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LAMP SERIES REPORT

(Laser, Atomic and Molecular Physics)

PRINCIPLES OF OPTICAL FIBRE COMMUNICATION TECHNIQUES: NONCOHERENT AND COHERENT

V.K. Jain

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Preface

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International Atomic Energy Agency
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PRINCIPLES OF OPTICAL FIBRE COMMUNICATION TECHNIQUES: NONCOHERENT AND COHERENT

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ABSTRACT

In this paper a brief historical description of optical fibre communication system (OFCS) has been presented and the main characteristics of the basic components used in it are summarized. Introduction of noncoherent and coherent (homodyne and heterodyne) system is given. In coherent OFCS, source linewidth requirement, phase and polarization – diversity and combined phase and polarization – diversity receivers are described.

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1. INTRODUCTION:

The principal motives behind the design of a communication systems are either to improve the transmission fidelity, to increase the data rate / bandwidth or to increase the spacing between the repeaters . Since available bandwidth for information transmission is directly related to the carrier frequency, the trend in the communication world is to use the higher and higher carrier frequency. This led to the birth of optical communication system.

In early 1960s, several communication experiments were conducted using atmospheric optical channels . However , the high installation cost and the limitations imposed on the atmospheric channel by rain , fog , snow and dust etc. made these systems unattractive from the practical point of view. Concurrent with the work on atmospheric channels, investigations were also carried out on guided propogation of optical signal through the optical fibres. These were thought to provide more reliable and versatile communication channel than the atmosphere.

Initially the attenuation coefficient of the fibre was nearly 1000 dB / km . In 1966 , Kao and Hockam [1] showed that the high attenuation of the fibres available at that time was not due to the intrinsic properties of the materials, but due to the presence of impurities in the fibre material. Reduction of such impurities to very low levels (in some cases of the order of one part per billion) would allow attenuation coefficient to be much lower than the ones usually found in copper cables. In 1970, Kapron, Keck and Maurer [2] of the Corning Glass Works fabricated a fibre having an attenuation coefficient of 20 dB/km. Now-a-days fibres with an attenuation coefficient of as low as 0.2 dB/km are available [3].

In the decade that followed the above breakthrough , extensive investigations were conducted on the possible use of optical fibre for telecommunication purposes. In the first half of 1970s , a number of field trials were carried out on digital transmission systems at various bit rates. These systems were operating in the 800 - 900 nm wavelength region, commonly known as first window. In this region , fibres at that time had their minimum attenuation and other key components i.e., sources and detectors were available. In the second half of the 70s, with the development of technology, other wavelength regions around 1300 nm and 1550 nm, often referred to as second and third window respectively became available. At these wavelengths , performance of the fibre has been reported to be much better than in the first window [3]. In early 80s, a number of optical fibre communication systems at 1300 nm were put on trial and now these are being put in service . Communication systems at 1550 nm range are still in an early stage of development [3].

This paper is organized as follows : In section 2, main characteristics of the basic components used in OFCS viz., fibre, source and detector are discussed. In section 3, a brief introduction to the noncoherent OFCS is given . Section 4 deals with the coherent OFCS . In this section, principles of operation of homodyne and heterodyne receiver is presented. Laser linewidth requirement and the impairment in the coherent receiver performance due to laser phase noise and polarization mismatching is discussed. Operation of phase and polarization - diversity and the combined phase nad polarization - diversity receiver to overcome the degradation in the performance has been discussed.

2.BASIC COMPONENTS:

There are three basic comonents in OFCS .These are: source, fibre and detector. A brief description of these components from the telecommunication point of view is given below.

2.1 Optical Fibre:

Optical fibre is analogous to waveguide in the microwave transmission system. As shown in Fig.1, it consists of a cylindrical core and a concentric cladding . Both of these are made of either silica based glass or plastic, but have different refractive index ,n .Refractive index of the core,n_1 ,is greater than the refractive index of the cladding , n_2 . Light in the the optical fibre propogates through the mechanism of total internal reflection.

Optical fibres are basically of two types :step index fibre and graded-index fibre. In the step-index fibre, refractive index changes abruptly fron cladding to core.In the graded-index fibre, refractive index changes smoothly from the cladding to the centre of the core, where it is maximum. The law of variation of refractive index is normally quasi-parabolical . Further step-index fibre is divided into monomode and multimode fibres. In a monomode fibre, only single mode can propogate, but in multimode fibre, several modes can propogate simultaneously. The monomode fibre has a profile behaviour similar to the multimode, but has a much smaller core radii. Graded-index fibres are of only multimode type. The multimode fibres have typical dimensions of 5o μm for the core and 125 μm for the cladding diameters. Monomode fibres may have a similar cladding diameter , but have a much smaller core diameter about 4 to 10 μm.

