IQ-5100

Polarization Controller

Instruction Manual

December 1998
P/N: MAN-107-I .3ACE

Third Edition

CE

If the equipment described herein bears the CE *symbol, the said equipment complies with the European Community Directive and Standards found in the Declaration of Conformity.*

If the equipment described herein bears an **FCC** *statement, the said equipment complies with the relevant Federal Communications Commission standards.*

EXFO's Commerce And Government Entities (CAGE) code under the North Atlantic Treaty Organization (NATO) is 0L8C3.

The information contained in this document is subject to change without notice.

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CERTIFICATION INFORMATION

F.C.C. INFORMATION TO USER

This unit has been tested and found to comply with the limits for a Class A digital device, pursuant to Part 15 (Subpart B) of the FCC Rules. These limits are designed to provide reasonable protection against harmful interference when the unit is operated in a commercial environment. This unit 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 unit 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.

WARNING

Changes or modifications not expressly approved by EXFO Electro-Optical Engineering could void the user's authority to operate the unit.

- Shielded remote I/O cables, with properly grounded shields and metal connectors, are recommended to be used in order to reduce radio frequency interference which may emanate from these cables.
- When the GPIB option is present, this unit is equipped with a shielded GPIB cable.

INDEPENDENT LABORATORY TESTING

This unit has undergone extensive CE certification testing both internally, at EXFO, and externally, at an independent, qualified laboratory. All pre-qualification tests were performed at EXFO while all final tests were performed at UltraTech Engineering Labs, Inc., a renowned test laboratory from Mississauga, Canada. This guarantees the unerring objectivity and authoritative compliance of all test results.

CE INFORMATION TO USER

This unit has been tested and found to comply with the limits for a Class A digital device. Please see the Declaration of Conformity.

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1 INTRODUCTION

EXFO Electro-Optical Engineering, Inc. (EXFO) is pleased to introduce the IQ-5100 Polarization Controller as part of the IQ-200 Optical Test System product line.

EXFO's commitment to superior design in all its fiber-optic instrumentation is respected throughout the industry and is based on the following four goals:

- reliable and accurate performance
- simple operation
- extensive features
- dedicated interest in customer needs

The IQ-5100 Polarization Controller will provide many years of reliable operation. To benefit fully from the many features offered by the IQ-5100 Polarization Controller, it is important to read the following instructions thoroughly.

1.1 IQ-200 Optical Test System Product Line

The IQ-200 Optical Test System product line is a modular optical test system designed for laboratory applications. Thanks to the Windows™ compatible IQ Software, the IQ-200 Optical Test System combines power, performance, and flexibility with a user-friendly interface. The main components of the system are the IQ-203 Mainframe, which can house three modules, and the IQ-206 Expansion Unit, which can house six modules. It is also possible to control one or several IQ-206 Expansion Units with an IQ-206 PC Expansion Card.

For more information on the IQ-200 Optical Test System and the IQ Software, please refer to the *IQ-200 Optical Test System Instruction Manual*.

1.2 Unpacking and Inspection

The IQ-5100 Polarization Controller is delivered with the following standard items:

- IQ-5100 Polarization Controller Instruction Manual
- Certificate of Quality
- accessory kit (optional)

The IQ-5100 Polarization Controller has been thoroughly inspected before shipment. If any damage has occurred during transportation or if any item is missing, please notify EXFO immediately. Retain the original packing material in case you need to return the IQ-5100 Polarization Controller.

1.3 Safety Conventions

The following conventions should be understood before operating the unit:

WARNING	Refers to a potential *personal* hazard. It requires a procedure which, if not correctly followed, may result in bodily harm or injury. Do not proceed beyond a **WARNING** unless the required conditions are understood and met.
CAUTION	Refers to a potential *product* hazard. It requires a procedure which, if not correctly followed, may result in component damage. Do not proceed beyond a **CAUTION** unless the required conditions are understood and met.
IMPORTANT	Refers to any information regarding the operation of the product which should not be overlooked.

1.4 Transportation and Storage

Maintain a temperature range within specifications when transporting or storing the unit. Transportation damage can occur from improper handling. The following steps are recommended to minimize the possibility of damage:

- Pack the unit in the original packing material when shipping.
- Store unit at room temperature in a clean and dry area. Avoid high humidity or large temperature fluctuations.
- Keep the unit out of direct sunlight.
- Avoid unnecessary shock and vibration.

1.5 Getting Help

If you encounter any difficulty while operating the unit, please call EXFO at one of the offices listed below. The Customer Service Group is available from 7:30 a.m. to 8:00 p.m. eastern time, Monday to Friday.

Corporate Headquarters 465 Godin Avenue Vanier QC G1M 3G7 Canada	1-800-663-3936 (USA and Canada) Tel.: (418) 683-0211 Fax: (418) 683-2170 support@exfo.com www.exfo.com
EXFO Europe Centre d'Affaires Les Metz 100, rue Albert Calmette 78353 Jouy-en-Josas, France	Tel.: 33 1 34 63 00 20 Fax: 33 1 34 65 90 93

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2 PRELIMINARY INFORMATION

2.1 Description of the IQ-5100

The IQ-5100 is used to change the state of polarization of incoming light by application of precise voltages to liquid crystal wave plates. Two modes of operation are available. The manual mode allows for modification of the optical delay for each of the four wave plates. The random scanning mode automatically goes through all states of polarization in a short period of time.

The polarization controller supports both local and remote control. Local control is via a Windows™ compatible software preinstalled in the IQ-203 or installed on a host PC when using the IQ-206 expansion card. The software provides a user-friendly interface offering flexible control of the different states of polarization.

Remote control of the IQ-5100 is accomplished either through a GPIB Interface or via a Windows Dynamic Data Exchange communication link. Please refer to the *IQ-200 GPIB and Application Development Guide* for detailed information about remote control of IQ components.

The product nameplate, shown in Figure 2-1, provides the following information:

- the part number **(P/N)** identifying configuration and connector type
- the serial number **(S/N)**
- the product version **(Ver.)**
- the date of manufacture **(Mfg. date)**

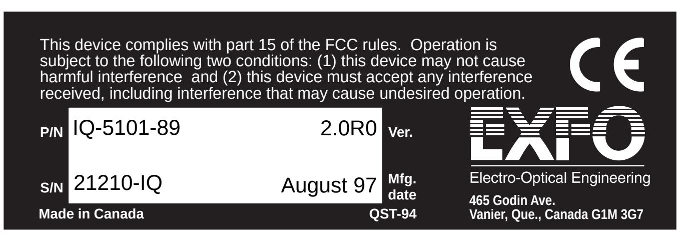

Figure 2-1. Module Nameplate

2.2 Front Panel Description

Note: Actual connectors may differ from those depicted in the illustration.

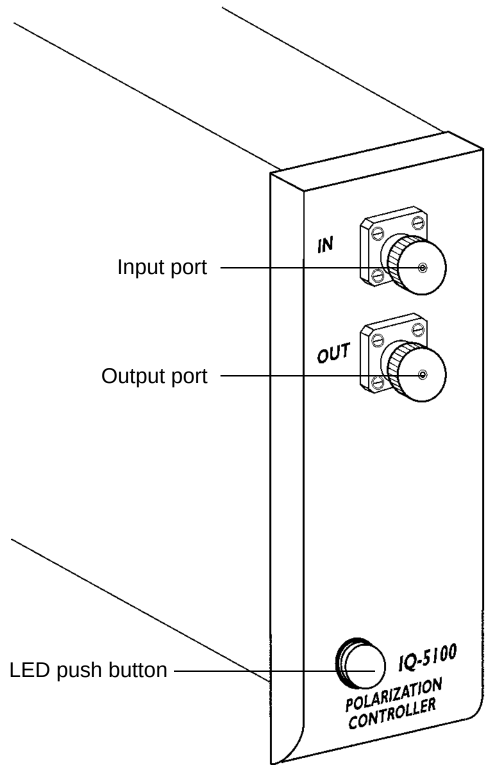

Figure 2-2. IQ-5100 Front Panel

2.2.1 Optical Ports

There are two optical ports located on the front face of the module.

