General Photonics
Making Light Work Lighter

PXA-1000

Distributed Polarization
Crosstalk Analyzer – PolaX™

User Guide

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General Photonics is located in Chino California.

For more information visit the company's website at:

www.generalphotonics.com

or call 909-590-5473

SAFETY CONSIDERATIONS

The following safety precautions must be observed during operation of this product. Failure to comply with these precautions or with specific warnings elsewhere in this manual violates safety standards of design, manufacture, and intended use of the product. General Photonics assumes no liability for customers' failure to comply with these requirements.

Before operation, the user should inspect the product and review the manual carefully.

Properly ground the chassis and work space using the chassis ground terminal.

Use only in a safe work environment in terms of temperature, humidity, electrical power and risk of fire or shock. The product is designed for indoor use. Avoid exposure to liquids or water condensation. Provide adequate ventilation for cooling.

Operate the product on a stable surface. Avoid excess vibration.

Standard laser safety procedures should be followed during operation.

> *Never look into the light source fiber connector when the light source is turned on. THE OUTPUT LIGHT FROM A HIGH POWER LASER IS HARMFUL TO HUMAN EYES. Follow industry standard procedures when operating a high power laser source. Since the light from the PXA-1000 is invisible, it is safer to turn it off before changing connections and when the light source is not in use.*

OPERATION CONSIDERATIONS

- **To ensure measurement accuracy, allow 10 minutes warm-up time before taking measurements.**
- **When powering the instrument off, wait at least 20-30 seconds before powering it back on to avoid damage to electrical components.**
- **The PolaX software program should be closed before powering off the PXA-1000.**

Section 1.0   Overview

The Distributed Polarization Crosstalk (X-Talk) Analyzer (PXA-1000) is a white light interferometer designed to obtain space-resolved stress information by analyzing stress-induced polarization cross-coupling along a length of polarization maintaining (PM) fiber. Its unique optical design eliminates the strong zero-order interference and reduces the multi-coupling interference common in traditional white light interferometers; as a result, the PXA-1000 has higher measurement sensitivity, higher dynamic range, and higher spatial measurement accuracy than traditional white light interferometers. The PXA-1000 enables the use of the PM fiber itself as the sensing medium, eliminating the need to place multiple fiber gratings along the fiber. It can therefore obtain higher spatial resolution of the stress distribution than grating-based systems. Because no discrete sensing elements are required, the system is easy to install and calibrate, making it ideal for monitoring space-resolved structural changes along bridges, tunnels, dams, oil pipes, or buildings. It can also be used as an intrusion detection system, because any mechanical disturbances to the PM fiber will cause polarization coupling. Another important application is PM fiber quality inspection. The PXA-1000 easily identifies defective sections of PM fiber, enabling the manufacturers or users to remove them. Furthermore, the PXA-1000 is ideal for quality inspection and screening of PM fiber coils, since it can pinpoint the locations of imperfections or areas of local stress on the fiber coil induced during the fiber winding process. The software displays the location and polarization coupling ratio of each stress point as a function of distance. It also generates a table listing the locations and polarization coupling strengths of all crosstalk peaks above a user-defined threshold. Other applications of the instrument includes measuring the extremely high polarization extinction ratio of a polarizing waveguide, obtaining the autocorrelation function of a light source, measuring the birefringence of a PM fiber and the lengths of PM and SM fibers, and matching the optical path lengths of an interferometer.

More detailed information on measurement principles is provided in section 3.

Figure 1 PXA-1000 Distributed Polarization Crosstalk Analyzer

Section 2.0   Features

2.1 Front Panel and Optical Inputs

The front panel of the PXA-1000 is shown in Figure 2.

Figure 2 PXA-1000 front panel

Front panel features:

Power:	Power on/off switch
Light:	Light source safety key
Light Out:	Adapter (narrow-key PM FC/PC standard) for SLD output (to FUT)
Light In:	Adapter (narrow-key PM FC/PC standard) for interferometer input (from FUT)

The recommended (default) connector type is a narrow-key FC/PC PM connector, although other connector types are available by customer request. The connector keys are aligned to the slow axis of the PM fiber.

Fiber Connectors

The front panel adapters are universal connector interfaces (UCI), which feature a male-type adapter top piece that can be removed for direct access to the ferrule end for routine cleaning and maintenance without removing the entire adapter from the panel. This feature helps avoid high insertion loss, high return loss and measurement instability caused by dirty or contaminated connectors

External fiber connectors should be cleaned using industry standard cleaning methods before connection to the PXA-1000. If this procedure is followed before each connection, the instrument's internal connector ferrules should not need regular cleaning. However, high insertion loss or measurement instability that does not improve after cleaning the external connectors may indicate that the instrument's internal connector ferrules require cleaning.

Ferrule Cleaning Procedure

Make sure light source is off before cleaning connectors.

Each connector ferrule is contained in a universal connector interface consisting of a front piece that connects to the external fiber connector, and a base piece that is mounted on the front panel of the instrument, as shown in Figure 3. To clean a connector ferrule, first, make sure no external connector is connected to the universal connector interface. Then, using a Phillips screwdriver, remove the two small screws connecting the front and back parts of the adapter, and carefully pull the front flange straight out. (Note: never remove the adapter base from the front panel). The ferrule end should now be exposed. Clean the ferrule using standard cleaning procedures (compressed air or a fresh lint-free tissue and alcohol or other connector-cleaning solvent), taking care to avoid scratching the ferrule surface. Finally, replace the front flange (position it so that the key notch faces up, and the small alignment pin lines up with the hole in the base piece, before pushing it in) and the screws.
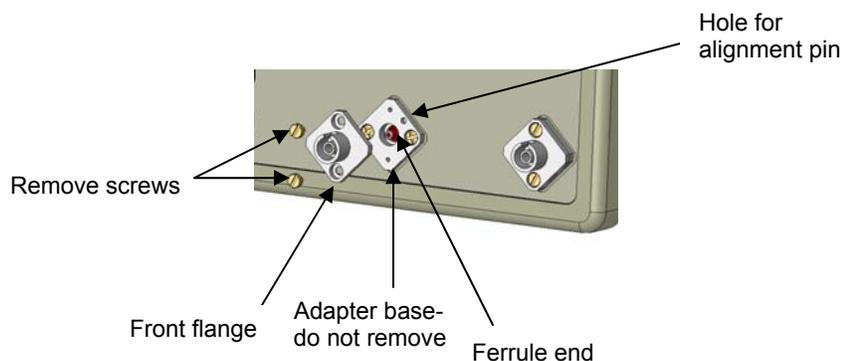

Figure 3 Diagram of universal connector interface

2.2 Rear Panel: Electrical and Remote Control Interfaces

The rear panel of the PXA-1000 is shown in Figure 4.

Figure 4 Rear panel

Rear Panel Features:

Cooling fan air intakes	Line: External AC input connector
USB interface port	⏚ : Chassis ground

The PXA-1000 uses a USB interface to communicate with the control computer. The control program and USB driver are pre-installed on the control computer.

Fuse location:

Figure 5 shows the location of the fuse compartment under the power cord plug. There are two fuses in the compartment- the one in use and a spare. The fuse further inside the compartment is active. The one closer to the compartment opening is the spare.

Replace the fuse with one with the exact rating of the original.

Figure 5 Fuse compartment

# Section 3.0   Operation Instructions

3.1 Unpacking

Inspect PXA-1000 for any physical damage due to shipping and transportation. Contact carrier if any damage is found. Check the packing list to see if any parts or accessories are missing.

Packing List

Item #	Description
1	PXA-1000
2	Power cord
3	USB cable
4	User guide
6	Control computer (laptop) with control program and drivers pre-installed
7	Power supply for computer
8	PM patchcord
9	Manual polarization controller

3.2 Setup

1. Connect instrument power cord and plug it into wall receptacle. Make sure the ground pin of the power cord is connected to earth ground.
2. Power on control computer.
3. Connect instrument to computer with USB cable. Wait for "device detected" message to appear.
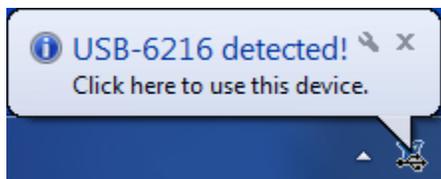
4. Connect input and output fibers (see next several sections for details on measurement setups). Make sure SLD source is turned off while cleaning connectors and making connections.
5. Power on PXA-1000.
6. Turn on the safety key for the internal light source, if applicable.

   Note: The safety key enables control of the internal SLD light source. It does not by itself

turn on the light source. Once the safety key is in the "on" position, the PolaX measurement software is able to turn on the light source.

7. Run the program "PXA-1000" from the desktop or Start menu shortcuts. The program files are in the folder C:\DPXA\. The user interface screen shown in Figure 6 will appear.

8. The PXA-1000 will run through an initialization sequence, which takes about 1 minute. During this time, a "System is initializing" message will be displayed in the system message box on the bottom left of the screen, and the progress bar immediately above the message box will show the status of the process. Once initialization is complete, the system is ready for measurement and the message box contents will change to "System is ready to test".

Figure 6 Main program interface

3.3 Software Interface Quick Reference

This is a quick reference guide for the software interface. Individual features and functions are described in more detail in the following sections.

Function Keys (bottom line of screen, or corresponding keys on keyboard)

F1 ⓘ About	F2 ▷ Run	F3 Load	F5 Default	F6 Save	F8 ⟳ Initialize	F9 ❌ Exit

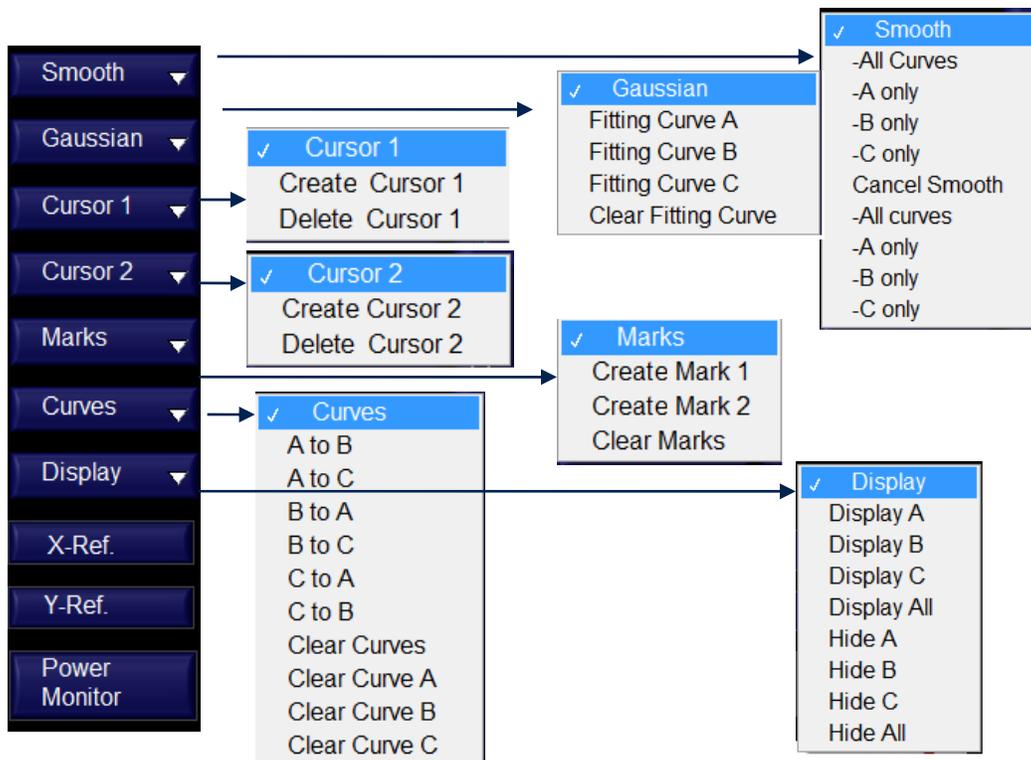|		
F1	(About)	Displays the PolaX™ software version. Features and interfaces described here correspond to PolaX v.3.5.2.
F2	(Run)	Executes the selected measurement.
F3	(Load)	Loads saved data from file. This function does not require connection to the PXA-1000.
F5	(Default)	Resets system parameters to default values: Delay Start: 0mm Delay End: 50mm Attenuation: 5 dB Gain: Low Δn: $5 \times 10E{-}4$
F6	(Save)	Stores measured data to file.
F8	(Initialize)	Delay line initialization; resets position to zero.
F9	(Exit)	Exits PXA-1000 control software PolaX. The PXA-1000 will run through an exit sequence before exiting the program. Do not disconnect or power down the instrument during this process.

Plot Options (top left side of screen)

Curve Titles

Curve Icons
(gray = hidden)

The plot options allow the user to customize curve appearance, as well as to export data from the selected plot.
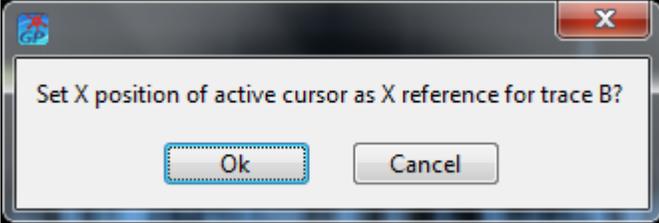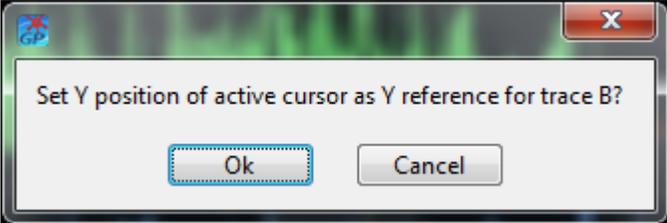
To customize the appearance of a plot, click on the icon for that plot to bring up a customization pull-down menu. "Plot Visible" hides or displays the plot. The pull-down menu also gives options to copy that curve's data to the clipboard or export it to an Excel file.

Trace Display and Fitting Options (left side of screen)

Smooth	Options to apply or remove smoothing from one or more curves. Curve smoothing method can be selected from the "Curve Analysis" tab on the right side of the screen. Once smoothing is applied, original data and curve are replaced by smoothed version.
Gaussian	Fits selected curve using Gaussian function for coherence length measurement or general peak characterization. The fitting curve is displayed in the graph window for comparison to the raw trace, and the fitting parameters are displayed in the "Curve Analysis" tab on the right of the screen.
Cursor 1	Displays/removes cursor 1. When the cursor is present, its coordinates on the active curve (selected at top right of screen) are displayed next to it.
Cursor 2	Displays/removes cursor 2. When the cursor is present, its coordinates on the active curve (selected at top right of screen) are displayed next to it.
Marks	Options to insert or remove markers 1 and 2. The selected marker is inserted at the active cursor's position. Marker coordinates are displayed in the "Curve Analysis" tab on the right of the screen. Note: Cursor must be on screen to insert marker.

Curves	Curve options include: 　　Copy one trace to another 　　Clear one or more traces
Display	Display or hide one or more curves.
X-Ref	Sets x position of active cursor as x-reference (zero point) for active trace. Set X position of active cursor as X reference for trace B? Ok　　Cancel
Y-Ref	Sets y position of active cursor as y reference (value set by the system) for active trace. Set Y position of active cursor as Y reference for trace B? Ok　　Cancel
Power Monitor	Power Monitor 1.18717 (mW) Exit Measured optical power at interferometer input (DUT output).
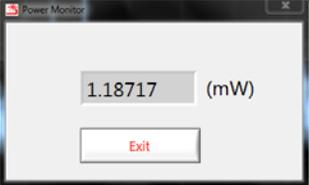
Measurement Setup Options (tab on right side of screen)

	Curve Selection	Select curve A, B, or C for Setup, Curve Analysis, Fiber information, or Events.
	Measurement	
	Xtalk Distribution	Sets system to measure polarization crosstalk distribution.
	Birefringence	Sets system to measure birefringence of PM fiber.
	Coherence length	Sets system to measure the coherence length of an input light source.
	Raw Interference	Sets system to measure and display raw interference signal data vs delay.
	PER	Measures the system's polarization extinction ratio (quick check for system setup).
	Delay Scan Range	Set up scan range for variable delay line
	Start Position	0mm by default
	Stop Position	Set end position depending on length of fiber or waveguide to be measured.
	SLD	
	Attenuation	Set attenuation of internal VOA

	SLD switch	Software switch turns light source on or off. Running a measurement will automatically turn on the light source.
	Gain	Sets the amplifier gain to low or high. When input optical power is low, setting the amplifier gain to high will increase SNR and system measurement sensitivity. The low gain setting is the default; it works well for most measurements.
	Δn of PM fiber	Sets the birefringence of PM fiber under test. This value is used to calculate the positions of coupling points on the PM fiber. To change the value, click on the number and type in the desired value, then press ENTER.
	Calibration	System calibration functions (may not be available to all users)
	PER Calibration	Calibrates the system using a 0 dB calibration standard.
	Set Mark1 as Zero Position	Sets Marker 1 position as x reference (0 position) for the system.
	Endpoint Autodetection	Enable/disable DUT endpoint autodetection. With this feature enabled, the program automatically detects the locations of the DUT input/output connectors and excludes data outside this region. Default: enabled.

Curve Analysis (tab on right side of screen)

	Cursor positions	The top block summarizes the x coordinates and corresponding y coordinates on the selected curve of cursors 1 and 2. Y-coordinates on other curves can be displayed by selecting another curve at the top of the screen.
	Marker positions	The next block summarizes the x coordinates and corresponding y coordinates of markers 1 and 2, as well as the x and y distances between them. Markers are placed on specific curves.
	Gaussian Fit Results	Displays the fit results with Gaussian fit model $a \cdot \exp\left(-\dfrac{(x-x_0)^2}{2\sigma^2}\right)$, where a is the amplitude, σ is the standard deviation (STDV) and x_0 is the center. Bandwidth is the 3dB bandwidth of the Gaussian fit curve. The fit residual is defined by $\dfrac{1}{N}\sum_{i=0}^{N-1}(y_{fit,i}-y_{raw,i})^2$.
	Smoothing Method	
	Third-order polynomial	Obtains a smooth curve using the third-order polynomial intercept method.

	Moving Average	Obtains a smooth curve using the moving average method: y[i]=(y[i]+y[i+1]+…+y[i+n])/n, where n is the average number.
	Moving Average number	Sets the average number for moving average method.

Fiber (tab on right side of screen)

Fiber measurement data

	Fiber PER Analysis	
	PER including internal fiber	Measured PER of the entire system, including internal fiber in the PXA-1000.
	Estimated PER of FUT	Calculated PER of the fiber under test (FUT) over the designated range.
	Set Fiber START	Sets start point for PER calculation and events table.
	Set Fiber END	Sets end point for PER calculation and events table.
	Calculation Method	Select calculation method for PER measurement. Peak: Include all peaks ≥threshold value within designated range in the calculation. Area: Integrate over area under the curve within the designated range to calculate PER.
	Calculate PER of FUT	Recalculate PER after changing settings (calculation method, fiber range, or peak threshold)
	Fiber Birefringence	Data summary for birefringence measurement
	Length of Fiber	Length of fiber under test (input by user)
	Delay between Input and Output (mm)	Measured delay for fiber under test
	Measured Birefringence	Measured birefringence of fiber under test
	Beat Length	Calculated beat length of fiber under test.
	Recalculate	Recalculate birefringence and beat length after changing measurement settings (e.g. fiber length).