Two important characteristics of the fibres for telecommunication application are attenuation and dispersion. The first characteristic determines the level of the transmitted signal for satisfactory performance/reproduction at the receiving end and is expressed in dB / km. The second characteristic determines the fibre bandwidth and is generally expressed in terms of either bandwidth (MHz.km) or time spread for a one kilometer length. For shorter distances, dispension will, of course, be proportionately less than the one kilometer rating. For example 100 metres of 250 MHz. km fibre will theoretically have a bandwidth of 2.5 GHz.

2.2 Optical Sources:

Once the optical fibre cable has been installed , a light source is required to launch optical power into it. The principal light sources used for OFCS are semiconductor laser diode (also known as laser diode or LD) and light emitting diode (LED) . These devices are suitable for OFCS because they have adequate output power for a wide range of applications; their optical power output can be directly modulated by varying the input current to the device; higher efficiency and compatibility with the fibre dimensions . The material commonly used for these devices are GaAs , GaAlAs and InGaAsP at 900, 800 - 900 and 1200-1600 nm wavelength range respectively.

An LED is based on spontaneous emission and LD on stimulated emission of radiation. A major difference between LED and LD is that the optical output from an LED is incoherent, whereas that from a LD is coherent.That is optical output of LD has spatial and temporal coherence implying that it is highly monocromatic and directional . On the otherhand, output of an LED has a broad spectral width and the large beam divergence.

In telecommunication application, surface emitting (or Burrus LEDs) are generally used. These LEDs can couple a power of 50-100 μW (using efficient coupling arrangements) into a 50/125 μm fibre and can be modulated upto 30 - 50 MHz.The spectral width of an LED output is 30 - 100 nm. The optical power emitted by an LED as a function of injection current has a behaviour showing appreciable nonlinearities. It gives rise problems in the transmission of analog signals. However no specific problems are encountered with digital signals. Lifetimes upto 10^8 hours has been reported for LEDs [3].

The power emitted by a semiconductor LD is commonly 1-10 mW . LDs emitting 40-80 mW in continuous operation are also available. Coupling efficiency of 30 to 50% can be easily obtained with 50/125 μm fibres .It is possible to achieve still better efficiency by using special arrangements like lens ended fibre etc.LDs can be modulated at very high speeds : bandwidths of several GHz are achievable. Therefore, it is possible to obtain higher bit rates and repeater spacing using LDs than with LEDs . Lasers are more expensive and have lower stability , reliability and lifetime(of the order of 10^5 -10^6 hours)than LEDs.

2.3 Detectors:

Optical receiver in an optical fibre link interprets the information contained in the incoming optical signal. The first element in the receiver is a photodetector / photodiode.It senses the optical power falling upon it and converts the variation of this optical power into a corresponding variation in the electric current . Generally the optical signal falling on the photodetector is weak and distorted, therefore the photodetector must meet the very high performance requirements. The main requirements are :high sensitivity at the transmitted wavelengths suitable bandwidth , low noise , stability of the characteristics against the variation of the environmental conditions , small dimensions and easy coupling to the optical fibre.

Out of different types of photodetectors viz. , photomultipliers, pyroelectric detectors, phototransistors, semiconductor - based photodetectors , photoconductors etc. , semiconductor - based photodetectors (referred as photodiode) are normally used in telecommunication OFCS.The main reasons for this are their small size, material availability , high sensitivity and fast reponse time. The material employed for these devices are Si in the 800 - 900 nm wavelength region ; Ge and InGaAsP (or InGaAs) in the 1200 - 1600 nm wavelength region.

There are two types of photodiodes viz., unity gain positive intrinsic negative (PIN) photodiode and avalanche photodiode (APD). Latter type of photodiode require much higher operational voltage. Moreover their characteristics are considerably affected by the temperature variation. Therefore a control of thermal drift and of the avalanche gain is generally required. Sensitivity of both PIN and APD is limited by the dark current i.e.,the noise current at the output of the device when there is not an optical signal at the input. APDs have an additional noise called excess noise which arises due to statistical nature of the multiplication process . As a result there is an optimum value of the gain which must be used to maximize the signal -to-noise ratio.