- input port
- output port

When making acquisitions, connect the external source to the input port and the device or system under test to the output port. Both optical ports have an ultra-polished physical contact (UPC), low reflectance connectors.

IMPORTANT

It is very important to keep optical ports clean. The protective caps should always be installed when the module is not being used.

2.2.2 LED Push Button

The LED push button on the front panel has two functions:

- It illuminates when the IQ-203 is powered ON.
- It activates the main IQ-5100 window when pressed.

2.3 Module Insertion

CAUTION

Never insert or remove any module while the IQ-203/IQ-206 is powered on. This will result in damage to the module and the IQ-203/IQ-206.

To insert the module

1. Power OFF the IQ-203/IQ-206.
2. Insert the module into any available slot. The IQ-203/IQ-206 will automatically recognize the IQ module no matter what slot it is inserted in.

IMPORTANT

Be sure to insert the module all the way to the back of the IQ-203/IQ-206 to ensure that the backplane connectors are properly mated. The module is correctly inserted when the module front panel is flush with the IQ-203/IQ-206 front panel.

2.4 Optical Connections

IMPORTANT

Always clean fiber end prior to insertion into the port as explained below.

The fiber-optic cable end should be cleaned at all times to ensure optimum performance and to avoid erroneous acquisitions.

To clean the fiber end

1. Gently wipe the end with a lint-free swab dipped in isopropyl alcohol.

2. Dry using clean compressed air.

To connect the fiber-optic cable to the port

1. Ensure the connector is dry.

2. Align the connector and port to avoid the fiber end touching the outside of the port or rubbing against other surfaces.

3. Do not overtighten.

2.5 Module Removal

CAUTION

Never insert or remove any module while the IQ-203/IQ-206 is powered on. This will result in damage to the module and to the IQ-203/IQ-206.

Depending on the locking system with which the module is designed, there are two ways to remove an IQ module from the IQ-203 Mainframe/IQ-206 Expansion Unit:

1. With the IQ-203 Mainframe/IQ-206 Expansion Unit powered off, place fingers under the front panel of the module and firmly pull module outward.

2. Put one of the supplied protective covers over the empty slot to prevent dust from entering the module housing.

Or:

1. As shown in the following figure, with the IQ-203 Mainframe/IQ-206 Expansion Unit powered off, push up the locking mechanism under the front panel of the module.

2. Pull out the module.

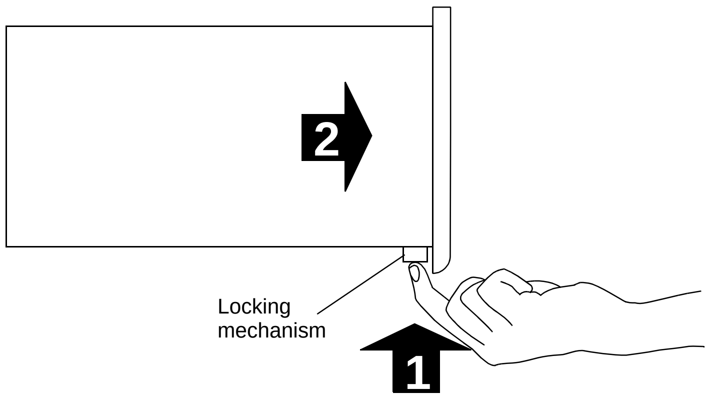

Figure 2-3. Removing an IQ Module

3. Put one of the supplied protective covers over the empty slot to prevent dust from entering the module housing.

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3 OPERATION

3.1 Starting the Application

There are two ways to load the application:

- Push the LED push button on the front panel.
- Double-click on the IQ-5100 icon in the IQ-200 Optical Test System main window.

Once the IQ-5100 application has been loaded, the communication with the IQ-5100 module is initialized.

3.2 Auto-diagnostic Windows

After the initialization process is completed, an auto-diagnostic is performed to verify the module operating parameters. If the auto-diagnostic is unsuccessful, the following window appears:

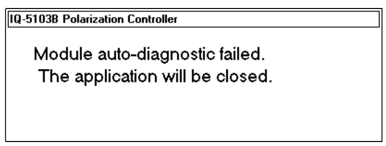


Figure 3-1. Unsuccessful Auto-diagnostic

The application then closes. In this case, try loading the application again. If the auto-diagnostic still fails, contact EXFO.

If the auto-diagnostic is successful, the following window appears:

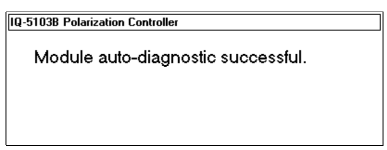


Figure 3-2. Successful Auto-diagnostic

The IQ-5100 application is then loaded, and the IQ-5100 main window opens. This window contains all the main commands to operate the polarization controller.

3.3 Main Window Description

The main window can be divided into five sections:

- title bar and menu bar
- function buttons
- Setup, Scan Period, and Wavelength (λ)
- controller page
- status bar

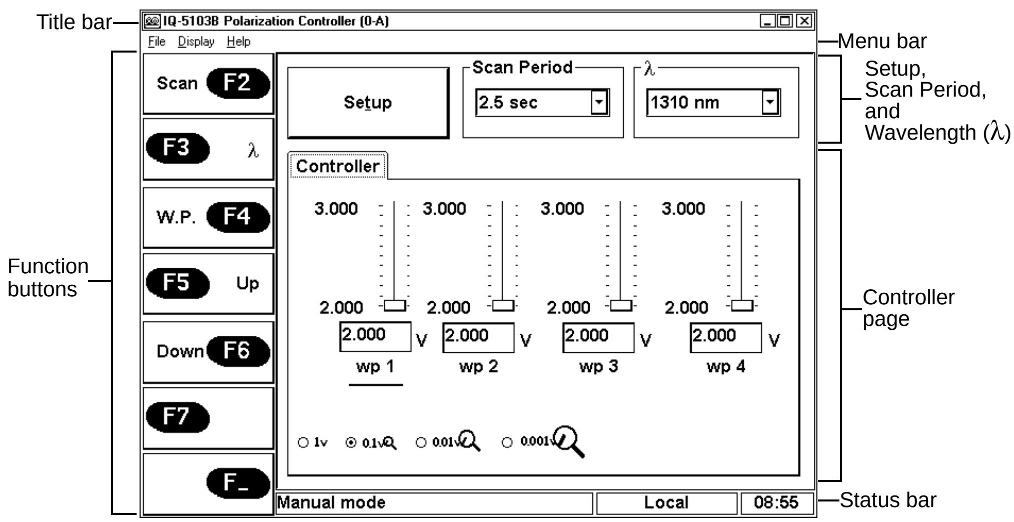


Figure 3-3. IQ-5100 Main Window

3.3.1 Title Bar and Menu Bar

The title bar shows the name of the application. The menu bar has three drop-down menus described below.

Menu	Item	Function
File	Open Config...	Opens a previously saved configuration.
	Save Config...	Saves the current configuration.
	Exit	Closes the application.
Display	Monitor	Opens the monitor window which displays the basic polarization settings.
Help	Online Manual...	Opens the application Help file, which contains the text of the present instruction manual.
	About...	Displays a window containing the following information: • application name and version • Customer Support phone and fax numbers • general system information

Table 3-1. Menu Bar Items

3.3.2 Function Buttons

The function buttons, found on the left side of the main window, are used to directly control of the polarization controller.

