Phase Diversity Techniques for Coherent Optical Receivers

A. W. DAVIS, M. J. PETTITT, J. P. KING, AND S. WRIGHT

***Abstract*—In the present state of the art, coherent optical receivers most often operate in the heterodyne mode. Here a photodiode-amplifier combination having bandwidth greater than twice the bit rate (B) is needed: indeed bandwidths considerably greater than $2B$ are preferably employed to ease design of the bandpass filter needed for noise limitation, and to avoid demodulator penalties in some modulation schemes. For the high bit rate systems now coming into service (560 Mbit/s–2.4 Gbit/s), the optical receiver design requirements become more stringent for coherent heterodyne operation. The various modes of "zero IF" operation, however, require only baseband receiver module bandwidth. The options available are either homodyne (phase locked) operation, or phase diversity (multiport) techniques. In this paper, we compare these options, and show that phase diversity techniques are capable of good performance for high bit rate coherent receivers. In phase diversity operation, not only is phase locking avoided, but also the necessary frequency locking does not have high stability requirements. Furthermore, there are advantages in operating with a small frequency offset from zero (of the order of 1 percent of the bit rate).**

An experimental receiver has been operated at 320 and 680 Mbit/s, demodulating both amplitude shift keying (ASK) and differential phase shift keying (DPSK). Operation with FSK is also possible. Sensitivities so far achieved of −47.5 dBm (320-Mbit/s ASK) and −42 dBm (680-Mbit/s ASK) with limited local oscillator power are capable of substantial improvement when higher power local oscillators and lower noise receive modules become available. Demodulation of DPSK at 320 Mbit/s has also been achieved and shows a measured receiver sensitivity improvement of over 4 dB over ASK at the same bit rate and local oscillator power. These practical results show clearly that phase diversity is a very realistic option for high bit rate systems.

I. INTRODUCTION

IN THE PRESENT state of the art, the majority of coherent optical receivers so far reported have operated in the heterodyne mode. For this, a photodiode-amplifier combination with bandwidth greater than twice the bit rate (B) is needed; indeed bandwidths significantly greater than twice B are usually employed to ease design of the bandpass filter which defines the receiver noise bandwidth [1], [2]. Systems operating at 560 Mbit/s are now coming into service, and higher rate systems (up to 2.4 Gbit/s and beyond) are being developed. For systems operating at such high rates, the wide-band low noise receivers required for heterodyne operation are not easily realized. In addition, noise peaks at photoelectron resonance frequencies in both transmitter and local oscillator lasers can fall within or be translated to the IF. In contrast, a "zero IF" receiver only requires a receiver module of baseband information bandwidth. The two possible modes of "zero IF" operation are homodyne (phase locked) operation [3]–[5] and phase diversity (multiport) techniques [6]–[8]. In this paper, we compare these modes, and show that phase diversity techniques offer robust and practical performance for high bit rate coherent receivers operating at high data rates.

In phase diversity operation, the need for phase locking of the optical local oscillator is avoided, and only frequency locking is required, as in heterodyne systems. We describe an experimental receiver operating at 320 and 680 Mbit/s, with both amplitude shift keying (ASK) and differential phase shift keying (DPSK). The results clearly show that phase diversity is a very realistic option for high bit rate systems. Moreover, phase diversity, in common with other forms of "zero IF" system, does not have the image problems associated with heterodyne operation [12].

II. PRINCIPLES OF COHERENT RECEIVERS

A. Quantum Limited Sensitivity

A block diagram of a coherent receiver (i.e., a receiver using an optical local oscillator (LO)) is shown in Fig. 1. The signal and local oscillator waves are combined in an optical hybrid which also spatially aligns the fields on the detectors. A polarization controller aligns the states of polarization of the two waves.

For a signal wave

$$E_S = \sqrt{P_S} \exp\left[j(w_s t + \phi_S)\right]$$

and a local oscillator (LO) wave

$$E_{\mathrm{LO}} = \sqrt{P_{\mathrm{LO}}} \exp\left[j(w_{\mathrm{LO}} t + \phi_{\mathrm{LO}})\right]$$

falling on the detector, the output current is

$$i = R\big(P_S + P_{\mathrm{LO}} + 2\sqrt{P_S P_{\mathrm{LO}}} \cdot \cos\left[(w_{\mathrm{LO}} - w_S)t - \phi_S + \phi_{\mathrm{LO}}\right]\big) + n_{sh}(t)$$

where

R	detector responsivity $\eta e/hf$,
η	detector quantum efficiency,
e	electronic charge,
h	Planck's constant,
f	optical frequency,
w_S	$2\pi f_S$, the signal angular frequency,

Manuscript received May 29, 1986; revised September 30, 1986.
The authors are with STC Technology Ltd., Harlow, Essex, U.K.
IEEE Log Number 8612963.

