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Performance limitations of an optical heterodyne continuous-phase frequency-shift keying transmission system affected by polarization mode dispersion in a single-mode fiber

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Abstract. A theoretical analysis is developed to evaluate the conditional and average bit error rate (BER) performance degradation of an optical heterodyne continuous-phase frequency-shift keying (CPFSK) system caused by signal phase distortion due to polarization mode dispersion (PMD) in a single-mode fiber. The probability density function (pdf) of the random phase fluctuation due to PMD at the output of the receiver is determined analytically. The average BER performance results are evaluated at a bit rate of 10 Gb/s, considering Maxwellian distribution for the differential group delay (DGD) based on the pdf of the random phase fluctuation. The results show that the performance of the optical heterodyne CPFSK direct detection system suffers power penalties of 0.75, 1.95, 4.00, and 9.15 dB, corresponding to mean DGD of 20, 30, 40, and 60 ps, respectively, at a average BER of 10^{-9} operating at 10 Gb/s. Furthermore, at increased values of the mean DGD, there occur BER floors above 10^{-9}, which cannot be lowered by further increasing the signal power. It is noticed that BER floors occur at about 2×10^{-8}, 10^{-5}, and 2.5×10^{-4}, corresponding to mean DGD of 60, 70, and 80 ps, respectively, at 10 Gb/s and a modulation index of 0.50. The effect of PMD is found to be more detrimental at higher modulation indexes and bit rates.
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Subject terms: polarization mode dispersion; differential group delay; bit error rate; Maxwellian distribution; heterodyne detection.

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1 Introduction

Optical continuous-phase frequency-shift keying (CPFSK) with low modulation index ($h \leq 1$) is an attractive modulation scheme for future multichannel optical systems. However, at high bit rate operation of such systems in a conventional single-mode fiber, the major limitation is the group velocity dispersion (GVD), unless a dispersion compensation scheme is used.[1] Further, a single-mode fiber is actually a two-mode fiber, because it can support two orthogonally polarized eigenmodes. Due to imperfections in the fiber manufacture and deployment, the propagation constants of the two eigenmodes are in general different, and mode coupling occurs as light propagates through a fiber. The different propagation speeds result in polarization mode dispersion (PMD), and maximum dispersion happens when two modes are equally excited. Consequently, an incident linearly polarized wave may be subjected to random phase fluctuation, which causes spectral broadening of the transmitted signal that leads to bit pattern corruption and higher bandwidth requirement, and eventually contributes to bit error rate (BER) deterioration, performance variation, or system fading even at moderate bit rates.[2–9]

PMD constitutes one of the main limiting factors for reliable optical fiber system transmission performance at bit rates of 10 Gb/s or higher. The effect of PMD has been the subject of considerable research interest during the past few years, and the developed ideas are briefly described in a series of publications.[3–9] The simulation results on the effects of PMD on an amplified intensity modulated direct detection (IMDD) system is reported in Ref. 3 as a function of the DGD. The effect of PMD on the conditional bit error rate performance of a heterodyne FSK system is presented in Ref. 6. Recently, the performance of an optical differential phase shift keying (DPSK) system with a direct detection receiver was reported in the presence of PMD.[8,9]

We provide an analytical approach to evaluate the BER performance limitations of an optical heterodyne CPFSK with a delay demodulation system impaired by PMD. The method is based on the linear approximation of the output phase of a linearly filtered angle-modulated signal, such as the CPFSK signal. The probability density function (pdf) of the random phase fluctuation due to PMD and group velocity dispersion (GVD) at the output of the receiver is determined analytically. Based on the pdf of the random phase fluctuation, a conditional BER expression is derived. The temporal behaviors of the fiber PMD are statistical in nature due to randomness of the birefringence variations

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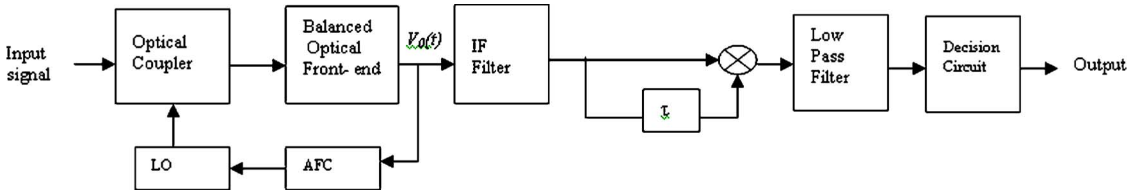

Fig. 1 Block diagram of a heterodyne CPFSK delay demodulation receiver.

along the fiber structure. Therefore, to assess accurately the optical transmission impairment due to PMD, we determine the average BER and power penalty for different mean values of DGD, considering Maxwellian probability density function for the DGD, at the receiver output in the presence of receiver noise. The bit error rate performance and power penalty suffered by the system due to PMD at a BER of 10^{-9} are evaluated at a bit rate of 10 Gb/s.