Button	Function
Scan F2	Toggles between manual and random scanning modes. When random scanning mode is selected, this button reads **Stop**, the status bar displays **Random Scanning Mode**, and all main window controls are inactive. When manual mode is selected, this button reads **Scan**, **Manual Mode** is displayed in the status bar, and all main window controls are active.
F3 λ	Changes the wavelength. When this button is selected, the *Wavelength* list box indicates the active wavelength.
W.P. F4	Selects the wave plate (from left to right). An on-screen indicator under the wave plate number indicates the selected wave plate.
F5 Up	Increases selected wave plate voltage.
Down F6	Decreases selected wave plate voltage.
F_	Transfers control to the IQ-203 front panel function keys.

Table 3-2. Function Buttons

3.3.3 Setup, Scan Period, and Wavelength (λ)

These items give access to or allow selection of certain controller settings.

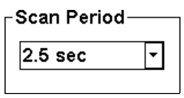
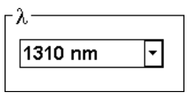
Item	Function
	Gives access to the Setup window (See Section 3.5, *Setting Test Parameters* for more information on the Setup window).
	Indicates the selected scan period and allows selection from a list of scan periods. The scan periods available are 2.5, 5, and 10 seconds.
	Indicates the selected wavelength and allows selection from a list of wavelengths. The wavelengths initially available are 1310 and 1550 nm. The list can be modified through the Setup window (See Section 3.5, *Setting Test Parameters* for more information on the Setup window).

Table 3-3. Setup, Scan Period, and Wavelength (λ) Items

3.3.4 Controller Page

The controller page shows the basic settings used by the controller.

Item	Function
Control switches (wp 1, 2, 3, and 4)	Sets the optical delay for each wave plate. You can also type in the desired optical delay in the control switch edit box under the switch.
Control switch edit boxes	Indicates the optical delay set for each wave plate.
Magnifying glass	Changes the scanning resolution.

Table 3-4. Controller Page Items

3.3.5 Status Bar

The status bar displays the current module status:

- **Manual mode -** Scanning is done only in accordance with the settings you determined manually on the Controller page.
- **Random scanning mode -** Random scanning is in progress for the duration of the selected scan. Scanning starts again after the first scan period is over.
- **Processing... -** The IQ-203 is processing the latest commands.
- **Initializing... -** The IQ-203 is initializing communication with the module.

On the status bar, you also find the inscription Local, Remote, or Lockout, which indicate if the Polarization Controller module is controlled locally or through a GPIB link. The table below explains the meaning of these inscriptions. For more information on how to control the different IQ modules through a GPIB link, refer to the *GPIB and Application Development Guide.* Finally, the status bar displays the time.

Indication	Meaning
Local	The unit is controlled locally.
Remote	The unit is controlled through a GPIB link but local commands can still be used.
Lockout	The unit is exclusively controlled through a GPIB link.

Table 3-5. Module Control Status

3.4 Temperature Stabilization (IQ-5102 only)

While the main window is opening, the controller will try to stabilize the internal temperature. If the controller temperature is unstable, the following warning message appears.

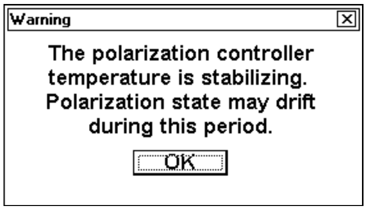


Figure 3-4. Temperature Stabilization Warning

When you click OK, the following icons toggle on and off until the controller temperature is stabilized. The warning message will reappear if you double-clicks on the icon.

Figure 3-5. Stabilizing Icons

3.5 Setting Test Parameters

To perform the desired tests, you must first set at least two parameters: wavelength and scan period

3.5.1 Wavelength Setup

The set the wavelength, choose the desired value from the *Wavelength* list box in the main window.

If the desired value is not available from the *Wavelength* list box in the main window, you must modify the wavelength list in the *Setup* window. To access this list, click on the **Setup** button. The *Setup* window appears.

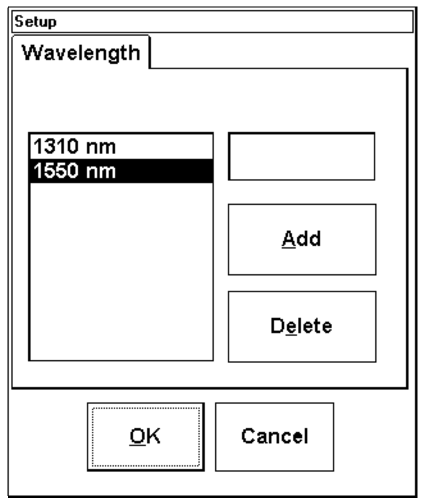


Figure 3-6. Setup Window

The **Wavelength** page contains the following items:

Item	Function
Scroll list	Lists all available wavelengths used by the controller.
Edit box	Allows typing of a new or existing wavelength.
Add	Adds the new wavelength typed in the edit box.
Delete	Deletes the wavelength appearing in the edit box.
OK	Confirms all changes made in the *Setup* window and closes it.
Cancel	Ignores all changes made in the *Setup* window and closes it.

Table 3-6. Wavelength Page Items

From the *Setup* window, either choose a wavelength from the scroll list or type a new one in the edit box. If you typed a new one, clicking **Add** will add it to the list. If you chose one from the scroll list, clicking **OK** will confirm your choice.

3.5.2 Scan Period Setup

The scan period, which helps determine the accuracy of the acquisition (the longer the scan period, the better the accuracy), can be set by choosing one from the *Scan Period* list box in the main window. See *Main Window Description* for available scan periods.

3.6 Data Acquisition

The IQ-5100 offers two modes of acquiring data. The Manual mode allows for modification of the optical delay of each of the four wave plates. In this mode, the data can be acquired as you manually set the voltage of each wave plate. The Random Scanning mode automatically goes through all states of polarization in a short period of time. In this mode, the data is acquired at a rate of over 500 samples per second; most of the Poincarré sphere values are measured in a few seconds.

3.6.1 Manual Mode

When you load the application software, the main window opens, and the Manual mode indication appears in the status bar. At this point, the IQ-5100 Polarization Controller module is active and waiting for you to manually define the desired voltage using one of the four control switches on the Controller page. To set the desired voltage for each wave plate

1. Select the desired wave plate by clicking on the **W.P.** button. Clicking directly on the wave plate control switch will achieve the same result.

2. Set the voltage of each wave plate manually by using the control switch or by typing it directly in the edit box. The value is indicated in the control switch edit box.

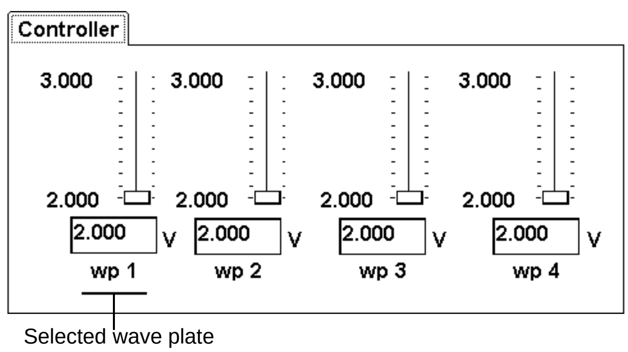


Figure 3-7. Control Switches

Note: *The IQ-5100 module applies the optical delay only* **after** *you changed the voltage of a specific wave plate. It automatically stops after the acquisition is done. For more information on the relation between optical delay and voltage, see Appendix B, Retardation Plates and Applications.*

3.6.2 Random Scanning Mode

To access Random Scanning mode, you click on the **Scan** button. At this point, the button changes from **Scan** to **Stop**, the status bar indicates **Random scanning mode**, and a window appears indicating **Random scanning in progress...** After two seconds, most of the values on the Poincarré sphere are measured.

