PERFORMANCE OF POLARIZATION SHIFT KEYING SYSTEM INCORPORATING DIRECT DETECTION JONES MATRIX RECEIVER

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Abstract

This paper presents a comprehensive analysis of a new direct detection polarization shift keying (DD POLSK) receiver structure that is based on Jones matrix technique. The bit – error – rate (BER) characteristics of the receiver is examined under system impairments and the results are compared with those related to other DD POLSK receivers reported in the literature. The results indicate that Jones matrix receiver is less sensitive to optical amplifier gain variation when compared with other receivers.

أداء نظام الإزاحة المفتاحية للاستقطاب المباشر وتقنية قلب مصفوفة جونز

الخلاصة

تقدم الورقة تحليل نظري مفصل عن أداء نوع جديد من أنظمة الاتصالات الضوئية ذات الكشف المباشر والـــــتي تعتمـــد علــى تقنيــة الإزاحة المفتاحية للاستقطاب (Polarization shift keying) إضافة إلى استخدام تقنية قلب مصفوفة جونز (Jones matrix technique) في دائرة الاستلام. تمتاز دائرة الاستلام في هذا النظام بحساسيتها القليلة ضد تغيرات كسب المصخمات الضوئية المستخدمة في القناة.

1. Introduction: -

Optical digital modulation based on state of polarization (SOP) has been named in the literature "polarization shift keying (POLSK)" [1 – 3]. Coherent detection (CD) and direct detection (DD) systems based upon POLSK have been theoretically analyzed and experimentally demonstrated [4 – 8]. The following facts have been established by the previous extensive work: fiber birefringence does not alter the polarization – encoded information and in particular the bit – error – rate (BER) is ideally unaffected since it only causes a rigid rotation of the constellation of signals points on the Poincare sphere; binary POLSK has 40 photons / bit quantum – limited sensitivity, whereas coherent amplitude shift keying (ASK) requires 80 photons / bit; and POLSK systems are largely insensitive to laser phase noise.

The advances in fiber amplifier and semiconductor optical amplifier technologies [9 – 12] have made it possible for DD systems to approach the sensitivity performance of CD systems. Therefore, there has been considerable shift of interest from CD systems to DD systems [13,14].

When a polarized optical signal is sent through a single – mode fiber (SMF), its state of polarization is altered due to the birefringence of the fiber. In the case of the transmission of a POLSK signal through the fiber, the fiber birefringence only causes a rigid rotation of the signal constellation over the Poincare sphere. In other words, each of the signal points is displaced, but the spatial relationship between them is preserved [15]. As a result the information is not corrupted.

To compensate for the constellation rotation, optical processing (i.e., polarization controller) or electronic processor is needed. However, if the employed receiver extracts the three Stokes parameters of the incoming signal, then optical birefringence compensation is not needed. The compensation is achieved by pure electronic processing at the decision stage [16]. Based on these facts, Benedetto et al. [17] have proposed two receiver structures (B – receiver and C – receiver) for direct detection of binary and multilevel digital optical modulation schemes employing POLSK modulation format. These structures extract the information from the Stokes parameters of the received signal and will be reviewed in Appendix A for the case of binary transmission. In this paper a comprehensive analysis of a new DD POLSK receiver structure that based on Jones matrix inversion technique is presented. The BER characteristics of the proposed receiver is computed and the results are compared with those related to B – and C – receivers. The three receiver structures are examined and compared in the presence of system impairments.

2. Jones Matrix Receiver: -

This section presents a detailed analysis of direct – detection POLSK receiver that employs Jones matrix inversion technique to compensate the constellation rotation of SOP in Poincare sphere. Signal and noise analysis is presented and used as a guideline to assess the error probability.

The proposed Jones matrix receiver is shown in Fig. 1. It uses an optical filter at the input to reduce the amplifier spontaneous emission noise (ASE) arriving from the in – line optical amplifiers. To reduce the effects of laser phase noise, the bandwidth B_0 of the optical filter is chosen wider than that of the matched filter, whose noise bandwidth is equal to the symbol rate. To reduce the penalty due to wider – than – matched optical filtering and to cutoff receiver electrical noise, a tight low – pass filter is placed at the output of the demodulated signal.

The optical field signal at output of the transmitter is given by

$$E_t(t) = \sqrt{2p_t} \begin{pmatrix} e_{tx} \\ e_{ty} \end{pmatrix} \qquad \text{...............(1a)}$$

$$|e_{tx}|^2 + |e_{ty}|^2 = 1 \qquad \text{................(1b)}$$

where

p_t: Transmitted optical power.

e_{tx} , e_{ty}: Components of the transmitted signal field with respect to two orthogonal linear fiber polarization $(\bar{x}, \bar{y})$.

The received signal $E_r(t)$ can be computed by including the effect of fiber Jones matrix [J]. The signal at the output of the receiver optical filter can be expressed as

$$E_r(t) = \sqrt{2G_t p_t} \begin{bmatrix} e_x \\ e_y \end{bmatrix} + \begin{pmatrix} N_x \\ N_y \end{pmatrix} \quad \text{........(2)}$$

Here,

G_t: Net power gain (the product of total gain times total loss) a long the transmissions line.

N_x, N_y: Complex Gaussian random variables accounting for the total filtered ASE noise.

Further,

$$\begin{bmatrix} e_x \\ e_y \end{bmatrix} = [J] \begin{pmatrix} e_{tx} \\ e_{ty} \end{pmatrix} \quad \text{.........(3a)}$$

[J] denotes the Jones matrix associated with the fiber and it is given by [13]

$$[J] = \begin{bmatrix} \Gamma e^{jx_1} & \sqrt{1-\Gamma^2}\, e^{jx_2} \\ -\sqrt{1-\Gamma^2}\, e^{-jx_2} & \Gamma e^{-jx_1} \end{bmatrix} \text{...(3b)}$$

where

x_1, x_2: Phase shifts due to SMF effect and they are independent random variables with uniform distribution between 0 and π.

Γ^2: Variation of power due to SMF effect and it is a random variable with uniform distribution between 0 and 1.