Events (tab on right side of screen)

The Events tab provides a table summarizing the position and amplitude of all measured crosstalk peaks between the designated start and end points (specified on the "Fiber" tab) that exceed the user-defined threshold and width settings.

	Sort by:	Crosstalk peaks can be sorted by position or amplitude
	Table	Lists position and amplitude of all peaks between Marker 1 and Marker 2 that meet the threshold criteria.
	Xtalk (Average)	Lists average crosstalk value, calculated using peaks listed in the table.
	Xtalk (Maximum)	Lists the maximum crosstalk, from peaks listed in the table.
	Save Events	Saves data in peak table to a file. Saved data includes index, position, and amplitude of listed peaks.
	Peak Detection Parameters	Define threshold parameters for table listings. To change a parameter, select it, type the new value, and press ENTER. The table will update automatically.
	Threshold	"Threshold" rejects peaks that are too small. The peak detection function ignores any peak found whose fitted amplitude is less than the specified **threshold**.
	Width	"Width" specifies the number of consecutive data points to use in the quadratic least squares fit. The **width** is coerced to a value greater than or equal to 3. The value should be no more than about 1/2 of the half-width of the peaks and can be much smaller (but > 2) for noise-free data.

The peak analysis region can be modified by changing the values of "Fiber START" and "Fiber END" on the "Fiber" tab.

3.4 Measurements

The PXA-1000 can perform several types of measurements related to polarization crosstalk. Measurement principles, setup descriptions, and results analysis for each type of measurement are described in this section.

Distributed Polarization Crosstalk Measurement (PM fiber)

Polarization maintaining (PM) fiber is widely used in fiber optic sensor systems. The performance of such a sensor system is directly limited by the quality of the PM fiber coil, especially by the magnitude of cross coupling between the two principal polarization modes. The PM fiber itself may have imperfections such that the local intrinsic stresses may cause polarization cross coupling. External stress on the PM fiber during the fiber winding process may also cause polarization cross coupling. In order to optimize PM fiber coil quality, one would first select PM fiber with low intrinsic polarization cross coupling and then wind the fiber so as to minimize externally induced cross coupling. In practice, one would also like to identify the exact stress points which cause polarization coupling during the winding process so as to remove the induced stress as it occurs. The distributed polarization crosstalk analyzer (PXA-1000) can reveal the location and magnitude of polarization coupling induced by both intrinsic and external stresses.
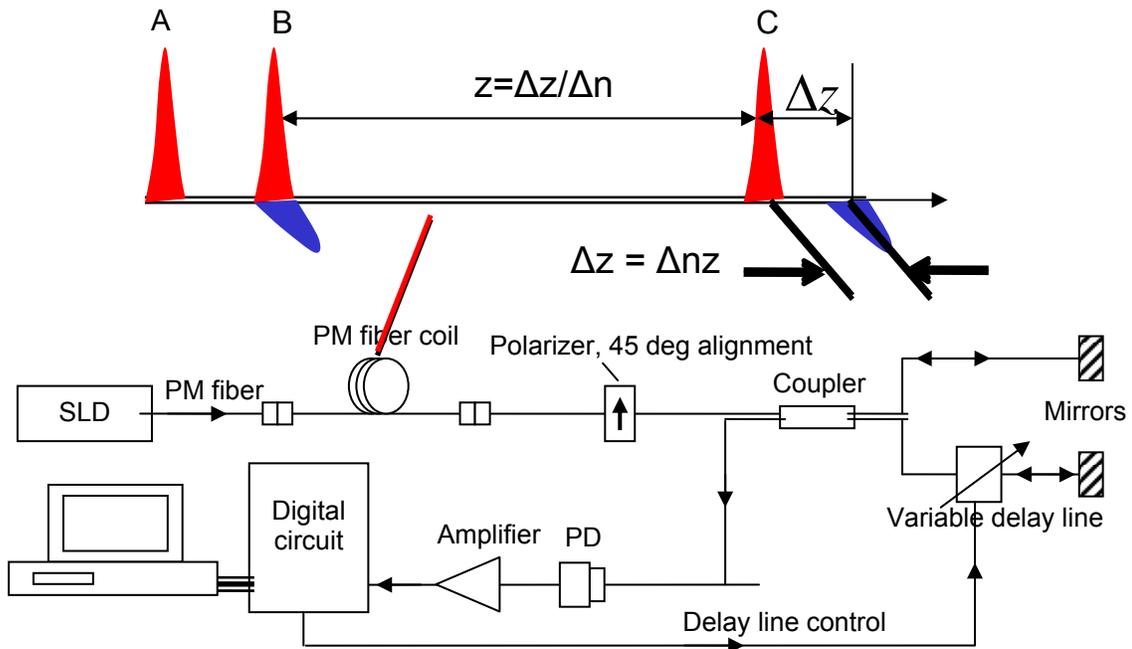
PXA-1000 System Schematic

Figure 7 PXA-1000 system schematic

As shown in Figure 7, the PXA-1000 system consists of three main parts: light source, interferometer and light detection/processing circuit. The light input to the DUT is linearly polarized and aligned to the slow-axis of the PM fiber, with a 30nm bandwidth and 1310nm or 1550nm center wavelength. Its power can be adjusted by a variable optical attenuator (VOA). After passing through the DUT, the light aligned to the fast- and slow axes are mixed together through an analyzer, generating interference peaks in a fiber based interferometer as the delay line is adjusted.

Distributed Polarization Crosstalk Measurement Principle
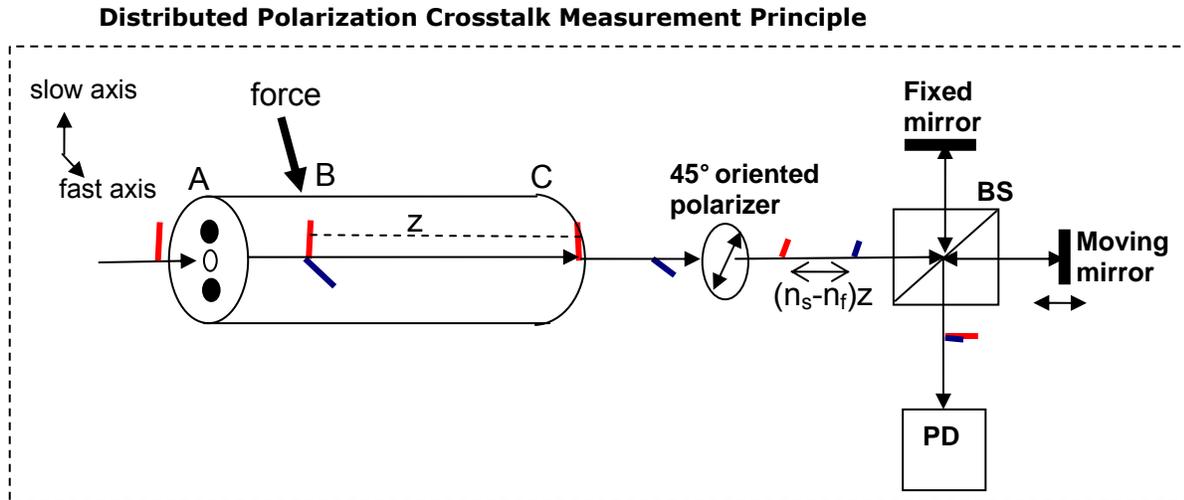
Figure 8 Polarization crosstalk measurement principle

As shown in Figure 8, when light enters the PM fiber at position A, it has only one polarization component, aligned to the slow axis (red). Stress at position B induces polarization coupling and produces a polarization component aligned to the fast axis (blue). Because the two polarization components travel at different group velocities, at the output of the fiber (position C), the two components will experience a delay difference

$$\Delta z = n_s z - n_f z = \Delta n z \qquad (1)$$

where n_s and n_f are the refractive indices of the slow and fast axes, respectively, their difference Δn is the birefringence, and z is the distance between the coupling point B and the output point C. If a polarizer oriented at 45 degrees from the slow axis is placed at the fiber output, half of the power in each of the polarization components will pass through the polarizer and emerge with the same polarization state (linear, aligned to the polarizer axis). Consequently, they will interfere in the Michelson interferometer shown in Figure 8 to produce interference peaks as the delay is adjusted. The distance between the two adjacent interference peaks is Δnz; therefore, from Eq. (1), the location of the coupling point is $z = \Delta z / \Delta n$. The coupling point can therefore be located using the interference graph. The coupling ratio can also be calculated from the strength of the interference peaks.

Setup for Distributed Polarization Crosstalk Measurement

The recommended distributed polarization crosstalk measurement setup is shown in Figure 9. All fibers used in the measurement should be PM fibers with connector keys aligned to their slow axes. The external connectors should be carefully cleaned before connecting to the PXA-1000.
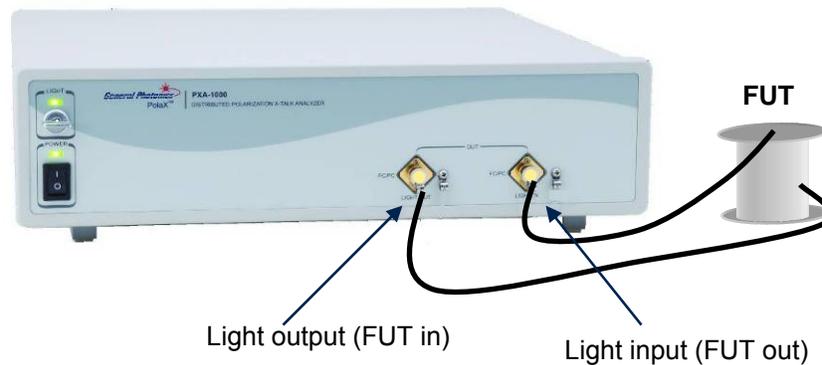

FUT

Light output (FUT in)   Light input (FUT out)

Figure 9 Distributed polarization crosstalk measurement setup

Distributed Polarization Crosstalk Measurement Procedure (for PM fiber)

1. Connect fiber under test (FUT) as shown in Figure 9.

2. On the measurement information section on the right side of the screen, select the curve (A, B, or C) on which to display measured data.

3. Select "Xtalk Distribution" from the Measurement menu on the Setup tab.

4. Set the delay scan range. The start position is fixed at 0mm. Set the "Stop Position" to the desired value (range is 0 to 700 mm for the 1.3 km PXA-1000, 0 to 1500 mm for the 2.6 km PXA-1000, or 0 to 1600 mm for the 3.1 km PXA-1000). Generally, the "Stop Position" should be longer than the minimum delay calculated by

$$\text{Minimum Delay} = \text{fiber length} * \Delta n * 1000 \text{ (mm)} \qquad (2)$$

The "Stop Position" can be changed either by using the up/down arrow buttons next to the value or by selecting the value and typing in a new number.

5. Check the attenuation setting.

   a. Make sure the light safety key is in the "on" position.

   b. If the SLD on/off button is red, as in the example above, click the button to turn on the SLD.

    c. Click the "Power Monitor" button on the lower left side of the screen.
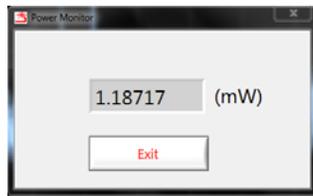
    Check that the optical power is at an appropriate level. Power ~1mW or so usually works well, although higher power may be necessary for sensitive measurements. If the power is too high or too low, change the attenuator setting (range 0 to 30 dB) and check the power again.

    d. If the measurement is run with the power level too high, the detector may saturate and the resulting data may not be accurate. In this case, the PXA-1000's message box will show "Detector is saturated. Please increase attenuation of VOA".

    e. The optical power level affects the position and width of the noise floor of the measurement. If the noise floor is too high or too broad, the optical power may be too low.

6. Set the amplifier gain. "Low gain" is recommended for most applications. "High gain" can be used for fiber systems with very high loss.

7. Set the birefringence of the PM fiber under test. If the birefringence is not known, measure it by following the procedure described in the next section. The birefringence setting can be changed by selecting the value and typing the new value in the box. The fiber birefringence setting determines the x positions of data points if the scale is set to "fiber length".

8. Autodetect setting: The PolaX program includes an endpoint autodetection function. When this function is enabled, after a measurement is completed, the program detects the locations of the DUT input and output connectors and excludes data outside of the immediate range of the DUT from the displayed graph and from saved data files. For most fiber measurements, this results in a cleaner display and smaller data files without losing relevant information. However, for certain applications such as waveguide measurement or measurement of very long fibers, for which the PXA cannot reliably detect the endpoints, it may be necessary to disable the autodetection.

9. Click the "Run" button at the bottom of the screen or press the F2 function key on the computer keyboard to start the measurement. During measurement, the message "Measuring xtalk" will be displayed in the message box at the bottom left of the screen, and the progress bar will indicate the status of the measurement.

Progress bar

Message box

10. When measurement is finished, the x-talk vs. position trace will be displayed (see below). The x position of the PXA light input connector (which connects to the DUT output) is zero on the plot (Marker 1). To the left of that is a peak corresponding to an internal input reference point. Marker 2 is placed at the PXA-1000 light output connector (DUT in). To the right of that is a peak corresponding to an internal output reference point.

Section 3.5 provides more details on analysis of the measured results.
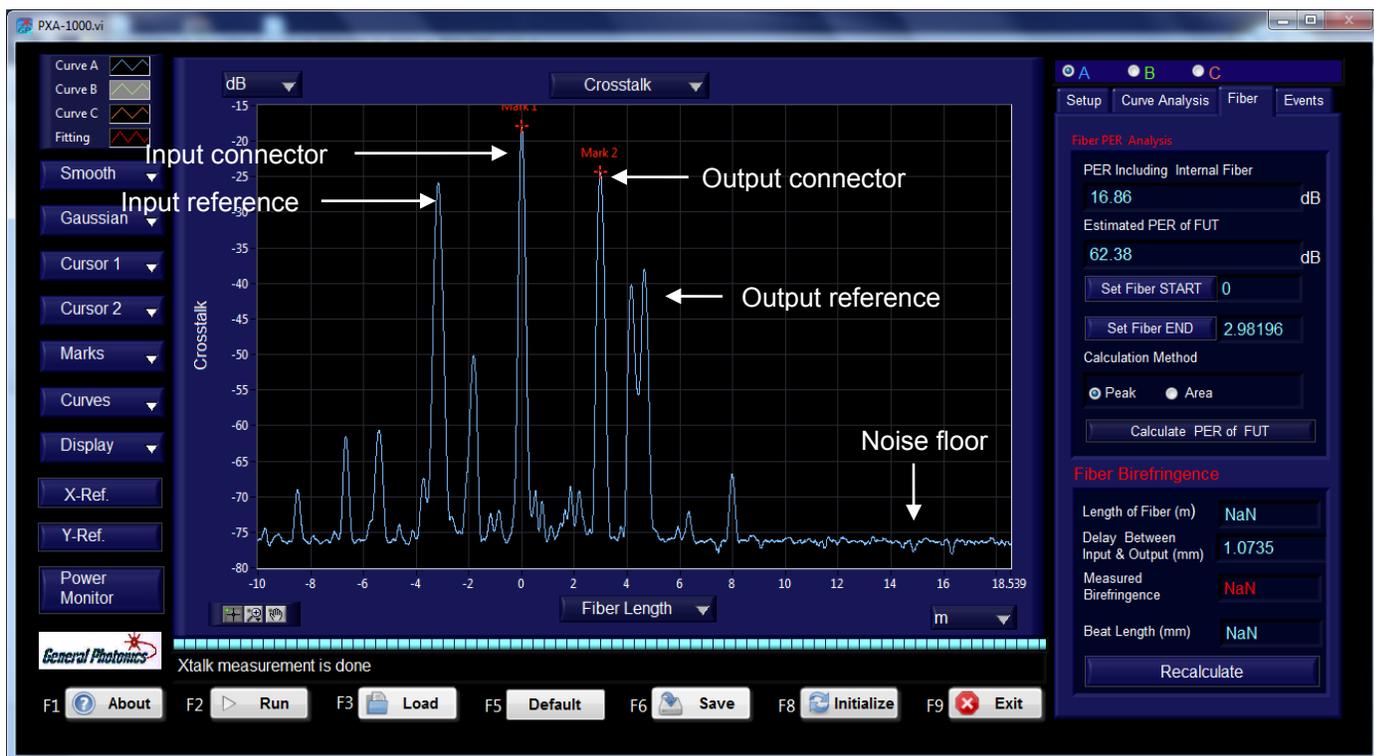
Figure 10 Crosstalk measurement of a 3m PM fiber.
Default plot shows crosstalk (dB) vs. fiber length (m).
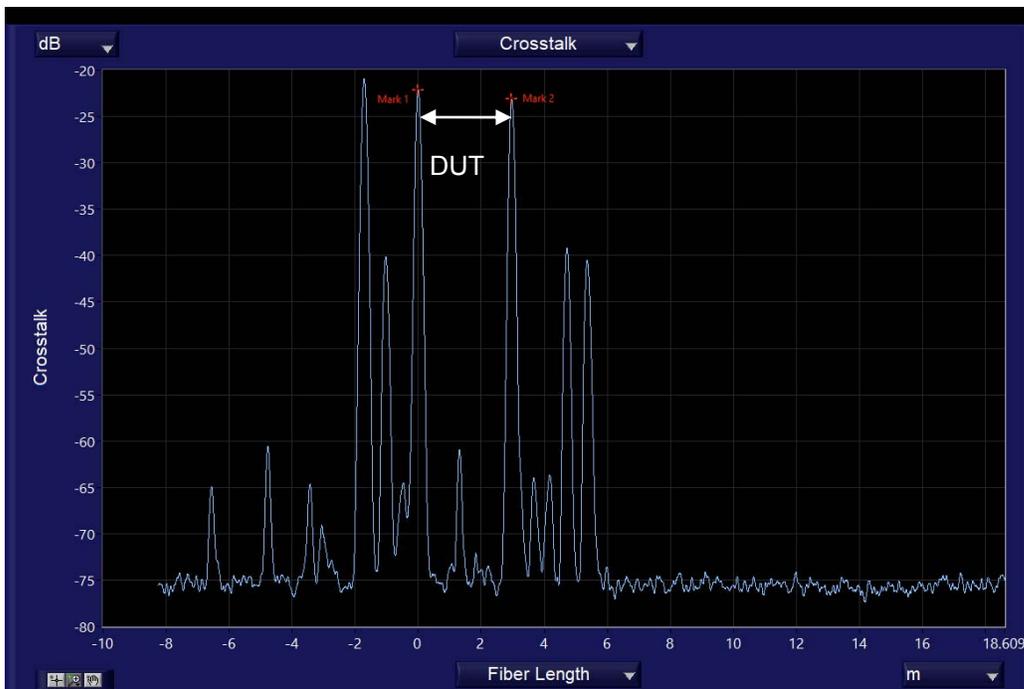
Autodetect enabled: Data is limited to a range of around 19 m.
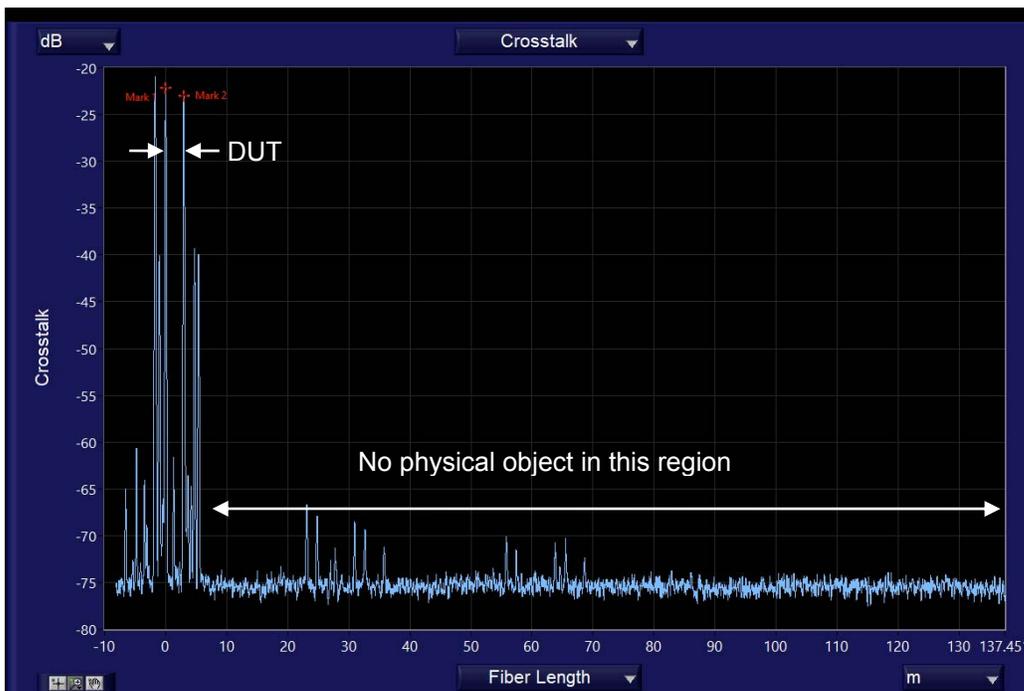
Autodetect disabled: The plot includes data for the full measurement range of about 130 m, but only the region between markers 1 and 2 correspond to the DUT.

