Automated, In-Line Polarization Crosstalk Measurement

Product Note 8509-3
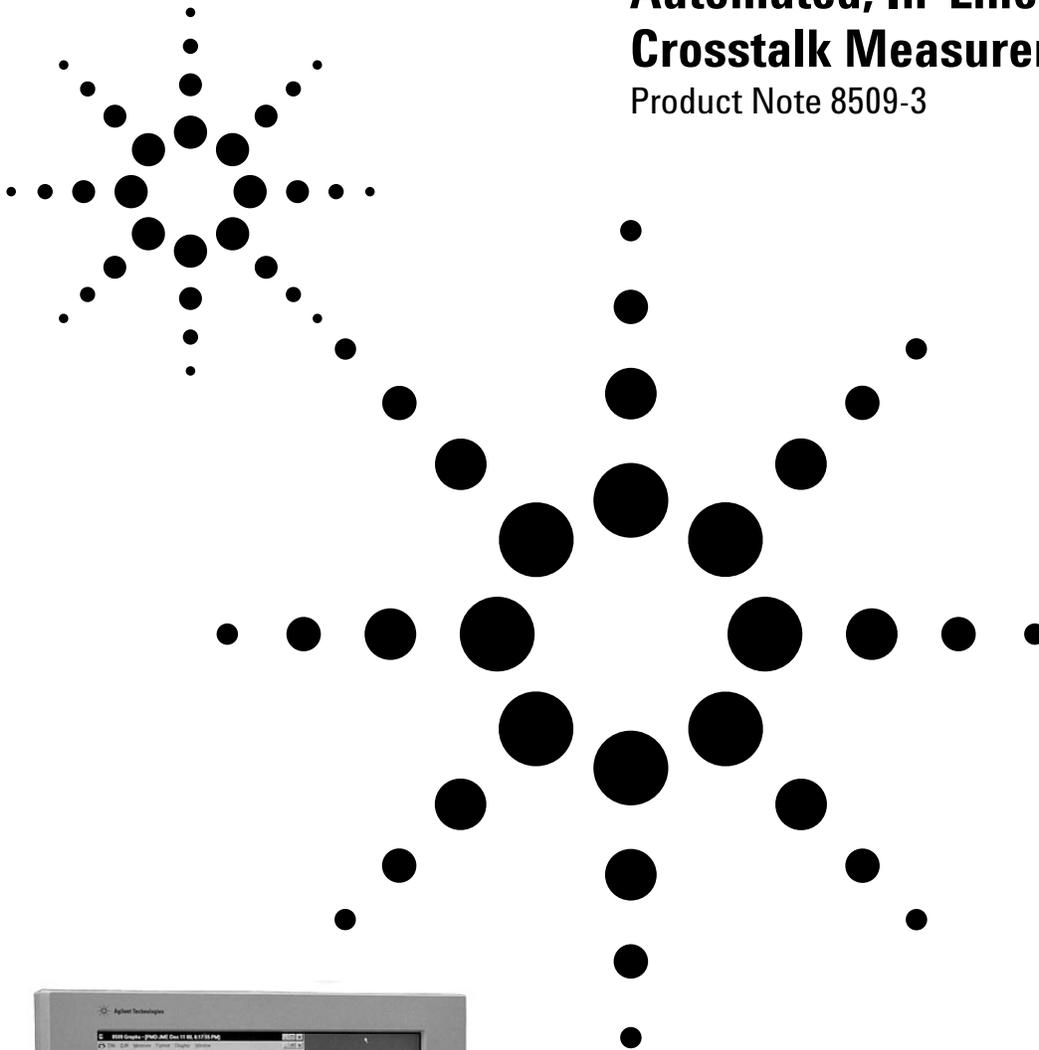
Agilent Technologies

Introduction

The Agilent lightwave polarization analyzer provides a powerful method for measuring the polarization crosstalk (PXT) on polarization maintaining (PM) fiber.[1] This fully polarimetric measurement has important advantages over other methods:

1) It is an 'in-line' method, measuring the crosstalk within a user-selected region of the PM fiber itself. As a result, the value is not affected by the quality of the output connector of the PM fiber.[2]

2) It takes advantage of the combination of high sensitivity and speed that are found in modern, space-division multiplexed polarimeters.[3] Crosstalk of over 50 dB is easily measured.