Silicon devices have a very low excess noise and therefore Si-APDs have a definite advantage (optimum gain is normally 100-150) over Si-PIN . At longer wavelengths (1200 - 1600 nm), advantage of APD is less evident. Therefore the most commonly used detectors are Ge-PIN and InGaAsP (or InGaAs) PIN photodiodes followed by an FET amplifier.

3. NONCOHERENT OFCS:

A block diagram of a noncoherent OFCS is shown in Fig.2.Like any other transmission system, it basically consists of three blocks: the transmitter, the optical fibre and the receiver. In the transmitter there is a line coder which converts the input binary sequence into another sequence. This new sequence is suitable for the transmission and contains adequate timing information . Two - level line codes of the mB-nB family are often used for coding. In these codes, words of m bits are converted into words of n bits (n>m) ; 3B4B and 5B6B codes are most widely employed. The coder output signal modulates, through a driver circuit, the intensity of the output of the optical source (LED or laser diode) . A part of this power is then coupled into the fibre and propogate along it. At the receiver, impinging optical signal is converted into an electric signal by a photodetector (PIN or APD) which is then amplified and equalized [3-6].

At a data rate of 140 Mbit/s or less, drive current of LED is modulated directly through a differential amplifier or an emitter follower. At higher data rates (565 Mbit/s or more), the laser source can be driven by a voltage amplifier through a matching circuit. Of course, with the laser source, a control loop to track both the drift of the threshold and modulation efficiency is required. As regards the receivers, at the lower bit rates like 2 and 8 Mbit/s , PIN photodiodes are often used to simplify the receiver. At higher bit rates, APDs are generally used though they require a high bias voltage and a circuit to control the thermal drift and avalanche gain. The transimpedence amplifier is the preferred choice for signal bandwidths upto 150 MHz ; above this value, the FET voltage preamplifier is used [3-6].

4. COHERENT OFCS:

Despite the rapid advances of optical technology over the past decade, intensity modulation (IM) of the source and direct detection (DD) of the receiver using a PIN or an APD have still been used in OFCS. However, advances in optical components technology have now offered significant advantages over the IM - DD systems. For example, coherent OFCS could offer receiver sensitivity 5 to 20 dB better than noncoherent OFCS. This would lead to increased repeater spacing or increase in transmission capacity or increase in power budget available for optical multiplexing /demultiplexing. It also offers better selectivity. As a result channel spacing of only, say 100 MHz instead of the 100 GHz is required in an optical fibre multiplex transmission system. In addition to these, there are several other advantages also [7-9].

In coherent detection, the low level received optical signal (E_S) is combined with a strong locally generated optical signal (E_L) (refer to Fig.3). Let the phase angle, ϕ, is the phase difference between these two electric fields defined at some arbitary time. Since photodetector is a square - law device, the photocurrent (i_t) assuming perfect optical mixing is given by

$$i_t = R_o (P_S + P_L + 2\sqrt{P_S P_L}\, \cos [2\pi(f_L - f_S)t + \phi]) \qquad (1)$$

where P_S is the incident optical power in the absence of modulation ; P_L local oscillator (LO) power . The parameter, R_o ($= \eta q/h\nu$) represents the responsivity of the photodetector (μA/ μW) . Here η represents detector quantum efficiency ; h Planck's constant, q electronic charge ; ν optical frequency, f_S signal frequency; f_L local oscillator frequency and ϕ as defined earlier. As P_L is much larger than P_S, (1) can be approximated as

$$i_t \simeq R_o (P_L + 2\sqrt{P_S P_L}\, \cos [2\pi(f_L - f_S)t + \phi]) \qquad (2)$$

Desired signal component of the current (i_s) from the above equation is given by

$$i_s = R_o (2\sqrt{P_S P_L}\, \cos [2\pi(f_L - f_S)t + \phi]) \qquad (3)$$

In the case of homodyne coherent detection f_L and f_S are equal and (3) becomes

$$i_s = R_o 2\sqrt{P_S P_L}\cos(\phi) \qquad (4)$$

For heterodyne detection f_L and f_S are not equal($f_L - f_S = f_{IF}$ and f_{IF} is called the intermediate frequency). Under this condition (3) can be written as

$$i_s = R_o 2\sqrt{P_S P_L}\cos(2\pi f_{IF} t + \phi) \qquad (5)$$

In homodyne detection, output signal from the photodiode is a baseband signal and local oscillator needs to be phase locked to the incoming optical signal. In heterodyne detection, output signal is centered around f_{IF} and it is stablized by incorporating the local oscillator in an automatic frequency control loop(AFC). Intermediate frequency (IF) signal is demodulated by using either a synchronous or nonsynchronous demodulator . It means in a heterodyne system all the three basic digital modulation schemes viz., on-off shift keying (OOK),frequency shift keying (FSK) and phase shift keying (PSK) schemes can be used and at the receiver, demodulator can be either synchronous or nonsynchronous type. In a homodyne system , only PSK and OOK signalling schemes can be used with synchronous demodulation at the receiver.

