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Multimode Optical Fiber Bandwidth Characterization

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This Applications Engineering Note (AE Note) discusses bandwidth characterization for multimode optical fiber (MMF), and bandwidth's impact on overall system performance. If a comprehensive guide on selecting the appropriate MMF for a particular system deployment is required, please consult AE Note 075, "Multimode Optical Fiber Selection & Specification".

Optical Fiber Bandwidth

Bandwidth (BW) is the information transmission capacity of a communications system, or the width of a communications channel. Specifically, it is the range or band of frequencies that exist for signal transmission in or through a particular medium. In the case of fiber optics, this medium is optical fiber and BW is the difference between the highest and lowest frequency light signal that can be transmitted for a given communication protocol over a specific wavelength. The nominal bandwidth of a circuit represents the range of frequencies in which the power level stays at above one-half its peak value.

ANSI/TIA/EIA-455-204 ("Measurement of Bandwidth on Multimode Fiber") describes a Fiber Optic Test Procedure (FOTP) for measuring what is known as the "-3 dB bandwidth". The -3 dB BW is the lowest frequency at which the magnitude of the baseband (single channel or signal) frequency response in optical power has decreased by 3 dB relative to the power at zero frequency (or an arbitrarily low baseband frequency). This is analogous to the BW determination on an oscilloscope in which the BW is specified as the frequency at which a sinusoidal input drops 3 dB relative to the signal's actual amplitude (at zero or negligible frequency). This optical BW measurement is the "Modal Bandwidth" (refer to **Figure 1**).

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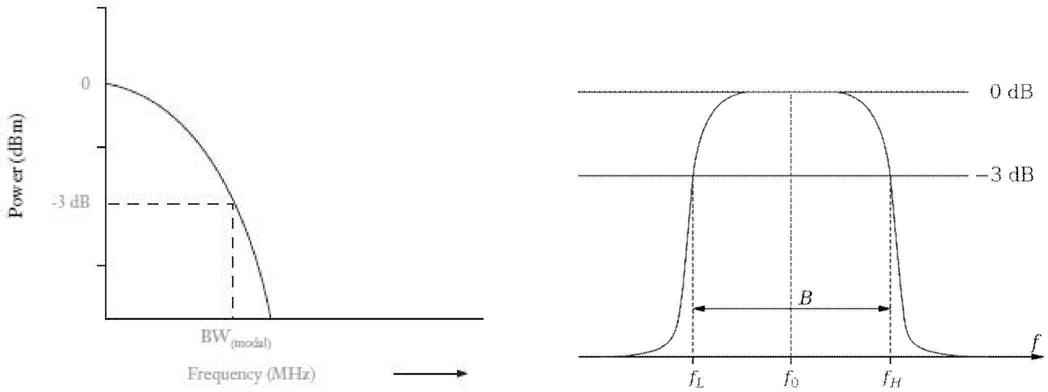

Figure 1: Modal (-3 dB) Bandwidth

The units of modal bandwidth are MHz●km. This metric defines the achievable transmission frequency for the optical fiber over a distance of one kilometer. Note that this is not a “per km” specification, as is the case with optical attenuation (dB/km). One kilometer is to some extent an arbitrarily chosen convention for comparing one optical fiber’s BW with another. Doubling the transmission distance does not necessarily reduce the BW by half. The established distance of one km merely serves as a point of reference when comparing specifications between different fiber manufacturers and different grades of MMF.

Launch Conditions

Modal BW, although specified for the fiber only, is really a characterization of the total BW of an optical fiber system. It is impacted by both the transmission properties of the fiber, as well as the end equipment that generates and receives the optical signal pulses. Optical fiber BW is capped by the distortion (modal dispersion) of optical pulses propagating through the optical fiber (**Figure 2**). Light is launched differently into an optical fiber with various types of light sources and affects how overall system BW is calculated. Conventional transmitters available today for MMF systems include Light Emitting Diodes (LEDs), Vertical Cavity Surface Emitting Lasers (VCSELs), as well as edge-emitting (e.g. Fabry Perot or Distributed Feedback) single-mode lasers.