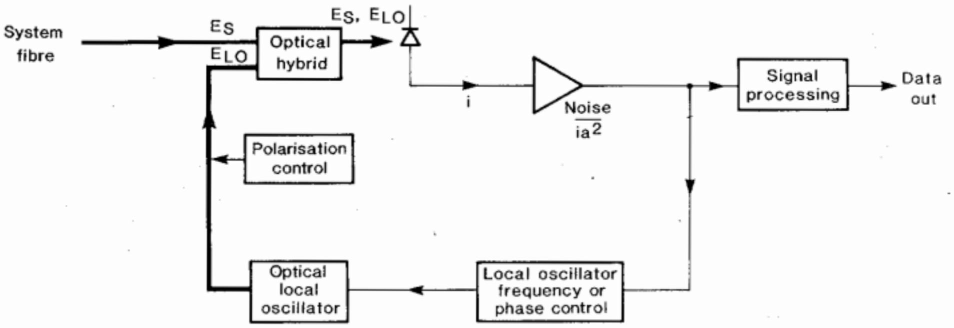


Fig. 1. Coherent optical receiver.

w_{LO}	$2\pi f_{LO}$, the local oscillator angular frequency,
P_S	signal power,
P_{LO}	local oscillator power,
ϕ_S	signal phase,
ϕ_{LO}	local oscillator phase,
$n_{sh}(t)$	shot noise associated with the direct current, component $R \cdot (P_S + P_{LO})$, and
B	bit rate.

Usually $P_S << P_{LO}$ and so the mean square shot noise current density is

$$\overline{i^2}_{sh} = 2e \frac{\eta e}{hf} P_{LO}.$$

Here the wanted signal is

$$R \cdot 2\sqrt{P_S P_{LO}} \cos \left[(w_{LO} - w_S)t - \phi_S + \phi_{LO}\right].$$

At the transmitter, either the amplitude ($\sqrt{P_S}$), the frequency (w_S), or the phase (ϕ_S) will have been modulated. In addition ϕ_S and ϕ_{LO} will be modulated by phase noise, and the amplitude may also be affected by intensity noise. There will be additional noise terms from detector dark current (normally negligible) and from noise originating in the photodiode preamplifier.

We shall consider as a reference an ideal homodyne coherent system where phase shift keying is employed and phase noise is negligible. For binary PSK, $\phi_S = 0$ or π, and for successful demodulation it is necessary that the LO is phase locked to the received signal, so that $w_{LO} \cong w_S$ and $\phi_{LO} = n\pi$. With sufficient LO power, the shot noise current dominates and the receiver sensitivity is quantum noise limited. In this case

$$\frac{\text{Peak–peak signal power}}{\text{Mean square noise power}} = \frac{16\eta \overline{P}_S}{hfB}$$

independent of local oscillator power.

For a BER of 10^{-9}, a signal/noise power ratio of 144 is required and hence

$$\overline{P}_S = 9B \frac{hf}{\eta}, \qquad \text{watts.}$$

For this system, 9 photoelectron/bit are required for quantum limited operation.

Practical coherent system sensitivity will fall short of this because of limitations caused by nonideal components, for example, finite linewidth and center frequency stability of semiconductor lasers, and losses in couplers and modulators. Some introductory discussion of this topic follows, together with system options which allow working systems to be built despite these limitations. Detailed discussion of possible receiver systems is reserved for later sections.

B. Modulation Formats

1. Phase Shift Keying (PSK): In binary phase shift keying the phase of the transmitted carrier is shifted from ϕ_1 to ϕ_2 to signal a change from data "zero" to "one." Biphase modulation ($\phi_1 - \phi_2 = \pi$) gives highest receiver sensitivity, but a phase locked loop locked to the suppressed carrier is needed for demodulation. Reducing the modulation depth slightly provides a residual carrier, and this eases phase locking. External modulation of the laser diode (e.g., with an integrated optic phase modulator) is necessary, and modulator losses (several decibels) can erode the system advantage of PSK.

Higher orders of phase shift keying (quadrature PSK, etc.) are possible but are not considered in this paper.

2. Differential Phase Shift Keying (DPSK): The signal is differentially encoded before modulation. In binary DPSK, a "one" is transmitted by changing the waveform phase by 180° between successive bits, while "zero" is transmitted by sending a pulse in phase with the previous bit. Demodulation and differential decoding can then be achieved by comparing the phase of one bit with the previous bit, so the system only requires bit to bit phase coherence in the optical sources. There is no need to lock to the suppressed carrier, though there is a sensitivity penalty of the order of 1 dB compared to PSK, due to demodulation with the (noisy) previous bit signal, rather than with a clean phase locked carrier. An external phase modulator with its associated losses is still necessary.

