Introduction

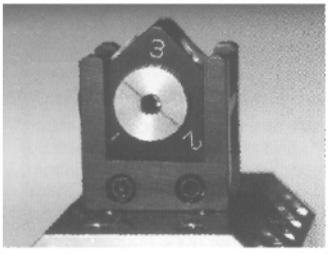
FB-PAM, the FiberBench Polarization Analyzer, is a highly accurate, intuitive, and easy-to-use manual polarimeter. The System completely describes the State of Polarization(SOP) of light, whether from an optical fiber, or from a free-space beam.

The FB-PAM consists of a Fiber Bench Collimator System on which is mounted a Module Capture Cage with State of Polarization(SOP) Module. Included are analysis software, applications notes and operations manual.

Description

The FB-PAM uses time-sequential polarimetry, the most fundamental method of polarization measurement. Here, four required intensities are measured in sequence.

The heart of the FB-PAM is the SOP Module, a triangular block in which are mounted a Polarizer and a 1/4-Wave Retarder. The Module is set into its Capture Cage which is mounted on the FiberBench base plate. The Module is inserted into the beam path, and the four intensity values are measured. These numeric values are entered into the supplied analysis software, which calculates and displays complete polarimetric information in graphical and tabular form.



SOP Module in Capture Cage (US patent 6,061,190), 2mm aperture

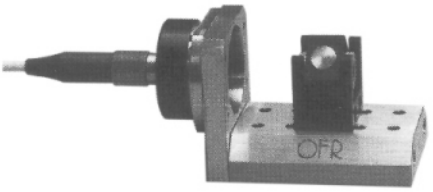
The accuracy of the FB-PAM is ensured by the tight manufacturing tolerances of the SOP Module. It is a precision machined 45° -45° -90° triangle, the simplest of geometric shapes. Measurements are made with the Module in each of three positions, corresponding to the three faces of the triangle. The design eliminates human error.

An added safety feature of the Module Capture Cage is that it does not allow the SOP Module to tilt during installation/removal, thus eliminating any chance of stray reflections from optical surfaces.

Finally, all optical surfaces are deeply recessed in the Module, thus preventing inadvertent fingerprints on optical apertures.

Operation

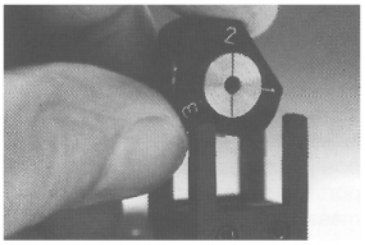
In order to analyze the SOP of light, the FB-PAM requires a collimated beam. Normally, the light-under-test is from an optical fiber. This fiber is connected to the FiberPort Collimator. From this, a collimated beam transmits through the optical components in the SOP Module and directly to a detector or power meter.

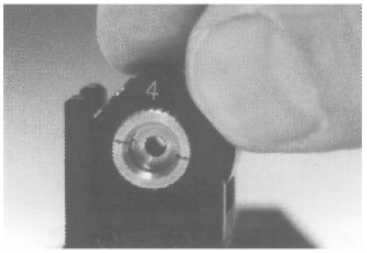


FB-PAM, FiberBench Polarization Analyzer

The FB-PAM can be bolted directly to the optical table, or it can be post-mounted to simplify alignment. Any detector or power meter can be used to measure the transmitted intensity.

A high strength magnet is imbedded in the Cage Base, and a magnetic disc is imbedded in each of the three facets of the SOP Module. When the Module is set in any of its three positions, the Cage Base magnet grabs against the corresponding magnetic disc in the SOP Module. This force of attraction, in combination with tight-tolerance machining, assures absolutely repeatable positioning, time-after-time, as the Module is set in sequence in the Cage.

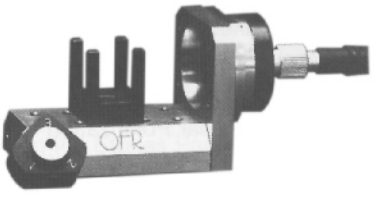




SOP Module is manually set in 4 positions.

The Sequence of Measurements is as follows.

Measurement #1 : the SOP Module is reset in the Cage so that the engraved '1' is at the top position, facing the beam. In this position, the horizontal, linearly polarized portion of the light-under-test is measured. The value on the power meter is entered into the appropriate box in the software.

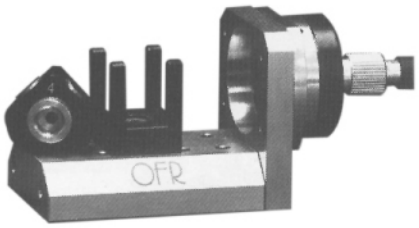


SOP Module sets into Module Capture Cage, in Positions 1 thru 3.

Measurement #2 : the SOP Module is reset in the Cage with the engraved '2' at the top position. The vertical, linearly polarized portion of the light-under-test is measured. The value is entered.

Measurement #3 : the SOP Module is reset with the engraved '3' at the top position. The 45° ,linearly polarized portion of the light-under-test is measured. The value on the power meter is entered.

