PAX1000VIS(/M), PAX1000IR1(/M), PAX1000IR2(/M)

Compact Polarimeter

User Guide



Table of Contents

Chapter 1 Introduction 1
1.1 Intended Use 1
1.2 Explanation of Safety Warnings 1
1.3 Description 1
1.4 Technical Data 2
1.4.1 Specifications 2
1.4.2 Mechanical Drawings 3
1.5 Components 5
1.6 Simplified Declaration of Conformity 6
1.7 FCC Designation 6
Chapter 2 Safety 8
Chapter 3 Installation 9
3.1 Warranty 9
3.2 Unpacking Instructions 9
3.3 Installing Hardware 9
3.4 Requirements 10
3.5 Installing Software 11
3.6 Return of Devices 11
Chapter 4 Graphical User Interface (GUI) 12
4.1 Menu File 14
4.2 Menu Device 16
4.3 Menu View 19
4.4 Menu Tools 20
4.5 Menu Help 20
4.6 Status Bar 21
4.7 Settings 21
Chapter 5 Operation 23
5.1 Operating Principle 23
5.2 Alignment Assistance 23
5.3 Measurements 24
5.3.1 Measurement Value Table 25
5.3.2 Polarization Ellipse 28
5.3.3 Poincaré Sphere 29
5.3.4 Scope Mode 31
5.3.5 Long Term Measurement 34
5.3.6 Virtual Device 35
5.3.7 Multiple Devices 36

5.4 Extinction Ratio Measurement Setup 37
5.4.1 ER Measurement Wizard 38
5.4.2 ER Measurement Tool 40
Chapter 6 Custom Software 43
6.1 32-Bit Operating System 44
6.2 64-Bit Operating System 45
Chapter 7 Tutorial 47
7.1 Nature of Polarization 47
7.2 Defenitions of Polarization Parameters 48
7.3 Representation of an Electromagnetic Wave 49
7.4 Polarization Ellipse 51
7.5 Poincaré Sphere 52
7.6 Handedness of Polarization 53
7.7 Rotating Waveplate Technique 57
7.8 Extinction Ratio Measurement on PM Fibers 60
7.9 Literature 66
Chapter 8 Maintenance and Cleaning 67
Chapter 9 Troubleshooting 68
Chapter 10 Disposal 70
Chapter 11 Thorlabs Worldwide Contacts 71

Chapter 1 Introduction

1.1 Intended Use

The PAX1000 Series of Polarimeters are intended for use in laboratory environments and complies with the requirements of EN 61326-1:2021.

The PAX1000 Series of Polarimeters may only be used in accordance with the instructions described in this user guide. Any other use will invalidate the warranty.

1.2 Explanation of Safety Warnings

NOTICE Indicates information considered important, but not hazard-related, such as possible damage to the product.



Hazard indicates a medium level of risk that, if not avoided, could result in serious injury or even death due to electrical shock.



Caution indicates a hazard with a low level of risk that, if not avoided, could result in minor or moderate injury.





The CE/UKCA markings on the product are the manufacturer's declaration that the product complies with the essential requirements of the relevant European health, safety, and environmental protection legislation.



The wheelie bin symbol on the product, the accessories or packaging indicates that this device must not be treated as unsorted municipal waste but must be collected separately.

1.3 Description

Thorlabs polarimeters are terminating, wave-plate-based modules for free-space and - with installed fiber collimator - fiber-based measurements of the state of polarization (SOP). Their high dynamic range of 70 dB, three models covering the visible to near-infrared range, and accuracy of ±0.25° on the Poincaré sphere opens a wide spectrum of application possibilities.

Each measurement sensor is calibrated at different wavelength points. These base points are interpolated.

The PAX1000 Series of Polarimeters is basically powered via the USB port. For a measurement speed higher that 50 samples per second, an additional power supply is required - please connect the DS15 power supply to your mains outlet and to the PAX1000 Series of Polarimeters.

NOTICE Polarization measurements with the PAX1000 Series of Polarimeters are possible only for monochromatic coherent light (e.g., laser emission)!

For warnings and safety information concerning this product, please see Chapter 2 Safety.

1.4 Technical Data

1.4.1 Specifications

All technical data are valid at 23 ± 5 °C and 45 ± 15% relative humidity (non-condensing).

Optical Parameters[a]	
Wavelength Range **PAX1000 Series of PolarimetersVIS(/M)** **PAX1000 Series of PolarimetersIR1(/M)** **PAX1000 Series of PolarimetersIR2(/M)**	 400 to 700 nm 600 to 1080 nm 900 to 1700 nm
Dynamic Range	-60 to +10 dBm
Sampling Rate **Maximum[b]** **Default**	 400 Samples/s 30 Samples/s
Measurable SOP States	Full Poincaré Sphere
Azimuth Accuracy[c]	±0.25°
Ellipticity Accuracy	±0.25°
DOP Accuracy	±1.0%
Input Fiber Connector	FC/PC
Free Space Aperture	Ø3 mm
Maximum Input Beam Divergence	2°
General Specifications	
Power Supply	Via USB 2.0 Interface External Power Supply 15.0 V | 1.2 ADC[d]
Maximum Power Consumption	69 W
Operating Temperature Range[e]	5 to 40 °C
Storage Temperature Range[f]	-40 to 70 °C
Warm-Up Time for Rated Accuracy	15 min
Dimensions (W x H x D)	51.0 mm x 55.0 mm x 56.3 mm (2.01" x 2.17" x 2.22")
Weight	280 g (0.62 lbs)

a. All polarization specifications are valid for optical powers from -40 dBm to +3 dBm.
b. One sample per half turn and 200 Hz motor drive speed; with connected external power supply.
c. For any SOP with -30° < Ellipticity < 30°
d. Required for high-speed measurements; included with the PAX1000 Series of Polarimeters
e. Non-Condensing
f. The storage temperature range of the DS15 power supply is -10 to 70 °C.

Table 1 Specifications for the PAX1000 Series of Polarimeters

1.4.2 Mechanical Drawings

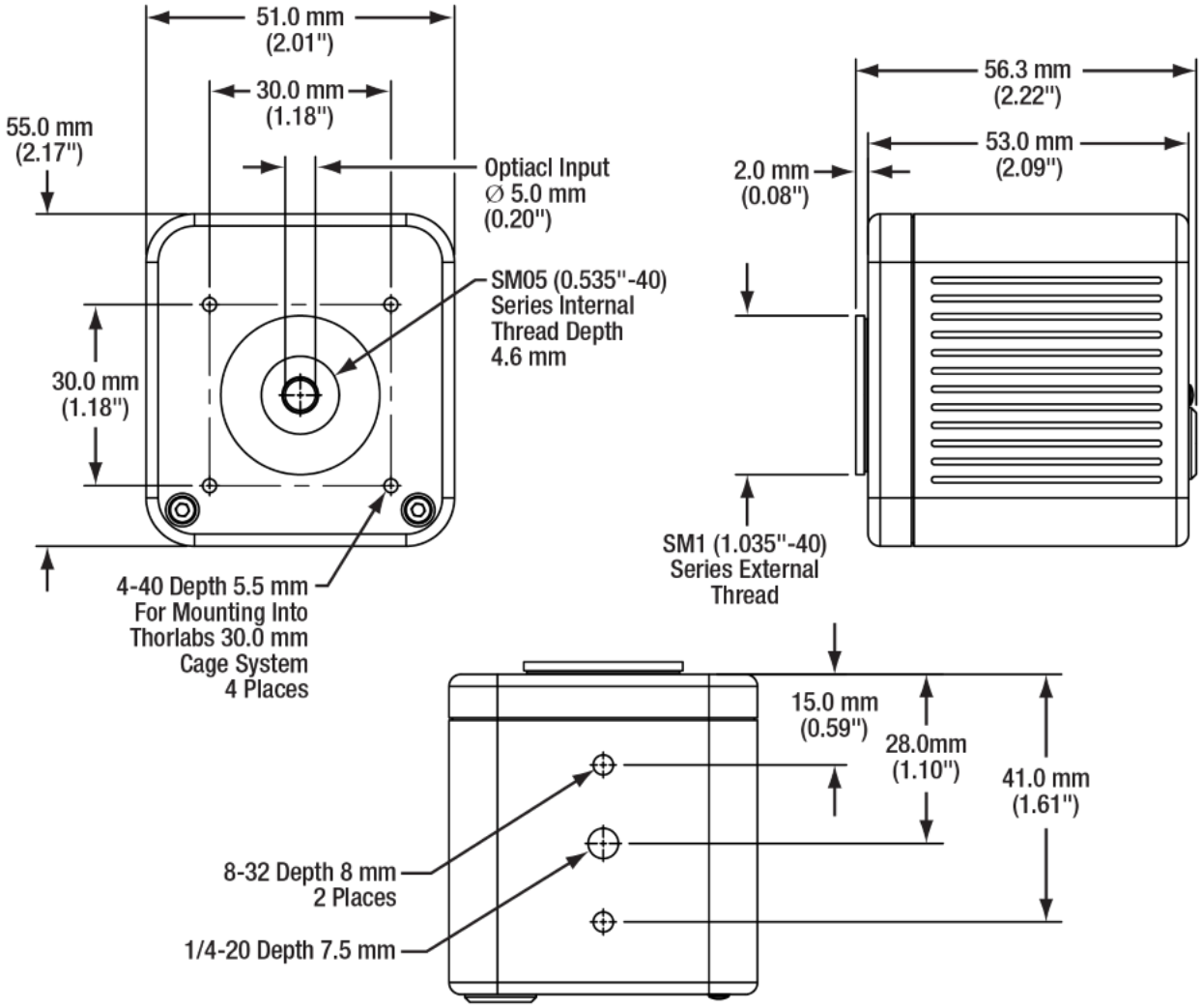


Figure 1 Mechanical Drawing (Imperial) for the PAX1000 Series of Polarimeters

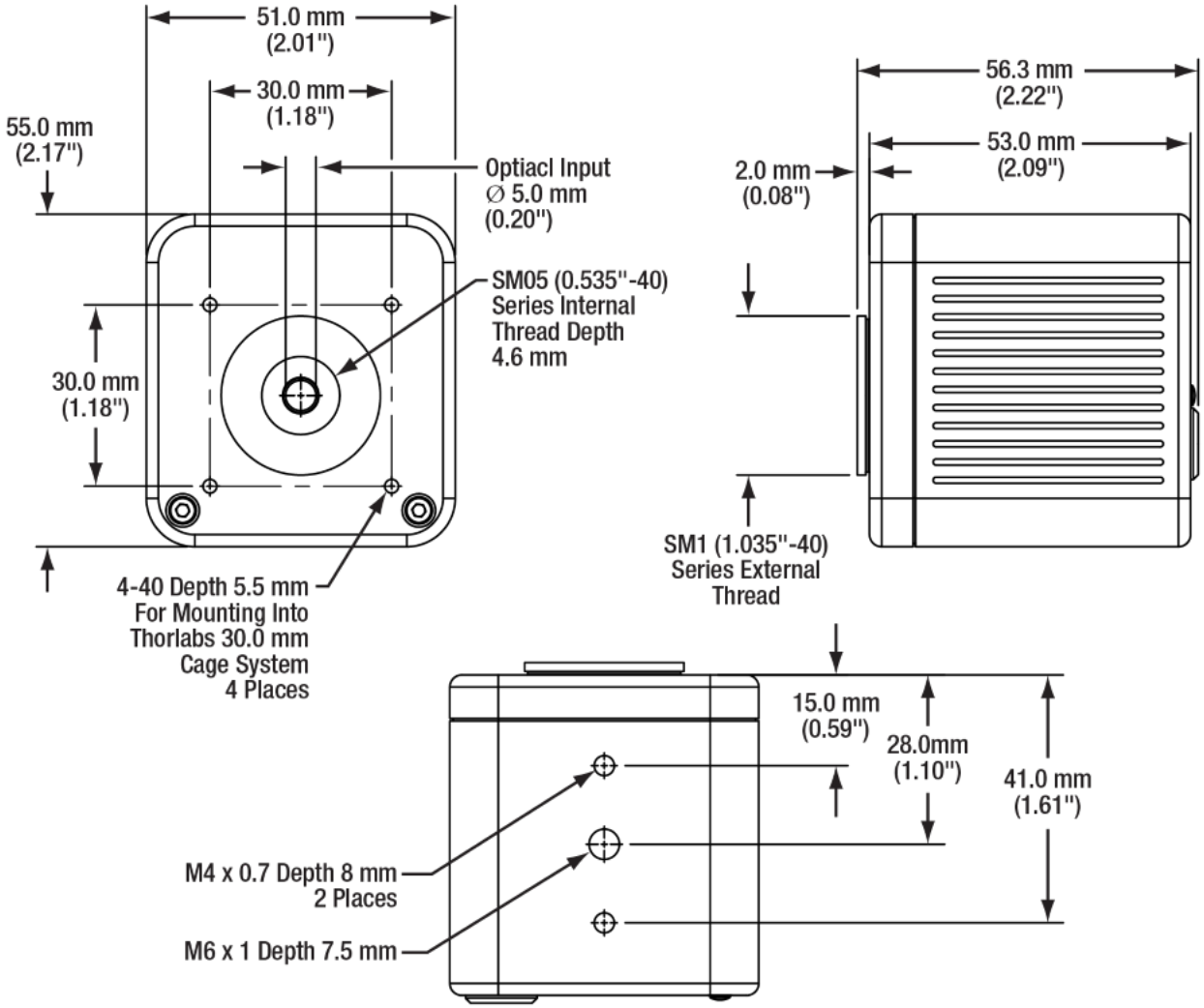


Figure 2 Mechanical Drawing (Metric) for the PAX1000 Series of Polarimeters

1.5 Components

Front Panel



Figure 3 Front Panel of the PAX1000 Series of Polarimeters

Front Panel	
Callout	**Description**
1	Mounting Hole for 30 mm Cage System (4-40, Depth 5.5 mm), 4 Places
2	Input Aperture with SM05 (0.535"-40) External Thread
3	Input Aperture with SM1 (1.035"-40) Internal Thread

Table 2 Front Panel of the PAX1000 Series of Polarimeters

Back Panel



Figure 4 Back Panel of the PAX1000 Series of Polarimeters

Back Panel	
Callout	**Description**
1	Connector for External Power Supply
2	Connector for USB Mini B
3	LED "Ready"

Table 3 Back Panel of the PAX1000 Series of Polarimeters

1.6 Simplified Declaration of Conformity

The full text of the EU declaration of conformity is available at the following internet adress:
https://www.thorlabs.com/polarimeter-systems-with-high-dynamic-range?tabName=Overview

1.7 FCC Designation

This equipment has been tested and found to comply with the limits for a Class A digital device, pursuant to part 15 of the FCC Rules and meets all requirements of the Canadian Interference-Causing Equipment Standard ICES-003 for digital apparatus. These limits are designed to provide reasonable protection against harmful interference when the equipment is operated in a commercial environment. This equipment generates, uses, and can radiate radio frequency energy and, if not installed and used in accordance with the instruction manual, may cause harmful interference to radio communications. Operation of this equipment in a residential area is likely to cause harmful interference in which case the user will be required to correct the interference at his own expense.

Thorlabs is not responsible for any radio television interference caused by modifications of this equipment or the substitution or attachment of connecting cables and equipment other than those specified by Thorlabs. The correction of interference caused by such unauthorized modification, substitution or attachment will be the responsibility of the user.

The use of shielded I/O cables is required when connecting this equipment to any and all optional peripheral or host devices. Failure to do so may violate FCC and ICES rules.

Mobile telephones, cellular phones or other radio transmitters are not to be used within the range of three meters of this unit since the electromagnetic field intensity may then exceed the maximum allowed disturbance values according to IEC 61326-1.

This product has been tested and found to comply with the limits according to IEC 61326-1 for using connection cables shorter than 3 m (9.8 ft).

Chapter 2 Safety

The safety of any system incorporating the equipment is the responsibility of the assembler of the system.

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.



WARNING: Risk of Serious Injury and Even Death Due to Electrical Shock

Improper grounding and connecting the power supply to the mains can cause electric shock.

Electric shock results in damage to your health or even death.

Observe the following instructions when applying power to the PAX1000 Series of Polarimeters:

- Make sure that the protective conductor for the 3 conductor mains power cord is correctly connected to the protective earth ground contact of the socket outlet.
- Before connecting the power supply to the mains make sure that the line voltage range marked on the power supply agrees with your local supply.



WARNING: Risk of Serious Injury and Even Death Due to Explosion

The PAX1000 Series of Polarimeters must not be operated in explosion endangered environments.



CAUTION: Risk of Serious Injuries of Incorrect Use

Pay attention to the following aspects during use:

- Do not obstruct the air ventilation slots in the housing.
- Do not remove covers or open the device. There are no user-serviceable parts inside.
- Refer servicing to qualified personnel.
- Changes to this PAX1000 Series of Polarimeters cannot be made nor may components not supplied by Thorlabs be used without written consent from Thorlabs.

NOTICE: Electrically Sensitive Product

Mobile telephones, cellular phones or other radio transmitters are not to be used within the range of three meters of this unit since the electromagnetic field intensity may then exceed the maximum allowed disturbance values according to IEC 61326-1.

NOTICE

The PAX1000 Series of Polarimeters has been tested and found to comply with the limits according to IEC 61326-1 for using connection cables shorter than 3 m (9.8 ft).

- The instrument must only be operated with a duly shielded and low resistance USB cable delivered by Thorlabs.
- Only connect duly shielded SMA cables to the SMA connector.

Chapter 3 Installation

3.1 Warranty

The precision devices are only serviceable if returned and properly packed into the complete original packaging including the complete shipment plus the cardboard insert that holds the enclosed devices. If necessary, ask for replacement packaging. Refer servicing to qualified personnel.

General Terms and Conditions of Sale can be found at https://www.thorlabs.com/legal.

3.2 Unpacking Instructions

Please inspect the shipping container for damage. Please do not cut through the cardboard, as the box might be needed for storage or returns.

If the shipping container appears to be damaged, keep it until you have inspected the contents for completeness and tested the PAX1000 Series of Polarimeters mechanically and electrically.

3.3 Installing Hardware

For accurate alignment and mounting of the PAX1000 Series of Polarimeters, various accessories are provided to ensure the incident beam is properly centered and oriented with respect to the input aperture (see Figure 5).



Figure 5 The PAX1000 Series of PolarimetersVIS (left) is delivered with a cross-hair engraved protection cap, while the PAX1000 Series of PolarimetersIR1 and PAX1000 Series of PolarimetersIR2 (right) are equipped with a mounted viewing target.

The PAX1000 Series of Polarimeters can be integrated into a free-space (open beam) setup using mounting options on either the bottom or the front of the housing.

Bottom Mounting

The underside of the housing provides three threaded holes for post mounting:

- One central hole: M6 × 1 (metric) or 1/4"-40 (imperial)

- Two additional holes: M4 × 0.7 (metric) or 8-32 (imperial)
  These holes allow secure attachment to standard metric or imperial posts and mounting plates, providing mechanical stability for free-space measurements.

Front Mounting

Four threaded holes are located on the front face of the housing:

- Thread size: 4-40 (imperial)
  These are fully compatible with the Thorlabs 30 mm Cage System, enabling integration into modular cage assemblies for precise optical alignment.

For exact dimensions and hole positions, please refer to section 1.4.2 Mechanical Drawings.

NOTICE

NOTICE: Alignment for Accurate Polarization Measurements

For accurate polarization measurements with the PAX1000 Series of Polarimeters, center the input beam on the aperture and align it perpendicular (normal) to the front surface.

- **Centering**
  Use the supplied protection cap for alignment. The PAX1000 Series of PolarimetersVIS includes a crosshair-engraved end cap; the PAX1000 Series of PolarimetersIR1 and PAX1000 Series of PolarimetersIR2 include a mounted viewing target.
- **Angular Alignment**
  Ensure normal incidence to the front surface. Use the PAX1000 Series of Polarimeters software Alignment Assistance tool to optimize angular positioning.

Proper centering and normal incidence preserve measurement accuracy and avoid polarization bias. Decentering or tilt can reduce accuracy and introduce systematic errors.

3.4 Requirements

The following PC specifications are required for remote operation of the PAX1000 Series of Polarimeters.

Minimum Hardware Requirements

- CPU : 2.4 GHz
- RAM : 2 GB Available RAM
- Graphics Card Resolution : 1024 x 768
- Hard Drive : 1.0 GB of Available Disk Space (32-bit)
  2.3 GB of Available Disk Space (64-bit)
- Interface : Free USB 2.0 Port

Software Requirements

The GUI Software which operates the PAX1000 Series of Polarimeters is compatible with the following operating systems:

- Windows® 8.1 (32-bit and 64-bit)
- Windows® 10 (32-bit and 64-bit)
- Windows® 11

For operation of the PAX1000 Series of Polarimeters by the GUI Software the following software is required als well:

- Microsoft .NET (V 4.6.1 or Later)

- NI-VISA™ Runtime (V 5.4 or Later)
- DirectX9 or Higher

Above mentioned software is included with the Thorlabs PAX1000 Series of Polarimeters installation package, and will be installed automatically, if the required minimum versions are not recognized.

