Optical Pulse Distortion Measurement Limitations in Linear Time Invariant Systems, and Applications to Polarization Mode Dispersion

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The optical pulse-distorting properties of a fiber network or device are sometimes deduced from spectral measurements or correlation measurements. In order to investigate the theoretical limitations on such deductions, single-mode optical networks are characterized in terms of linear, time-invariant filters. An optical impulse response is discussed which directly models pulse distortion in the time domain. This linear systems approach is then applied to measurements of polarization mode dispersion by Jones matrix eigenanalysis, low-coherence interferometry, and Fourier-transformed wavelength scanning (i.e., fixed analyzer) techniques. We show that, without restrictive assumptions of negligible chromatic dispersion, these techniques allow calculation of autocorrelations of output pulses, but not the output pulse shapes. We discuss the conditions under which chromatic dispersion may be neglected, and show that in this case the Jones matrix method allows calculation of the complete output pulse shape in response to an arbitrary input pulse.

1 Introduction

The importance of polarization mode dispersion (PMD) measurements for specification and evaluation of single-mode optical fiber transmission systems is now widely recognized, especially for systems designed to operate near the chromatic dispersion minimum. PMD describes the proneness of an optical channel to broaden and distort a transmitted pulse by offering two different propagation delays according to state of polarization (SOP). In simple devices with no polarization mode coupling, a single pulse at the input can be split into two orthogonally polarized pulses at the output, with the time delay between these two pulses given by the differential group delay (DGD). In practice, a long fiber typically exhibits extensive polarization mode coupling, resulting in a DGD which may be a strong function of optical frequency. In addition, details of the polarization mode coupling may change over time as temperature and strains along the fiber vary, so that a statistical model may best describe the PMD of a real system [1,2].

In the presence of extensive polarization mode coupling, the principal states of polarization and DGD may vary enough over the spectrum of an input pulse that the output pulse is smoothly broadened by PMD instead of arriving as two discrete pulses separated in time and in polarization. Under this condition, it is natural to wonder whether DGD is the most relevant quantity to be measured, i.e. the quantity most descriptive of the pulse-broadening properties of the optical channel. Among the techniques currently used for PMD measurement, Jones matrix eigenanalysis [3] calculates DGD as a function of frequency from a measured series of Jones matrices; low-coherence interferometry [4,5] measures mutual coherence between orthogonal polarizations as a function of time delay; and wavelength scanning [6,7] measures transmission through an output polarizer as a function of frequency, in response to a polarized input wave. Wavelength scanning data are sometimes inverse Fourier transformed in order to present the results as a function of time, and this temporal information is sometimes incorrectly understood to represent the output pulse shape that would be excited by a very narrow input pulse. The object of this paper is to examine whether any information relevant to pulse broadening and distortion, beyond DGD measurement, can be gleaned from any of these techniques.

For the purposes of this analysis we assume that all fibers and devices to be measured are linear, time-invariant (LTI) systems. This assumption excludes from consideration soliton transmission systems and other techniques which employ large peak optical powers and depend upon nonlinear effects in fibers. Even though the PMD characteristics of long fibers are known to drift over time, the drifts are observed to occur very slowly compared to the duration of a transmitted pulse. The restriction of time invariance is therefore easily satisfied for the purposes of analysis.

2 Linear, time-invariant filters

A LTI device or filter is completely characterized by its impulse response $\underline{h}(t)$, or equivalently by its frequency response $h(\nu)$. These two quantities are related by the Fourier transform: $\underline{h}(t) \supset h(\nu)$. [Underscored symbols represent functions of time, and the symbol $\supset$ is used to denote both forward and inverse Fourier transform relations: $\underline{h}(t) = \int h(\nu) \exp(i2\pi\nu t)\, d\nu$ and $h(\nu) = \int \underline{h}(t) \exp(-i2\pi\nu t)\, dt$.] In the case of a one-dimensional device such as an electrical filter with one input and one output, $\underline{h}(t)$ and $h(\nu)$ are scalar quantities which may in general be complex. In the time domain an input signal $\underline{a}(t)$ is related to the output signal $\underline{b}(t)$ by convolution with the impulse response; $\underline{b}(t) = \underline{h}(t) * \underline{a}(t)$, while in the frequency domain the input-output relation is multiplicative: $b(\nu) = h(\nu)\, a(\nu)$. The one-to-one relationship between the temporal convolution and frequency multiplication descriptions of the filter's behavior is central to the subject of this paper. Each relation implies the other [8]:

$$\underline{b}(t) = \underline{h}(t) * \underline{a}(t) \quad \supset \quad b(\nu) = h(\nu)\, a(\nu). \tag{1}$$

In many practical applications measurement of the phase of a filter's frequency response is difficult or impossible. In this case, deduction of temporal information is limited to finding the autocorrelation of the filter's impulse response. In terms of the correlation integral $\underline{R}\,[\underline{u}, \underline{w}]\,(t) = \int \underline{u}\,(x+t)\, \underline{w}^*(x)\, dx$, the autocorrelation of the impulse response $\underline{h}(t)$ is given by $\underline{R}\,[\underline{h}, \underline{h}]$. The power spectrum $|h(\nu)|^2$ is related to this autocorrelation by the relation $|h(\nu)|^2 \subset \underline{R}\,[\underline{h}, \underline{h}]$. The impulse response, which cannot be deduced from its autocorrelation, clearly contains the most information and is to be preferred for predicting the pulse-distorting properties of a filter. However, when only the power spectrum or autocorrelation can be measured, we still obtain the more limited description of the temporal effects of the filter given by

$$|b(\nu)|^2 = |h(\nu)|^2\, |a(\nu)|^2 \quad \subset \quad \underline{R}\,[\underline{b}, \underline{b}] = \underline{R}\,[\underline{h}, \underline{h}] * \underline{R}\,[\underline{a}, \underline{a}]. \tag{2}$$

Although the complete temporal output signal cannot be determined based on phase-insensitive spectral measurements, the autocorrelation of the output signal can be found by convolving the autocorrelation of the impulse response with the autocorrelation of the input signal.

3 Impulse responses, autocorrelations, and pulse distortion

Pulse distortion caused by propagation through a filter is directly revealed through the filter's impulse response. A Dirac delta function is the impulse response of a perfectly transparent filter which transmits a pulse with no distortion. An impulse response whose width is significant compared to an input pulse indicates that the output pulse will be distorted and broader than the input pulse. Distortion of an input pulse is modeled exactly by convolution with the filter's impulse response, but usually we find that the broader the impulse response of a filter, the stronger the filter's pulse-broadening effect, and the smoother and more gradual the transitions of the output pulse.

While measurement of an impulse response directly in the time domain is sometimes possible, often the measurement is only practical in the frequency domain, in which case measurement of the frequency response phase, as well as magnitude, is essential. At optical frequencies the frequency dependence of the phase of the frequency response, i.e. the relative phase spectrum, is much more significant than the absolute phase at any particular frequency. The relative phase spectrum determines the propagation delay, chromatic dispersion, and higher-order dispersion effects.