Figure 11 Endpoint utodetection examples. The plots show full-range data displays for measurements of a 3m PM patchcord with autodetection enabled (top) and disabled (bottom). MDL range is 50 mm in both cases.

Polarization Extinction Ratio (PER) Measurement (PM fiber)

PER Determination from Distributed Polarization Crosstalk Measurement

Polarization extinction ratio (PER) is the ratio between the power in the principal polarization component of a light beam and the power in the orthogonal polarization component, expressed in dB. It is a measure of the linearity and degree of polarization of a polarized light source, or of the polarization preserving or suppressing properties of a fiber or optical component. It is one of the principal parameters used to evaluate the quality of a PM fiber. When evaluating a PM fiber or PM fiber system, the principal polarization component is usually the one aligned to the slow axis of the PM fiber. In this case, the PER can be expressed as:

$$PER = 10\log(P_s/P_f) \hspace{3cm} (3)$$

where P_s is the total power in the slow axis, and P_f is the total power in the fast axis.

Most PER meters and measurement systems can only measure the total PER of the fiber or system under test. Because of this, it is impossible to isolate the effects of particular connectors or splice points. In addition, the measured value is heavily dependent on the alignment of the input light at its launch point into the FUT, which limits both the accuracy and repeatability of the measurement.

As described in the previous section, the PXA-1000 measures crosstalk at all points along the fiber under test. The PER of a particular section of the FUT can be calculated by integrating the effects of all crosstalk events between the designated points on the fiber.

When a distributed polarization crosstalk measurement is done, the PXA-1000 provides measurement results for system PER and PER of the fiber under test on the Fiber tab (Figure 12).

"PER including Internal Fiber" is the PER of the entire system, including the effects of internal fibers and reference points in the PXA-1000.

"Estimated PER of FUT" is the PER of the fiber under test (FUT), calculated using the crosstalk contributions from all crosstalk events that meet the threshold conditions (as listed in the events table) between the designated start point and the designated end point for the calculation.

When the distributed crosstalk measurement is first completed, the algorithm automatically identifies and excludes the contributions of misalignments at the FUT input and output connectors. The start point for the PER measurement is denoted by Marker 1, which is automatically placed at the PXA-1000 input connector (FUT output), and the end point for the PER measurement is set at Marker 2, which is automatically placed at the PXA-1000 output connector (FUT input).
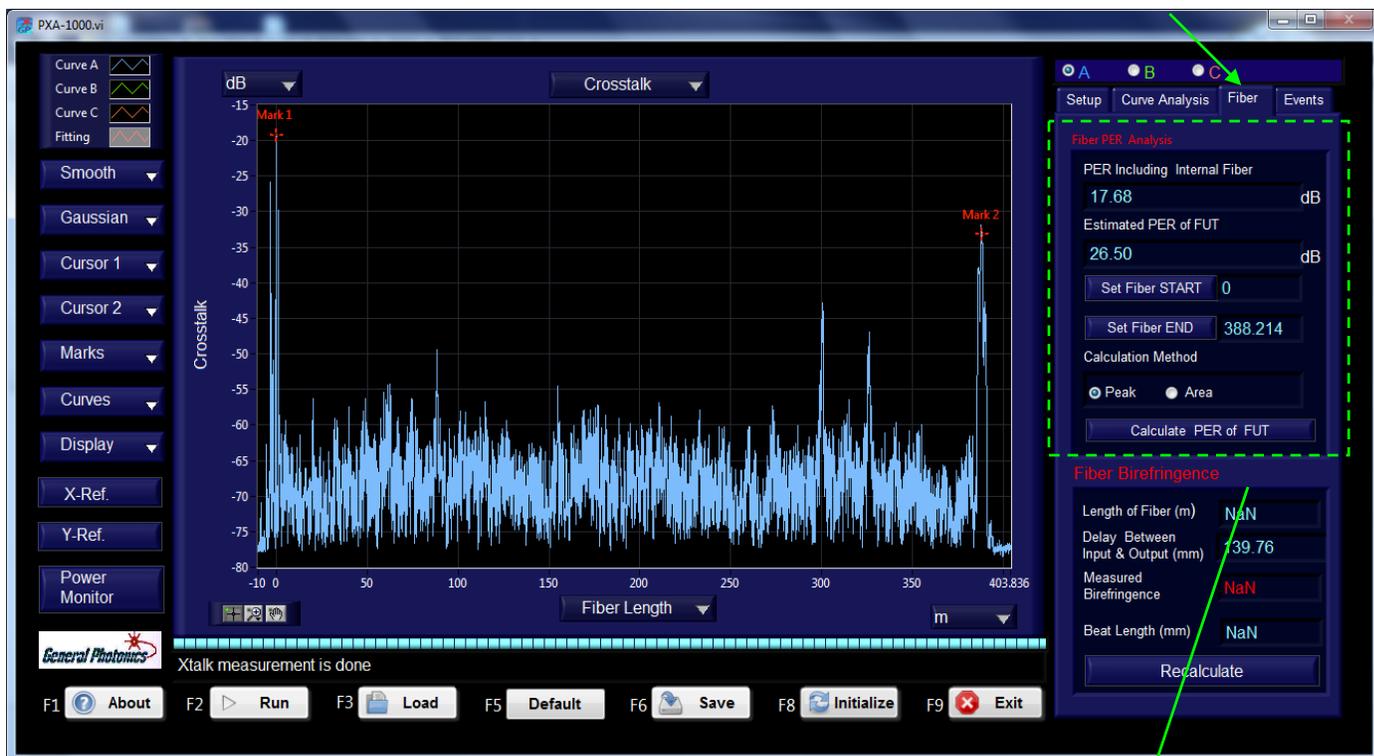
System PER, includes the effect of internal fiber in the PXA-1000

PER of DUT, calculated using the measured crosstalk from the designated start point
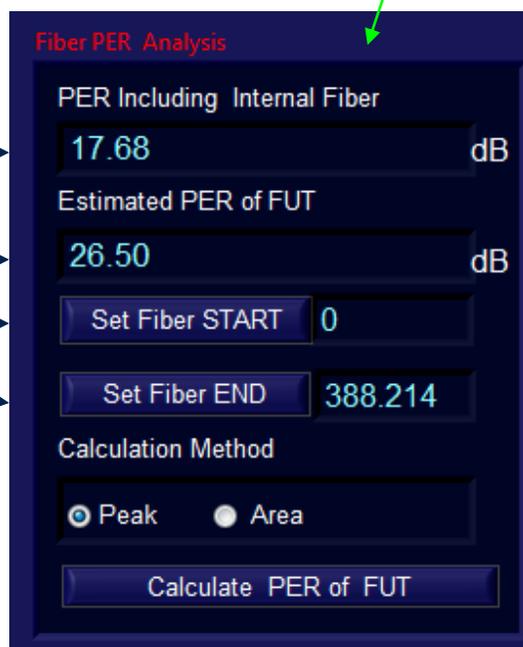to the designated end point

Figure 12 Results of polarization crosstalk measurement of 388m fiber coil, with closeup of PER results section on Fiber tab

Fiber Range for PER Measurement

The user can choose to calculate the PER between any two points on the FUT (for example, to exclude the effects of connectors, splice points, etc.) by changing the start and end points used for the PER calculation. Figure 13 shows some examples.
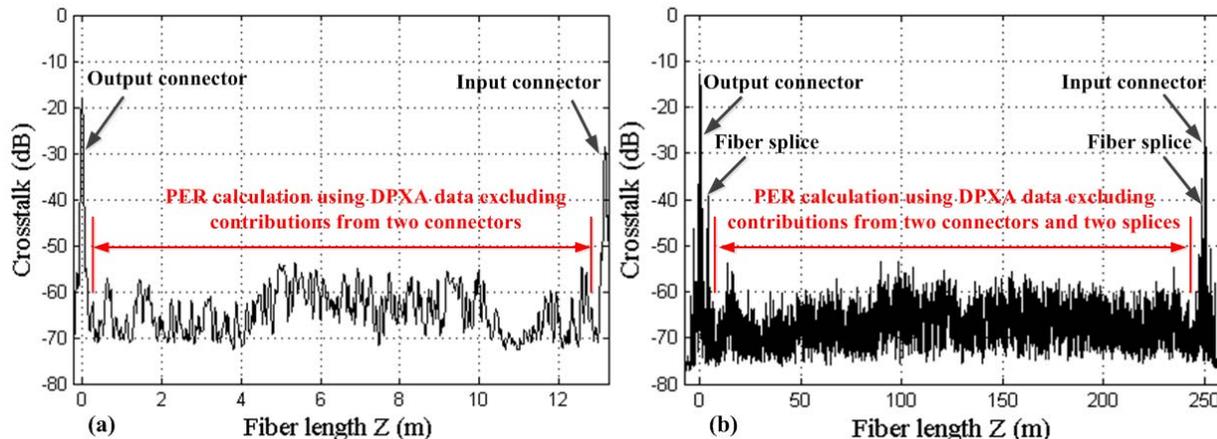
Figure 13 Polarization crosstalk curves of a 13 m jumper with two FC/APC connectors a) and a 250 m PM fiber coil spliced with two FC/APC connectors. PER measurement with a commercial PER meter always includes the contributions of the input connector and two splices, while the PXA-1000 has the ability to identify and eliminate the polarization crosstalk contributions of all connectors and splices in the measurement system. Note that fiber length in the horizontal axis is obtained by dividing the fiber delay line distance ΔZ by the average birefringence obtained using the procedure described in Section 3.2 of the referenced paper.[1]

Start or end points can be set to an active cursor position (place cursor, drag to desired position, and click "Set Fiber START" or "Set Fiber END") or can be set to particular values by selecting the values in the start or end point boxes and typing in new values.

Note: either cursor 1 or cursor 2 can be used to reset the fiber start or end position. If both cursors are on the screen, the active cursor is the one most recently moved.
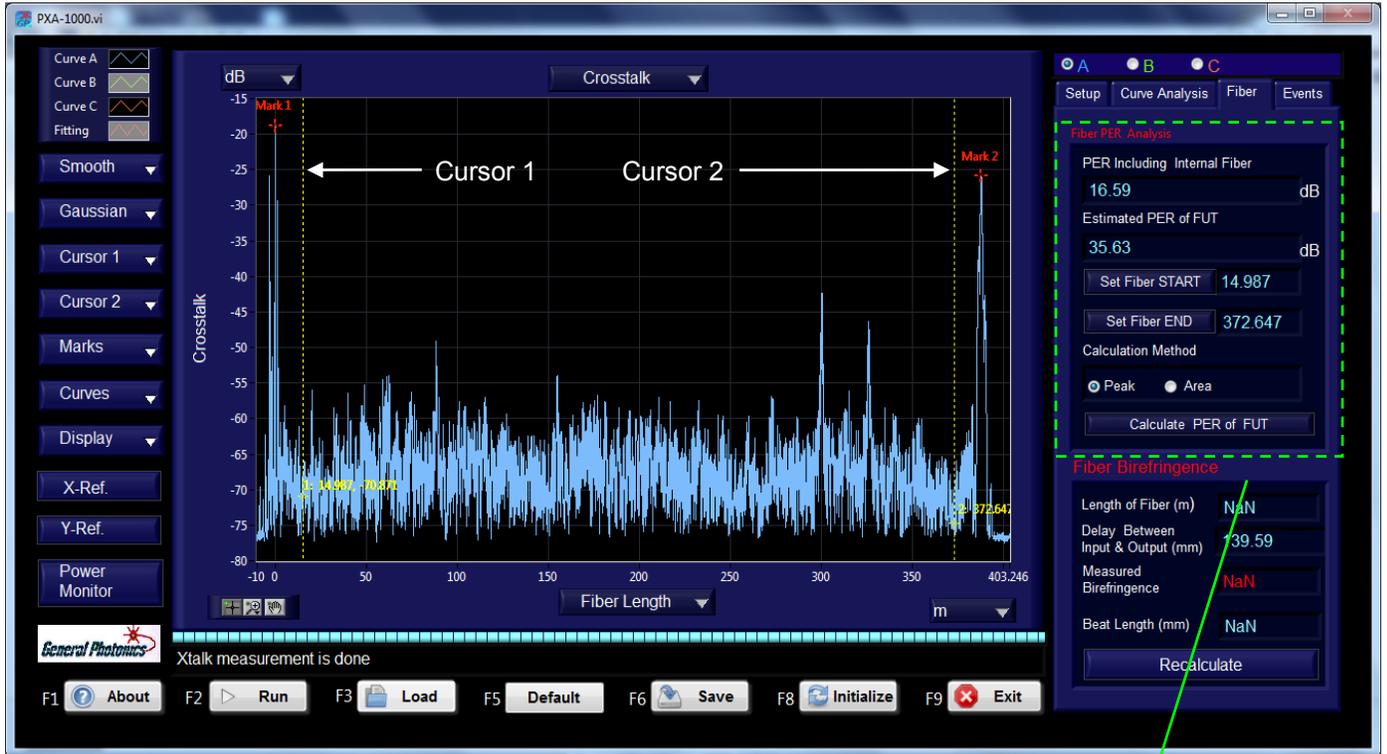
PER Calculation Method

There are two methods available for PER calculation. "Peak" uses all crosstalk peaks within the designated range that meet the user-defined peak threshold criteria (defined on the Events tab on the right side of the screen). This method is generally more suited to a FUT that includes multiple discrete crosstalk peaks (for example, from multiple connector interfaces, splice points, or localized stress points on the fiber).

"Area" uses the integrated area under the curve to calculate the PER. This method is generally better for a single length of fiber or a system with more continuous or quasi-continuous coupling rather than discrete crosstalk events. If this method is selected when the distributed crosstalk measurement is made, the initial PER measurement is made from the input connector to the output connector and will include half of the area under the peaks for the input and output

---

[1] Zhihong Li, X. Steve Yao, Xiaojun Chen, Hongxin Chen, Zhuo Meng, Tiegen Liu, "Complete characterization of polarization-maintaining fibers using a distributed polarization crosstalk analyzer" Preprint paper.

connectors. The user can choose to exclude these peaks by redefining the start and end points for fiber PER measurement.

PER of DUT, recalculated with new start and end points

Start point: Cursor 1 position

End point: Cursor 2 position

Peak threshold setup (from Events tab) used for PER calculation

Click "Calculate PER of FUT" button to recalculate PER after changing setup parameters (fiber range, peak threshold, etc.)

Figure 14 PER measurement of same 388m fiber coil as in Figure 12, with different fiber range

Birefringence Measurement of PM Fiber

Birefringence Measurement Principle
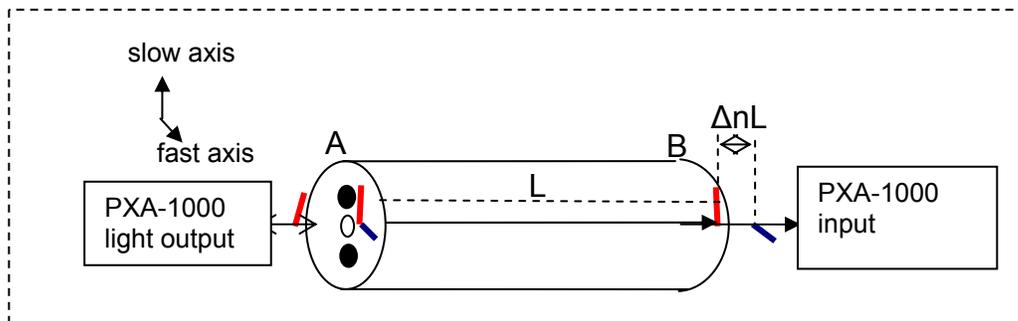
Figure 15 Birefringence measurement principle

As shown in Figure 15, when light enters the PM fiber under test from the PXA-1000 light source output position A, two polarization components aligned to the slow axis and fast axis, respectively, of the fiber are launched because of the misalignment between the PM fiber output of the PXA-1000 light source and the fiber under test. Due to the birefringence of the PM fiber, the two polarization components travel at different group velocities and experience a delay difference at the end (position B) of the fiber under test:

$$Delay_{slow-fast} = n_s L - n_f L = \Delta nL \qquad (4)$$

where L is the length of the fiber under test.

The delay $_{slow-fast}$ generated by the PM fiber under test can be measured by adjusting the delay line in the PXA-1000's interferometer. The birefringence of the PM fiber can therefore be calculated by

$$\Delta n = n_s - n_f = \frac{Delay_{slow-fast}}{L} \qquad (5)$$

It should be noted that the delay measured by the PXA-1000 is related to the group velocity of light in the fiber, not the phase velocity. Therefore, the measured birefringence is group birefringence, not phase birefringence, and the beat length calculated by λ/Δn is consequently only an approximate value.

Setup for Birefringence Measurement

The recommended setup for measuring the birefringence of PM fiber is shown in Figure 16. The slow axis of the PM fiber under test should be aligned to the connector key.
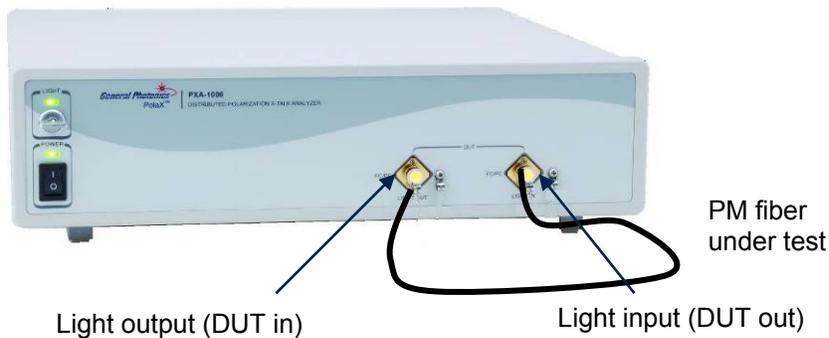
PM fiber under test

Light output (DUT in)   Light input (DUT out)

Figure 16 Setup for birefringence measurement of PM fiber

Birefringence Measurement Procedure (for PM fiber)

1. Precisely measure the length of the PM fiber under test, then connect it to the PXA-1000 as shown in Figure 16.
2. On the measurement information section on the right side of the screen, select the curve (A, B, or C) on which to display measured data.


