High-Resolution Differential-Mode Delay Measurements in Optical Fibers Using a Frequency-Domain Phase-Shift Technique

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Abstract—A frequency-domain phase-shift technique, with a temporal resolution of 0.2 ps, is used to obtain differential mode delay measurements in graded-index multimode fibers. This resolution is a significant improvement over previously reported time-domain methods. As a consequence, useful results can be obtained from fibers as short as 15 m. Measurements performed at 850 nm, on 62.5-μm core diameter fibers from several different manufacturers, indicate a rich variety of mode delay profiles. Measurements on lengths ranging from 3 to 500 m, indicate that delay profiles are established in the first few meters of fiber, and the general characteristics are retained over long distances.

Index Terms—Optical fiber communication, optical fiber dispersion, optical fiber measurements, optical fibers, optical fiber testing.

I. INTRODUCTION

MULTIMODE graded-index fibers are an essential component in local area data networks, and bandwidth is a key parameter describing fiber performance. Differential mode delay (DMD) refers to the difference in time of flight between various mode groups which can be excited in the fiber. DMD measurements are an important diagnostic tool allowing manufacturers to optimize refractive index profiles for desired performance. Moreover, a knowledge of the DMD profile allows one to understand how bandwidth varies as a function of launching conditions to the fiber.

Current industry standards recommend that fiber bandwidth be measured with overfilled launching conditions, that is, a launch spot having a uniform intensity distribution across the core and a launch numerical aperture (NA) exceeding the NA of the fiber [1]. Different launch conditions, however, will yield different values for fiber bandwidth. Local area networks often use laser sources near 850 nm. Some of these systems use inexpensive Fabry–Perot (compact disk) lasers, while others plan to use vertical cavity surface-emitting lasers. Depending on launch optics, both of these sources are capable of launching a mode distribution which significantly underfills the available mode volume of the fiber. For many fibers, an underfilled launch can yield a significantly higher bandwidth than from an overfilled launch. The specific behavior, however, depends on the fiber’s DMD characteristic.

Past DMD measurements have been performed in the time domain using kilometer lengths of fiber [2]–[4]. In those cases, the time resolution was determined by system jitter and the pulse duration of the source; typical resolutions were on the order of ±10 ps [4]. This letter describes a frequency-domain phase-shift technique capable of 0.2-ps temporal resolution, a factor of 50 improvement in temporal resolution over earlier measurements. Such resolution means measurements are now possible on very short lengths of fiber. Typically, mode-coupling in multimode fiber is small enough so that performance over long-fiber lengths can be predicted by the fiber’s DMD characteristics. The DMD system described in this letter was implemented at 850 nm because of industry interest in data networks operating near this wavelength; some projections envision maximum link lengths of 500 m for this application. The phase-shift technique described here has been applied previously to chromatic dispersion measurements on single-mode fibers and is the basis of a NIST system to calibrate the zero dispersion wavelength of single-mode reference fibers [5], [6].

II. EXPERIMENTAL APPARATUS

Fig. 1. A schematic diagram of the frequency-domain differential-mode delay measurement system.