In a direct detection receiver, signal current is given by

$$i_s = R_o . P_S \qquad (6)$$

where R_o is as defined earlier.From (4), (5) and (6), it is clear that in coherent receiver , desired signal current (i_s) is amplified by a factor proportional to $\sqrt{P_L / P_S}$. This gain factor increases the signal power without changing the preamplifier noise and leads to better receiver sensitivity compared to direct detection.

Performance of experimental coherent receiver has fallen short of the theoretical prediction so called " quantum limit " of the receiver senstivity (~10 photons at a bit error rate of 10^{-9}). One of the reason of this degradation has been identified as laser phase noise. This noise arises due to spontaneous emissions within the laser cavity. It causes the phase of the optical output wave to execute a random walk and leads to broadning of linewidth(5 to 100 MHz) of the semiconductor lasers. These unwanted phase fluctuations in the received signal degrades the receiver performance . Degradation is much more severe when phase modulation scheme like PSK is used . At low bit rates, the accumulated phase wander during a bit interval might be so great that PSK can not be used at all. At high bit rates, impairment due to phase noise may be negligibly small [8], but the limited receiver bandwidth may become a problem. In a coherent receiver, the frequency response of the photodiode and of the IF circuit must extend to at least $f_{IF} + R_b$ where R_b is the bit rate . Thus at high bit rates, it is desirable to keep IF as low as possible. If IF is equal to zero as in homodyne detection, photodiode current is proportional to cos ϕ. If ϕ is left random (no phase locking), the current is equal to zero when ϕ is equal to 90°, rendering the system useless. If ϕ is kept small, by using optical phase - locked loop (OPLL) at the receiver, required linewidths of the laser at the transmitter as well as of LO source become extremely small.

Degrading effect of laser phase noise on receiver performance depends on the modulation and demodulation scheme used and on the type of system i.e., whether the system is heterodyne or homodyne type. Homodyne and synchronous heterodyne systems place greatest demand on laser phase stability. Laser linewidth requirements for the various modulation and demodulation schemes are listed in Table I given below [7].

Modulation	Demodulation		Linewidth to Bit Rate Ratio
	Heterodyne	Homodyne	
ASK, FSK, PSK	Sync	Yes	0.1 %
DPSK	Delay	No	0.3 %
ASK, FSK	Non synch	No	20 %

Table-I : Coherent system linewidth requirements

The second main reason for the degradation in the receiver performance is the polarization mismatching of the received and LO optical signal. As the conventional monomode fibre do not preserve the state of polarization of the trasmitted optical signal, polarization of the signal arriving at the receiver is unknown. It is changing continuously with time and produces polarization mismatching. As a result, the amplitude of the detected current also changes with time introducing severe fading and even complete signal loss under certain conditions [10]. Matching of the state of polarization (SOP) of the signal and local oscillator can be accomplished by an appropiate polarization control in either the signal or LO path.

As evident from Table-I, problem of phase noise/laser linewidth is not so serious in heterodyne, ASK and FSK nonsynchronous OFCS. However the requirement of small linewidth to bit rate ratio in homodyne system (of course in synchronous heterodyne system also) is still a problem. An elegant solution to this problem is to use a phase-diversity homodyne system instead of a simple homodyne system. Further in a high speed multichannel coherent system, phase - diversity receivers lead to a smaller required LO tuning range than conventional heterodyne receivers [12].

The problem of polarization fluctuation with time can be overcome by using a polarization - diversity receiver. In this receiver, incoming optical signal is resolved into two orthogonal polarization components and these components are separately demodulated. From the demodulated outputs, a signal which is virtually independent of the state of the polarization of the received signal is generated [13].

Principles of phase and polarization - diversity receivers are described below.