Measurement #4 : during the previous three measurements, the engraved #4 has faced away from the input beam. Now, it is necessary to turn the SOP Module "backwards" so that the #4 faces forward, and is at the top. In this position, the right-circularly polarized portion of the light-under-test is measured. The value is entered.



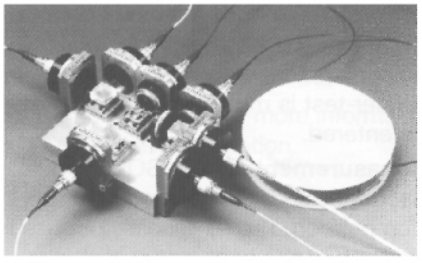
Position 4 is on the reverse side of Module, behind position 3.

Data analysis

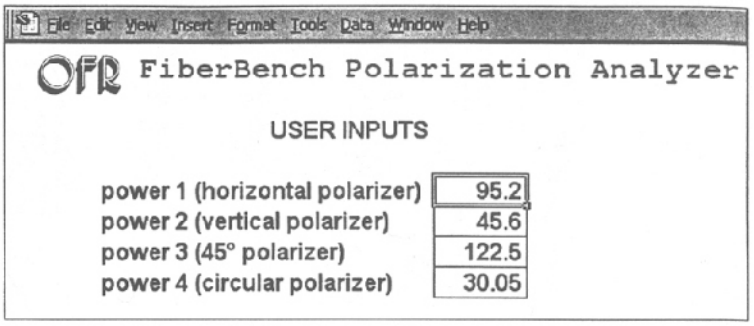
These four intensity measurements are all that is required to calculate all of the polarimetric information about the light-under-test. The software processes the data via matrix multiplication(the exact details of which depend on the Calibration Option selected by the user).

The following quantities are calculated and displayed in the software :

- Stokes Parameters
- Jones Vector
- Degree of Polarization
- Degree of Linear Polarization
- Linear Polarization Extinction
- Azimuth Angle
- Degree of Circular Polarization Ellipticity, Helicity (handedness)



Custom Polarization Analyzer with 100 meter-phase delay line.

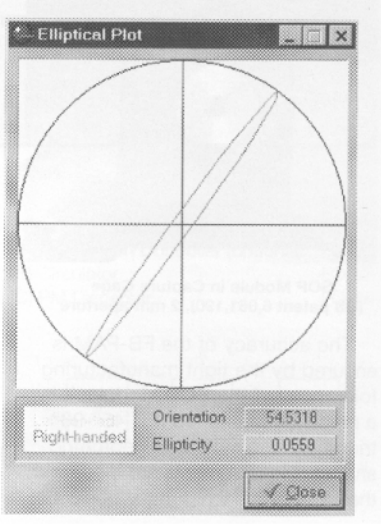


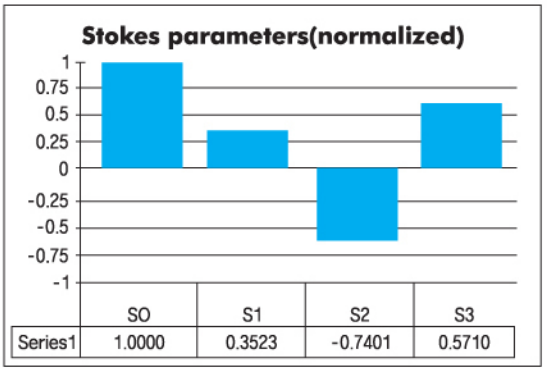
Stokes parameters	*Joness Vector*		
S0	1.000	Ex	0.8223
S1	0.3523	Ey	0.5692
S2	-0.7401	d(degrees)	142.2432
S3	0.5732	d(waves)	0.3951

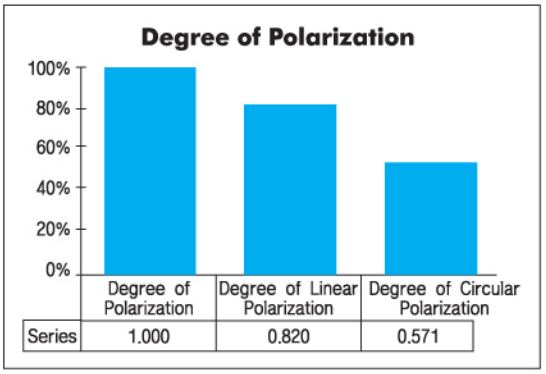
Polarimetric Data			
Degree of Polarization	1.0000	orientation angle	-32.273
Degree of Linear Polarization	0.820	ellipticity(E-field)	0.315
Degree of Circular Polarization	0.573	helicity	right handed
Linear Extinction(dB)	-10		

Sample data box generated by analysis spreadsheet

Plots of the Degree of Polarization, Stokes Parameters, and Polarization Ellipse are generated, and can be printed or exported to other applications.







In addition, the Excel™ platform allows the user to customize the program and to add calculations, plots, and graphs.