3. Frequency Shift Keying (FSK): Binary FSK, where one frequency denotes a "one" and another denotes a "zero," can be modulated and demodulated coherently or noncoherently. For the more common case of noncoherent FSK, the "one" and "zero" frequencies are spaced by an integral multiple of B Hz. Since it is difficult at present to create precise frequency shifts in semiconductor lasers, an alternative is the FSK single filter method [2], where one optical frequency falls entirely outside the

TABLE I

MODULATION FORMAT	CLASS OF DETECTION	RECEIVER SYSTEM	OPTICAL LOCAL OSCILLATOR	IF/BASEBAND PROCESSING	PRACTICAL RELATIVE SENSITIVITY PENALTY (Received Mean Power)	SYSTEM LINEWIDTH/ BIT RATE RATIO
PSK	Synchronous	Homodyne (Ideal)	Phase locked to suppressed carrier	-	0	
		Homodyne	Carrier Phase-locked loop (reduced carrier)	-	~1 dB	6×10^{-6} [17]
			Decision-driven Phase-locked loop (suppressed carrier)	-	~1 dB	3×10^{-4} [18]
			Costas Phase-locked loop (suppressed carrier)	-	~1 dB	5×10^{-4} [20]
		Heterodyne	Frequency Locked	Phase Locked	≳3 dB	5×10^{-3}
DPSK	Synchronous	Homodyne				
DPSK	Non-synchronous	Heterodyne/ Phase Diversity	Frequency Locked	Delay Line + Multiplier	≳4 dB	3×10^{-3} [14]
FSK	Non-synchronous	Heterodyne/ Phase Diversity	Frequency Locked	Discriminator	≳7 dB	1.8×10^{-2} - 7.5×10^{-2}
				Dual Filter/ Envelope	≳6 dB	2.5×10^{-2} - 0.1
				Single Filter/ Envelope	≳9 dB	0.1
ASK	Synchronous	Homodyne	Phase Locked	-	~3 dB	0.1
	Non-synchronous	Heterodyne	Frequency Locked	Phase Lock	~6 dB	
	Non-synchronous	Heterodyne/ Phase Diversity	Frequency Locked	Envelope	≳6 dB	

receiver passband, and the signal is received as ASK with 3-dB system penalty.

The phase coherent systems such as minimum shift keying (MSK) require less bandwidth but are more demanding and will not be considered in this paper.

4. Amplitude Shift Keying (ASK): With binary ASK, "zeros" and "ones" are transmitted by complete amplitude modulation. Modulation must be achieved without significant carrier frequency shift, so that direct modulation of the laser is not possible, and an external modulator is required. For the receiver, envelope detection with a heterodyne or phase diversity receiver suffices, and only frequency locking of the LO is necessary. Receiver sensitivity is least favorable of all systems.

C. Linewidth Requirements

Finite linewidth sources add phase noise (and possibly amplitude noise) at both transmitter and receiver. This will be considered in more detail in Section III, but we may note that phase-locked systems require unrealistic fractional linewidths of 5×10^{-6} to 5×10^{-3}, while ASK is least demanding, requiring approximately $0.1B$. Noncoherent FSK requires intermediate values. In each case, system linewidth has been derived to give negligible penalty (<0.5 dB) at the BER $= 10^{-10}$ level, and is a combination of transmitter and LO linewidth. Assuming that each is Lorenzian, each will require a linewidth of half the system figure. With greater linewidths, system BER floors become apparent.

Practical coherent optical systems will use semiconductor sources. Taking as a practical example a source linewidth requirement of $0.3 \times 10^{-2}B$ for DSPK this translates to 1.68 MHz for 560 Mbit/s. Linewidths better than this have been measured for simple line-narrowed distributed feedback (DFB) laser sources in this laboratory and elsewhere.

The discussion of system fundamentals and options is summarized in Table I. The options which are possible using practically achievable source linewidths utilize heterodyne or phase diversity receivers. Of these, only phase diversity operation retains the advantage of baseband receivers and processing. One further component is needed to realize such a system—a suitable optical hybrid.

D. Optical Hybrids

The optical hybrid that combines LO and signal waves is a key component in a phase diversity system. Ideally, it should combine the two waves with quadrature relative phases at its different outputs. In a symmetrical four port coupler, signal and LO waves appear in antiphase (180°) at the two outputs, and so both give zero output for the same values of ϕ_{LO}. This cannot be used for phase diversity, but the antiphase property can be used to reduce the

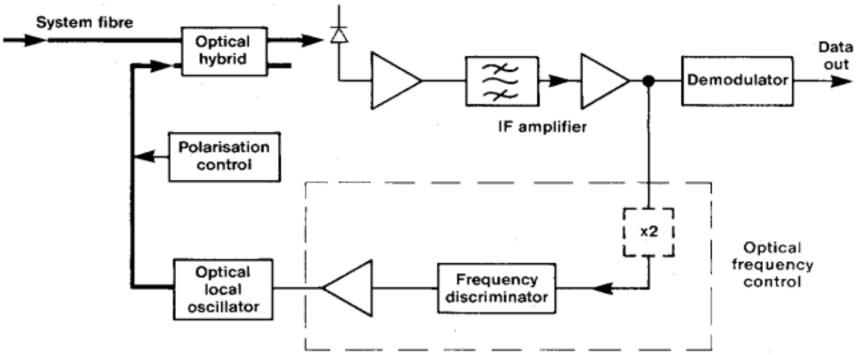


Fig. 2. Heterodyne receiver.