2 Receiver Model

The block diagram of a CPFSK delay demodulation receiver is shown in Fig. 1. The received optical signal is combined with the optical signal output from the local oscillator, and the two signals are detected by a photodetector. The output of the photodetector, which is an intermediate frequency (IF) signal, is amplified by the receiver preamplifier and then filtered by a Gaussian filter with center frequency set to the IF. The bandwidth of the IF is kept twice the bit rate for optimum demodulation. The output of the filter is then demodulated using a delay line discriminator. The output of the discriminator is then filtered by a low-pass filter and fed to a sampler followed by a comparator. The threshold voltage of the comparator is set to zero value. If the output voltage is greater than zero, then a binary 1 is detected, otherwise a binary 0 is detected.

3 Theoritical Analysis

The complex electric field at the output of the continuous-phase FSK (CPFSK) transmitter and input to the fiber is represented as

$$E_1(t) = \sqrt{2P_T}\exp[j2\pi f_c t + j\phi_s(t)][c_1 \cdot e_1], \tag{1}$$

$$E_2(t) = \sqrt{2P_T}\exp[j2\pi f_c t + j\phi_s(t)][c_2 \cdot e_2], \tag{2}$$

where f_c is the carrier frequency, P_T is the transmitted optical power, and the CPFSK modulating phase $\phi_s(t)$ is given by

$$\phi_s(t) = 2\pi\Delta f\int_{-\infty}^{t} I(t)dt + \phi_n(t), \tag{3}$$

$$I(t) = \sum_{k=-\infty}^{\infty} a_k p(t-kT), \tag{4}$$

where $a_k = \pm 1$ is the kth bit of random nonreturn to zero (NRZ) bit pattern, Δf is the peak frequency deviation, $p(t)$ is the elementary pulse shape of duration T seconds, and $\phi_n(t)$ is the phase noise of the transmitting laser. Here, c_1 and c_2 represent unit vectors and e_1 and e_2 represent the two principal states of polarization (PSPs), respectively.

The electric field output of the fiber is then given by

$$E_{01}(t) = \sqrt{2P_T}\exp[j2\pi f_c t + j\phi_s(t)][c_1 \cdot e_1] \otimes h_1(t), \tag{5}$$

$$E_{02}(t) = \sqrt{2P_T}\exp[j2\pi f_c t + j\phi_s(t)][c_2 \cdot e_2] \otimes h_2(t), \tag{6}$$

where $\otimes$ denotes convolution, and $h_1(t)$ and $h_2(t)$ are the inverse Fourier transform of the low-pass equivalent transfer function of a nondispersion shifted lossless fiber $H_1(f)$ and $H_2(f)$, respectively, which include the effect of PMD and group velocity dispersion and are given by

$$H_1(f) = \sqrt{\alpha}\exp\left[j2\pi f\left(-\frac{\Delta\tau}{2}\right) - j\gamma(\pi f T)^2\right], \tag{7}$$

$$H_2(f) = \sqrt{1-\alpha}\exp\left[j2\pi f\left(\frac{\Delta\tau}{2}\right) - j\gamma(\pi f T)^2\right], \tag{8}$$

where α is the PMD power splitting ratio, $\Delta\tau$ represents the DGD between the two PSPs, and γ is chromatic dispersion index. Here, we assume that there is a negligible amount of polarization-dependent loss.

