Bandwidth Measurement of Multimode Fibers through System Level Bit Error Rate Testing

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Abstract: A new bandwidth measurement method for multimode fibers is developed through measuring bit error rate and power penalty associated with the testing system. Experimental calibration procedure and actual fiber measurement results are presented.

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Multimode fibers (MMFs) have seen increased interest and use in recent years in short distance communications, such as in data centers, and enterprise networks. A number of standards cover the area, which include 10G Ethernet standards, Fiber Channel, 40-100Gb Ethernet and Infiniband. The grade of multimode fiber is mainly determined by the bandwidth. There exist many methods to measure the bandwidth of multimode fiber. One type of measurement is the time domain method based on differential mode delay (DMD) measurement as described in FOTP-220 standard. The DMD measurement data can be converted into fiber bandwidth following standard procedures. Another type of the measurement method is the frequency domain method [1-2].

It is well known that the fiber bandwidth, which is limited by modal dispersion and chromatic dispersion, is directly related to the system performance. Previous results link the bandwidth with Intersymbol Interference (ISI) using the Gigabit Ethernet model [3]. Despite the linkage between bandwidth and system performance, to our knowledge, a method that can measure the multimode fiber bandwidth using system BER is lacking. It is the goal of the current paper to propose and demonstrate such a method.

One key difficulty of using system testing to determine fiber bandwidth is to know precisely the relationship between the BER performance of the testing system and the bandwidth of the multimode fibers. In a typical system, this relationship is affected by many parameters. Intuitively, to be able to establish this relationship, one has to know the bandwidth of the fiber that is put into the testing bench and measure the related system performance, as gauged by the power penalty. However, this is difficult because the fiber bandwidth can change when migrating from one deployment condition to another and it is sensitive to the launch condition of the transmitter. In the current paper, we overcome such difficulty by emulating the fiber bandwidth effect using a well characterized electrical filter. The multimode fiber is considered to be a low pass filter [3], and its frequency response is considered to be Gaussian. In practice, a Gaussian electrical filter is sufficiently approximated by a Bessel-Thompson 4^{th}-order filter, which is commercially available and can be used for the calibration.

Fig. 1 shows the schematic layout of the experimental setup that we used to obtain the calibration information. A 10G analog transmitter (Tx) with an 850nm VCSEL is driven by a pattern generator. The optical signal passes through a short multimode fiber and a variable optical attenuator (VOA) before reaching the receiver. The multimode fiber in this setup is short with length of around 1m and is considered as a back to back condition in contrast to the situation where a longer fiber is used in application length. The VOA is used to control the optical power to the transmitter so that we can generate a water fall curve (Bit error rate vs. received power). The receiver is a linear photo-detector connected with a linear transimpedance amplifier (TIA). In choosing the receiver, care is taken so that the receiver will have a linear response to the signal and no signal conditioning circuit including data recovery and electronic dispersion compensation chip is used. A number of electric filters with Bessel-Thompson 4^{th} spectrum shape (obtained from Picosecond Pulse Labs) and varying cutoff frequency are inserted between the transmitter and the pattern generator. A water fall curve is obtained for each electric filter, which emulates a multimode fiber with a particular bandwidth. Since the filter has a slight attenuation and the spectrum limitation alters the signal shape, the peak to peak magnitude of the signal reaching the Tx is different slightly for each filter. To ensure the consistency between measurements, we adjust the peak to peak driving voltage of the pattern generator at the output of each electrical filter to be the same. The same adjustment is also performed when we take out the electric filter and replace the short fiber with a longer fiber under test in actual measurements.

The water fall curves for a number of electrical filter cutoff frequencies are shown in Fig. 2. The power penalty is determined from the increased receiver power, relative to the water curve in back to back condition, for BER equal to 10^{-9}. The power penalty as a function of the filter cutoff frequency is shown in Fig. 3. The electrical filter

