Limitations of Transmission Distances over Multimode Fiber

Abstract

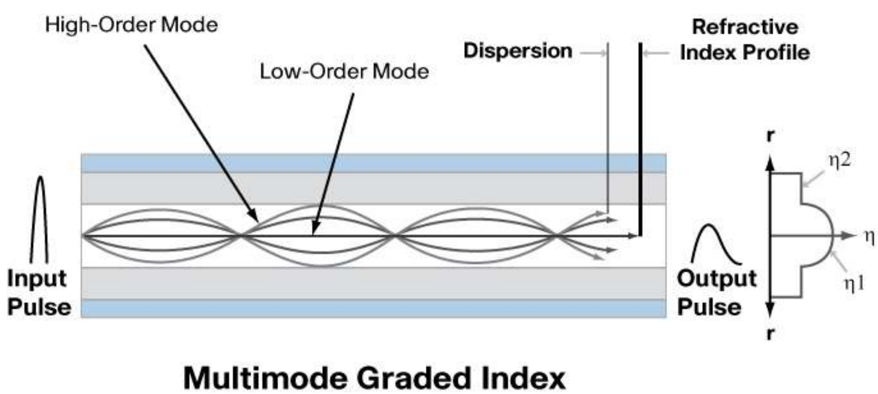
This paper details the limitations in transmission distances suffered by laser-based Gigabit networks operating near a wavelength of 1300nm over multimode fibers. The discussion focuses on the relationship between the actual fiber modal bandwidth and various launch conditions.

Fundamental Concepts of Multimode Fibers

Multimode fiber simply refers to the fact that numerous modes or light rays are carried simultaneously through the waveguide. One key characteristic of a multimode fiber is its modal bandwidth. It represents the capacity of a fiber to transmit a certain amount of information over a certain distance and is expressed in MHz*km. An intuitive model is to consider that the signal consists in a number of delayed lines, each of which corresponds to a particular mode.

In this scheme, and due to the index profile properties of a graded-index multimode fiber, the “high-order modes” propagating near the edges of the core travel faster for a longer distance, thereby transiting the fiber in approximately the same time as the “low-order modes” or rays traveling more slowly near the center of the core (see Figure 1). However, due to fiber imperfections, these rays cannot arrive simultaneously and the delay between the fastest and slowest modes is known as modal dispersion. Another aspect to consider is that the intermediate modes carry most of the power. Therefore, the power from “high-order modes” traveling near the edges arrives late relative to most of the power, and the power from “low-order modes” arrives early. As a consequence, the bandwidth is reduced and the information-carrying capacity is limited. This model proves that the bandwidth depends on the way modes are excited in the fiber, and therefore that the transmission capacity depends on the launch conditions.

Figure 1. Impulse Response and Modal Dispersion of a Multimode Graded-Index Fiber