The scanning will continue until you click on the **Stop** button. When you do, the **Stop** button returns to **Scan**, the status bar indicates **Manual mode** once again and the **Random scanning in progress...** window disappears.

3.7 Viewing Acquisition Results

Acquisition results cannot be viewed directly using the software provided with the IQ-5100 module. To view the results, you will have to use the IQ-3400 PDL/OL Meter module and software offered by EXFO. For more information, call EXFO.

3.8 Monitor Window Description

The monitor window displays basic scanning data. Used in conjunction with other IQ monitor windows, it allows you to create an integrated data display screen (for further information, refer to *Section 6.10* of the *IQ-200 Optical Test System* Instruction Manual). The monitor window can be resized by dragging the corners, or moved by dragging the title bar.

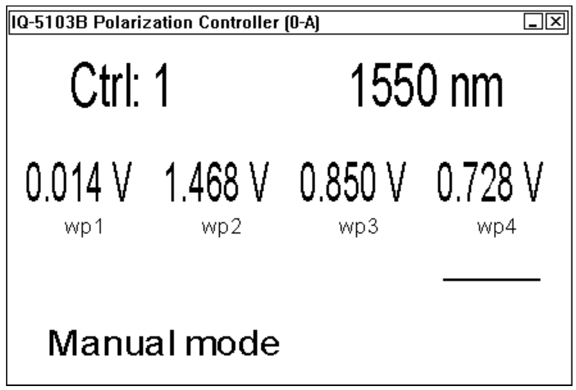


Figure 3-8. Monitor Window

3.8.1 Opening the Monitor Window

There are two ways to open the monitor window:

- In the main window, choose **Monitor** from the *Display* menu.
- Push the LED push button on the front panel of the IQ-5100 module.

3.8.2 Closing the Monitor Window

There are two ways to close the monitor window and return to the main window:

- Double-click anywhere in the monitor window.
- Push the LED push button on the front panel of the IQ-5100 module.

Note: *The function buttons can be accessed while in monitor window mode by positioning the cursor inside the monitor window and clicking the right mouse button. The function buttons will appear to the left of the monitor window.*

3.9 Exiting the Application Software

The application software can be closed either from the main window or from the monitor window.

3.9.1 From the Main Window

There are two ways to exit the application software from the main window:

- Choose **Exit** from the *File* menu.
- Click either of the two active buttons in the upper right corner of the window.

3.9.2 From the Monitor Window

- Choose **Exit** from the *File* menu.
- Click in the **X** icon in the upper right corner of the window.

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4 MAINTENANCE AND TROUBLESHOOTING

4.1 Maintenance

There are no user-serviceable components in the IQ-5100, notwithstanding the procedure described in this section. The module has been designed to require minimum maintenance and to provide reliable operation for many years to come.

The fiber ends must be kept clean at all times, as explained in Section 2.4, *Optical Connections*, to ensure optimum performance.

However, the ports should be cleaned occasionally to ensure minimum insertion loss.

IMPORTANT

When the module is not being used, the protective caps should be fitted over the ports.

To clean the connector ports of the polarization controller,

1. Remove the protective caps.

2. Gently wipe the ports with a lint-free swab dipped in isopropyl alcohol.

3. Dry using clean compressed air.

4.2 Troubleshooting

Problem	Probable Cause	Recommended Actions
LED push button does not illuminate.	Power not ON.	Check AC power cord and power ON the IQ-203 and IQ-206.
	Module is not properly inserted.	Power OFF the IQ-203 and IQ-206, remove and reinsert the module.
	Computer is locked up.	Restart the IQ-203.
	LED is burnt.	Refer to IQ-200 manual to locate and verify fuse.
Pushing the LED push button does not open the main window.	Computer is locked up.	Restart the IQ-203.

Table 4-1. Problems, Causes, and Recommended Actions

In all cases, if problem persists after performing recommended action, call EXFO.

5 TECHNICAL SPECIFICATIONS

Optical[a]		
Model	**IQ-5101**	**IQ-5102**
Spectral Range[b] (nm)	1200 to 1635	1200 to 1635
Polarization Dependent Loss (dB)		
Typical	<0.2	<0.2
Maximum	<0.5	<0.5
Polarization Extinction Ratio (dB)	≥23	≥23
Insertion Loss (dB)		
Minimum[c]	1.2	1.2
Typical[d]	1.6	1.6
Maximum[e]	2.2	2.2
Return Loss (dB)		
Typical	>55	>55
Maximum	>50	>50
Response Time[f] (typical) (ms)		
Rise Time		
min:	15	15
max:	35	35
Fall Time		
min:	100	100
max:	200	200

Table 5-1. Optical Specifications

a. at 25 °C and 1550 nm.

b. Range for PDL measurement only (not range for specifications).

c. Excluding connectors effects and Polarization Dependent Loss (PDL).

d. Including connectors effects only (typical Insertion Loss).

e. Including connectors effects only (maximum Insertion Loss).

f. Measurements are made between 0 and 90% of the transmitted output as one cell is modulated between 0 and ½ wave at 1550 nm. This specification is not guaranteed and is specified only for your information.

Mechanical		
Model	**IQ-5101**	**IQ-5102**
Dimensions		
Width	1.5 in./3.8 cm	1.5 in./3.8 cm
Height	4.75 in./12.0 cm	4.75 in./12.0 cm
Depth	10.3 in./26.2 cm	10.3 in./26.2 cm
Weight	1.25 lbs./0.56 kg	1.60 lbs./0.72 kg

Table 5-2. Mechanical Specifications

Operating environment	
Operating Temperature	32 to 120 °F/0 to +50 °C
Relative Humidity	0 - 95% (non-condensing)

Table 5-3. Operating Environment

Specifications are subject to change without notice.

6 WARRANTY

6.1 General Information

EXFO Electro-Optical Engineering, Inc. (EXFO) warrants this equipment against defects in material and workmanship for a period of two years from the date of original shipment. EXFO also warrants that this equipment will meet applicable specifications under normal use.

During the warranty period, EXFO will, at its discretion, repair, replace, or issue credit for any defective product. This warranty also covers recalibration during two years if the equipment is repaired or if the original calibration is erroneous.

IMPORTANT

The warranty can become null and void if

- ***the equipment has been tampered with, repaired, or worked upon by unauthorized individuals or non-EXFO personnel,***
- ***the warranty sticker has been removed,***
- ***case screws, other than those specified in this manual, have been removed,***
- ***the case has been opened, other than as explained in this manual,***
- ***the equipment serial number has been altered, erased, or removed,***
- ***the equipment has been misused, neglected, or damaged by accident.***

THIS WARRANTY IS IN LIEU OF ALL OTHER WARRANTIES EXPRESSED, IMPLIED OR STATUTORY, INCLUDING, BUT NOT LIMITED TO, THE IMPLIED WARRANTIES OF MERCHANTABILITY AND FITNESS FOR A PARTICULAR PURPOSE. IN NO EVENT SHALL EXFO BE LIABLE FOR SPECIAL, INCIDENTAL, OR CONSEQUENTIAL DAMAGES.

6.2 Liability

EXFO shall not be liable for damages resulting from the use of the purchased product, nor shall be responsible for any failure in the performance of other items to which the purchased product is connected or the operation of any system of which the purchased product may be a part.