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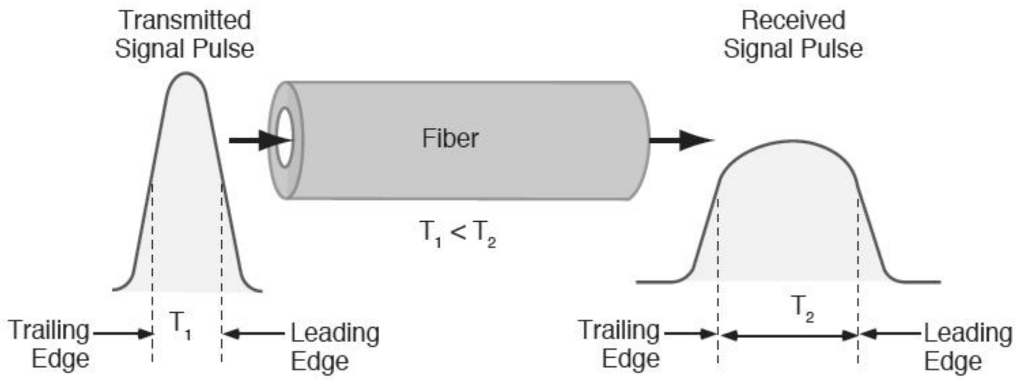

Figure 2: Pulse Dispersion in Optical Fiber (Pulse Power vs. Time, T)

Overfilled Launch (OFL)

LEDs tend to produce what is known as an Overfilled Launch (OFL) of light into the core and cladding of an optical fiber, in which all modes (paths of light) of the optical fiber are energized. An LED emits light broadly (approaching a 180° sweep) and uniformly spreads its optical power across both the core and cladding of an optical fiber. Because of this distribution pattern, light pulses generated by LEDs are more prone to dispersive effects in MMF (and BW is inversely proportional to pulse dispersion). LED modulation rates also top out at approximately 622 Mbps, which serves as an upper bound on their transmission capabilities and MMF BW. In actual testing, an OFL pattern is generated through the use of a laser that is coupled into a mode scrambler (**Figure 3**) that effectively mimics an LED while allowing measurements to be made on long manufacturing lengths. In addition, because power distributions of lasers vary from one to another, a mode scrambler is used to generate a spatially, angularly and uniformly overfilled launch condition to achieve consistent measurement results. TIA/EIA-455-54B (FOTP-54) stipulates the mode scrambler requirements for overfilled launching conditions on multimode fibers.

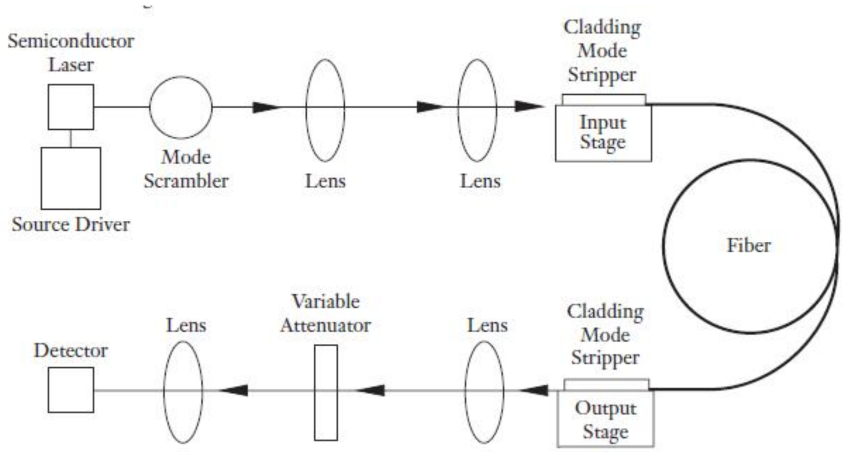

Figure 3: OFL Modal BW Measurement Apparatus

Restricted Mode Launch (RML)

With the emergence of VCSELs in the late 1990's, the need arose for a better method of characterizing the launch conditions into MMF systems. While 850/1300 nm LEDs tend to emit lower power pulses into a broader area at slower speeds, VCSELs (which operate at 850 nm) have a smaller spot size, energize fewer modes while achieving higher modulation rates (ability to signal at higher frequencies) than LEDs. Refer to **Figure 4** for a comparison between an OFL launch produced by an LED vs. an RML launch typically produced by a VCSEL.