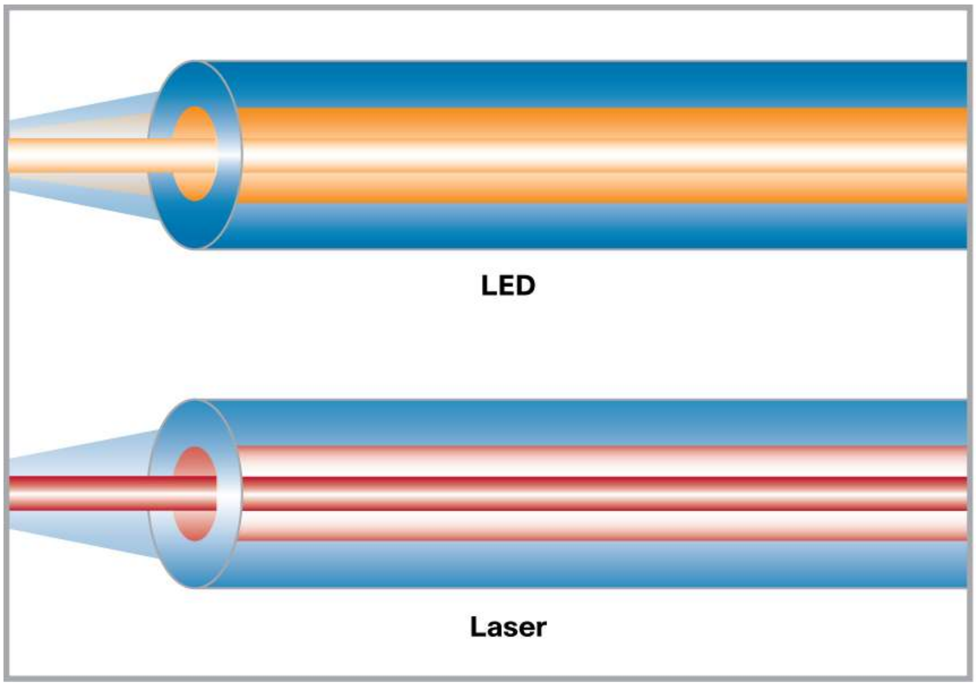


Limitations of Traditional Methods for Measuring Fiber Bandwidth

In January 1996, the IEEE Computer Society LAN MAN Standards Committee approved a project to develop a supplement to the Ethernet standard to support operation at a data rate of 1000 Mbps. The new standard's physical layers include 1000BASE-SX, a short-wavelength transceiver operating at 850 nanometers (nm) over multimode fibers only, and 1000BASE-LX, a long-wavelength laser operating at 1300nm over both multimode and single-mode fibers.

During September 1997, it was demonstrated that technical issues remained to be solved to achieve the targeted Gigabit Ethernet multimode fiber operating distances for 1000BASE-LX. The issues were related to the use of laser sources with multimode fibers. More specifically, it was proven that the small spot size of a laser compared to an LED was causing the reduction of bandwidth available in the multimode fiber. Figure 2 depicts the difference between these launch conditions, showing how an LED illuminates the entire core of the fiber, while a laser source only illuminates a small portion of the fiber core. The laser does not energize as many dispersive modes of the fiber waveguide as does the overfilled-launch (OFL) of an LED, so the fiber modal dispersion and bandwidth performance are different than might be expected from the OFL measurements.

Figure 2. OFL Light Source Versus Laser Light Source



Since multimode fibers were first designed to work with LED-based systems, OFL bandwidth (OFLBW) is the traditional method to characterize their modal properties and capacity. However, during the standardization of Gigabit Ethernet, for operation near a wavelength of 1300nm using OM1 fiber, it was found that the effective modal bandwidth (EMB) of center launch (CL) was significantly less than the OFLBW specification. This was experimentally and theoretically verified to be true for a high percentage of cases (approximately 10 to 30 percent), thus proving the lack of correlation between CL EMB and OFLBW.

OFL Bandwidth Test Setup: the Traditional Way

OFLBW is the originally standardized fiber bandwidth measurement method where the source launches light uniformly into all modes of the multimode fiber. The launch condition of this measurement is similar to that of an LED source. Therefore this measurement method gives a good indication of system performance when using legacy protocols utilizing LED sources. Figure 3 depicts the OFL bandwidth measurement test setup defined by the FOTP-204 standard.

