Fourier-domain low-coherence interferometry for differential mode delay analysis of an optical fiber

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We propose a novel mode analysis and differential mode delay measurement method for an optical fiber using Fourier-domain low-coherence interferometry. A spectral interferometer based on a Mach–Zehnder interferometer setup was used with a broadband source and an optical spectrum analyzer to detect relative temporal delays between the guided modes of a few-mode optical fiber by analyzing spectral interference signals. We have shown that experimental results of the proposed method agree well with those results obtained by using a conventional time-domain measurement method. We have demonstrated that this new mode analysis technique has high sensitivity (>60 dB) and very good resolution (<1 ps/m). © 2006 Optical Society of America

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Differential mode delay (DMD) defines relative group delay within guided modes in a multimode optical fiber or an optical waveguide device. As each mode in a fiber or a waveguide is propagating with a different speed, there exist temporal delays between optical pulses at the end of a device after propagating through different modes in it when an optical short pulse is launched into a fiber. The maximum value in this relative temporal delay is called the DMD of a multimode optical device.¹ There are several DMD analysis methods for a multimode optical device: optical time-domain method,² optical frequency-domain method,³,⁴ and interferometric method.⁵ The optical time-domain DMD measurement method uses a short optical pulse as an optical impulse to a device under test (DUT) and measures the output impulse response of the DUT. The output pulse form is measured in the time domain with a high-speed detection system. Either a streak camera or a fast photodetector combined with a sampling oscilloscope is normally used for a high-speed temporal pulse-shape measurement. Optical frequency-domain differential mode delay measurement method is based on an optical frequency-domain reflectometer.

In this Letter we propose a novel new temporal mode delay measurement method based on Fourier-domain low-coherence interferometry (fLCI) or Fourier-domain optical coherence tomography (FD OCT).⁶ fLCI is a recently proposed technique to obtain depth-resolved spectra of scattered light that adapts techniques used in light-scattering spectroscopy and low-coherence interferometry. Unlike in optical low-coherence reflectometry⁸ or conventional time-domain optical coherence tomography⁹ (OCT), no moving part is needed to obtain interference data in a fLCI or a FD OCT system. This makes the use of fLCI or FD OCT to obtain very accurate and reliable interference data much faster than optical frequency-domain reflectometer or time-domain OCT.

By employing techniques used in fLCI or FD OCT, we have demonstrated the possibility of resolving modal delays of excited modes in an optical fiber. To our knowledge, this is the first time that an analysis of the mode distribution in a short length optical fiber is done by using a fLCI or a FD OCT system. Figure 1 shows the schematic diagram of our proposed method to analyze modal delays in an optical fiber. The configuration is based on a fiber Mach–Zehnder interferometer with a broadband light source and an optical spectrum analyzer (OSA, Agilent 86142B). Instead of using a Michelson interferometer, we use a Mach–Zehnder interferometer to have a single pass through a sample fiber. A few-mode optical fiber is prepared and inserted into one arm of the interferometer, and the other arm has a free-space delay path with two fiber collimators. In this configuration spectral frequency components in fLCI data are due to differences in temporal propagation speed for the excited modes of an optical fiber. Fourier transformation of spectral interference data can yield peaks in the time domain that correspond to temporal delays between excited modes in an optical fiber. The inter-

Fig. 1. (Color online) Schematic diagram of the Mach–Zehnder-type fLCI for mode analysis of an optical fiber. 5/5, 50/50 directional coupler; pc, polarization controller; FUT, fiber under test; OSA, optical spectrum analyzer; Ref., reference air line.
is the length of the tested fiber, the translation stage to control the modulation period of light into two different paths. The length of the reference signal and the signal in the \( m \)th excited mode. After doing Fourier transformation we have the relative phase term as

\[
\phi_m(f) = \beta_m(f)L - 2\pi \tau_0 f,
\]

where \( \beta_m(f) = \beta_m - 2\pi f_0 \) and \( \beta_m = \beta_m / L \) where \( \beta_m = \) the propagation constant for the \( m \)th excited mode.

We can rewrite the relative phase term as

\[
\phi_m(f) = \beta_m(f) L - 2\pi \tau_0 f,
\]

where \( \beta_m(f) = \beta_m - 2\pi f_0 \) and \( \beta_m = \beta_m / L \) where \( \beta_m = \) the propagation constant for the \( m \)th excited mode. After doing Fourier transformation we have

\[
\phi_m(f) = \beta_m(f) L + 2\pi \beta_m(L - \tau_0 f)
\]

where \( \beta_m = \beta_m / L = \) the group delay of the \( m \)th excited mode. After doing Fourier transformation we have

\[
\Gamma(t) = \left( N + \sum_m a_m^2 \right) G(t) + \sum_m a_m \left( \delta(t - (\tau_m - \tau_0)) \right)
\]

where \( \delta(t) \) is a standard convolution operator, \( G(t) \) is the Fourier transform of the source spectrum given as

\[
G(t) = \int |E(f)|^2 e^{i2\pi ft} df.
\]

Equation (3) indicates that there are peaks at \( t = \pm (\tau_m - \tau_0) \), and these peaks correspond to the group delays of excited modes in an optical fiber.