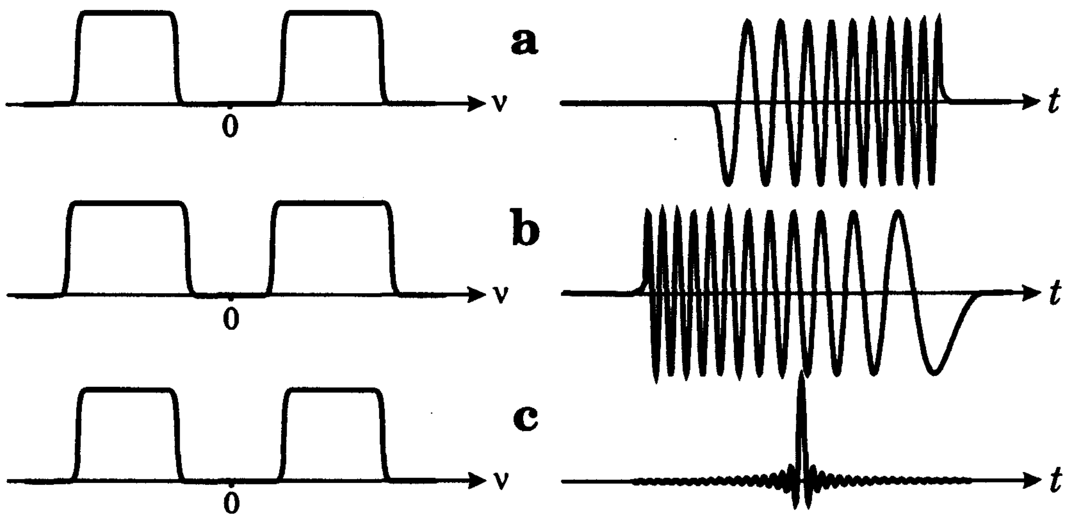

Figure 1. Interaction of a linear chirp with a matched dispersive filter. a) power spectrum and time evolution of chirped input pulse, b) matched filter frequency response magnitude and impulse response, c) power spectrum and time evolution of compressed output pulse.

When only the magnitude of a filter's frequency response is measured, allowing calculation of only the autocorrelation of the impulse response, modeling of the pulse distortion caused by the filter is much more limited and restricted in application. As an example analogous to the effect of chromatic dispersion upon a chirped optical pulse, consider a long chirped rf pulse interacting with a matched dispersive filter, as shown in Fig. 1. The magnitude of the spectrum of a long chirped pulse is essentially constant over the frequency range of the chirp, while the phase of the spectrum is quadratic in frequency. The impulse response of the matched filter is a time-reversed conjugate version of the input pulse, and has a similar spectrum. The output pulse, which is much shorter than the input pulse, is accurately predicted by convolution of the impulse response with the input pulse, or by multiplication of the frequency response with the input spectrum, including the phases of each. However, if we cannot measure phase, our view of the filtering effect is much more limited. In that case, the power spectrum of the input pulse and the frequency response magnitude are both constant over the frequency range of the chirp, resulting in identical power spectra for the input and output pulses. These identical power spectra, while satisfying (2), do not represent identical pulses. This demonstrates that the pulse-compressing effect of the matched filter cannot be discerned by phase-insensitive spectral measurements or by measurement of the impulse response autocorrelation. The same analysis can be applied to a chirped optical pulse propagating through a fiber exhibiting chromatic dispersion. Therefore, the effects of chromatic dispersion cannot be discerned by measurements not sensitive to the relative phase spectrum of an optical filter.

If the effects of the relative phase spectrum, such as chromatic dispersion, are assumed to be negligible, the pulse distortion caused by a filter can be modeled through the convolution of autocorrelations (2). Again, a broader impulse response autocorrelation indicates a stronger pulse-broadening effect. However, given the strong effect of the relative phase spectrum upon the output pulse shape, properties of the phase spectrum must not be assumed carelessly.

4 Two-dimensional linear systems and polarization

The clarity and familiarity of linear systems theory can be extended to the analysis of single-mode fiber systems by adding a second dimension to accommodate the effects of polarization, birefringence, and dichroism. Just as a one-dimensional electrical signal can be uniquely represented by a spectrum including both amplitude and phase, an optical signal can be uniquely represented by a two-element complex vector spectrum. The two elements of the vector represent the amplitudes and phases, at a fixed point in space, of two orthogonal electric field vectors giving rise to the traveling optical wave. In general the vector is a function of the optical frequency, hence it is the vector spectrum of the optical field at a particular point.