Making use of eqns. (3a) and (3b), eqn. (2) can be rewritten as:

$$E_r(t) = \sqrt{2G_t p_t} \cdot$$

$$\begin{bmatrix} \Gamma e^{jx_1} e_{tx} - \sqrt{1-\Gamma^2}\, e^{-jx_2} e_{ty} \\ \Gamma e^{-jx_1} e_{ty} + \sqrt{1-\Gamma^2}\, e^{jx_2} e_{tx} \end{bmatrix} + \begin{bmatrix} N_x \\ N_y \end{bmatrix} \text{...(4)}$$

The variance of each of the two polarization components of the filtered ASE noise is given by [17]

$$\sigma_v^2 = 2N_v B_o \quad \text{........(5)}$$

where

N_v: Power spectral density of the white ASE noise arriving on each polarization.

B_o: Bandwidth of the optical filter.

The signal after the polarization beam splitter (PBS) is given by

$$E_x' = \sqrt{2p_r}\, e_x' \quad \text{........(6a)}$$

$$E_y' = \sqrt{2p_r}\, e_y' \quad \text{........(6b)}$$

where

$$\begin{bmatrix} e_x' \\ e_y' \end{bmatrix} = [J] \begin{pmatrix} e_{tx} \\ e_{ty} \end{pmatrix} + \begin{bmatrix} n_x \\ n_y \end{bmatrix}, \quad p_r = G_t p_t,$$

$$n_x = \frac{N_x}{\sqrt{2p_r}}, \qquad n_y = \frac{N_y}{\sqrt{2p_r}}. \quad \text{Therefore,}$$

$$E_x' = \sqrt{2p_r} \left[\Gamma e^{jx_1} e_{tx} - \sqrt{1-\Gamma^2} e^{-jx_2} e_{ty} + n_x \right. \quad \text{....(7a)}$$

$$E_y' = \sqrt{2p_r} \left[\Gamma e^{-jx_1} e_{ty} + \sqrt{1-\Gamma^2} e^{jx_2} e_{tx} + n_y \right. \quad \text{....(7b)}$$

The receiver estimates the Jones matrix parameters by an estimator and then an inversion transformation of the matrix is performed by electronic adaptive circuit. Then the two components of signal is given by

$$E_{xx} = \sqrt{2p_r}\, e_{xx} \quad \text{...........(8a)}$$

$$E_{yy} = \sqrt{2p_r}\, e_{yy} \quad \text{...........(8a)}$$

where

$$\begin{bmatrix} e_{xx} \\ e_{yy} \end{bmatrix} = [J]^{-1} \begin{bmatrix} e_x' \\ e_y' \end{bmatrix} \quad \text{...........(9)}$$

Or

$$e_{xx} = e_{tx} + \Gamma\, e^{-jx_1} n_x + \sqrt{1-\Gamma^2}\, e^{-jx_2} n_y \text{........(10a)}$$

$$e_{yy} = e_{ty} + \Gamma\, e^{jx_1} n_y - \sqrt{1-\Gamma^2}\, e^{jx_2} n_x \text{.........(10b)}$$

The two components of the signal are subsequently detected by two photodiodes with responsivity $\Re = \eta(q/hf)$, where η is the diode quantum efficiency, q is the electron charge, h is Planck's constant, and f is the optical frequency. The photocurrents are given by

$$i_{xx}(t) = \Re p_r |e_{xx}|^2 \qquad \ldots\ldots\ldots(11a)$$

$$i_{yy}(t) = \Re p_r |e_{yy}|^2 \qquad \ldots\ldots\ldots(11b)$$

The two current components are subtracted to get the current signal $i_{diff}(t)$:

$$i_{diff}(t) = \Re p_r \left(|e_{xx}|^2 - |e_{yy}|^2 \right) \ldots\ldots(12)$$

Note that i_{diff} is proportional to the Stokes parameter S_1.

Let us carry the analysis further to include the effect of the electrical part of the receiver. Assume that each photodiode has an internal load that is matched to the input resistance of the electronic amplifier. In this way, one can directly use the amplifier noise figure F to characterize its noise contribution. The electronic amplifier gain or the output load are irrelevant in the noise analysis and will be omitted in the following. Both signal and noise will be expressed in terms of currents

At the output of the low – pass filter, the signal can be written as [17]

$$E_u(t) = \beta_A S_1 + N_{th} \qquad \ldots\ldots\ldots\ldots(13)$$
with $\quad \beta_A = R\, p_r \quad$ and

$$S_1 = (|e_{xx}|^2 - |e_{yy}|^2) * h_{LP}(t)$$

Here R is the bit rate, $h_{LP}(t)$ is the impulse response of the electrical low – pass filter, and N_{th} is a zero – mean Gaussian random variable that represents the low – pass filtered receiver noise current. This noise current is characterized by a variance [17]

$$\sigma_{th}^2 = \frac{2kT_k}{R_e} \cdot \frac{1}{T_s} \cdot F \qquad \ldots\ldots\ldots(14)$$

where

k: Boltzmann's constant.

T_k: Absolute temperature.

F: Noise figure of the electrical amplifier.

R_e: Input resistance of the electronic amplifier.

T_s: Symbol duration ($\equiv 1$/bit rate)

The post – detection filter is assumed to be an ideal integrate – and – dump filter of integration time T_s, and hence its bandwidth is $B_e = 1/T_s$.

3- Evaluation of Bit – Error – Rate (BER): -

The BER characteristics of the Jones matrix direct - detection systems described in sections 2 can be estimated using the same method described in [17]. In Ref. [17], a tight upper bound for the error probability has been computed numerical. In this section we carry the analysis further to find an analytical expression describing the tight upper bound of BER. Both the numerical and analytical results are in excellent agreement.

The BER Pe can be expressed as

$$Pe \le P(\xi + \eta < 0) = P(\zeta < 0) \qquad \ldots\ldots\ldots(15)$$

where P denoted probability, and the random variable ζ is the sum of two random variables, ξ and η, whose randomness is determined by ASE and receiver noise, respectively. ξ and η are statically independent phenomena.