Now, assuming linear phase approximation, the output electric fields for two polarization states can be given as,

$$E_{01}(t) = \sqrt{2P_s}\exp[j2\pi f_c t + j\phi_{01}(t)][c_1 \cdot e_1], \tag{9}$$

$$E_{02}(t) = \sqrt{2P_s}\exp[j2\pi f_c t + j\phi_{02}(t)][c_2 \cdot e_2], \tag{10}$$

where,

$$\phi_{01}(t) = 2\pi\Delta f\int_{-\infty}^{t}\sum_k a_k \operatorname{Re}[p(t-kT) \otimes h_1(t)]dt, \tag{11}$$

$$\phi_{02}(t) = 2\pi\Delta f\int_{-\infty}^{t}\sum_k a_k \operatorname{Re}[p(t-kT) \otimes h_2(t)]dt. \tag{12}$$

The signal at the output of the IF filter is given by

$$i_0(t) = R_d\sqrt{P_s P_{\mathrm{Lo}}}\{\exp[j2\pi f_{\mathrm{IF}}t + j\phi'_{01}(t)] + \exp[j2\pi f_{\mathrm{IF}}t + j\phi'_{02}(t)]\} + i_n(t), \tag{13}$$

where $i_n(t)$ represents the total noise current consisting of shot noise and receiver thermal noise, R_d is the responsivity of the photodetector, P_s is the output power at the fiber end,

P_{Lo} is the local oscillator power, and f_{IF} is the IF frequency. The phases $\phi'_{01}(t)$ and $\phi'_{02}(t)$ are given by

$$\phi'_{01}(t) = 2\pi\Delta f \int_{-\infty}^{t} \sum_k a_k g_1(t-kT)dt, \tag{14}$$

$$\phi'_{02}(t) = 2\pi\Delta f \int_{-\infty}^{t} \sum_k a_k g_2(t-kT)dt, \tag{15}$$

where,

$$g_1(t) = \mathrm{Re}[p(t) \otimes h_1(t) \otimes h_{\mathrm{IF}}(t)], \tag{16}$$

$$g_2(t) = \mathrm{Re}[p(t) \otimes h_2(t) \otimes h_{\mathrm{IF}}(t)], \tag{17}$$

where $h_{IF}(t)$ is the impulse response of the IF filter. The IF signal current is then given by,

$$i_0(t) = 2R_d\sqrt{P_s P_{\mathrm{Lo}}}\cos\phi''_0(t)\cos[2\pi f_{\mathrm{IF}}t + \phi'_0(t)] + i_n(t), \tag{18}$$

where,

$$\phi'_0(t) = \frac{\phi'_{01} + \phi'_{02}}{2} \quad \text{and} \quad \phi''_0(t) = \frac{\phi'_{01} - \phi'_{02}}{2}.$$

The output of the IF filter can be expressed as,

$$v_0(t) = 2R_d\sqrt{P_s P_{\mathrm{Lo}}}a(t)\cos[2\pi f_{\mathrm{IF}}t + \phi'_0(t)] + n(t), \tag{19}$$

where $a(t)=\cos\phi''_0(t)$, which is the amplitude fluctuations due to PMD and GVD, and $n(t)$ is the receiver shot noise with variance $\sigma_n^2 = 2e(Ps+P_{\mathrm{Lo}})B_{\mathrm{IF}}$, B_{IF} being the IF filter bandwidth. Following the delay demodulation (delay time τ) and low-pass filtering (wide enough to pass the signal undistorted), the low-pass filter (LPF) output is given by,

$$v_{\mathrm{out}}(t) = A(t)\cos[\Delta\phi_0(t,\tau)], \tag{20}$$

where,

$$A(t) = 2R_d\sqrt{P_s P_{\mathrm{Lo}}}\cos\phi''_0(t);$$

$A(t)$ is the amplitude, and the differential output phase of $v_{\mathrm{out}}(t)$of the LPF can be expressed as,

$$\Delta\phi_0(t,\tau) = 2\pi f_{\mathrm{IF}}\tau + \Delta\phi'_0(t,\tau) + \Delta\theta_n(t,\tau), \tag{21}$$

$$\Delta\phi'_0(t,\tau) = 2\pi\Delta f\left[\int_{t-\tau}^{t} a_0 g_0(t-kT)dt + \int_{t-\tau}^{t} \sum_{k\neq 0} a_k g_0(t-kT)dt\right], \tag{22}$$

which can be rewritten as,

$$\Delta\phi'_0(t,\tau) = 2\pi\tau\Delta f q(t) + 2\pi\tau\Delta f \sum_{k\neq 0} a_k q(t-kT), \tag{23}$$