3.5 Installing Software

The GUI Software supports the PAX1000 Series of Polarimeters and is available for download from the website.

As a part of our green initiative, Thorlabs no longer ships physical data carriers for installation of software. The GUI Software can be accessed and installed from the website instead. The most recent version of the GUI Software will always be available online.

NOTICE

NOTICE: Clean Installation

- Do not connect the PAX1000 Series of Polarimeters to the PC prior to software installation.
- Uninstall all previous versions of the software relating to the same device before installing the latest version.
- Exit all running applications on your PC as the installer may require a reboot of your PC during installation.
- Please make sure that the installation is carried out completely, including the reboot requests.

NOTICE

NOTICE: System Configuration Windows 8.1 and 10 Users

To ensure proper installation, disable the Windows Fast Startup feature if prompted by the NI-VISA™ installer.

Failure to do so may prevent correct hardware recognition by NI-VISA™ on Windows 8.1 and 10 systems.

1. Download the the GUI Software from the website.
2. Save the ZIP-file to your PC.
3. Unpack the ZIP-file.
4. Select the *ThorlabsPAX1000Setup.exe* file and double click to install the GUI Software.
5. Follow the installation guide.
6. Read and accept the End-User License Agreement and the GNU Lesser General Public License.
7. After installing the GUI Software, connect the PAX1000 Series of Polarimeters to the PC.
8. Start the GUI Software from the desktop icon.

3.6 Return of Devices

This precision device is only serviceable if returned and properly packed into the complete original packaging including the complete shipment plus the cardboard insert that holds the enclosed devices. If necessary, ask for replacement packaging. Refer servicing to qualified personnel.

Chapter 4 Graphical User Interface (GUI)

Prior to explaining the GUI in detail, there are some general comments to make about the interactions between the PAX1000 Series of Polarimeters hardware and the control software. Please read these comments carefully as this information is important to understanding the functionality.

The PAX1000 Series of Polarimeters calculates the polarization parameters (power, degree of polarization and the three normalized Stokes vectors) in its firmware. These 5 parameters are transferred as a data set to the GUI via the USB connection.

Note

It is important to establish the USB connection prior to starting the software. Only this way the correct drivers can be installed and the PAX1000 Series of Polarimeters can be recognized.

When the GUI starts for the first time, factory default settings for the GUI and default settings for the recognized PAX1000 Series of Polarimeters are applied.

Upon exit, the software automatically saves the most recent workspace to an XML-type file that is located at:

`C:\Users\[user name]\AppData\Local\Thorlabs\PAX1000`

This file contains:

- Recent GUI Appearance
- All Measurement Settings
- All PAX1000 Series of Polarimeters Devices that Ever were Connected (with their Individual Settings)

This file is automatically updated any time the GUI is closed by the user. Please see section 4.1 Menu File for detailed information about the workspace.

Note

When powered via USB, a 50 to 100 Hz sample rate can be set. With connected external power supply, it can be set between 50 and 400 Hz.

The GUI consists of a Tool Bar (1), several Ribbons (2), selectable Views (e.g. (3) and (4)) and the Status Bar ((5)). The ribbons can be minimized and restored using the small icon (6). Click to an area of the screenshot below to be directed to the appropriate section for detailed information.

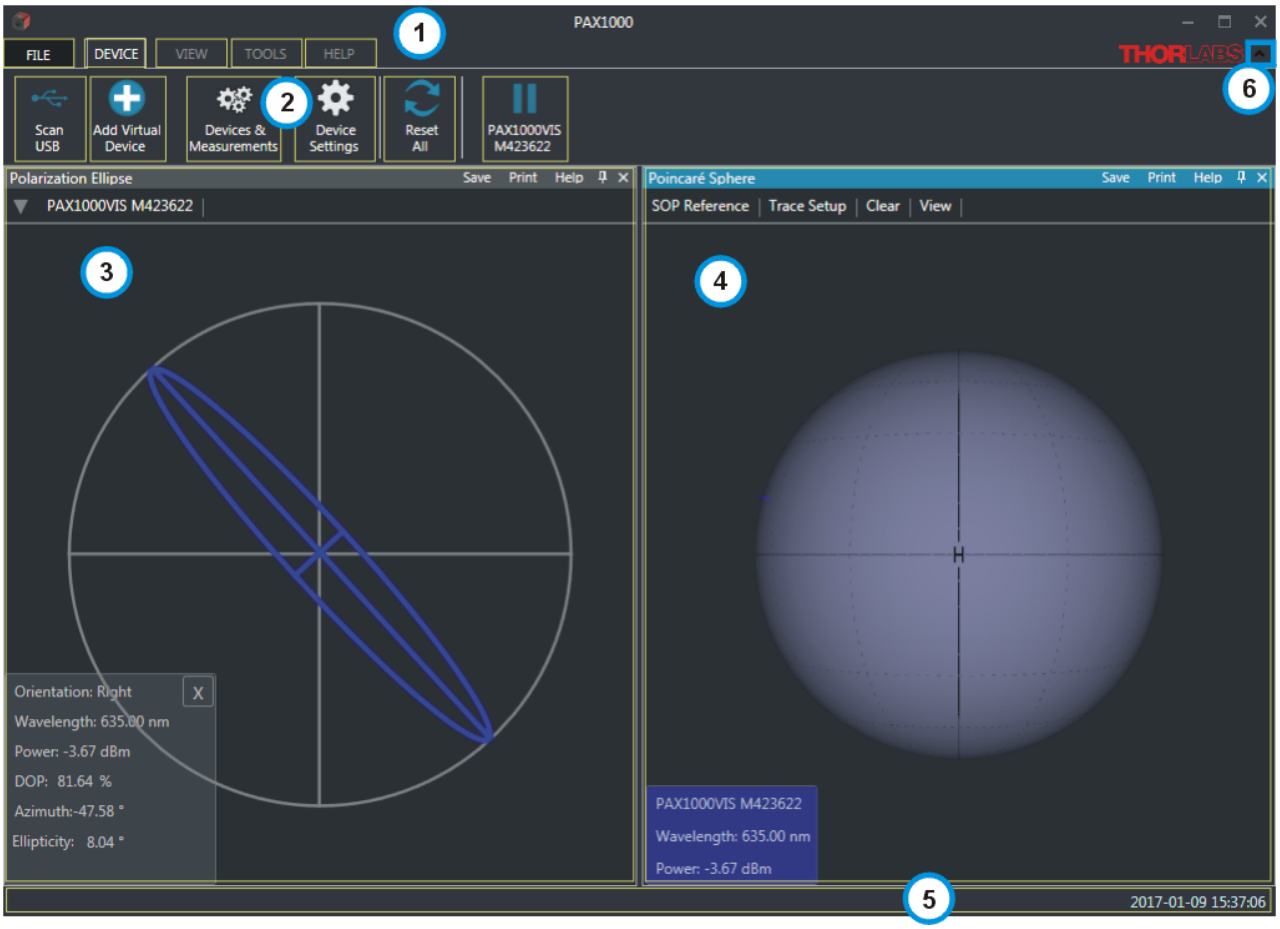


Figure 6 GUI Overview

Callout	Component	Description
1, 2	**Ribbon/Toolbar**	The Ribbon / Toolbar located below the menu bar, this section contains large, icon-based buttons for quick actions like scanning USB devices, adding virtual devices, managing measurements, and resetting all settings.
3, 4	**Views**	The central area of the interface, divided into two panels. The left panel shows the Polarization Ellipse, while the right panel displays the Poincaré Sphere. Each panel includes its own mini toolbar with tabs for additional functions.
5	**Status Bar**	Found at the bottom of the window, typically used to display status messages, progress indicators, or contextual information related to the current operation.

Table 4 GUI Overview

Functions in View Panels



Figure 7 Polarization Ellipse

Each View panel has a header with five options:

- **Save** opens a dialog to save the content of the appropriate panel as a JPG, PNG or BMP image file.
- **Print** creates a screenshot of the appropriate panel in order to print it out to any installed system printer.
- **Help** opens the appropriate section in the PAX1000 Series of Polarimeters software online help.
- The **Pin** (see Figure 8) allows to temporarily unpin the appropriate view from the GUI. Click the *pin* and the *Polarization Ellipse* view collapses and appears like a bookmark on the left, while the other active view (here: Poincaré Sphere) is expanded over the entire GUI:To recover the collapsed view, click to the *bookmark* and then the *pin*:



Figure 8 Polarization Ellipse (Pin Button)

The collapsed view is recovered.

As all active views share the GUI area, the pin/unpin function is helpful to keep the GUI clearly arranged and ensure a quick access to desired or often used view panels.

- The **X** in upper right corner allows to close the active view. They can be recalled in the View menu by clicking the appropriate icon.

4.1 Menu File

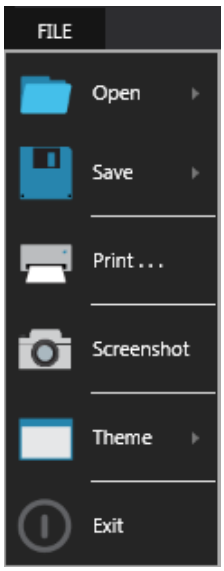


Figure 9 Menu File Menu

Button	Description
Open/Save	Here you can open or save either a configuration or a measurement results file. For a detailed explanation, please see below.
Print	Opens a new window with a screenshot of the actual GUI. This screenshot can be sent to any of your system printers, including PDF driver.
Screenshot	Creates a screenshot of the actual GUI and opens a dialog for saving this screenshot as JPG, PNG or BMP file.
Theme	Allows to toggle between a light or dark design of the GUI.
Exit	Closes the application. You can use the X icon in the upper right corner of the GUI as well.

Table 5 Buttons of the Menu File Menu

Save Configuration

This option allows the setup of the GUI and/or the connected PAX1000 Series of Polarimeters Polarimeters to be saved. The saved configuration can be loaded later for use in future experiments, or with a different optical setup, or copied to and loaded into the software running on a different computer.

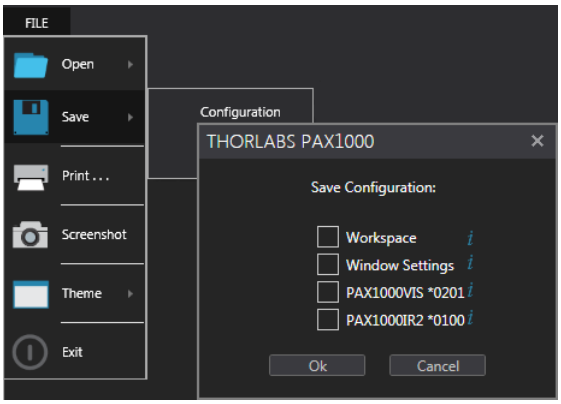


Figure 10 Save Configuration

A configuration is an XML file, that may contain a selectable set of information and that is saved by default to `["My Documents"]\Thorlabs\PAX1000.`

From the list in the Save Configuration dialog you can select:

- **Workspace** saves the configuration of the GUI view, i.e., which sub-panels are displayed, how they are located and sized.
  Example: If the GUI displays only the Scope, with a single diagram expanded, selecting Workspace will save this view.
- **Window Settings** saves the size, position and color theme of the GUI main window.
  Example: You are using two monitors in extended mode, and you the GUI was placed to the extension monitor with a certain size. Using the Window Settings, this arrangement will be saved.
- **PAX1000xxx** saves:
  - Device settings and device information of the connected PAX1000 Series of Polarimeters.
  - All actual settings of the Measurement Value Table, Polarization Ellipse, Poincaré Sphere, Scope Mode and ER Measurement.

After selecting any of above options, a dialog opens to save the configuration file.

Note

Please assign an appropriate file name that tells you about the file content, because you can load afterwards just the entire configuration file, without any option to select workspace, window setting or device setting.

Save Measurement

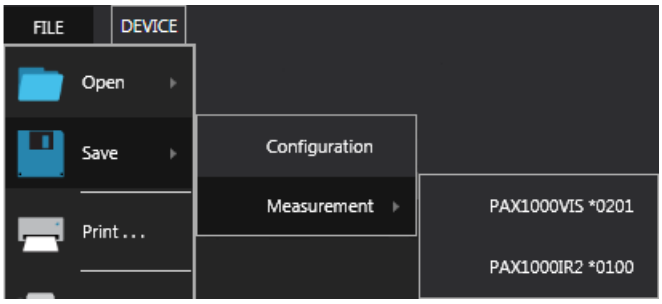


Figure 11 Save Measurement

The **Measurement** file is an CSV file that contains:

- Device settings and device information of the PAX1000 Series of Polarimeters that was used for measurement.
- The most recent 1000 measurement results with time stamp.

	A	B	C	D	E
1	Device:	PAX1000VIS			
2	Serial Number :	E00000201			
3	Firmware Version :	1.0.1			
4	Software Version :	1.0.1257.583			
5	Wavelength [nm] :	633			
6	Basic Sample Rate [Hz] :	60			
7	Operating Mode :	1 revolution for one measurement, 1024 points for FFT			
8					
9	Time[date hh:mm:ss]	Elapsed Time [h	Normalized s	Normalized s	Normalized s

Figure 12 Screenshot of the Measurement CSV File

Open



Figure 13 Open Configuration / Measurement

Here you can open a previously save configuration or a measurement results file.

4.2 Menu Device

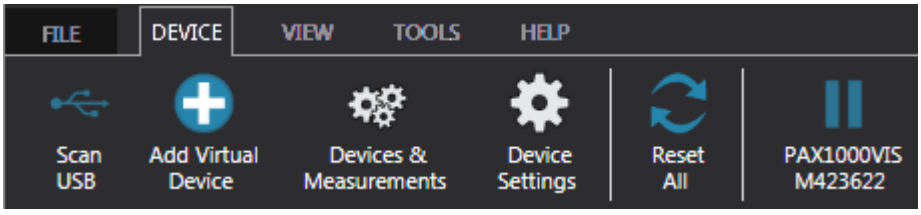


Figure 14 Tool Bar Showing Device Ribbons

Scan USB

Use the *Scan USB* button to rescan all USB Ports in the case the connection was interrupted or an additional PAX1000 Series of Polarimeters was connected during the session.

Note

The PAX1000 Series of Polarimeters software is able to connect up to five PAX1000 Series of Polarimeters device per session, see also the Multiple Devices section.

Add Virtual Device

Virtual devices can be used to test the software features without a PAX1000 Series of Polarimeters hardware connected, for example for evaluation purposes.

Devices & Measurements

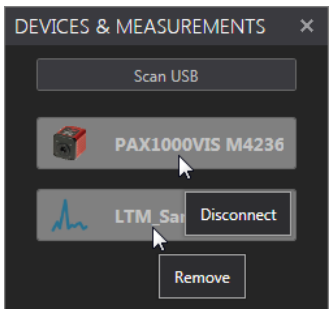


Figure 15 Devices & Measurements Window

A dialog opens that shows presently connected PAX1000 Series of Polarimeters instruments and opened long-term measurement files. This way, an instrument can be disconnected and/or a measurement can be closed - just click on the *entry*.

Device Settings (Polarimeter)

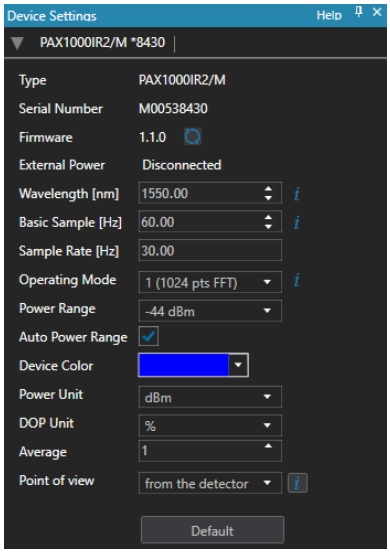


Figure 16 Device Settings (Polarimeter) Window

This dialog lists the PAX1000 Series of Polarimeters device information (read-only) and adjustable settings (within framed boxes).

The  icon in the header shows information about connected devices and loaded measurements and allows a selection.

Device Information

Model version, serial number, firmware version and external power supply status.

Settings

The Basic Sample rate is based on the rotation speed of the waveplate, while the Operating Mode defines measurement averaging and resolution. Please see the PAX1000 Settings section for detailed explanations of the parameters Basic Sample, Sample Rate and Operating Mode.

Wavelength

Enter the operating wavelength to the best known accuracy. This is mandatory for correct measurements. The allowed value range is shown when hovering the mouse over the *i* icon.

Power Range

The PAX1000 Series of Polarimeters has a large input power dynamic range of 70 dB. To achieve a high measurement accuracy, a switchable gain amplifier is used. Each gain value corresponds to a certain maximum input power. By default, the gain is switched automatically (box "Auto Power Range" is checked). In particular cases it might be useful to fix the power range - uncheck the box and set the power range then manually.

Device Color

Select a color for the selected PAX1000 Series of Polarimeters instrument. This color will be used for Polarization Ellipse and Poincaré Sphere display of the measurement data. For each connected and active PAX1000 Series of Polarimeters a different color is assigned that can be changed individually.

Point of View

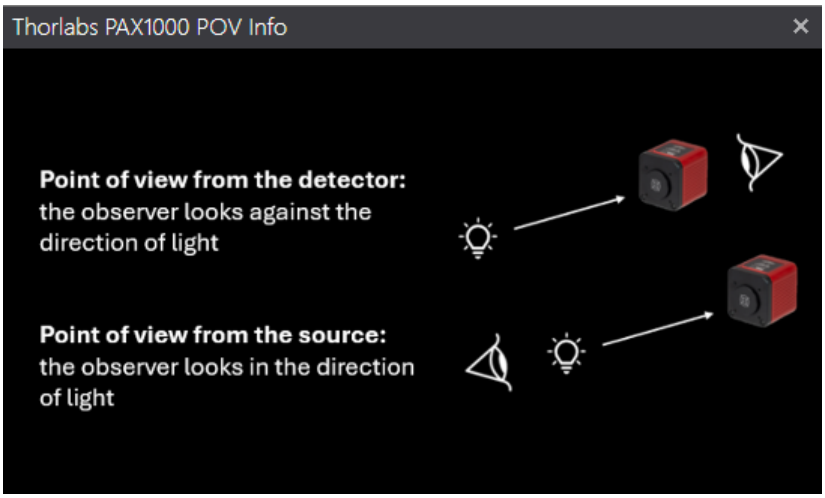


Figure 17 Point of View Window

The dropdown lets you choose the point of view. From the detector means the observer looks against the direction of propagation, while from the source means the observer looks along the light's travel. Clicking the "i" icon opens an info popup with this explanation and a small diagram illustrating both viewpoints.

Default Button

The *Default* button resets the device settings of the selected PAX1000 Series of Polarimeters to default:

- Operating Wavelength Depending on the Device Type:
  VIS 633 nm

IR1 980 nm

IR2 1550 nm

- Basic Sample Rate to 60 Hz
- Operating Mode to 1 (1024 pts FFT)
- Power Ranging to Auto
- Device Color to Blue
- Power Unit to dBm
- Point of View (POV) from the Detector

Device Settings (Measurement)

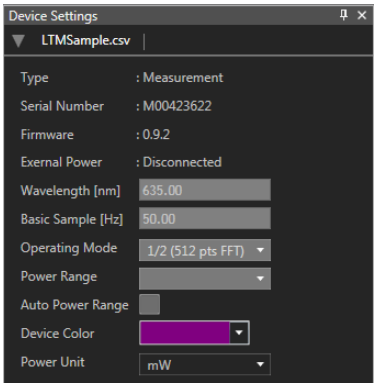


Figure 18 **Device Settings (Measurement)**

This dialog lists the settings of the PAX1000 Series of Polarimeters device when the loaded measurement was executed.

Only the settings within the framed boxes can be changed, these are Device Color and Power Unit.

Reset All

Resets both the GUI and the active PAX1000 Series of Polarimeters settings to default:

The GUI shows the ribbon device with the Polarization Ellipse and the Poincaré Sphere pane, while the PAX1000 Series of Polarimeters device settings are reset to factory defaults.

Pause/Run

This toggle icon allows to pause and resume the current data acquisition from the PAX1000 Series of Polarimeters with the displayed below serial number.

4.3 Menu View

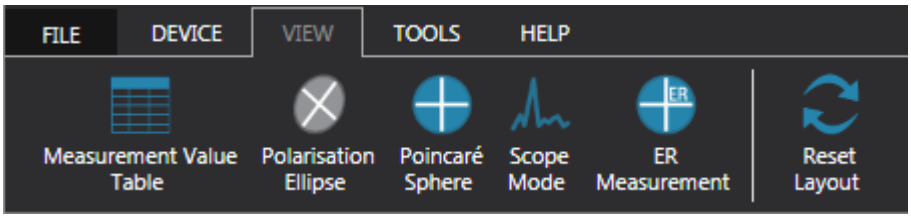


Figure 19 ***Tool Bar showing View Ribbons***

Click to an icon in the above shown screenshot to view the appropriate manual section.

Reset Layout

The *Reset Layout* button resets only the GUI layout:

- Polarization ellipse with numerical values for azimuth and ellipticity
- Poincaré sphere in default view (H (horizontal SOP) in front); clears all traces, clears marker circle

There is no impact on device settings (e.g., wavelength) and measurement settings (e.g., SOP references remain).