The BER in the RHS of eqn. (16) can be computed using the Fourier – Riemann formula [10].

$$Pe \le -\frac{1}{2\pi j} \int_{s_o - j\infty}^{s_o + j\infty} \frac{C_\zeta(s)}{s} ds \qquad \ldots\ldots(16)$$

where $C_\zeta(s)$ is the characteristic function of ζ, is given by

$$C_\zeta(s) = C_\xi(s) \cdot C_\eta(s) \qquad \ldots\ldots\ldots(17)$$

In eqn. (16), s is Laplace frequency and $b_0 < 0$ is a constant identifying a suitable Bromwich integration path. The statistical structure of the ASE noise affecting the direct – detected signal is the same as that of local oscillator (LO) shot affecting the coherent – detected signal and its expression is

$$C_\xi(s) = \frac{1}{\left(1 - \frac{s^2}{\rho^2}\right)^N} \exp\left[\frac{Ns}{1 - \frac{s^2}{\rho^2}}\left[\frac{s}{\rho} + 1\right]\right] \quad ..(18)$$

where $N = B_o / B_e$, and ρ is the signal – to – noise ratio (SNR).

If the system uses only one optical amplifier acting as a preamplifier for the receiver, then

$$\rho = \frac{p_r T_s}{N_o} \qquad \ldots\ldots(19)$$

with

$$N_o = h f n_{sp} \frac{G-1}{L} \qquad \ldots\ldots\ldots(20)$$

Here

n_{sp} (≥ 1): Spontaneous emission parameter of the optical amplifier.

L (≥ 1): Amplifier wave coupling loss.

h: Planck's constant.

f: Laser (optical) frequency.

G: Optical amplifier gain.

The characteristic function of the Gaussian random variable η is given by [17]

$$C_\eta(s) = e^{\left(\frac{s^2 \sigma_\eta^2}{2}\right)} \qquad \ldots\ldots(21)$$

where the variance σ_η^2 is given by

$$\sigma_\eta^2 = \frac{1}{\beta_A^2} \sigma_{it}^2 \qquad \ldots\ldots\ldots\ldots(22)$$

The BER of the system can be evaluated after computing the integral in eqn. (16). For N = 1 the result is

$$Pe \leq \frac{1}{2} \exp\left[\frac{-\rho(1 - \rho\sigma_\eta^2)}{2}\right] \qquad \ldots\ldots\ldots(23)$$

4   Illustrative Results: -

Illustrative results will be presented for the three types of direct detection POLSK system. Unless otherwise stated, the parameter values are used to produce the simulation results are listed in Table 1

Table 1   Parameter values used to get the simulation results.

Parameter	Symbol	Value
Wave length	λ	1.55 µm
Bit rate	R	10 Gbit/s
Bandwidth of the optical filter	B_o	10 Gbit/s
Bandwidth of the electrical filter	B_e	10 Gbit/s
Optical amplifier coupling loss	L	1
Photodiode responsivity	$\Re$	1 A/W
Spontaneous emission parameter	n_{sp}	1

Figure 2 displays the variation of BER with signal – to – noise ratio ρ for Jones matrix, B-, and C- receivers and assuming G = 40 dB and $R_s/F = 25$ Ω. The result indicates clearly that the three receivers show identical performance with 40 photons/bit is required to yield 10^{-9} BER. However, this picture is altered when the

optical amplifier gain G is reduced as depicted in Figs. 3a – 3c. The results in these figures are calculated assuming G=30 dB, and for three values of R_c/F=12.5, 25 and 50 Ω, respectively. The main conclusion to be drawn from Figs. 3a – 3c is that the best performance is obtained with Jones matrix receiver which shows almost negligible performance degradation as G reduces from 40 dB to 30 dB. This result in more pronounced when R_c/F increases. The Jones matrix receiver show almost the same performance when the values of G and R_c/F changed from 40 dB and 25 Ω to 30 dB and 50 Ω.

Figures 4a – 4c show, respectively, the penalty due to the reduction of amplifier gain for Jones matrix, B – and C – receivers. The penalty is evaluated as 10 log ρ/ρ_o, where ρ_o is the signal – to – noise ratio required to achieve a given BER when G tends to ∞. The calculations are performed for BER=10^{-9}, where ρ_o=39.8=16 dB. Note that the penalty reduces as G increases with minimum values are associated with Jones matrix receiver.

Table 2 lists a performance comparison among Jones matrix, B – and C – receivers for different values of G and R_c/F. Reducing the amplifier gain from 40 dB to 30 dB yields a penalty of 0.423 dB, 2.81 dB and 10.9 dB for Jones matrix, B – and C – receivers, respectively, and assuming R_c/F=12.5 Ω. These results are to be compared with 0.115 dB, 0.9 dB and 5.8 dB when R_c/F increases to 50 Ω.

5 - Conclusions: -

The performance of Jones matrix POLSK receiver is analysed in details for direct – detection systems. The results are compared with those related to other DD POLSK receivers reported in [17], namely the B – and C – receivers. The effect of optical amplifier gain and receiver circuit noise parameter R_c/F on system performance are addressed. The result indicates clearly that receivers have identical performance when the received signal is optically preamplified using large – (>40 dB) gain amplifier. Further, Jones matrix receiver is less sensitive to amplifier gain variation when compared with other receivers.

Appendix A
Stokes Parameters Receivers

1 - The B – Receiver: -

Figure A1 shows a simplified block diagram for one of DD POLSK receiver structures proposed in [17]. This receiver (which has been called the B – receiver in [17]) extracts the three Stocks parameters from the received lightwave signals.

At the input of the receiver, the optical field is divided into six components by three types of polarization beam splitters (PBS) and retardation plates that supply the following outputs:

- The two linear polarization components on $\bar{x}, \bar{y}$.

- The two linear polarization components on the axis $\bar{x} \pm \bar{y}$, i.e. the previous components tilted by 45°.

- The two circular polarization components, clockwise and counterclockwise.