3. Select "Birefringence" from the Measurement menu on the Setup tab.
4. Set the delay scan range. The start position is fixed at 0mm. Set the "Stop Position" to the desired value. For short fibers (up to several tens of meters), the default value of 50mm should be sufficient. For longer fibers, the delay range should be increased.
5. Check the attenuation setting.

a. Make sure the light safety key is in the "on" position.

b. If the SLD on/off button is red, click the button to turn on the SLD.

c. Click the "Power Monitor" button on the lower left side of the screen.

Check that the optical power is at an appropriate level. Power ~1mW or so usually works well. If the power is too high or too low, change the attenuator setting (range 0 to 30 dB) and check the power again.

6. Set the amplifier gain. "Low gain" is recommended for most applications. "High gain" can be used for fiber systems with very high loss.

7. Click the "Run" button at the bottom of the screen or press the F2 function key on the computer keyboard to start the measurement. During measurement, the message "Measuring birefringence" will be displayed in the message box at the bottom left of the screen.

8. When the measurement is finished, the message "Birefringence measurement is done" is displayed, and the dialog box shown below appears. Enter the length of the PM fiber and click "OK".
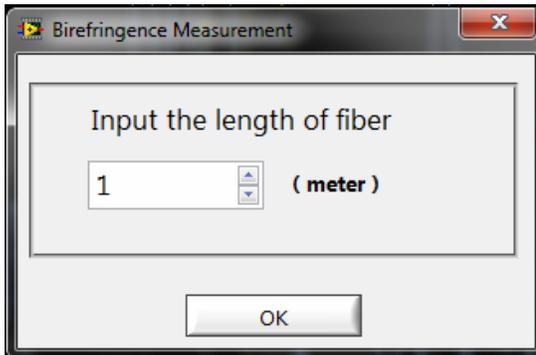
9. After the fiber length is entered, the birefringence will be calculated. Go to the Fiber tab on the right side of the screen to view the data. The "Fiber Birefringence" box shows the fiber length, measured delay between input and output connectors, measured birefringence, and estimated beat length. The user can change the fiber length used for birefringence calculation by selecting the value in the "fiber length" box and typing in a new value, then clicking the "Recalculate" button.

On the plot, Marker 1 and Marker 2 indicate the PXA-1000 input and output connector positions, respectively. The default x-axis for the plot is delay, so the distance between the markers is the measured delay $D = (n_s - n_f)L$, where L is the fiber length.
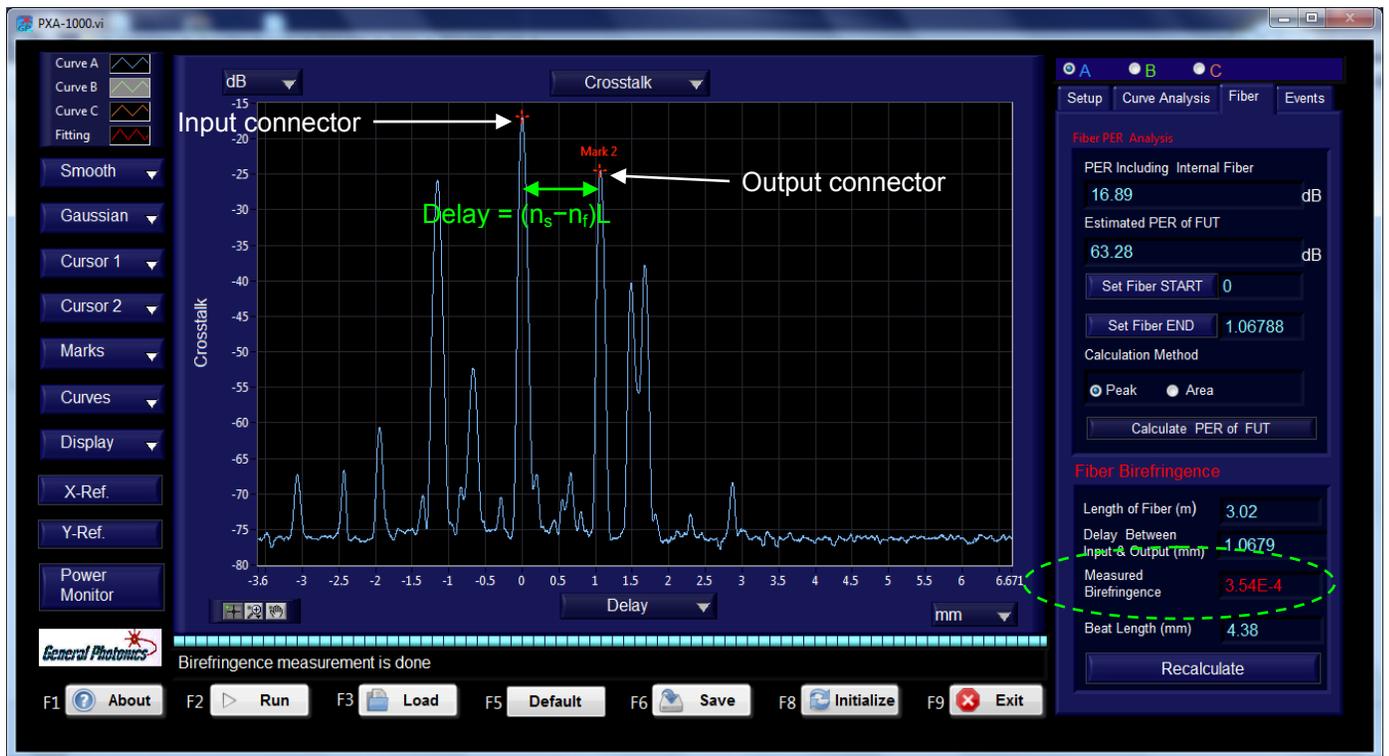
Figure 17 Birefringence measurement of a 3m PM fiber.
Default plot shows crosstalk (dB) vs. delay (mm)

Coherence Length Measurement of a Light Source

Measurement Principle

The interference pattern generated by the PXA-1000 is shown in Figure 18. It has the form of an amplitude modulation signal. The modulation frequency is a constant determined by the center wavelength of the light source and the sweep speed of the delay line. The amplitude of the envelope represents the x-talk magnitude, and its full width at half maximum (FWHM) is related to the linewidth of the light source.

$$FWHM = \frac{2\ln 2}{\pi}\frac{\lambda_0^2}{\Delta\lambda} \approx 0.44\frac{\lambda_0^2}{\Delta\lambda} \qquad (6)$$

where λ_0 is the center wavelength of the input light source and $\Delta\lambda$ is the FWHM of the power spectrum of the light source. The coherence length of the light source can be calculated by

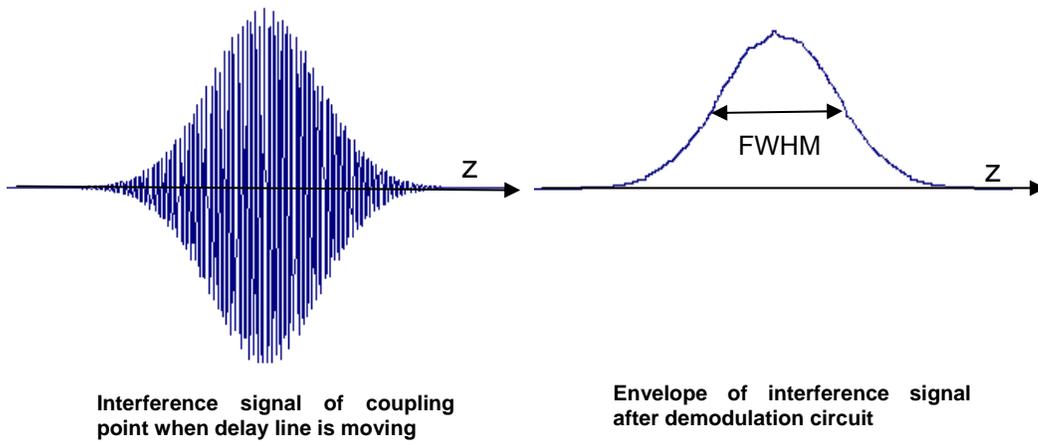$$l_c = FWHM * \frac{\pi}{2\ln 2} \approx 2.266 * FWHM \qquad (7)$$

Interference signal of coupling point when delay line is moving

Envelope of interference signal after demodulation circuit

Figure 18 Interference signal and its envelope

Setup for Coherence Length Measurement

The recommended setup for coherence length measurement of a light source is shown in Figure 19. If the degree of polarization (DOP) of the light source under test is very low, the interference signal can be too small to be detected by the PXA-1000. It is therefore recommended that a polarizer be placed between the light source and the PXA-1000 input. A PM pigtailed polarizer is preferred because SM pigtail fiber may result in coupling between different interference peaks and reduce the measurement accuracy.
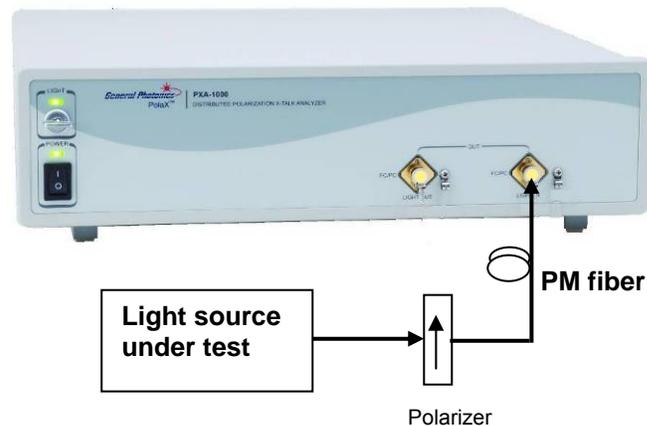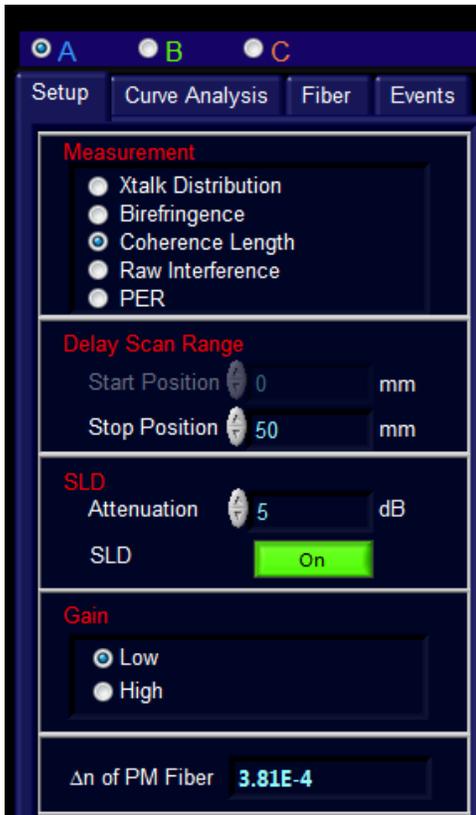

Figure 19 Setup for coherence length measurement

Coherence Length Measurement Procedure

1. Connect light source under test to a PM pigtailed polarizer, then connect the polarizer's PM output to the PXA-1000's input connector.

2. On the measurement information section on the right side of the screen, select the curve (A, B, or C) on which to display measured data.

3. Select "Coherence Length" from the Measurement menu on the Setup tab.

4. The coherence length measurement uses the default delay range settings.

5. Check the light source power level.

   a. Click the "Power Monitor" button on the lower left side of the screen.
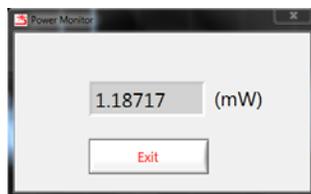
   Check that the optical power is at an appropriate level. Power ~1mW or so usually works well. If the power is too high or too low, change the power level of the light source (if possible) and check the power again.

6. The coherence length measurement uses the default gain setting.

7. Click the "Run" button at the bottom of the screen or press the F2 function key on the computer keyboard to start the measurement. During measurement, the message "Coherence

length is being measured" will be displayed in the message box at the bottom left of the screen, and the status of the measurement will be indicated by the progress bar.

8. When the measurement is finished, the message "Coherence length measurement is done" is displayed in the message box at the bottom left of the screen.
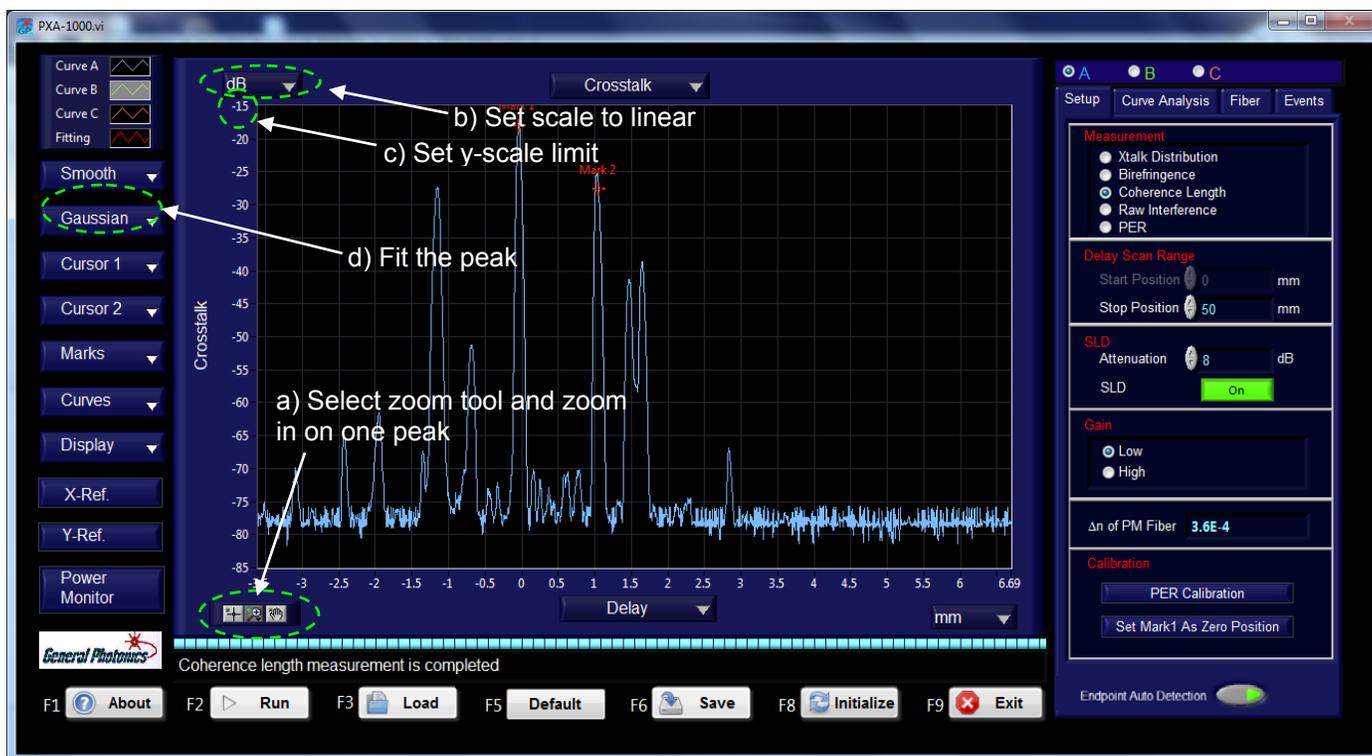
Figure 20 Initial data display after coherence length measurement
Plot shows crosstalk (dB) vs. delay (mm).

9. The plot will show the crosstalk (dB) vs. delay (mm).

    a. Select and zoom in on one peak from the measured curve (see section 3.5 for details on zooming the graph). For best results, choose a peak with a good shape that does not overlap with other peaks.

    b. Set the y-scale to linear using the y-scale pull-down menu at the top left of the plot.

    c. If necessary, change the y-scale limits by selecting the value of the upper y-scale limit and typing in a new value, then pressing ENTER.

    d. From the "Gaussian" pull-down menu on the left of the screen, select the Gaussian fitting option for the active curve (curve A in the example above). The calculated coherence length will be displayed in the message box at the bottom of the screen. The corresponding Gaussian fitting curve is displayed as a red line on the plot and the fitting parameters are displayed in the Curve Analysis tab on the right of the screen.
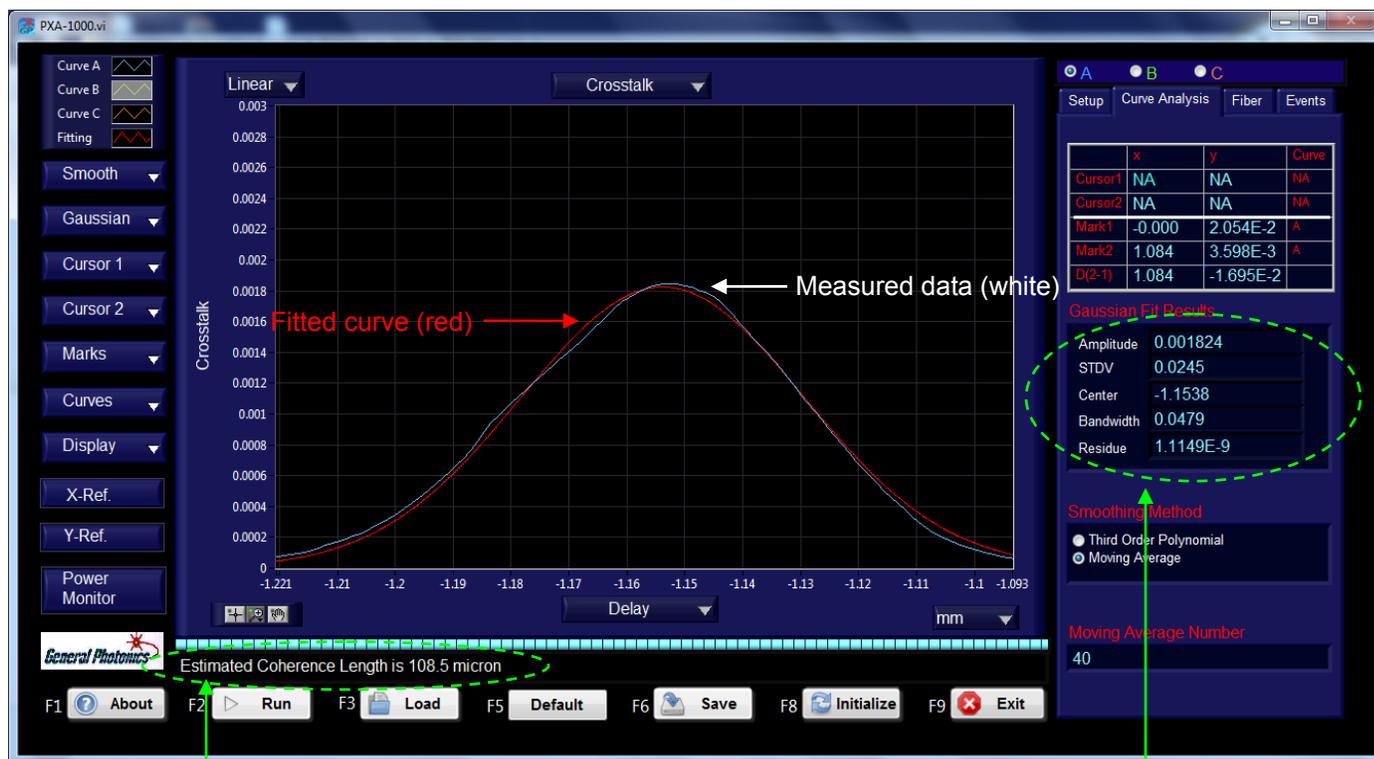
Estimated coherence length   Gaussian fitting parameters

Figure 21 Coherence length measurement results after curve fitting

Polarization Extinction Ratio (PER) Measurement (System)

In addition to the PER measurement from the crosstalk data, the PXA-1000 has a quick system PER measurement function that can be used to check a measurement setup before doing crosstalk characterization of a device or fiber under test.

