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Performance of Double – Frequency Parameter Shift Keying (DFPSK) System in the Presence of Dichroism

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Abstract

The reliability and feasibility of optical coherent communication system are strongly conditioned by laser phase noise and fluctuations of the state of polarization (SOP) of the optical field at the output of conventional single – mode fiber. The double – frequency parameter shift keying (DFPSK) system has been proposed in the literature as an efficient scheme that allows compensation of both effects by sending a reference channel that is suitably frequency shifted by using polarization modulation. This paper presents a comprehensive theoretical analysis for the performance of this system in the presence of dichroism which in introduced when the transmission channel have polarization – dependent losses or amplifications. The results indicate that the performance of DFPSK system is affected by dichroism even in the low – noise frequency regime.

أداء نظام **DFPSK** بوجود الثنوانية

الخلاصة

تعتمد ثبوتية وموثوقية أنظمة الاتصالات الضوئية المتزامنة على ضوضاء الطور لليزر وتغيرات حالة الاستقطاب للمجال الكهربائي من إخراج الكيبل الضوئي.

تقدم هذه الورقة تحليل لنظام DFPSK (الذي يعتمد على ارسال اشارة مرجعية اضافة الى اشارة مضمنة بالمعلومات) بوجود الثنوانية (Dichroism) المتولدة في القناة الناقلة.

1. Introduction: -

Coherent optical communication systems offer significant improvement over conventional direct detection in two main areas [1,2]: increase in receiver sensitivity and the possibility of using frequency division multiplexing to efficiently utilize the fiber bandwidth. However, the performance of these systems is strongly affected by the laser phase noise and the random fluctuation of the state of polarization (SOP) of the optical field at the output of a conventional single – mode fiber (SMF) [3,4].

Different schemes have been reported in the literature to solve the problem of phase noise in coherent communication systems. Among these schemes are: (i) employing phase diversity transmission [5]; (ii) using laser sources with improved spectral characteristics (e.g., external cavity semiconductor laser) [6]; (iii) adopting envelope detection for ASK (amplitude shift keying) and FSK (frequency shift keying) systems [7,8] in spite of their reduced sensitivity with respect to synchronous PSK (phase shift keying) coherent systems.

Regarding the problem of SOP fluctuations, different solutions have been proposed to overcome it including the utilizing of (i) polarization diversity scheme [9]; (ii) polarization shift keying (POLSK) technique [10 – 12]; (iii) polarization controller in the receiver to match the polarization states of the received signal wave and the local oscillator wave [1]. Although these solutions prevent complete fading, they add extra complexity to the transmission system.

Recently, there is increasing interest in coherent systems that offer high immunity to both laser phase noise and SOP fluctuations. One of the binary modulation schemes, that achieves this purpose with a limited penalty with respect to the quantum limit of conventional coherent systems, is the double – frequency parameter shift keying (DFPSK) system depicted in Fig.1 [13]. In this system, the transmission of a reference signal derived from a common optical laser, and suitably frequency shifted with respect to the phase modulated signal, allows practical insensitiveness to phase noise. Compatibility with the use of a polarization – independent detection scheme makes the DFPSK system independent of SOP fluctuations. The performance of this system has been studied by Betti et al. [13] in the absence of dichroism. In this paper, we extend the analysis of [13] to address the effect of dichroism on the system performance.

The problem of dichroism arises in optical communication links due to the presence of polarization – dependent attenuation or/and optical amplification. Splices, couplers, switches, and semiconductor optical amplifiers usually show polarization – dependent characteristics [14]. The dichroism phenomenon seems to be present even in erbium - doped fiber amplifiers. Thus we expect that dichroism becomes important when a large number of optical amplifiers is employed. Here, when a two orthogonally polarized waves are coupled to the fiber, the orthogonality is not assured between fiber output SOPs.

2. System Performance Evaluation: -

A simplified block diagram of the DFPSK system is shown in Fig.1 [13]. At the transmitter, the laser beam, which is assumed to have an optical frequency f_1, is divided into two orthogonal polarization components. The x component is phase modulated by the input data m(t) while the y component is frequency shifted to a new frequency f_2. The frequency difference ($f_1 - f_2$) is to be suitably chosen such that a negligible crosstalk is produced at the receiver. The two components are then combined together using polarization beam splitter (PBS) and coupled to the fiber.

The received field is first decomposed into the x and y components (according to the geometrical reference system defined at the receiver site). The two components are mixed with the corresponding components of the local oscillator (LO) laser field and separately detected. The resulting intermediate frequency (IF) signals are filtered by two bandpass filters, F_1 for the modulated signal and F_2 for the reference carrier. Further beating and filtering (using a bandpass filter F_3) allow phase noise compensation. The phase – locked loop (PLL) system is used to recover the IF carrier.

In the absence of birefringence, coupling, and dichroism , the received optical signal field can be expressed as

$$E(t) = [a\exp[j\{2\pi f_1 t + \Phi_t(t) + \psi + m(t)\pi\}]$$
$$- c\exp[j\{2\pi f_2 t + \Phi_t(t)\}]]\bar{x} +$$
$$[a\exp[j\{2\pi f_1 t + \Phi_t(t) + m(t)\pi\}] +$$
$$c\exp[j\{2\pi f_2 t + \Phi_t(t) - \psi\}]]\bar{y} \ldots\ldots\ldots\ldots(1)$$

where

$\vec{x}, \vec{y}$: Reference axis unit vectors.