4.4 Menu Tools

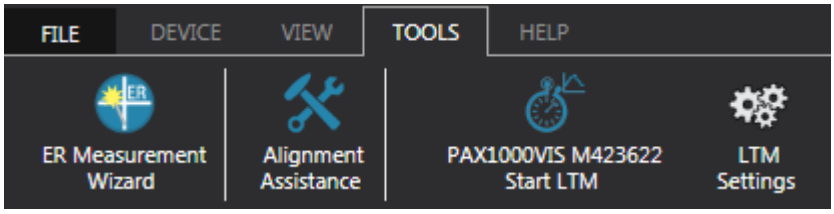


Figure 20 Tool Bar showing Tools Ribbons

Click to an icon in the above shown screenshot to view the appropriate manual section.

4.5 Menu Help

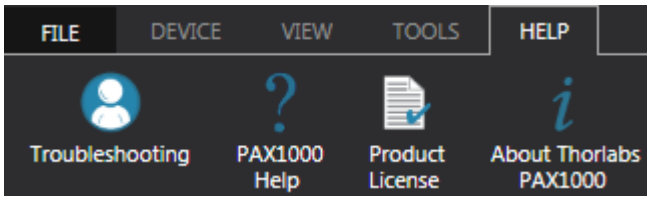


Figure 21 Tool Bar showing Help Ribbons

Troubleshooting

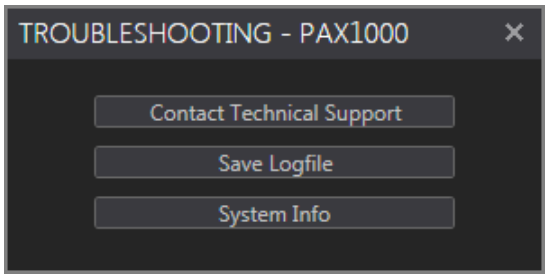


Figure 22 Troubleshooting Window

- **Contact Technical Support**
  Opens Thorlabs web site with the list of world-wide contacts.
- **Save Logfile**
  This file logs the most recent 5 software sessions. It might be helpful to attach this file to a Tech Support request.
- **System Info**
  Displays the Windows System Information about the used PC.

PAX1000 Help

Click the *PAX1000 Help* button to open the online help. When pressing the F1 key, the online help opens with the section of the currently active view (context sensitive help).

Product License

Opens the License.rtf file.

About Thorlabs PAX1000 Series of Polarimeters

Displays information about the current PAX1000 Series of Polarimeters software.

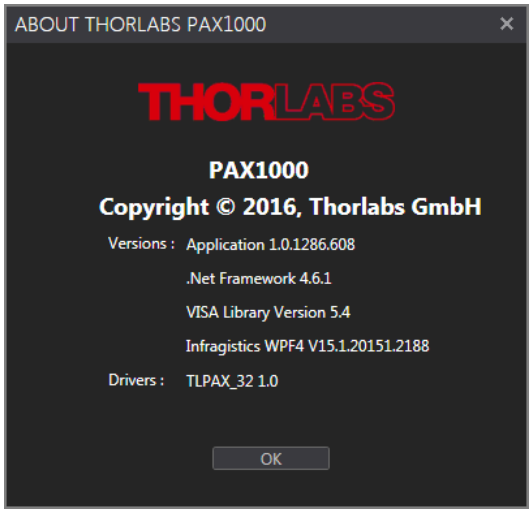


Figure 23 About Window

4.6 Status Bar

By default, the status bar displays only the actual date and time:



Figure 24 Status Bar Displaying Actual Date and Time

It is used to indicate common errors as well as information about long-term measurement (LtM) progress and errors that were observed during the current LtM session:



Figure 25 Status Bar Displaying Actual Date and Time, Progress and Errors

Please see Chapter 9 Troubleshooting for detailed explanations.

4.7 Settings

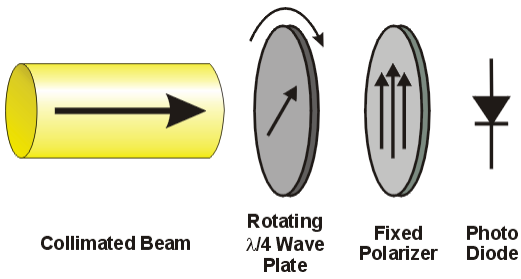


Figure 26 Optical Setup with Collimated Beam, Rotating QWP, Linear Polarizer and Photodiode

Prior to explaining PAX1000 Series of Polarimeters settings, let's briefly recapitulate the measurement procedure that is discussed in detail in the section 7.7 Rotating Waveplate Technique.
The PAX1000 Series of Polarimeters uses a rotating quarter waveplate for polarization analysis.

A half turn of the waveplate is sufficient to uniquely determine the state of polarization. The parameter Basic Sample rate is always related to this half-turn.

The photo current measured during this half turn is analyzed by a Fast Fourier Transformation (FFT). By default, the FFT "splits" the data into 512 measurement points (ADC values).

In order to increase the measurement accuracy:

- the number of FFT points can be set to 1024 or 2048
- the FFT can be carried out over a full turn or over two full turns of the waveplate

The parameter Operating Mode reflects that:

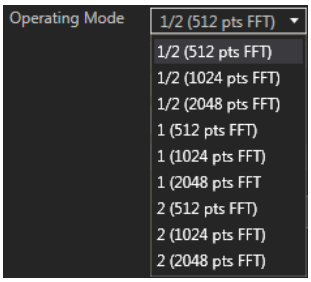


Figure 27 Device Settings in Operating Mode

For example, the operating mode "1/2 (512 pts FFT)" means, that the data for calculation are collected per 1/2 revolution of the waveplate (number of basic periods = $^1/_2$), and the FFT is carried out on 512 points (number of AD converter values) within this half turn. So, the resulting sample rate or measurement speed can be written

$$\text{Resulting Sample Rate} = \frac{\text{Basic Sample Rate}}{2 \cdot \text{Operating Mode}}$$

Mathematically, the number of points used for FFT does not impact the measurement speed. The more FFT points are used, the higher the measurement accuracy, but the higher is also the workload of the microcontroller. Particularly, at high measurement speed and high FFT resolution, measurement data might be not captured because the microcontroller is busy with FFT calculation.

Recommendations

For fast measurements use a high basic sample rate, a small operating mode value and fewer FFT calculation points. At this setting, measurement accuracy might be impacted.

When measuring an optical signal at low power power or with significant noise, decrease the basic sample rate, increase the operating mode and use more FFT points.

Note

When the PAX1000 Series of Polarimeters is powered via USB only, the Basic Sample Rate can be set between 50 and 100 Hz. With external power supply, the maximum Basic Sample Rate is 400 Hz.

Chapter 5 Operation

5.1 Operating Principle

There are several methods to measure the state of polarization. Among these, the Rotating Quarter-Waveplate (QWP) technique has proven to be one of the most reliable and is the principle used in the PAX1000 Series of Polarimeters.

In this technique, a true zero-order λ/4 waveplate is mounted on a low-vibration DC motor. As the motor rotates the waveplate, the incident polarization state is continuously modulated. The modulated light then passes through a fixed linear polarizer, which converts the polarization changes into amplitude variations of the transmitted intensity. A photodiode positioned behind the polarizer detects this signal and generates a photocurrent proportional to the optical power.

The resulting photocurrent consists of three distinct spectral components: a constant DC term from the unpolarized portion of the light, a component at twice the waveplate's rotation frequency, and a phase-shifted component at four times this frequency. These components contain all the necessary information about the polarization of the incoming light.

By applying a Fast Fourier Transformation (FFT) to the photocurrent, the normalized Stokes parameters (s1, s2, s3) can be determined. From these, both the polarized optical power and the degree of polarization (DOP) are derived. Together, these values fully characterize the polarization state of the incident light.

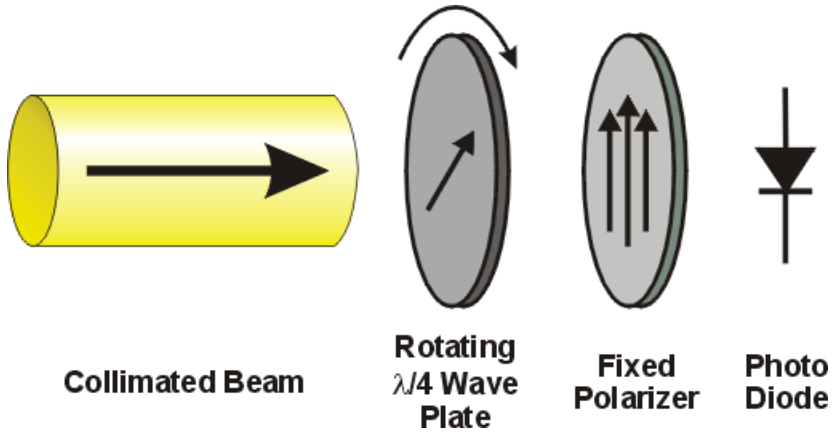


Figure 28 Optical Setup with Collimated Beam, Rotating QWP, Linear Polarizer and Photodiode

For more information, please see section 7.7 Rotating Waveplate Technique.

5.2 Alignment Assistance

For accurate measurements, it is essential to align the incident beam so that it is centered in the input aperture and is normally incident on the rotating λ/4 waveplate.

The beam centering is particularly important in the case of large incident beam diameters, close to the aperture diameter (Ø3 mm). In such cases the correct centering is essential to avoid beam cutting and reflections from the inner surface of the hollow shaft that holds the waveplate. The beam centering can be achieved by using the protection cap with engraved cross-hair (PAX1000 Series of PolarimetersVIS) or with a viewing target (PAX1000 Series of PolarimetersIR1 and ~IR2).

The angular alignment is critical for another reason: As explained in the section Rotating Waveplate Technique, the photo current is analyzed by a Fast Fourier Transformation and ideally consists only of even-numbered components (harmonics). If the beam hits the waveplate not exactly perpendicular, unwanted odd-numbered harmonics will appear in the photo current. The same happens if the incident

beam consists of components reflected from the inner surface of the hollow light shaft.These unwanted components have a significant impact on the measurement accuracy. The Alignment Assistance tool can be used to align the beam, which will minimize the contribution from unwanted components.

1. Click the *Tool* button in the Tools ribbon. A new screen (see Figure 28) comes up.
   The Alignment graph shows the fraction of wanted components in the photo current. The green portion of the scale defines the range of acceptable alignment values.
2. Click the *Start Alignment* button.

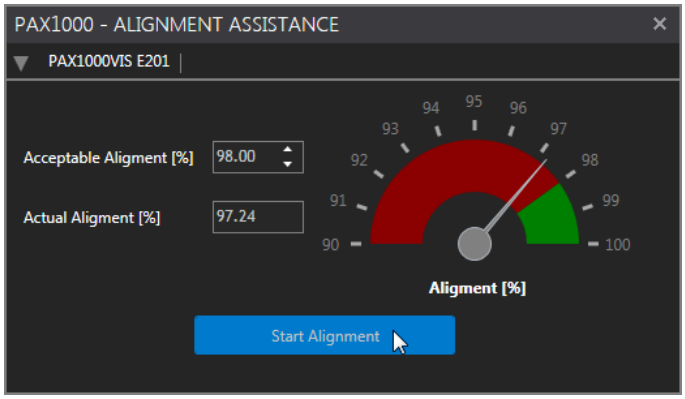


Figure 29 Alignment Assistance window for device PAX1000VIS E201 with Acceptable Alignment set to 98% and Actual Alignment at 97.24%. The control shows Start Alignment.

3. Adjust the alignment of the beam with respect the PAX1000 Series of Polarimeters beam. When the best alignment is achieved, click the *Stop Alignment* Button and close the window.

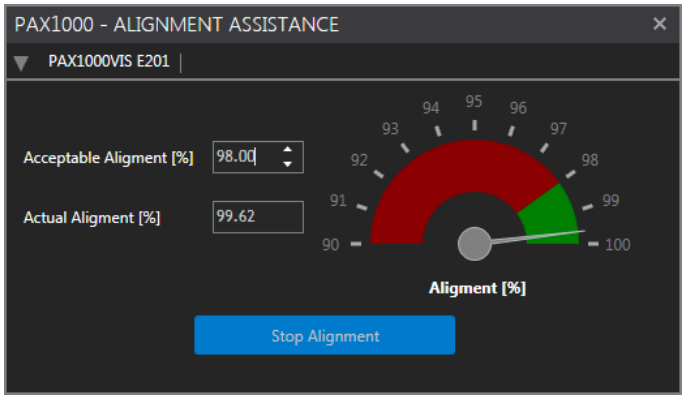


Figure 30 Alignment Assistance window for device PAX1000VIS E201 with Acceptable Alignment set to 98% and Actual Alignment at 99.62% (green range). The control shows Stop Alignment.

5.3 Measurements

Before starting a measurement, ensure that all device settings are configured correctly. In particular, verify that the operating wavelength is entered and that the power range is set appropriately (recommended setting: Auto Range) to guarantee accurate results.

The PAX1000 Series of Polarimeters software offers several polarization measurement views, which can be accessed from the View ribbon. If the ribbon is hidden, click the small arrow next to the Thorlabs logo (highlighted in yellow) to expand it.



Figure 31 Ribbon View

These views are described in detail in the subsequent sections:

- Measurement Value Table
- Polarization Ellipse
- Poincaré Sphere
- Scope Mode
- Long Term Measurement
- Extinction Ratio Measurement

The *Reset Layout* button resets the GUI layout to:

- Polarization Ellipse with Numerical Values for Azimuth and Ellipticity
- Poincaré Sphere in Default View H (Horizontal SOP) in Front (Clears all Traces, Clears Marker Circle)

There is no impact on device settings (e.g., wavelength) and measurement settings (e.g., SOP references remain).

5.3.1 Measurement Value Table

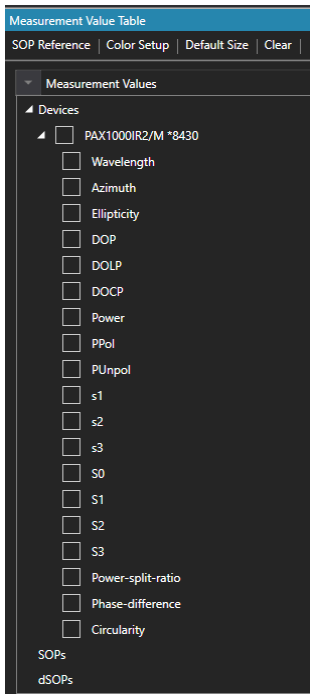


Figure 32 Measurement Value Table

Click the  icon to show the Measurement Value Table. It displays a selectable number of polarization parameters numerically in a list. Click the drop-down arrow (marked yellow) to expand the list and select the desired parameters. When checking the box of the active PAX1000 Series of Polarimeters, all parameters will be enabled, with the possibility to disable any of them.

For detailed explanation of the polarization parameters, please see the section 7.2 Definitions of Polarization Parameters.

If more than one PAX1000 Series of Polarimeters is connected and active, this selection can be made for each of these devices.

If at least one SOP Reference is enabled, you can select the polarization parameters of the reference that shall be displayed numerically, as well as the dSOP:

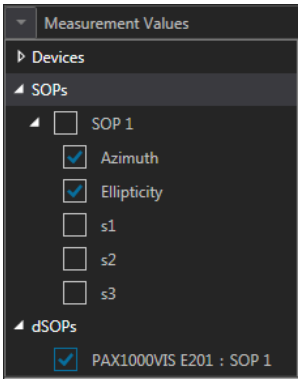


Figure 33 Azimuth, Ellipticity and PAX1000 Series of PolarimetersVIS Selected in the Measurement Value Table

A SOP reference is a certain, user-configurable state of polarization that can be used as a reference point. In combination with the dSOP parameter, this allows to measure the polarization shift of the actual state of polarization from the reference point.

Up to 20 reference SOPs can be defined.

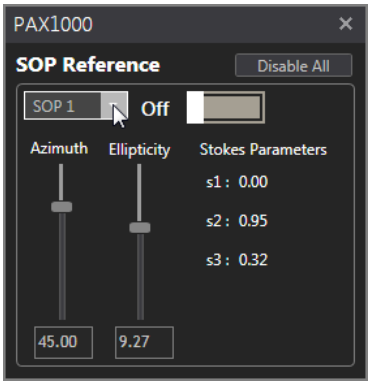


Figure 34 SOP Reference Disabled

Click to the menu item *SOP Reference*. A dialog opens:

Select from the drop-down menu one of SOP 1 to SOP 20.

Define the azimuth and ellipticity for this reference point, either by using the slider or by entering the desired value numerically. The software automatically calculates the appropriate normalized Stokes vectors.

Note

The Stokes vectors cannot be entered by the user.

Set the switch from Off to On to enable the actual SOP reference.

The *Disable All* button disables all SOP references at once.

dSOP

dSOP is the difference between the actual measured SOP and a SOP reference, in degree. This is the angle between the two polarization vectors on the Poincaré sphere. Using the normalized Stokes vectors, this can be written mathematically as:

$$\mathrm{dSOP} = \arccos\left(\begin{bmatrix} S_{1,\mathrm{Ref}} \\ S_{2,\mathrm{Ref}} \\ S_{3,\mathrm{Ref}} \end{bmatrix}^{\mathrm{T}} \cdot \begin{bmatrix} S_{1,\mathrm{Meas}} \\ S_{2,\mathrm{Meas}} \\ S_{3,\mathrm{Meas}} \end{bmatrix}\right) = \arccos\left(S_{1,\mathrm{Ref}}\, S_{1,\mathrm{Meas}} + S_{2,\mathrm{Ref}}\, S_{2,\mathrm{Meas}} + S_{3,\mathrm{Ref}}\, S_{3,\mathrm{Meas}}\right)$$

Note

Above formula takes into account that the normalized Stokes vectors with an absolute value =1 are used for calculation.

The dSOPs will be displayed in Measurement Value Table this way:

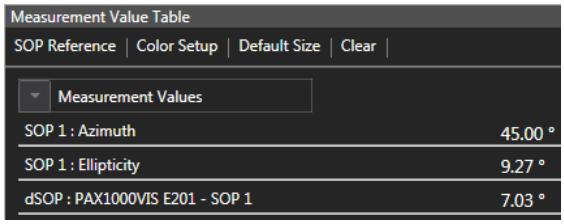


Figure 35 dSOP Display

By clicking to the area outside the parameter selection window, the parameter selection panel closes and in the GUI will be displayed the table with measurement results:

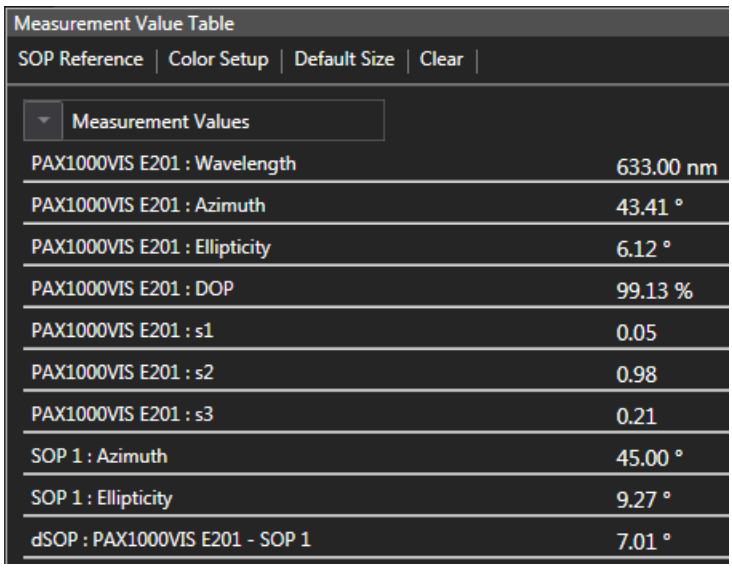


Figure 36 Measurement Results in the Measurement Value Table

5.3.2 Polarization Ellipse

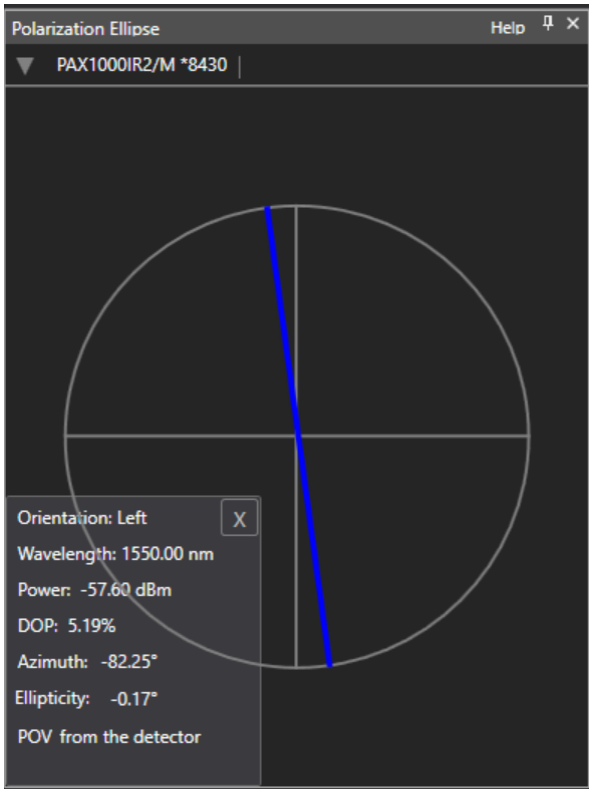


Figure 37 Polarization Ellipse

In this view, the polarization ellipse is displayed. The ellipse color depends on the device setting.