In general, this function gives the same PER value as the "PER including internal fiber" calculated from the distributed polarization n crosstalk measurement.

Measurement Principle

For the quick PER measurement, the PXA-1000 uses an optical switch to block or transmit slow axis-aligned light. Assuming that the measured light powers are P_{total} and P_{fast}, respectively, when the slow axis is unblocked or blocked, the PER of the system including the PM fiber under test can be calculated by

$$PER = -10 \left| \log(\frac{P_{fast}}{P_{total} - P_{fast}}) \right| \tag{8}$$

It should be noted that the measured PER includes the x-talk generated by the misalignment at both the input and output connectors, so the measured PER is not equal to the PER of the PM fiber under test.
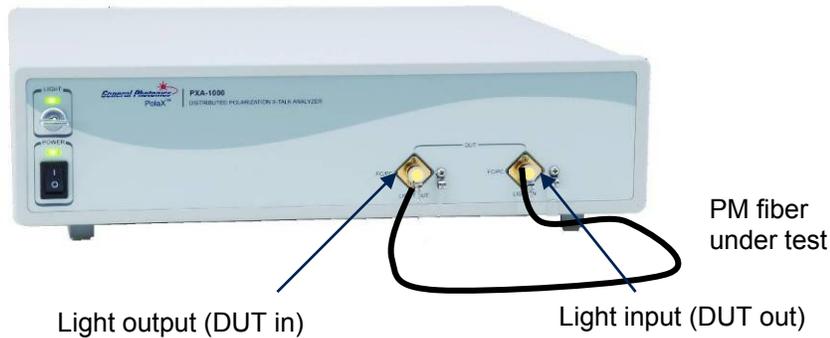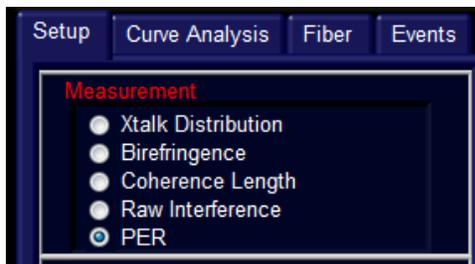
Setup for PER Measurement

Light output (DUT in)   Light input (DUT out)   PM fiber under test

Figure 22 Setup for PER measurement

PER Measurement Procedure

1. Connect DUT as shown in Figure 22.
2. Select "PER" from the Measurement menu on the Setup tab.

3. Click the "Run" button at the bottom of the screen or press the F2 function key on the computer keyboard to start the measurement. During measurement, the message "PER is being measured" will be displayed in the message box at the bottom left of the screen.
4. When the measurement is finished, the measured PER will be displayed in the message box at the bottom left of the screen.

Measured PER is 16.82dB
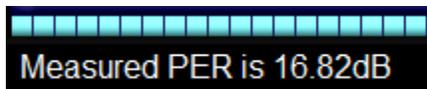
3.5 Advanced Data Analysis

Graph Operations

Using the graph operation functions shown in Figure 23, the user can zoom in and out in the data plot, use cursors to read the coordinates of measured points, place two markers on the curves and measure the coordinate differences between the two markers.
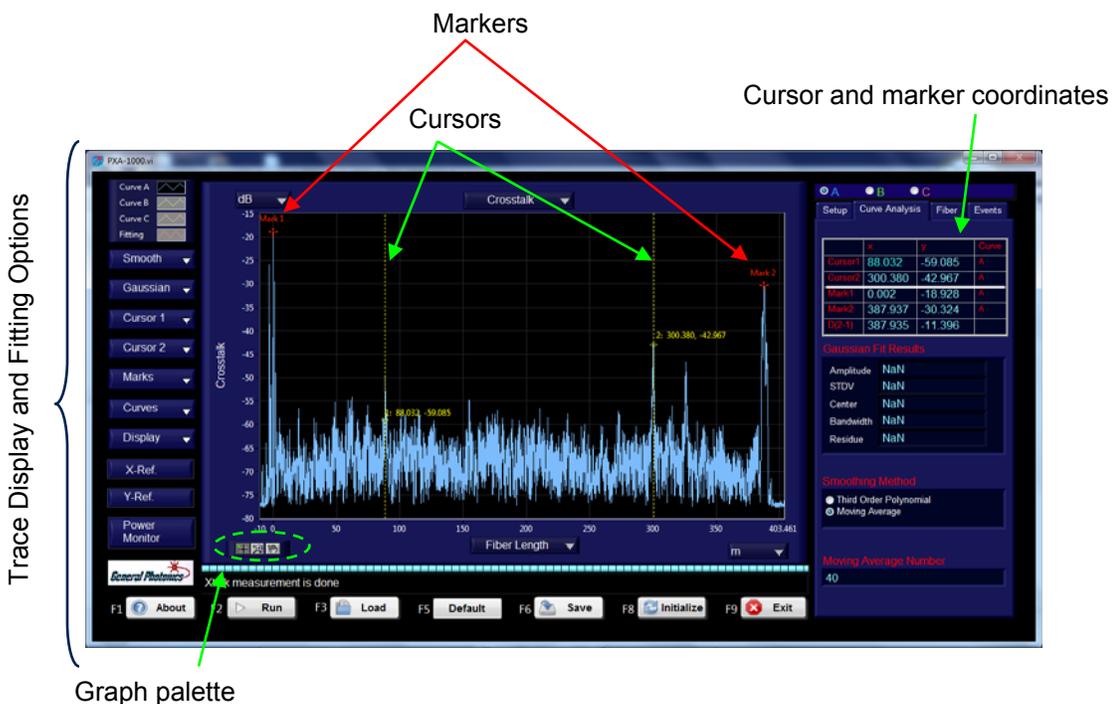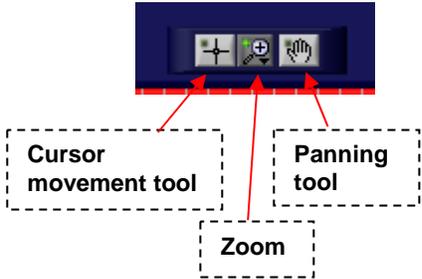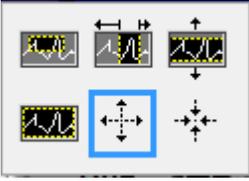

Figure 23 Graph operations interface

Graph Palette

<table>
<tr>
<td>

Cursor movement tool

Panning tool

Zoom
</td>
<td>
The graph palette can be used to move cursors and to zoom and pan the graph display. Click the corresponding button in the graph palette to enable cursor movement, display zooming, or display panning. Each button has a status indicator in its upper left corner which turns green when that option is enabled.

- **Cursor Movement Tool** (graph only)—Allows cursor or marker to be dragged on the display.
- **Zoom**—Zooms in and out of the display.
- **Panning Tool**—Picks up the plot and moves it around on the display.
</td>
</tr>
<tr>
<td>

</td>
<td>
The Zoom tool (middle button on the graph palette) allows the user to zoom in or out on the graph. When the Zoom tool is clicked, a pop-up menu of zoom options appears. This menu is shown below.

</td>
</tr>
<tr>
<td></td>
<td>Zoom by selection rectangle. Only the area in the selected rectangle is displayed.</td>
</tr>
<tr>
<td></td>
<td>Zoom by rectangle; with zooming restricted to x data, (the y scale remains unchanged).</td>
</tr>
<tr>
<td></td>
<td>Zoom by rectangle; with zooming restricted to y data, (the x scale remains unchanged).</td>
</tr>
<tr>
<td></td>
<td>Undo last zoom. Resets the graph to its previous setting.</td>
</tr>
<tr>
<td></td>
<td>Zoom in about a point. If you hold down the mouse on a specific point, the graph continuously zooms in until you release the mouse button.</td>
</tr>
<tr>
<td></td>
<td>Zoom out about a point. If you hold down the mouse on a specific point, the graph continuously zooms out until you release the mouse button.</td>
</tr>
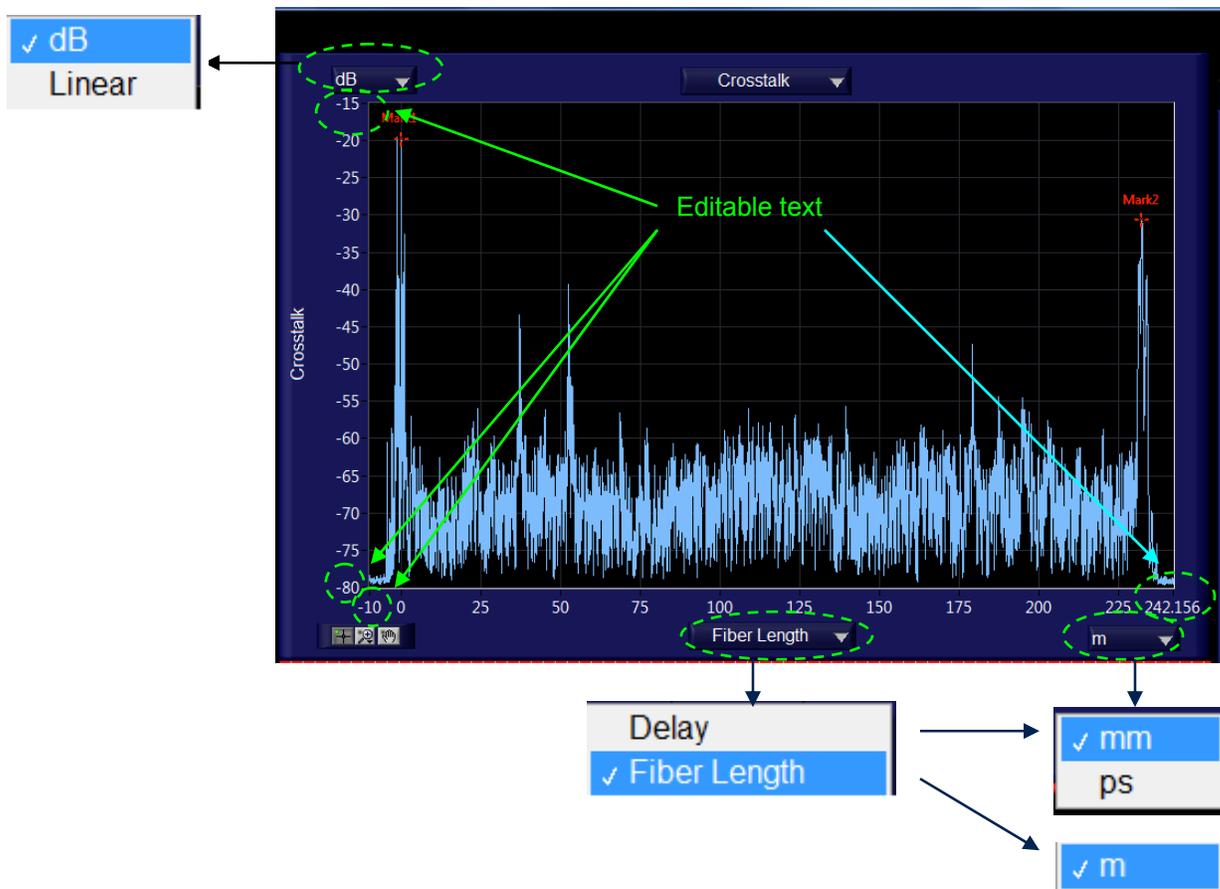</table>

Graph Scale Options

Figure 24 Graph scale options

The y axis parameter is always crosstalk or interference amplitude. The scale of the plot can be log scale (dB) or linear. The default is log scale, because smaller peaks may not be visible in linear scale; however, linear scale is useful for viewing some data and for curve fitting.

The x axis parameter can be the position along the fiber (fiber length) or the delay. The default parameter depends on the measurement being made. If the x parameter is fiber length, it will be expressed in meters. If the x-parameter is delay, it can be displayed in terms of length (mm) or time (ps).

Both the x and y scale limits can be edited by selecting the text and typing in new values. This can be a more precise way of rescaling the plot than using the zoom options.

Cursor Options

Curve A is selected

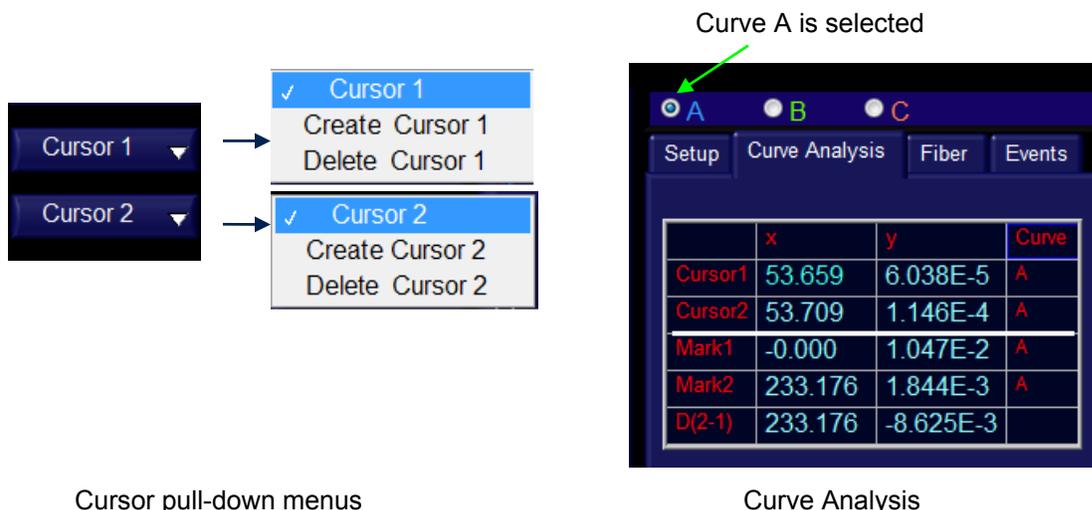Cursor pull-down menus   Curve Analysis

Figure 25 Cursor control

The cursor pull-down menus on the left side of the screen allow the user to add or delete cursors. Selecting "Create Cursor x" from a cursor menu causes the corresponding cursor to appear on the plot. With the cursor-movement tool selected, the cursor can be moved to different positions on a measured curve using the mouse. The coordinates (x, y) of the current cursor position will be displayed next to the cursor. The (x, y) coordinate display can also be moved with the mouse. The cursor coordinates are also shown in the table on the Curve Analysis tab on the right side of the screen.
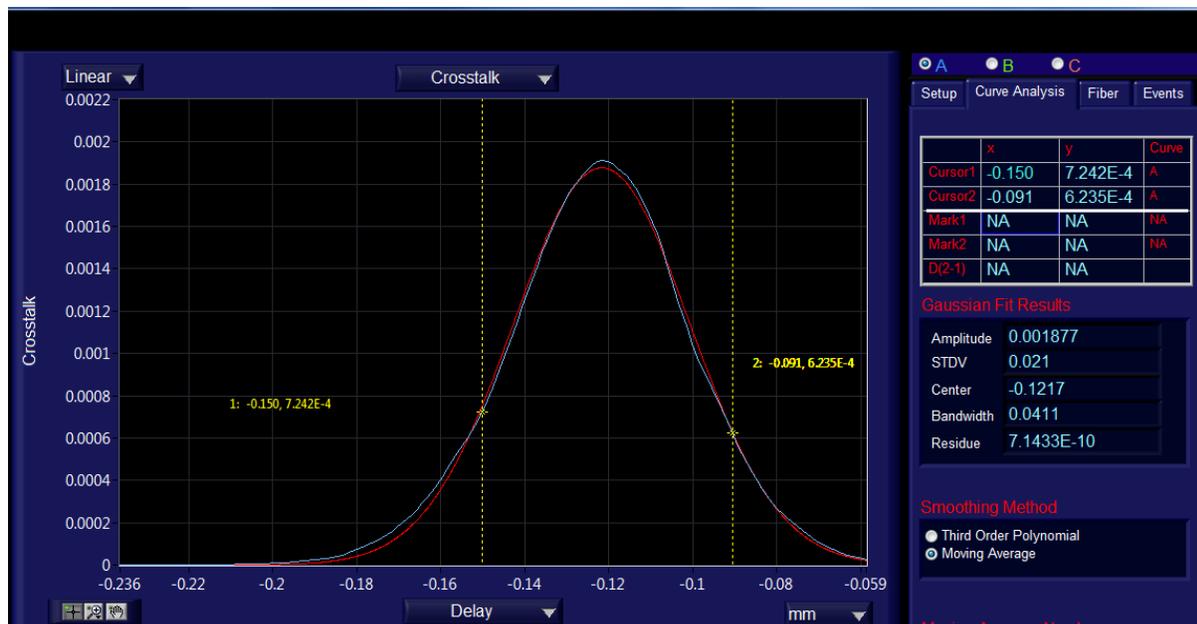
If there is data for more than one curve on-screen, the user can select which curve's coordinates will be displayed for a particular cursor position. In the example shown in Figure 25, curve A is selected, so the cursor coordinates displayed on the plot and in the curve analysis table are the coordinates on curve A that correspond to the current positions of cursor 1 and cursor 2. If the user selects curve B, the coordinates displayed will be those that correspond to the cursor positions on curve B. This is useful for comparing peak heights or widths on different curves.
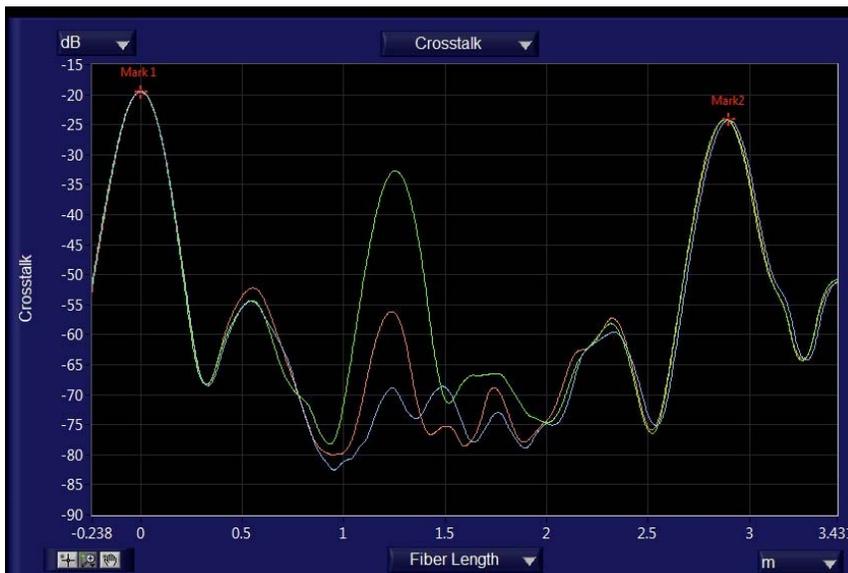
For example, in the plot above, curves A, B, and C are the measured crosstalk in the same test fiber with different amounts of pressure applied at a particular point. The effects can be compared by placing a cursor at the peak in the center of the plot and switching the curve selection between A, B, and C.