$\Phi_t(t)$: Transmitter laser phase noise.

ψ : Phase shift between the output polarization (assumed constant during a bit time)

$m(t)$: 0 (1) when a binary 0 (binary 1) is transmitted.

a, c : field amplitudes.

The presence of birefringence and coupling along the optical link yields rotation in the received Poincare sphere by angles χ and ζ, respectively. [See the appendix]. The presence of dichroism affects the system performance via three parameters

i. ρ which represents the effect of dichroism on the rotation angle χ.
ii. δ which represents the effect of dichroism on the rotation angle ζ.
iii. β which represents the dichroism – induced amplitude unbalance.

If $\beta = \delta = \rho = 0$, the transmission medium is not dichroic and the output SOPs are orthogonal.

Under non-ideal transmission characteristics, the received optical signal field can be expressed as

$$E_1(t) = [a_{1x}\exp[j\{2\pi f_1 t + \Phi_t(t) + \Theta_{1x} + \psi\}]$$
$$+ c_{1x}\exp[j\{2\pi f_2 t + \Phi_t(t) + \Theta_{1x}\}]]\bar{x}$$
$$+ [a_{1y}\exp[j\{2\pi f_1 t + \Phi_t(t) + \Theta_{1y}\}] +$$
$$c_{1y}\exp[j\{2\pi f_2 t + \Phi_t(t) + \Theta_{1y} - \psi\}]]\bar{y} \ldots\ldots(2a)$$

$$\begin{aligned} E_0(t) = {} & [a_{0x} \exp[j\{2\pi f_1 t + \Phi_1(t) + \Theta_{0x} + \psi\}] \\ & - c_{0x} \exp[j\{2\pi f_2 t + \Phi_1(t) + \Theta_{0x}\}]]\vec{x} \\ & + [a_{0y} \exp[j\{2\pi f_1 t + \Phi_1(t) + \Theta_{0y}\}] + \\ & c_{0y} \exp[j\{2\pi f_2 t + \Phi_1(t) + \Theta_{0y} - \psi\}]]\vec{y} \quad \text{.....(2b)} \end{aligned}$$

where E_1 and E_0 refer, respectively, to the field associated with the message bit m = 1 and 0. Further,

$$\left.\begin{aligned} a_{1x} &= -a(1+\frac{\beta}{2})\sin(\zeta+\frac{\delta}{2}) \\ a_{0x} &= a(1-\frac{\beta}{2})\cos\zeta \\ a_{1y} &= -a(1+\frac{\beta}{2})\cos(\zeta+\frac{\delta}{2}) \\ a_{0y} &= a(1-\frac{\beta}{2})\sin\zeta \\ \Theta_{1x} &= \frac{\rho}{2}+\chi \\ \Theta_{0x} &= \chi \\ c_{1x} &= -c(1+\frac{\beta}{2})\sin(\zeta+\frac{\delta}{2}) \\ c_{0x} &= -c(1-\frac{\beta}{2})\cos\zeta \\ c_{1y} &= c(1+\frac{\beta}{2})\cos(\zeta+\frac{\delta}{2}) \\ c_{0y} &= c(1-\frac{\beta}{2})\sin\zeta \\ \Theta_{1y} &= -\frac{\rho}{2}-\chi \\ \Theta_{0y} &= -\chi \end{aligned}\right\} \text{........ (3)}$$

At the receiver, the received field is mixed with the LO field which is linearly polarized at 45° with respect to the reference axis. The LO laser generates the optical field

$$E_{LO}(t) = \cos[2\pi f_{LO} t + \Phi_{LO}(t)] \text{.............(4)}$$

where f_{LO} and $\Phi_{LO}(t)$ are, respectively, frequency and phase noise.

By means of suitable normalization of the optical LO power, the IF signal after detection and filtering can be written as follows

$$\begin{aligned} I_{0x}(t) = 2\,[& a_{0x}\cos[2\pi f_{13}t + \Phi(t) + \Theta_{0x} + \psi] + \\ & c_{0x}\cos[2\pi f_{23}t + \Phi(t) + \Theta_{0x}]] \\ & + n_{0x}(t) \quad \text{..............................(5a)} \\ I_{1x}(t) = 2\,[& a_{1x}\cos[2\pi f_{13}t + \Phi(t) + \Theta_{1x} + \psi] + \\ & c_{1x}\cos[2\pi f_{23}t + \Phi(t) + \Theta_{1x}]] \\ & + n_{1x}(t) \quad \text{..............................(5b)} \\ I_{0y}(t) = 2\,[& a_{0y}\cos[2\pi f_{13}t + \Phi(t) + \Theta_{0y}] + \\ & c_{0y}\cos[2\pi f_{23}t + \Phi(t) + \Theta_{0y} - \psi]] \\ & + n_{0y}(t) \quad \text{..............................(5c)} \\ I_{1y}(t) = 2\,[& a_{1y}\cos[2\pi f_{13}t + \Phi(t) + \Theta_{1y}] + \\ & c_{1y}\cos[2\pi f_{23}t + \Phi(t) + \Theta_{1y} - \psi]] \\ & + n_{1y}(t) \quad \text{..............................(5d)} \end{aligned}$$

where $f_{13} = |f_1 - f_{LO}|$ and $f_{23} = |f_2 - f_{LO}|$ are the IF frequencies, $\Phi(t) = \Phi_1(t) - \Phi_{LO}(t)$ is the overall phase noise of the transmitter and LO lasers, and n_{ix}, n_{iy} (i=0, 1) are the detection noise sources.