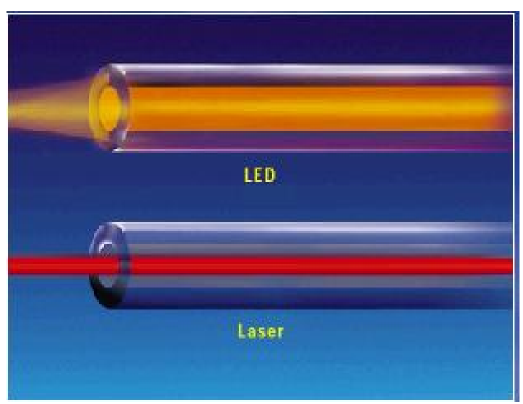

Figure 4: OFL (LED) vs. RML (Laser)

The transition from LED transmission to Laser-Optimized MMF (LOMMF) began in 1998 with the introduction of Corning® InfiniCor® fiber into the industry. The OFL BW measurement used in the 1980's in turn was superseded by RML in 1998. RML is formally defined in ANSI/TIA/EIA-455-204 (FOTP-204, "Measurement of Bandwidth on Multimode Fiber"), and is generated by filtering the OFL (as defined in FOTP-54) with a special 23.5 µm (± 0.1 µm) core optical fiber (**Figure 5**). This special RML fiber (that is between 1.5 m and 5 m in length) effectively serves to simulate the launch characteristics of a VCSEL for Gigabit Ethernet transmission. RML BW measurements are only relevant for legacy 62.5 µm optical fiber now. Today's 50 µm optical fiber specifications utilize more advance BW measurement techniques.

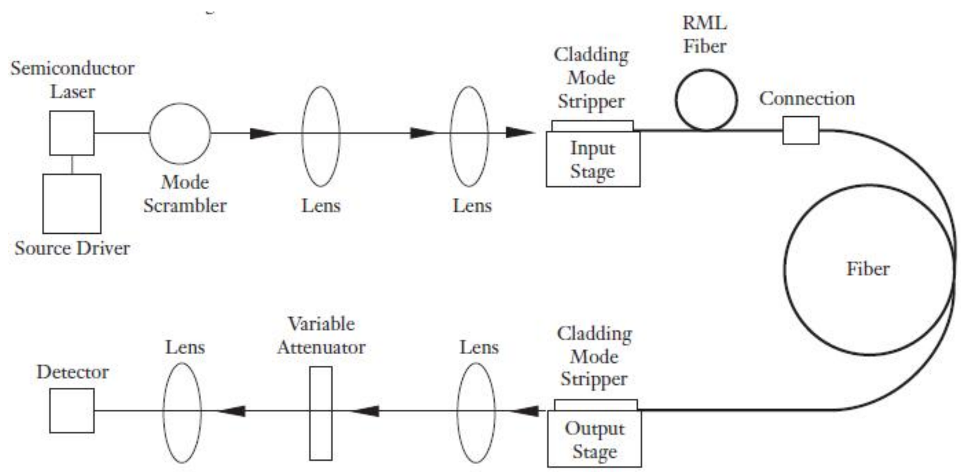

Figure 5: RML Modal BW Measurement Apparatus

Bandwidth Measurement: Standard Methods

BW measurement in recent years has become more increasingly complex due to the introduction of VCSELs and the desire to achieve even further transmission distances over more sophisticated MMF types. Up until January of 2003, TIA/EIA-455-204 (FOTP-204, "Measurement of Bandwidth on Multimode Fiber") had detailed the two standard methods for accurately measuring MMF BW. Method A is known as the "Optical Time Domain Measurement Method (Pulse Distortion)", and Method B is known as the "Frequency Domain Measurement Method". Each method can be carried out using either an OFL or RML condition, which is performed in a manufacturing or research environment.

Time Domain Measurement Method

In this method a laser diode (OFL or RML) is used to inject power into a test fiber, and the pulse generated is monitored on a calibrated oscilloscope. Although oscilloscopes are generally thought of as devices that produce visual images of electrical signals, in this case the optical signal is converted to electrical for visualization by the oscilloscope. The recorded fiber output pulse (which is displayed as the pulse's amplitude as a function of time on the oscilloscope display) is then compared to the fiber input pulse, and after some mathematical manipulation (Fourier transform) it is converted to a frequency representation. The BW is then defined as the lowest frequency at which the output frequency response drops to half the input frequency response. This frequency is then multiplied by the fiber length to determine the normalized bandwidth (MHz•km) and is repeated at both 850 and 1300 nm wavelengths. For a complete explanation of this procedure, please refer to FOTP-204 (TIA/EIA-455-204).