4.1 Phase - Diversity Homodyne Receiver

In order to understand the operation of phase-diversity homodyne receiver (Fig.4). let us first consider the working of a 90° optical hybrid. In this hybrid, there are two branches and the electric field at these branches are given by

$$E_1 = 0.5\,L\,(E_S + E_L) \qquad (7a)$$

and

$$E_2 = 0.5\,L\,(E_S + i\,E_L) \qquad (7b)$$

where E_S and E_L represent the electric field corresponding to the signal and local oscillatior respectivily. The parameter L represents the loss in 90° hybrid. If these electric fields are demodulated, the corresponding signal currents are given by

$$i_1 = LR_0\sqrt{P_S P_L}\,\cos\phi \qquad (8a)$$

and

$$i_2 = LR_0\sqrt{P_S P_L}\,\sin\phi \qquad (8b)$$

Inspection of (8) reveals that if the currents are squared and added together ,the resultant current is independent of phase noise and is given by

$$i_t = LR_0\sqrt{P_S P_L} \qquad (9)$$

Advantage of two branch receiver (over three and four branch receivers) is that it will require minimum LO power to suppress the receiver noise . It has got two main disadvantages also. These are :(i) 90° hybrids are inherently lossy device and (ii) receiver imperfections such as polarization mismatching, LO excess noise etc. have more degrading effect on 90° hybrid. These disadvantage of two branch receiver can be overcome to a considerable extent in three branch (0°, 120°, 240°) and four branch(0°, 90°, 180°, 270°) receivers, but these receivers have some problems of their own viz.,requirement of larger LO power, complex signal processing circuitry etc. [10].

It may be noted that phase-diversity homodyne receivers have the same sensitivity and linewidth requirement as heterodyne receivers, but require a much smaller bandwidth. The main disadvantages of phase - diversity receivers are their complexity and sensitivity to implementation imperfections. In additon to this, phase-diversity receivers are less tolerant to polarization fluctuations than conventional heterodyne receiver [14]. The reason for this is that optical hybrids rely on the correct SOP for proper operation . When the SOP deviates from the design value, phase relationship between the branches is disturbed too.

In order to simplify the practical implementation of the phase-diversity receiver,sometimes the IF is taken to be several megahertz or even half of the bit rate instead of zero. Such receivers are called quasi-homodyne or intradyne receiver. Intradyne-phase diversity receivers have the same sensitivity and linewidth requirement as homodyne phase-diversity receivers, but need a somewhat larger bandwidth [14].

4.2 Polarization - Diversity Receiver

Block diagram of a polarization- diversity receiver is shown in Fig.5 . The polarization controller (PC) on the LO path is adjusted to produce equal LO powers at the outputs E_1 and E_2. It need not to be readjusted as the signal polarization varies with time. Let the coupler loss is 3 dB i.e. both signal and LO suffer a 3 dB loss while passing through the coupler . The output current generated by the two detectors for the ASK format are given by

$$i_1 = \sqrt{2}LR_0 d\sqrt{P_S P_L}\cos\theta\cos(2\pi ft+\phi) \qquad (10a)$$

and

$$i_2 = \sqrt{2}LR_0 d\sqrt{P_S P_L}\sin\theta\cos(2\pi ft+\phi+\psi) \qquad (10b)$$

The signal polarization for simplicity is considered to be linear with an angle θ with respect to polarization of E_1 and ψ is an arbitary angle. The parameter d is equal to 1 or 0 corresponding to bit one and zero respectively. The currents i_1 and i_2 are squared and added together and lowpass part of the resultant current is given by

$$i_t = LR_0 d\sqrt{P_S P_L} \qquad (11)$$

It may be noted that the resultant current is independent of both polarization (θ) and of the phase noise (ϕ). Though (11) is derived for linear polarization, it is valid for other types of polarizations also [10].

It is not necessary to use two photodiodes in the polarization - diversity receiver.In fact polarization - diversity can be achieved with one photodiode also if the two orthogonal polarization of the LO have different frequencies as shown in Fig.6 [15]. The mixing between the input signal and LO signal produces two IF components at the photodiode output. These IFs when separated out and demodulated, produce two components which fade in antiphase with SOP variations in the signal. As a result information encoded on input signal is always recoverable by combining the output from the two IF channels.

In the above polarization-diversity receivers,optical power available at only one branch of the coupler is used for demodulation purpose and power at the other branch is going waste. A balanced receiver uses power available at both the branches. Block diagram of a balanced polarization - diversity receiver is shown in Fig.7 [15].

A polarization - diversity receiver employing N detectors / preamplifier modules (N > 2) is affectd by thermal noise of all of them. In order to suppress the impact of these noises, the required LO power is N times larger than that needed for a single detector / preamplifier receiver. Reflections of optical power due to mismatching have the same affect on polarization - diversity receivers as on other heterodyne receivers.

