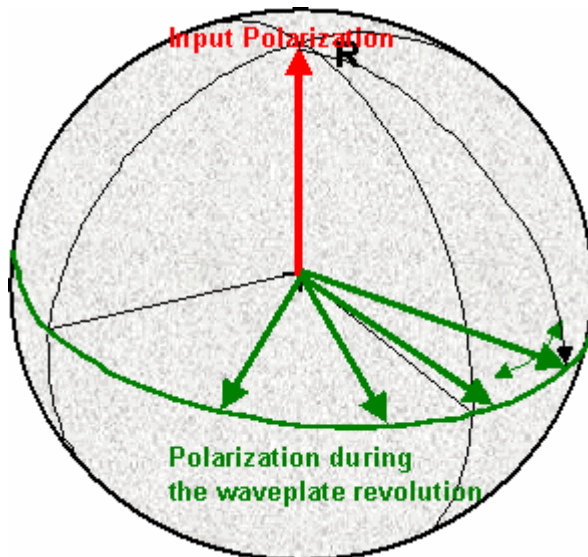
Figure   **Polarization during the Revolution of the λ/4 Waveplate**

The resulting amplitude modulation is proportional to the double rotation frequency of the quarter waveplate.
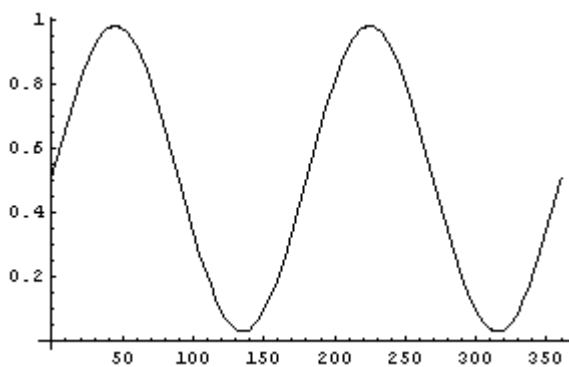

Figure   **Photocurrent over one Waveplate Revolution for circular Polarization**

The phase of the part of the double frequency is constant and in this example zero.

$$I(t) \approx \hat{I}_2 \sin\left(2\omega_{QWP} t_2\right)$$

Linear and circular polarizations are special cases. Elliptical polarization will produce a part with the double and a part with the quadruple rotation frequency of the waveplate as well as a DC part. The sinusoidal current can be analyzed with a Fourier transformation. The amplitudes and phases for the double and quadruple frequencies and the DC part are obtained. All other frequencies have an amplitude of zero by theory.

The polarization parameter like azimuth, ellipticity, degree of polarization (DOP) and the Stokes parameter can be calculated from the amplitudes A0, A2 and A4 and the phases Phi2 and Phi4.

A typical photocurrent over on waveplate revolution for an elliptical polarization is

displayed in the following figure.
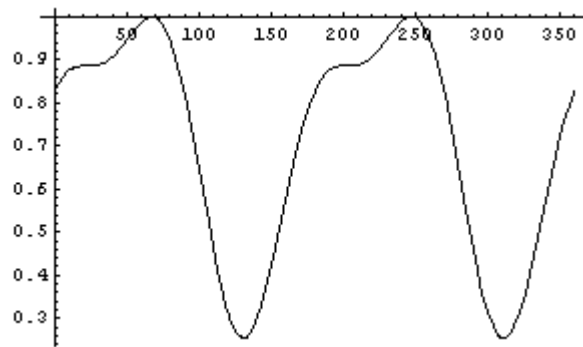
Figure **Photocurrent over one Waveplate Revolution for elliptical Polarization**

7.4 Polarization Measurement Application

7.4.1 Measurement of Retardation

The retardation of a waveplate is an important property of a waveplate. Similar to a waveplate retardation sheets show also birefringence. This optical component is for example applied in liquid crystal displays (LCD) to increase the contrast and enhances the readability. The retardation of a retardation sheet is a key parameter.