Figure 3. OFL Bandwidth Measurement Test Setup

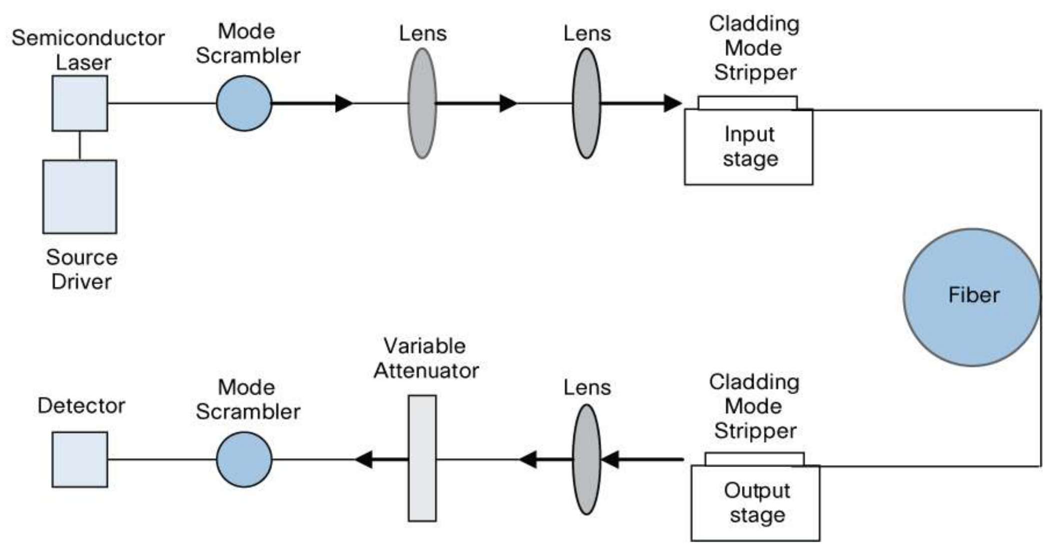
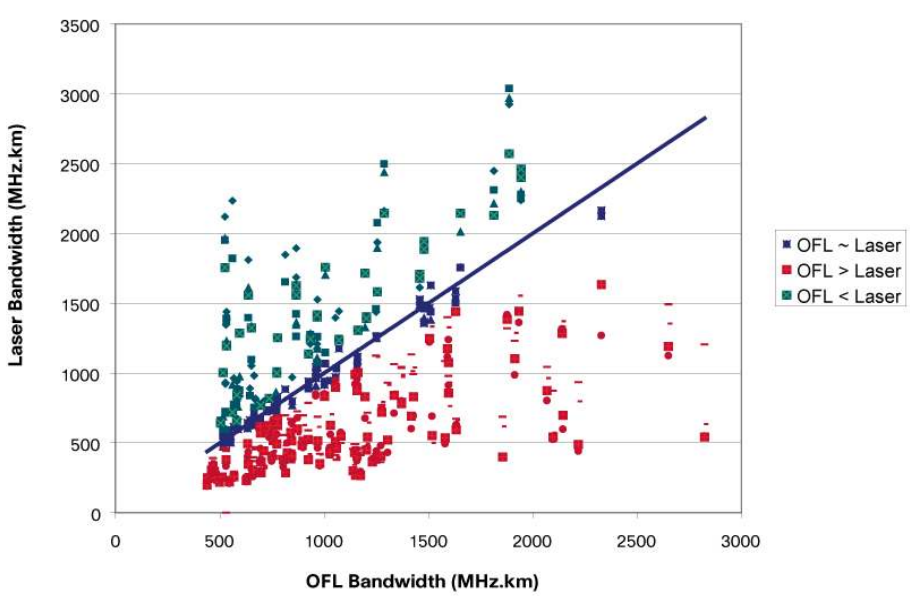


Figure 4 depicts the results of the experiment conducted by the TIA FO-2.2.1 Task Group on Modal Dependence of Bandwidth formed in 1996 to study the interaction between fiber and laser source. It clearly shows the lack of correlation between advertised OFL bandwidth and the actual fiber bandwidth measured for laser-based transmitters using the OFL characterization method.

Figure 4. Fiber Bandwidth Characterization for Laser Transmitters Using the OFLBW Measurement Method

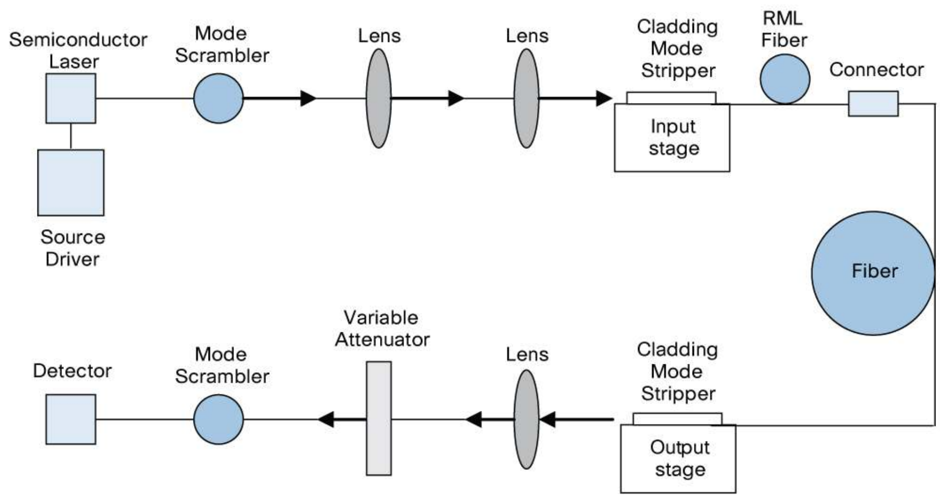


RML Bandwidth Test Setup: New Optical Sources, New Measurement Method

Because LEDs have a uniform and consistent power profile that excites all the modes in a multimode fiber, the traditional OFL method of bandwidth measurement accurately predicts fiber bandwidth for LED applications. But because lasers only excite some of the fiber's modes, and in a varying manner, the OFL bandwidth measurement cannot predict what the fiber's bandwidth would be if the fiber were to be used in a laser-based application.