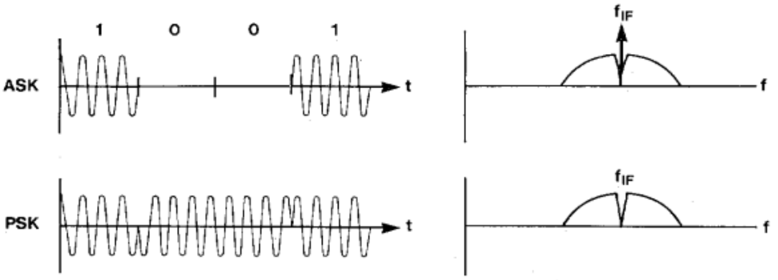


Fig. 3. Photodiode output signals in heterodyne receivers.

effect of LO amplitude noise in a balanced receiver [15], [16].

Four-port 180° hybrids are realized in single-mode fiber using fusing techniques [19]. The same basic techniques can be used to make 120° and 90° diversity couplers, and these have enabled phase diversity receivers to be constructed. They are discussed in more detail in Section III.

III. CLASSES OF COHERENT OPTICAL RECEIVER

A. General

Coherent receivers can be divided into three classes—heterodyne, homodyne (phase locked), and phase diversity. In heterodyne operation, the data is converted to an intermediate frequency and the resulting bandpass signals are demodulated. In a phase locked homodyne receiver, demodulated data emerges directly from one photodiode as a result of synchronous optical mixing. In phase diversity operation, at least two baseband sampled data streams are available from different photodetectors as a result of asynchronous optical mixing. They are then subsequently demodulated and combined. Heterodyne and homodyne methods have now been extensively investigated at optical frequencies, and are widely used in radio frequency systems. In contrast, phase diversity operation has so far been mainly used at optical frequencies for sensors [9], [10]. However, its use for communication receivers at all bit rates is equally valid, both at RF and optical. At RF, the technique has been employed recently for radio paging, navigation, and radar receivers [11], [12]. In the following sections, we shall consider heterodyne and phase-locked homodyne systems as a preliminary to discussing phase diversity receivers.

B. Heterodyne Receiver

A heterodyne coherent optical receiver is shown in Fig. 2. The incoming signal and the optical local oscillator are applied to the input ports of a four port optical hybrid network. The signal and LO differ in optical frequency by the desired IF, and the electrical current from the photo detector contains an IF signal containing the modulation, together with direct detected signal and local oscillator components. In practice, the local oscillator will add amplitude and phase noise. With ASK and PSK modulation the IF signal and spectra are as in Fig. 3. FSK with moderate deviation will also appear as a conventional IF signal. Heterodyne operation thus involves a receiver bandwidth typically of $3B$ or greater [1]. To keep the IF at the desired value, the local oscillator laser will need to be frequency (but not phase) locked to the incoming signal.

The optical hybrid can be symmetrical and utilize a balanced receiver for optimum performance, or asymmetrical to preserve sensitivity with an unbalanced receiver. In the latter case the available LO power must be larger, and amplitude noise cannot be cancelled. At best, ideal heterodyne operation can achieve a sensitivity of 18 photon/bit as opposed to the 9 photon/bit which should be available in a coherent system. In addition, wide-bandwidth receivers are needed. It is to overcome these limitations that homodyne operation has been considered a desirable goal. However, it will be seen that the necessary conditions to achieve this goal are unrealistically demanding.

C. Homodyne Receiver

There are two classes of synchronous homodyne receiver: those deriving phase lock from a full or residual

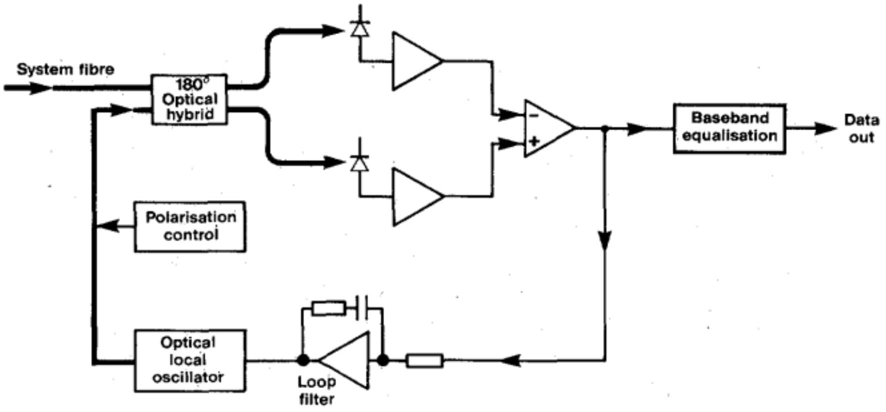


Fig. 4. Homodyne receiver carrier phase locked loop.

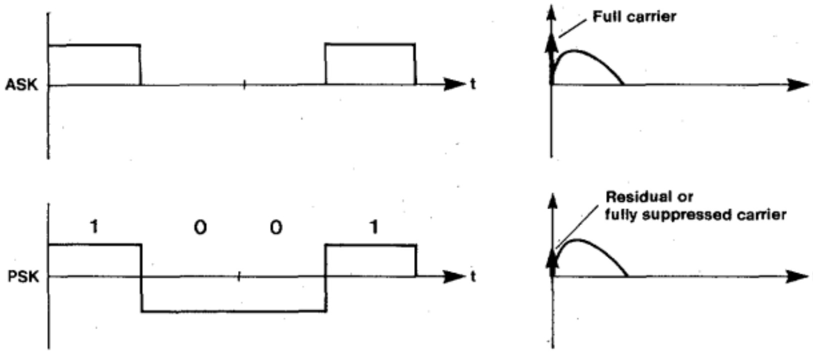


Fig. 5. Photodiode output signals in homodyne receiver.

carrier in the incoming signal (carrier phase locked loop) and those using nonlinear techniques to recover a suppressed carrier (Costas loop or decision driven loop [5]). Consideration of the Costas Loop will lead naturally to phase diversity operation.