Frequency Domain Measurement Method

In this method a laser diode (OFL or RML) is used to inject power into a test fiber and modulated from a low frequency (for an approximately zero reference level) to a high frequency (in excess of the 3 dB bandwidth). The relative output optical power is recorded as a function of the frequency, and then the input modulated signal that is launched into the test fiber is determined in a similar manner by measuring the output on a shorter reference length of fiber. Once the input and output powers are determined (as a function of frequency), the BW can be calculated through the same mathematical techniques as applied in the time domain measurement method discussed above. Refer to FOTP-204 for more specific details.

Differential Mode Delay (DMD)

The previously discussed methods for BW characterization are sufficient for MM systems operating at less than 1 Gbps (i.e. Gigabit Ethernet). During the development of the 10 Gigabit Ethernet Standard (IEC 802.3ae 2002), differential mode delay (DMD), a more complex laser BW test method was introduced that enabled a more precise BW measurement on emerging laser-optimized MMF types (i.e. OM3 and higher). DMD is essentially a time domain-based analysis, albeit a conceptually more difficult measurement method to visualize. It is more accurate to describe DMD as a method for characterizing the modal structure or profile of a graded index MMF, as it does not take into full account the laser source characteristics in predicting laser BW.

In DMD, a special laser probe scans across the end-face of the fiber, and the delay times required for laser pulses to travel to the end of the fiber are measured at specific increments. From this measurement data, a picture or map (refer to Corning white paper #4253 for an image of this map) can be generated that depicts where the fastest and slowest mode groups exist in the core of the optical fiber. The time difference between these mode groups depends not only on where they are launched along the radius of the fiber, but also on the temporal width of the optical pulse, the finite BW of the optical detector, and the broadening of each mode due to source spectral width and the fiber's chromatic dispersion. This picture can then be compared to other pre-defined templates (i.e. "masks", as defined by the relevant ANSI/TIA or ISO/IEC optical fiber detail specification) in predicting the fiber's BW capabilities.

Encircle Flux Requirements (EF)

It is important to realize that the modal bandwidth predicted by DMD is not explicitly measured, but rather, it is ensured by testing, modeling and simulation. The optical specifications outlined by TIA or IEC, and subsequent predicted BW, also require that in addition to meeting the defined DMD masks, the laser transmitter used to transmit over the specified fiber must meet particular "Encircled Flux (EF)" requirements. EF is a measurement that quantifies the total amount of optical power that emanates from a source and penetrates a specific region of a fiber end-face as defined by prescribed radius limits. ANSI/TIA/EIA-455-203 (FOTP-203) describes the measurement procedure for launched power distribution for MMF transmitters. For a more complete explanation of EF, refer to AE Note #129, "What is Encircled Flux?"

Effective Modal Bandwidth (EMB, EMBc and minEMBc)

Effective Modal Bandwidth (EMB) is the implied system BW that is ensured by specification of both the optical fiber (mode delays) and transmitter (mode power distribution) together in a laser-based digital system. EMB can be predicted from DMD and EF criteria, but it can also be calculated (and more accurately determined) by what is known as calculated EMB, or "EMBc", which was standardized in 2004 with the emergence of 10 Gbps and higher systems. The minimum EMBc is the minimum calculated modal BW of a particular fiber resulting from a particular set of weightings associated with a typical laser population. Currently, TIA-492 detail specifications for LOMMF provide DMD weightings for ten lasers that are representative of the range of laser diodes commercially available with prevailing optical transmitters.

The term "weightings" refers to the proportionality factors (unit-less fractions) that are specified at various radial positions (out from the centerline of the fiber) for each of the ten defined lasers. DMD weights are generated from EF data per TIA specified procedures. The mathematics involved with calculating EMBc is similar to the Time Domain Measurement Method outlined in FOTP-204, except the resultant output pulse must be weighted, or more specifically, multiplied, by the DMD weighting factor at each radial offset position prior to conversion to the frequency domain. The subsequent weighted, or scaled, output pulses at each radial position are then summed for the overall corrected output pulse response as a function of time. The actual process for this calculation can be represented by the following summation (Σ) formula:

$$P_o(t) = \sum_r U(r,t)W(r)$$

where:

$P_o(t)$ is the resultant total output power pulse (as a function of time, t).
U(r,t) is the output pulse measured at each radial offset, r, as a function of time, t.
W(r) is the DMD weighting function corresponding to the transmitter used.

