# Interferometric Measurement of Dispersion in Optical Components

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## 1. Introduction

As optical communications systems begin to fill the available bandwidth in an optical fiber by transmitting either 40 Gb/s on 200 GHz channel spacings or 10 Gb/s on 50 GHz channel spacings, the optical phase response of the components deployed in the systems will need to be carefully controlled. The dominant method of obtaining this optical phase measurement is commonly called the modulation phase-shift method[1], and uses an amplitude modulation of a narrow linewidth tunable laser to measure dispersive properties of optical devices.

If the bit rate is a small fraction of the channel spacing, the dispersion caused by the transmission system, optical fiber and amplifiers, will dominate the phase characteristics of the entire system. If one wishes to measure the dispersive qualities of a long (>1km) broadband (10's of nm) device, such as a length of optical fiber, the modulation phase-shift method is ideal and produces excellent results. The success of the modulation phase-shift measurement technique for fiber-link characterization has lead to its acceptance as the preferred method of characterizing the optical phase response of optical components, and in particular DWDM (Dense Wave Division Multiplexing) components.

When the modulation phase-shift method is applied to DWDM components, however, some problems can arise. In particular, DWDM devices are not spectrally broad by design, and as a result, both the phase and amplitude can vary rapidly with wavelength. Since the modulation phase-shift method measures the derivative of the phase with respect to frequency (i.e. group delay), the optical phase response of the device must be recovered through integration. This additional step of integrating the measurement introduces further error into the measurement, thus tightening the tolerance on the underlying group-delay measurement.

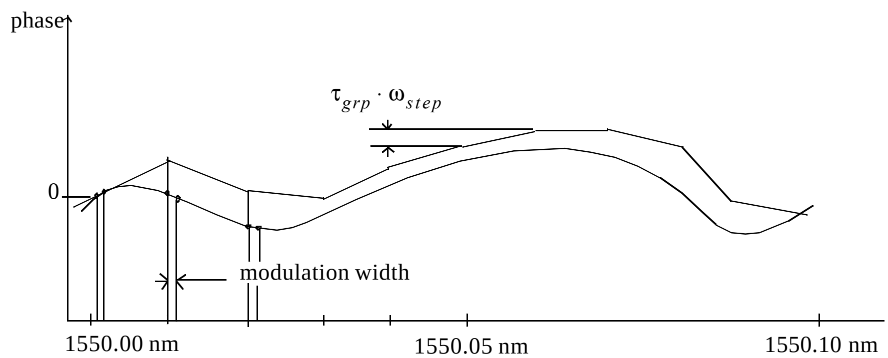


Figure 1. Graphical description of the phase reconstruction process from a typical modulation phase-shift technique (200 MHz modulation, 10 pm step size). Note that in addition to the uncertainty of the group delay measurement, effects of uncertainty in the wavelength at which the measurement was taken must also be taken into account.

Interferometric approaches to optical phase measurement avoid this problem by measuring the optical phase directly through interference techniques. If the goal of a measurement is to characterize some linear system, $H(\omega)$, then the amplitude and phase of the system must be measured at a frequency resolution that will satisfy the Nyquist sampling criterium,

$$\frac{2\pi}{\Delta\omega} > t_{duration}\,. \qquad (1)$$

where $t_{duration}$ is the duration of the impulse response of the device under test (DUT). Equivalently, one could measure the amplitude and phase of $h(t)$, where,

$$h(t) = \frac{1}{2\pi}\int_{-\infty}^{\infty} H(\omega)e^{i\omega t}d\omega \qquad (2)$$

and the time resolution of the measurement satisfies the Nyquist criteria,

$$\frac{2\pi}{\Delta t} > \omega_{width}\,. \qquad (3)$$

where $\omega_{width}$ is the spectral width of the DUT. Each of these functions, $h(t)$ or $H(\omega)$ can be measured using a simple Mach-Zehnder interferometer like that shown in Figure 2

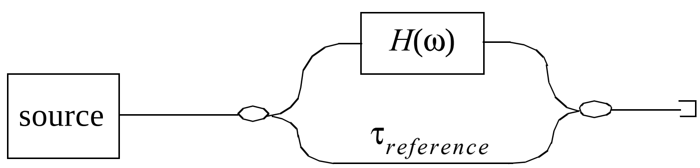


Figure 2. Basic Mach-Zehnder set-up for interferometric characterization of optical components. If a broadband source is used and $\tau_{reference}$ is varied, then $h(t)$ is measured in a technique known as Optical Low Coherence Reflectometry (OLCR). If $\tau_{reference}$ is held constant, and the source is a scanning tunable laser, then $H(\omega)$ is measured in a technique known as Optical Frequency Domain Reflectometry (OFDR)