where,

$$q(t) = \frac{1}{\tau}\int_{t-\tau}^{t} g_0(t)dt, \tag{24}$$

and

$$g_0(t) = \frac{1}{2}[g_1(t) + g_2(t)]. \tag{25}$$

Using the notation,

$$\Delta\theta_n(t,\tau) = 2\pi\int_{t-\tau}^{t} \theta_n(t_1)dt_1, \tag{26}$$

and

$$\theta_n(t) = \arctan\left[\frac{n_s(t)}{A(t) + n_c(t)}\right], \tag{27}$$

$n_c(t)$ and $n_s(t)$ are the in-phase and quadrature components of noise $n(t)$, respectively, with zero mean and variance σ_n^2. It is assumed that the IF filter is a finite bandpass integrator that is symmetric around f_{IF} with bandwidth $B_{\mathrm{IF}}=2/T$ and demodulation time $\tau=T/2h$, $h\leq 1$ (narrowband CPFSK), and for the IF filter chosen, the correlation between $\theta_n(t)$ and $\theta_n(t-\tau)$ is zero. For other types such as a Gaussian or second-order Butterworth, the noise correlation is negligibly small for $B_{\mathrm{IF}}\geq 2$ and $h\leq 1$ (for NRZ data).

In a delay demodulation receiver, the data decisions are based on the polarity of $v_{out}(t)$. Assuming a "mark" is transmitted (say $a_0=1$) and under ideal CPFSK demodulation conditions, $2\pi f_{\mathrm{IF}}\tau=(2n+1)\pi/2$; n is an integer and $2\pi\Delta f\tau=\pi/2$ for NRZ data.

Now, applying the previous conditions, the phase of $v_{out}(t)$ at the sampling instant t_0 can be written as,

$$\Delta\phi_0(t_0,\tau) = 2\pi f_{\mathrm{IF}}\tau + \frac{\pi}{2} - \frac{\pi}{2} + \frac{\pi}{2}q(t_0) + \frac{\pi}{2}\sum_{k\neq 0} q(t_0-kT) + \Delta\theta_n(t_0,\tau). \tag{28}$$

Note that the first two terms in Eq. (28) provide the expected phase change during the demodulation interval τ corresponding to the ideal situation. The next three terms, in fact, represent the undesired contribution to the phase due to PMD and GVD, and the last term $\Delta\theta_n(t_0,\tau)$ represents the phase distortion due to receiver noise. Denoting the phase distortion of the signal only due to PMD and GVD as

$$\eta = -\frac{\pi}{2} + \frac{\pi}{2}q(t_0) + \frac{\pi}{2}\sum_{k\neq 0} a_k q(t_0-kT) = \bar{\Delta}\alpha_0(t,\tau) + \xi, \tag{29}$$

where $\bar{\Delta}\alpha_0(t,\tau)$ is the mean output phase error and ξ is the random output phase fluctuation due to intersymbol interference (ISI) for random bit pattern caused by PMD and GVD.

We define the IF signal-to-noise ratio (SNR) as $\rho = V_0^2/2\sigma_n^2$. For a given IF SNR, the conditional bit error probability $P(e|\xi)$, conditioned on a given value of ξ and differential group delay $\Delta\tau$, can be obtained following Ref. 10. The probability density function (pdf) of ξ, $P_\xi(\xi)$, can

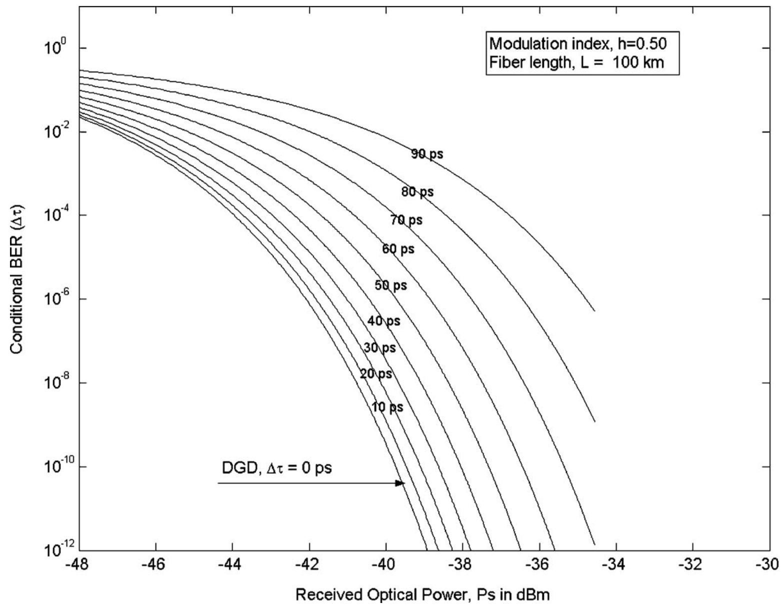

Fig. 2 Plot of conditional BER versus received power ps for heterodyne CPFSK impaired by PMD at modulation index 0.50.