The six optical field components are expressed by

$$E_{x1}'(t) = \sqrt{\frac{p_r}{3}}\, e_x'$$

$$E_{x2}'(t) = \sqrt{\frac{p_r}{3}}\, \frac{e_x' + e_y'}{\sqrt{2}}$$

$$E_{x3}'(t) = \sqrt{\frac{p_r}{3}}\, \frac{e_x' + je_y'}{\sqrt{2}}$$

$$E_{y1}'(t) = \sqrt{\frac{p_r}{3}}\, e_y' \qquad ....(A1)$$

$$E_{y2}'(t) = \sqrt{\frac{p_r}{3}}\, \frac{e_x' - e_y'}{\sqrt{2}}$$

$$E_{y3}'(t) = \sqrt{\frac{p_r}{3}}\, \frac{e_x' - je_y'}{\sqrt{2}}$$

where (je_y') means e_y' are polarization – rotated by $90°$ and

$$\begin{bmatrix} e_x' \\ e_y' \end{bmatrix} = [J]\begin{pmatrix} e_{x1} \\ e_{y1} \end{pmatrix} + \begin{bmatrix} n_x \\ n_y \end{bmatrix}$$

The signal components are detected by the photodiodes and the resultant photocurrents are

$$i_{x1}(t) = \beta_B \left| e_x' \right|^2$$

$$i_{x2}(t) = \beta_B \frac{\left| e_x' + e_y' \right|^2}{2}$$

$$i_{x3}(t) = \beta_B \frac{\left| e_x' + je_y' \right|^2}{2}$$

$$i_{y1}(t) = \beta_B \left| e_y' \right|^2 \qquad ....(A2)$$

$$i_{y2}(t) = \beta_B \frac{\left| e_x' - e_y' \right|^2}{2}$$

$$i_{y3}(t) = \beta_B \frac{\left| e_x' - je_y' \right|^2}{2}$$

To obtain the low – pass filtered estimates of the Stokes parameters, the above currents are processed as follows:

$$i_1(t) = (i_{x1} - i_{y1}) * h_{LP}(t) + N_{th}^{(1)}$$
$$= \beta_B S_1 + N_{th}^{(1)} \qquad ....(A3a)$$

$$i_2(t) = (i_{x2} - i_{y2}) * h_{LP}(t) + N_{th}^{(2)}$$
$$= \beta_B S_2 + N_{th}^{(2)} \qquad ....(A3b)$$

$$i_3(t) = (i_{x3} - i_{y3}) * h_{LP}(t) + N_{th}^{(3)}$$
$$= \beta_B S_3 + N_{th}^{(3)} \qquad ....(A3c)$$

where the $N_{th}^{(i)}$ $(i=1, 2, 3)$ are three independent Gaussian filtered electrical receiver noise processes.

Equation (A3) can be expressed in matrix for

$$[i(t)] = \beta_B[S] + [N_{th}] \qquad...........(A4)$$

Where

$$[i(t)] = \begin{bmatrix} i_1(t) \\ i_2(t) \\ i_3(t) \end{bmatrix} \qquad \text{and} \qquad [N_{th}] = \begin{bmatrix} N_{th}^{(1)} \\ N_{th}^{(2)} \\ N_{th}^{(3)} \end{bmatrix}$$

Each of the noise term $N_{th}^{(i)}$ has a variance σ_{th}^2 as defined in eqn. (14).

2 - The C – Receiver: -

Figure A2 illustrates the block diagram of another DD Stocks parameter receiver structure proposed in [17] and has been called the C – receiver. This receiver uses simple polarizers instead of PBSs used in the B – receiver.

The received optical signal, after passing through the optical filter, is splitted into four components. Three of these components pass through polarizers before applying to the photodiodes. The optical field components incident on the photodiodes can be expressed as

$$E_1'(t) = \sqrt{\frac{p_r}{4}}\, e_x' \qquad ....(A5a)$$

$$E_2'(t) = \sqrt{\frac{p_r}{4}}\, \frac{e_x' + e_y'}{\sqrt{2}} \qquad ....(A5b)$$

$$E_3'(t) = \sqrt{\frac{p_r}{4}}\, \frac{e_x' + je_y'}{\sqrt{2}} \qquad ....(A5c)$$

where

$$\begin{bmatrix} e_{x}' \\ e_{y}' \end{bmatrix} = [J]\begin{bmatrix} e_{x'} \\ e_{y'} \end{bmatrix} + \begin{bmatrix} n_{x} \\ n_{y} \end{bmatrix}$$

The photocurrent signals are given by

$$\left. \begin{aligned} i_{a}(t) &= \beta_{C}\left| e_{x}' \right|^{2} \\ i_{b}(t) &= \beta_{C}\frac{\left| e_{x}' + e_{y}' \right|^{2}}{2} \\ i_{c}(t) &\approx \beta_{C}\frac{\left| e_{x}' + je_{y}' \right|^{2}}{2} \\ i_{d}(t) &= \beta_{C}\left[\left| e_{x}' \right|^{2} + \left| e_{y}' \right|^{2} \right] \end{aligned} \right\} \quad............(A6)$$

where $\beta_{C} = \dfrac{R \, p_{L}}{4}$

The signals at the output of the low – pass filters are given by

$$i_{1}(t) = (2i_{a} - i_{d}) * h_{LP}(t) + 2N_{th}^{(1)} - N_{th}^{(4)}$$
$$i_{2}(t) = (2i_{b} - i_{d}) * h_{LP}(t) + 2N_{th}^{(2)} - N_{th}^{(4)}$$
$$i_{3}(t) = (2i_{c} - i_{d}) * h_{LP}(t) + 2N_{th}^{(3)} - N_{th}^{(4)}$$
$$.........(A7)$$

Equation (A7) can be rewritten as

$$i_{1}(t) = \beta_{C}S_{1} + 2N_{th}^{(1)} - N_{th}^{(4)} \quad.........(A8a)$$
$$i_{2}(t) = \beta_{C}S_{2} + 2N_{th}^{(2)} - N_{th}^{(4)} \quad.........(A8b)$$
$$i_{3}(t) = \beta_{C}S_{3} + 2N_{th}^{(3)} - N_{th}^{(4)} \quad.........(A8c)$$

Or in a matrix form

$$[i(t)] = \beta_{C}[S] + 2[N_{th}] - N_{th}^{(4)}\begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix} \quad......(A9)$$

where all the Gaussian random variables $N_{th}^{(i)}$ have the same variance σ_{th}^{2} defined in eqn. (14).

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Table 2 Performance comparison among Jones matrix, B – and C – receivers for different values of G and R_c / F.