Measurement accuracies of better than 1 ps have been reported for both Optical Low-Coherence Reflectometry (OLCR) measurements [2], and Optical Frequency Domain Reflectometry (OFDR). It is crucial to recognize, however, that in these measurements, the group delay is a computed value and not the basic measurement. In these interferometric measurements, the optical phase response of the device is obtained directly, and the group delay computed from this direct measurement of the optical phase. Since optical phase is a more fundamental quantity for describing the behavior of optical components, it might be worthwhile to examine the sort of specification that is needed for measurement systems capable of optical phase measurements.

**2. Example Tolerances on Measurements for 40 Gb/s**

We will assume here, a 40 Gb/s data link, and, for simplicity, a NRZ format will be assumed. A theoretical spectrum of such a signal is shown in Figure 3.

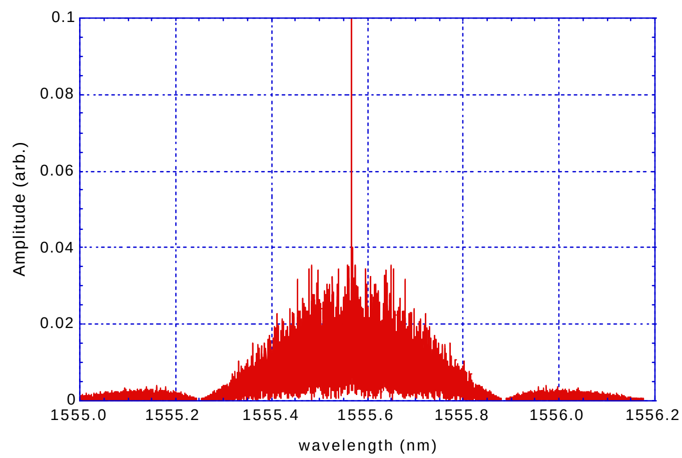


Figure 3. A calculated spectrum of a 40 Gb/s NRZ signal.

If the signal is to be accurately reconstructed, a general rule of thumb is that the largest phase error (deviation from linear phase) over the operational bandwidth must be less than a quarter of a wave, or $\pi/2 \approx 1.6$ radians. In order to keep the phase error below this level, the average group delay must be constant over the width of the signal spectrum to a tolerance of,

$$\tau_{grp} < \frac{d\varphi_{max}}{\Delta\omega_{width}} = \frac{\pi/2}{2\pi(80\times10^{9}\ \text{Hz})} = 3.1\ \text{ps}\,. \qquad (4)$$

In practice, a single component cannot use the entire error budget, and so it will be necessary to decrease the tolerance on any single component by some factor; here we will use a factor of 5 simply for argument. At a minimum, the measurement system will need to be a factor of 3 better than the specified tolerance on the component and we end up requiring a measurement system with an accuracy of,

$$\Delta\tau_{grp} < \frac{3.1}{5\cdot 3}\ \text{ps} = 0.2\ \text{ps}\,. \qquad (5)$$

If we have a direct measurement of optical phase, as presented here, then the required accuracy of the phase measurement in order to maintain the equivalent component performance is,

$$\Delta\varphi < \frac{\pi/2}{5\cdot 3}\ \text{radians} = 0.10\ \text{radians} \qquad (6)$$

This level of phase error will cause an apparent group delay error of 13 picoseconds over a 10 pm differentiation interval. This apparent reduction in the required accuracy of the instrument occurs because the phase change can be referred directly to any particular point in the spectrum, and so, if we calculate the group delay accuracy over the entire 80 GHz spectrum, we obtain the same required tolerance of 0.2 ps.

It is interesting to note that the specification of the direct phase measurement is not a function of the bandwidth of the signal. When using direct phase measurement the tolerancing of parts also does not change with bandwidth (unless the error budget of $\pi/2$ is changed or reallocated), only the spectral range over which the tolerance must be maintained. The ability to standardize on a single error level and simply extend this level over a broader range for wider bandwidth components would put an end to a great deal of confusion in the industry over how to characterize the phase response of optical components.