The 8509's in-line PXT method is widely used in the manufacture and test of PM fiber pigtailed lasers, modulators and passive components. This has led to a demand for automating what had originally been a manual, graphical user interface-oriented method. This note describes a method for automating the 8509's in-line PM fiber crosstalk measurement.

PM fiber background

High-speed modulators and polarization scramblers operate most effectively with input light that is linearly polarized in a particular orientation. For this reason, these devices are usually input-pigtailed with polarization-maintaining (PM) fiber. The difference in index of refraction between the 'fast' and 'slow' axes of PM fiber is approximately 1000 times larger than that of conventional single-mode fiber. This strong and uniform linear *birefringence* (index difference) is achieved by placing the fiber core in a transverse mechanical stress field. Several widely used PM fiber designs are shown in Figure 1.

Given an arbitrary input polarization, PM fiber splits light into fast and slow linearly polarized waves according to the projection of the electric field on the birefringence axes of the fiber. Since the waves travel down the fiber at slightly different speeds, the polarization state at any specific location along the fiber depends on the relative phases and amplitudes of the fast and slow waves at that point. Under this condition of arbitrary input polarization, PM fiber does not maintain polarization. In fact, the output polarization becomes a sensitive function of temperature and fiber movement (a great thermometer and a great microphone). In the modulator application described earlier, all of the light is launched into a single axis. Under this condition, the PM fiber preserves the linear polarization state from input to output. The behavior of PM fiber for ideal and non-ideal input polarizations is illustrated in Figure 2.
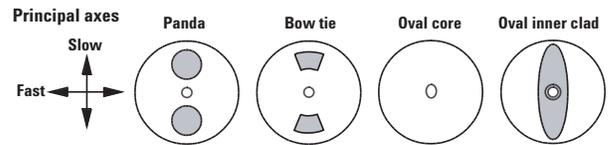
Figure 1. Examples of polarization maintaining fiber construction.
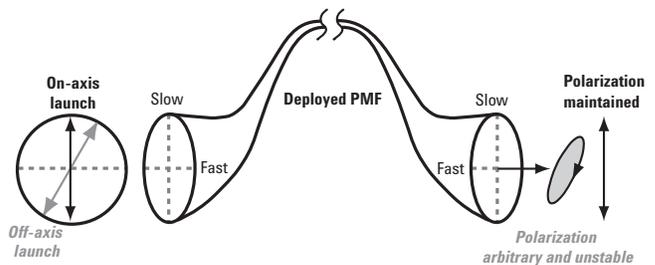
Figure 2. Polarization-maintaining fiber preserves a linear state of polarization if the input electric field is aligned with a principal axis.

PM fiber crosstalk

In most fiber optic industry applications, the input electric field is aligned with the slow axis of PM fiber.[4] The extent to which the light is confined to the slow polarization 'mode' is represented by the attribute *polarization crosstalk*, abbreviated in this document as PXT. The use of the term *polarization extinction ratio* (PER) is discouraged by the TIA subcommittee on PM fiber topics, as it is too easily confused with the extinction ratio of a polarizer. If linearly polarized input light is aligned with the

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1. Historically, this parameter has been called 'polarization extinction ratio'. However, this usage was easily confused with the polarization extinction ratio (polarizing strength) of polarizers and polarizing fibers. For this reason, the TIA standards committee (US) has standardized on 'polarization crosstalk' to express the extent to which light is confined to the desired axis of PM fiber.
2. It is well known that connectorization is a major cause of crosstalk problems in PM fiber cables and components. Issues include physical stresses generated by connector attachment and by polishing, orientation errors caused by inaccurate registration of the key with the desired axis, and tolerances of mechanical parts.
3. The Agilent 8509 polarimeter optical unit splits the incoming beam into four parallel paths, for simultaneous filtering and detection. This allows approximately 3000 samples per second.
4. The de facto industry standard is to launch light into the slow axis of the PM fiber. The TIA standards organization (US) supports this convention.

slow axis of the PM fiber, the polarization crosstalk measured at a particular location is given by

$$PXT = 10\log \frac{\text{optical power of the fast wave}}{\text{optical power of the slow wave}}$$

(1)

If instead the input light is aligned with the *fast* axis, the numerator and denominator of Equation 1 are reversed.