6.3 Exclusions

EXFO reserves the right to make changes in the design or construction of any of its products at any time without incurring any obligation to make changes whatsoever on units purchased. Accessories, including but not limited to fuses, pilot lamps and batteries used with EXFO's products are not covered by this warranty.

6.4 Certification

EXFO certifies that this equipment met its published specifications at the time of shipment from the factory.

6.5 Service and Repairs

To obtain service or repair for any equipment, follow the procedure below.

1. Call EXFO Customer Service Group. Support personnel will determine if the equipment requires service, repair, or calibration.

2. If the equipment must be returned to EXFO or an authorized service center, support personnel will issue a Return Merchandise Authorization (RMA) and an address for return.

3. If the unit has an internal storage device, do a backup of your data before sending the unit for repairs.

4. Pack the equipment in its original shipping material. Be sure to include a statement or report fully detailing the defect and the conditions under which it was observed.

IMPORTANT

Never send any unit or accessory back to EXFO without a Return Merchandise Authorization (RMA).

5. Return the equipment, prepaid, to the address given by the support personnel. Be sure to write the RMA on the shipping slip. EXFO will refuse and return any package which does not bear an RMA.

Note: *A test setup fee will apply to any returned unit which, after test, is found to meet the applicable specifications.*

After repair, the equipment will be returned with a repair report. If the equipment is not under warranty, the customer will be invoiced for the cost appearing on this report. Return-to-customer shipping costs will be paid by EXFO for equipment under warranty. Shipping insurance is at the customer’s expense.

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APPENDIX A – POLARIZATION - PRINCIPLES AND APPLICATIONS

Introduction

The continuous demand for faster and larger capacity in telecommunication systems has increased the need of fiber optics. However, with fiber-optic network capacity being further increased, new limitations have been identified. Problems such as attenuation and dispersion are now well understood and under control. Polarization effects in optical fibers such as polarization dependent loss (PDL) and polarization mode dispersion (PMD) are presently the most interesting challenges to the continuous improvement of fiber-optic network capacity.

PDL is the total attenuation (loss in dB) provided by a device considering all the polarization states of the input signal. PMD is a statistical phenomenon by which the two principal states of polarization of an input signal will suffer a delay caused by a device such as a length of fiber or cable in the field. PDL and PMD can be best understood if polarization is well understood.

Polarization Concept

Light is composed of a magnetic field and an electric field orthogonally (perpendicular to each other) propagating in a direction called the axis of propagation. We will concentrate only on the electric field, and will assume that this beam of light or lightwave propagates in a glass medium such as an optical fiber.

Light properties such as polarization are influenced by the medium in which light propagates. There are different states of polarization defined by the electric field influenced by the geometrical behavior of the index of refraction of the medium in which the electric field propagates.

Figure A-1 illustrates the lightwave with its electric field vector propagating in the y-z and x-z planes.

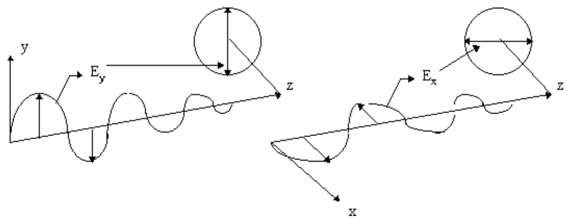

Figure A-1. Representation of Y-Z and X-Z Plane Waves

The wave can also simultaneously propagate in both planes as illustrated in Figure A-2.

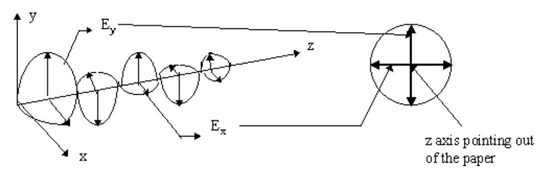

Figure A-2. Representation of Simultaneous Y-Z and X-Z Plane Waves

These waves are also called plane waves as they propagate in a plane (x-z and y-z planes). When the wave has its electric field vector in any random orientation around the z-axis and at the same time shows all the possible orientations (such as shown in Figure A-3 below), this wave is said to be unpolarized.

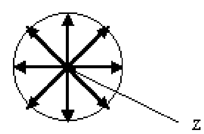

Figure A-3. Representation of Unpolarized Wave

The lightwave is said to be polarized when its electric field vector is oriented at a certain angle around the propagating z-axis. The electric field vector of the wave may be defined in the x-z plane only, and the wave would be said to be horizontally linearly polarized because looking though the z-axis, its vector is moving back and forth in the horizontal plane and is linear (moving along a straight line). This case is illustrated on the right side of Figure A-1. The wave can also propagate vertically in the y-z plane (as shown on the left side of Figure A-1) and would be said to be vertically and linearly polarized. Now the wave can be defined as the product of x-z and y-z plane waves, such as the ones shown in Figure A-4. The resulting wave would then propagate at a certain angle such as 45° or any other angle. This product is a vectorial product and not a simple arithmetic product such as shown in Figure A-5 below.

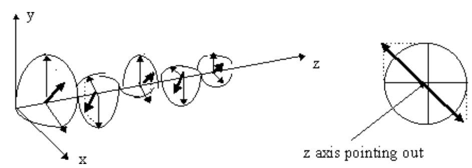

Figure A-4. Representation of a -45° Angle Polarized Wave

Figure A-5. Various Representations of a Vectorial Product

If the x-z plane wave is now propagating in the (-)x-z plane, the wave is said to be +45° angle polarized (looking from the end of the arrow of the z-axis, as shown in the figures). Its resulting vector will be rotated 90° clockwise from the one shown in Figure A-4.

When one of the waves propagating in the x-z plane is 90° out of phase from the wave propagating in the y-z plane, the resulting wave electric vector is circularly polarized. The sense of this circular polarization, either clockwise or counterclockwise, depends on the relative phase shift between the two waves. The resulting wave is counterclockwise circularly polarized when the relative phase shift is +90° (x-z plane wave in front of the y-z plane wave by +90°) as shown in Figure A-6, and clockwise circularly polarized when the relative phase shift is -90° (x-z plane wave retarded from the y-z plane wave by -90°).

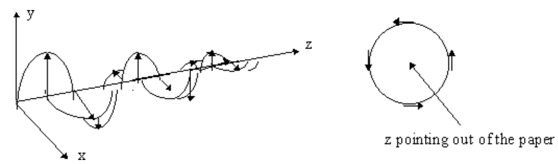

Figure A-6. Representation of a Counterclockwise Circularly Polarized Wave

Circular polarization can also be represented with right-hand and left-hand orientation with the thumb representing the z-axis direction. In the more general case of an arbitrary, nonzero relative phase shift between the x-z and y-z plane waves, the resulting wave will be elliptically polarized depending on the amount of phase shift between the x-z and y-z plane waves.

Birefringence

When the index of refraction of a material is uniformly distributed inside the material, the material is said to be optically isotropic. Liquids and amorphous solids, such as glass and crystalline solids having cubic symmetry, are optically isotropic. Many other materials are not optically isotropic and are thus called anisotropic. Mica, crystalline graphite, calcite, and optical fiber are anisotropic. Their index of refraction is different in one preferred plane (optical plane) than in any other particular direction. In this case, these materials have two indices of refraction and are doubly refractive or called birefringent. One index is associated with the ordinary beam or ray (following the normal Snell law of refraction) and is called n_o, while the other is linked to the extraordinary beam or ray (not following the normal Snell law of refraction) and is called n_e (see Figure A-7).