The lowest of the ten values is then assigned as the “minEMBc” BW value. TIA-455-220 A (FOTP-220) provides a complete description of both DMD and EMBc measurement procedures in MMF. EMBc is standardized in both TIA/EIA 492AAAC and TIA 492 AAAD, and IEC 60793-2-10. Refer to Corning Optical Communications’ document LAN-639-EN ("Calculated EMB Enhances 10 GbE Performance Reliability for LOMMF") for a more detailed explanation.

Bandwidth Measurement: Field Testing

The need for BW testing in the field occasionally arises in legacy systems whose installed fiber base must support upgraded network electronics operating at higher data rates (e.g. migration from Gigabit Ethernet to 10 Gigabit Ethernet and beyond). Previously installed fiber optic cable systems may also need to be characterized if the original cable data sheet is lost or misplaced. Unfortunately, no field BW tester is commercially available that would reliably predict the maximum reach or “certify” a fiber optic link for multi-Gb/s performance. The only proven field test methods on installed fiber optic links are attenuation and insertion loss measurements.

The best prediction of field fiber optic system performance is a standard-compliant BW measurement carried out by the optical fiber manufacturer at the manufacturing facility (which typically measures fiber lengths up to a set length). For example, Corning measures laser BW on every meter of every reel of 50 µm fiber with standardized MM measurement methods (minEMBc), where all measurements are directly traceable to world master reference benches at Corning’s Center for Fiber-Optic Testing (CFT). BW is complex to test even in laboratory environments, and at the CFT, in-house testing on short lengths is accomplished via bit-error-rate and eye diagram analysis using a variety of commercially available transceivers and high-speed oscilloscopes. Such equipment typically costs in excess of $1 million and is not transportable to a field location.

The short-wavelength lasers used in EMB calculations that involve a high-resolution DMD bench are also hazardous (Class IV), in addition to being very expensive and immobile. So a specialty high-power single-mode laser source must be used with DMD/EMB measurements. One other consideration is that any determination of minEMBc BW with BER test methods can be misleading and erroneous unless the tests are performed with a wide variety of fiber-transceiver combinations and the transceivers used in such tests are fully characterized. For example, Corning used over 1500 fiber-transceiver combinations to validate minEMBc for OM4 LOMMF. For these reasons, manufacturer-determined BW specifications should be relied upon for system planning, and upon request, Corning can retrieve and provide laser BW metrics for individual fibers, which may be used for documentation of fiber performance.

Bandwidth Measurement Summary

Continuous improvement in optical fiber transmission characteristics and network electronics (i.e. faster data rates) requires more accurate and consistent BW measurement methodologies. The most accurate BW representation of high data rate (≥ 1 Gbps) 50 µm fiber optic systems today is minEMBc, which incorporates the effects of both LOMMF properties (i.e. mode delays) and the properties (i.e. flux distribution) of the full range of prevailing, commercially available standard-compliant VCSELs. The DMD mask approach is a pass/fail characterization of the optical fiber only, and taken alone, was originally intended to verify 10 GbE over 300 m on OM3 MMF only . The minEMBc methodology integrates the EF launch characteristics of 850 nm VCSEL sources with the modal delays induced by MMF to provide a calculated system BW that represents the worst-case performance of the system.

For data rates beyond 10 Gbps (e.g 40 Gbps and 100 Gbps Ethernet), minEMBc will still be the relevant BW metric because of its scalability and adaptability to evolving VCSEL and fiber technology and extended distances. Refer to Corning white paper WP1184, “Standards Review: OM4 Optical Fiber and Status of 40G and 100G” for more information.

Refer to Corning white paper WP1150 for a table of specific Corning® optical fiber types and their associated relevant BW measurement methods and values. In general, final EMB laser BW is provided for all OM2, OM3 and OM4 fibers based on the minEMBc method. RML BW is used for all OM1 fibers.

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