Polarization-Mode Dispersion

A single-mode optical fiber can support two polarization modes, these two polarization modes are used for polarization-division multiplexing (PDM) or polarization-shift keying (PolSK). If the core of a single-mode fiber is perfectly circular, the two polarization modes propagate with the same speed. However, due to manufacturing tolerance, the core of the fiber varies slightly from prefect circle. The propagation speeds of the two polarization modes have small difference, leading to polarization-mode dispersion (PMD). The optical signal transmitted through the two polarizations arrives with a timing offset at the receiver, called differential group delay (DGD).

For a short piece of fiber less than the birefringence correlation length of a single mode fiber, the DGD increases with fiber length. The birefringence correlation length of a fiber is typically less than 20 m (Galtarossa and Palmieri, 2004, Galtarossa et al., 2001, Huttner et al., 1998). Within the birefringence correlation length, the timing offset between two polarization modes is $\delta\tau = (\beta_{1x} - \beta_{1y})\delta L$, where β_{1x} and β_{1y} are the first-order propagation coefficients of the two polarization modes and δL is the fiber length.

Even if the fiber is perfectly circular, external mechanical or thermal stresses cause small asymmetric to the fiber core. The DGD changes with time due to external stress. Other than polarization-maintained fiber (PMF), beyond the birefringence correlation length, the two polarization axes of the fiber are uncorrelated. A long optical fiber can model as the cascade of many pieces of polarized components, each polarized component corresponds to a short piece of fiber with a length about the birefringence correlation length. When many short pieces of polarized fiber are randomly oriented in a long fiber, the whole fiber can still be modeled as a single polarized component with two principle states of polarization (PSP) and a group delay of DGD. The two PSPs are randomly oriented and the DGD is a random variable, depending on the alignment of individual polarized fiber pieces. Time varying external stress changes both the PSP and DGD.

With a mean DGD of $\langle\Delta\tau\rangle$, the instantaneous DGD has a Maxwellian distribution of

$$p(\Delta\tau) = \frac{32\Delta\tau^2}{\pi^2 \langle\Delta\tau\rangle^3} \exp\left(-\frac{4\Delta\tau^2}{\pi \langle\Delta\tau\rangle^2}\right), \quad \Delta\tau > 0, \tag{1}$$

with a DGD second-order moment of $E\{\Delta\tau^2\} = 3\pi \langle\Delta\tau\rangle^2 /8$. For a long optical fiber, all statistical PMD properties of the fiber depend solely on the mean DGD of $\langle\Delta\tau\rangle$.

With random coupling of light between the polarization modes, the mean DGD of $\langle\Delta\tau\rangle$ increases with $\sqrt{L}$, where L is the fiber length. Before early 90's, the PMD coefficient of fiber may be as large as 1 ps/$\sqrt{\text{km}}$. Currently, optical fiber has a PMD coefficient commonly around 0.1 ps/$\sqrt{\text{km}}$, with some commercially available fiber types have PMD coefficient even approaching 0.05 ps/$\sqrt{\text{km}}$.

Figure 1 shows the eye-penalty as a function of normalized instantaneous DGD of $\Delta\tau/T$ for different modulation formats. Using numerical simulation, the eye-penalty is calculated as the ratio of eye-closure to the nominal eye opening without dispersion and other distortions. ASK or on-off keying signal is assumed to be directly detected using only a photodiode. PSK signal is demodulated using a synchronous homodyne receiver with phase tracking. Both DPSK and MSK signals are demodulated using an interferometer with a path delay of T.

For ASK, PSK, and DPSK signals, the transmitters for Fig. 1 use amplitude modulator. The drive signal is a rectangular pulse passed through a fifth-order Bessel filter with a bandwidth of $0.75B_d$. The receiver also has the same Bessel filter to shape the waveform.

The MSK signal of Fig. 1 is assumed to be an ideal MSK signal in the transmitter. The receiver has a fifth-order Bessel filter with a bandwidth the same as the data-rate.

ASK and PSK modulation formats have the same tolerance to DGD. MSK modulation format, due to its pulse shape, has the least tolerance to DGD. The simulation of Fig. 1 assumes that the two PSP has equal optical power, the worst case for pulse spreading.

Figure 2 shows the eye-penalty for the popular RZ-DPSK format. The DGD tolerance is the smallest for RZ format with a duty-cycle of 1/3. The NRZ DPSK scheme has the largest tolerance to DGD.