As originally introduced, the elements of the Jones vector $\boldsymbol{a}$ represented the x and y components of the electric field vector of the propagating light wave at a fixed point in space [9]. All fields were assumed to be periodic, and since only LTI devices were treated the ubiquitous periodic phase term $\exp(i2\pi\nu t)$ could be dropped. The remaining amplitude and phase terms formed a vector which described the optical polarization. These ideas can be expanded to allow treatment of more complicated, nonperiodic signals. By retaining the optical phase of each vector element, and by dealing with vectors which are functions of the optical frequency ν, we generalize Jones vectors to form vector spectra. The frequency-dependent vector spectrum $\boldsymbol{a}(\nu)$ can be related to the time-dependent electric field vector $\underline{a}(t)$ through the Fourier transform $\underline{a}(t) \supset \boldsymbol{a}(\nu)$. Any physically meaningful optical signal can be equivalently represented in either form.

The Jones calculus models the changes imposed on an optical field by propagation through an optical device by multiplying the input Jones vector by a Jones matrix representing the device. Just as for optical fields, by retaining the optical phase of each matrix element, and by dealing with a matrix which is a function of ν, we can generalize this idea to form a frequency response matrix $\boldsymbol{T}(\nu)$ analogous to the frequency response of one-dimensional linear systems. Given a vector spectrum $\boldsymbol{a}(\nu)$ at the input to a device whose frequency response matrix is $\boldsymbol{T}(\nu)$, the output vector spectrum $\boldsymbol{b}(\nu)$ is then given by $\boldsymbol{b}(\nu) = \boldsymbol{T}(\nu)\, \boldsymbol{a}(\nu)$. Because we are dealing with LTI systems, the Fourier transform allows direct calculation in the time domain through the concept of the impulse response. Hence, any single-mode optical LTI device can be characterized by an impulse response matrix $\underline{T}(t)$ as well as by a frequency response matrix $\boldsymbol{T}(\nu)$, and the two matrices form a Fourier transform pair: $\underline{T}(t) \supset \boldsymbol{T}(\nu)$. The relationship between the input field $\boldsymbol{a}(\nu)$ and the output field $\boldsymbol{b}(\nu)$ represented by multiplication in the frequency domain is then equivalently represented by convolution in the time domain, i.e.

$$\underline{b}(t) = \underline{T}(t) * \underline{a}(t) \quad \supset \quad \boldsymbol{b}(\nu) = \boldsymbol{T}(\nu)\, \boldsymbol{a}(\nu), \tag{3}$$

where the matrix convolution is carried out similarly to matrix multiplication.

The analogy between the matrix relation (3) and the scalar relation (1) is obvious. Evidence of pulse distortion caused by propagation through a LTI device or network is revealed in the time domain within the impulse response matrix. The diagonal terms of $\underline{T}(t)$ describe the x-polarized response to an x-polarized impulse, and the y-polarized response to a y-polarized impulse. The off-diagonal terms describe the x-polarized response to a y-polarized impulse, and the y-polarized response to an x-polarized impulse. $\underline{T}(t)$, when it can be measured or inferred, can be used to completely determine how the shape of a pulse is distorted by propagation through a fiber channel, including the effects of chromatic dispersion and PMD.

In many situations the relative phase spectrum cannot be measured, in which case the best we can do is to look for an analog to (2) which will describe the effect of a transmission system upon the autocorrelation of an input signal. The most direct analog in the frequency domain is $|\boldsymbol{b}(\nu)|^2 = \boldsymbol{a}^\dagger(\nu)\, \boldsymbol{T}^\dagger(\nu)\, \boldsymbol{T}(\nu)\, \boldsymbol{a}(\nu)$, where $\boldsymbol{a}^\dagger$ is the transposed complex conjugate of $\boldsymbol{a}$. To see how this relation can be expressed in terms of correlation integrals it is simplest to directly calculate the squared magnitudes of the components of the input-output relation $\boldsymbol{b}(\nu) = \boldsymbol{T}(\nu)\, \boldsymbol{a}(\nu)$:

$$|b_1|^2 = |T_{11}|^2 |a_1|^2 + |T_{12}|^2 |a_2|^2 + 2\,\mathrm{Re}(T_{11}\, T_{12}^*\, a_1\, a_2^*) \tag{4a}$$