Figure 4, is an example of a phase characterization of a fiber optic component. In this case, the component is a dispersion compensating fiber Bragg grating manufactured by Lucent Specialty Fiber devices in Somerset, NJ.  A dispersion compensator with perfectly linear group delay will have a

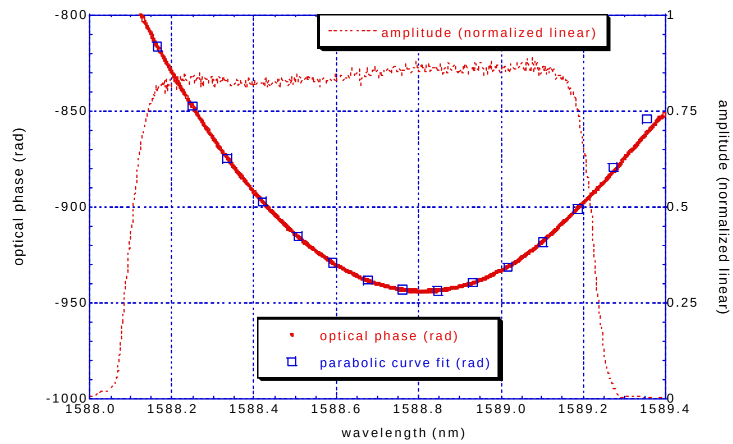


Figure 4.  Graph of the amplitude and phase characteristics of a dispersion compensating fiber Bragg grating. Selected points of a parabolic curve fit to the phase data are also shown to illustrate the accuracy of the phase profile.

parabolic optical phase. Any departure from this parabolic phase will lead to distortions in the detected signal. In Figure 5 we have plotted the result of subtracting a fitted parabola from the measured optical phase.   Above we estimated the required tolerancing on an optical component to be around 0.3 radians

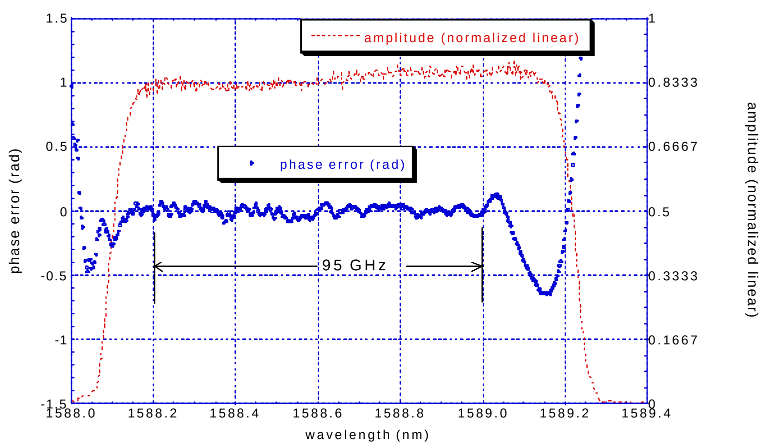


Figure 5. Plot of the phase deviation from parabolic of the data shown in Figure 4. This grating would introduce very little phase(<0.2 radians) distortion over a 95 GHz bandwidth.

over 80 GHz for a 40 Gb/s link, and this device appears to satisfy this requirement over a range greater than 95 GHz.

### 3. Polarization Fading and the Vector Nature of Light

A general problem with interferometric measurement techniques is that light is a complex vector, and the dot product of the reference and measurement fields affects the amplitude of the measured field. This is most commonly dealt with by inserting a polarization controller in the reference of measurement arm such that the light is incident on one of the principle states of the device. Another, more effective means of dealing with the vector nature of light in interferometry is polarization diversity detection [3]. Polarization diversity detection uses a polarizing beam splitter following the recombining coupler. If the reference power is equally distributed between the two states of the polarizing beamsplitter, then two orthogonal components of the light transmitted by the device will be detected.

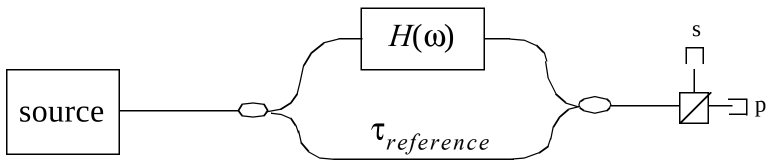


Figure 6. A Mach-Zehnder set-up for interferometric characterization of optical components using polarization diversity detection.

If one constructs this apparatus and carries out the measurement of the complex response of the device a vector response is obtained,

$$\vec{H}(\omega) = \begin{bmatrix} H_s(\omega) \\ H_p(\omega) \end{bmatrix} \tag{7}$$

from this measurement, we can calculate the group delay using a dot product to be,

$$\tau_{grp}(\omega) = \frac{\arg\{\vec{H}(\omega + \Delta\omega) \bullet \vec{H}^*(\omega)\}}{\Delta\omega} . \tag{8}$$

The system shown in Figure 6 characterizes the system response to a particular input polarization. If we want to know how a system responds to all polarization states, we will need a matrix characterization, commonly known as the Jones matrix. If we are able to measure a Jones matrix of a device,

$$\bar{J}(\omega) = \begin{bmatrix} a(\omega) & b(\omega) \\ c(\omega) & d(\omega) \end{bmatrix} \tag{9}$$

then we should be able to calculate all of the polarization dependent characteristics as well as the insertion loss and group delay. Fortunately the algorithms by which Polarization Mode Dispersion (PMD) and Polarization Dependent Loss (PDL) can be calculated have already been derived and can be found in the literature.