The ▼ icon in the left upper corner allows to select one of the connected polarimeters for display.

Below the ellipse, a box with numerical parameters is shown. These five parameters are shown at any time:

- Orientation (Handedness)
- Wavelength
- Total Power
- DOP (Degree of Polarization)
- POV (Point of View)

By clicking to the grey area, the display of the additional parameters can be changed:azimuth and ellipticity, or

- power split ratio and phase difference, or
- the 3 normalized Stokes vectors s1, s2 and s3.

Please see Chapter 7 Tutorial for detailed information on these parameters. The numerical parameters can be hidden (X); then the small i icon will restore them.

For functions in the blue header line, please see Chapter 4 Graphical User Interface (GUI).

5.3.3 Poincaré Sphere

The default view of the Poincaré sphere is shown in the screenshot.

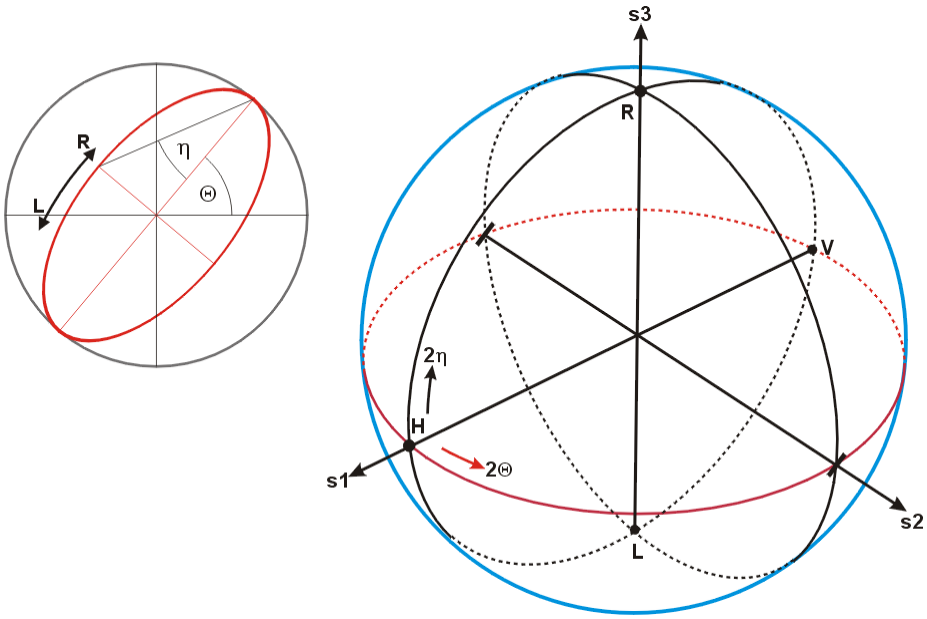


Figure 38 Poincaré Sphere Representation

Viewing Options

- Click the colored box to show the current SOP in front. If you have more than one PAX1000 Series of Polarimeters connected, the click shows the current SOP of the selected device.
- Hold the *Left Mouse* button and drag to rotate the sphere.
- Scroll the mouse wheel or press + (-) to zoom the view.
- To move the sphere, press A (left), D (right), W (up) or S (down).
- Press Ctrl and *Left Mouse* button to create a SOP reference.
- Press Ctrl, hold down *Right Mouse* button and drag to create a circular marker on the sphere.

For functions in the blue header line, please see Chapter 4 Graphical User Interface (GUI).

Menu SOP References

A SOP reference is a certain, user-configurable state of polarization that can be used as a reference point. In combination with the dSOP parameter, this allows to measure the polarization shift of the actual state of polarization from the reference point.

Up to 20 reference SOPs can be defined.

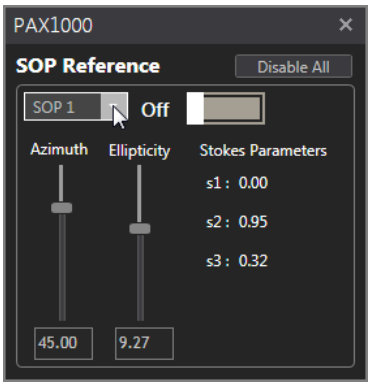


Figure 39 SOP Reference Disabled

Click to the menu item SOP Reference. A dialog opens:

Select from the drop-down menu one of SOP 1 to SOP 20.

Define the azimuth and ellipticity for this reference point, either by using the slider or by entering the desired value numerically. The software automatically calculates the appropriate normalized Stokes vectors.

Note

The Stokes vectors cannot be entered by the user. Set the switch from **Off** to **On** to enable the actual SOP reference. The *Disable All* button disables all SOP references at once.

Menu Trace Setup

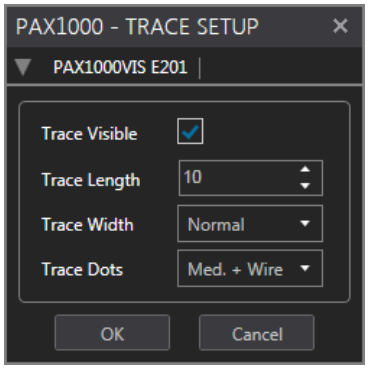


Figure 40 Display SOP Tracking on the Poincaré Sphere

In this menu you setup the SOP trace on the Poincaré sphere. When enabled, each SOP measurement point is added to the trace until the selected trace length is reached. The dwell time of a trace this way depends on the trace length and the measurement speed.

Trace Visible

The Trace Visible enables/disables the trace display.

Trace Length

The Trace Length values between 1 and 50.000 can be entered.

Note

The maximum trace length is limited for memory load reasons and it is available only in case of a single device is connected. Please refer to section 5.3.7 Multiple Devices.

Trace Width

The Trace Width can be selected to thin, normal and bold.

Trace Dots

The Trace Dots select the shape of the trace:

- small, medium or large dots only
- small, medium or large wired dots, or - wire only.

Click the *OK* button to apply settings and close the panel.

Menu Clear

The Menu Clear clears the trace. SOP references remain.

Menu View



Figure 41 Display of the Poincaré Sphere Adjustment

Adjust, how you want to look at the Poincaré sphere.

H and **V** rotate the sphere to position the equatorial points corresponding to the linear horizontal and vertical polarizations, respectively, at the front.

R and **L** rotate the sphere to bring the polar points corresponding to the right or left handed circular polarizations, respectively, to the front.

Finally, \ and / rotate the sphere to bring the points corresponding to an azimuth of -45° and +45°, respectively, to the front.

The 3 buttons to the right provide the following functions:

- Saves the current Poincaré sphere orientation and zoom factor as user view..
- Recalls the saved user view.
- Resets the zoom to default, all other view settings are not impacted.

5.3.4 Scope Mode

In Scope Mode, the 1000 most recently measured polarization parameters are shown plotted to a graph. The graph can be continuously updated as values are acquired. The data logging

- starts with the connection of a PAX1000 Series of Polarimeters device
- restarts after pressing the *Clear Data* button.

Select from the View ribbon the item Scope Mode.

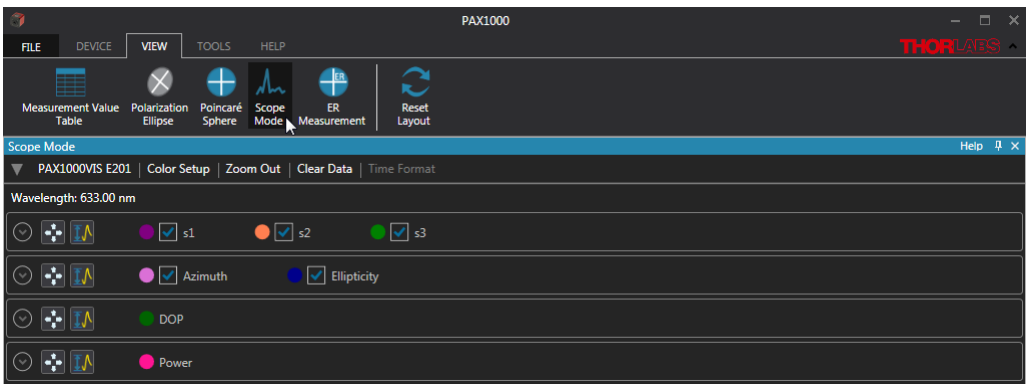


Figure 42 Scope Mode Start View

In the initial view shows four parameter groups, with the display of the scope graphs collapsed. Use the icon to show the desired diagram.

Select Data Source

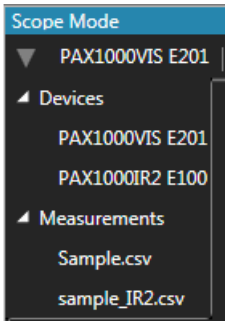


Figure 43 Scope Mode Select Source View

Click the icon and expand Devices and/or Measurements to select a data source.

Note

In order to select a saved measurement, it must be opened first from the File menu!

Color Setup

This menu assigns the color to the individual graphs. Select your preferred color.

Clear Data

Clear Data deletes the accumulated measurement value and restarts the display. The time axis is then zoomed until the maximum of 1000 measurement values is reached. After reaching 1000 samples, the diagram shows the most recent 1000 samples, i.e., with each new sample, the oldest is discarded, and the times axis shifts.

Time Format

If a measurement is loaded and selected for display, the time format can be toggled between time stamp and elapsed time. For running measurements (a PAX1000 Series of Polarimeters is selected), only the time stamp is used.

Diagram Options

Each of the four diagrams can be modified for the best view. Additionally, for the first two diagrams (normalized Stokes vectors; ellipticity/azimuth) you can select the parameters to be displayed. The diagram options are explained below using the example of the Stokes vectors diagram with a saved measurement loaded from a file.

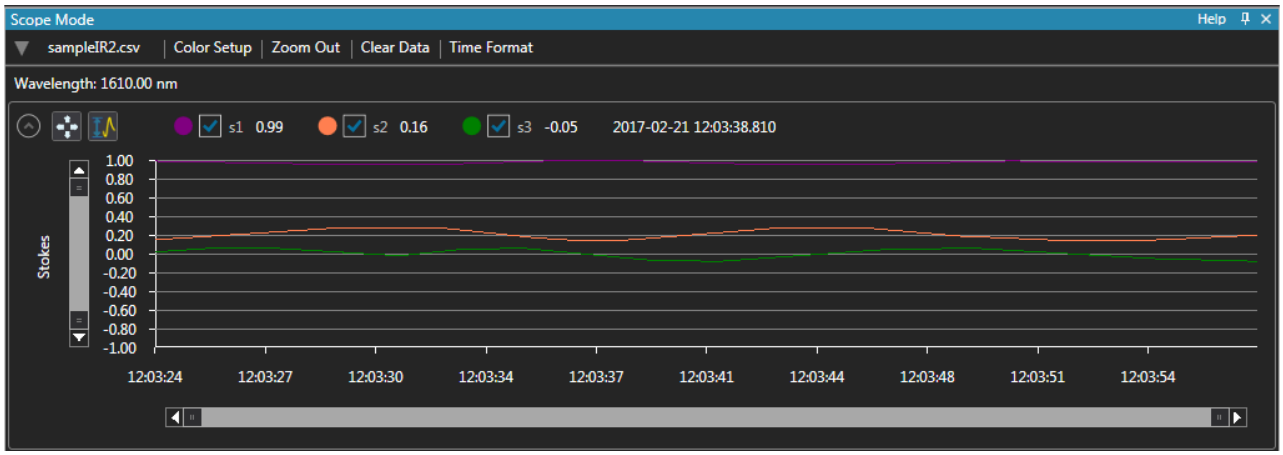


Figure 44 Scope Mode View Stokes

Toggle the diagram view between expanded and collapsed.

Expand the diagram over the entire GUI window by hiding the other 3 charts.

Set the upper and lower limits of the Y scale:

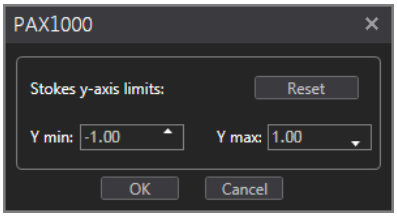


Figure 45 Scope Mode View Stokes Limits

Set the desired limits either by entering numerically or using the up/down arrows.

Click the *OK* button to apply changes.

Click the *Reset* button to restore the scale limit to the maximum in accordance with the actual parameter.

Zoom and Pan

Place the mouse pointer to the point in the diagram that you want to zoom in. A yellow marker appears. Scroll the mouse wheel and the diagram will be zoomed in around the moose pointer in both the Y and time scale directions:



Figure 46 Hover the mouse pointer over the diagram area ...



Figure 47 and scroll the mouse wheel

Note

The yellow marker appears instantly when hovering the mouse over the diagram only if a loaded measurement is displayed.

In live mode, when the measurement of a PAX1000 Series of Polarimeters is displayed, the yellow marker appears only after the mouse wheel was rotated. Then the display of the current measurement is paused and the diagram can be zoomed.

Another way to zoom and pan the diagram is the use of the zoom-pan-sliders to the left and below the chart:



Figure 48 Pan-Slider



Figure 49 Pan-Slider



Figure 50 Pan-Slider

Using the *Zoom Out* button in the diagram header, you can instantly return to the full diagram view:



Figure 51 Scope Mode View Zoom Out

5.3.5 Long Term Measurement

The LTM buttons can be found in the Tools ribbon.

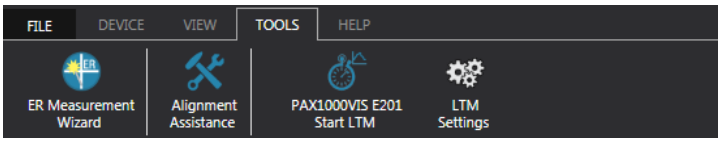


Figure 52 LTM Buttons

The long-term measurement tool records the following parameters:

- Stokes Vectors S0, S1, S2 and S3 (mW)
- Normalized Stokes Vectors s1, s2 and s3
- Azimuth (°)
- Ellipticity (°)
- DOP (%)
- Degree of Linear Polarization (%)
- Degree of Circular Polarization (%)
- Total Power (mW/dBm)
- Polarized Power (mW/dBm)
- Unpolarized Power (mW/dBm)
- Power Split Ratio
- Phase Difference

Settings

Each set of above listed parameters is provided with the exact time stamp (dd.mm.yyy hh:mm:ss) and the elapsed time with millisecond resolution (d.hh:mm:ss:msec). The recorded file format is *.csv and can be easily imported to Microsoft Excel. Alternatively, the data can be saved as a *.txt file.

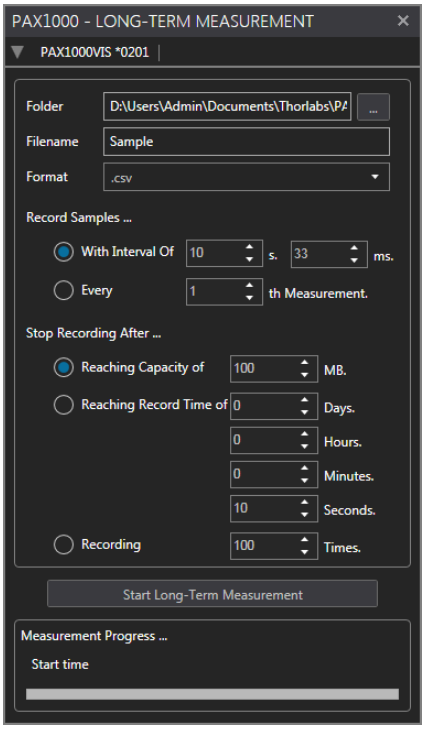


Figure 53 LTM Settings

Prior to starting a long-term measurement, open the LTM Settings panel and enter the measurement conditions.

1. Select a folder, the file name and file format.
2. Select the sampling frequency options:
   - Set the sample acquisition time interval to a value from 50 ms to 60 s in increments of 1 ms.
   - Specify which measurements to record to file, with a value of 1 recording every measurement and a maximum value of 10000 recording every 10000th measurement.
3. Select the Stop criteria:
   - after reaching a file size between 0.1 and 1000 MB
   - after reaching a record time between 10 sec and 365 days 23:59:59 hours
   - after recording 1 to 10000 measurement data sets

Measurement

After completing the desired settings for your long-term measurement, the recording can be started by clicking the *Start Long-Term Measurement* button in the settings panel or the button in the ribbon Tools.

The measurement progress is shown in the settings panel (see Figure 53) and in the status bar (see Figure 54).

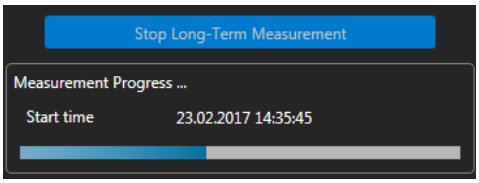


Figure 54 LTM Running in the Settings Panel



Figure 55 Status Bar

5.3.6 Virtual Device

A virtual PAX1000 Series of Polarimeters can be connected. This is an easy way to evaluate the PAX1000 Series of Polarimeters software without the hardware. This device is based on a PAX1000 Series of PolarimetersIR1 with its default settings. These settings cannot be changed.

The virtual device delivers random measurement values that can be used to test all measurement functionality, except the ER measurement on PM fibers.

5.3.7 Multiple Devices

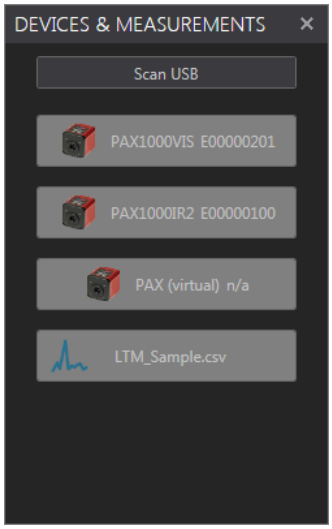


Figure 56 Devices & Measurements View

The PAX1000 Series of Polarimeters software allows up to five PAX1000 Series of Polarimeters devices, including live devices and measurement files, to be simultaneously connected. Connect the PAX1000 Series of Polarimeters. Open menu Devices & Measurements in the DEVICE ribbon - all connected and recognized PAX1000 Series of Polarimeters devices are listed here, along with loaded measurement files.

Note

If you do not see the device that you want to connect, please make sure that the USB connection is made properly. Click the *Scan USB* button to force device recognition.

Each view of the GUI allows a selection of the device to be displayed from a drop-down menu. In the Poincaré sphere view all connected devices are displayed at the same time:

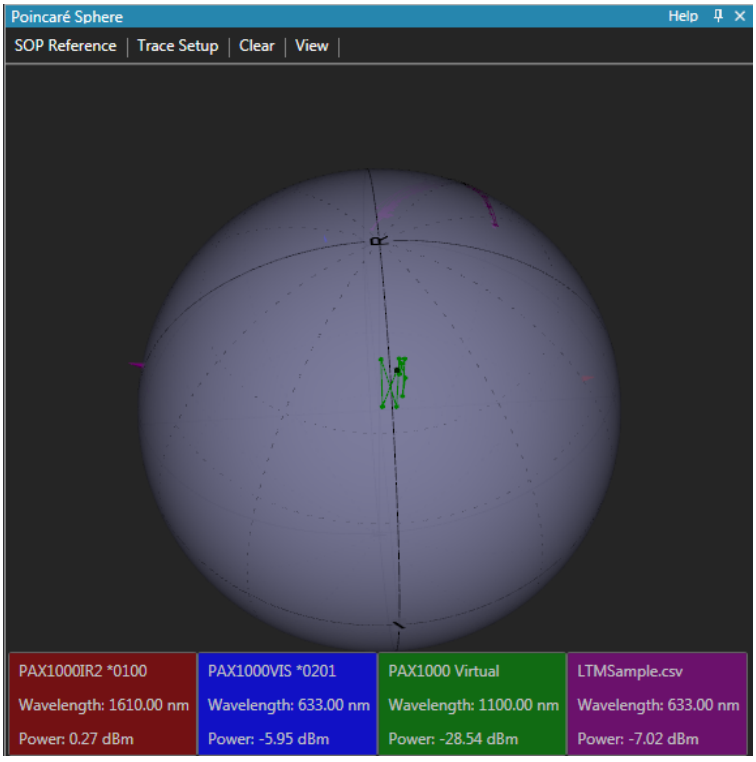


Figure 57 Multiple Devices View

Note

A total of 50 000 measurement values can be displayed on the Poincaré sphere. This limitation was set in order to save system resources. This limitation affects the maximum trace length. If more than one PAX1000 Series of Polarimeters is connected, the maximum number of points that can be displayed on the Poincaré sphere, equal to the maximum trace length, will be shared:

- 1 PAX1000 Series of Polarimeters: max. 50 000 points
- 2 PAX1000 Series of Polarimeters: max. 25 000 points
- 3 PAX1000 Series of Polarimeters: max. 15 000 points
- 4 PAX1000 Series of Polarimeters: max. 12 500 points
- 5 PAX1000 Series of Polarimeters: max. 10 000 points

For any loaded measurement file, a maximum of 1000 most recent points will be displayed on the Poincaré sphere. However, in the Scope Mode, all measurement data of a loaded file will be displayed.