What limits PM fiber performance?

For the optimum guiding of linearly polarized light, several conditions must be met. The manufacturer of a PM fiber cable must accurately align the optical connector anti-rotation key with a principal axis of the fiber. The connector attachment and fiber polishing processes must be controlled to avoid building up internal stresses that can transform the linearly polarized input light to an elliptical state. The user of PM fiber must ensure that input light is highly polarized and aligned (conventionally with the slow axis). If sections of PM fiber are cascaded using connectors or splices, rotational alignment of the mating fibers is critical. If all of these requirements are met, it is possible to guide polarized light with 10 to 100,000 times more optical power in the slow axis than in the fast.

Measuring PM fiber crosstalk

The Agilent 8509 provides an in-line polarization crosstalk measurement method. The method takes advantage of the fact that a phase change between orthogonal polarization states traces out a circle on the Poincare sphere. In PM fiber, the fast and slow polarization modes are linear and orthogonal (or perpendicular, in the case of linear light).

The user heats or gently stretches a 0.3 to 0.5 m long portion of the PM fiber in the region where crosstalk is to be measured. The resulting fiber elongation causes the phase shift between waves in the fast and slow axes, which in turn produces a circular arc on the Poincare sphere. The diameter of this circle has a direct relationship to the relative illumination of the fast and slow modes of the fiber, allowing the crosstalk value to be calculated from the diameter of the circle.

A *great circle* indicates that fast and slow axes carry equal power. At very low crosstalk, the optical power is confined to a single polarization mode (slow by convention) and the circular trace collapses toward a point. This point represents the slow linear polarization mode of the PM fiber, transformed to an arbitrary location on the Poincare sphere by the arbitrary birefringence of the interconnecting single-mode fiber.

The polarization crosstalk (PXT) value is computed by entering the radius R of the circle (a value between 0 and 1) into Equation 2:

$$PXT = 10\log \frac{1 - \sqrt{1-R^2}}{1 + \sqrt{1-R^2}} \qquad (2)$$

In manual operation, the user generates the circle and then clicks at three points on the circular trace using the mouse. The 8509 automatically fits a circle to the three points and then computes and displays the PXT value. The focus of this note is to replace this manual, mouse-oriented evaluation of the circle with an automated process.
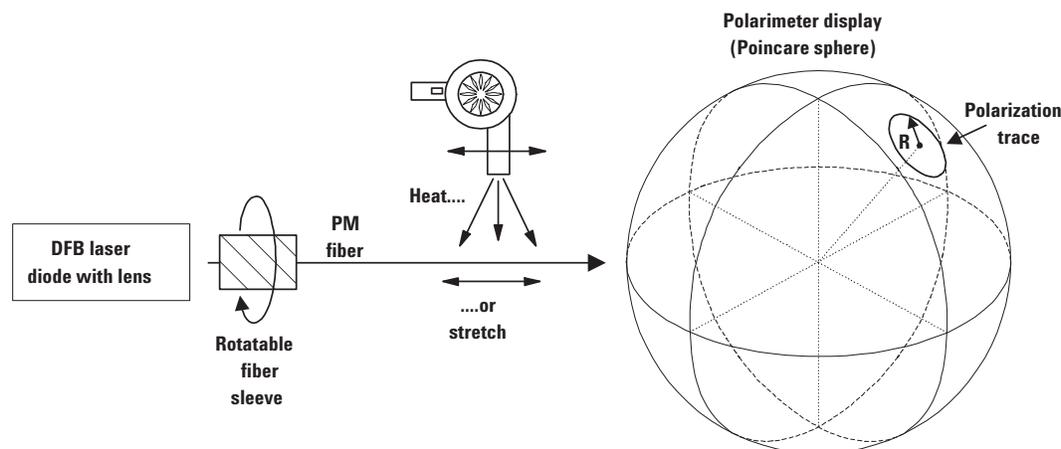
Figure 3. An example of the measurement of polarization crosstalk along a PM fiber using a narrowband source and polarimeter.