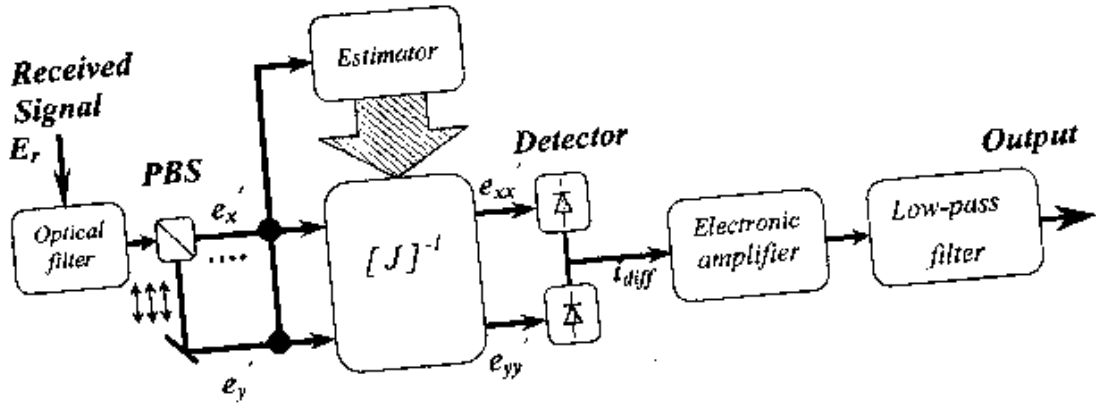| G (dB)	R_c / F (Ω)	Jones matrix receiver		B - receiver		C - receiver	
		Power (dBm)	Power penalty (dB)	Power (dBm)	Power penalty (dB)	Power (dBm)	Power penalty (dB)
40	12.5	- 43	0	- 43	0	- 43	0
30	12.5	- 42.5	0.423	- 40.1	2.81	- 32	10.9
40	25	- 43	0	- 43	0	- 43	0
30	25	- 42.7	0.22	- 41.27	1.63	- 34.67	8.23
40	50	- 43	0	- 43	0	- 43	0
30	50	- 42.8	0.115	- 42	0.9	- 37.07	5.83

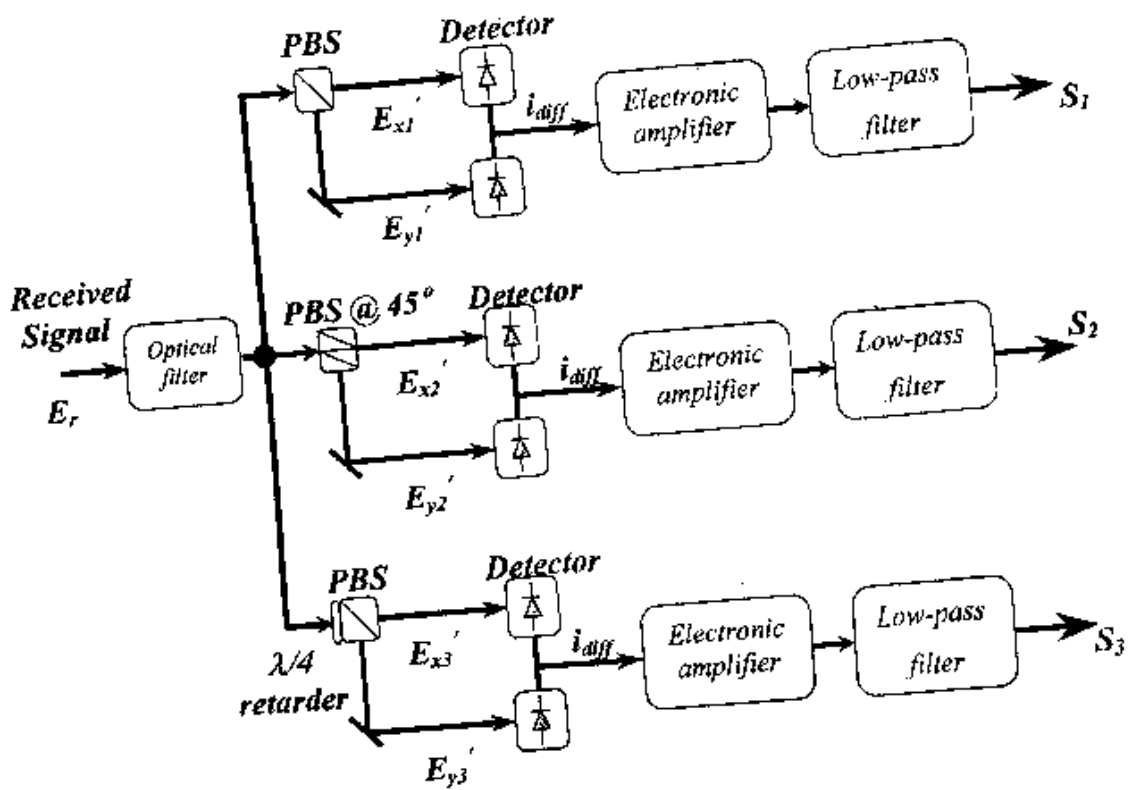Fig. 1 A block diagram of Jones matrix receiver.
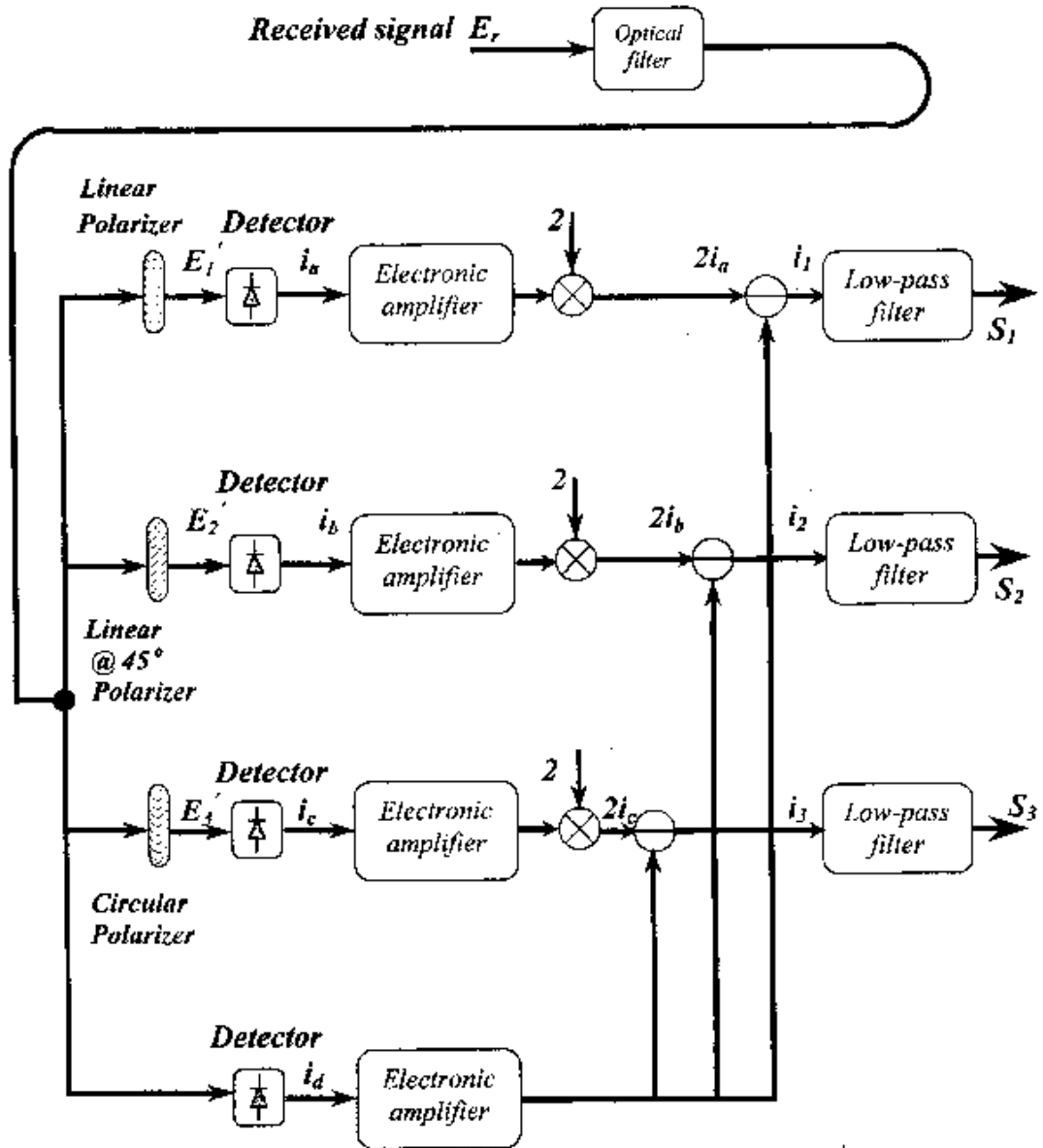