Cursors can also be used to update the fiber range to be used for PER calculation and peak detection. After a crosstalk measurement is made, the PER will be calculated for the FUT between Marker 1 and Marker 2 (PXA-1000 input and output connectors, respectively). This is also the range used for peak detection for the Events table. The user can select a more limited range to be used for the PER measurement and peak detection by dragging a cursor to the desired position on the plot, then clicking on "Set Fiber START" or "Set Fiber END" on the Fiber tab on the right side of the screen. Then, click "Calculate PER of FUT" to recalculate the PER over the new range. The Events table will also update to cover the new range.
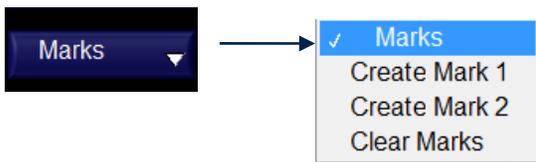
Marker Options

The marker pull-down menu on the left side of the screen allows the user to add or delete markers. Selecting "Create Mark x" from the menu adds (or moves, if the marker is already on-screen) the specified marker at the current active cursor position. If both cursor 1 and cursor 2 are on-screen, the active cursor position is the position on the selected curve of the cursor that was most recently moved. The coordinates of the markers are displayed in the table at the top right of the screen. The coordinate differences between the two markers are automatically calculated and displayed in the bottom line of the table on the Curve Analysis tab on the right side of the screen.

Unlike the cursors, the marker coordinates do not change with curve selection. In fact, the two markers can be placed on different curves. This is also useful for calculating differences in position or amplitude of crosstalk events on different curves.

Curve Smoothing

In most cases, curve smoothing is not necessary, but occasionally, it can be useful to help enhance hard-to-resolve crosstalk features.

The bottom section of the Setup tab allows the user to select the smoothing method to be used, and for the moving average method, to specify the moving average number. Smoothing can be applied to or removed from one or more curves from the pull-down menu at the left of the screen.
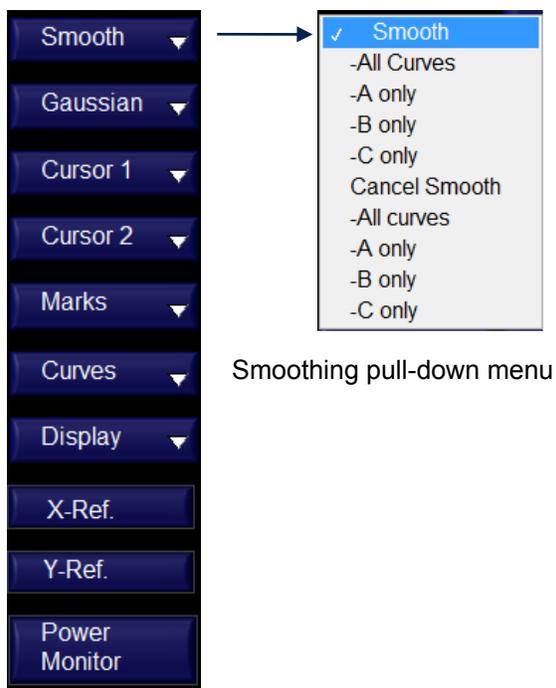
Smoothing pull-down menu

Smoothing method selection on Setup tab
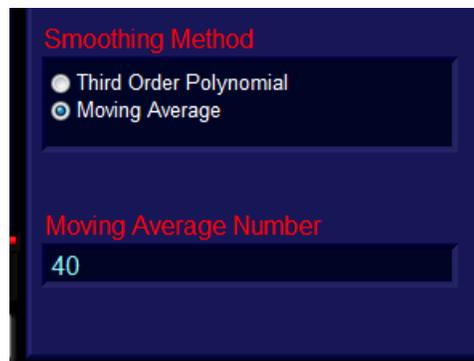
The third-order polynomial method is useful to resolve detailed features of peaks. It fits the peaks with no changes to peak widths.

The moving average method can change the width and amplitude of crosstalk peaks, so it is not recommended for detailed analysis of individual peaks. However, it is useful for separating crosstalk features from noise when the noise is too high.

Gaussian Fit

The Gaussian Fit function was described in the Coherence Length Measurement section. Besides its use for light source coherence length measurement, it is also useful for characterizing individual crosstalk peaks. It can be used to determine the center and width of a particular peak.

Data Interpretation

Figure 26 shows a typical x-talk measurement curve. Marker 1 and Marker 2 show the x-talk peaks generated by the input and output connectors, respectively, of the PXA-1000. The curve between the two markers represents the x-talk distribution of the PM fiber under test. There are also some small peaks outside the region bounded by the two markers. These are caused by x-talk reference points built into the system for x-talk calibration and from the misalignment between the polarizer chip and the pigtailed PM fiber.
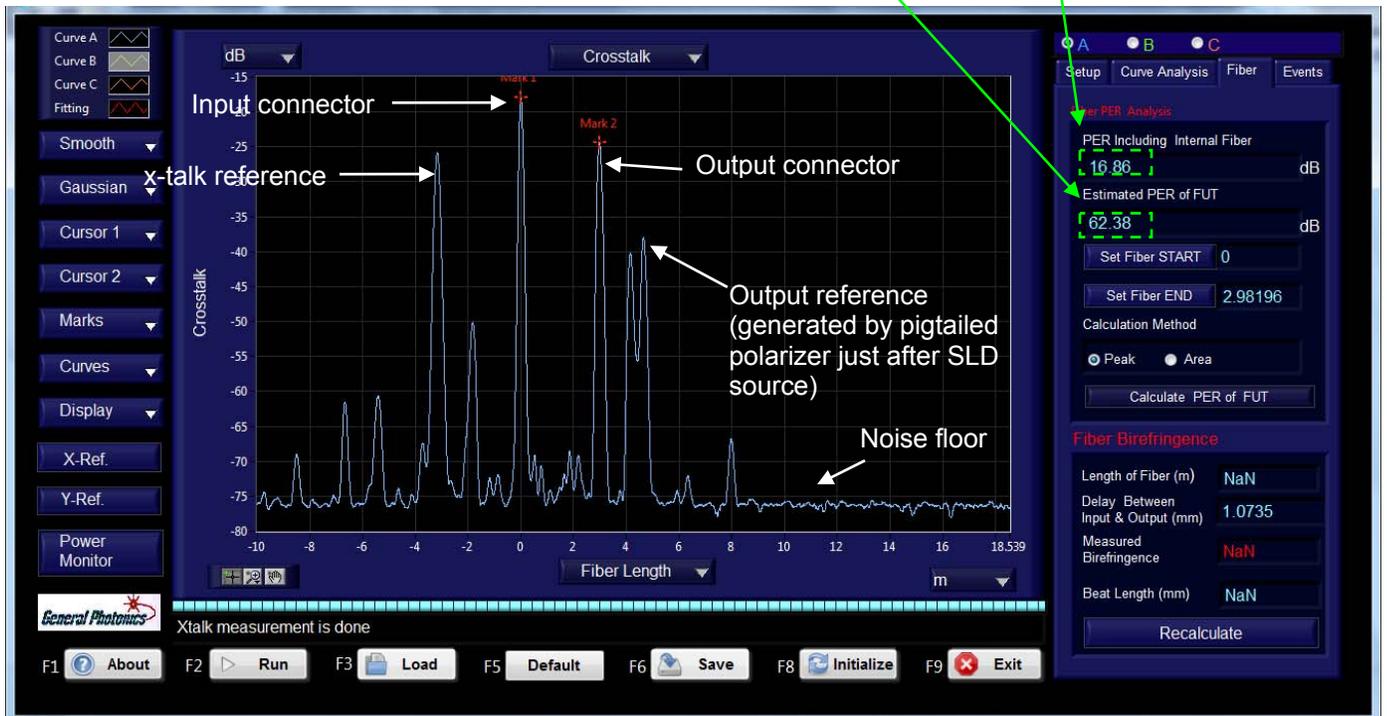

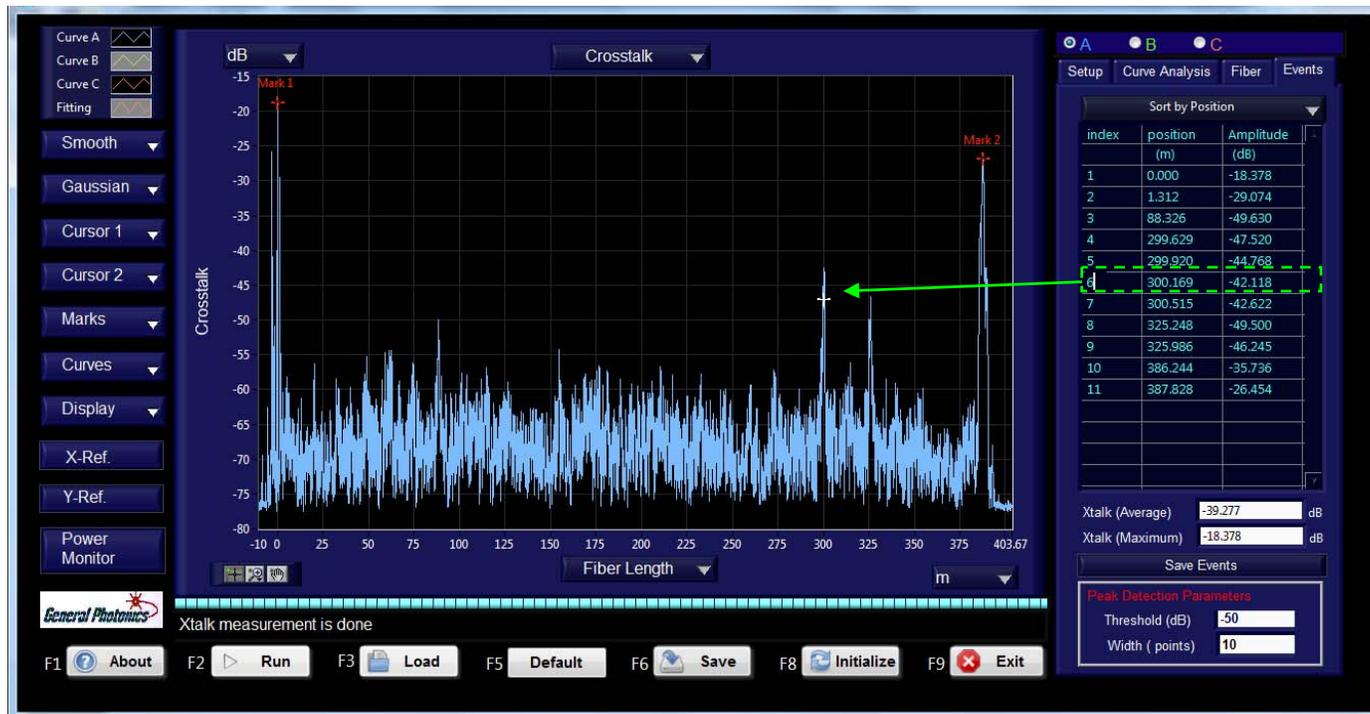**Figure 26 Measurement example 1: 3m PM patchcord**

Figure 27 Measurement example 2: PM fiber coil

Figure 27 shows the results of a distributed polarization crosstalk measurement of a fiber coil. Marker 1 and Marker 2 show the positions of the input and output connectors of the coil. Between them are several smaller crosstalk peaks at semi-regular intervals, possibly due to winding defects.

The table in the Events tab on the right of the screen summarizes the crosstalk peaks within the analysis area defined by Markers 1 and 2 that meet the threshold conditions. The "Sort by" pull-down menu at the top of the table allows the user to sort peaks by position or amplitude. In this example, the table lists the amplitudes and locations of all crosstalk peaks >-50 dB. Clicking on the index number of any peak in the table causes a cross-shaped marker to appear at that peak (the marker is at peak 6 in this example).

The average and maximum crosstalk, calculated from the peaks listed in the table, are shown below the table.

The threshold level can be changed by typing in the text box. After changing the threshold, press ENTER or click outside the text box to update the table to include peaks above the new threshold.

The peak analysis region can be redefined by moving Markers 1 and 2 on the curve to be analyzed. The table will update automatically.

The information in the table (index, position, and amplitude of crosstalk peaks) can be saved to a file by clicking on the "Save Events" button. The user will be prompted for a filename and location to which to save the data. The saved data file will have file extension ".pks" to avoid

confusion with other types of data files, but it can be opened using applications such as Notepad or Excel.
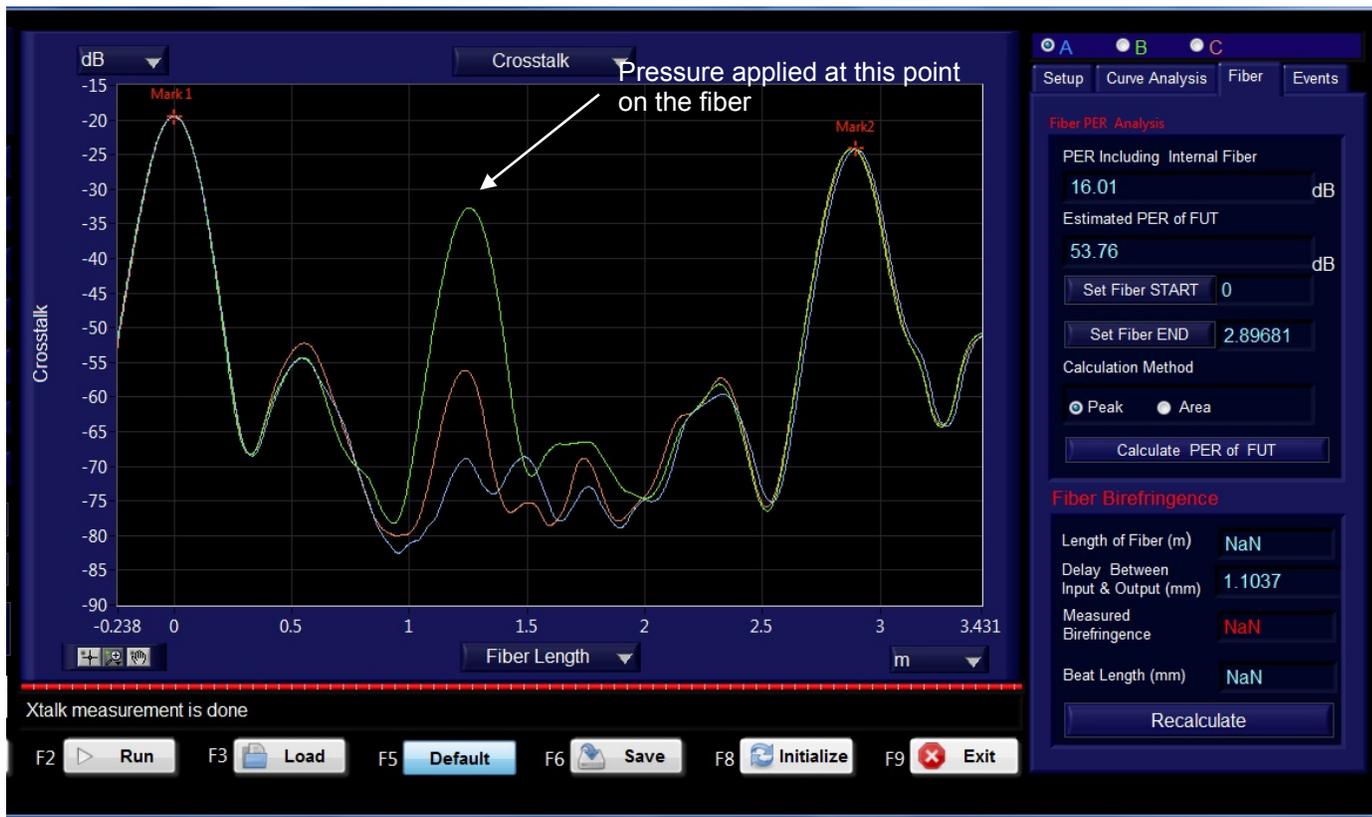
Figure 28 Measurement example 3: PM patchcord with 900μm loose tube, with different amounts of pressure applied over a 1cm section of fiber.
>   **Curve A (blue): no pressure applied.**
>   **Curve B (green): 1kg applied**
>   **Curve C (red): 500g applied**

Figure 28 illustrates how the PXA-1000 can detect changes in crosstalk in a fiber due to environmental factors. It shows 3 consecutive crosstalk measurements of a PM patchcord with 900μm jacket, with different weights placed over a particular 1cm section of the fiber. Curve A (blue) is the baseline measurement with no weight applied. Curve C (red) shows the same fiber with a 500g weight placed on it. The weight causes crosstalk of about −55 dB at the point where it was applied, but the rest of the curve is relatively unchanged. Curve B (green) shows the same fiber with a 1kg weight placed on it at the same point. The crosstalk at that point increases to almost −35 dB.

Note that many factors can affect the amount of crosstalk caused by pressure on a fiber, including the axis along which the pressure is applied (for example, pressure applied along the slow or fast axis of a fiber will have a different effect than the same pressure applied along an axis 45° between the fiber axes), how much the fiber is insulated from the pressure (jacketing, etc.), and whether the pressure is applied to a discrete point or distributed over a longer length of fiber.

Saving Data

Data from any completed measurement can be saved to a file using the "Save" button (F6). The user will be prompted to specify which curve is to be saved:

Select the desired curve and click "OK".

The user will be prompted for a filename and location to which to save the data. The saved data file will have file extension ".pxa" to avoid confusion with other types of data files, but it can be opened using applications such as Notepad or Excel.
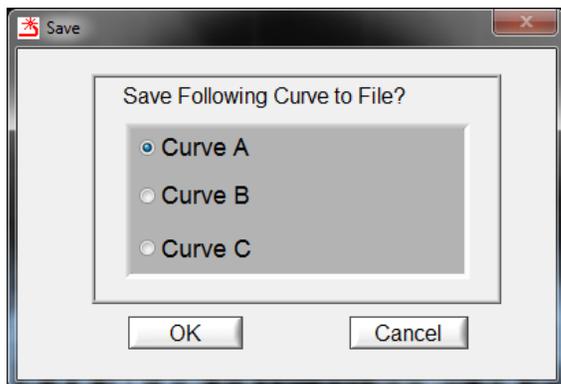
Saved curve data (with file extension ".pxa") can be loaded for display, further analysis, or comparison with other curves by using the "Load" button (F3). The software can be used for display and analysis of saved data without the PXA-1000 connected to the computer.

3.6 PER and Position Reference Calibrations (Optional Feature)

To ensure maximum accuracy and repeatability, General Photonics recommends periodic factory calibration of the PXA-1000. However, an option is available for users to quickly re-establish the PER measurement and input connector position references.

Note: These user calibrations write to the system file, so they must be done carefully.

X Position Reference

X-talk and position references in the PXA-1000

In order to calibrate the x-talk in the PXA-1000, a standard coupling point is built into the optical path just after the input connector. Its position and coupling ratio (x-talk) have been factory calibrated and stored in the PXA-1000 system files. After every x-talk measurement, the PolaX control software automatically locates the reference point position and adjusts the y-position of the measured trace such that the x-talk at the reference point matches the calibrated value. Then, the software automatically locates the input connector and sets its x-axis position to zero. Therefore, the x-position of a coupling point indicates its distance from the input connector of the PXA-1000.