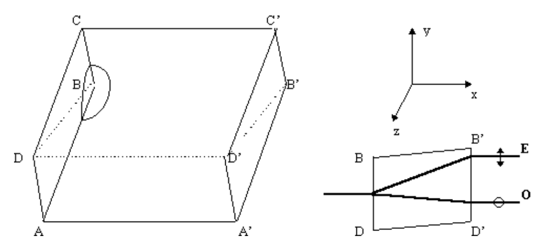

Figure A-7. Representation of Double Refraction or Birefringence

Depending on their respective values, and consequently depending if the waves are traveling at slower or faster velocities compared to one another, the optical axis corresponding to one index of refraction will be said to be either a fast or slow axis. Table 7.1 gives examples of some crystals with their respective n_e and n_o with the e-axis defined as a fast (- sign) or slow (+ sign) axis depending on the sign of the n_e-n_o difference.

Crystal	Formula	n_o	n_e	n_e-n_o	e-axis
Ice	H_2O	1.306	1.307	+0.001	slow
Quartz	SiO_2	1.544	1.553	+0.009	slow
Wurzite	ZnS	2.356	2.378	+0.022	slow
Calcite	$CaCO_3$	1.6583	1.4864	-0.1719	fast
Dolomite	$CaO.MgO._2CO_2$	1.681	1.500	-0.181	fast
Siderite	$FeO.CO_2$	1.875	1.635	-0.240	fast

Table A-1. Principal Indices of Refraction of Doubly Refracting Crystals (589 nm)

Polarization States

As shown previously, the electric field wave can be represented in the Cartesian plane (x, y, z) by the following expressions (for the x-z plane wave propagating in time along the z-axis but varying in amplitude in the x-axis):

$$(z, t) = E_x \sin(\omega t + kz + \varphi) \qquad \text{Equation A-1}$$

Where E_x is the electric field of the wave vector, E_x its amplitude, ω its angular frequency defined as $2\pi v/\lambda$ (v being the speed of light in the material, with v defined as c/n, where c is the speed of light and n the index of refraction and λ the wavelength). Where t is the time span, k the propagation constant in the z direction of propagation and φ the phase of the wave. Equation (1) describes perfectly the wave shown in Figure 7.1. In the case of Figure 7.2, where we have two orthogonal waves, each one and the resultant wave would be described by the following expressions:

$$(z, t) = E_x \sin(\omega t + kz + \varphi_x)$$ Equation A-2

$$(z, t) = E_x \sin(\omega t + kz + \varphi_y)$$ Equation A-3

$$E_{xy}(z,t) = E_x(z, t) + E_y(z, t)$$ Equation A-4

As we have seen, the resulting wave is the vectorial product of other waves (here two orthogonal waves). The following expression would describe this vectorial product, assuming that the y-z wave will suffer the phase delay between both the x-z and y-z waves:

$$E_{xy}(z,t) = ((E_x)^2 + (E_y)^2)^{1/2} \sin(\omega t + kz + \varphi_{xy})$$ Equation A-5

Here we obviously assume that the index of refraction is the same for both the x-z and y-z planes. If the index is different for each plane such as in uniaxial crystals or in optical fiber, then one wave will be retarded as compared to the other. As in the case of E- and O-waves we have previously seen. The wave can also suffer absorption, and its propagating constant will be different for one wave as compared to the other.

Now, the waves can also be represented in other ways such as using Jones vectorial representation. Assuming both waves to be in phase and orthogonal, then the Jones vector will be the following:

$$\text{Jones Vector} = \begin{bmatrix} E_x e^i \varphi_x \\ E_y e^i \varphi_y \end{bmatrix}$$ Equation A-6

We can also use the Jones vector as three numbers, E_x, E_y, and φ_{xy} to describe any polarization state of a wave defined in the Cartesian plane by using the x-z and y-z waves and the phase difference or shift between the two x-z and y-z waves. For example, the wave described in Figure 7.1 is defined as $E_x = 0$ (1 taken as a general reference), $E_y = 1$, and $\varphi xy = 0$ (linear vertical polarization). Figure 7.2 wave is defined as $Ex = 1$, $Ey = 1$ and $\varphi_{xy} = 0$ (linear -45° polarization). Figure 7.6 wave is defined as $E_x = 1$, $E_y = 1$, and $\varphi_{xy} = +90°$ (right-hand circular polarization). Consequently all the polarization states can be described with the Jones vector in such a way as the following display and values.

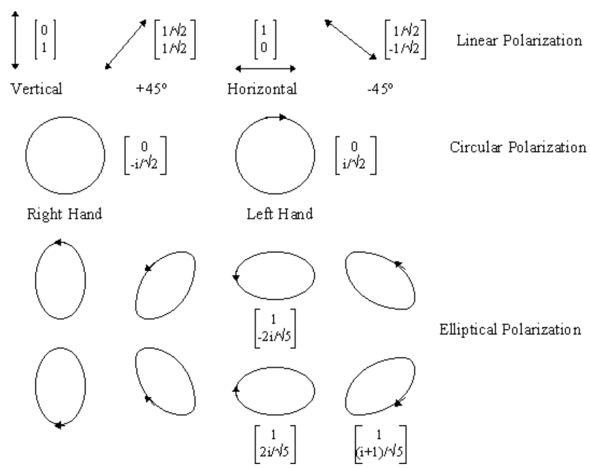

Figure A-8. Schematic Representation of All Polarization States

Degree of Polarization

As we have seen, polarization is a very important phenomenon when lightwaves interact with materials such as crystals or optical fibers. Some light sources such as broadband noncoherent sources exhibit unpolarized light or a very low degree of polarization: surface-emitting LEDs show virtually no degree of polarization, whereas edge-emitting LEDs typically exhibit less than 40% degree of polarization. On the other hand, lasers such as DFBs exhibit strong polarization, most often in the range of 98% to 100%. When these strongly polarized light sources interact with birefringent material such as optical fiber, they can be strongly influenced and affected.

Polarization Mode Dispersion and Polarization Dependent Loss

Optical fiber is a birefringent material because even if we assume that the fiber has a circular shape, its structure exhibits in fact anisotropy due to stresses induced during manufacturing or in the outside field environment. In fact, the fiber is not perfectly circular, and as such, often exhibits ellipticity locally or distributed along its span, which in turn creates birefringence. Bending, twisting, lateral force, and other stressful phenomena can induce birefringence in fiber. Birefringence in optical fiber and components using polarization sensitive material is responsible for dispersion and loss such as polarization mode dispersion (PMD) and polarization dependent loss (PDL).

PDL, the measurement of the insertion loss of a device as a function of the various polarization states, is a critical parameter when a birefringent material such as optical fiber or component interacts with a polarized lightwave.

PMD is another example of a parameter that is critical when a fiber-optic network transmitter is sending its light beam in a particularly long birefringent medium such as a cabled optical fiber. Fiber-optic network transmitters now use strongly polarized and powerful DFB lasers, and optical fiber is a material subjected to anisotropic effect with strong birefringence through its two principal axes. Consequently, the fiber structure can be deformed and provide a change in the index of refraction and an associated change in the relative velocity between the x-z and y-z plane waves (called also the principal states, x and y being the principal axes). This change provides a delay between the two polarization states, and PMD is the indication of this delay.

Table A-2 shows typical values of PDL and PMD for various optical components used in fiber optics.

Components	PDL (dB)	PMD (ps)
Singlemode fiber 1 meter or so Long span (cams)	 < 0.02 < 0.5	 < 0.02 typically > 0.5
Connector PC APC	 < 0.1 < 0.2	 < 0.01 < 0.01
Isolator	< 0.3	< 2
Erbium-doped fiber amplifier (EDFA)	< 0.02[a]	< 1
Coupler	< 0.1	< 0.02
Polarizer	> 30	< 0.02

Table A-2. Typical Values of PDL and PMD for Various Optical Components

a. Polarization dependent gain (PDG)

The improvement in optical component and fiber manufacturing will tend to control the limiting effect of the polarization change in devices or fiber; however, since polarization is a property of the lightwave propagating in the medium, it will always need to be accounted for in component or system design.