Please note also, that in the case of large trace lengths and multiple device operation, the software performance may degrade significantly, depending on the computer's resources.

5.4 Extinction Ratio Measurement Setup

Extinction Ratio (ER) Measurement on Polarization-Maintaining Fibers

The PAX1000 Series of Polarimeters supports measurement of the Extinction Ratio (ER) of polarization-maintaining fibers (PMF). For theoretical background and general principles, please refer to the section Extinction Ratio Measurement on PM Fibers.

Requirements for Accurate Measurements

1. Use a linearly polarized light source.
   Examples: pigtailed laser diode with PMF output fiber, or a free-space laser combined with a fiber coupler and a PAX1000 Series of Polarimeters Fiber-to-Fiber U-Bench or a manual fiber polarization controller.
2. The DOP of the source should be as close to 100% as possible.
3. The operating wavelength must be well defined.
4. The optical input power must not exceed the PAX1000 Series of Polarimeters specification.
5. Couple the linearly polarized light parallel to the slow axis of the fiber under test.

Measurement Setup

NOTICE

NOTICE: Use of Correct Fiber Collimator Required

Using the wrong collimator type may result in poor coupling efficiency or unstable measurement results.

Observe the following instructions when using fibers:

- Do not force an FC/APC connector into an FC/PC collimator, as this may scratch or damage the connector end face.
- Use an F240FC-x collimator for FC/PC connectors. For FC/APC connectors, use a F240APC-x collimator instead.
- The suffix "x" specifies the wavelength range of the anti-reflective coating and must match both the PAX1000 Series of Polarimeters and the operating wavelength of your setup.

Connect the output of the fiber under test to the PAX1000 Series of Polarimeters using the supplied fiber collimator with SM1 adapter.

Applying Stress to the Fiber

1. For reliable ER results, the PMF must be dynamically stressed during the measurement: The optical test signal is typically generated by a DFB laser diode and connected to a Thorlabs PL100S deterministic polarization controller.
2. The PMF under test is connected between the output of the polarization controller and the input of the PAX1000 Series of Polarimeters.
3. Stress can be applied by heating (e.g., using a filament bulb placed at the center of a looped fiber) or mechanically (e.g., gentle manual pulling).

Please note that these stress methods are suitable only for bare PMF without protective tubing.

Measurement Process

When the ER Measurement Wizard is running and the fiber is stressed, the PMF output SOP (state of polarization) traces a circle on the Poincaré Sphere. For reliable ER results, at least one full circle must be completed, meaning that the stress variation during the test must be sufficient to produce the required change in polarization state.

5.4.1 ER Measurement Wizard

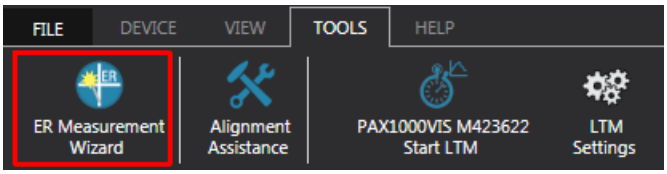


Figure 58 ER Measurement Wizard Ribbon

Running the ER Measurement Wizard

If you are already familiar with this measurement, you may use the ER Measurement tool directly.

1. Open the ER Measurement Wizard from the Tools menu.
   The Start window provides a summary of the measurement setup.
2. If necessary, select the PAX1000 Series of Polarimeters to be measured and click the *Next* button.
3. Enter the operating wavelength of your light source and select the desired measurement time.
4. Select the option Stop on Circle Completed, which will terminate the measurement as soon as the SOP change reached a full circle
5. When done, click the *Next* button.

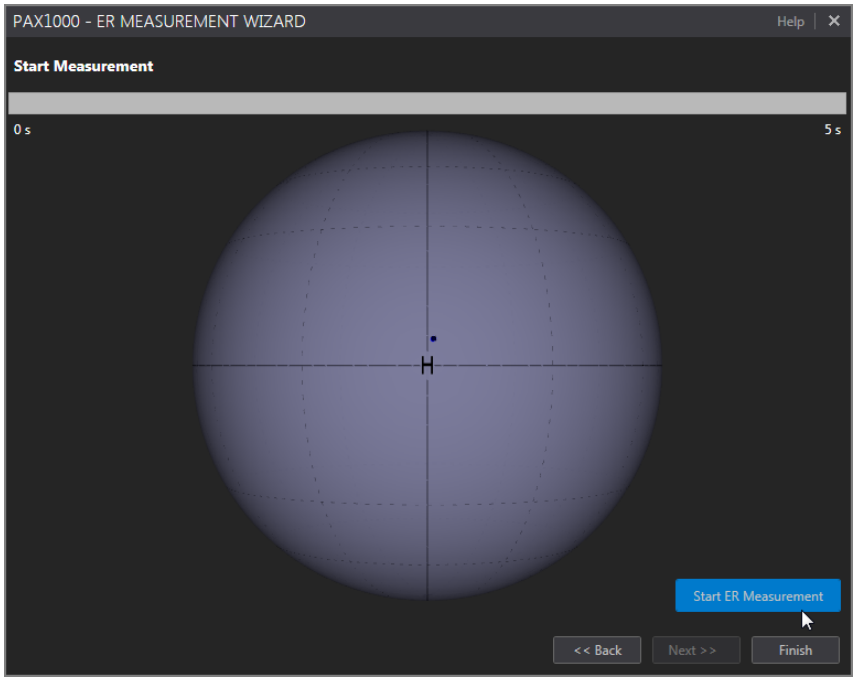


Figure 59 ER Measurement Wizard - Start ER Measurement

6. The current SOP is displayed on the Poincaré Sphere. Click *Start ER Measurement* button to proceed.
7. After finishing the measurement, the final screen (see Figure 59) appears.

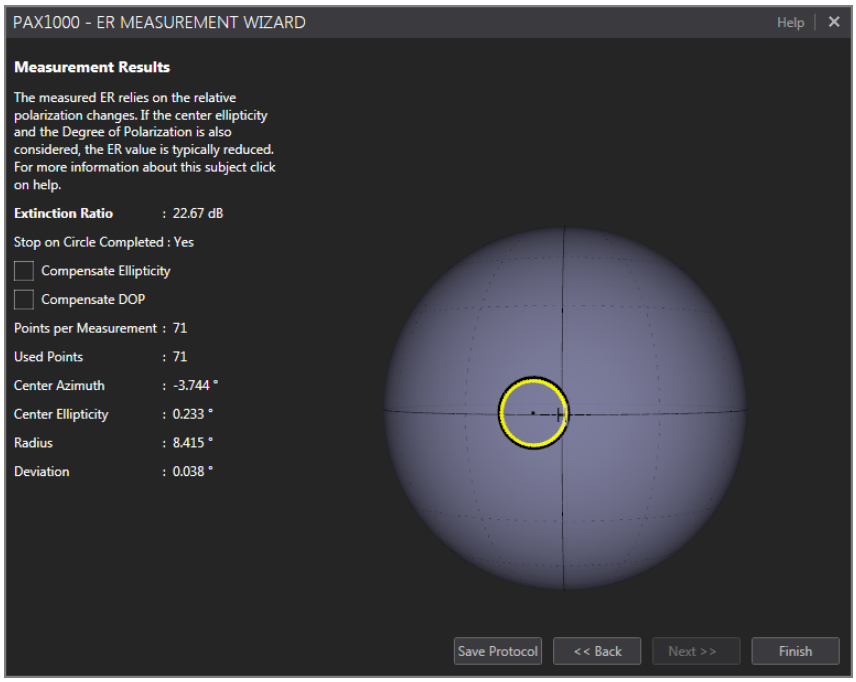


Figure 60 ER Measurement Wizard - Measurement Results

Button	Description
Save Protocol	Save the numeric test results and the Poincaré Sphere screenshot to a PDF file.
Back	Return to the previous window.
Finish	Close the ER Measurement Wizard and return to the PAX1000 Series of Polarimeters GUI.

Table 6 Buttons of the ER Measurement Wizard

Please see the chapter Tutorial for detailed explanation of the options Correction for Absolute Ellipticity and Correction for DOP.

Please see the section ER Measurement Tool for detailed explanations of the numerical results.

If a warning or an error message appears, please see chapter Troubleshooting for possible reasons and solution proposals.

5.4.2 ER Measurement Tool

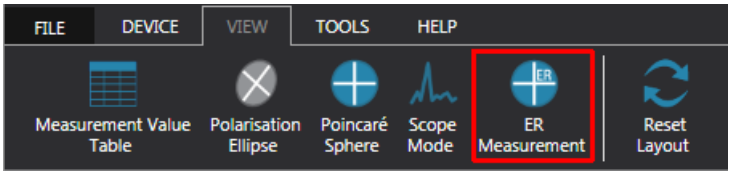


Figure 61 ER Measurement Ribbon

The ER Measurement tool allows the easy measurement the Extinction Ratio of PM fibers. During the measurement, the fiber must change enough to cause at least a change of polarization that describes a circle on the Poincaré Sphere: The smaller the circle diameter, the higher the ER value.

1. Prepare your setup. Ensure a correct coupling of the light signal into the fiber - the dot on the Poincaré Sphere representing the SOP out of the fiber should lay as close as possible to the H mark. Azimuthal deviations from the horizontal polarization are not critical, whereas a position towards the poles indicates an ellipticity that is caused by miscoupling of the light into the fiber under test.
2. Start the ER Measurement tool from the appropriate button in the view ribbon:

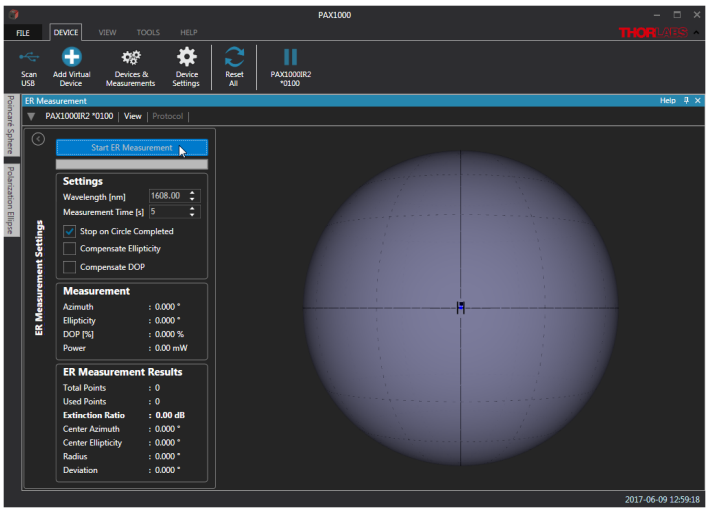


Figure 62 ER Measurement Tool

3. Enter the operating wavelength of your light source.
   Please note that an exact wavelength value is essential for minimum measurement errors.
4. Select the measurement time between 3 and 10 s. During measurement, the fiber stress must cause at least a full circle on the Poincaré Sphere. The higher the stress applied to the fiber, the shorter the time to achieve this.
   You may select for a first try the maximum time of 10 s and check the box *Stop on Circle Completed*.
5. Start the fiber stress and the ER measurement.
6. After finishing the measurement, the GUI will display the measurement results:

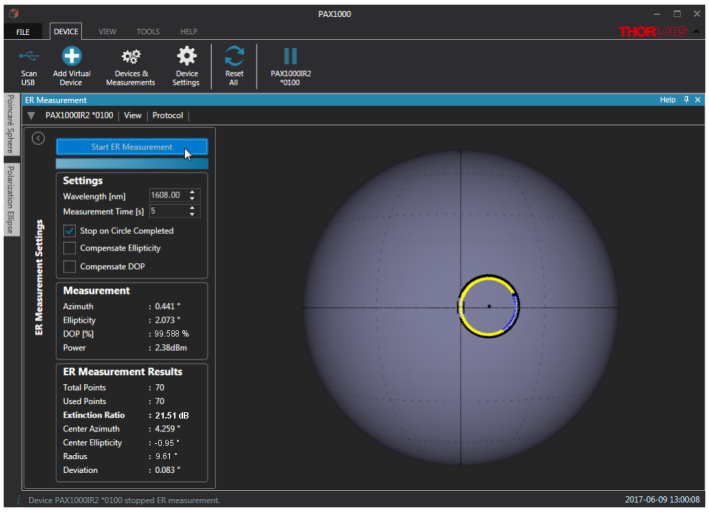


Figure 63 ER Measurement Tool - Measurement Results

7. The yellow circle represents the measured states of polarization, while the black circle is the approximation that is used for calculation of the ER.

Measurement Results

The box Measurement displays the parameters that were measured at the end of the ER Measurement.

The box ER Measurement Results displays several parameters:

Parameter	Description
Total Points	The total number of measured states of polarization (SOPs).
Used Points	The points that remain after internal filtering and are used for circle approximation and ER calculation.
Extinction Ratio	The calculated extinction ratio, displayed according to the settings of the Compensate Ellipticity and Compensate DOP check boxes. For more details, see the section Extinction Ratio Measurement on PM Fibers.
Center Azimuth	The azimuth angle of the center of the calculated circle on the Poincaré Sphere.
Center Ellipticity	The ellipticity angle of the center of the calculated circle on the Poincaré Sphere.
Radius	The radius of the calculated circle in degrees on the Poincaré Sphere.
Deviation	The standard deviation of the used points from the fitted circle.

Table 7 Parameters Used for ER Measurement Calculation

If a warning or an error message appears, please see section Troubleshooting for possible reasons and solution proposals.

Chapter 6 Custom Software

In order to write your own application, you need specific instrument driver(s) and some tools for use in different programming environments. The driver and tools are included in the installer package on the website.

In this section the location of drivers and files, required for programming in different environments, are given for installation under Windows 10 (32-bit and 64-bit) and Windows 11.

GUI Software and drivers contains 32-bit and 64-bit applications.

In 32-Bit systems, only the 32-Bit components are installed to:

C:\Program Files\...

In 64-Bit systems the 64-Bit components are being installed to:

C:\Program Files\...

while 32-Bit components can be found at:

C:\Program Files (x86)\...

In the table below you will find a summary of what files you need for particular programming environments.

Programming Environment	Necessary Files
C, C++, CVI	*.fp (Function Panel File; CVI IDE only) *.h (Header File) *.lib (Static Library) *.dll (Dynamic Linked Library)
C#	*.net wrapper dll
Visual Studio	*.h (Header File) *.lib (Static Library) or *.net wrapper dll
LabVIEW™	*.fp (Function Panel) and NI-VISA™ Instrument Driver Beside that, LabVIEW™ driver vi's are provided with the *.llb container file.

Table 8 Files for Programming Environments

All above environments require also the NI-VISA™ instrument driver dll.

During NI-VISA™ Runtime installation, a system environment variable VXIPNPPATH for including files is created. It contains the information where the drivers are installed to, usually to C:\Program Files\IVI Foundation\VISA\WinNT\.

After installation of a NI-VISA™ Runtime, a system reboot is required: This environment variable is necessary for installation of the instrument driver GUI Software components.
In the next sections the location of above files is described in detail.

6.1 32-Bit Operating System

According to the VPP6 (Rev 6.1) Standard the installation of the 32-bit VXIpnp driver includes both the WINNT and GWINNT frameworks.

VXIpnp Instrument Driver

`C:\Program Files\IVI Foundation\VISA\WinNT\Bin\TLDC_32.dll`

`C:\Program Files\Thorlabs\TLDC\Drivers\Instr\bin\TLDC_32.dll`

This instrument driver is required for all development environments!

Header File

`C:\Program Files\IVI Foundation\VISA\WinNT\include\TLPAX.h`

Static Library

`C:\Program Files\IVI Foundation\VISA\WinNT\lib\msc\TLPAX_32.lib`

Function Panel

`C:\Program Files\IVI Foundation\VISA\WinNT\TLPAX\TLPAX.fp`

Online Help for VXIpnp Instrument Driver

`C:\Program Files\IVI Foundation\VISA\WinNT\TLPAX\Manual\TLPAX.html`

NI LabVIEW™ Driver (Including an Example VI)

The LabVIEW™ driver is a 32-bit driver and compatible with 32bit NI-LabVIEW™ versions 8.5 and higher only.

`C:\Program Files\National Instruments\LabVIEW xxxx\instr.lib\TLPAX…`
`…\TLPAX.llb`

The LabVIEW™ container file with driver vi's and an example. "LabVIEW xxxx" stands for actual LabVIEW™ installation folder.

.net wrapper dll

`C:\Program Files\Microsoft.NET\Primary Interop Assemblies…`
`…\Thorlabs.PAX1000.Interop.dll`

`C:\Program Files\IVI Foundation\VISA\VisaCom\Primary Interop…`
`…Assemblies\Thorlabs.PAX1000.Interop.dll`

Example for C

Source File:

`C:\Program Files\IVI Foundation\VISA\WinNT\TLPAX\Examples\CSample\…`
`…sample.c`

(C program how to communicate with a PAX1000 Series of Polarimeters Series Polarimeter)

Example for C#

Solution File:

`C:\Program Files\IVI Foundation\VISA\WinNT\TLPAX\Examples…`
`…\CSharp\Thorlabs.PAX_CSharp_Demo.sln`

Project File:

`C:\Program Files\IVI Foundation\VISA\WinNT\TLPAX\Examples…`
`…\CSharp\Thorlabs.PAX_CSharp_Demo\Thorlabs.PAX_CSharp_Demo.csproj`

Executable sample Demo:

```
C:\Program Files\IVI Foundation\VISA\WinNT\TLPAX\Examples…
…\CSharp\Thorlabs.PAX_CSharp_Demo\bin\Thorlabs.PAX_CSharp_Demo.exe
```

Example for LabVIEW™

Included in LabVIEW™ .llb container.

6.2 64-Bit Operating System

According to the VPP6 (Rev 6.1) Standard, the the installation of the 64-bit VXIpnp driver includes the WINNT, WIN64, GWINNT and GWIN64 frameworks. This means, that the 64-bit driver includes the 32-bit driver as well.

In case of a 64-bit operating system, 64-bit drivers and applications are installed to:

"C:\Program Files"

while the 32-bit files - to

"C:\Program Files (x86)"

Below are listed both installation locations, so far applicable.

VXIpnp Instrument Driver

```
C:\Program Files (x86)\IVI Foundation\VISA\WinNT\Bin\TLPAX_32.dll
C:\Program Files\IVI Foundation\VISA\Win64\Bin\TLPAX_64.dll
```

This instrument driver is required for all development environments!

Header file

```
C:\Program Files (x86)\IVI Foundation\VISA\WinNT\include\TLPAX.h
C:\Program Files\IVI Foundation\VISA\Win64\include\TLPAX.h
```

Static Library

```
C:\Program Files (x86)\IVI Foundation\VISA\WinNT\lib\msc…
…\TLPAX_32.lib
C:\Program Files\IVI Foundation\VISA\Win64\Lib_x64\msc\TLPAX_64.lib
```

Function Panel

```
C:\Program Files (x86)\IVI Foundation\VISA\WinNT\TLPAX\TLPAX.fp
```

Online Help for VXIpnp Instrument Driver

```
C:\Program Files (x86)\IVI Foundation\VISA\WinNT\TLPAX\Manual…
…\TLPAX.html
```

NI LabVIEW driver (Including an Example VI)

The LabVIEW™ driver supports 32-bit and 64-bit NI-LabVIEW™ 2009 and higher.

32 bit NI-LabVIEW™ Version

```
C:\Program Files (x86)\National Instruments\LabVIEW xxxx\instr.lib…
…\TLPAX\TLPAX.llb
```

64 bit NI-LabVIEW™ Version

```
C:\Program Files\National Instruments\LabVIEW xxxx\instr.lib…
…\TLPAX\TLPAX.llb
```

The LabVIEW™ container file with driver vi's and an example. "LabVIEW xxxx" stands for actual LabVIEW™ installation folder.