Re-establishing the X=0 position reference

Under normal circumstances, the PXA-1000 places Marker 1 at the input connector position and references the x-axis of the plot such that the input connector position corresponds to X = 0.

If the x-reference becomes corrupted such that the PXA-1000 consistently misidentifies the position of the input connector, the user can re-establish the x-reference using the "Set Mark1 as Zero Position" function in the "Calibration" block at the bottom of the Setup tab on the right side of the screen. The procedure is as follows:

1. Connect a good PM patchcord, for which the input connector peak can be easily identified, as the DUT.
2. Follow the standard procedure for a distributed polarization crosstalk measurement.

3. Identify the peak corresponding to the input connector and place Marker 1 on that peak.
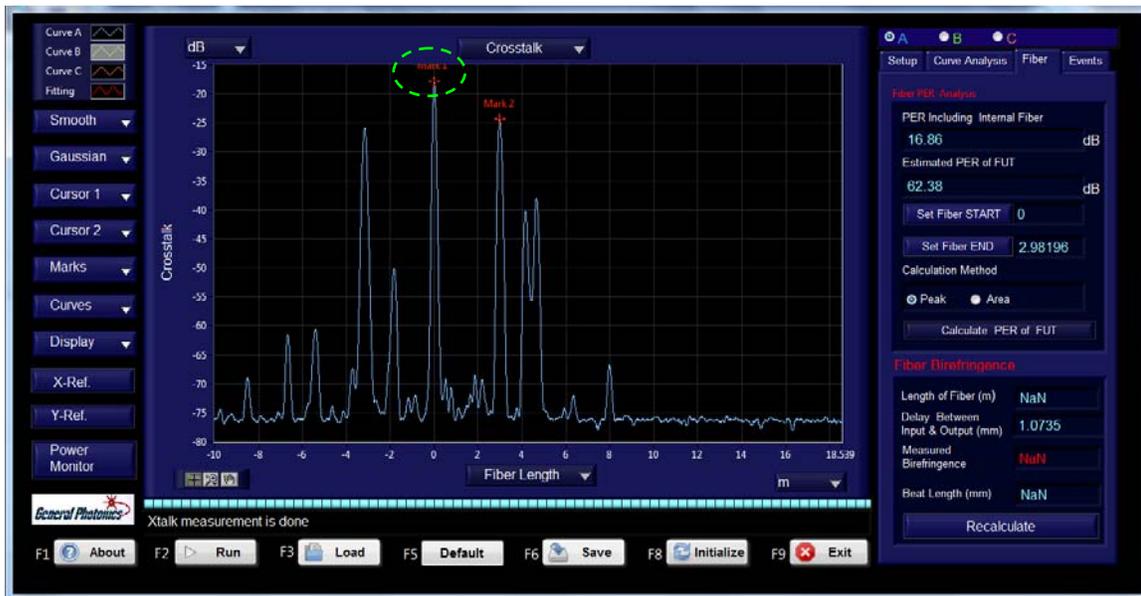
4. Click "Set Mark1 as Zero Position" at the bottom of the Setup tab.
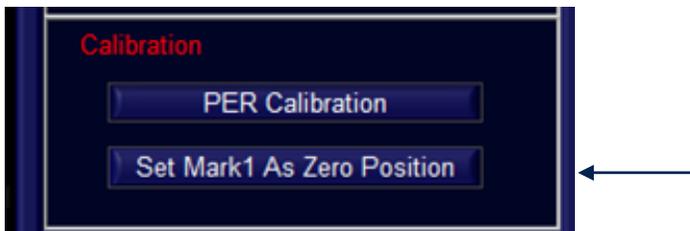
5. You will be prompted for a password.

6. Enter the password and click "OK". The Marker 1 position will be set as the system x-reference.

PER Reference

General Photonics can provide an optional 0-dB PER calibration artifact for users to verify and, if necessary, re-establish the PXA-1000's PER reference.

The procedures are as follows:

PER Verification

1. Connect the 0-dB PER artifact as the DUT. Make sure connectors are clean, connections are good, and fibers are stationary.
2. Run the PER measurement. If the measured system PER is ≤0.2 dB, the PXA-1000 does not require PER calibration.

Re-establish the PER reference

1. Click "PER Calibration" at the bottom of the Setup tab.

2. You will be prompted for a password.

3. Enter the password and click "OK". You will be prompted to connect the 0-dB PER artifact.
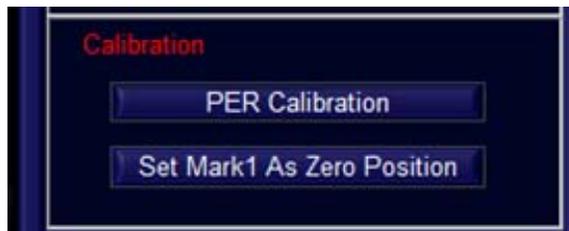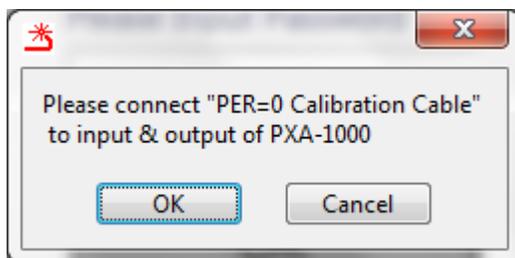

4. Connect the 0-dB PER artifact as the DUT. Make sure connectors are clean, connections are good, and fibers are stationary. Click "OK".
5. The PXA-1000 will perform a measurement and recalibrate its PER reference. When it is finished, the progress bar and message box at the lower left of the screen will indicate that the process is finished.

3.7 Troubleshooting

The following table lists some common issues and probable causes.

Symptom	Probable Cause
Program shows "PXA-1000 not connected"	Check the USB connection. Reconnect the cable and wait for the "device detected" message before running the control program. If necessary, restart the PXA-1000 and the control computer before reconnecting.
Plot shows inaccurate fiber length or peaks not at expected positions.	1. Check Δn of fiber. If the value used is not the actual Δn of the fiber, the displayed fiber length will be incorrect. 2. Check that the DUT connector keys are aligned to the slow axis of the FUT/DUT.
Noise floor of plot is too high.	If the DUT output power is too low, the noise floor of the plot may increase. Generally, it should be 10 dB below the lowest crosstalk peaks to be measured. Use the "Power Monitor" function to check the DUT output power, and, if necessary, adjust the attenuation.
Program shows "Detector saturated" message in the message box.	DUT output power is too high. Use the "Power Monitor" function to check the DUT output power, and increase the attenuation as needed.
Program shows estimated PER of FUT as "Inf"	There are not enough detected peaks to calculate a PER. Either change the PER calculation method to "Area" or change the threshold level used for peak detection for "Peak" method PER calculation (for example, from −50 to −60 dB).
Markers incorrectly placed after measurement of a long coil or a waveguide.	Check that the delay range for the MDL is set correctly. If the measurement curve does not include a peak at the right corresponding to the output connector, the MDL scan range may be too short to measure the entire DUT, and the PXA-1000 software will not be able to place Marker 2 correctly. Check the required scan length for the DUT and adjust the MDL stop position accordingly.

Section 4.0   Specifications

Optical

Operating wavelength	1310 or 1550nm
Polarization X-talk measurement sensitivity	<-75 dB (for DUT output power >5dBm) -80dB typical
Polarization X-talk measurement noise floor[1]	-95 dB
Polarization X-talk resolution	0.25 dB
Polarization X-talk repeatability[2]	±0.5 dB
Polarization X-talk accuracy[3]	±0.5 dB
Measurement or sensing range (Assuming PM fiber Δn of 5×10^{-4})	1.3 km or 2.6 km standard 3.1 km available
Measurement speed[4]	8 s/ 100 m (with fiber $\Delta n = 5 \times 10^{-4}$)
Spatial resolution[5]	6 cm (assuming no fiber dispersion, birefringence $\Delta n=5 \times 10^{-4}$)
PER measurement range	> 30 dB
Spatial accuracy[6]	±20 cm (with fiber $\Delta n =5 \times 10^{-4}$)
Waveguide polarization dependent attenuation	Up to 75dB (for DUT power output >5dBm)
$LiNbO_3$ waveguide spatial resolution	0.75 mm
SLD Power	>7 dBm
SLD bandwidth	> 30 nm
SLD PER	>20 dB

Electrical/Communication

Power Supply	100-240VAC, 50-60 Hz
Communication Interfaces	USB 2.0
Display	Laptop control computer (supplied)
Software	PolaX polarization X-talk measurement program: Identifies polarization X-talk magnitude/location Zoom-in function X-talk related calculations

Physical and Environmental

Dimensions	2U ¾ 19" rack mount size 14" (L) × 14" (W) × 3.5" (H)
Fiber Type	PM fiber
Fiber Input/Output Connectors	FC/PC narrow key standard
Weight	13.5 lb
Operation temperature	10 to 50°C
Storage Temperature	−20 to 60°C

Notes:
Specifications listed in table apply for standard 1550 or 1310nm operation at 23±5°C.

1. Defined as the system noise displayed on the polarization X-talk curve if the input power is disconnected during a measurement for which the DUT output power is >5dBm.
2. Defined as the standard deviation of twenty successive measurements of the amplitude of an X-talk peak between −15 and −40 dB.
3. At 23 ± 5°C. Guaranteed by design and calibration in manufacturing process.
4. Average speed for full-length scan.
5. Defined as the minimum resolvable distance between two polarization X-talk points of equal amplitude, based on Sparrow Criterion (two peaks of equal height overlap at 3dB point, resulting in a flat-top curve) and measured when the peaks are between −15 and −40 dB.
6. Defined as the standard deviation of twenty successive measurements of the distance of an X-talk peak of height between −15 and −40 dB from the X-talk peak induced by the input connector (zero position).

Appendices

Appendix 1.0 Comparison of PXA-1000 to Traditional White Light Interferometer

It is well known that only the two eigenpolarization modes HE_{11}^s and HE_{11}^f can propagate in polarization maintaining fiber. HE_{11}^s is polarized along the slow axis and HE_{11}^f along the fast axis of the fiber. After traveling through a piece of PM fiber, an input wave packet is split into a series of small wave packets separated in time because of the birefringence and mode coupling of the PM fiber. This section describes a simple model to simulate the wave packets aligned to the slow and fast axes of the fiber. Assume that the light input to the PM fiber has no fast axis component and that there are three coupling points x_1, x_2 and x_3 along the fiber (see Figure 29). It should be emphasized that light is coupled not only from the slow axis to the fast axis, but also from the fast axis to the slow axis at each coupling point; therefore, the resulting wave packet series will include wave packets caused by multiple couplings.
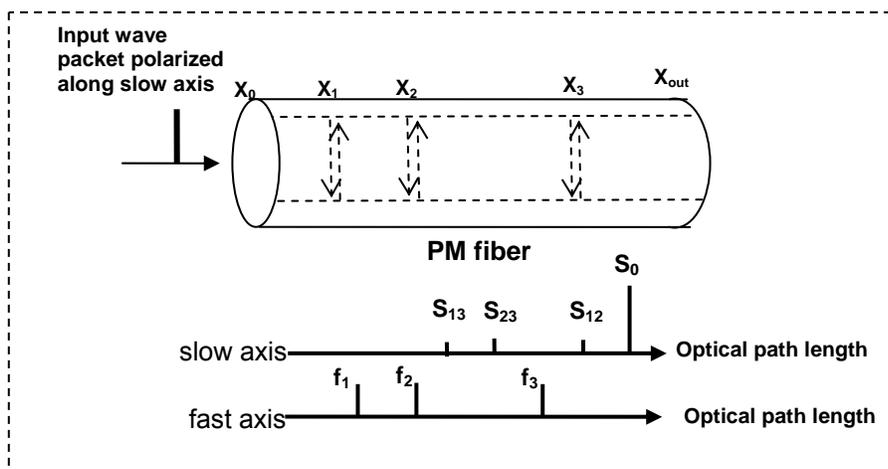
Figure 29 Wave packet sequence generated by coupling between slow and fast axis

Figure 29 shows the significant output wave packets at the end of the fiber (x_{out}). S_0 is the principal wave packet, aligned to the slow axis. f_1, f_2, and f_3 are wave packets aligned to the fast axis, generated by first-order coupling. S_{12}, S_{23}, and S_{13} are wave packets aligned to the slow axis, generated by second-order coupling.
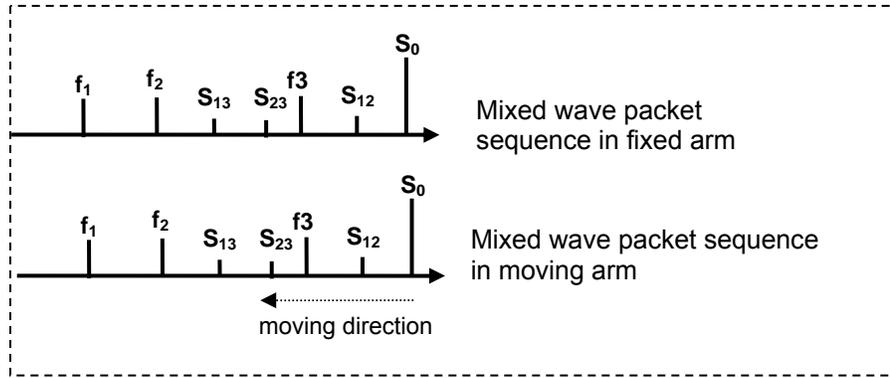
Figure 30 Wave packet sequence in traditional interferometer after passing a 45°-oriented analyzer

After passing through a 45° oriented analyzer, the wave packets aligned to the slow and fast axes will be mixed together (see Figure 30). If this mixed light is input to an interferometer, a series of interference peaks can be observed as the delay in one arm of the interferometer is changed. Table 1 lists all possible interference peaks for the example shown in Figure 29. Only the peaks generated by the interference between $S_0 \leftrightarrow f_1$, $S_0 \leftrightarrow f_2$, and $S_0 \leftrightarrow f_3$ represent the coupling points x_1, x_2 and x_3. The other peaks listed in Table 1 are ghost peaks that can cause errors in the identification of coupling points. They can also be superimposed on the real peaks, reducing the x-talk measurement accuracy.

In order to minimize the number and magnitude of ghost peaks, the PXA-1000 uses a patented technique to prevent the zero order, second order and most higher order interference signals from being generated as the delay line scans (see Table 1). Consequently, the PXA-1000 is able to achieve higher position measurement accuracy, higher dynamic range and higher sensitivity than traditional white-light interferometers.

Table 1 Interference peaks for PM fiber model shown in Figure 29

	Traditional White-light Interferometer	PXA-1000
Zero-order interference	$S_0 \leftrightarrow S_0$, $S_{12} \leftrightarrow S_{12}$, $S_{23} \leftrightarrow S_{23}$, $S_{13} \leftrightarrow S_{13}$, $f_1 \leftrightarrow f_1$, $f_2 \leftrightarrow f_2$, $f_3 \leftrightarrow f_3$	None
Interference from first order coupling	$S_0 \leftrightarrow f_1$, $S_0 \leftrightarrow f_2$, $S_0 \leftrightarrow f_3$	$S_0 \leftrightarrow f_1$, $S_0 \leftrightarrow f_2$, $S_0 \leftrightarrow f_3$
Interference from second order coupling	$S_0 \leftrightarrow S_{12}$, $S_0 \leftrightarrow S_{23}$, $S_0 \leftrightarrow S_{13}$ $f_1 \leftrightarrow f_2$, $f_1 \leftrightarrow f_3$, $f_2 \leftrightarrow f_3$	None
Interference from higher order coupling	$S_{12} \leftrightarrow f_3$, $S_{12} \leftrightarrow S_{23}$, $S_{12} \leftrightarrow S_{13}$, $S_{12} \leftrightarrow f_2$, $S_{12} \leftrightarrow f_1$ $f_3 \leftrightarrow S_{23}$, $f_3 \leftrightarrow S_{13}$ $S_{23} \leftrightarrow S_{13}$ $S_{23} \leftrightarrow f_2$, $S_{23} \leftrightarrow f_1$ $S_{13} \leftrightarrow f_2$, $S_{13} \leftrightarrow f_1$	most higher order couplings are eliminated

Appendix 2.0 Spatial Resolution of PXA-1000

According to interference theory, the full width at half maximum (FWHM) of an interference single envelope can be calculated by

$$\mathbf{l}_{FWHM} = \frac{2\ln 2}{\pi}\frac{\lambda_0^2}{\Delta\lambda} \approx 0.44\frac{\lambda_0^2}{\Delta\lambda} \qquad (9)$$

where λ_0 and $\Delta\lambda$ are the center wavelength and spectral width, respectively, of the light source used for measurement. Thus, the spatial resolution of a PM fiber measurement can be obtained by

$$L_{resolution} = \frac{l_{FWHM}}{\Delta n} \qquad (9)$$

where Δn is the birefringence of the PM fiber.

For example, when λ_0=1310nm, $\Delta\lambda$=30nm, and Δn=5x10^{-4}, then the spatial resolution of the PXA-1000 will be about 5cm.

Appendix 3.0 Polarization Crosstalk in PM Fiber

Classification of Polarization Crosstalk by Cause

Polarization crosstalk in a PM fiber arises from three principal causes. 1) Fiber axis misalignment at fiber connection interfaces, such as connectors or fusion splices, typically causes extremely localized, large-amplitude crosstalk. The amplitude depends on the misalignment angle. Examples are shown on the left side of Figure 31. Figure 31a shows crosstalk sources along a fiber, and Figure 31b shows the resulting crosstalk measurement plot. 2) PM fiber imperfections, such as local birefringence variations, internal shape variations, or internal stress, cause polarization coupling that is generally small in amplitude and occurs gradually over a certain length of the PM fiber (see center section of Figure 31). 3) External mechanical stresses on sections of the fiber, such as fiber bending, fiber crossing, fiber squeezing, or pressure on the fiber, can cause complicated composite crosstalk effects that can include polarization couplings that occur at sharp points in space, as well as some that occur gradually along a length of fiber, with varied amplitudes that depend on the stress orientations with respect to the slow axis and on the stress intensities, as shown in the right section of Figure 31.

Classification of Polarization Crosstalk by Measurement Results

In general, the PXA-1000 distributed polarization crosstalk analyzer can accurately measure the strength of polarization crosstalk occurring at different locations along a fiber with a spatial resolution of a few centimeters. Although the causes of the crosstalk cannot always be identified from measurement results, educated guesses can be made based on the shape and strength of the measured crosstalk at each location. It is also feasible to classify the crosstalk based on the shapes of the measured curves, as discussed below.
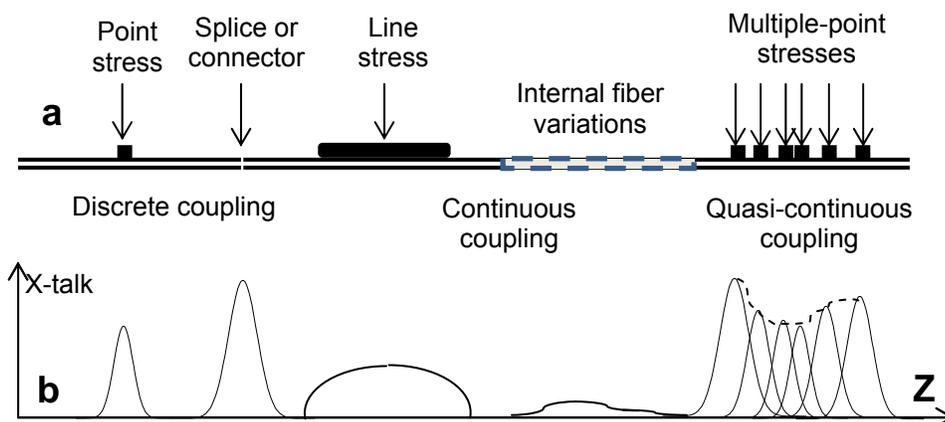
Figure 31 Illustration of different types of polarization crosstalk. a) Different sources of polarization crosstalk. b) The resulting crosstalk peak profiles. Left: discrete polarization x-talk peaks induced by a point stress or a splice. Each such peak is a Gaussian curve with a shape determined by the coherence function of the light source. The spatial resolution is also determined by the width of the coherence function. Center: continuous polarization x-talk induced by a line stress and by internal fiber imperfections, respectively. Right: quasi-continuous x-talk induced by multiple densely packed stress points spaced on the order of or less than the resolution of the instrument.