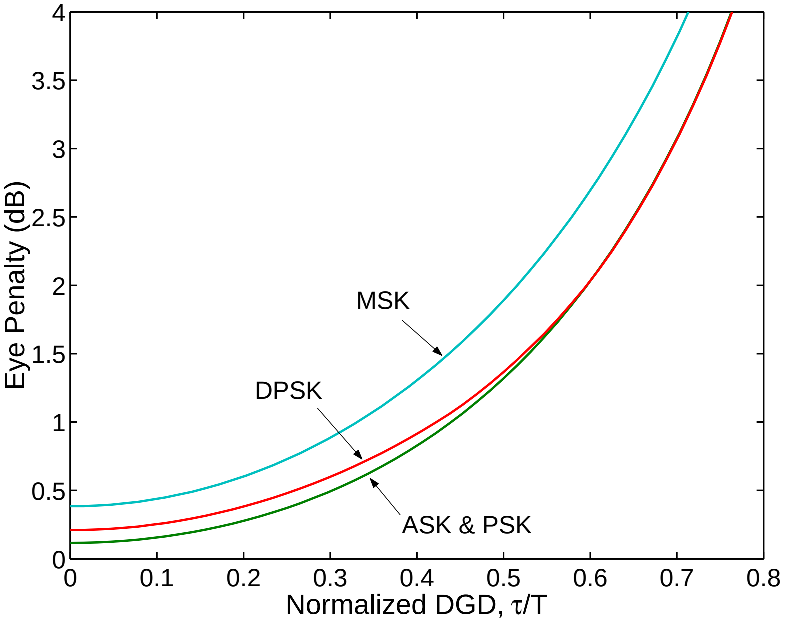

Figure 1: Eye penalty as a function of normalized instantaneous DGD of $\Delta\tau/T$ for different modulation formats.

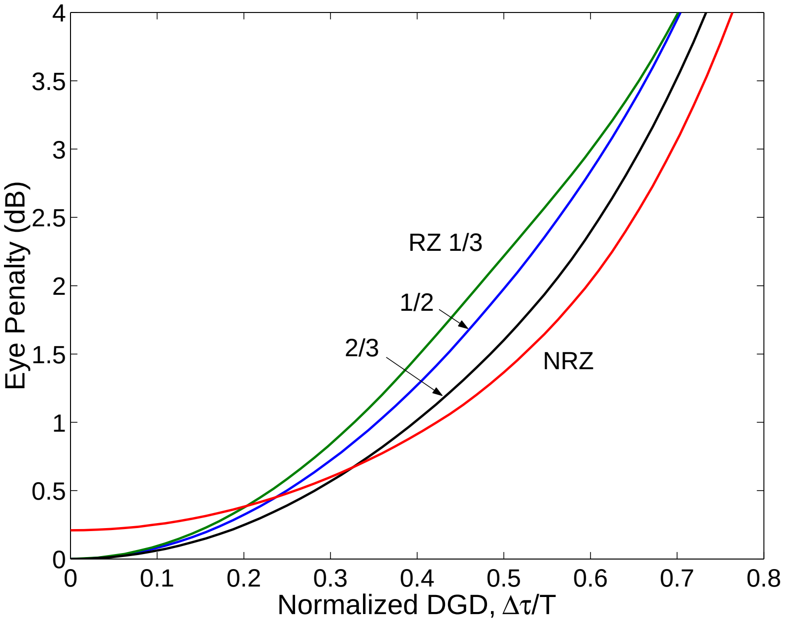

Figure 2: Eye penalty as a function of normalized instantaneous DGD of $\Delta\tau/T$ for direct-detection DPSK signals.

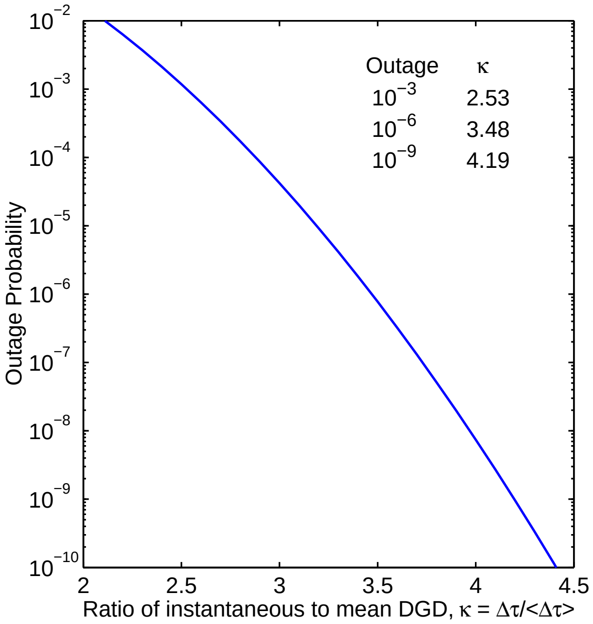

Figure 3: The outage probability as a function of the ratio of instantaneous to mean DGD of $\kappa = \Delta\tau / \langle\Delta\tau\rangle$. Also list the ratio of $\kappa = \Delta\tau / \langle\Delta\tau\rangle$ for some typical outage probabilities.