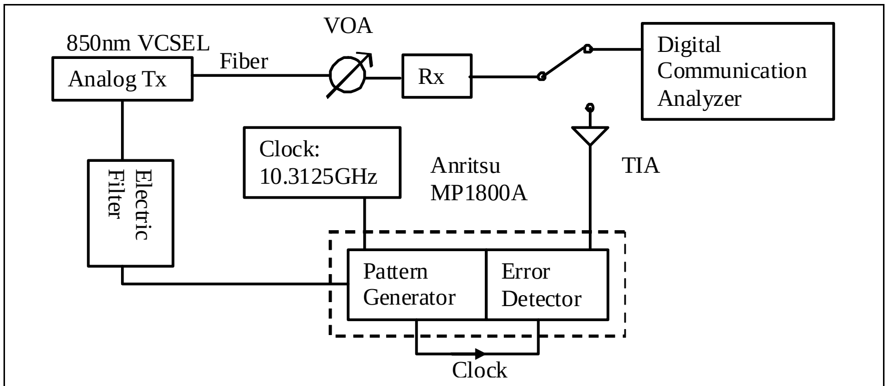

Figure 1. The experimental schematic layout of setup that is used to obtain calibration curve.

frequency is specified at the electrical 3dB level. However, in the optical domain, the bandwidth is defined at the optical 3dB level, which is equivalent to the electrical 6dB level. For a Bessel-Thompson 4th order filter, the electrical 6dB point is greater than the electrical 3dB point by a factor of 1.3654. With an added axis, Fig. 3 also illustrates the relation between the power penalty and the optical bandwidth. The experimental data between power penalty and filter cutoff frequency is fitted into a functional with the form of $P = a \cdot x^b$ with ‘a’ to be 30.37 and ‘b’ to be -1.66.

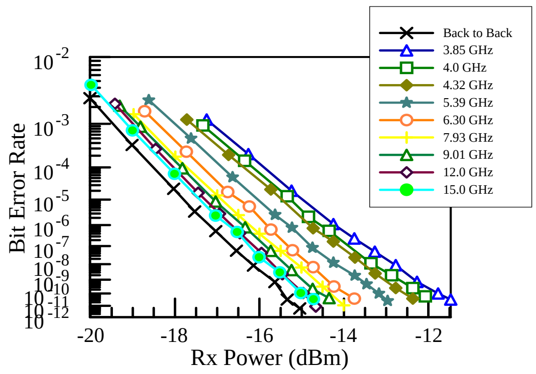

Figure 2. Waterfall curves for different filter frequencies.

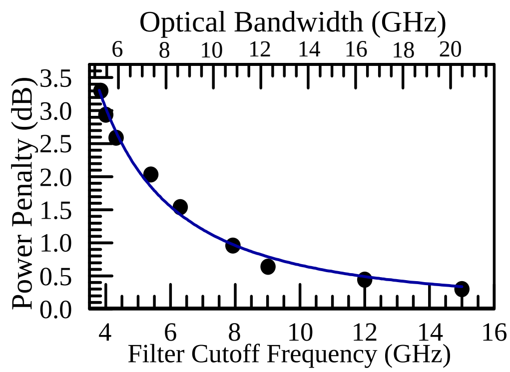

Figure 3. The Power penalty as a function of the filter cutoff frequency at 10^{-9} BER level.

With the calibration curve, we were able to test the bandwidth measurement method on real fibers. A low bandwidth experimental multimode fiber with 250m length was chosen, which had a measured bandwidth of 1100MHz.km minEMBc value over the whole reel with a much longer length. Using a setup slightly modified from Fig. 1 by taking out the electric filter and replacing the short fiber with this fiber, we measured the water fall curve and compared that with the back to back case at 10^{-9} BER level. The power penalty is 3.42dB. Using the calibration curve in Fig. 3, this power penalty is related to an optical bandwidth of 5.19 GHz. When scaled to 1km, the bandwidth of this fiber is 1300Mhz.km. This result is fairly consistent with the minEMBc bandwidth which is a lower bound obtained from a number of restricted launch conditions computed in a standard compliant fashion. We further illustrate the measurement capability of the new measurement method by cutting back the fiber into several shorter lengths to study the length dependence of this fiber bandwidth in short length with a fixed launch condition. The fiber has been prepared in a condition that we can access several middle points to cut short the fiber while not disturbing the launch end that is secured on the table. As shown in Fig. 4, the absolute fiber bandwidth increases for shortened length. An important aspect illustrated by this experiment is the ability to measure the fiber bandwidth well above 10GHz using 10GHz system testing equipment. This is understandable since with the Gaussian type of frequency response, the bandwidth limiting effect is incurred in well below 10GHz even for fiber with bandwidth higher than 10GHz, producing a system impairment. This feature is an advantage over the frequency domain method [1-2], which has to use 20GHz equipment to get to similar measurement capability. In the regime of high bandwidth, smaller errors in power penalty can cause larger errors in measured bandwidth than in the lower bandwidth regime because of the nonlinear relation between power penalty and bandwidth. The method still produces reasonable prediction for scaled bandwidth as we often measure the fiber in a short length, *l*, much shorter than 1km and the error is reduced by a factor of (1000/*l*) for the scaled bandwidth.