The advantages of phase and polarization-diversity receiver can be combined in a single receiver shown in Fig.8. This receiver consists of two phase - diversity receivers, each recovering an orthogonal polarization of the signal via post - detection combining [16].

5. CONCLUSIONS:

Noncoherent receiver which ignores the phase and polarization of the incident optical field may be easily implemented with the currently available optical components. However, sensitivity of these receivers are often limited by the noise generated in the preamplifier and the following electronic circuitry. In coherent receiver, for large local oscillator power, signal-to-noise ratio which is independent of above noise can be obtained. This allows a significant improvement in the receiver sensitivity.

Source and local oscillator laser linewidths and polarization fluctuation of the received signal will degrade the performance of a coherent receiver. The phase and polarization-diversity are alternative techniques for maintaining the coherent receiver sensitivity at maximum. Polarization - diversity might even be mandatory in multichannel coherent systems where fast channel acquisition is needed and SOP tracking and control requirements might become too difficult. However, these receivers are much more complex than conventional receivers and require larger, LO power and more complex signal processing. In future, advantages of diversity receivers may outweigh the disadvantages. So intensive research in this area is likely to continue in future.

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FIGURE CAPTIONS:

Fig.1: Comparison of monomode and multimode step-index and grade -index fibres.

Fig.2: Block diagram of a noncoherent optical fibre communication system.

Fig.3: Block diagram of a coherent optical fibre communication system.

Fig.4: Block diagram of a phase -diversity receiver.

Fig.5: Block diagram of a polarization-diversity receiver.

Fig.6: Principle of operation of a polarization -insensitive dual IF heterodyne receiver.

Fig.7: Principle of operation of a balanced polarization-diversity receiver.

Fig.8: Schenmatic diagram of a receiver comprising phase and polarization-diversity.

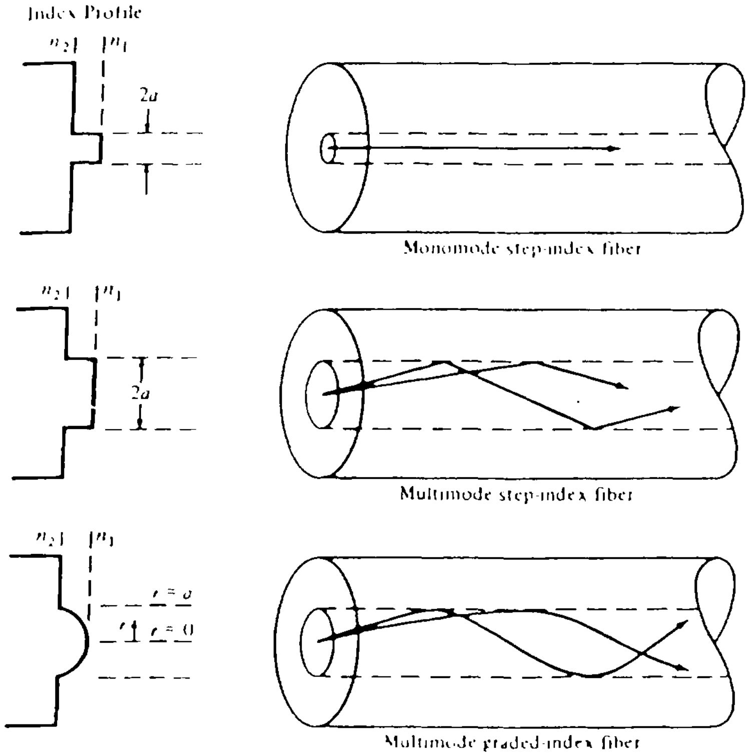


Fig.1 : Comparison of monomode and multimode step-index and grade-index fibres.