be obtained by inverting the characteristic function of ξ. The characteristic function of random output phase ξ can be expressed as,

$$F_{\xi}(j\xi) = \prod_{i=1}^{\infty} \cos[\xi q_i(t)] = \sum_{i=1}^{\infty} \frac{(j\xi)^{2i}}{(2i)!} M_{2i}, \tag{30}$$

where $q_i(t) = |q(t-iT)|$, and M_{2i} are the even order moments of the characteristic function of random output phase ξ. Moments M_{2i} can be evaluated by using the following recursive relations,

$$M_{2r} = Y_{2r}(N), \tag{31}$$

$$Y_{2r}(i) = \sum_{j=0}^{r} {}^{2r}C_{2j} Y_{2j}(i-1) q_i^{2r-2j}, \tag{32}$$

where ${}^{2r}C_{2j}$ is the binominal coefficient and N is the actual number of terms. The pdf of the random output phase ξ can be written as,

$$P_{\xi}(\xi) = F^{-1}[F_{\xi}(j\xi)]. \tag{33}$$

So for a given value of differential group delay (DGD), $\Delta\tau$ the conditional BER can be expressed as,

$$\mathrm{BER}(\Delta\tau) = \int_{-\infty}^{\infty} P(e|\xi) P_{\xi}(\xi) d\xi, \tag{34}$$

where $P_{\xi}(\xi)$ is the pdf of ξ, which can be evaluated following Ref. 10. The prior integration can be carried out by the Gauss-quadrature rule.

PMD is a stochastic process. The random configuration of birefringence, which causes PMD, depends on the stress induced by spooling, cabling, temperature changes, and any other environmental factor that may cause the core of the fiber to deviate from being perfectly cylindrical. The statistical properties of PMD have been experimentally and theoretically studied and it was found that the evolution of DGD at a particular frequency over time yields a Maxwellian probability density function given by,

$$P_{\Delta\tau}(\Delta\tau) = \frac{32\Delta\tau^2}{\pi^2\langle\Delta\tau\rangle^3} \exp\left(-\frac{4\Delta\tau^2}{\pi\langle\Delta\tau\rangle^2}\right), \quad \Delta\tau > 0, \tag{35}$$

where $\langle\Delta\tau\rangle$ is the quadratic mean of instantaneous DGD, $\Delta\tau$. Thus, the average error probability can be evaluated as,

$$\mathrm{BER} = \int_{-\infty}^{\infty} \mathrm{BER}(\Delta\tau) P_{\Delta\tau}(\Delta\tau) d(\Delta\tau). \tag{36}$$

4 Results and Discussion

Following the analytical approach outlined before, we evaluated the conditional and average bit error rate performance result of an optical heterodyne CPFSK transmission system with delay demodulation for several values of mean DGD at a bit rate of 10 Gb/s. The plot for conditional BER versus received optical power ps are shown in Figs. 2 and 3 for different values of DGD at a modulation index of 0.5 and 1.0, respectively.

The results from Figs. 2 and 3 show that the BER is degraded when the instantaneous DGD is higher for a given fiber length, and the system suffers a significant amount of power penalty due to the effect of PMD. At BER 10^{-9}, the penalty is found to be approximately 0.70, 1.75, 3.50, and 5.75 dB, corresponding to instantaneous DGD of 20, 40, 60, and 80 ps respectively, at modulation index 0.50. It is further observed that the penalty is much higher at a higher modulation index such as $h=1$, compared to $h=0.5$, e.g., the penalty is approximately 5.25 dB when instantaneous DGD is 70 ps and $h=1.0$.