Fig. A1 A block diagram of B – receiver.

Fig. A2 A block diagram of the C – receiver.

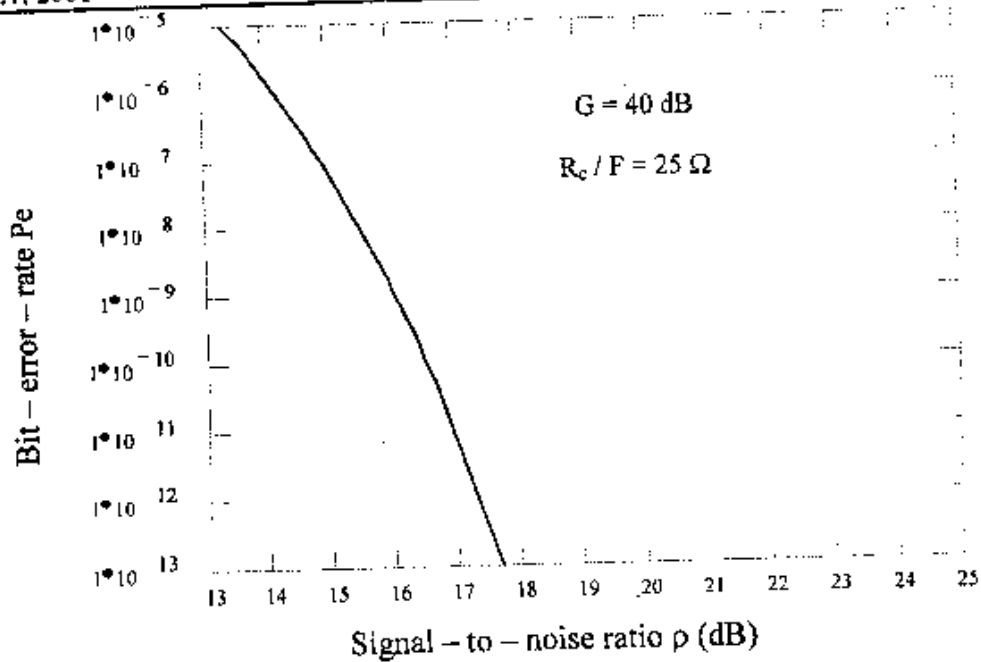$G = 40$ dB

$R_c / F = 25 \ \Omega$
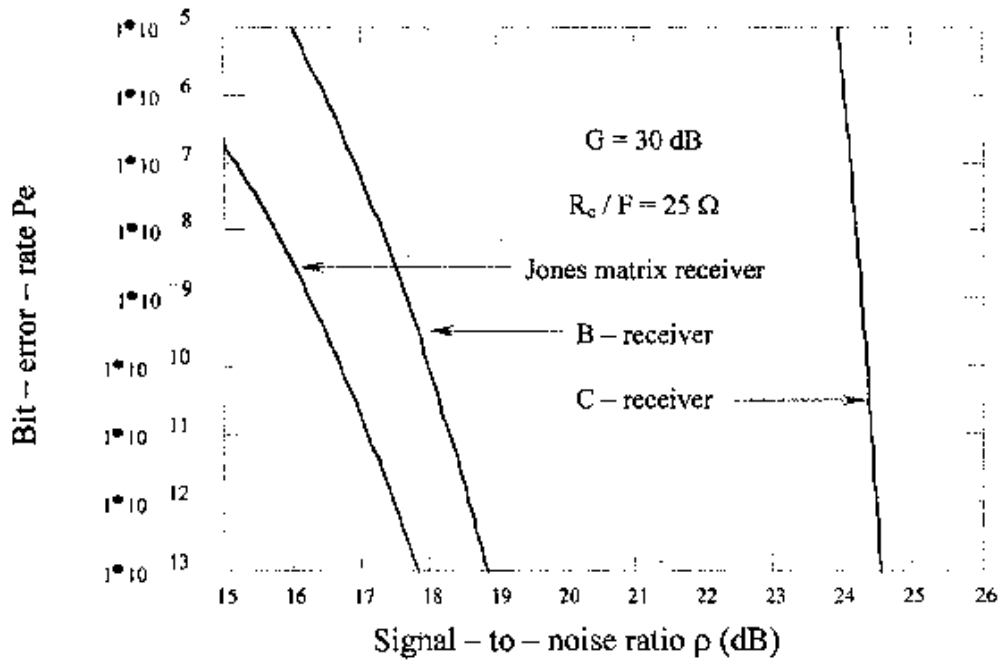
Bit $-$ error $-$ rate Pe