1. Carrier Phase Locked Loop (CPLL) Receivers: An outline block diagram of a CPLL receiver is shown in Fig. 4, with photodiode output signals and spectra in Fig. 5. The local oscillator at the frequency of the carrier of the modulated input signal is applied to one arm of a 180° four-port optical hybrid. When phase synchronism with the signal carrier is achieved, the photodiode output is the demodulated data signal. To achieve phase synchronism, a residual pilot carrier must be transmitted: for PSK modulation, incomplete modulation of $\pm 85°$ gives a carrier component 10 dB below the total signal power. Phase locking to such a pilot carrier has been demonstrated [3], and Hodgkinson [4] and Kazovsky [17] have analyzed the necessary loop conditions in the presence of signal and LO phase noise.

The system has a number of attractive features. It needs only baseband photodiode and amplifier bandwidth and no further demodulator is necessary. A simple symmetrical four-port hybrid can be employed.

However, there are several practical difficulties. In the first place, direct detection of LO and signal gives a dc output, which masks the desired phase dependent dc signal. Similarly, LO amplitude noise would adversely affect the lock quality. These effects can be overcome by employing a balanced receiver as shown, but drift and noise affecting the balance may well be severe problems, since the receiver must be dc coupled. The data and phase lock signals are both taken from the differential output. Penalties are then incurred because of the need for finite carrier power to phase lock, and due to phase variation on the recovered carrier, caused by phase noise, shot noise, and data to phase lock crosstalk. A total phase variation of $\sim 10°$ is the maximum permissible to ensure low penalty at a BER of $10^{-9} - 10^{-10}$. To maintain phase lock to this accuracy, it has been derived [17] that a system linewidth (due to transmit and LO lasers) of 6×10^{-6} of bit rate is needed. This sets a very severe requirement linewidth requirement and hence the carrier PLL appears to be an unlikely choice for operational systems.

2. Costas Loop Receivers: An alternative to the CPLL receiver is the Costas loop, shown in Fig. 6. Here the carrier (dc) component is recovered by nonlinear methods from the data sidebands and so the carrier can be fully suppressed and the optical receivers can be ac coupled. Signal and local oscillator waves are applied to an optical 90° hybrid having a transfer function such that the two photodiode outputs are (neglecting direct detected components):

$$KM(t) \exp{(jwt + \phi_0)}$$

$$KM(t) \exp{(jwt + \phi_0 + \pi/2)}$$

where w is the angular frequency difference between sig-

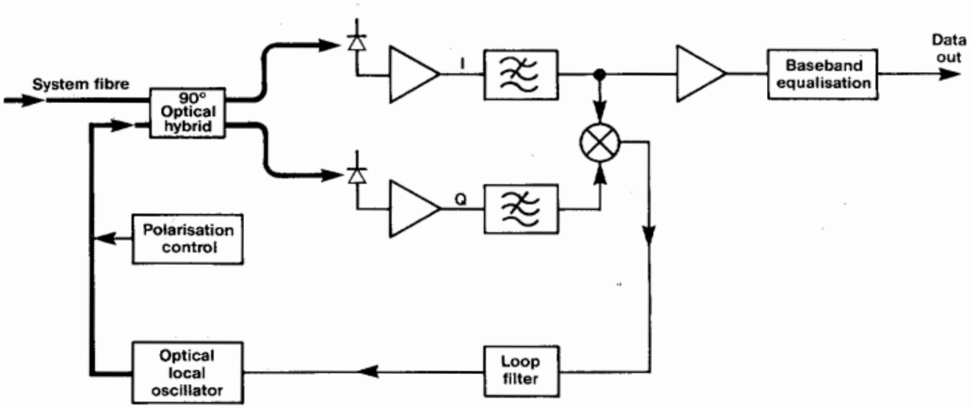


Fig. 6. Homodyne receiver—Costas loop.