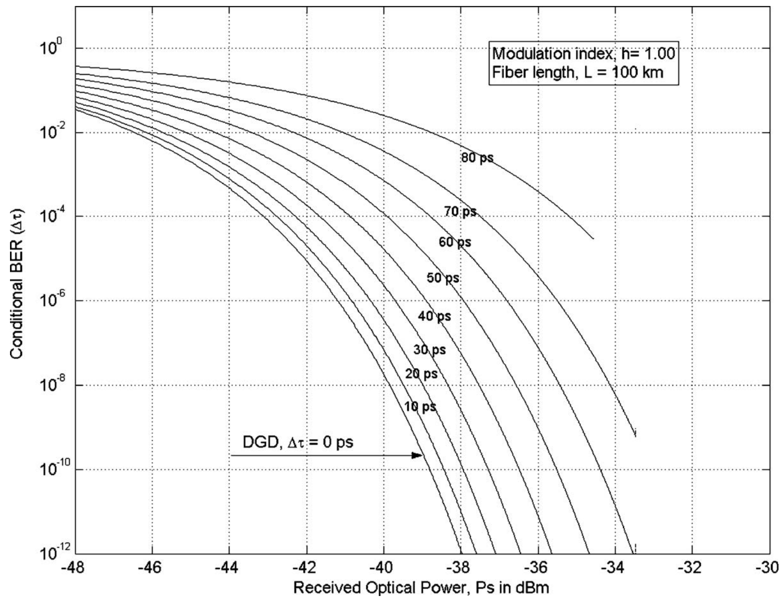

Fig. 3 Plot of conditional BER versus received power ps for heterodyne CPFSK impaired by PMD at modulation index 1.00.

Figures 4 and 5 show the plot of average BER versus received power ps, shown at a modulation index of 0.50 and 1.0, respectively, at bit rate 10 Gb/s for different values of mean DGD. The results show that the BER performance is more affected at higher values of mean DGD and at higher modulation indexes.

The penalty due to PMD suffered by the heterodyne CPFSK system at BER 10^{-9} is plotted in Fig. 6 as a function of DGD normalized by bit duration. It is observed from Fig. 4 that the penalty at $\mathrm{BER}=10^{-9}$ is increasing with increasing values of the mean DGD. It is observed that the amount of power penalty is approximately 0.75, 2.00, 3.50, and 5.70 dB, corresponding to mean DGD of 20, 30, 40, and 50 ps, respectively, at a modulation index of 0.50. Further increase of DGD leads to a BER floor above 10^{-9}, which cannot be lowered by further increasing the signal power.

It is noticed that BER floors occur at about 2×10^{-8}, 10^{-5}, and 2.5×10^{-4}, corresponding to mean DGD of 60, 70, and 80 ps, respectively, at 10 Gb/s and a modulation index of 0.50. The amount of penalty is approximately 6.80 dB when mean DGD is 40 ps at modulation index 1.0. The plot of penalty due to other modulation schemes as reported in Ref. 7 are also shown in Fig. 6 for comparison.

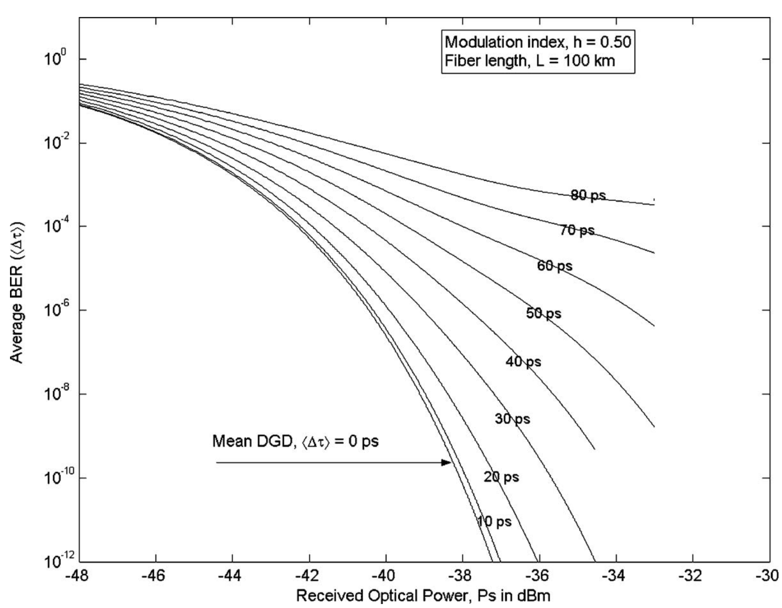

Fig. 4 Plot of average BER versus received power ps for heterodyne CPFSK receiver impaired by PMD at modulation index 0.50.