Signal $-$ to $-$ noise ratio ρ (dB)

Fig. 2 BER Pe as a function of signal $-$ to $-$ noise ratio ρ for Jones matrix , B $-$ and C $-$ receivers.

$G = 30$ dB

$R_c / F = 12.5 \ \Omega$

Jones matrix receiver

B $-$ receiver

C $-$ receiver

Bit $-$ error $-$ rate Pe

Signal $-$ to $-$ noise ratio ρ (dB)
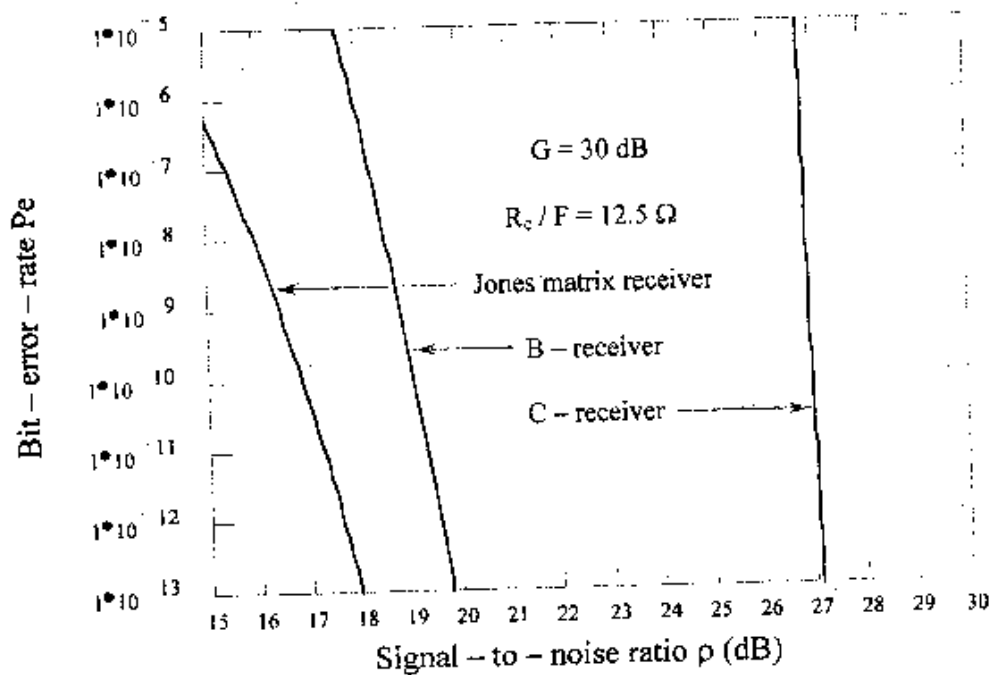
(a)

Fig. 3 Effect of amplifier gain on the BER characteristics of Jones matrix, B $-$ and C $-$ receivers.
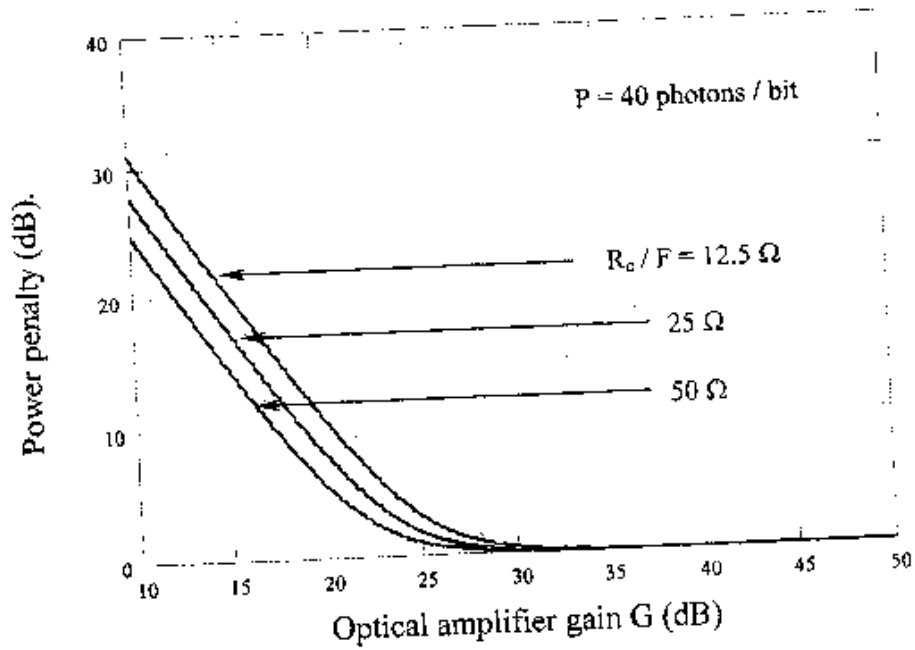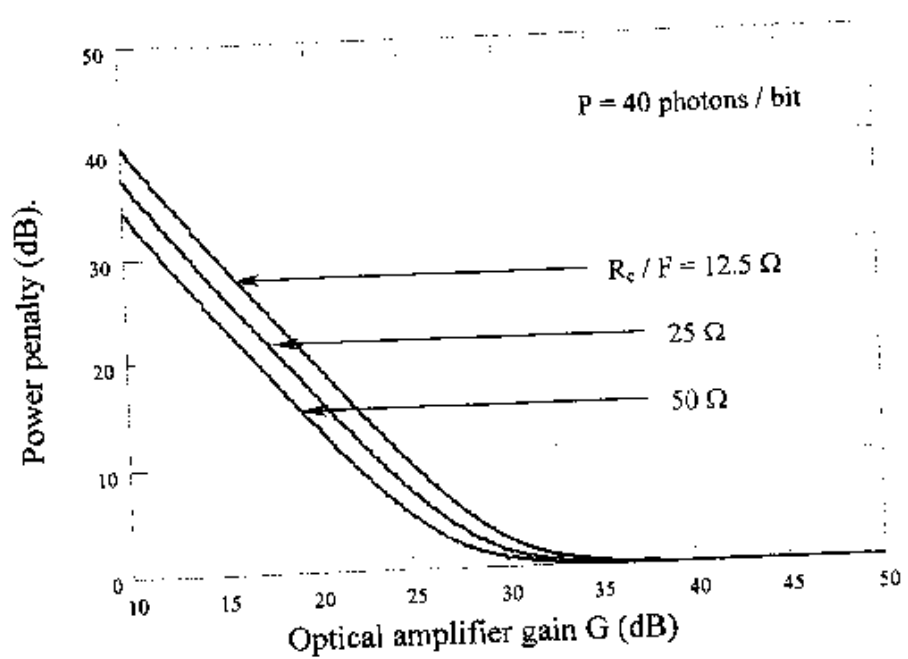**(a) $R_c / F = 12.5 \ \Omega$, (b) $R_c / F = 25 \ \Omega$, (c) $R_c / F = 50 \ \Omega$.**