.net wrapper dll

`C:\Program Files (x86)\Microsoft.NET\Primary Interop Assemblies…`
`…\Thorlabs.PAX1000.interop.dll`

`C:\Program Files (x86)\IVI Foundation\VISA\VisaCom\…`
`…Primary InteropAssemblies\Thorlabs.PAX1000.Interop.dll`

`C:\Program Files\IVI Foundation\VISA\VisaCom64\…`
`…\Primary Interop Assemblies\Thorlabs.PAX1000_64.Interop.dll`

Example for C

Source File:

`C:\Program Files (x86)\IVI Foundation\VISA\WinNT\TLPAX\Examples\…`

`…CSample\sample.c`

(C program how to communicate with a PAX1000 Series of Polarimeters Series Polarimeter)

Example for C#

Solution File:

`C:\Program Files (x86)\IVI Foundation\VISA\WinNT\TLPAX\Examples…`
`…\CSharp\Thorlabs.PAX_CSharp_Demo.sln`

Project File:

`C:\Program Files (x86)\IVI Foundation\VISA\WinNT\TLPAX\Examples…`
`…\CSharp\Thorlabs.PAX_CSharp_Demo\Thorlabs.PAX_CSharp_Demo.csproj`

Executable Sample Demo:

`C:\Program Files (x86)\IVI Foundation\VISA\WinNT\TLPAX\Examples…`
`…\CSharp\Thorlabs.PAX_CSharp_Demo\bin\Thorlabs.PAX_CSharp_Demo.exe`

Example for LabVIEW™

Included in LabVIEW™ .llb container.

Chapter 7 Tutorial

7.1 Nature of Polarization

When talking about polarization, light is considered as 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 an unpolarized and polarized part. The plane of polarization of unpolarized light, also called natural light, fluctuates arbitrarily around the direction of propagation, so that in average no direction is favored.

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. The following pictures illustrate different states of polarization:

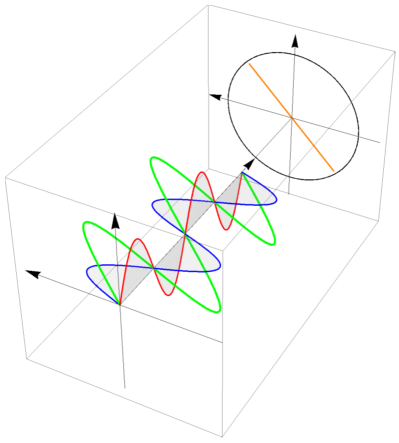


Figure 64 Linear Polarization

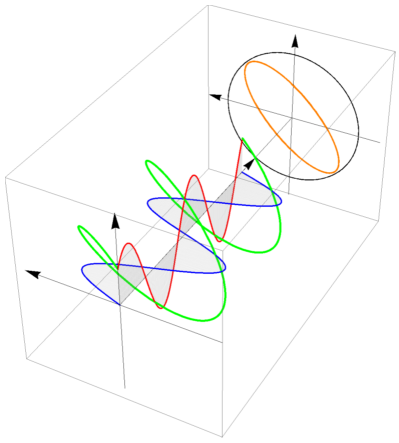


Figure 65 Elliptical Polarization

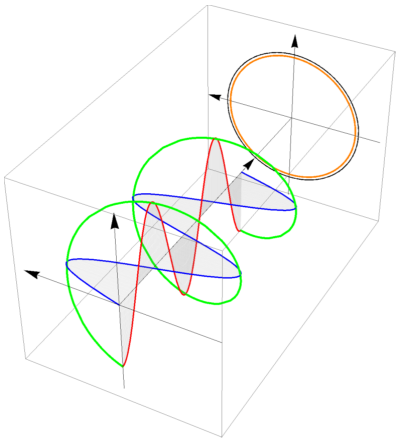


Figure 66 Circular Polarization

The first example is linear polarized light. The phase difference between the two orthogonal states is 0° or 180°, and superposition results in a total electric field that is always oriented in the same direction when viewed in the transverse plane.

The second diagram shows an elliptical polarization state. The phase difference between the orthogonal states is >0° and ≤90°. The projection results in an ellipse with a right or left direction of rotation.

A special case of elliptical polarization is circular polarization (3rd example), where the phase difference between the orthogonal states is 90°. Then the amplitude of the rotating vector is constant over the entire 360° rotation.

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 (SMF), 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 of each mode at the end of the fiber is arbitrary. The superposition of the polarization of all modes results in unpolarized light.

The spectral width of the emitted light needs to be considered as well. If the spectral line width of the emission is narrow enough, then the light is polarized. An example is a DFB laser diode with a linewidth of about 3 MHz.

Light sources with a broad spectrum like LEDs are generally unpolarized. A polarizer can be used to polarize light with a large spectral width.

7.2 Defenitions of Polarization Parameters

In this section all polarization parameters used in the PAX1000 software are explained.

Azimuth/Ellipticity

For more information, please see section 7.4 Polarization Ellipse or section 7.5 Poincaré Sphere.

DOP

The Degree of Polarization (DOP) is the ratio of the polarized power to the total power of the measured light signal. It is calculated as follows,

$$\mathrm{DOP} = \sqrt{\frac{S_1^2 + S_2^2 + S_3^2}{S_0^2}}$$

Please note, that S_1, S_2, S_3 and S_0 are the non-normalized Stokes Vectors!

DOLP

Degree of linear polarization, it is the ratio of the linearly polarized share of polarized power to the total power. Its calculated as follows,

$$\mathrm{DOLP} = \sqrt{\frac{S_1^2 + S_2^2}{S_0^2}}$$

Please note, that S_1, S_2 and S_0 are the non-normalized Stokes Vectors!

DOCP

The Degree of circular polarization (DOCP) is the ratio of the circularly polarized share of polarized power to the total power. Its calculated as follows,

$$\mathrm{DOCP} = \sqrt{\frac{S_3^2}{S_0^2}}$$

Please note, that S3 and S0 are the non-normalized Stokes Vectors!

Power

Power is the total optical power, incident on the PAX1000 Series of Polarimeters.

P_{Pol}

P_{Pol} is the polarized share of the total optical power.

P_{Unpol}

P_{Unpol} is the unpolarized share of the total optical power.

S1, S2, S3 and S0

S1, S2, S3 and S0 are are the non-normalized Stokes vectors. The Stokes vector represents the state of polarization (SOP) and is a four-element vector (S0, S1, S2, S3), where:

- S0 is related to power and represents the overall intensity, but it does not indicate the exact power.
- S1 represents the difference between vertical and horizontal linear polarization.
- S2 represents the difference between linear polarization at +45° and −45°.
- S3 represents the difference between left- and right-hand circular polarization.

s_1, s_2 and s_3

These are the Stokes vectors that are normalized with the total power S0 as reference. There is the following relation between the azimuth θ and ellipticity η and the normalized Stokes parameters:

$$s_1 = \cos(2\eta)\ \cos(2\theta)$$
$$s_2 = \cos(2\eta)\ \sin(2\theta)$$
$$s_3 = \sin(2\eta)$$

Power Split Ratio and Phase Difference

These parameters can be alternatively used to represent the polarization state based on an ellipse. This representation has the advantage that the retardation of the E_x vector to the E_y vector is simply defined by the phase difference Δ:

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

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

For more information, please see section 7.4 Polarization Ellipse.

7.3 Representation of an Electromagnetic Wave

An electromagnetic wave of frequency ω traveling in **Z** direction has its polarization vector in the **X**-**Y** plane. The E-field direction is always perpendicular to the direction of propagation. Any location of the polarization vector at different times t can be written by superposition of the **X**- and **Y**- vector components:

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

with

$\hat{E}_X$, $\hat{E}_Y$	Amplitudes of the Electric Field Intensity in X or Y Direction
E_X, E_Y	Instantaneous Electrical Field Intensity in X or Y Direction
δ_X, δ_Y	Phase of the Electrical Field Intensity in X or Y Direction ($-\pi \le \delta_X, \delta_Y \le +\pi$)
ω	Angular Frequency
k	Wavenumber

The wavenumber k can be calculated by the frequency or wavelength:

$$k = n\frac{\omega}{c} = n\frac{2\pi}{\lambda}$$

with

- n Refraction Index
- c Speed of Light
- λ Wavelength in Vacuum

Jones Vector Formalism

In optics, polarized light can be described using the Jones calculus, developed by R. C. Jones in 1941 [1]. Polarized light is represented by a Jones vector, and linear optical elements are represented by Jones matrices. The Jones vector describes the polarization of light in free space or another homogeneous isotropic non-attenuating medium, where the light can be properly described as transverse waves.

Omitting the time dependency $e^{i\omega t}$, the electromagnetic wave can be fully characterized by the complex envelopes:

$$E_X = \hat{E}_X\, e^{\,i\,(\omega t - kz + \delta_X)}$$
$$E_Y = \hat{E}_Y\, e^{\,i\,(\omega t - kz + \delta_Y)}$$

of the X and Y components of the electric field. The Jones vector is:

$$\vec{J} = \begin{bmatrix} E_X \\ E_Y \end{bmatrix} = \begin{bmatrix} \hat{E}_X\, e^{\,i\delta_X} \\ \hat{E}_Y\, e^{\,i\delta_Y} \end{bmatrix}$$

The Jones vector is not a vector in real space, but a mathematical abstraction in complex space. The following figure shows the spatial curves of the X and Y components of the electric field intensities as a function of time:

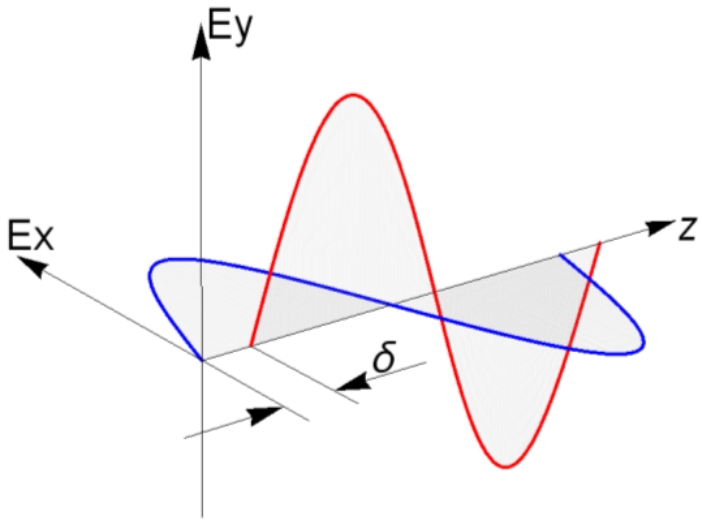


Figure 67 Electric field components Ex (blue) and Ey (red) of a monochromatic wave propagating along z. The phase retardance δ between the components produces an elliptical polarization state (shaded ellipse).

The vector of the electric field intensity E(t) is determined by the superposition of the X and Y components. At a fixed time it points to a defined direction and has a defined magnitude.

The following figure is used to illustrate a case of circular polarization, in which

$$\hat{E}_x = \hat{E}_y, \quad \delta_x = 180^\circ, \quad \delta_y = 90^\circ$$

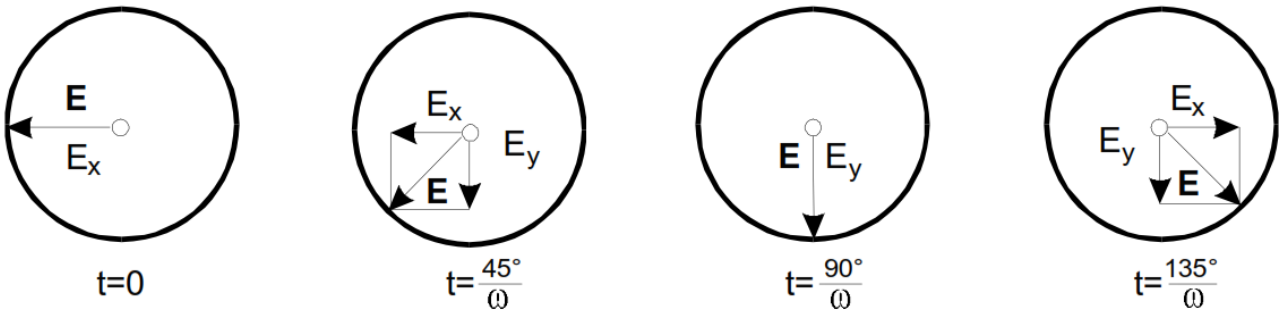


Figure 68 Origin of a Circular Polarized Wave

When these values and the times noted beneath each of the following figures are inserted into equation, E_x and E_y values for each case can be calculated.

The vector sum of E_x and E_y is the total electric field intensity E. In this example, the head of the vector moves anti-clockwise around the circumference of a circle as the wave propagates toward the observer.

When $\hat{E}_x \neq \hat{E}_y$, the electric field vector traces out an ellipse.

When the phase difference between the E_x and E_y components is 0°, instead of 90°, the circle becomes a line, which corresponds to linearly polarized light.

7.4 Polarization Ellipse

The state of polarization can be represented by an ellipse.

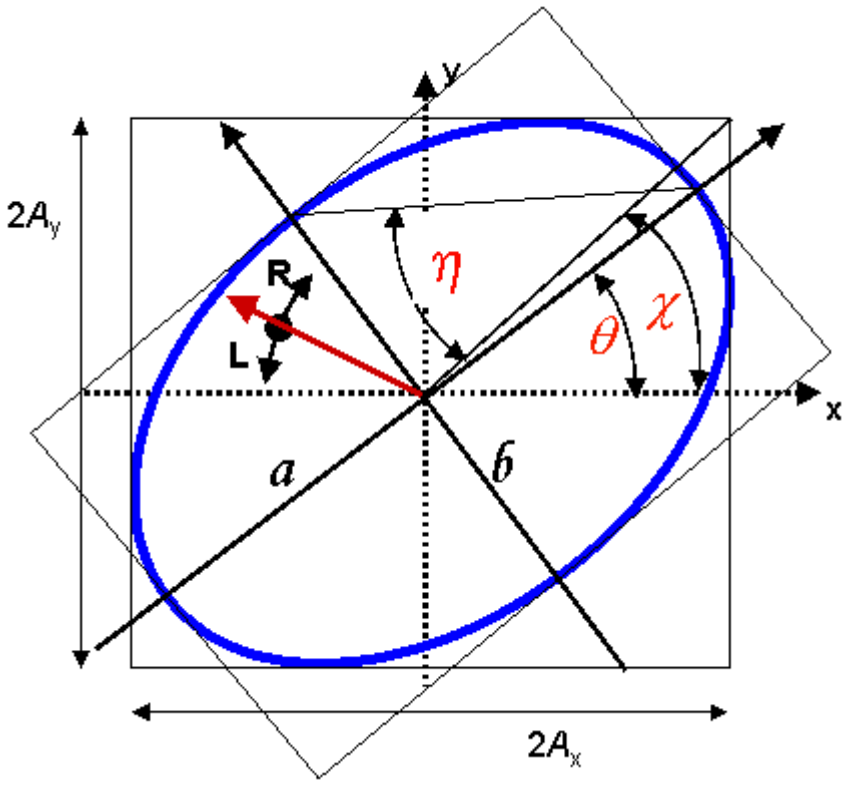


Figure 69 Geometric Representation of an Ellipse with Axes, Rotation Angles, and Reference Vectors

The (virtual) spectator looks towards the light source.

Definition of Right and Left Handed Polarization

The parameters ellipticity (η) and azimuth angle (θ) as well as the handedness (right and left which corresponds to the sign of η) are necessary to uniquely describe the polarization. The azimuth angle (θ) is the angular deviation of the major axis 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 dimensions according to the following equation:

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

η > 0; The light is right-handed polarized.

η = 0; The light is linear polarized.

η < 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 power split ratio is defined between $0 \le a \le 1$ and the phase difference can obtain values between $-180° \le \Delta \le 180°$.

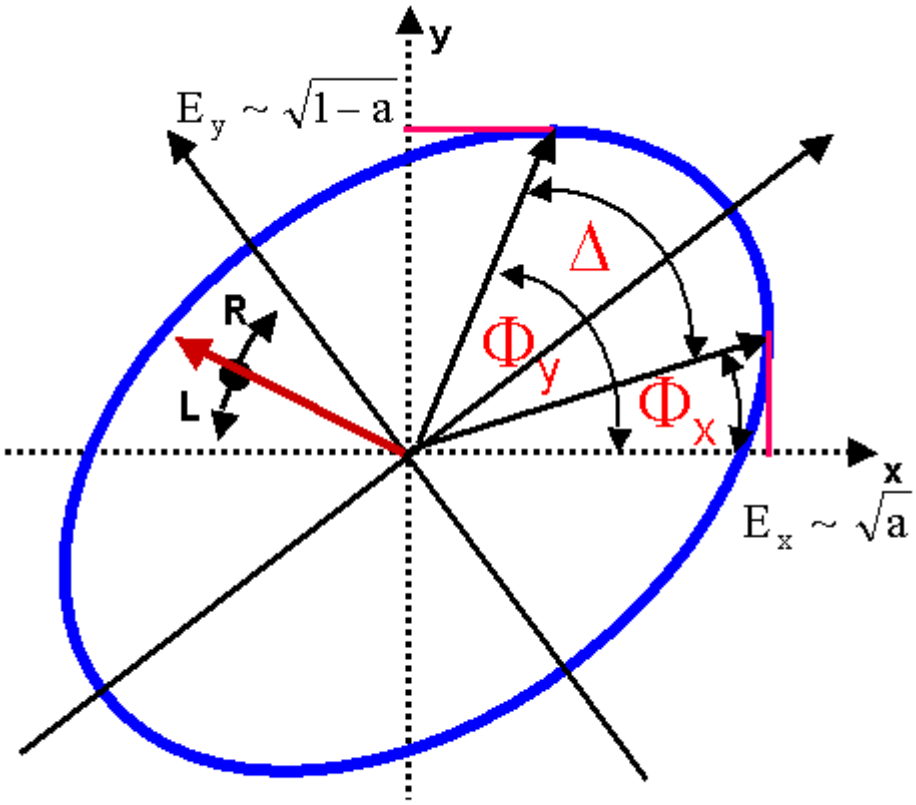


Figure 70 Ellipse Representation Showing Field Components E_x and E_y, Phase Angles Φ_x, Φ_y, and Phase Difference Δ.

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

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

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

7.5 Poincaré Sphere

An appropriate way to display the state of polarization is the Poincaré sphere representation. The center of the Poincaré sphere is located in the origin of a Cartesian coordinate system.

Any point on the surface of the Poincaré sphere is uniquely represented by its Cartesian coordinates, also known as the three normalized Stokes Parameters s1, s2 and s3 - these are the projections of this point onto the three coordinate axes.

The polarization ellipse parameter azimuth (Θ) angle is represented on the Poincaré sphere as the longitude = 2Θ, the ellipticity (η) angle appears as the latitude = 2η. Please note the factor of 2 involved in the mapping (see Figure 75)

The handedness defines the position on the northern (right handed rotation) or southern (left handed rotation) hemisphere.

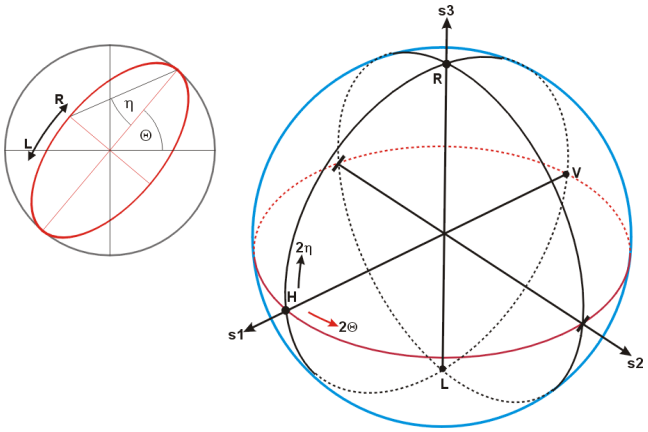


Figure 71 Poincaré Sphere Representation Illustrating Polarization States, with Azimuth Angle Θ and Ellipticity Angle η

The equatorial plane (shown in red) represents all linear states of polarization.

The north pole represents right-turning circular polarization, the south pole - left-turning circular polarization.

All other points on the northern and southern hemisphere correspond to elliptical states of polarization with correspondingly right and left handed rotation.

Polarization State		Azimuth	Ellipticity
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°

Table 9 Typical States of Polarization, and their Azimuth and Ellipticity Values

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

7.6 Handedness of Polarization

Convention

When light is elliptically polarized, the electric field (E field) vector rotates with respect to a Cartesian coordinate system as it propagates. The software of the PAX1000 Series of Polarimeters and the predecessor, the PAX57xx Polarimeter System, plot the E field vector with respect to a right-handed coordinate system with x, y, and z axes. The light wave propagates in the +z direction, and the (virtual) observer looks along the -z direction towards the light source. The handedness of the elliptically polarized

light describes the direction of rotation of the E field vector as seen by this observer. This convention is common in the technical literature.

Each state of polarization can be split into two linearly polarized orthogonal components, in which one is oriented in the x direction and one in the y direction. If both components have equal magnitudes and the phase shift of the y component relative to the x component is $+\pi/2$ or $-\pi/2$, the light is circularly polarized. The sign of the phase difference determines the handedness of the rotation. A clockwise rotation corresponds to a right-hand circular polarization state and a phase shift of $+\pi/2$, while a counterclockwise rotation refers to left-hand circular polarization state and a phase shift of $-\pi/2$.

