APPLICATION NOTE

No. 100 9/22/98

Polarization Mode Dispersion (PMD), and PMD Testing

Introduction

Fiber optic communications systems are evolving to carry data at faster rates and over longer distances. With the advent of 10 Mb/s transmission speeds in many systems, Polarization Mode Dispersion (PMD) is now recognized as a fundamental limiting factor in these systems. Previously largely unknown, systems planners and fiber optic test engineers are increasingly aware of the problem of PMD, and PMD testing has emerged as an important new technology. PMD testing is needed to verify the ability of a particular fiber span (especially old fiber) to carry high data rate signals. Experience has shown that most new fiber is capable of carrying 10 Mb/s signals (called the "OC-192 signal"), whereas a significant fraction of older fiber fails the PMD test for carrying these signals. As a general rule, whenever the data rate exceeds 2.5 Gb/s ("OC-48" signals), a PMD test should be performed. Even newly installed fiber may be subject to large PMD values due to changing environmental conditions.

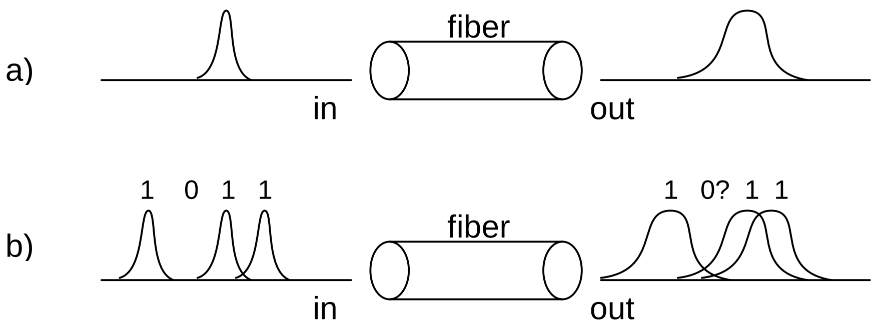


Figure 1: a) The effect of dispersion on a single laser pulse is to broaden the pulse. b) The effect of dispersion on a sequence of binary digits. This effect is essentially the same whether it is due to chromatic dispersion or polarization mode dispersion (PMD). Because modern fiber has low chromatic dispersion, PMD becomes a dominant limiting factor in system performance at high data rates.

How Dispersion Effects Limit System Performance

For a given bit rate the signal degrades with increasing distance. In other words, the usable transmission distance L goes down as you increase the bit rate B. Thus it is the product BL (bit rate times distance) that is limited for a given system. In most fiber optic systems of the past, the limiting factor of the BL product has usually been chromatic dispersion, which causes short laser pulses to spread out based on their different frequency components. Because it is precisely this type of pulse that is used to encode binary data (1s and 0s), the rate of errors at the receiver (for example, erroneously detecting a 1 instead of a 0) goes up when the pulses spread out. In other words, dispersion, the spreading of the laser pulses, causes the Bit Error Rate (BER) to increase. See Figure 1. Modern systems operate on fiber with very low chromatic dispersion, and for systems operating at 10 GB/s or greater, PMD becomes a critical limiting factor in system performance.

What is PMD?

PMD is a form of dispersion caused by the fact that light can exist in various polarization states. The fundamental propagation mode of "single-mode" fiber can actually be viewed as two distinct polarization modes, pictured as perpendicular wave pulses in Figure 2. In general, both these modes are present, and both are detected by the receiver. In a typical fiber optic transmission system, where the fibers are many kilometers long, these two modes propagate at slightly different speeds and so arrive at the detector at slightly different times. As they propagate down the fiber they disperse, or spread apart from one another, thus the term Polarization Mode Dispersion. The idea is analogous to chromatic dispersion, where different wavelengths travel at different speeds in the fiber.

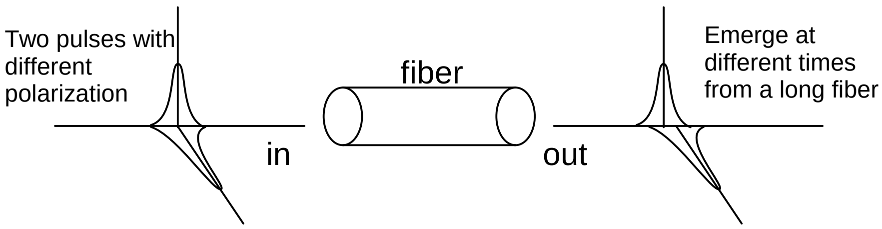


Figure 2: Laser pulses with different initial polarization travel with slightly different propagation speeds, and thus emerge from the fiber with a slight delay between them. This delay time is called the Differential Group Delay (DGD).