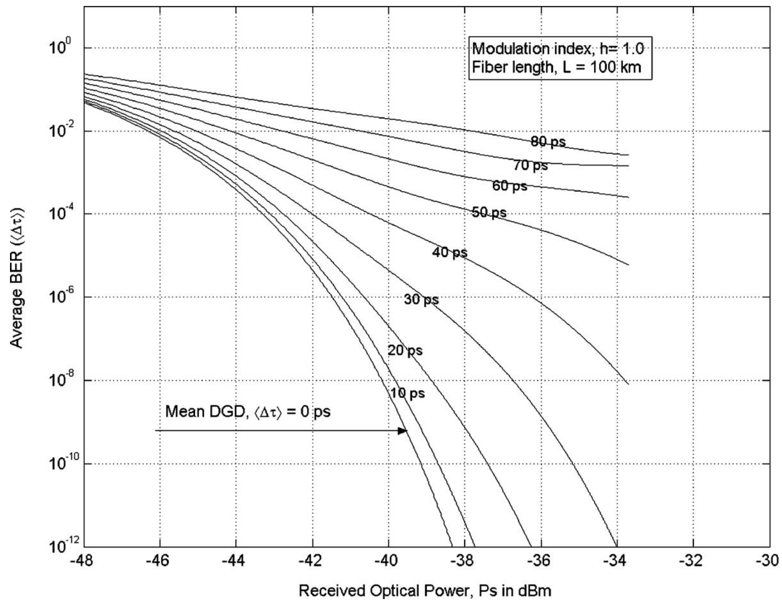

Fig. 5 Plot of average BER versus received power ps for heterodyne CPFSK impaired by PMD at modulation index 1.00.

It is further noticed that the penalty suffered by heterodyne detection CPFSK with a modulation index of 0.50 is higher than that of the NRZ-on-off keying (OOK) system. But at a higher modulation index, the penalty suffered by heterodyne CPFSK is also higher than that of OOK and DPSK systems.

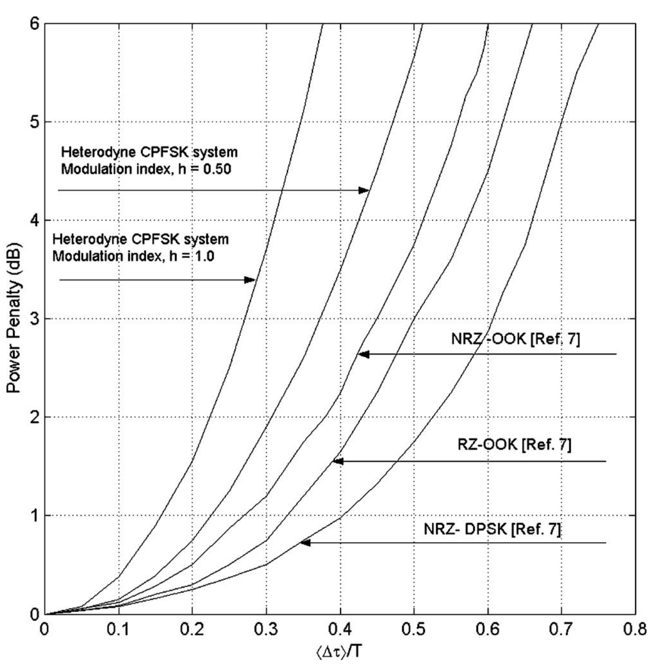

Fig. 6 PMD-induced power penalty (considering average BER) as a function of DGD/bit duration ($<\Delta\tau>/T$) for NRZ- and RZ-OOK, NRZ-DPSK, and heterodyne NRZ-CPFSK systems.

5 Conclusion

An analytical approach is presented to evaluate the impact of polarization mode dispersion on the BER performance of a heterodyne CPFSK system. The results show how PMD induces a sensible penalty degradation in such a system when the fiber link presents a mean DGD equal to 80 ps. Our analysis allows us to conclude that PMD generally induces a relevant degradation in the heterodyne CPFSK long haul transmission link, and controls have to be made to avoid the presence of either fibers or optical components with higher values of PMD.

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