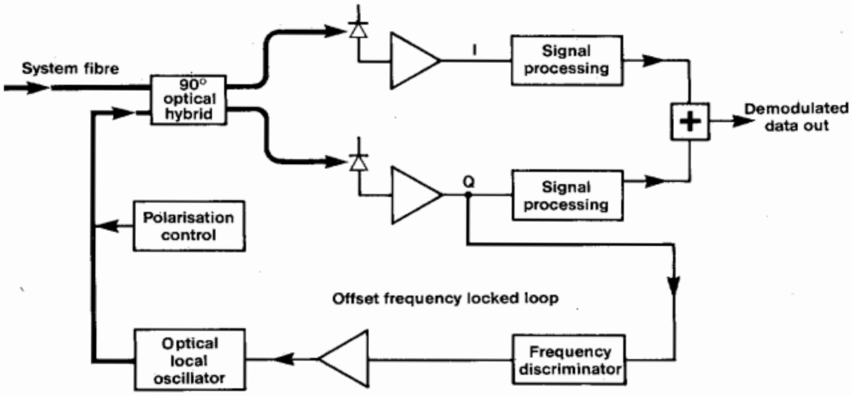


Fig. 7. Phase diversity receiver—two phase.

nal and LO waves and $M(t)$ is the (PSK) modulation. Suitable optical hybrids can take two forms [9], [18], and we shall discuss them further in connection with phase diversity receivers.

The Costas loop shares the CPLL receiver advantages of baseband receiver requirements and direct demodulation. Additionally we may note that the receive system may be ac coupled (to the third multiplier output) and there is no restriction on LF data content since, ideally there is no data/phase lock crosstalk. Mainly for this reason, laser system linewidth requirements derived in [18] are reduced to $\sim 3 \times 10^{-4}$ of bit rate, for decision directed loops. Linewidth requirements for Costas loops would be similar but this is still a very severe specification.

In view of the necessary conditions, allowing the system to operate asynchronously and processing the phase diverse outputs looks an attractive alternative.

D. Phase Diversity Receivers

A "zero IF" receiver which avoids the need for phase locking is evidently most desirable. The advantage of baseband processing can be retained by employing a system which gives phase diversity outputs from two or more arms. In the two-phase case, outputs must be mutually phased at 90° (In-phase and quadrature, referred to as I and Q signals).

In each case, the signal in each arm can be processed to recover either ASK, DPSK, or FSK modulation. There will be only a partial signal from each arm, since at some phase condition, each arm signal can fade to zero, but when one is zero, the other(s) are still present. Summing the outputs gives a full demodulated signal.

Since the hybrids must be symmetrical, the signal and LO are split two or three ways. This leads, under shot noise limited conditions, to a 3-dB (2 times) sensitivity penalty for 2-phase processing (compared with homodyne with a coupler giving negligible loss in the signal path) and a 4.8-dB (3 times) penalty for 3-phase processing. At best, therefore, phase diversity sensitivity is the same as for heterodyne, but with the great advantage of baseband operation.

Phase diversity receivers are possible using both 90° hybrids and other types, such as three phase 120° hybrids. In the 90° case, the receiver is similar to a Costas loop without completion of the phase locked loop. An outline block diagram of a two phase receiver is shown in Fig. 7.

Output waveforms and spectra from one photodiode are shown in Fig. 8. The other photodiode output waveform will be similar, but with the offset frequency envelope shifted by 90°. Fig. 9 shows an outline of a three phase receiver. In this case, the offset frequency envelopes will be mutually phased at 120° intervals.

For two phase

$$i = K_1 M(t)\, e^{j(2\pi f_{\text{offset}} t + n\pi/2)}, \qquad n = 0, 1.$$

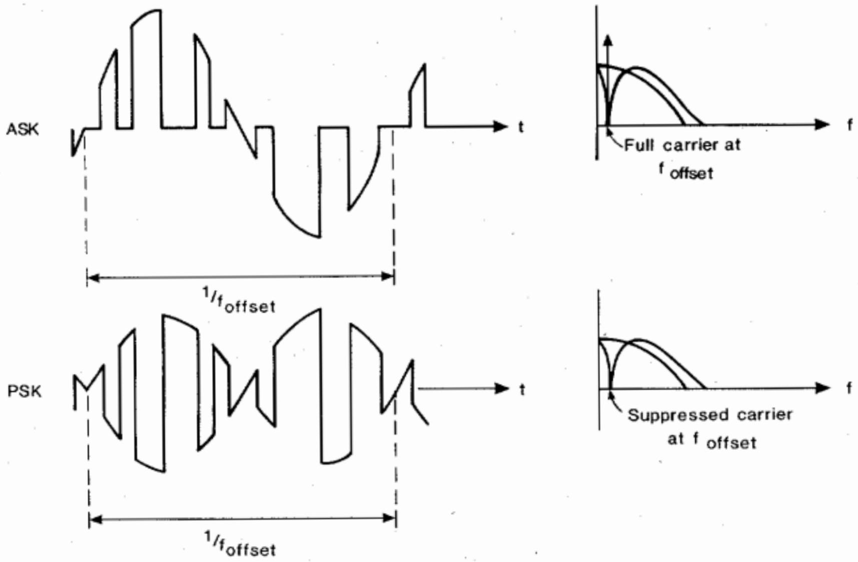


Fig. 8. Photodiode output signals in phase diversity receiver.