A system with PMD is usually studied for the outage probability larger than certain instantaneous DGD. For example, for NRZ-DPSK format, the instantaneous DGD of $\Delta\tau = 0.42T$ gives 1-dB power penalty. If more than 1-dB power penalty is defined as outage, based on the probability density of Eq. (1), the outage probability is

$$\Pr\{\Delta\tau > \kappa \langle\Delta\tau\rangle\} = \frac{4\kappa}{\pi} \exp\left(-\frac{4\kappa^2}{\pi}\right) + \operatorname{erfc}\left(\frac{4\kappa}{\pi}\right), \tag{2}$$

as shown in Fig. 3. From Fig. 3, with $\Delta\tau = 0.42T$, the mean DGD must be less than $\langle\Delta\tau\rangle < 0.17T$ or $\langle\Delta\tau\rangle < 0.12T$ for an outage probability less than 10^{-3} and 10^{-6}, respectively. In additional to the dependence on modulation formats from Figs. 1 and 2, the tolerance to PMD is also a function of the allowance of eye-penalty and the outage probability. For example, the eye-penalty may be 2 dB instead of 1 dB for outage.

The PMD of single-mode fiber had been studied for a long time by Rashleigh and Ulrich (1978) and Kaminow (1981), mainly focused on polarization fluctuation in an optical fiber and the requirement of automatic polarization control (APC) for coherent optical communications (Noé et al., 1988, Okoshi, 1985, Walker and Walker, 1990). The statistical model for PMD was developed by Poole and Wagner (1986), Poole et al. (1991), and Foschini and Poole (1991) that gave the Maxwellian distribution of Eq. (1). Gordon and Kogelnik (2000) and Poole and Nagel (1997) provided a review of PMD issues in optical fiber.

The simulation of Figs. 1 and 2, even for the same modulation format, depends on the transmitter and receiver (Garcia et al., 1996, Sunnerud et al., 2003, Winzer et al., 2003). The eye-penalty for RZ pulses in Fig. 2 can be reduced using a receiver with smaller bandwidth than $0.75B_d$. Practical RZ-DPSK signal can have a large tolerance to PMD if the receiver is optimized accordingly.

With some improvements in Tomizawa et al. (2002), forward-error correction cannot in principle improve a system with PMD (Ho and Lin, 1997). Polarization scrambling may be used with forward-error correction to improve the system performance (Liu et al., 2004, Wedding and Haslach, 2001).

In additional to first-order PMD, higher-order PMD also degrades the performance of a system (Bruyère, 1996, Bülow, 1998, Francia et al., 1998). The statistical properties of second-order PMD were studied in Foschini et al. (1999, 2001).

PMD can be compensated by both optical and electrical techniques (Buchali and Bülow, 2004, Hakki, 1997, Haunstein et al., 2004, Lanne and Corbel, 2004, Noé et al., 2004, Sunnerud et al., 2002, Takahashi et al., 1994, Winters and Gitlin, 1990). Typical optical based PMD compensators eliminate all first-order PMD and part of the second-order PMD.

The impact of PMD to coherent optical signal was first studied in Winters and Gitlin (1990). The impact of PMD to DPSK signal was studied in Kim et al. (2002), Pan et al. (2003), Wang and Kahn (2004a,b), and Xie et al. (2003).

Small amount of polarization-dependent loss exists in most optical components (Giles et al., 1991, Yamamoto et al., 1993). In a long-haul network, polarization-dependent loss is induced by the cascade of many those polarized components. When fiber between those polarized components also has PMD to randomize the input polarization into those components, the output optical power is fluctuated due to polarization-dependent loss (Huttner et al., 2000, Willner et al., 2004, Xie and Mollenauer, 2003). The statistics of polarization-dependent loss with PMD is studied in Fukada (2002), Lu et al. (2001), Yu et al. (2002), and Mecozzi and Shtaif (2004).

For single channel system, the EDFA gain in the polarization of the signal is reduced due to polarization hole-burning. Polarization-dependent gain increases the noise in the polarization orthogonal to the signal (Bruyère and Audouin, 1994, Lichtman, 1995, Mazurczyk and Zyskind, 1994, Taylor, 1993). Polarization-dependent gain is not an issue for WDM system with many channels that have random polarization. Even if all channels are launched to the fiber co-polarized, the polarization is randomized after a short piece of fiber due to PMD effects. For WDM system with many channels, common counter-pump Raman amplifier does not have large polarization-dependent gain, even stimulated Raman scattering is polarization dependent (Stolen, 1979).

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