Sample formula(calculates degree of polarization). Formulas can be added or modified to suit specific needs or applications.

Applications

In addition to measuring the SOP of light-under-test, the FB-PAM can also characterize fiber-pigtailed devices and bulk optics. For example, the FB-PAM can answer the following questions:

- What is the SOP of a signal (free-beam or fiber-optic)?
- What is the Polarization-Dependent Loss/Gain of a fiber device?
- What is the extinction ratio after propagating through PM or PZ fiber?
- What is the retardance of a retarder?
- Has a signal been depolarized after propagating through a long single mode fiber? Through a multi mode fiber?
- Is the SOP changed after propagating through short lengths of single mode fiber?
- What are the effects of multilayer coatings on the SOP?
- What are the polarizing effects of a beamsplitter?
- Does a beamsplitter change the phase of the polarization?
- How effective is a depolarizer at reducing degree of polarization?

Theory

The State of Polarization (SOP) of light describes the orientation and oscillation of its electric field. It is uniquely specified by four quantities known as the Stokes Parameters. These Parameters, designated as S_0,S_1,S_2 and S_3, are defined as:

$S_0=I_{0°}+I_{90°}$	horizontal + vertical
$S_1=I_{0°}-I_{90°}$	horizontal - vertical
$S_2=I_{45°}-I_{135°}$	45° -135°
$S_3=I_{RCP}-I_{LCP}$	right circular-left circular

Where:

- $I_{x°}$ refers to the intensity of the light that transmits through a Linear Polarizer oriented at x° .
- I_{RCP} and I_{LCP} are the intensities transmitted through a right-hand and left-hand circular polarizer, respectively.
- S_0 is the total intensity of the light.
- S_1 represents the dominance of horizontally polarized light vs. vertically-polarized light.
- S_2 represents the dominance of 45 ˚ polarized light vs. 135° polarized light.
- S_3 represents the dominance of right-circular polarization vs. left-circular polarization.

Although six intensity values are required to define the Stokes Parameters, a fundamental relationship allows the four measurements: $I_{0°}+I_{90°}=I_{45°}+I_{135°}=I_{RCP}+I_{LCP}$.

When the Stokes Parameters are known, the SOP can be completely described. It is a remarkable result that the electric field can be determined solely by these intensity values.

Polarization State	*S0*	*S1*	*S2*	*S3*
Linear, Horizontal	1	1	0	0
Linear, 135°	1	0	-1	0
Linear, 30°	1	0.5	0.866	0
Circular, right handed	1	0	0	1
Unpolarized	1	0	0	0
50% unpolarized, 50% elliptical	1	0.235	-0.120	-0.424

Calibration

Conversion of intensity measurements to Stokes Parameters is achieved by multiplying the data by an "instrument matrix" , which uniquely characterizes the Polarization Analyzer. This instrument matrix is a function of the operation wavelength, because the optics will be wavelength dependent. However, the FB-PAM is designed to have low wavelength dependence.

In order to determine the instrument matrix, the entire System must be calibrated. Two Calibration Modes are available with the FB-PAM:

Built-in Data Tables are used for compensation when operating at wavelengths other than the design wevelength.

Matrix Calibration makes no assumptions about the system components. Therefore, a more rigorous calibration procedure is used to describe system characteristics at any wavelength.

The FB-PAM FiberBench Polarization Analyzer includes:

- State of Polarization Module
- Module Capture Cage
- FiberBench with Input FiberPort
- Analysis Software
- Bare Fiber Adaptor

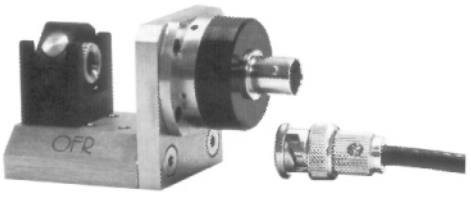
For free-space applications, the Input FiberPort is easily removed from the FiberBench. The FB-PAM can be post-mounted or table-mounted.

Specifications

Standard Wavelengths	630-1600 nm(specify λ)
Bandwidth	±10% of the design wavelength
power handling	< 200 mW(higher with optional attenuator)
Degree of Polarization uncertainty	1% calibrated
Orientation Angle uncertainty	0.5% for linear polarization(15 minutes)
Software	2 versions : Excel based for windows or MAC and PC based executable
System Requirements	Detector or Power Meter, computer (PC or Mac)

DetectorPorts

An optional means of measuring intensities is the DetectorPort, which is mounted on a FiberBench or FiberTable. The DetectorPort contains an amplified silicon or InGaAs detector(for visible or infrared operation, respectively), whose output voltage is proportional to the average(cw) intensity of light. This voltage is measured using any voltmeter or oscilloscope.



Specifications

Detector area	0.8mm^2(InGaAs)
Bandwidth	50 MHz
Wavelength	400-1100 nm(silicon) 800-1800 nm(InGaAs)
Input	110VAC(power supply included)
Output	BNC connector