To simplify the analysis, the following assumptions are assumed

i. The detection noise sources are assumed to be characterized by uncorrelated Gaussian white processes which are dominated by the LO shot noise components [5].

ii. The crosstalk between the modulated and reference IF signals is negligible.

The bit – error – rate P_e can be calculated by averaging the bit – error – rate conditioned to mark or space transmission:

$$P_e = ½ [P_{e0} + P_{e1}] \quad ....(6)$$

In writing eqn. (6) it is assumed that the transmission of mark and space occurs at equal probability. The error probabilities associated with mark and space transmission (P_{e1} and P_{e0}) can be calculated using the following expressions

$$P_{em} = \frac{1}{2}\Big[1 - Q\left(\sqrt{d_{1m}}, \sqrt{d_{2m}}\right) + Q\left(\sqrt{d_{2m}}, \sqrt{d_{1m}}\right)\Big] \quad ....(7)$$

where Q(*,*) is the Marcum function and

$$d_{1m} = \frac{1}{2}\left(\sqrt{\gamma_{1m}} + \sqrt{\gamma_{2m}}\right)^2 \quad ....(8a)$$

$$d_{2m} = \frac{1}{2}\left(\sqrt{\gamma_{1m}} - \sqrt{\gamma_{2m}}\right)^2 \quad ....(8b)$$

In the eqn. (8) the signal -- to -- noise ratios (SNRs) γ_{1m} and γ_{2m} (m = 0, 1), are given by (assuming ideal bandpass filters F_1 and F_2):

$$\gamma_{1m} = \frac{1}{2B}\left(a_{mx}^2 \cos^2(\Theta_{mx}) + a_{my}^2 \cos^2(\Theta_{my})\right) \quad ....(9a)$$

$$\gamma_{2m} = \frac{1}{2W}\left(c_{mx}^2 \cos^2(\Theta_{mx}) + c_{my}^2 \cos^2(\Theta_{my})\right) \quad ......(9b)$$

where

B : Bandwidth of the IF filter F_2.

W : Bandwidth of the IF filter F_1.

If the SNRs are high enough, i.e. $\gamma_{1m} >> 1$ and $\gamma_{2m} >> 1$ (m = 0, 1), the bit – error – rate can be approximated by

$$P_{em} \approx \frac{1}{2}\operatorname{erfc}\left[\frac{\sqrt{d_{1m}} - \sqrt{d_{2m}}}{\sqrt{2}}\right] \quad ....(10)$$

where erfc is the error function complement.

3. Simulation Results: -

Unless otherwise stated, the simulation results will be presented using the parameter values given in Table 1. The filters F_1 and F_2 are assumed to be ideal bandpass filters that $W = R + kB_L$ and $B = kB_L$ wide, respectively. R is the bit rate and B_L is the sum of the transmitter and LO laser linewidths. In addition, k is a coefficient that allows transmission of both the modulated and reference signal to be undistorted through the filters.

P_e	10^{-9}
p	47 photons/bit
R	10 Gbit/s
B_L	1 GHz
$\zeta = \chi$	0°
$\delta = \rho$	0°
β	0 %

Table 1 Parameter values used to assess the performance of DFPSK system.

In Fig. 2, we plot the BER characteristics of DFPSK receiver for different values of bit rate to laser linewidth ratio R/B_L. The number of photons per bit, P, required to achieve a BER of 10^{-9} is equal to 47 and 18 when $R/B_L=10$ and ∞, respectively. The result of 18 photons / bit at $R/B_L = \infty$ indicates clearly that the performance of DFPSK system tends to that of synchronous PSK in the low – phase noise regime. The value of P is computed from

$$P = \frac{a^2 + c^2}{R} = \frac{a^2}{\varphi R} \qquad \text{..........(11)}$$

where $a^2 = a_x^2 + a_y^2$, $c^2 = c_x^2 + c_y^2$, and φ is the power splitting ratio.

The optimum value of φ (the minimizes the BER) is approximately given by

$$\varphi_{opt} \approx \frac{W}{B+W} = \frac{1 + k\frac{B_L}{R}}{1 + 2k\frac{B_L}{R}} \qquad \text{..........(12)}$$

Equation (12) can be obtained by maximizing the argument of the error function in eqn. (10).

Figures 3a – 3c show the variation of BER with the splitting ratio φ for different values of R/B_L and assuming P = 47 photons/bit. The result reveals that the optimum value of φ is an accord with that computed from eqn. (12). Note further as R/B_L tends to zero, the optimum value of φ approaches 1. This result is expected since no reference signal is needed to be transmitted in this case.

The variation of BER with dichroism parameter ρ and β are depicted in Figs. 4 and 5, assuming P = 47 photons/bit. The results are independent of the third dichroism parameter, δ. Note that the system performance degrades with increasing ρ and β. The power penalty due to the presence of dichroism effect is evaluated for BER = 10^{-9} and the results are depicted in Figs 6 and 7. Power penalty as high as 2 dB may occur (for example, when β = 60 % and ρ = 60°). Note further that the effect of β on system performance is more pronounced than the effect of ρ.