Automating the PM fiber crosstalk measurement

The process discussed below automatically extracts the PXT value from the polarimetric data that was generated by heating or stretching the fiber. The data may occupy a full circle, as shown in Figure 4, or a portion of a circle. For best accuracy, at least half of a circle should be acquired.
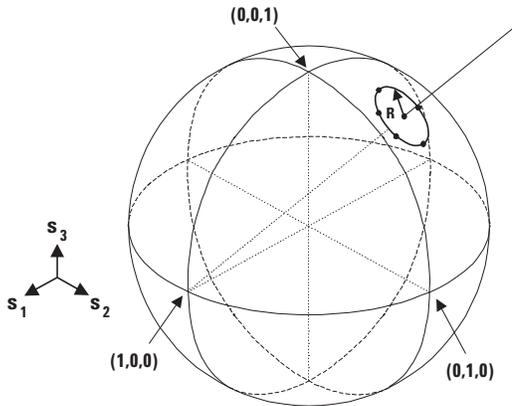
Figure 4. Polarimetric data resulting from heating or stretching the PM fiber.

If the data acquisition process were ideal, all of the data points would fall on a perfect circle. In reality, instrumentation noise and handling of the fiber cause the points to fall slightly off the ideal circle. For this reason, a circle must be fit to the acquired data. The problem is simplified by the fact that the circle is on the Poincare Sphere. Since the circle is defined by the intersection of a plane with the sphere, the diameter of the circle is defined indirectly when we specify the distance of the plane from the center of the sphere. However, the fitting process has two steps. First the center vector must be found by minimizing the variance of the distance between the vector and each of the data points. The second step is then to fit to find the radius.

We simplified the problem by stereographically projecting the sphere onto the complex polarization plane. This approach reduces the problem to two variables and a single fitting step. An interesting property of stereographic projections is that circles on the sphere are transformed into circles on the plane. Figure 5 illustrates the projection of a circle onto a tangent plane. The origin of the projection is P*, and P is the point of tangency between the plane and sphere. Once the data is projected, the problem is reduced to finding the center of the projected circular pattern and then calculating its average distance from the projected points. The center is found by minimizing the variance of the distance between the center point and each of the projected data points. The Nelder-Mead algorithm as outlined in Appendix C is a simple way of numerically finding the maximum or the minimum of a function of one or more variables.

Poincare introduced the complex plane representation of polarization states as he developed the better known Poincare Sphere. Both the sphere radius S0 and the projection origin P* can be arbitrarily chosen. However, the most common definitions were S0 equal to 0.5 and P* identical with linear vertical polarization (-S0, 0,0). In this way, the horizontal polarization falls at the origin of the Plane, the other linear states fall along the horizontal

axis, and the circular states fall at ±1 on the vertical axis. The mathematical analysis presented in this application note follows the convention

$$|\chi| = \frac{|\overline{E}_x|}{|\overline{E}_y|} = \left|\frac{E_x e^{i\delta x}}{E_y e^{i\delta y}}\right| \qquad (3)$$

where the numerator and the denominator represent the x- and y-components of the electric field. Equation 4 describes the projection operation

$$\chi_x = \frac{\frac{S_2}{S_0}}{\frac{S_1}{S_0}+1} \quad \chi_y = \frac{\frac{S_3}{S_0}}{\frac{S_1}{S_0}+1} \qquad (4)$$

where the subscripts refer to the x- and y-axes of the plane shown in Figure 5.

One problem with this method is that if the data points are far away from P (that is, near the projection origin P*), the projection falls on the plane far from P and thus the projection becomes very large and less accurate. One
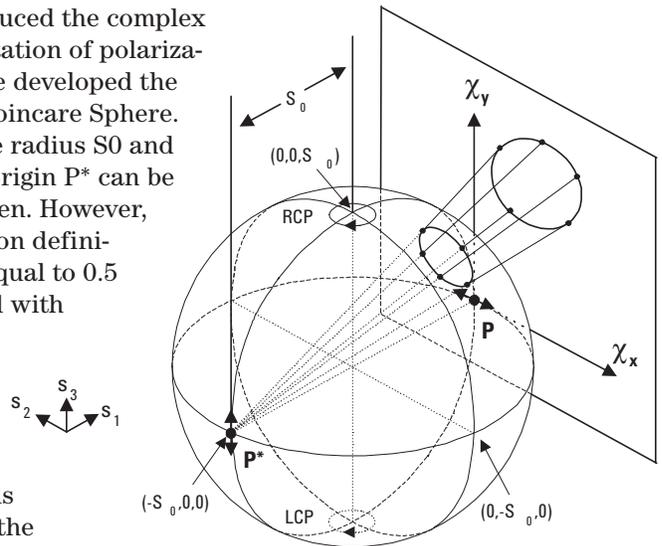
Figure 5. Stereographic projection of a circular pattern of polarimetric data onto a plane that is tangent to the sphere.