$$\begin{aligned} \subset \quad \underline{R}[\underline{b}_1, \underline{b}_1] &= \underline{R}[\underline{T}_{11}, \underline{T}_{11}] * \underline{R}[\underline{a}_1, \underline{a}_1] \;+\; \underline{R}[\underline{T}_{12}, \underline{T}_{12}] * \underline{R}[\underline{a}_2, \underline{a}_2] \\ &\quad + \underline{R}[\underline{T}_{11}, \underline{T}_{12}] * \underline{R}[\underline{a}_1, \underline{a}_2] \;+\; \underline{R}[\underline{T}_{12}, \underline{T}_{11}] * \underline{R}[\underline{a}_2, \underline{a}_1], \end{aligned} \tag{4b}$$

$$|b_2|^2 = |T_{21}|^2 |a_1|^2 + |T_{22}|^2 |a_2|^2 + 2\,\mathrm{Re}(T_{21}\, T_{22}^*\, a_1\, a_2^*) \tag{5a}$$

$$\begin{aligned} \subset \quad \underline{R}[\underline{b}_2, \underline{b}_2] &= \underline{R}[\underline{T}_{21}, \underline{T}_{21}] * \underline{R}[\underline{a}_1, \underline{a}_1] \;+\; \underline{R}[\underline{T}_{22}, \underline{T}_{22}] * \underline{R}[\underline{a}_2, \underline{a}_2] \\ &\quad + \underline{R}[\underline{T}_{21}, \underline{T}_{22}] * \underline{R}[\underline{a}_1, \underline{a}_2] \;+\; \underline{R}[\underline{T}_{22}, \underline{T}_{21}] * \underline{R}[\underline{a}_2, \underline{a}_1], \end{aligned} \tag{5b}$$

$$\text{where}\quad \boldsymbol{a} = \begin{bmatrix} a_1 \\ a_2 \end{bmatrix}, \quad \boldsymbol{b} = \begin{bmatrix} b_1 \\ b_2 \end{bmatrix}, \quad \boldsymbol{T} = \begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix}.$$

Relations (4b) and (5b) are analogous to (2) in that they express the connections between correlations of the output signal, input signal, and impulse response. The important distinction of the two-dimensional case lies in the third and fourth right-hand terms of (4b) and (5b), where we see the output autocorrelation is influenced by the cross-correlation between input signal polarizations convolved with cross-correlations between elements of the impulse response matrix. Consequently, prediction of the autocorrelation of an output pulse requires knowledge of both: 1) correlations between elements of the impulse response matrix, which reflect differential propagation delay, and 2) correlations between orthogonal polarizations of the input signal, which reflect their mutual temporal coherence.

5 Application to PMD measurements

We now address the issue of what fundamental limitations apply to the information deduced from various PMD measurements. Measurements obtained by Jones matrix eigenanalysis and by wavelength scanning, i.e. the fixed analyzer technique, will be considered in some detail, and measurements obtained by interferometry will be analyzed more briefly. PMD measurement by Jones matrix eigenanalysis (Fig. 2) is based upon a series of Jones matrices measured at a sequence of discrete optical frequencies. The matrices are calculated from measurements of three states of polarization at the device output in response to three known input states at each frequency [10]. This series of matrices $\boldsymbol{C}_n$ is the frequency response matrix $\boldsymbol{T}(\nu)$ sampled at a sequence of frequencies $\nu_0 + n\,\Delta\nu$, with the exception that in the measurement process each matrix is multiplied by an arbitrary phase term

$\exp(\phi_n)$, so that $C_n = \exp(\phi_n) T(\nu_0 + n\,\Delta\nu)$. ϕ_n is usually chosen to obtain a zero imaginary component for one element of C_n, e.g. $\mathrm{Im}(C_{n,22}) = 0$.

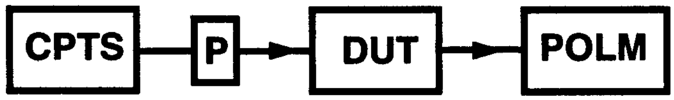

Figure 2. Measurement of polarization mode dispersion using Jones matrix eigenanalysis. CPTS: circularly-polarized tunable source; P: linear polarizer; DUT: device or network under test; POLM: polarimeter. At each of a series of optical frequencies, P is rotated to three known orientations and the resulting three output states of polarization are measured, yielding a Jones matrix representing the DUT.