To show the effect of birefringence parameter χ on BER characteristics, we plot the curves in Fig. 8. Investigating these plots reveals the following fact: the minimum BER is achieved when χ = 0°.

4. conclusions: -

The performance of double frequency parameter shift keying (DFPSK) is addressed in the presence of dichroism effect. Signal analysis and BER characteristics are reported in the presence of system impairments. The results indicate clearly that the amplitude unbalance parameter β has more effect on system performance when compared with the effect mismatch angle ρ. Power penalty of 0.8 dB will be occurred when the system is affected by dichroism having $\beta = 30\ \%$ and $\rho = 30^{0}$. The penalty increases to 2 dB when $\beta = 60\ \%$ and $\rho = 60^{0}$.

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shift keying modulation", IEEE J. Sel. Commun., vol. 13, no. 3, Apr., pp. 531-542, 1995.

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Appendix

Representation χ and α on the Poincare sphere

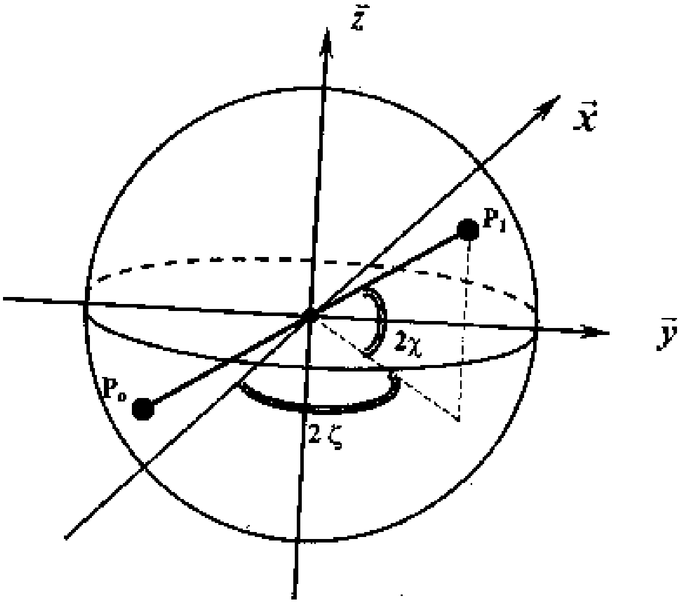
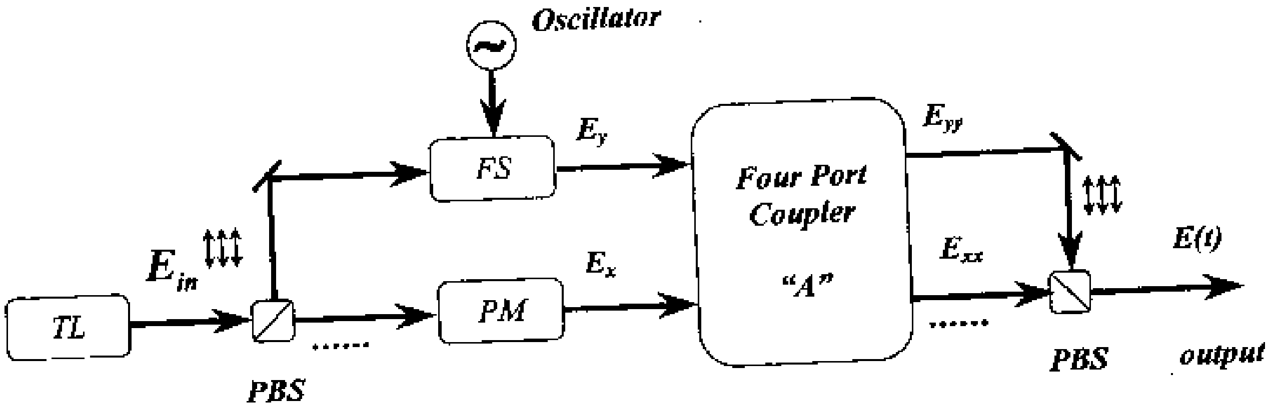


Figure shows the location of χ and ζ on the Poincare sphere.