way to solve this problem is to choose a different P nearer the data. Another method is to simply reflect the data about the equator of the sphere if a majority of the data is on the upper half of the sphere. This method is valid because reflection does not cause any sort of distortion and it is only the radius of the circle, not its position, that is important. The advantage to this second method is that it does not require any modification to any of the projection equations. This method is used in the example program in Appendix A for this reason.

Once this circle is fitted on the plane, simple trigonometry can be used to determine the radius of the circle on the sphere, which in turn is used to find the cross talk. This is outlined in Figure 6.

Equation 5 provides background for the mathematical relationships shown in Figure 6.

As fitting is the most complicated and time-consuming operation, the advantage of this projection-based process is that only one fitting step

is needed. The processes of projecting the points onto the plane and then calculating the radius of the circle on the sphere from the fitted circle on the plane are much simpler than the fitting. This is because these processes are only performed once where as numerical fitting algorithms require several iterations of a complicated loop.

The following pages provide references and the following appendices:

Appendix A Additional applications of the in-line PXT method

Appendix B Derivation of Equations 4d and 4e

Appendix C The Nelder Mead fitting algorithm

Appendix D Communications with the Agilent 8509 polarization analyzer

Appendix E Example polarization crosstalk program

References

Azzam, R. M. A. and N. M. Bashara, "Ellipsometry and Polarized Light", North Holland Publishing Co., 1977.

Henderson, D. W., "Experiencing Geometry: On Plane and Sphere", Prentice Hall, 1995.

Lagarius, J.C., J.A Reeds, M.H. Wright, and P.E. Wright, "Convergence Properties of the Nelder-Mead Simplex Method in Low Dimensions," SIAM Journal of Optimization, Vol. 9, Num. 1, pp 112-147, 1998.

Nelder, J.A and R. Mead, "A Simplex Method for Function Minimization," Computer Journal, Vol. 7, pp 308-313, 1965.

Figure 6. Analyzing the projection to find the radius of the data on the Poincare sphere.

4a.	$\sin\alpha = 2\dfrac{R}{D}$
4b.	$\tan(\dfrac{\beta+\alpha}{2}) = \dfrac{L'+R'}{D}$
4c.	$\tan(\dfrac{\beta-\alpha}{2}) = \dfrac{L'-R'}{D}$
4d.	$R' = \dfrac{\sin(\alpha)}{\cos(\alpha)+\cos(\beta)}$
4e.	$L' = \dfrac{\sin(\beta)}{\cos(\alpha)+\cos(\beta)} = \sqrt{X_0{}^2 + Y_0{}^2}$
	$V_0 = (X_0, Y_0)$ center of the projected circle

Equation 5. Equations for determining R from R′ and L′.

Appendix A—Additional applications of the in-line PXT method

End-to-end PXT measurements

The main text provided a general example of measuring polarization crosstalk (PXT) along a PM fiber. However, there are special cases where it is not possible to measure the PXT 'in-line'. One example is a PM component with connectors mounted directly on the walls of the package. PM fiber jumpers and cables may fall into this category in cases where it is required to measure the fiber as a whole, including both connectors (that is, *outside* the connectors). To measure the PXT in such 'end-to-end' cases, it is necessary to attach an auxiliary 'measurement PMF' to the output of the component, shown as PMF B in Figure A1(b), and perform the in-line PXT measurement along this added fiber.

The primary limitation on PM fiber crosstalk performance is usually the quality of the launch into the fiber. This is also true in the end-to-end measurements. To assure the best quality launch to the component or cable under test, adjust the input launch of the input PM fiber (PMF A) as shown in Figure A1(a). The three-loop item to the left of the input PM fiber is a polarization

controller. Alternatively, a precision connectorized source can be used. When the PXT has been adjusted far below the level required, attach the input PM fiber (PMF A) to the test device and a second PM fiber (PMF B) to the output. Take care not to change the quality of the launch into PMF A when moving the fiber connector from the polarimeter to the test device.