The experimental apparatus is illustrated schematically in Fig. 1. Selective mode excitation of the multimode fiber is achieved by scanning an 850-nm single-mode fiber, with a mode field diameter of 5 μm, across the multimode fiber core [4]. The fiber ends are aligned within a few micrometers in
the horizontal plane with a video microscope employing top illumination. After horizontal alignment, the single-mode fiber is scanned vertically with a step size of 1 μm. Fiber ends are inspected interferometrically before starting measurements to assure flat, perpendicular faces. The gap between end faces is typically 5 μm. The source is a single-mode distributed-feedback (DFB) laser diode operating at 850 nm. This source was chosen over multimode Fabry–Perot lasers because of the relatively high value of fiber chromatic dispersion at this wavelength \[120 \text{ ps/(nm km)}\]. Mode hops would result in time delays which are a significant fraction of the measured DMD’s. The source, followed by an isolator, is sinusoidally modulated at 1.9 GHz using an integrated-optic Mach–Zehnder intensity modulator. A low phase noise crystal oscillator provides the electrical drive to the modulator. A power of approximately 0.3 mW exits the single-mode fiber. The output end of the multimode fiber is imaged onto a 200-μm diameter silicon detector having a spatially uniform response. The detector output is filtered by a 1.9-GHz bandpass filter and connected to the RF signal port of the vector voltmeter. Part of the electrical drive to the modulator is split off and connected to the reference port of the vector voltmeter. Any change in the path length (either optical or electrical) after the modulator results in a phase shift, which is indicated by the vector voltmeter. The least significant digit of the vector voltmeter is 0.1°, which corresponds to 0.15 ps at a modulation frequency of 1.9 GHz. The performance of the system with respect to stability and temporal resolution is experimentally illustrated in Fig. 2. To obtain these data, we recorded the output of the vector voltmeter for 80 s, which is typical of a scan time used in actual DMD measurements. During this time, known delays were generated by axially translating the detector in steps of 250 μm that corresponds to changes in time delay of approximately 0.8 ps. The steps are readily distinguishable; the smallest delay that could ultimately be resolved is approximately 0.2 ps. The 0.1° granularity of the vector voltmeter readily appears in the data. To obtain DMD profiles of multimode fibers, a computer acquires the phase information from the vector voltmeter as the single-mode fiber is scanned across the multimode core. At any given radial position, the phase signal represents a vector sum of modes being excited in the multimode fiber.

III. MULTIMODE FIBER MEASUREMENTS

The fibers used in this study were recently purchased from multiple vendors and are therefore examples that could be encountered in practice. The results reported here are for 62.5-μm core diameter fibers having NA’s near 0.27. By measuring fiber lengths less than a meter, we found residual delays in the system optics to be small; consequently, measurements on 15-m fiber lengths or longer give a good indication of actual DMD profiles. Fig. 3 shows the DMD profile from a 15-m length of fiber #1. Here, three consecutive measurements are superimposed to indicate the reproducibility. The left vertical axis gives the DMD normalized to the fiber length (ps/m), while the right axis indicates the measured DMD (ps). DMD profiles measured on all of the fibers used in this study exhibit good symmetry with respect to the core center.
Fig. 4 shows DMD profiles at lengths of 15, 50, and 500 m for fiber #2. All of the profiles in Fig. 4 have been normalized with respect to length. Even though the length changed by a factor of 33, the DMD profiles are similar, indicating only a small amount of mode coupling. There is negligible change in going from 15 to 50 m; however by 500 m, the variations start to smooth, and the higher-order modes show smaller DMD. For all measurements, fibers were wound on 15-cm diameter spools, and winding tension was set by the weight of a 20-g mass. For the longer 500-m lengths, measurements were also performed using 30-cm diameter spools with little noticeable difference in DMD characteristics.

DMD profiles observed for fibers #3 and #4, Fig. 5(a) and (b), are quite different. Fiber #3 shows a very sharp central peak with a diameter of approximately 10 μm, corresponding to late arrival times for the lowest order modes. The sides of the peak have a slope of 0.6 (ps/m)/μm. This is the steepest DMD slope encountered in the fibers measured. The steep on-axis characteristic should make this fiber exhibit large variations in bandwidth as a small launch spot is slightly decentered. Fiber #4 exhibits almost the opposite behavior as fiber #3. Fiber #4 has a wider but inverted on-axis peak with respect to fiber #3, indicating an early arrival time for the lowest order modes. Also shown in Fig. 5(b) is a measurement on a 5 m length. The rather distinctive shape of the DMD profile is already established at this short length. To illustrate profile compensation, we fusion-spliced 6 m of fiber #3 to 15 m of fiber #4. We found that the longer composite fiber had much lower total DMD over the central 30 μm than either of the two individual fibers.

IV. CONCLUSION

The frequency-domain phase-shift method described here offers an improvement in performance that should prove useful as multimode fiber bandwidth becomes an important issue. Data acquisition is simpler than with time-domain methods, because an entire waveform does not have to be acquired for a measurement at each radial position. In this letter, most of the differential delays measured generated phase shifts much less than 2π at 1.9 GHz; measurements of larger delays may lead to ambiguous results due to multiple 2π phase shifts.

REFERENCES