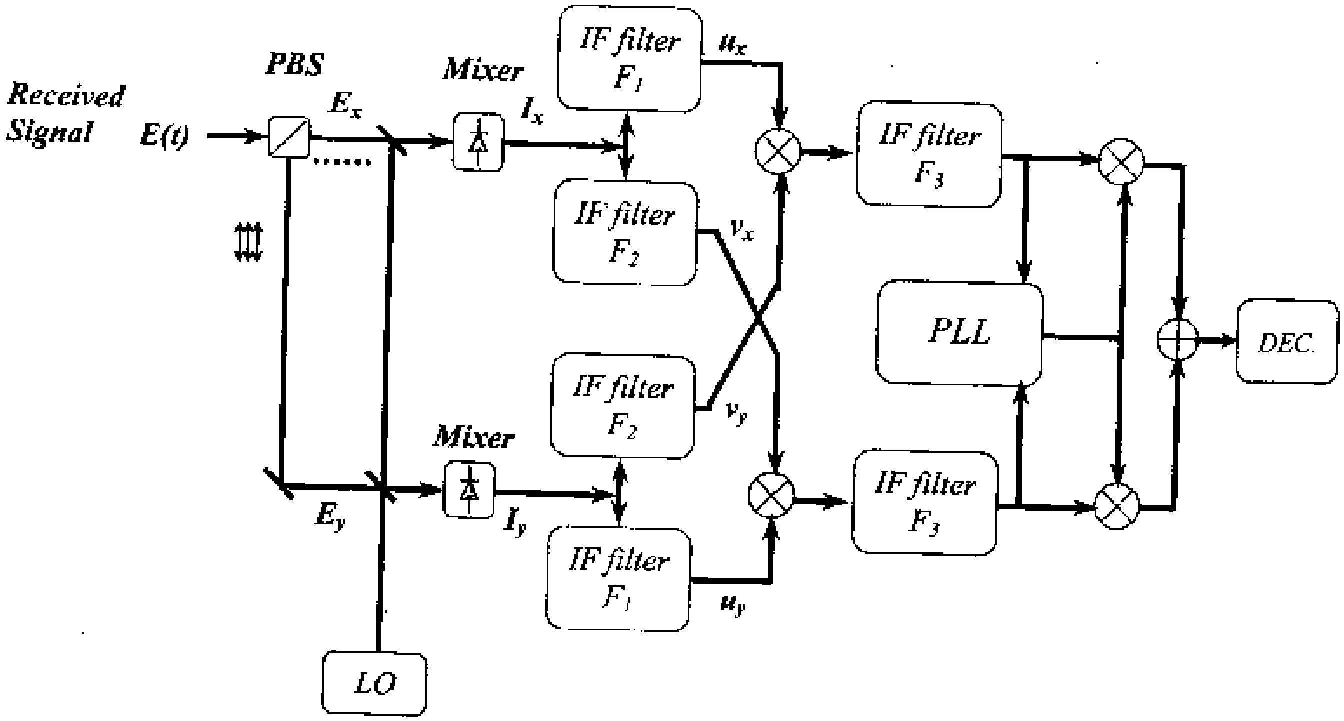
The angles χ and ζ represent the rotation of the Poincare sphere due to birefringence and coupling, respectively.



TL: Transmitter laser.
PBS: Polarization beam splitter.
PM: Phase modulator.
FS: Frequency shifter.

(a) Transmitter.

Fig. 1 A block diagram of DFPSK system.



F_1, F_2: Intermediate frequency (IF) selector filters center around w_{13} and w_{23} respectively.
F_3: IF bandpass filter center around w_{12}.
PLL: Phase locked loop.
DEC: Decision circuit.
LO: Local oscillator.

(b) Receiver.

Fig. 1 (cont.)