The difference between the arrival times of the two polarization modes is called the differential group delay (DGD), and is measured in picoseconds (1 ps = 10^{-12} s). To keep PMD from causing errors, the DGD must be at most a small fraction of the time needed to transmit a single bit. For a 2.5 Gb/s bit rate, the time to transmit a single bit is 1/2.5Gb/s = 0.4 ns/bit = 400 ps/bit. The DGD must be kept to about 1/10 this value, or 40 ps. For a 10 Gb/s transmission rate (4 x 2.5 Gb/s), the differential group delay must thus be kept below 10 ps.

Note: Because the DGD is the most important parameter to measure for a given span of fiber, it is commonly referred to as simply the “PMD”. The PMD440 Interferometric Measurement System uses this terminology. In this Application Note, however, we will continue to use “DGD” to refer to this quantity.

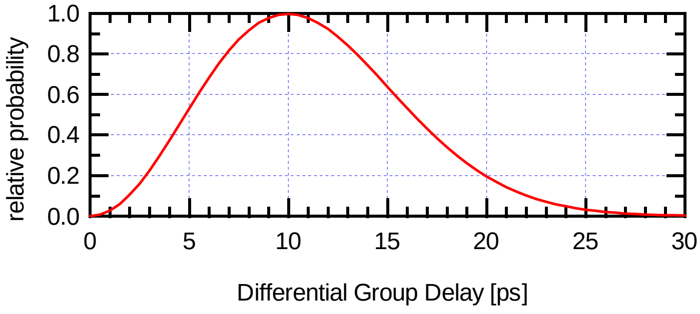
What causes PMD?

PMD is caused by two main factors. First, the shape of the fiber is not perfectly cylindrically symmetric, and varies along the length of the fiber. Second are external stresses on the fiber, caused either by environmental factors (e.g. temperature variations, shifts in the ground) or cabling effects (e.g. adjacent fibers in the bundle, etc). This dependence of the PMD on the external stresses applied to the fiber mean that the PMD changes with time due to environmental effects. It also means that the PMD for a given piece of fiber will be different if that fiber is on a spool or buried underground in a bundle. Thus PMD measurements must be made after the fiber is installed. Periodic PMD measurements may also need to be performed, especially in areas where the ground is likely to shift, causing changing levels of stress on individual fibers.

Statistical Nature of PMD

The DGD can be directly measured in the laboratory using sophisticated techniques like "Jones Matrix Eigenanalysis" and "Spectral Scanning". These techniques require a great deal of expertise, and are susceptible to the slightest motion of the fiber under test. However, even when these tests are performed properly on a long (>1 km) single mode fiber, it is found that the DGD does not have a reproducible value! Instead, the measured DGD is found to fluctuate randomly about some average value, obeying a statistical rule called a Maxwellian distribution (see Figure 3). This statistical behavior of the DGD is a fundamental property of the PMD effect. Clearly, the measured DGD increases when a longer piece of fiber is measured. It is desirable to have a measure of the PMD that describes the fiber under study without regard to its particular length. We expect to be able to speak of the "DGD per kilometer." However, experiments show that the length of the fiber must be *quadrupled* for the average DGD to *double*. Likewise, the length must be increased by a factor of 9 to triple the average DGD. This odd behavior is characteristic of random processes, and can be summarized by saying that "the average DGD scales as the square root of the length of the fiber." Thus the quantity of interest, called the **PMD coefficient** (or simply the "coefficient") thus has units of $\mathrm{ps}/\sqrt{\mathrm{km}}$, or "ps per root km".

Figure 3: Repeated measurements of the differential group delay (DGD) in a very long piece of single mode fiber reveals a statistical distribution of values, following the Maxwellian function shown. In this example the average DGD measurement is about 10 ps, and measured values up to about 25 ps are not uncommon. If measurements were taken for a long period of time, some of the measured values would fall under the "tail" of the distribution, yielding DGD values > 30 ps.



Modern fiber typically has a PMD value of about 0.2 $\mathrm{ps}/\sqrt{\mathrm{km}}$, whereas older fiber typically has a PMD of 1 – 2 $\mathrm{ps}/\sqrt{\mathrm{km}}$. For example, when the PMD is 0.5 $\mathrm{ps}/\sqrt{\mathrm{km}}$ and the length of the fiber is 50 km, the average DGD is $0.5\times\sqrt{50}=3.5\,\mathrm{ps}$. Recall that for 10 Gb/s transmission speeds the DGD must be kept below about 10 ps. For PMD of 0.5 $\mathrm{ps}/\sqrt{\mathrm{km}}$ and a 500 km length of fiber, the average DGD is $0.5\times\sqrt{500}=11.2\,\mathrm{ps}$, an unacceptably high value. The table below summarizes the acceptable average PMD values for various data rate systems.

Data Rate	Signal Type	Maximum Allowable Average DGD
2.5 Gb/s	OC-48	40 ps
10 Gb/s	OC-192	10 ps
40 Gb/s	OC-768	2.5 ps

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