In another experiment, we measured a few cabled multimode fibers with higher bandwidth and compared the results with those obtained from the frequency domain method [1-2]. The results of frequency domain method were obtained using a network analyzer which includes a frequency sweeping source to modulate a 850nm VCSEL and an analyzer that processes the signals from the photo-detector. The transmitter is the same as that in Fig. 1. The measurement results are shown in Table 1. The data from the frequency domain method is processed in two different ways by either retrieving the optical 3dB bandwidth from measured spectrum data or retrieving from the 3dB of the best Gaussian fit of the measured data. It can be found that the results from different methods agree reasonably well, but in some cases (for example, Fiber #2) the difference is significant. The bandwidth obtained from BER method can be above or below those from the frequency domain method. We believe the difference is largely due to the deviation of the measured frequency response from ideal Gaussian shape. Note that although the Gaussian model is widely used in the MMF field, it may deviate from the actual fibers frequency response more or less. When such deviation occurs, the optical 3dB bandwidth is a less accurate measure of the bandwidth and becomes less well tracked with the system performance. The BER bandwidth for Fiber #2 is substantially lower than the 3dB bandwidth. This is understandable as shown in Fig. 5, in most parts of the frequency response, the frequency response curve falls below from the ideal Gaussian shape. We believe the BER testing provide a more accurate measure as it has taken into account the contribution for each portion of the spectrum response. The obtained bandwidth matches that from an ideal Gaussian fiber that yields the same system performance. The benefit is that the bandwidth reported from the BER testing is truly ranked with the system performance.

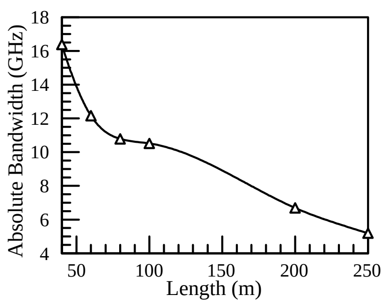

Figure 4. Absolute bandwidth over several shortened fiber lengths.

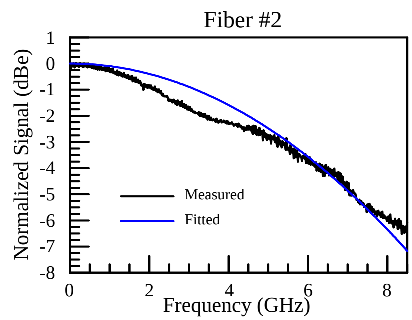

Figure 5. The frequency response of Fiber #2.

Another factor to consider is the chromatic dispersion of the fiber that may affect the measurement results (see chap.6 of [4]). Strictly what is measured from the BER method is the link bandwidth. Chromatic dispersion can also contribute to the broadening of laser pulse and increase system impairment through contribution to the link bandwidth when the VCSEL is multimoded. The spectrum width of the VCSEL we used is 0.4nm. The chromatic dispersion effect is negligible for OM3 quality fiber but additional care is needed for OM4 quality fiber [5]. However, we note that since the electric filters are used to emulate multimode fibers, the calibration curve is free of the chromatic dispersion effect.

Table 1. The bandwidth measurement results from three cabled fibers.

	Power Penalty (dB)	Length (m)	Bandwidth from BER Testing(MHz.km)	Optical 3dB Bandwidth (MHz.km)	Optical 3dB Bandwidth from Best Fit (MHz.km)
Fiber #1	0.75	200	2500	3000	2570
Fiber #2	2.7	400	2340	2840	3130
Fiber #3	1.23	400	3700	3440	3760

In conclusion, we have proposed a new method of measuring multimode fiber bandwidth through the use of system level bit error rate testing to obtain the power penalty related to the fiber bandwidth. Using 10GHz testing equipment we were able to demonstrate the bandwidth testing capability up to 20GHz, which allows us to test multimode fiber in short lengths. With the calibration from well characterized Bessel-Thomspon 4^{th} filter, which emulate the bandwidth limitation of multimode fiber, we conducted a few actual fiber measurements. Through analyzing the data, we further find that the system level BER testing provide bandwidth results more closely linked to and ranked with the system performance than optical 3dB cutoff used in other methods.

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