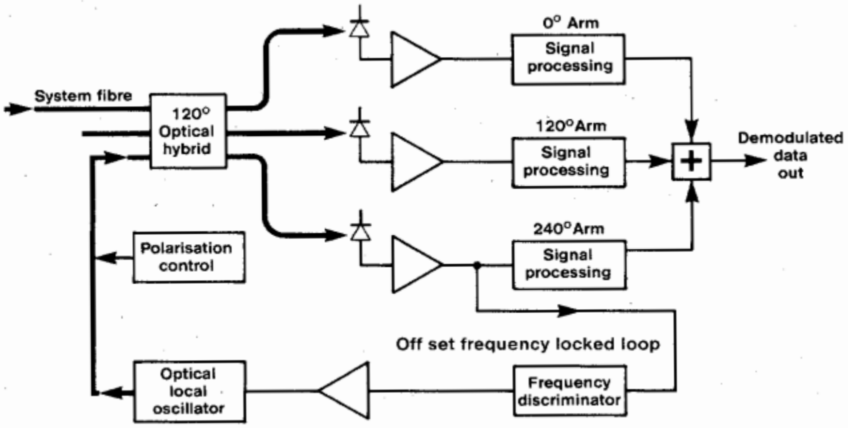


Fig. 9. Phase diversity receiver—three phase.

For three phase,

$$i = K_2 M(t)\, e^{j(2\pi f_{\text{offset}} t + 2n\pi/3)}, \qquad n = 0, 1, 2.$$

1. Optical Hybrids: A key component is an optical hybrid giving two or more outputs containing in-phase and quadrature signals. Of the available four-port, six-port, and eight-port couplers, only the six and eight port types satisfy this requirement (Fig. 10).

a. Six port (120°): This is the smallest number of ports that enables I and Q components to be obtained. Quadrature outputs are obtainable by suitable linear combination [10] or the 120° outputs can be processed individually. Because of shot (and thermal) noise introduced in the detection process, best sensitivity is, however, achieved by processing each channel individually and then combining.

Stable practical six-port fiber couplers are easily made in fused fiber form by fusing three fibers until equal power appears at each outport. The 120° phase relationship is then obtained. No control of adjustment in use is needed. Because of its practicality and robustness, this coupler

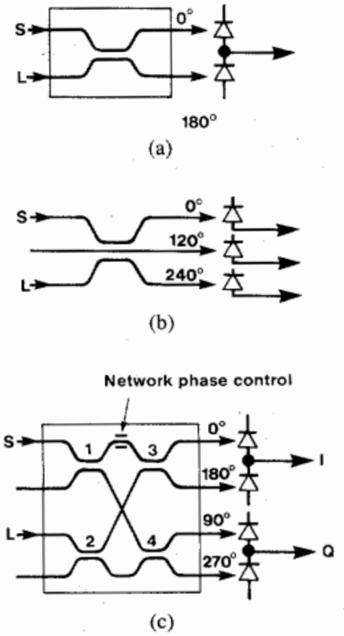


Fig. 10. Optical hybrids: (a) four port, (b) six port, (c) eight port.

type is the most useful for phase diversity receivers at this time.

b. Eight port (90°): This has been realized from 4 four-port (180°) couplers by Stowe [9]. With control of the path length in the cross coupling, quadrature components of $(W_s \sim W_L)$ appear as differential pairs in the detector currents as shown. All signal and local oscillator power is used and local oscillator amplitude noise is cancelled, given symmetry. Phase diversity receivers of best achievable performance—the same as heterodyne—could be made with such a hybrid. Alternative forms, relying on polarization splitting or mode conversion have been proposed [13], but the four coupler method is the only one realised as a practical component so far. The need for differential length control within the coupler to $<<\lambda/4$ makes this coupler less attractive for practical robust phase diversity receivers. A robust eight-port requiring no control or adjustment in use is a desirable component.

2. Signal Processing: The form of signal processing used in each arm will depend on the received modulation format—ASK, DPSK, or FSK (Fig. 11).

a. ASK: Envelope detection (either linear or square law) is used in each channel. The offset frequency can vary quite widely since the only distorting factor is the band limiting of the front end receive modules and any noise filtering. If the system is dc coupled, varying through zero frequency is permissible. However, one advantage of phase diversity operation is that ac coupling can be used. In this case, a small positive offset frequency $(\sim B/100)$ is required to avoid notching out the carrier. The zero notch appears in one sideband and has negligible effect.

b. DPSK: The well known technique of splitting the signal, delaying one path by one bit, and multiplying is employed in each arm. This effectively demodulates the signal and performs differential decoding in one operation. The bit stream must be differentially encoded at the transmitter. The offset frequency is more critical than with ASK, because a penalty results if the bit rate is not integrally related to the IF frequency as

$$f_{\rm IF} = NB/2, \qquad N = 0, 1, 2 \cdots$$

i.e., if $f_{\rm IF} = NB/4$, $N = 1, 3, 5, \cdots$, the one bit delayed and the undelayed carriers are in quadrature, and no output results from the multiplier.

This penalty is apparent for all IF values, including zero IF.

Since the signal format is already suppressed carrier, variation of offset frequency through dc is possible even with ac coupling.

c. FSK: Two basic methods are available for demodulating FSK in phase diversity receivers.

d. Discriminator: A frequency discriminator can be inserted in each channel and the outputs combined. Alternatively, there is an elegant solution for I and Q receivers that has been used by Vance at RF [11] and by Stowe and others for optical sensors [9]. In the latter case, output proportional to phase change was required, so output from the discriminator was integrated. As seen in Fig. 11, differentiation of each signal is required, before cross multiplication with the other channel. It is not known how well this could be implemented for high bit rate systems.