(149)

(b)
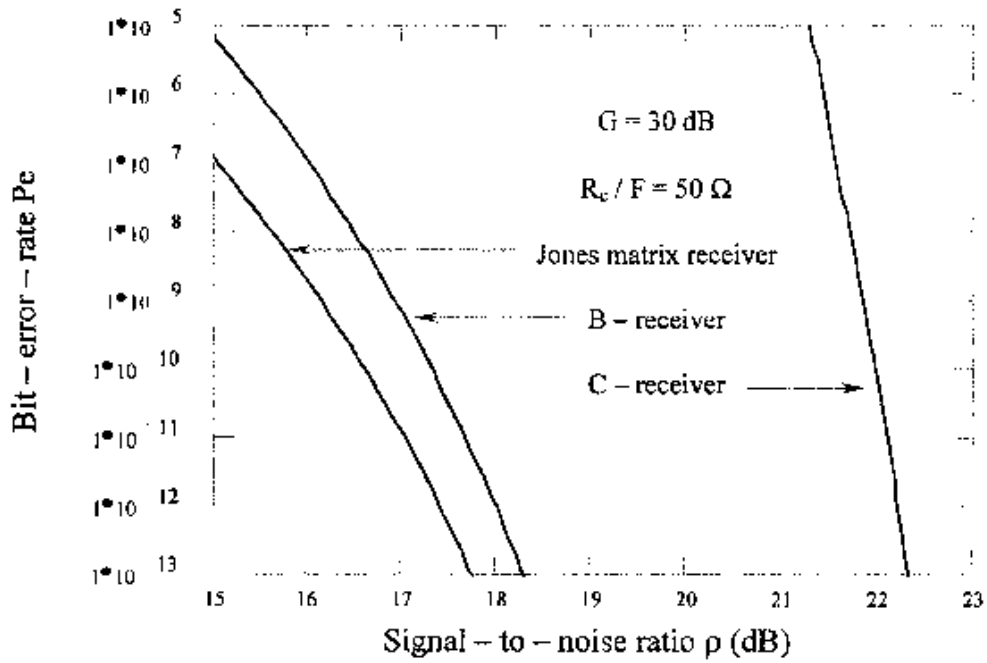
(c)

(a)

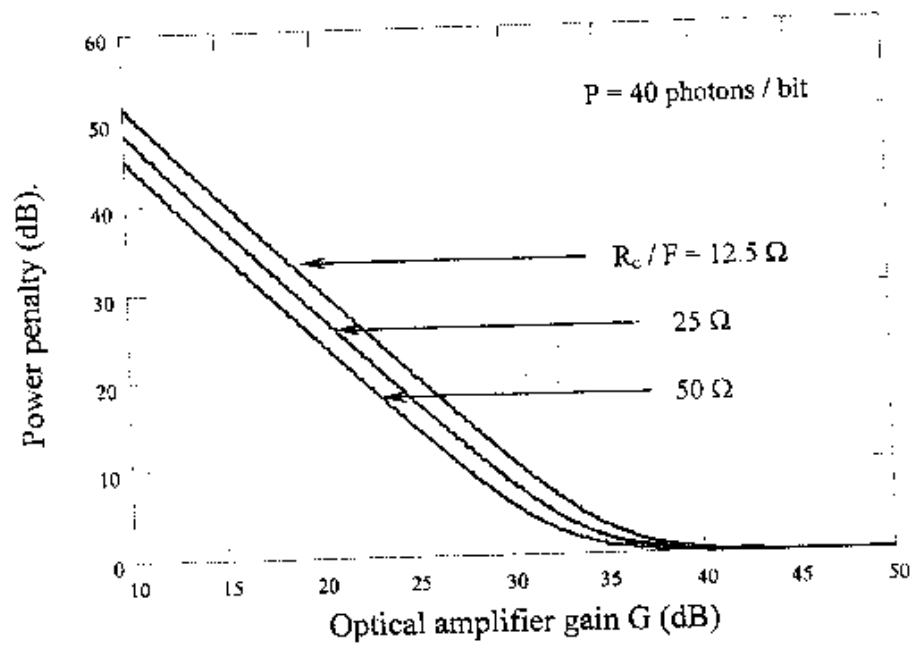**Fig. 4 Power penalty versus optical amplifier gain G.**
(a) Jones matrix receiver, (b) B – receiver, (c) C – receiver.

(b)

(151)

(c)