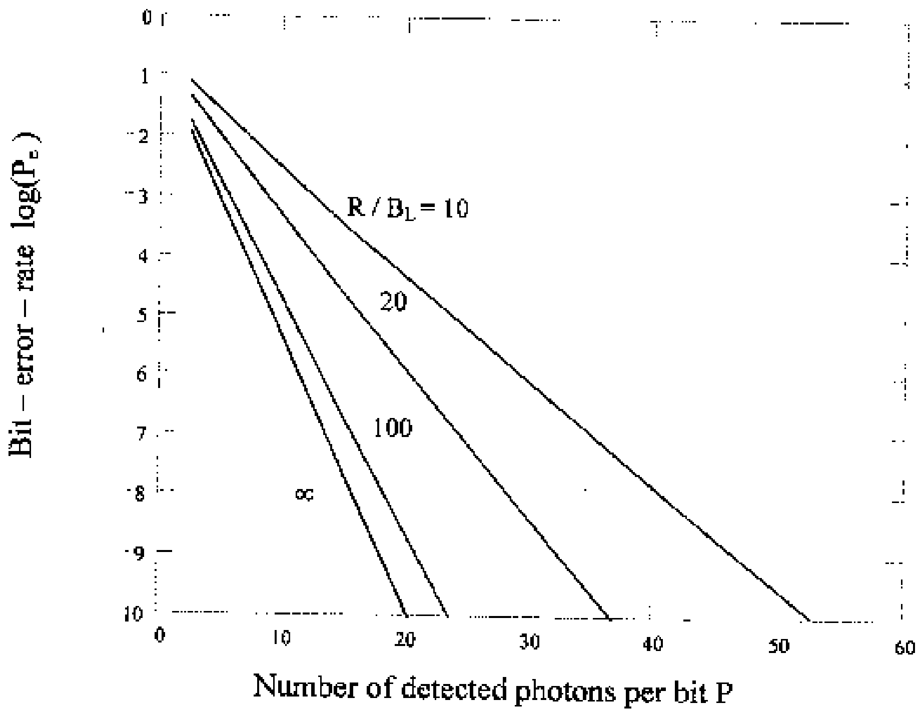
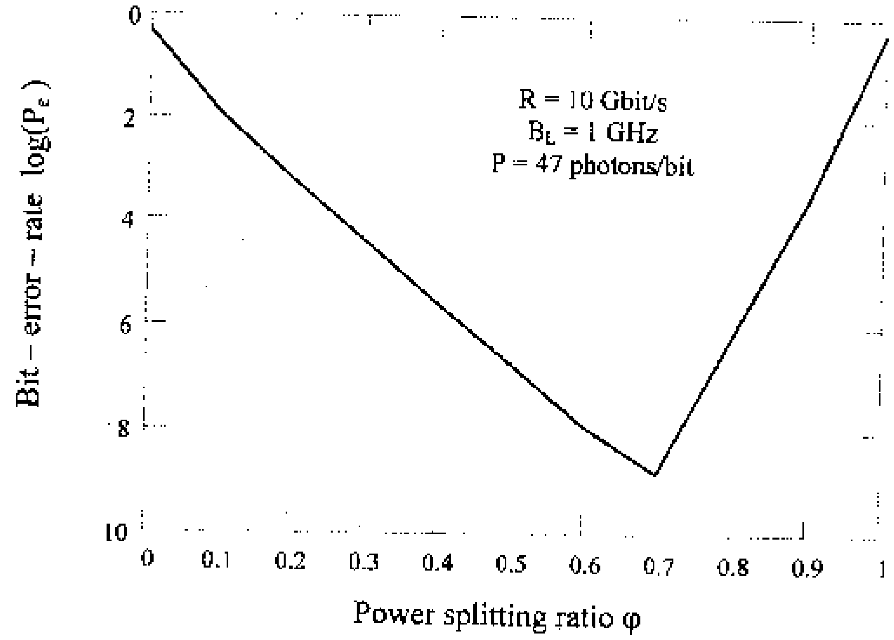
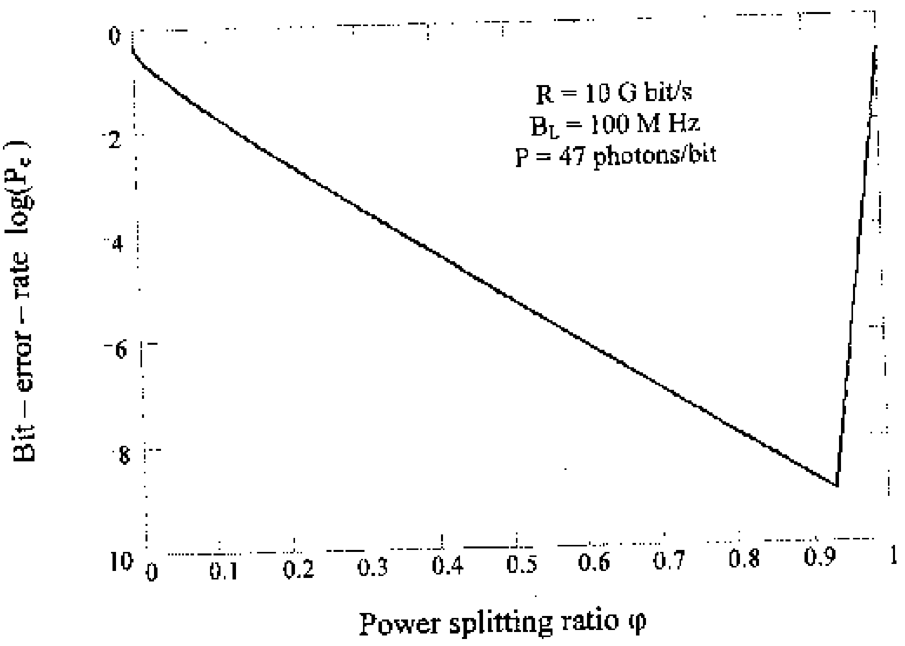


Fig. 2 BER as a function of number of detected photons per bit P for DFPSK receiver.

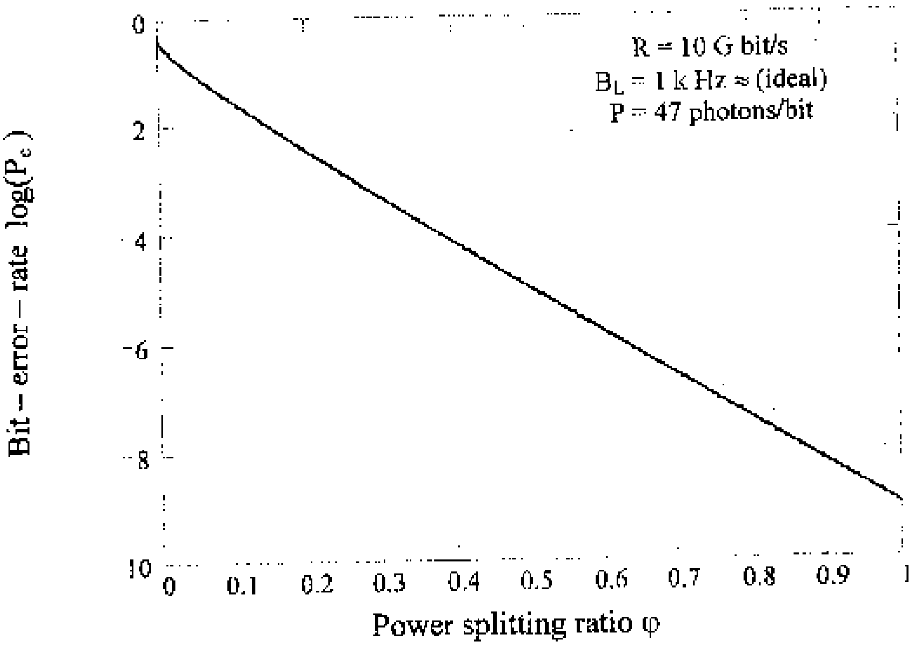


(a)

Fig. 3 BER versus power splitting ratio φ for DFPSK receiver. (a) R/B_L=10, (b) R/B_L=100, (c) R/B_L=10^7.