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APPENDIX B – RETARDATION PLATES AND APPLICATIONS

Retardation plates (also called birefringent wave plates) are very useful when you want to synthesize and analyze the different states of polarization of a lightwave. For example, you can toggle the polarization of an input beam between linear and circular (or elliptical) using a quarter-wave plate, and you can continuously adjust the polarization angle of a linearly-polarized beam using a half-wave plate.

The common retardation plate is no more than a precisely cut and polished slice of uniaxial crystal, the plane of which contains the extraordinary (or optic) axis. An input beam that is normally incident on the wave plate will be resolved into ordinary and extraordinary axis components, each with a different refractive index. The beam that emerges has a retardation (phase-delay difference) between the axes of:

$$\Gamma = \frac{2p}{\lambda} \cdot (n_e - n_o) \cdot L$$ *Equation B-1*

in which Γ is expressed in radians.

To change the polarization state of an incoming beam of light, EXFO’s IQ-5100 uses **liquid** crystals technologies. It changes the polarization state by applying a voltage (between 2 and 12 V) to a wave plate. Precision is assured up to 0.001 V. The next figure shows the retardation plate arrangement used in the IQ-5100.

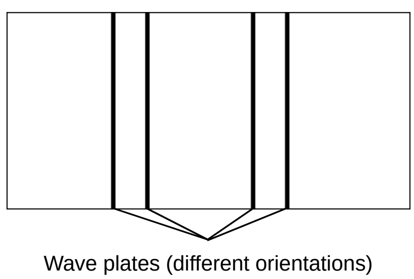

Figure B-1. IQ-5100 Retardation Plates

Table 2-1 below summarizes the most common applications of wave plates. For the information given in Table 2-1 to make sense, you have to find the fast and slow axes of your wave plate, and rotate the wave plate so that the input or output polarization is at the proper angle.

Input	Output
Quarter-wave	
Linear, θ=45°	Right circular
Linear, θ=–45°	Left circular
Right circular	Linear, θ=–45°
Left circular	Linear, θ=45
Linear, any θ≠45°	Elliptical
Half-wave	
Linear, angle θ	Linear, angle –θ
Left circular	Right circular
Right circular	Left circular
Any wave plate	
Linear, θ=0° or 90°	Unchanged

Table B-1. Wave Plates Applications

Remember, you must have precise control of the polarization of your light beam if you want to achieve optimal performance. The IQ-5100 Polarization Controller is specifically designed to help you convert the polarization from one state to another.

APPENDIX C – GPIB COMMANDS

The following commands are addressed to the IQ operating system otherwise known as the IQ Optical Test System. It should be noted that these commands do not require the command address modifier.

INITiate:SCAN

Description This command is used to start or stop random scanning.

Syntax INIT(0..26):SCAN<space><state>

Parameters The <state> parameter is a boolean parameter:
"1"-start random scanning
"0"-stop random scanning

Example INIT3:SCAN 1

INITiate:SCAN?

Description This query returns a value indicating whether random scanning is in progress.

Syntax INIT(0..26):SCAN?

Response A boolean value:
"1"-random scanning in progress
"0"-random scanning not in progress

Example INIT3:SCAN?

INPut:CELL:VOLTage

Description	This command is used to set the voltage for each waveplate. This command cannot be performed while a scan is in progress.
Syntax	INP(0..26):CELL:VOLT<space><plate>,<voltage>[<space> V]
Parameters	The <plate> parameter identifies the waveplate whose voltage will be set: “1”-first waveplate “2”-second waveplate “3”-third waveplate “4”-fourth waveplate The <voltage> parameter represents the voltage to be set to the specified waveplate in the format “99.999”. The voltage must be between 2.000 and 12.000 volts. The <V> parameter is optional and indicates units of volts
Example	INP3:CELL:VOLT 1,4.521 V

INPut:CELL:VOLTage?

Description	This query returns the voltage currently set for each waveplate. This query cannot be performed while a scan is in progress.
Syntax	INP(0..26):CELL:VOLT?
Response	The voltage currently set for each waveplate (from the first to the fourth) in the format “99.999 99.999 99.999 99.999”. The voltage is in volts.
Example	INP3:CELL:VOLT?

INSTrument:PERIod

Description This command is used to select a scan period. This command cannot be performed while a scan is in progress.

Syntax INST(0..26):PERI<space><period>[<space>SEC]

Parameters The <period> parameter represents the new scan period in seconds: 2.5, 5.0, or 10.0. The <SEC> parameter is optional and indicates units of seconds.

Example INST3:PERI 5.0 SEC

INSTrument:PERIod?

Description This query returns the currently set scan period.

Syntax INST(0..26):PER?

Response The currently set scan period in seconds: 2.5, 5.0, or 10.0.

Example INST3:PER?

INSTrument:WAVE

Description This command is used to select a wavelength. This command cannot be performed while a scan is in progress.

Syntax INST(0..26):WAVE<space><wave>[<space>NM]

Parameters The <wave> parameter represents the new operating wavelength in nm in the format “9999”. The “NM” is optional and indicates units of nanometers.

Example INST3:WAVE 1310 NM

INSTrument:WAVE?

Description	This query returns the currently set wavelength in nanometers.
Syntax	INST(0..26):WAVE?
Response	The currently set wavelength (in nm) in the format “9999”.
Example	INST3:WAVE?

Note: *The commands followed by the * symbol cannot be performed when a SCAN is in progress.*

GLOSSARY

AC	Alternating current
adapter	A device for coupling two connectors.
amplitude	The distance between high and low points of a waveform or signal.
ASCII	American Standard Code for Information Interchange. A system used to represent letters, numbers, symbols, and punctuation as bytes of binary signals.
attenuation	The diminution of average optical power. Attenuation results from absorption, scattering, and other radiation losses. Attenuation is generally expressed in dB without a negative sign.
attenuation coefficient	A factor expressing attenuation per unit length, expressed in dB/km.
attenuator	An optical device, either fixed or adjustable, that reduces the intensity of light propagating through it.
axis of birefringence	One of two generally orthogonal orientations transverse to the fiber core corresponding to fast and slow propagation of the group velocity of a light beam. In general, these orientations are elliptical and the orientation and amplitude vary along the fiber. In the special case of a HiBi fiber, the axes are linear and constant along the length of the fiber.
backscattering	That portion of scattered light that returns in a direction generally opposite to the direction of propagation.
baud rate	Measurement of data transmission speed, expressed in bits per second or bps.
beat length	In a reasonably uniform, birefringent medium, the distance over which a light wave propagating along the slow axis will accumulate a phase lag of one wavelength (2π) with respect to light propagating along the fast axis. As a rule, the shorter

	the beat length, the higher the fiber birefringence. Typical HiBi fibers have a beat length of 3 mm at 1550 nm.
Bellcore	Bell communications research, an organization that contains much of the former Bell labs. It specializes in telephone network technology, standards and interfaces.
BER	Bit error rate. On a transmission link, the number of digital "highs" that are interpreted as "lows", and vice versa, divided by the total number of bits received. In modern networks, BERs much better than 10^{-9} are expected.
birefringence	The property whereby the effective propagation speed of a light wave in a medium depends upon the orientation of the electric field (state of polarization) of the light.
c	Velocity of light in a vacuum = 2.997925×10^8 m/s
°C	Degree Celsius. To convert to Fahrenheit: $F = \frac{9}{5}C + 32$.
CFR	Code of Federal Regulations
coherence	A phenomenon whereby the phases of the photons (or constituent wavetrains) of a light beam maintain a definite relationship with each other. A narrow-linewidth laser is said to exhibit a high "degree of coherence".
connector	A junction that allows an optical fiber or cable to be repeatedly connected or disconnected to a device such as a source or detector.
coupler	A device whose purpose is to distribute optical power among two or more ports or to combine optical power from two or more fibers into a single port.
coupling ratio	Value obtained by measuring the power at both output ports and providing the output ratio between them. Also, CR.
CW	Abbreviation for continuous wave. Refers to non-modulated, constant-intensity light.
CR	Coupling ratio
dB	Decibel