A polarimeter can be used to determine the retardation of a birefringence component. The PAX offers a simple method to measure the retardation angle. A laser source, a polarizer, a rotation stage to hold the sample, and the PAX polarimeter are necessary for this measurement setup.
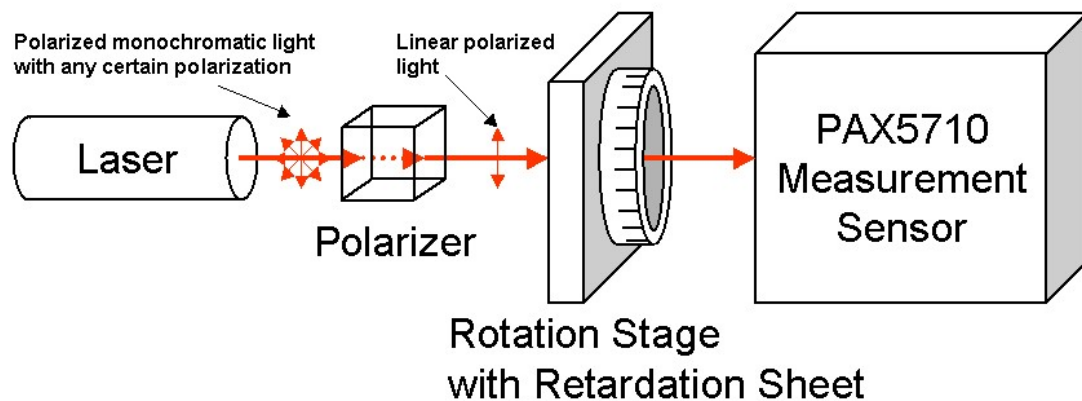
| **Figure** | **Measurement Setup for Retardation Angle of Birefringence Components** |

The light of a laser source emits monochromatic polarized light. A polarizer creates linear polarized. This linear polarized light enters the retardation sheet. The output polarization of the retardation sheet depends on azimuth angle of the linear input light with respect to its slow and fast axis. If linear polarized light travels along the fast (or slow) axis the polarization remains unchanged and the output polarization will be also linear polarized light. If linear polarized light enters the birefringence component with 45° in respect to the slow axis one half will travel along the slow axis where as the other half will travel along the fast axis. The waves will travel with different speeds. Recombined at the end of the retardation sheet the resulting polarization depends on the optical path difference. Assuming the retardation sheet is a $\lambda/4$ waveplate the resulting polarization is circular.

To measure the retardation angle for a certain wavelength rotate the retardation sheet until you obtain the maximum ellipticity angle η or the maximum phase difference Δ. Both parameters are used to describe the polarization ellipse. Refer to the Polarization Ellipse section for more details.

The PAX software offers both description of the polarization ellipse. It is favorably

to use the powersplit ratio and the phase difference since the phase difference corresponds to the retardation angle in the case of linear polarized light enters the birefringent component with 45° in respect to the slow axis. This is the case if the phase difference Δ achieves its maximum.
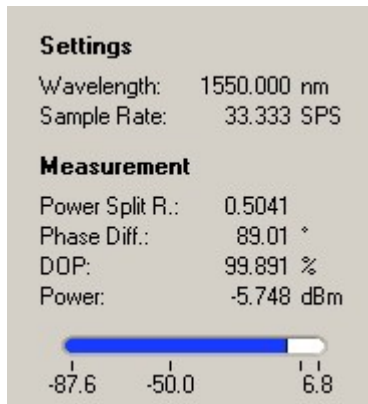

Settings
Wavelength: 1550.000 nm
Sample Rate: 33.333 SPS

Measurement
Power Split R.:   0.5041
Phase Diff.:   89.01 °
DOP: 99.891 %
Power: -5.748 dBm

-87.6   -50.0   6.8

Figure   Numerical Values in the Poincaré Sphere Mode

Keep in mind that you can only measure phase differences in the range of -90° an +90°. This measurement method is not suitable to determine the absolute phase. Phase differences between ±90° and ±180° will be mapped to ±90° and 0°.