Clearly, the impulse response matrix of a network is the most useful quantity to obtain because it reflects *all* of the network's linear properties, including pulse distortion induced by PMD and chromatic dispersion. Within the limitations of discrete inverse Fourier transforms [8], the sequence C_n would yield the impulse response matrix if ϕ_n were known. Effects of PMD become most important when the transmission system is operated at a wavelength where chromatic dispersion is minimum. In this region one might assume that the frequency response phase is proportional to frequency, reflecting a pure nondispersive propagation delay, and that for purposes of modeling pulse distortion the relative phase spectrum can be approximated as a constant phase since time delay is irrelevant. Again, this assumption must not be made carelessly, as chromatic dispersion will generally not vanish even at the dispersion minimum. Once this assumption is accepted, however, the sequence $C_n = T(\nu_0 + n\,\Delta\nu)$ yields the impulse response matrix $\underline{T}(t) \supset T(\nu)$, which can be used as a measure of all linear behavior of the network in question, including pulse distortion caused by any degree of distributed birefringence and polarization mode coupling, and even pulse distortion caused by mutual coherence between input pulses occurring at different times and polarizations. Because spectral measurements are transformed to obtain the impulse response matrix, in order to obtain a temporal resolution of δt it is necessary to measure over a frequency range of at least $1/\delta t$, and the assumption of sufficiently small chromatic dispersion must be evaluated over this full range. Chromatic dispersion, measured as $d\tau/d\nu$ where τ is the group delay through the entire system or device, is sufficiently small when it is less than δt^2.

We next consider what conclusions can be drawn from the Jones matrix sequence C_n when assumption of negligible chromatic dispersion is not appropriate.

In this more general case our deductions regarding temporal behavior are restricted to the correlations expressed in (4b) and (5b). As the phase term ϕ_n does not affect (4a) and (5a), the autocorrelations of the two output pulse polarizations can be calculated exactly, even allowing for mutual coherence between orthogonal polarizations of the input pulse. The Jones matrix sequence C_n upon which eigenanalysis is based can be inverse Fourier transformed to yield a matrix form of system impulse response autocorrelation which is valid for any input pulse conditions of polarization and mutual coherence.

Figure 3. Measurement of polarization mode dispersion using wavelength scanning. LED: broadband light emitting diode; P: linear polarizer; DUT: device or network under test; OSA: optical spectrum analyzer. The density of extrema in the spectral transmission through the polarizers and DUT yield an average value of differential group delay.

Analysis of the wavelength scanning or fixed analyzer PMD measurement technique (Fig. 3) is simplified by working in an orthonormal input basis comprised of the blocked and preferred SOP's defined by the input polarizer, and an output orthonormal basis similarly defined by the output polarizer. The wavelength scanning technique directly measures the squared magnitude of one element of the frequency response matrix represented in this basis pair. By measuring the transmission spectrum as the input and output polarizers are sequentially set to 0 and 90 degrees, it is possible to measure the squared magnitudes of all four elements of the frequency response matrix. Because power spectra are measured, deductions regarding temporal behavior are again restricted to the correlations expressed in (4b) and (5b). When the input pulse is polarized at 0 or 90 degrees, $\underline{R}\,[\underline{a}_1, \underline{a}_2] = 0$ and the autocorrelations of the two output pulse polarizations can be calculated using (4b) and (5b). However, other input pulse polarizations will result in a nonzero $\underline{R}\,[\underline{a}_1, \underline{a}_2]$, in which case no autocorrelation of the output pulse can be found because $T_{11}(\nu)\, T_{12}^{*}(\nu)$ cannot be calculated from the squared magnitudes of the elements of $\boldsymbol{T}(\nu)$. In other words, inverse Fourier transformed wavelength scanning data yields the autocorrelation of the system impulse response only when the input is restricted to the polarization at which the measurement was taken. This restriction becomes less important for measurements of systems with extensive polarization mode coupling because the characteristics of such systems are understood to be statistical in nature, so that the measured autocorrelation of the system impulse response is understood to be merely representative of the actual impulse response at a particular time.