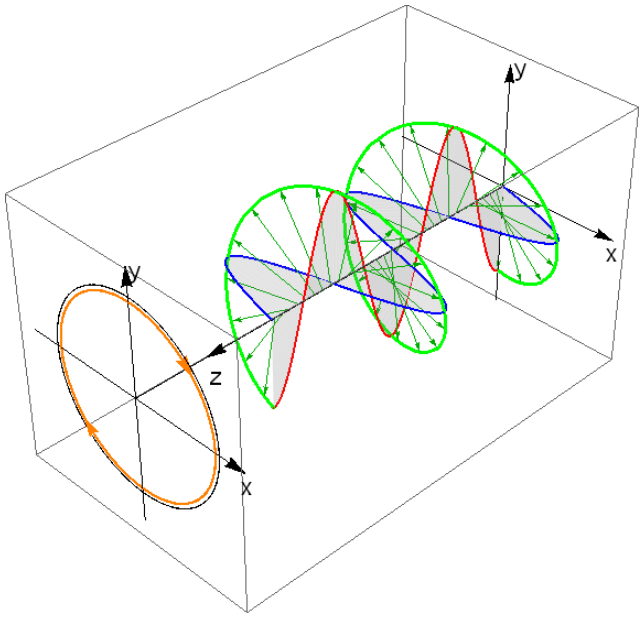


Figure 72 Right-Circularly Polarized Light

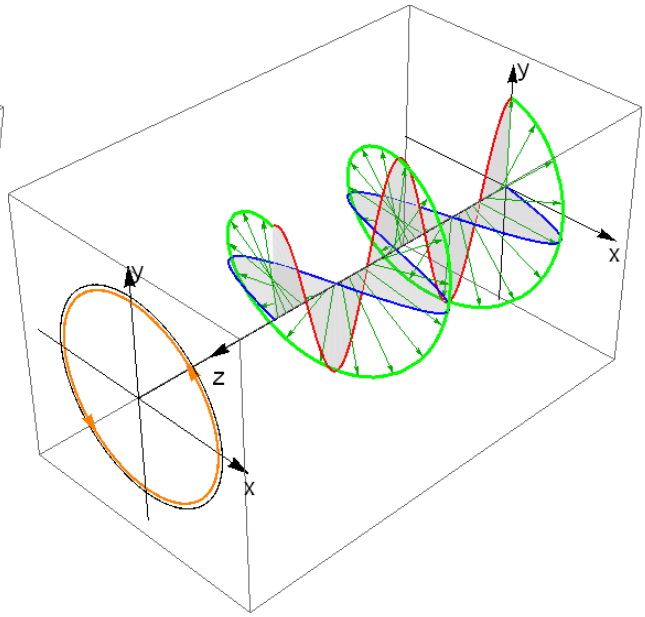


Figure 73 Left-Circularly Polarized Light

In above figures, the projection of the rotating E field vector on a virtual screen generates a circle over time as the E field vector rotates clockwise (counterclockwise) representing right (left) circular polarization.

Generation of Circularly Polarized Light

A circular polarization state can be generated using linearly polarized light and a quarter waveplate. When the E field vector of the incident linearly polarized light is oriented at a 45° angle to the slow and fast axes of the quarter waveplate, the output light is circularly polarized. It is convenient to mathematically describe this transformation using matrix algebra, with Jones vectors representing the polarized light and a Jones matrix representing the quarter waveplate. The Jones matrix, describing a quarter waveplate with its slow axis oriented along the x (horizontal) axis is:

$$M_{\lambda/4} = e^{i\pi/4} \begin{bmatrix} 1 & 0 \\ 0 & i \end{bmatrix}$$

The phase factor $e^{i\pi/4}$ can be omitted in almost all cases.

The Jones vector of a linear polarization state oriented at + 45° is written as:

$$\vec{J}_{+45} = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 \\ 1 \end{bmatrix}$$

When this linearly polarized light travels through a quarter waveplate with its slow axis oriented along the x axis, the Jones vector of the output light can be calculated as follows:

$$\vec{J}_{RHC} = M_{\lambda/4}\ \vec{J}_{+45} = \begin{bmatrix} 1 & 0 \\ 0 & i \end{bmatrix} \frac{1}{\sqrt{2}} \begin{bmatrix} 1 \\ 1 \end{bmatrix} = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 \\ i \end{bmatrix}$$

The output polarization is right-hand circular. The figure below illustrates this case:

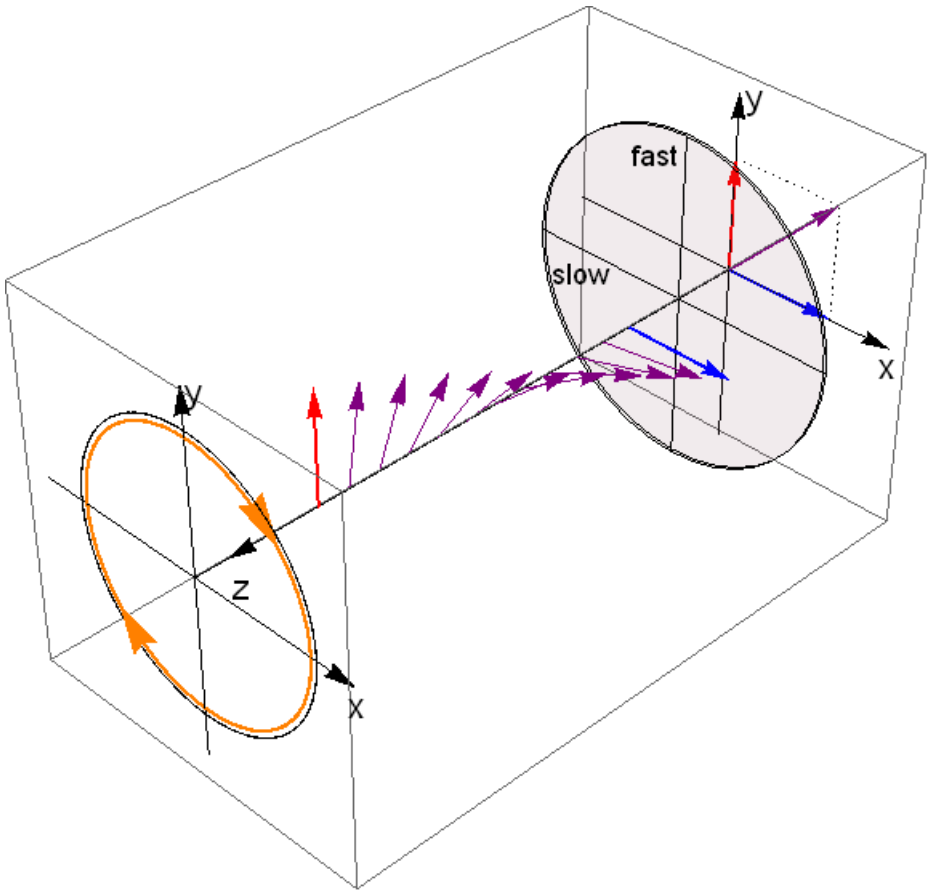


Figure 74 Transformation of Circular Polarization through a Birefringent Medium, Showing Fast and Slow Axes and the Evolution of the Polarization State

The slow axis of the quarter waveplate is aligned with the x axis, and the fast axis of the QWP is aligned with the y axis of the coordinate system. The input polarization is +45° linear and it is transformed into a right-hand circular polarization.

The purple vector at the origin indicates the orientation of the incident +45° linearly polarized light, while the red and blue vectors represent this E field decomposed into its orthogonal components. These two components are in phase. The x axis component, which is represented by the blue vector, is aligned with the slow axis of the waveplate and travels at a slower velocity through the waveplate than the y axis component, which is aligned with the fast axis and represented by the red vector. Propagating through the waveplate, the phase of the x axis component is retarded with respect to the phase of the y axis component. The amount of the retardation is determined by the thickness of the waveplate. A quarter waveplate is designed to intoduce a phase shift of $+\pi/2$. This retardation results in a right-hand circularly polarized output light, and its E field vector rotates clockwise when it propagates along the z axis.

When the incident beam has a -45° linear polarization, its Jones vector is:

$$\vec{J}_{-45} = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 \\ -1 \end{bmatrix}$$

The output polarization state is then expressed:

$$\vec{J}_{\mathrm{LHC}} = M_{\lambda/4}\, \vec{J}_{-45} = \begin{bmatrix} 1 & 0 \\ 0 & i \end{bmatrix} \frac{1}{\sqrt{2}} \begin{bmatrix} 1 \\ -1 \end{bmatrix} = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 \\ -i \end{bmatrix}$$

The output light is left-hand circularly polarized.

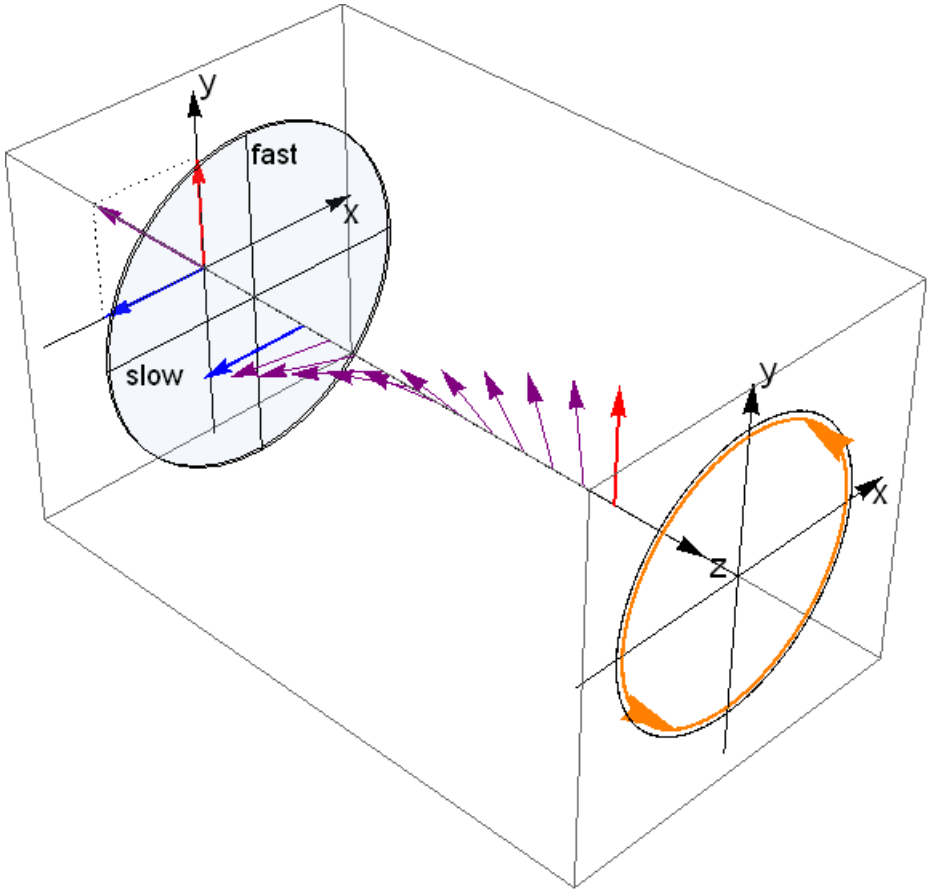


Figure 75 Transformation of Left-Handed Circular Polarization through a Birefringent Medium, Showing Fast and Slow Axes and the Evolution of the Polarization State

Above illustrates this case.

Again, the slow axis of the quarter waveplate are aligned with the x axis, and the fast axis of the QWP is aligned with the y axis of the coordinate system. The input polarization is -45° linear and it is transformed into a left-hand circular polarization.

The purple vector at the origin again represents the orientation of the incident linearly polarized light. As for this, there is no phase difference between the x and y axis components of the E field.

The -45° orientation of the polarization vector means that it is azimuthally rotated.

Propagating through the quarter waveplate causes the component aligned along the slow axis to add a phase shift of $-\pi/2$ with respect to the component aligned along the fast axis. The output light is left-hand circularly polarized and has an E field vector that rotates counterclockwise when it propagates along the z axis.

Jones Vectors and Matrices

The following tables contain the Jones vectors for selected polarizations of light and the Jones matrices of standard optical elements, respectively.

State of Polarization	Jones Vector
Horizontal Linear Polarization	$\begin{bmatrix}1\\0\end{bmatrix}$
Vertical Linear Polarization	$\begin{bmatrix}0\\1\end{bmatrix}$
Linear Polarization at +45°	$\frac{1}{\sqrt{2}}\begin{bmatrix}1\\1\end{bmatrix}$
Linear Polarization at -45°	$\frac{1}{\sqrt{2}}\begin{bmatrix}1\\-1\end{bmatrix}$
Right Circular Polarization	$\frac{1}{\sqrt{2}}\begin{bmatrix}1\\\mathrm{i}\end{bmatrix}$
Left Circular Polarization	$\frac{1}{\sqrt{2}}\begin{bmatrix}1\\-\mathrm{i}\end{bmatrix}$

Table 10 Common Polarization States and their Corresponding Jones Vectors

Linear Optical Element	Jones Matrix
Horizontal Linear Polarizer	$\begin{bmatrix}1&0\\0&0\end{bmatrix}$
Vertical Linear Polarizer	$\begin{bmatrix}0&0\\0&1\end{bmatrix}$
Linear Polarizer at +45°	$\frac{1}{2}\begin{bmatrix}1&1\\1&1\end{bmatrix}$
Linear Polarizer at -45°	$\frac{1}{2}\begin{bmatrix}1&-1\\-1&1\end{bmatrix}$
Quarter Wave Plate, Slow Axis Horizontal	$\mathrm{e}^{\mathrm{i}\pi/4}\begin{bmatrix}1&0\\0&\mathrm{i}\end{bmatrix}$
Quarter Wave Plate, Slow Axis Vertical	$\mathrm{e}^{\mathrm{i}\pi/4}\begin{bmatrix}1&0\\0&-\mathrm{i}\end{bmatrix}$

Table 11 Common Linear Optical Elements and their Corresponding Jones Matrices

7.7 Rotating Waveplate Technique

Linear Polarization

This section considers input light with a linear state of polarization (SOP).

Assume that for a rotation angle of 0° the fast axis of the quarter waveplate is aligned with the polarization direction of the input light. The linear polarized light travels along the fast axis and is not changed. When the waveplate is rotated 45°, the SOP is transformed to right circular.

Another 45° rotation, which gives in total 90°, aligns the slow axis of the waveplate with polarization direction of the incoming light. The SOP is not changed by the waveplate. A rotation of 135° yields left circular polarization.

A half turn, corresponding to 180°, again aligns the fast axis of the waveplate with the polarization of the light. The waveplate does not change the SOP.

The following picture demonstrates the change of the polarization on the Poincaré Sphere. The dark-green trace represents points laying in the foreground of the sphere, the light-green - in the background ("dark side"). As can be seen, after a half revolution of the QWP, a trace with the shape of an "8" is drawn onto the sphere:

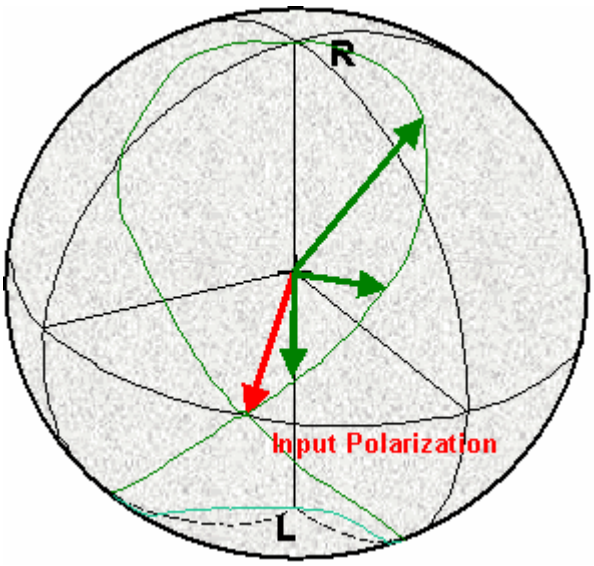


Figure 76 Poincaré Sphere Representation Showing Input Polarization and its Transformation Along the Sphere

In the case of linearly polarized incident light, the photo diode current I(t) is proportional to the quadruple rotation frequency, ω_{QWP}, while the phase shift, φ_4, reflects the azimuth angle:

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

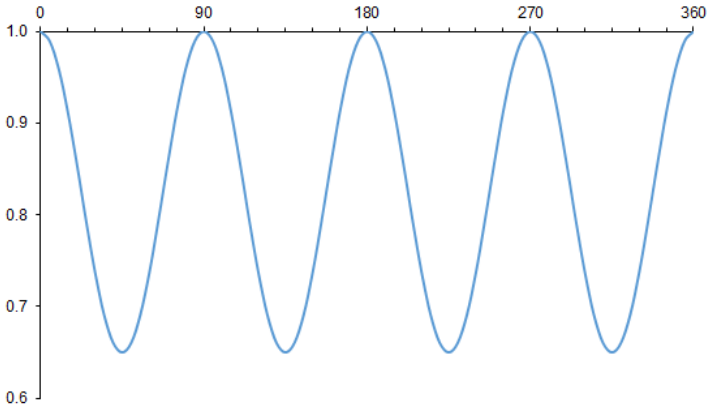


Figure 77 Intensity Variation of Linearly Polarized Light as a Function of Rotation Angle

Circular Polarization

This section considers the case of right circularly polarized light incident on the QWP . Circular polarization will be transformed into linear polarization by a quarter waveplate. Rotating the waveplate rotates the azimuth angle of the generated linear polarization. When plotted on the Poincaré sphere, the polarization state moves around the equator as the QWP rotates. A full revolution of the waveplate results in two turns around the equator (green trace on the figure below):

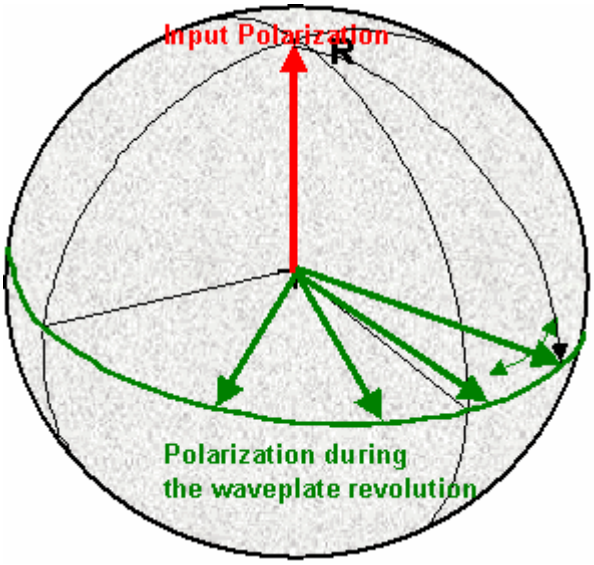


Figure 78 Poincaré Sphere Representation Showing Input Polarization and its Evolution During Waveplate Rotation

After passing the linear polarizer, the frequency of the resulting amplitude modulation is proportional to twice the rotation frequency of the QWP, and the phase of this component is constant and in this example zero:

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

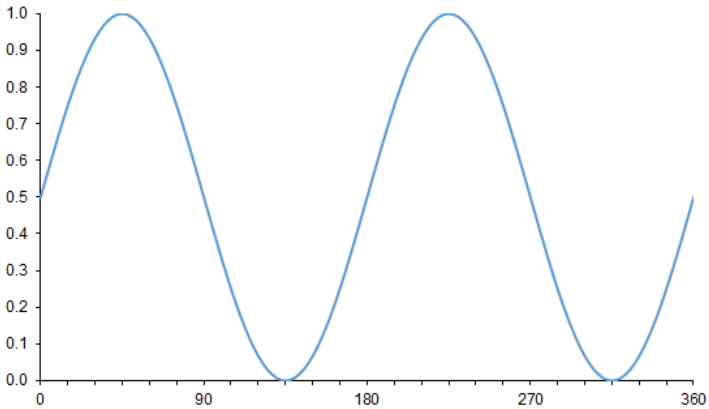


Figure 78 Poincaré Sphere Representation Showing Input Polarization and its Evolution during Waveplate Rotation

General case

Linear and circular polarizations are special cases of polarization.
Elliptical polarization generates a photodiode current with a DC term, a term that varies with twice the rotation frequency of the waveplate, and a term that varies with four times the rotation frequency of the QWP.

The Fourier transformation of the resulting photodiode current obtains the amplitudes and phases of the DC, the 2ω and the 4ω QWP components.

The DC component has an amplitudes of A_0, the 2ω component has an amplitude of A_2 and a phase of φ_2, and the 4ω QWP component has an amplitude of A_4 and a phase of φ_4. Other frequency components are assumed to have zero amplitude, in accordance with theory.

The polarization parameters azimuth, ellipticity, degree of polarization (DOP) and the Stokes parameters can be calculated from the amplitudes A0, A2 and A4 and the phases φ_2 and φ_4, accordingly.