R = 10 G bit/s
B_L = 100 M Hz
P = 47 photons/bit
Bit – error – rate log(P_e)
0
-2
-4
-6
-8
10
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Power splitting ratio φ

(b)


R = 10 G bit/s
B_L = 1 k Hz ≈ (ideal)
P = 47 photons/bit
Bit – error – rate log(P_e)
0
2
4
-6
-8
10
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Power splitting ratio φ

(c)

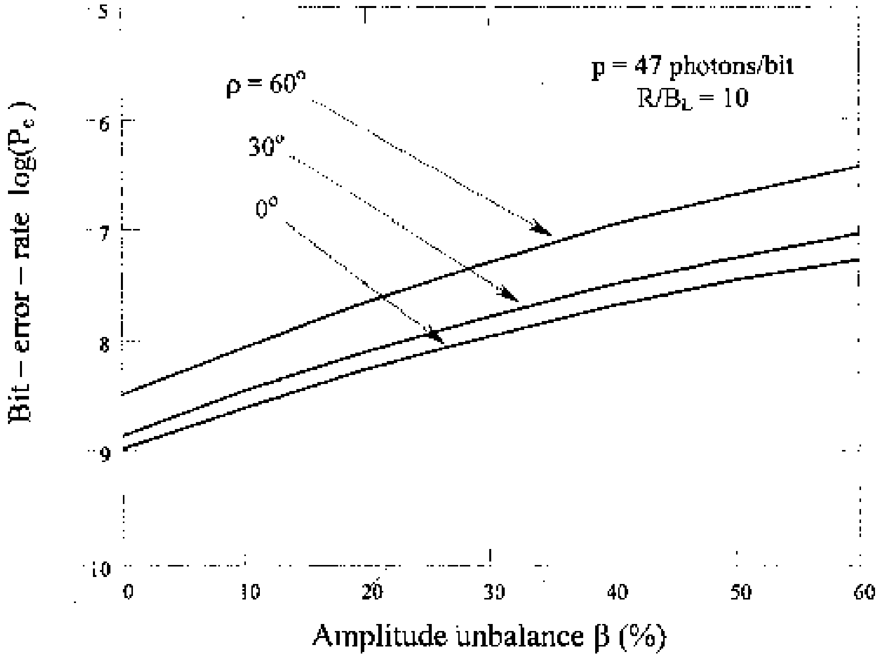


Fig.4 BER versus the dichroism – induced amplitude unbalance β.

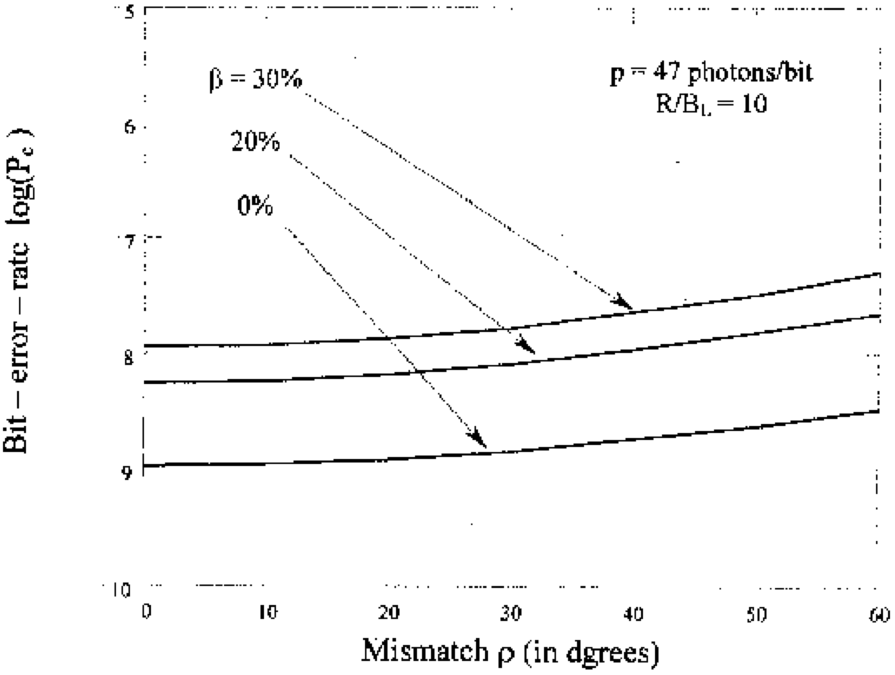


Fig. 5 BER versus the dichroism –induced mismatch ρ.