The measurement 'floor' of the end-to-end PXT measurement is a function of the quality of the initial launch and the quality of the various interfaces between cables and components. Better measurements can be obtained by selecting input and output PM fibers (PMF-A and -B) that have particularly good alignment and very low stress-induced birefringence. Once selected, these 'reference PM fibers' can be used repeatedly, and only occasionally replaced.

Measurement of concatenated PM fibers and components[1]

The polarimetric method also provides insight into the performance of *concatenations* of PM fibers and components. As the number of fiber

interfaces increases and the crosstalk degrades, the output polarization state becomes more strongly dependent upon temperature and mechanical stresses. An example application is shown in Figure A2. Both spans of PM fiber are stretched randomly (and independently) and the worst-case crosstalk is computed from the outer diameter of the resulting donut pattern.

It is important to realize that the worst-case PXT of a concatenation cannot be determined by stretching or heating the last segment alone. The reason for this is that the launch condition for the last segment results from the combined behavior of all of the preceding fibers and interfaces. As a result, measurement of in-line crosstalk along the final segment will give different results at different temperatures. To obtain the overall worst case, as shown in Figure A2, it is necessary to stimulate all of the fibers simultaneously and somewhat randomly. The effect of this on the Poincare sphere is to 'shade in' a region within a surrounding circle. The diameter of that circle gives the crosstalk value.
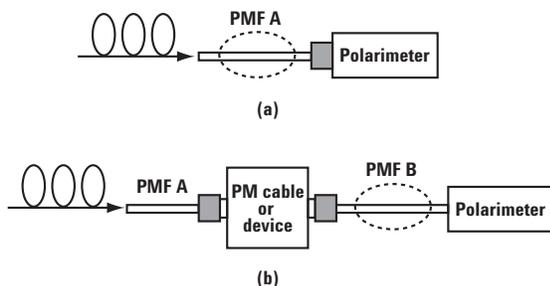
Figure A1. End to end measurement of PXT for PM fiber cables or devices.
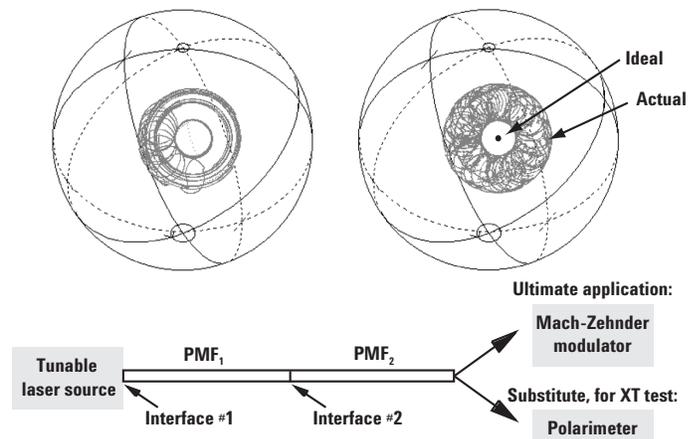
Figure A2. Measurement of the worst-case crosstalk of concatenated PM fibers.

[1]This is a very powerful 'diagnostic' type of application of the polarimetric PXT method, but the software described in this product note is not designed to process the resulting data.

Appendix B—Derivation of Equations 4d and 4e

Equations 4d and 4e are derived using trigonometric identities and defining D=1 (so that the plane is normalized). The required trigonometric identities are:

$$\cos x + \cos y = 2\cos\left(\frac{x-y}{2}\right)\cos\left(\frac{x+y}{2}\right)$$

$$\sin(x+y) = \sin x \cos y + \sin y \cos x$$

$$\sin(x-y) = \sin x \cos y - \sin y \cos x$$

$$R' = \frac{D}{2}\left(\tan\left(\frac{\alpha+\beta}{2}\right) - \tan\left(\frac{-\alpha+\beta}{2}\right)\right)$$