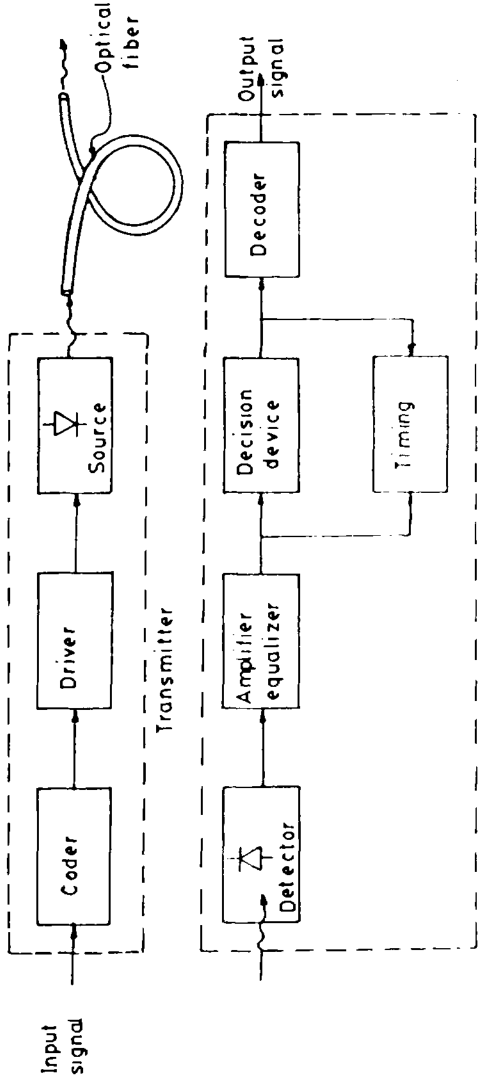


Fig.2 : Block diagram of a noncoherent optical fibre Communication System.

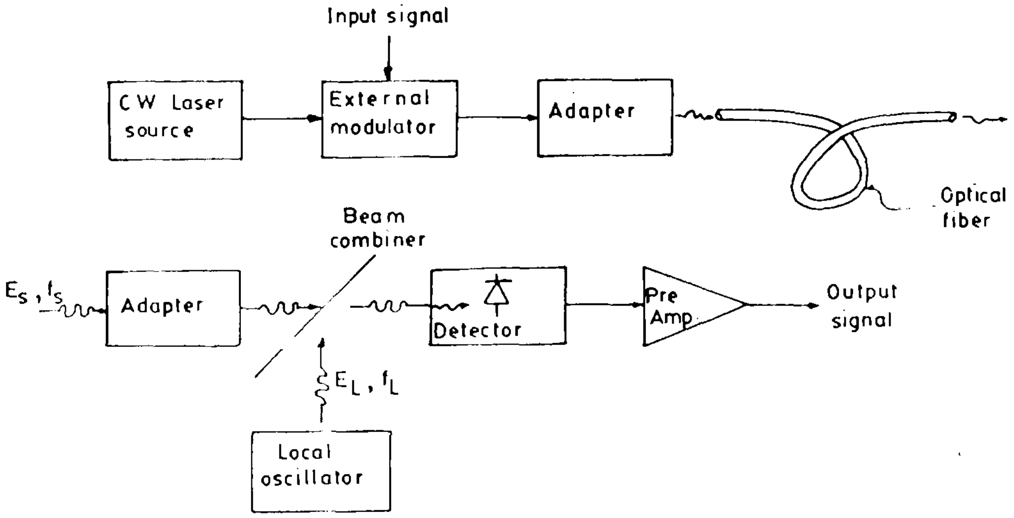


Fig.3 : Clock diagram of a coherent optical fibre communication system.

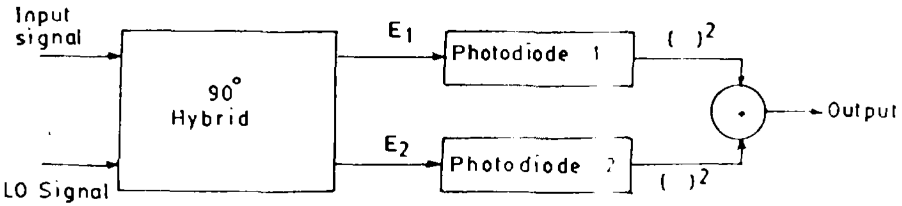


Fig.4 : Block diagram of a phase-diversity receiver.