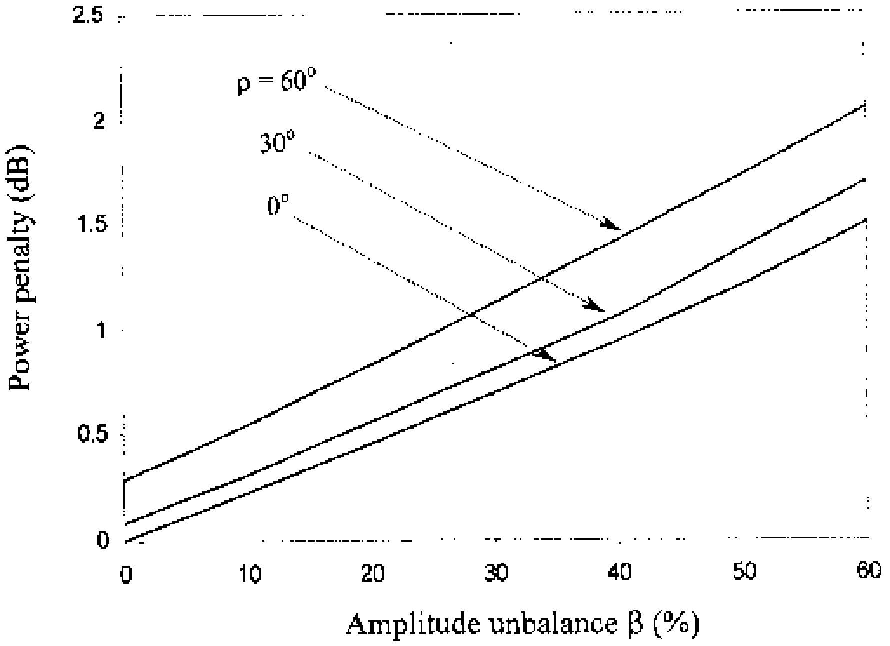


Fig. 6 Power penalty versus the dichroism – induced amplitude unbalance β.

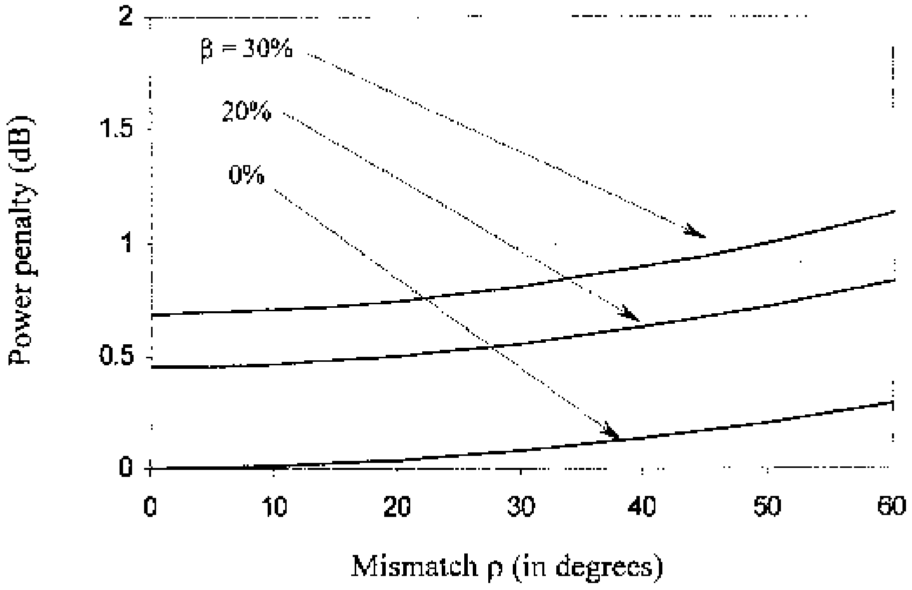


Fig. 7 Power penalty versus the dichroism – induced mismatch ρ.

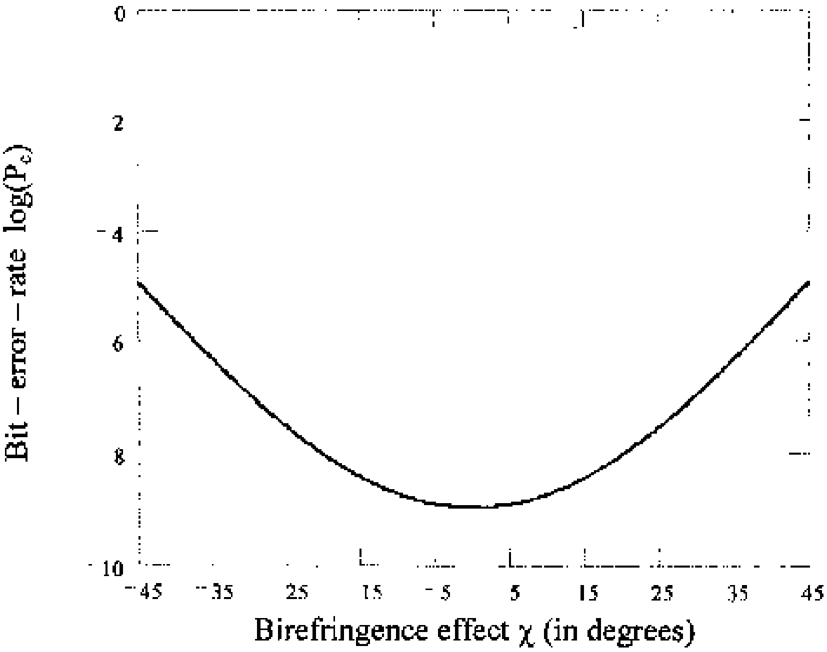


Fig. 8 BER P_e versus birefringence parameter χ.