7.4.2   Mueller Matrix Method

As explained in the topic above this measurement method is limited and useful for research and development applications. If fast measurements are required for example to check the performance of optical components in production the Mueller matrix method is preferable.

Mueller Matrix Measurement
The 16 real-valued elements m_{ij} (i,j = 0,1,2,3) that build the Mueller matrix of an optical component can be determined by measuring the 4 different Stokes vectors that enter and leave the component. The PAX polarimeter gives out the 3x1 normalized Stokes vector, to get the 4x1 Stokes vector each element is multiplied by the total measured intensity of light I.

$$S = \begin{pmatrix} I \\ s_q \cdot I \\ s_2 \cdot I \\ s_3 \cdot I \end{pmatrix} = \begin{pmatrix} S_0 \\ S_1 \\ S_2 \\ S_3 \end{pmatrix} = \begin{pmatrix} I_H + I_V \\ I_H - I_V \\ I_P - I_M \\ I_R - I_L \end{pmatrix}$$

H = horizontal linear; V = vertical linear; P = +45° linear; M = -45° linear; R = right circular; L = left circular → S_0 represents the overall intensity; S_1 the tendency to be horizontal (>0) or vertically (<0) polarized; S_2 the tendency to be +/- 45° linearly polarized and S_3 to be right or left circularly polarized.

The light that enters the device under test must be differently polarized, at least one of the four polarizations must be circular. The best result is given, when the 4

different polarizations span a tetraeder within the poincarè sphere; that means the optimised angle difference is 109°. The 4 different polarizations can be generated with a polarizer creating linear polarization and afterwards transforming it into any elliptical polarization using a $\lambda/4$ retarder.
For each of the 4 different polarizaions the Stokes vector, that is the mathematically representation of polarization state of light, is measured by a polarimeter with and without device under test. The Mueller matrix can then be calculated out of the 8 determined Stokes vectors.
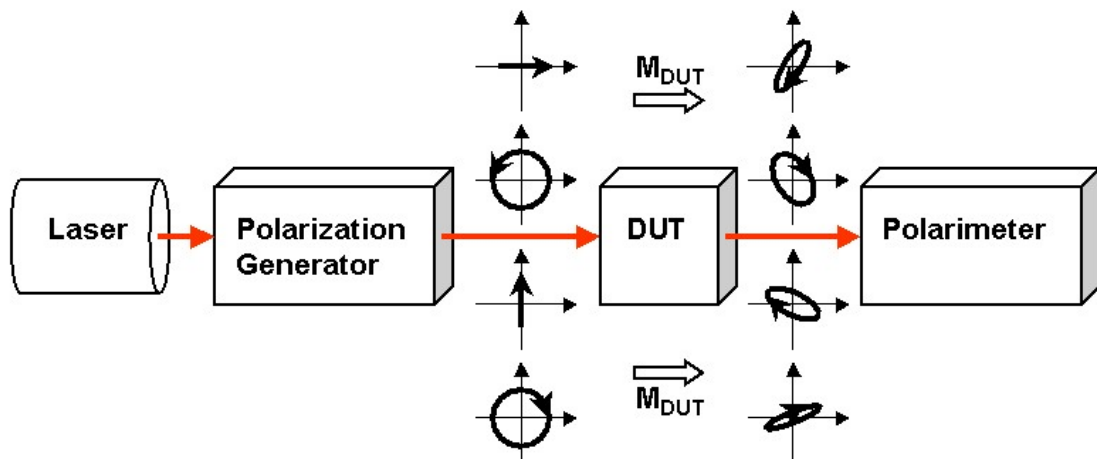
Figure   Mueller Matrix Method

Once the elements of the Mueller matrix are determined it is possible by performing a polar decomposition of the matrix (described by Lu and Chipman, 1995) to obtain all polarization-altering properties of the device under test for a particular optical beam.
The matrix can be decomposed shown in the following equation:

$$M = M_\Delta \cdot M_R \cdot M_D$$

M_Δ is the depolarizing matrix; M_R the retardance matrix and M_D the diattenuation matrix.