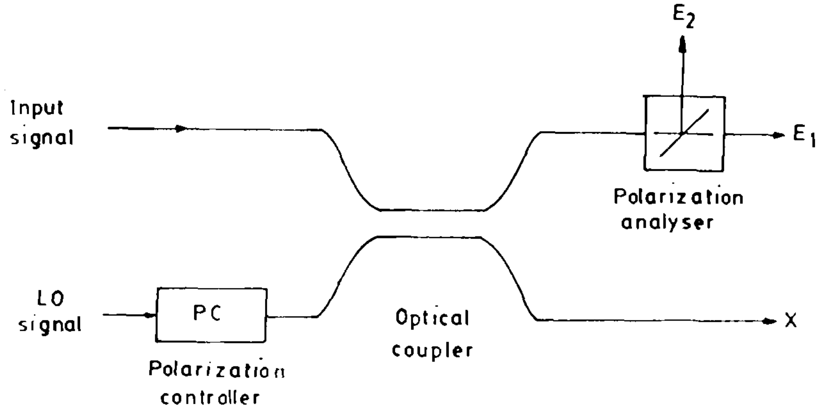
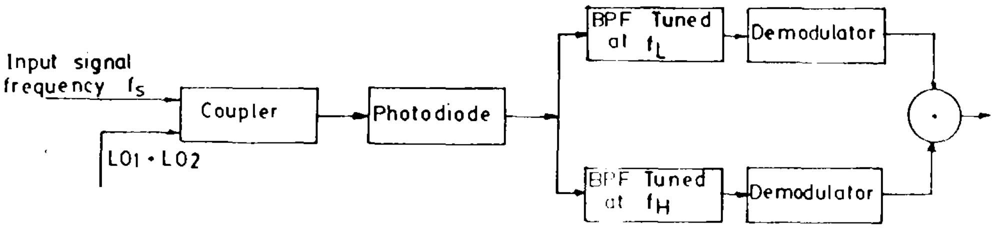


Fig.5 : Block diagram of a polarization-diversity receiver.



LO1: **Vertical polarization frequency, f_1**
LO2: **Horizontal polarization frequency, f_2**
f_L : **equals to $|f_s - f_1|$**
f_H : **equals to $|f_s - f_2|$**

Fig.6: **Principle of operation of a polarization -insensitive dual IF heterodyne receiver.**

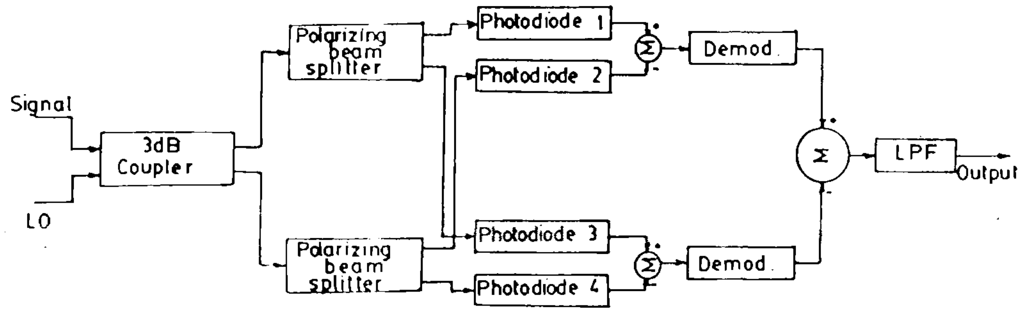


Fig.7 : Principle of operation of a balanced polarization-diversity receiver.

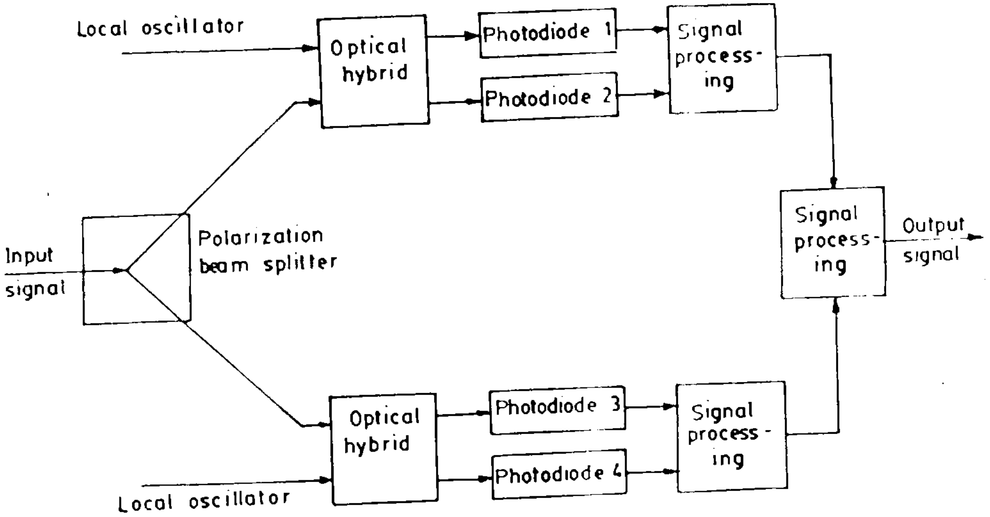


Fig.8 : Schenmatic diagram of a receiver comprising phase and polarization-diversity.