With PMD, we once again encounter the same problem that we did with group delay. PMD is a derivative measurement, and even more problematic, it is always positive. Thus, if we wish to accumulate the phase delay over frequency, it is not possible for any cancellation to occur.  This difference in the rate of change of phase between two polarization states is not really of central interest, though. The goal of the system is to accurately reconstruct the optical signal at the detector. In order to do this, the electric fields comprising the signal must maintain a constant polarization across the transmission bandwidth. As frequency components of the signal move out of alignment with each other, they do not properly interfere at the detector, and signal definition is lost. This "fading" of signal elements is the most direct measure of the impact of PMD on our signal reconstruction.

From this idea, we can construct an "effective polarization spectrum." First, an electric field vector is propagated through the system matrix, $\bar{J}(\omega)$ at the nominal center frequency of the channel, $\omega_0$. Generally, $\omega_0$ will be a frequency on the ITU grid. The same electric field is then propagated at all frequencies, and the dot product of these propagated fields is taken with the field propagated through the center wavelength matrix. The amplitude of this dot product is then minimized with respect to the input electric field state to give the worst possible fading to the signal component. If we then normalize the result to eliminate loss effects, we can write this as,

$$P_r(\omega) = \frac{\min_{\theta\phi}\left|\left\{\bar{J}(\omega_0)\begin{bmatrix} e^{i\phi}\sin\theta \\ e^{-i\phi}\cos\theta \end{bmatrix}\right\} \bullet \left\{\bar{J}(\omega)^*\begin{bmatrix} e^{-i\phi}\sin\theta \\ e^{i\phi}\cos\theta \end{bmatrix}\right\}\right|}{\left|\bar{J}(\omega_0)\begin{bmatrix} e^{i\phi}\sin\theta \\ e^{-i\phi}\cos\theta \end{bmatrix}\right|\left|\bar{J}(\omega)^*\begin{bmatrix} e^{-i\phi}\sin\theta \\ e^{i\phi}\cos\theta \end{bmatrix}\right|}. \qquad (10)$$

The polarization spectrum defined above in Equation 10 will by definition be unity at the center wavelength, and decrease from there.

If we apply this measurement to a PM fiber length having a total differential delay of 7 ps, we get the data shown in Figure 7. If we allow a total fringe fading of 75%, and allocate a fifth of this error to the device in question, we find that we have about 30 GHz of usable bandwidth.

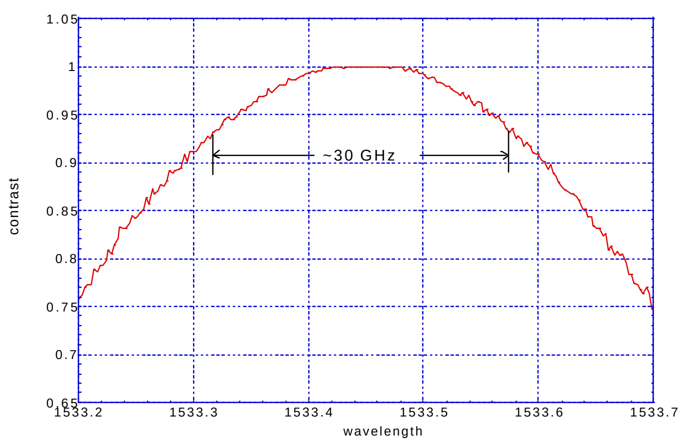


Figure 7. Plot of the effective polarization spectrum of a PM fiber patchcord having a differential group delay of 7 ps. The effective polarization spectrum was computed from the Jones Matrix representing the device using Equation 10.

## 4. Conclusion

The development of high quality tunable lasers and very bright incoherent sources has made high quality interferometric measurements available to the telecommunications community. These measurements have advantages at the fundamental level because they allow linear systems concepts and analysis to be brought to bear on optical fiber systems. In particular phase characteristics that have been previously measured as derivatives can be acquired directly allowing more consistent evaluation and qualification of optical components for high bit-rate systems.

## 5. References


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