An LED that has a center wavelength of 1550 nm and a 3 dB bandwidth of 50 nm is used as a broadband light source. A 3 dB fiber coupler is used to split light into two different paths. The length of the reference arm of the interferometer is changed by a translation stage to control the modulation period of the test sample. The calculated DMD of the test fiber using our proposed method is plotted with a thick solid curve in Fig. 4. The horizontal axis was normalized by the length of the sample fiber. The positions of the first, second, and third peaks are 55.72, 66.59, and 71.80 ps/m, respectively. The DMD or the maximum modal delay in the excited modes of a fiber is 16.08 ps/m, which is the relative temporal delay between the first and the third peaks.

The full width at half-maximum (FWHM) of the first and the third peaks are about 0.7 ps/m, while the FWHM for the second peak is quite broad. We have verified that the second peak is from the highest-order mode of the few-mode sample fiber because this mode disappeared when we bent the tested fiber; the higher-order mode has a larger bending loss than a lower mode. We believe that the broad FWHM...
for the second peak is due to chromatic dispersion for that mode. If we neglect the chromatic dispersion effect, the FWHM of a peak in the Fourier-transformed graph represented by Eq. (3) is determined by only $G(t) = \int |E(f)|^2 e^{i2\pi ft} df$, which is the Fourier transform of the source spectrum. When the chromatic effect is included, the delta functions in Eq. (3) are replaced with broad functions by the chromatic dispersions for excited modes in a sample fiber. As we have used a very broad source spectrum of 50 nm, the chromatic effect in our measurement would be very large, and the broad second peak in Fig. 4 is due to this chromatic dispersion effect. We have observed that the width of the second peak is reduced when a finite-size window function is multiplied to the spectral interferogram data to reduce the spectral width of the source before doing Fourier transformation.6

DMD for the sample fiber was also measured with a conventional time-domain DMD measurement method3 to validate our proposed method. For the time-domain method, a gain-switched semiconductor laser (OPG-1500, Optune, Inc.) was used as an input pulse source. It has 28 ps pulse width at 1550 nm wavelength, and its repetition rate is 50 MHz. A sampling oscilloscope was used for short optical pulse detection (86100A, Agilent, Inc.). The length of the test fiber was 50 m for this measurement. The input pulse is split into three different pulses as a result of the group velocity differences of the three different excited modes in the sample fiber. Those impulse responses for the sample fiber measured with a fast detector and a sampling scope are plotted with a thin dotted curve in Fig. 4. The positions of the first, second, and third peak are at 55.70, 67.15, and 71.32 ps/m. The DMD, or the maximum modal delay in the excited modes, is 15.62 ps/m. A comparison of our proposed mode analysis results with those results obtained using the time-domain measurement method is shown in Table 1. This comparison shows that our results show good agreement with those obtained with the time-domain measurement method.

We have demonstrated a new, powerful DMD measurement by use of fLCI. We have shown that the DMD in a few-mode fiber can be obtained with sub-picosecond accuracy for a fiber with less than 1 m length. Measurement results have good agreement with a commercial time-domain DMD measurement method. This mode analysis method has several advantages compared with conventional time-domain techniques; it is low cost, has high sensitivity (<60 dB) and good accuracy (<1 ps/m), and can be used for a short-length optical fiber. To our knowledge, this is the first time that mode analysis or DMD measurement in an optical fiber has been done by employing a fLCI or FD OCT technique.

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Table 1. Comparison of Mode Analysis Results (in ps/m) in a Few-Mode Fiber Obtained by Our Proposed Method and by the Time-Domain Method

<table>
<thead>
<tr>
<th>Method</th>
<th>First Peak</th>
<th>Second Peak</th>
<th>Third Peak</th>
<th>Measurement Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Our method</td>
<td>55.72</td>
<td>66.59</td>
<td>71.80</td>
<td>0.7</td>
</tr>
<tr>
<td>Time-domain method</td>
<td>55.70</td>
<td>67.15</td>
<td>71.32</td>
<td>0.7</td>
</tr>
</tbody>
</table>

References