$$R' = \frac{D}{2}\left(\frac{\sin\left(\frac{\alpha+\beta}{2}\right)}{\cos\left(\frac{\alpha+\beta}{2}\right)} - \frac{\sin\left(\frac{-\alpha+\beta}{2}\right)}{\cos\left(\frac{-\alpha+\beta}{2}\right)}\right)$$

$$R' = D\left(\frac{\sin\left(\frac{\alpha+\beta}{2}\right)\cos\left(\frac{-\alpha+\beta}{2}\right) - \sin\left(\frac{-\alpha+\beta}{2}\right)\cos\left(\frac{\alpha+\beta}{2}\right)}{2\cos\left(\frac{\alpha+\beta}{2}\right)\cos\left(\frac{-\alpha+\beta}{2}\right)}\right)$$

$$R' = \frac{\sin\alpha}{\cos\alpha + \cos\beta}$$

$$L' = D\tan\left(\frac{\alpha+\beta}{2}\right) - R' = D\tan\left(\frac{\alpha+\beta}{2}\right) - \frac{D}{2}\left(\tan\left(\frac{\alpha+\beta}{2}\right) - \tan\left(\frac{-\alpha+\beta}{2}\right)\right)$$

$$L' = \frac{D}{2}\left(\tan\left(\frac{\alpha+\beta}{2}\right) + \tan\left(\frac{-\alpha+\beta}{2}\right)\right)$$

$$L' = \frac{D}{2}\left(\frac{\sin\left(\frac{\alpha+\beta}{2}\right)}{\cos\left(\frac{\alpha+\beta}{2}\right)} + \frac{\sin\left(\frac{-\alpha+\beta}{2}\right)}{\cos\left(\frac{-\alpha+\beta}{2}\right)}\right)$$

$$L' = D\left(\frac{\sin\left(\frac{\alpha+\beta}{2}\right)\cos\left(\frac{-\alpha+\beta}{2}\right) + \sin\left(\frac{-\alpha+\beta}{2}\right)\cos\left(\frac{\alpha+\beta}{2}\right)}{2\cos\left(\frac{\alpha+\beta}{2}\right)\cos\left(\frac{-\alpha+\beta}{2}\right)}\right)$$

$$L' = \frac{\sin\beta}{\cos\alpha + \cos\beta}$$

Appendix C—The Nelder Mead fitting algorithm

This appendix provides a short explanation of the Nelder-Mead algorithm. For a more thorough explanation, see Lagarius or Nelder, referenced in the main text.[5]

The Nelder-Mead algorithm, also called the amoeba algorithm, is a very simple numerical method of finding the minimum of a function of one or more variables. This algorithm is computationally simple and requires neither differentiation nor integration. This algorithm can also be used to find a maximum, but since this application deals with a minimum, the discussion will be based on finding a minimum. The basic concept of the algorithm is to find the minimum point of an n-variable function by defining a subspace of n+1 points that hopefully contains the minimum point. After that, the subspace is repeatedly moved and reshaped to close in on the minimum point. The weakness of this algorithm is that it can converge on a local minimum rather than global minimum and there is some debate on whether the algorithm converges completely in all cases. In this application, there is really only one minimum and the absolute convergence is not really important as precision is limited by measurement uncertainty far more than by the algorithm itself.

To fit the projected circle on the polarization plane, the function that is minimized is the standard deviation of the distance from each data point to the given point, as shown in this equation:

where n is the number of data points and x, y are the coordinates of the point under test.

$$F(x,y) = \sqrt{\frac{\sum_{i=1}^{n}\left(\sqrt{(x-x_i)^2 + (y-y_i)^2} - \sum_{i=1}^{n}\frac{\sqrt{(x-x_i)^2 + (y-y_i)^2}}{n}\right)^2}{n}} \tag{C1}$$

5. Lagarius, J.C., J.A Reeds, M.H. Wright, and P.E. Wright, "Convergence Properties of the Nelder-Mead Simplex Method in Low Dimensions,"
   SIAM Journal of Optimization, Vol. 9, Num. 1, pp 112-147, 1998.
   Nelder, J.A and R. Mead, "A Simplex Method for Function Minimization," Computer Journal, Vol. 7, pp 308-313, 1965.

Appendix C—continued

The Nelder-Mead algorithm is explained below.

Choose $n+1$ distinct arbitrary points $X_i \in \Re^n$ and let $f_i = F(X_i)$.