A typical photo current for elliptical polarization for one waveplate revolution is displayed in the following figure:

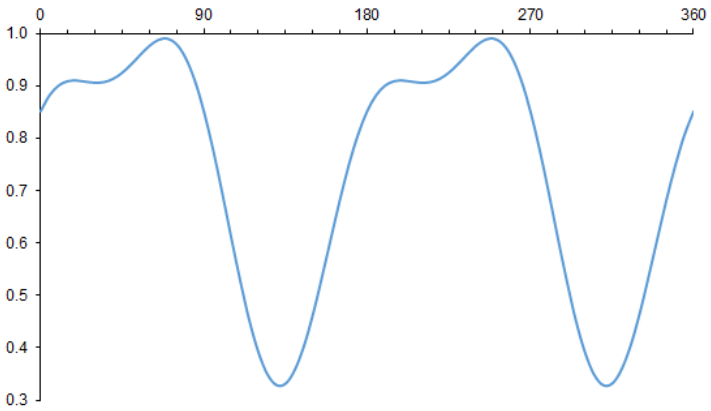


Figure 79 Intensity Variation of Elliptically Polarized Light as a Function of Rotation Angle

Note

In the PAX1000 Series of Polarimeters a true zero order $\lambda/4$ waveplate is used. For this type of waveplate, the exact $\lambda/4$ retardation is given only at its reference wavelength. In order to enable a broad operating wavelength range of the polarimeter, the wavelength-dependent retardation must be compensated in order to achieve accurate measurements. For this reason, the operating wavelength must be entered into the device settings.

7.8 Extinction Ratio Measurement on PM Fibers

Definition

A Polarization Maintaining Fiber (PMF) is only effective if linearly polarized light is launched parallel to the fast or slow axis.

The ratio of the power in the fast and slow axis (dB), the so-called Extinction Ratio (ER), is a measure of the quality of this coupling.

The extinction ratio is measured at the output of the PMF. First the polarization state is described using the polarization ellipse, which is the 2D curve traced out by the rotating polarization vector. The length of the major and minor axes of the ellipse are proportional to the amount of optical power coupled into the two axes of the PMF. For example, if all power is coupled into one axis, the ellipse will be a line, and if the power is evenly split between the two axes the ellipse will be a circle. As the instantaneous position of the polarization vector on the ellipse is a function of the distance from the output of the PMF, the measurement plane should be translated back and forth to determine the maximum and minimum values of optical power, $P_{MainAxis1}$ and $P_{MainAxis2}$ respectively.

$$ER = 10\log\left(\frac{P_{MainAxis1}}{P_{MainAxis2}}\right) = 20\log\left(\frac{LargeEllipseHalfAxis}{SmallEllipseHalfAxis}\right) = 20\log\left(\frac{1}{\tan(|\theta_{Max}|)}\right)$$

Given a linear polarization state launched optimally into either the fast or slow axis, the ER expresses the ability of the PMF to maintain that state by suppressing cross-coupling that would transfer power to the orthogonal polarization state. The ER is therefor 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 linearly polarized light is coupled into both the fast and the slow axes of the PMF, the two components will propagate independently of one another through the fiber. For this discussion it can be assumed that there is no cross-coupling between them. Due to the PMF's birefringence, the phase shift between the two components increases continuously with propagation distance through the fiber. Consequently, the polarization ellipse also depends on propagation distance. 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 phenomenon is the reason it is critical to optimally align linearly polarized optical input with one axis of the PMF, whether the optical input is from a laser or from another PMF.

Measurement

For ER measurement the fiber must be dynamically "stressed" during data acquisition by

- either mechanically "pulling" the fiber
- or heating or cooling the fiber
- or changing the wavelength.

There are two different main techniques for Extinction Ratio (ER) Measurement of PM fibers. One is based on a polarimeter while the other utilizes a rotating analyzer (polarizer) and a photodiode based power meter.

The two techniques cannot be compared directly since the polarimeter technique does not take into account the depolarized part of the light and is focused only on the relative change of the polarization and not on the absolute ellipticity.

An ER meter based on the rotating analyzer considers the Degree of Polarization (DOP) as well as the absolute ellipticity.

Polarimeter Technique

The polarimeter records the polarization at the exit of the fiber during stress application. If there is a non-optimal launch condition (misalignment) or a poor fiber, the output polarization will result in a circle being traced on the Poincaré sphere, in which the diameter of the circle is a measure for the extinction ratio. The smaller the circle the higher is the ER:

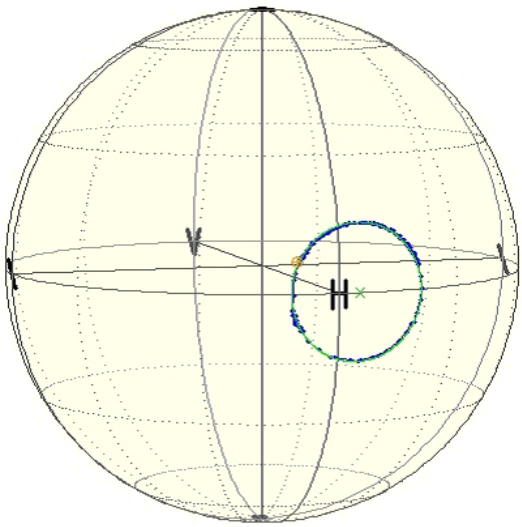


Figure 80 ER Measurement Screen of a PAX1000 Series of Polarimeters

ER Meter Technique

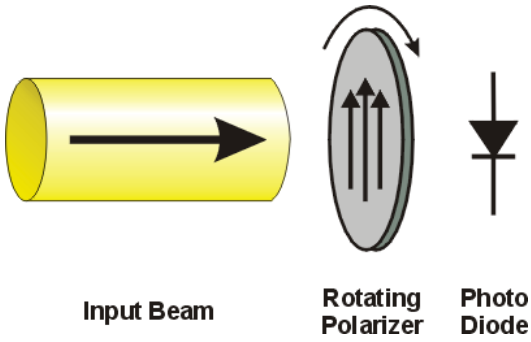


Figure 81 Optical Setup with Collimated Beam, Rotating Linear Polarizer and Photodiode

The polarizer transmits only the polarized part of the light parallel to its transmission axis. The transmitted power depends not only on the input polarization but also on the degree of polarization (DOP). A photodiode after the spinning polarizer detects the power.

If the input light is linearly polarized and the DOP is 100%, the measured photo current is sinusoidal with its minimum at zero.

An elliptical input polarization or a DOP less than 100% causes a minimum > 0 of the photodiode current. However, there are more factors that can influence the measurement data like dark current and noise of the photodiode, but these are neglected for our considerations.

If the input light is circularly polarized with a DOP of 100% a constant (DC) photocurrent would be the result. A purely unpolarized input light would also generate a DC photo current.

Both the ellipticity as well as the DOP will affect the measurement result.

Correction of the Polarimeter ER Measurements

When performing ER measurements on PM fibers with a polarimeter, the DOP will not affect the measurement results and only the relative polarization changes (circle on the Poincaré Sphere) are taken into account.

Correction for Absolute Ellipticity

Ideally, optimally coupling linearly polarized light into either the slow or fast axis of the PM fiber ensures that linearly polarized light will be output from the fiber. However, externally applied mechanical stress, such as from fiber connectors, can cause the propagating light to undesirably couple into the orthogonal polarization. This cross-coupling will transform the linearly polarized light into elliptically polarized light. A polarimeter measurement can determine the ER of the output light.

The center of the circle represents the center Azimuth and Ellipticity. It should be positioned on the equator. As the light is predominantly linearly polarized, the center of the circle should be positioned on the equator. Each measurement point can be expressed as an Azimuth/Ellipticity pair. Plotting all measurement points will describe a circle. The measurement value which is most distant from the equator has the maximum ellipticity.

In the following example, the extinction ratio (ER) was determined based on the relative polarization changes observed during the measurement, which form a circular trace on the Poincaré sphere. The corresponding measurement parameters are summarized below.

ER (Uncorrected):	21.51 dB
Radius α:	9.61°
Center Ellipticity:	-0.95°
DOP:	99.588%

$$\mathrm{ER} = -20\log\left(\tan\left(\frac{\alpha}{2}\right)\right)$$

α is the radius in degrees. The factor ½ is due to the fact that azimuth and ellipticity are mapped with a factor ½. The domain for azimuth is -90 to +90° (180 Area). A circle has a range of 360°.

In our measurement example this yields:

$$\mathrm{ER} = -20\log\left(\tan\left(\frac{9.61^\circ}{2}\right)\right) = 21.51\,\mathrm{dB}$$

The center ellipticity is -0.9°. That means even if the circle would have a radius = 0°, an ellipticity remains.

This center ellipticity corresponds to:

$$\mathrm{ER} = -20\log\left(\tan\left(|-0.95^\circ|\right)\right) = 35.61\,\mathrm{dB}$$

Both the radius and the center ellipticity have to be considered.

The maximum ellipticity corresponds to α/2 + |center ellipticity|:

$$\mathrm{ER} = -20\log\left(\tan\left(\frac{9.61^\circ}{2} + |-0.95^\circ|\right)\right) = 19.93\,\mathrm{dB}$$

This is the corrected for center ellipticity ER.

Correction for DOP (Degree of Polarization)

A polarimeter's ER measurement must also be corrected for DOP, as the unpolarized part of the light is not considered. In other words, while the DOP does not affect the ER measurement made by a polarimeter, the DOP may actually have a strong impact on the ER. This is especially true of the ER for linearly polarized light.

The spinning analyzer method takes DOP into account and accurately measures ER. As an example of how the DOP affects the ER, consider the following plot.

If the input light is linearly polarized, the measured photocurrent which is equivalent to the optical power, shows two maxima and two minima per revolution of the polarizer.

If the light is 100% polarized, the maximum normalized power will be 1, and the minimum will be 0. If the light is only partially polarized the maximum will shrink and an offset will be added. The following diagram illustrates that:

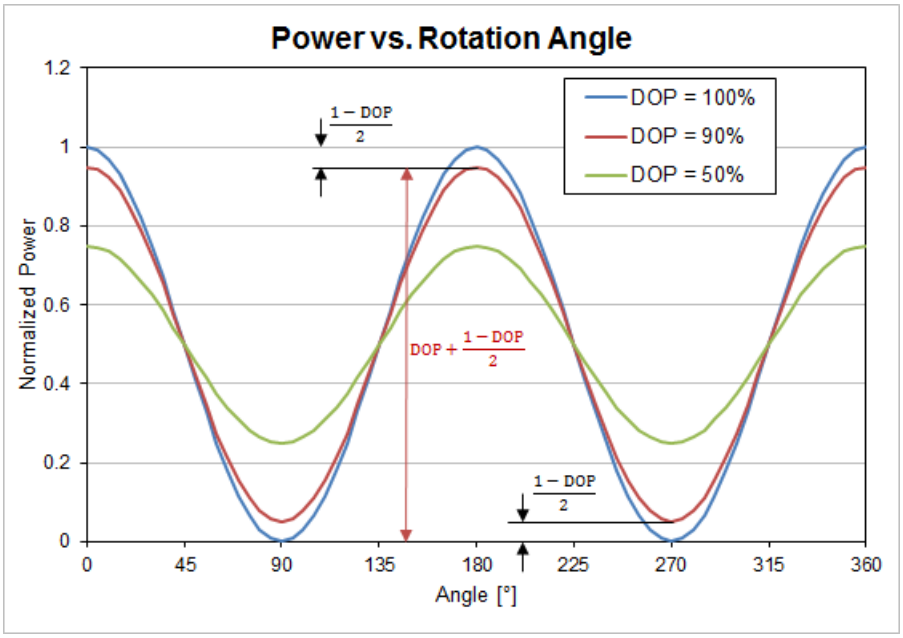


Figure 82 Impact of the DOP on the ER Result (Spinning Analyzer Method)

The ER at 100% polarized light (DOP = 100%) can be expressed as

$$ER = -10 \log\left(\frac{T_{min}}{P_{max}}\right)$$

For a lower degree of polarization DOP, the maximum and minimum normalized power will change:

$$P_{min} = P_{max,100\%} \cdot \left(\frac{1 - DOP}{2}\right)$$

$$P_{max} = P_{max,100\%} \cdot \left(DOP + \frac{1 - DOP}{2}\right)$$

The extinction ratio of strongly polarized light with a DOP < 100% can be written then:

$$ER = -10 \log\left(\frac{P_{max,100\%} \cdot \left(\frac{1-DOP}{2}\right)}{P_{max,100\%} \cdot \left(DOP + \frac{1-DOP}{2}\right)}\right) = -10 \log\left(\frac{1 - DOP}{DOP}\right)$$

Degree of Polarization [%]	Extinction Ratio [dB]
100	∞
99.998	50.00
99.99	43.01
99.98	40.00
99.95	36.02
99.90	33.01
99.5	26.01
99.0	22.99
98.0	19.96
90.0	12.79

Table 12 Extinction Ratios (ER) Calculated for Different DOPs Between 90% and 100%, Illustrating the Significant Influence of DOP on the ER of Linearly Polarized Light

This illustrates the importance of correcting the ER measurements made by the polarimeter to take into account DOP. Working with the measurement example, the correction for DOP can be made to the value of ER that was previously corrected for ellipticity. That corrected value was 19.93 dB (Equation).

Assuming a DOP < 100%, an equation to correct for DOP can be derived as follows.

$$\mathrm{ER_{corr}} = -10\log\left(\frac{\mathrm{P_{min}}}{\mathrm{P_{max}}}\right) = -10\log\left(\frac{\mathrm{P_{min,100\%}} + \frac{1-\mathrm{DOP}}{2}\cdot\mathrm{P_{max,100\%}}}{\mathrm{P_{max,100\%}} - \frac{1-\mathrm{DOP}}{2}\cdot\mathrm{P_{min,100\%}}}\right)$$

$$\mathrm{ER_{corr}} = -10\log\left(\frac{\frac{\mathrm{P_{min,100\%}}}{\mathrm{P_{max,100\%}}}\cdot\left(1+\frac{1-\mathrm{DOP}}{2}\cdot\frac{\mathrm{P_{max,100\%}}}{\mathrm{P_{min,100\%}}}\right)}{1-\frac{1-\mathrm{DOP}}{2}}\right)$$

$$\mathrm{ER_{corr}} = -10\log\left(10^{-\frac{\mathrm{ER_{meas}}}{10}}\cdot\frac{1+\frac{1-\mathrm{DOP}}{2}\cdot 10^{\frac{\mathrm{ER_{meas}}}{10}}}{1-\frac{1-\mathrm{DOP}}{2}}\right)$$

The degree of polarization was determined to be 99.588%, and this value was used to correct the ER value for DOP. Using the numbers given in this measurement example, the corrected value of ER is:

$$\mathrm{ER_{corr}} = -10\log\left(10^{-\frac{19.93}{10}}\cdot\frac{1+\left(\frac{1-0.99588}{2}\cdot 10^{\frac{19.93}{10}}\right)}{1-\frac{1-0.99588}{2}}\right) = 19.12\,\mathrm{dB}$$

Summarize

- Using the polarimeter, an ER of 21.51 dB was measured.
- The ER value corrected for ellipticity (the center ellipticity was measured to be -0.95°) was 19.93 dB.

- Taking into account the measured DOP of 99.588 %, the corrected for center ellipticity and DOP extinction ratio is 19.12 dB.
  Note that this is the ER that would have been measured by an instrument (such as ERM200) that uses the spinning analyzer technique.

The difference between the uncorrected and the fully corrected ER measurement is more than 2 dB. When comparing ER measurements made by polarimeters and instruments using the spinning analyzer technique, it is necessary to correct the polarimeter's ER measurements for both ellipticity and DOP.

The PAX1000 Series of Polarimeters ER measurement software allows the user to correct the ER measurement result for center ellipticity or DOP or both.

For further reading and reference material, please see the chapter Literature.

7.9 Literature

[1] Jones Calculus (https://en.wikipedia.org/wiki/Jones_calculus, WP:CC BY-SA)

[2] Solid Angle (https://en.wikipedia.org/wiki/Solid_angle, WP:CC BY-SA)

[3] Serge Huard, Polarization of Light, Wiley, New York, 1997

[4] Eugene Hecht, Optics, Addison Wesley, New York, 2016

[5] Christian Brosseau, Fundamentals of Polarized Light: A Statistical Optics Approach, Wiley, New York,1998

Chapter 8 Maintenance and Cleaning

NOTICE

NOTICE: Risk of Damaging the PAX1000 Series of Polarimeters

The PAX1000 Series of Polarimeters is not water resistant. If the PAX1000 Series of Polarimeters comes into contact with fluids, the PAX1000 Series of Polarimeters can be damaged.

To avoid damaging, do not expose the PAX1000 Series of Polarimeters to:

- Spray
- Liquids
- Solvents
- Adverse Weather Conditions

The unit does not need regular maintenance by the user. It does not contain any modules and/or components that could be repaired by the user himself. If a malfunction occurs, please see the Return of Devices section and contact Thorlabs for return instructions.

Do not remove covers!

Chapter 9 Troubleshooting

Common Error Messages

ADC Underrun during Last Measurement

The incident optical power was too low.

- ⇨ The PAX1000 Series of Polarimeters is set to a fixed gain.
- ⇨ Set the instrument to Auto Power Range or select an appropriate power range manually.

ADC Overflow during Last Measurement

The incident optical power was too high.

- ⇨ The PAX1000 Series of Polarimeters is set to a fixed gain.
- ⇨ Set the instrument to Auto Power Range or select an appropriate power range manually.

TIA Gain Switching is in Progress

- ⇨ This is a status message during the automatic adjustment of power range.
- ⇨ No action required.

An One-Time TIA Auto Ranging is in Progress

- ⇨ This is a status message during the automatic adjustment of power range.
- ⇨ No action required.

Out-Of-Sync Condition Occurred during the last Measurement

- ⇨ If this message appears, the measurement results are not reliable. The PAX1000 Series of Polarimeters should resolve this error automatically.
- ⇨ If the error message persists, please contact Thorlabs.

Motor speed too Low (too High)

- ⇨ This is a status message when the measurement speed was changed.
- ⇨ If this message appears frequently or permanently, please contact Thorlabs.

PAX1000 Series of Polarimeters Operating Temperature is Below (Above) Limit

- ⇨ This error message may appear in the case of too low (too high) environmental temperature.
- ⇨ If this message appears at normal operating temperature, please contact Thorlabs.

USB Power Supply Voltage is too Low

- ⇨ The PAX1000 Series of Polarimeters requires a higher operating current than the standard USB2.0 port can deliver, e.g. at hing measurement speed.
- ⇨ Connect the external power supply.

Extinction Ratio Warnings Error Messages

Incomplete Circle due to Insufficient Number of Measurement Values - Increase Fiber Stress or Extend Measurement Time

The change of polarization during the measurement was insufficient to draw a full circle on the Poincaré Sphere.

- ⇨ Increase the fiber stress during measurement.
- ⇨ Alternatively, increase the measurement time.

Circle completed, but the distance between adjacent measurement points is too large for accurate measurement. Decrease fiber stress and increase measurement time.

The change of polarization during the measurement was sufficient to draw a full circle on the Poincaré Sphere, but the number of measurement points was insufficient to approximate a circle with the necessary accuracy.

⇨ Decrease the fiber stress during measurement and increase the measurement time.

Eigenmodes of the fiber under test are not strictly linear or measurement is noisy. ER cannot be calculated.

The change of polarization led to a non-circular trace on the Poincaré Sphere.

⇨ The optical power is too low, so that noise interfered the measurement.
Check your setup for possible power loss, or increase the optical power of your laser source.

⇨ The fiber under test behaved not like a PM fiber.
Check if the fiber as specified as a PMF.
If so, check if the operating wavelength of your PM fiber matches with the measurement wavelength.

The circle on the Poincare sphere is too small. The calculated ER is above the theoretical maximum accuracy. Please check if stress was applied to the fiber during the measurement.

The measured ellipticity change is close to or less than the PAX1000 Series of Polarimeters measurement accuracy.

⇨ Was the fiber Increase the fiber stress during measurement?

The ellipticity of some points is bigger than |25°|. Eventually there is a problem on the coupling into the fiber or there is constantly stress on the fiber.

The output SOP was of a too high ellipticity.

⇨ Check your setup for proper coupling of the light source into the fiber under test. The light must be coupled in parallel to the slow axis of the fiber.

⇨ Check your light source for strictly linear polarization.

⇨ Check if your fiber under test is exposed to a permanent stress due to extreme bending or squeezing. Also, the connectorization of the fiber might be not stress-less.

Chapter 10 Disposal



Thorlabs verifies our compliance with the WEEE (Waste Electrical and Electronic Equipment) directive of the European Community and the corresponding national laws. Accordingly, all end users in the EC may return “end of life” Annex I category electrical and electronic equipment sold after August 13, 2005 to Thorlabs, without incurring disposal charges. Eligible units are marked with the crossed out “wheelie bin” logo (see right), were sold to and are currently owned by a company or institute within the EC, and are not dissembled or contaminated. Contact Thorlabs for more information. Waste treatment is your own responsibility. “End of life” units must be returned to Thorlabs or handed to a company specializing in waste recovery. Do not dispose of the unit in a litter bin or at a public waste disposal site. It is the user's responsibility to delete all private data stored on the device prior to disposal.

Chapter 11 Thorlabs Worldwide Contacts

For technical support or sales inquiries, please visit us at www.thorlabs.com/contact for our most up-to-date contact information.



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