dBm	Decibel referenced to a milliwatt.
DC	Direct current
DDE	Dynamic Data Exchange
decibel (dB)	The standard unit used to express gain or loss of optical power. A standard logarithmic unit for the ratio of two powers.
directivity	In a 3-port optical circulator, the ratio of power launched into port 1 that exits via port 2 vs. the fraction that exits via port 3.
DLL	Dynamic Link Library
DMA	Direct Memory Addressing
DUT	Device under test
dynamic range	For an optical instrument, generally defined as the ratio (in dB) of the smallest signal that can be observed (at a specified wavelength separation) in the presence of a strong, nearly saturating signal.
EDFFA	Erbium doped fluoride fiber amplifier
EDFSA	Erbium doped silica fiber amplifier
EIA	Electronics Industries Association
EL	Excess loss
electromagnetic interference	Any electrical or electromagnetic interference that causes degradation, failure in electronic equipment, or undesirable response. Optical fibers neither emit nor are affected by EMI.
EMI	Electromagnetic interference.
excess loss (EL)	In relation to multiport components, the excess loss is a measure of the insertion loss over and above that induced by the splitting ratio.Excess loss is normally defined (in dB units) as the ratio of the input power divided by the sum of the powers in the output ports.
EOI	End of Image Marker

EOS	Effective Opening Size
ESB	Event Summary Bit
ESE	Standard Event Status Enable Register
ESR	Standard Event Status Register
f	Abbreviation for femto, which indicates 10^{-15} units.
f	Frequency, often also designated by ν.
FCC	Federal Communications Commission. A U.S. government body overseeing and regulating national electrical and radio communications. The FCC, formed in 1934, also deals with licences, tariffs, and limitations. The members of the commission are appointed by the U.S. president.
FIFO	First In First Out
frequency	The number of cycles per second, denoted by hertz (Hz).
G	Abbreviation for giga, which indicates 10^9 units.
Ge	Germanium
GeX	High power germanium
GPIB	General Purpose Interface Bus
HiBi	High birefringence (fiber)
hr	Hour
Hz	Hertz. Denotes number of cycles per second.
IEC	International Electrotechnical Commission. A standardization body at the same level as ISO.
IEE	Institute of Electronic Engineering. It is a professional body covering all aspects of electronics and electrical engineering, including software, network, and computer engineering.
IEEE	Institute of Electrical and Electronics Engineering. It is a professional body very active, among other things, in many fiber-optic and opto-electronic related fields.

IL	Insertion loss
index matching material	A material, often a liquid or a cement, whose refractive index is nearly equal to the core index, used to reduce Fresnel reflections from a fiber's endface.
index of refraction	The ratio of the group velocity of light in a vacuum to the group velocity of light in a given medium.
InGaAs	Indium gallium arsenide.
insertion loss	The ratio of input power to output power in dB units (for a given output port) for an optical component such as a connector, splice, or coupler. For a multiport device, the insertion loss includes the splitting ratio and the excess loss.
ISA	Industry Standard Architecture
ISO	International Organization for Standardization. Commonly believed to stand for International Standards Organization. In fact, ISO is not an abbreviation—it is intended to signify uniformity (derived from the Greek *iso* meaning "equal"). ISO is responsible for many standards including those for data communications and computing.
ITU	International Telecommunications Union. The ruling body for telecommunications and the source of many network standards.
jumper	Fiber-optic cable that has connectors terminated on both ends. Used to connect two pieces of equipment, modules, or components.
LoBi	Low birefringence (fiber)
LD	Laser diode
LED	Light emitting diode
loopback	Type of diagnostic test in which the transmitted signal is returned to the sending device after passing through a communications link or network.
M	Abbreviation for mega, 10^6 units.

m	Abbreviation for milli, 10^{-3} units.
min	Minute
mode coupling	The exchange of power among modes.
n	Abbreviation for nano, 10^{-9} units.
n	Refractive index. For the silica glass used in optical fibers, $n \approx 1.465$.
NIST	National Institute of Standards and Technology. U.S. governmental body that provides the assistance in developing standards. It was formerly the National Bureau of Standards.
noise figure	A measure of the quality of an amplifier, defined as the ratio of output to input SNRs.
optical rejection ratio	Another commonly used term for “dynamic range” in an optical system.
optical return loss (ORL)	The ratio (expressed in units of dB) of optical power, reflected by a component or an assembly, to the optical power incident on a component or assembly that is introduced into a link or system.
p	Abbreviation for pico, 10^{-12} units
P	Power
PC	In optical schematics, used to designate a polarization controller.
PCS	Plastic-clad silica (fiber)
PDCR	Polarization dependent coupling ratio
PDEL	Polarization dependent excess loss
PDG	Polarization dependent gain
PDL	Polarization dependent loss
PMF	Polarization maintaining fiber

Poincaré sphere	A three-dimensional graphical representation of the state of polarization of a light beam.
polarization controller	Instrument used to control the polarization state of the light. This type of equipment can produce different polarization states of the input light.
polarization dependent loss	A transmission loss that varies with input polarization state. Normally defined as T_{max}(dB) - T_{min}(dB)
polarization mode dispersion (PMD)	Pulse spreading in a singlemode fiber that arises on account of the different group velocities associated with each of the two principal states of polarization of the fiber.
polarizer	Component used to polarize light.
principal states of polarization (PSP)	The two generally orthogonal states of polarization of a monochromatic light beam launched into a fiber (input PSP) that will propagate through the fiber without spreading or distortion. The SOP of this light beam as it exits the fiber will be in one of two, generally orthogonal, output PSPs. In general, the output PSPs are not the same as the input PSPs, and the orientation of these PSPs changes with wavelength. Not to be confused with axes of birefringence. Only in the spectral case of a single HiBi fiber are the PSPs and the axes of birefringence the same.
RMA	Return merchandise authorization
s	Second
SCPI	Standard Commands for Programmable Instruments
sensitivity	For an optical instrument, the smallest signal that can be detected in the absence of any other signal.
Si	Silicon
SNR	Signal-to-noise ratio. The ratio of the received optical power, divided by the noise floor for the optical system.
SRE	Service Request Enable Register
SRQ	Service Request

state of polarization (SOP)	The orientation of the electric field vector of a propagating optical wave. In general, this vector will trace an ellipse as it propagates. In special cases, it will remain oriented in one direction (linear polarization) or will trace out a circle (left or right circular polarization).
STB	Status Byte Register
t	Time
T	Abbreviation for tera, 10^{12} units.
V	volt
VA	volt-ampere
W	watt
wavelength	For monochromatic light, the distance between two successive peaks (or troughs) of the sinusoidally-varying electric-field amplitude. Note that, unlike frequency, the wavelength of light is inversely proportional to the refractive index of the medium through which it propagates. It is for this reason that accurate wavelength measurements are generally specified as being determined in “air” or in “vacuum”.
λ	lambda. Greek letter used to denote wavelength.
μ	Abbreviation for micro, 10^{-6} units.
ν	nu. Greek letter used to denote frequency. Traditionally, the physics community uses “ν” to denote frequency whereas the engineering community uses “*f*”.

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