The retardation introduced by birefringent structures of the device under test is an important information which can be calculated from the retardance matrix. The lower 3x3 sub matrix contains this information. The retardance can be expressed as angle in degrees or radians, or as a fraction of a wavelength (for example $\lambda/4$) or in nanometers. The polarization state that passes the device under test fastest is called the fast axis.

$$R = \cos^{-1}\left[\frac{trace(M_R)}{2}\right] - 1$$

The Mueller matrix also contains information about diattenuation which is the difference in transmission between two orthogonal polarization states. This value can be converted to other terms like the polarization dependent loss (PDL),

extinction ratio (ER) or contrast ratio. Furthermore you can obtain the polarizance (P) which is defined as the degree of polarization of the transmitted light, when unpolarized light is incident on the sample. In addition the degree of polarization (DOP) and the depolarization (DEP) can be calculated from the Mueller matrix.

Measurement Setup
Thorlabs offers all the necessary equipment to perform the measurement of a Mueller matrix.

A wide range of laser source are available like HeNe lasers or blue and red laser diodes. Collimation optics or already pigtailed laser diodes can be used for fiber based measurements. Laser diodes can be driven with one of Thorlabs laser diode drivers.

The polarization generator will be a new product. Bistable solenoids will bring optical components like polarizers and waveplates into the beam path. These components or the combination of them will generate the necessary polarizations. The solenoids are controlled by a solenoid driver based on the TXP technology. It is a simple TXP card and can be controlled analog to the PAX polarimeter.

A complete setup can be based on the TXP platform and therefore easily integrated into a production environment. Measurements at one or several wavelengths are done within seconds.
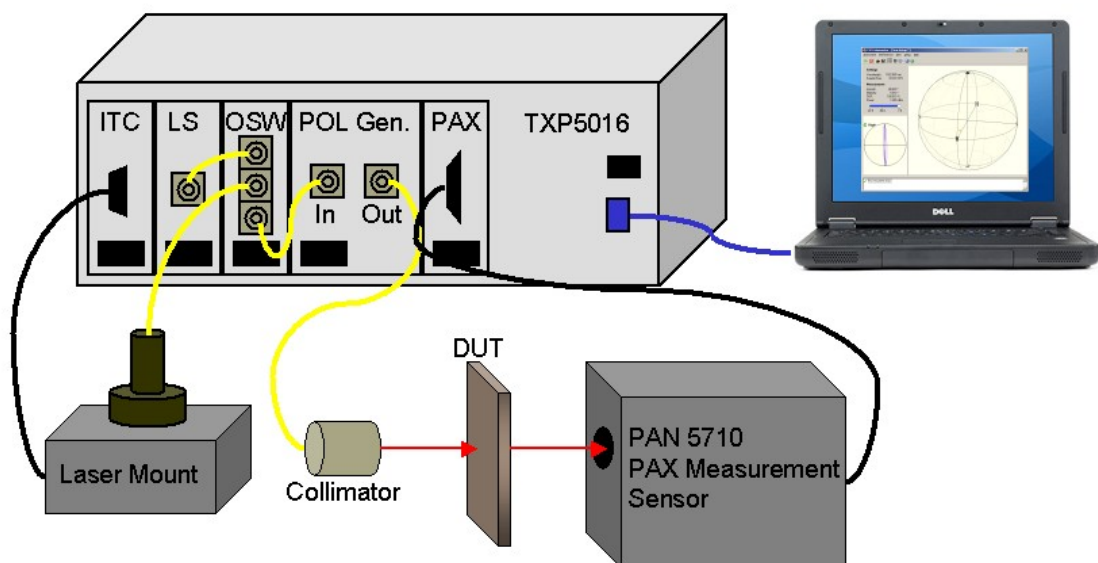
Figure   Measurement Setup for Mueller Matrix based on TXP Platform

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