Also choose four algorithm constants ρ, χ, γ and σ such that:

$$\rho > 0, \quad 0 < \gamma < 1, \quad \chi > 1, \quad \chi > \rho, \quad 0 < \sigma < 1$$

(usually $\rho = 1$, $\chi = 2$, $\gamma = \sigma = 0.5$).

Step 1. ORDER the points, such that $f_1 < f_2 \ldots < f_{n+1}$.

Step 2. REFLECT $x_r = \bar{x} + \rho(\bar{x} - x_{n+1}) = (1 + \rho)\bar{x} - \rho x_{n+1}$

where $\bar{x} = \sum_{i=1}^{n} \frac{x_i}{n}$.

If $f_1 \leq f_r < f_n$ replace x_{n+1} with x_r and go to step 1.

Step 3. EXPAND If $f_r < f_1$, calculate x_e where

$$x_e = \bar{x} + \chi(x_r - \bar{x}) = \bar{x} + \rho\chi(\bar{x} - x_{n+1}) = (1 + \rho\chi)\bar{x} - \rho\chi x_{n+1}$$

If $f_e < f_r$, replace x_{n+1} with x_e and go to step 1.

Otherwise, replace x_{n+1} with x_r and go to step 1.

Step 4. CONTRACT if $f_r \geq f_n$

A. Outside if $f_n \leq f_r < f_{n+1}$.

$$x_c = \bar{x} + \gamma(x_r - \bar{x}) = \bar{x} + \rho\gamma(\bar{x} - x_{n+1}) = (1 + \rho\gamma)\bar{x} - \rho\gamma x_{n+1}$$

If $f_c \leq f_r$, replace x_{n+1} with x_{cc} and go to step 1.
Otherwise, go to step 5.

B. Inside if $f_r \geq f_{n+1}$.

$$x_{cc} = \bar{x} - \gamma(x - x_{n+1}) = (1 - \gamma)\bar{x} + \gamma x_{n+1}$$

If $f_{cc} < f_r$, replace x_{n+1} with x_{cc} and go to step 1.
Otherwise, go to step 5.

Step 5. SHRINK Replace points x_2 through x_{n+1} with $x_i = x_1 + \sigma(x_i - x_1)$.

Appendix D—Communications with the Agilent 8509 polarization analyzer

Retrieving data from the Agilent 8509 polarization analyzer is a straightforward process. Since the data is acquired while the stress or heat is applied, it is easiest to set up a timed measurement, save the data as a text file on the 8509, then retrieve the data via GPIB for processing. One caveat is that the DDE server on the 8509 server can only handle text files containing up to 83 points, so the program is limited in that respect (unless multiple data files are used). Table D-1 shows the GPIB commands

used in the data transfer. For more information, see the 8509 programmer's guide.

The data file is a comma separated text file. The first line contains the wavelength. Each line after that contains the optical power, the Stokes Parameters, and the Degree of Polarization (DOP) for one measurement point.

Single:Mode:Timed	Chooses timed measurement mode
Single:Period:0.1	Sets the measurement period to .1s
Single:Points:83	Sets the number of acquired points to 83
Single:Start	Starts the timed measurement
*OPC?	Detects the end of the timed measurement
Single:Save:"C:\data.txt"	Saves the timed measurement data to the file data.txt on the 8509
Getfile:"C:\data.txt"	Retrieves the file data.txt from the 8509

Table D1 - GPIB commands used to set-up a timed measurement and retrieve the result.

Appendix E—Example Software for the Automated, In-Line Polarization Crosstalk Measurement

A program is available that illustrates how to retrieve the raw polarization data from an Agilent 8509 polarization analyzer via GPIB, save it to a file, and then calculate the crosstalk from that data. This example was written in Microsoft Visual C++ 6.0®.

The example program can be found at **www.agilent.com/cm/rdmfg/lpa/8509c/index.shtml** in the library section of the page. (Or go to **www.agilent.com** and enter 8509C in the Quick Search box. Select the 8509C link, and go to the library section of the page.)

Because of the program size, it consists of several separate files, which are marked accordingly.

This example program is provided as an illustration "as is", and Agilent Technologies makes no warranty of any kind with regard to this example.

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