In an attempt to overcome this uncertainty, a restricted-mode launch (RML) method of measuring bandwidth was developed. This measurement technique is the same as OFL, but as the name suggests, a restricted or smaller launch is used to light only some of the fiber's modes. Figure 5 depicts the RML bandwidth measurement test setup defined by the FOTP-204 standard.

Figure 5. RML Bandwidth Measurement Test Setup



The main difference between OFL and RML test setups is that, in the latter, the overfilled launch condition is filtered with the use of a mode conditioning patch cord consisting of a special RML fiber: a graded multimode fiber with a 23.5 micron core and a 0.208 numerical aperture.

With the spot size allowed, this restricted launch is intended to replicate a Vertical Cavity Surface Emitting Laser (VCSEL). However, test results can still vary depending on exactly how the light source is coupled with the fiber. In other words, the actual bandwidth achieved in an installed system may differ from the RML tested bandwidth.

DMD: A Superior Method

A superior method of ensuring bandwidth in Gigabit Ethernet transmissions is based on measuring differential modal delay (DMD). This technique allows the characterization of the delay time of mode groups within a multimode fiber, and is in fact the only measurement technique recommended in standards for 10-Gbps speeds.

In DMD testing, high-powered laser pulses are transmitted in small steps across the entire core of the fiber. The technique consists of starting with center launch and gradually offsetting the launch across the radius of the fiber core. Therefore, only a few modes are excited at each step, and their arrival time is recorded. The DMD of the fiber is the difference between the earliest and the latest arrival times, of all modes at all steps.

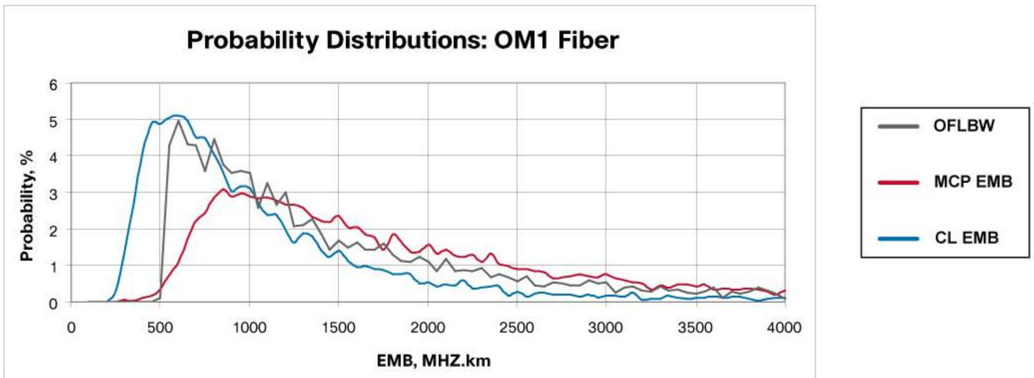
The lower the DMD, the higher the bandwidth of the fiber.

Experimental results show that a launch offset of about 15 microns along the fiber core radius enables the OFL bandwidth to be achieved. Mode conditioning patch cords (MCPs) are therefore used to excite the fiber modes appropriately and make use of the bandwidth theoretically available.

Conclusion

Additional experiments were carried with 1000BASE-LX lasers over OM1 fiber. The following graph (Figure 6) shows the probability distributions of effective modal bandwidth (EMB) for center launch (CL) and offset launch with MCP cables (MCP launch). The OFLBW curve is also shown for reference.

Figure 6. EMB Probability Distributions for OFLBW, CL, and MCP Launch



All bandwidth parameters of multimode fiber are known to follow log-normal like distributions. Statistically, CL (blue) has the lowest bandwidth, MCP launch (red) has the highest bandwidth, and OFL (black) is intermediate between the two. It is noticeable that only OFLBW is guaranteed to be a minimum of 500 MHz*km.

As a conclusion, no optical launch can guarantee 2-km operation for 1000BASE-LX transmitters over OM1 fiber. Offset launch is the best method. It was proven that approximately 50 percent of links would operate to 2 km with the MCP launch. However, this is not guaranteed and the cable plant needs to be tested in order to verify the 2-km reach is achievable. Therefore, on close inspection, the data sheets of the transceivers that claim 2-km operation for Gigabit Ethernet, should have a note to indicate that the 2-km link length is dependent on cable quality.

References

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