X-talk caused by discrete polarization coupling points

This category includes polarization coupling induced by a sharp stress, a splice point or multiple stress/splice points separated by distances much larger than the resolution of the measurement instrument, as shown on the left side of Figure 31a. These types of discrete coupling result in sharp, distinct peaks in the x-talk measurement trace, with the width of the peak determined by the spatial resolution of the instrument, as shown in Figure 31b. For this type of coupling, the peak x-talk value for each coupling point conveys useful information. The x-talk values listed in the table at the right of Figure 32b result from such discrete coupling points.
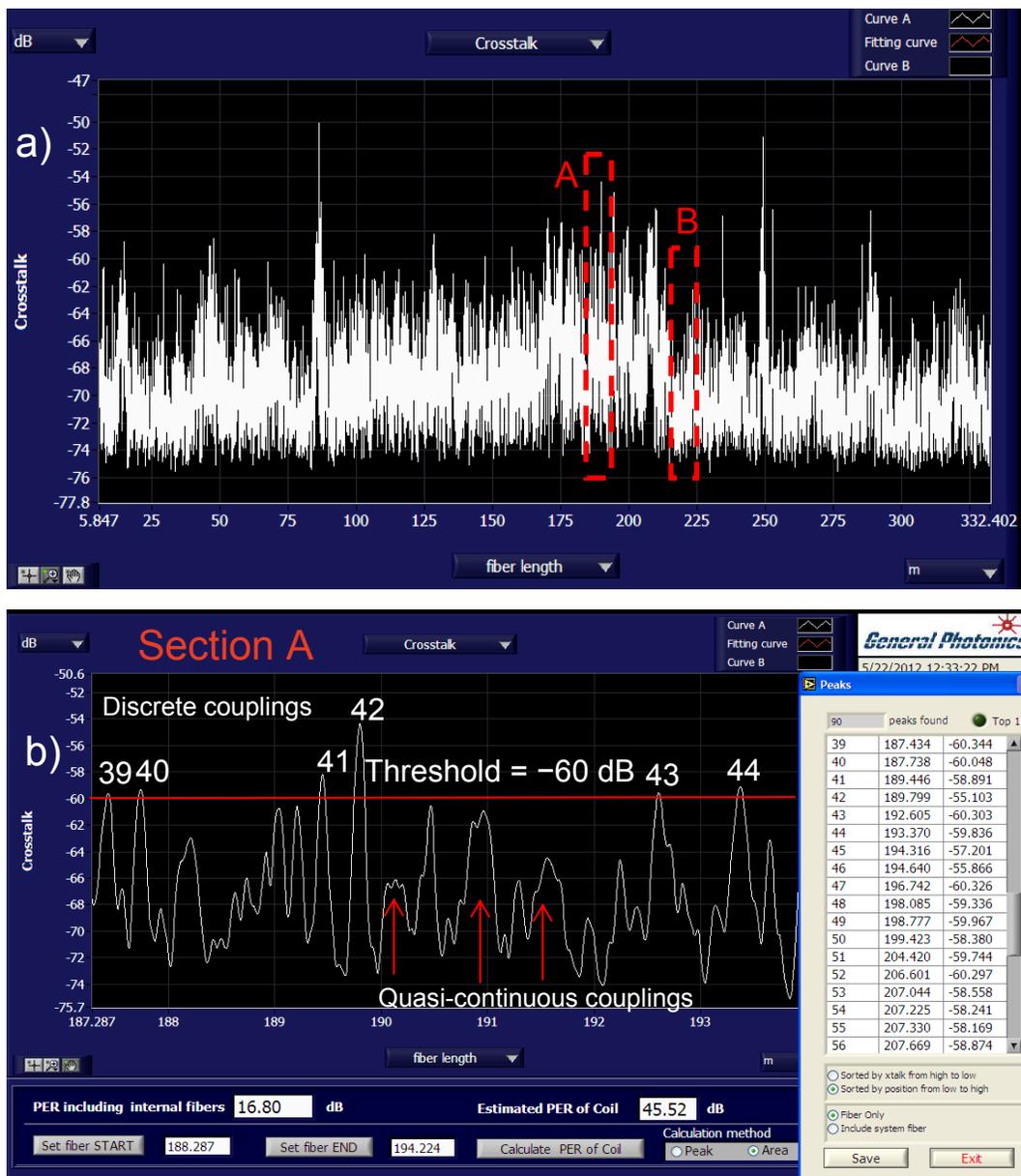
Figure 32 a) X-talk measurement of a 340 meter long fiber coil. Two significant sections (labeled A and B) are marked. b) Closeup view of section A, showing both discrete and quasi-continuous coupling peaks. The table on the right of the screen lists the magnitudes of discrete x-talk peaks larger than −60 dB. Note that the shape and width of discrete x-talk peaks are determined by the coherence function of the light source.

X-talk caused by continuous polarization coupling

This category includes polarization coupling that accumulates gradually over a section of fiber, induced by a line stress or by fiber internal imperfections, where the length of the affected section of fiber is comparable to or larger than the resolution of the measurement instrument, as shown in the center section of Figure 31a. The crosstalk measurement result of such continuous coupling is a broad dome with a width and shape determined mainly by the length of the section

of fiber under stress, as shown in Figure 31b. In general, crosstalk caused by a section of imperfect fiber is very small in amplitude - on the order of −60 dB or lower. Because of this curve structure (low amplitude, wide peak), the peak x-talk value for crosstalk resulting from continuous polarization coupling is not meaningful. However, the cumulative coupling occurring in a section of fiber can be obtained by defining the starting and ending positions of the continuous-coupling section of fiber using the PXA-1000 software's cursors, as shown in Figure 33. In this example, the cumulative value is −61.32 dB.
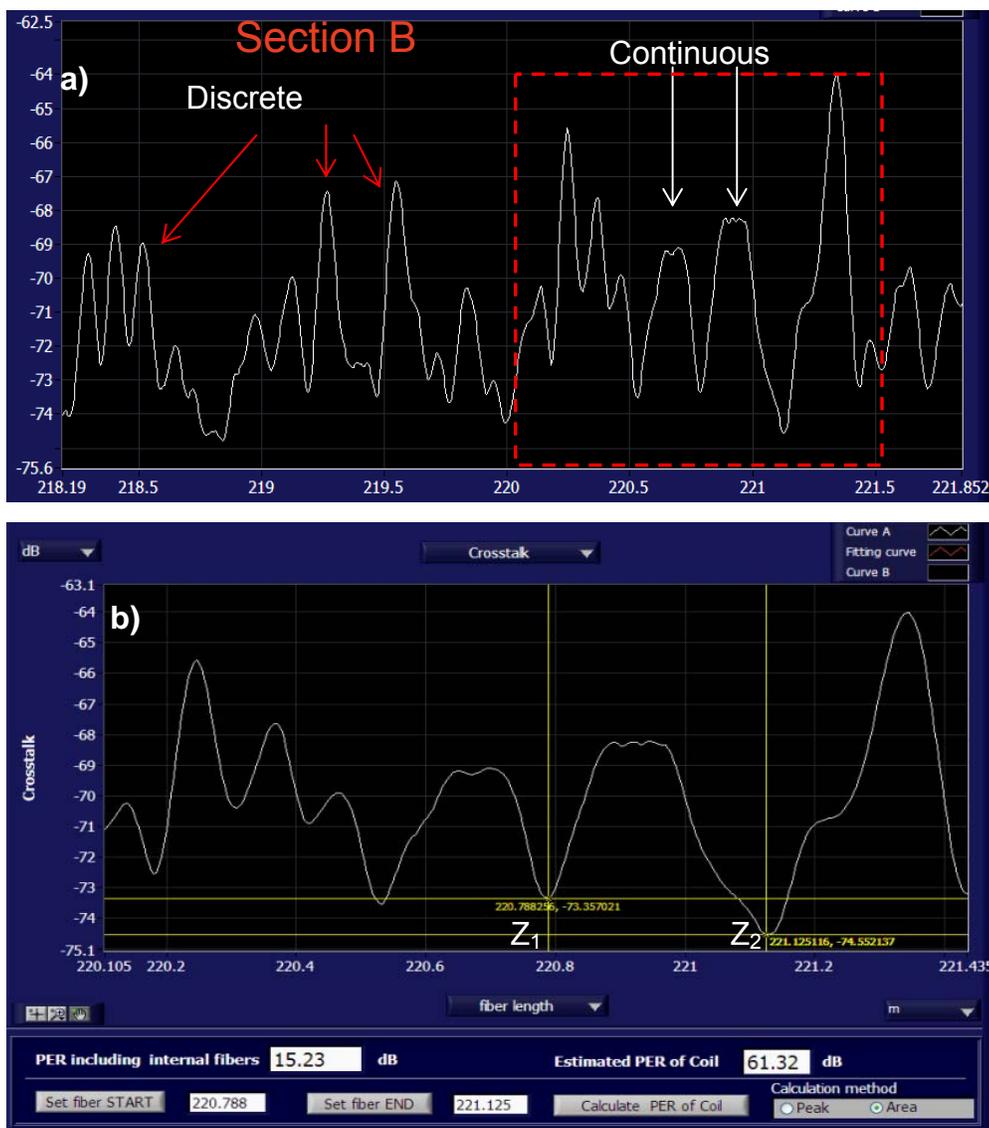

Figure 33 Closeup view of section B of the x-talk measurement plot shown in Figure 32a, in which two continuous or quasi-continuous x-talk peaks are identified. b) Cumulative x-talk value of a continuous/quasi-continuous coupling is obtained by setting the locations of cursors Z_1 and Z_2 and calculating the integrated PER of the corresponding fiber section. The resulting value, −61.32 dB, is shown at the bottom right of the screen.

X-talk caused by quasi-continuous polarization coupling

This category includes polarization coupling induced by multiple stress points spaced on the order of or less than the resolution of the measurement instrument, as shown in Figure 31a. This type of polarization coupling appears in polarization crosstalk measurements as a broad composite peak with height variations, with a width and shape determined by the number of stress points, their relative positions, and their relative strengths, as shown in Figure 31b. Quasi-continuous coupling cannot reliably be distinguished from continuous coupling. As in the case of continuous coupling, it is not meaningful to give a peak x-talk value for quasi-continuous coupling. However, the cumulative coupling occurring in a section of fiber can be obtained by defining the starting and ending positions of the continuous-coupling section of fiber using the PXA-1000 software's cursors, as shown in Figure 34b.
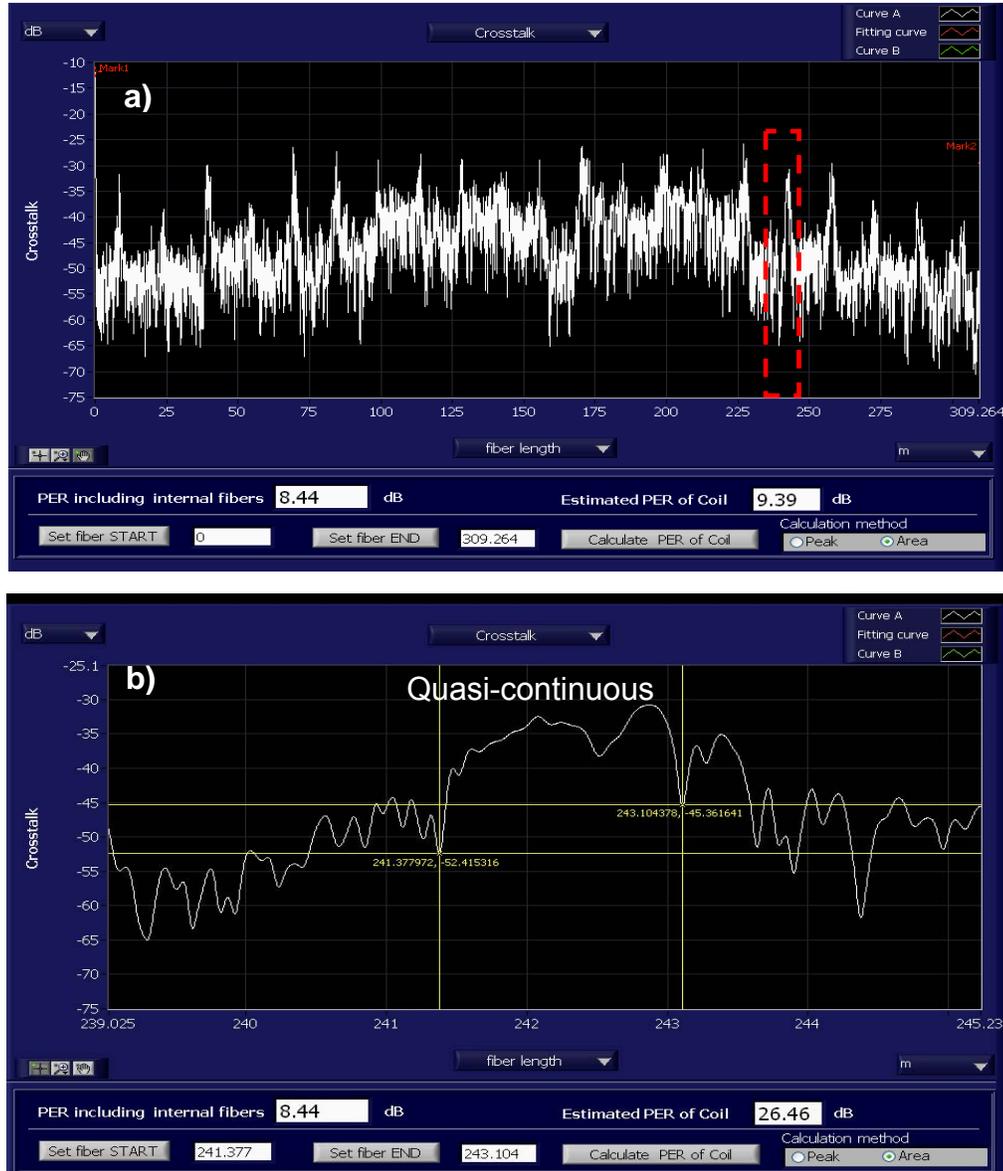
Figure 34 a) X-talk measurement of a low quality PM fiber coil of length 309 meters. b) Closeup view of the boxed section in a), showing more detailed structure of quasi-continuous couplings. The cumulative x-talk of the region between the two cursors is −26.46 dB.

Capabilities and limitations of the PXA-1000

The PXA-1000 can take crosstalk measurements at spatial intervals of about 4-6 mm, much finer than the specified x-talk resolution of the instrument (on the order of 5 cm). The exact spacing between two adjacent data points is dependent on the birefringence of the fiber; it is defined as the ratio of the delay resolution of the variable delay line used in the PXA-1000 to the

fiber birefringence. However, depending on the type of the polarization coupling, a given x-talk reading may not represent the true x-talk value at that point in space, as will be discussed below.

For X-talk induced by discrete polarization coupling points, the PXA-1000 is able to display the corresponding discrete x-talk peaks, to provide an accurate x-talk value for each x-talk peak, and to list in a table all peak values above a defined threshold, as shown in Figure 32b. Note that each peak has a Gaussian shape corresponding to the coherence function of the light source used; however, only the peak value is meaningful and represents the x-talk value at the point in space at which the x-talk occurs. The other points on the Gaussian curve are due to the light source's coherence function and do not represent meaningful x-talk values for the corresponding points, as shown in Figure 35. Note that the instrument's x-talk accuracy specification is based on measurement of the peak values of such discrete x-talk points.
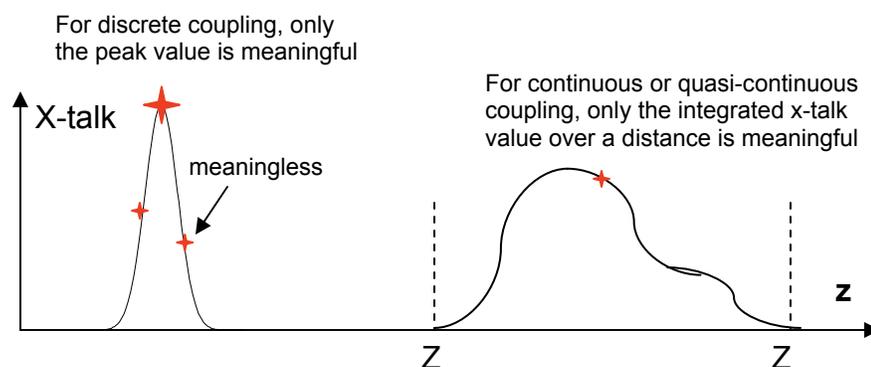

Figure 35 Left: Illustration of a crosstalk peak caused by discrete coupling, with peak and off-peak values marked. The off-peak values are artifacts caused by the coherence function of the light source; they have no relation to real x-talk points on the fiber. Right: Illustration of a x-talk dome induced by continuous or quasi-continuous polarization coupling. A point on the dome does not correspond to a x-talk point on the fiber. In this case, only the integrated cross coupling between the points Z_1 and Z_2 is meaningful. Points Z_1 and Z_2 can be defined in the software interface.

For X-talk induced by the continuous or quasi-continuous coupling shown in Figure 31, the x-talk value of any single point on the broad x-talk composite peak is not meaningful. The PXA-1000 is unable to give an accurate x-talk value for such a point, although the x-talk data file includes data points every 4-6 mm. For a x-talk composite peak caused by continuous or closely packed quasi-continuous coupling points, only the cumulative cross-talk value is meaningful, as shown in Figure 33b and Figure 34b. The PXA-1000's data display and analysis software, PolaX, has a function that calculates the cumulative x-talk from point Z_1 to point Z_2, where Z_1 and Z_2 are defined by the locations of the cursors, as shown in Figure 33b and Figure 34b. In general, the distance between Z_1 and Z_2 should be much larger than the spatial resolution of the instrument in order to obtain an accurate result. In addition, the two points should also be chosen at valleys on the x-talk curve and the "Area" calculation method should be selected, as shown at the bottom right of Figure 33b and Figure 34b.

Note that the primary purpose of the PXA-1000 is to obtain accurate x-talk measurements of discrete x-talk peaks; the accuracy of a cumulative x-talk calculation is not guaranteed. However, the instrument records measurement data every 4-6 mm, and this data is available to users to optimize the calculation for specific cases where higher accuracy is required. Data is available to the user in two forms: the raw interferometer signal data as a function of the relative delay between the two arms of the interferometer ("Interferometer Only" data) and the x-talk data as displayed on the screen. The x-talk data is the raw interferometer data with the horizontal and vertical axes shifted according to internal position and x-talk references.