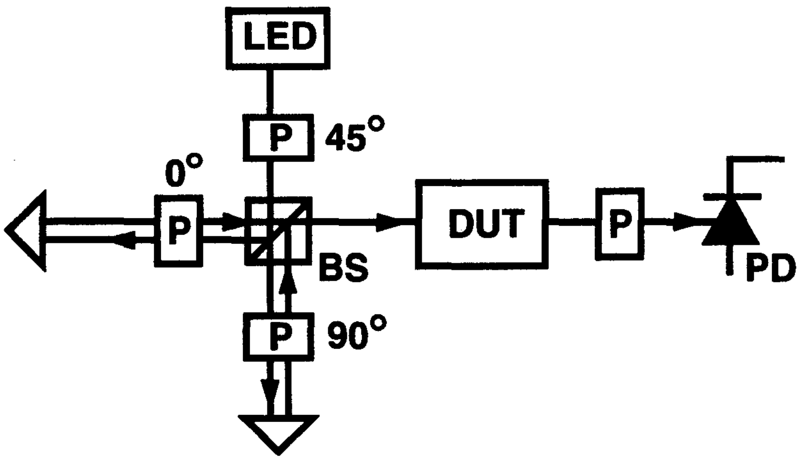

Figure 4. Measurement of polarization mode dispersion using interferometry. LED: broadband light emitting diode; P: linear polarizer; BS: beamsplitter; DUT: device or network under test; PD: photodiode. Interference fringes are detected only when the differential delay between orthogonal input states is compensated by the differential group delay of the DUT.

The interferometric method of PMD measurement (Fig. 4) is directly sensitive to correlations between orthogonal polarizations of the output of a system in response to a polarized input, or to correlations between orthogonal input components when detected through an output analyzer. The result is measured directly in the time domain. This measurement has been shown to duplicate the results of inverse Fourier transformed wavelength scanning measurements to within the variation caused by small fiber pigtail birefringences [11]. As a result, interferometric measurements are similarly limited to autocorrelations of the system impulse response, and are rigorously valid only when the input is restricted to the polarization(s) at which the measurement was taken.

6 Summary

A single-mode optical transmission network or component can be modeled as a linear, time-invariant filter with a 2-by-2 matrix frequency response and matrix impulse response. The matrix impulse response can be convolved with an input pulse to directly yield the output pulse in time and polarization. When only the autocorrelation of the impulse response can be measured, it provides a more limited, but still useful, model of the pulse-distorting properties of the network or component.

The three PMD measurement techniques investigated, Jones matrix eigenanalysis, wavelength scanning, and interferometry, are as a group limited to measurement of correlations of the elements of the impulse response matrix, allowing calculation in some cases of an output pulse autocorrelation in response to an input pulse. Just as in the case of a chirped rf pulse interacting with a dispersive matched filter, autocorrelations of the output pulse do not rigorously specify the pulse shape or the pulse width, but they can give a tentative indication of the output pulse width when there is no reason to expect that the relative phase spectrum of the output pulse is significantly chirped or in other ways able to hide a broad pulse within a narrow autocorrelation. The Jones matrix technique can rigorously model the output pulse autocorrelation for any input signal, while the wavelength scanning and interferometric techniques yield autocorrelation models which are valid only when the input and output pulses are limited to the polarizations allowed by the polarizers used in the measurement process. This distinction is not important in measurements of highly mode-coupled systems such as long fibers.

Finally, when chromatic dispersion is known to be negligible over the frequency span of interest, the Jones matrix technique yields the full matrix impulse response. This allows calculation of the output pulse shape, not merely its autocorrelation, in response to any input pulse covered by the measured frequency span, including pulse distortion caused by any degree of distributed birefringence and polarization mode coupling, and even caused by mutual coherence between input pulses occurring at different times and polarizations.

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