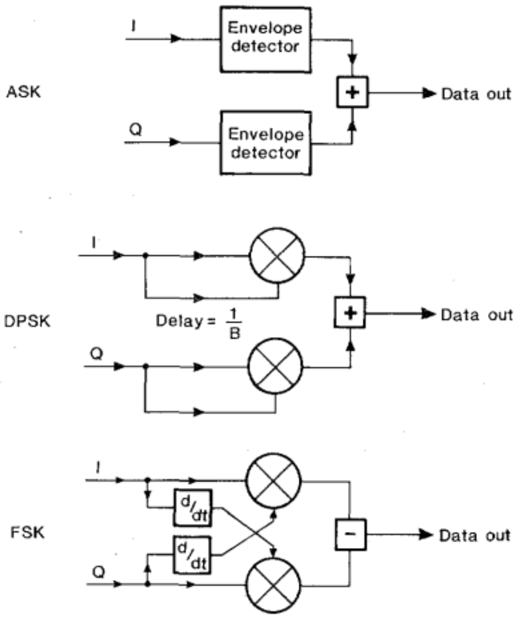


Fig. 11. Phase diversity receivers—demodulation.

e. Filter and envelope detect: Filters for "mark" and "space" frequencies (one of which may be the "zero IF") are inserted in each channel, envelope detected and summed. An extreme case of this is the "FSK single filter method" [2] already reported at optical frequencies, where the deviation is so wide that one frequency only is received.

f. Other functions: In addition to the demodulation process, other functions such as amplification, AGC, and noise filtering and equalization are needed. With phase diversity systems, these can all be baseband, leading to the possibility of total integrated circuit realization, and the use of existing direct detection hardware.

IV. EXPERIMENTAL PHASE DIVERSITY RECEIVERS

An experimental phase diversity receiver has been used for demodulation of both ASK and DPSK signals. The receiver block diagram is shown in Fig. 12. The demodulator blocks are full-wave envelope detectors for ASK, and differential 1 bit delay and multiplier for DPSK.

It will be noted that the receiver is a 3-phase (120°) type. This was chosen because the 3 × 3 coupler is a stable, robust device that requires no adjustment or control in use. The coupler was made at STL, using an extension of the process used routinely to make 3-dB couplers.

When two unmodulated optical waves of mean power $P_{\rm sig}$ and $P_{\rm LO}$ are input to two of the three input arms, the intensity-modulated signals at the three outputs are

$$\frac{2}{3}\sqrt{(P_{\rm sig}P_{\rm LO})}\,\cos\left((2\pi f_{\rm offset})t + \frac{n2\pi}{3}\right), \qquad n = 0, 1, 2$$

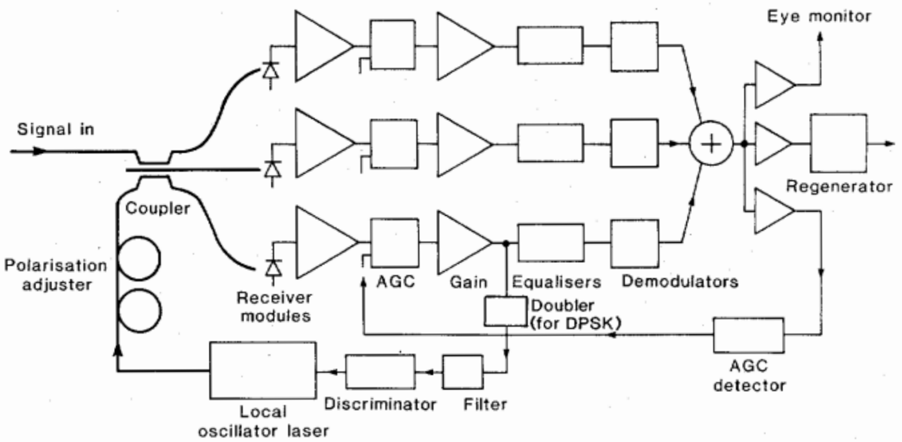


Fig. 12. Experimental three-phase receiver.

i.e., three signals at the difference frequency f_{offset} mutually phased at intervals of 120°.

If now P_{sig} is amplitude-modulated (ASK) with a signal of bandwidth B, each of these outputs will be modulated (sampled) by the data signal. With $f_{\text{offset}} > B$, the output of each port would be a heterodyne IF ASK signal requiring bandwidth $>2B$. However, using the multiport network the offset frequency can be set within B and the signal can still be recovered. With f_{offset} at some low frequency (of the order of $B/100$) the output from one channel will appear as a sampled data signal as shown in Fig. 8.

With a DPSK signal, the carrier will be reversed at appropriate bit times, and the offset frequency waveform will appear as in Fig. 8.

In each case the three available phase-diverse waveforms allow signal demodulation and reconstruction by the means already discussed. The bandwidth required in each arm is only slightly greater than B, and baseband optical receiver modules, AGC, amplifiers, and equalizers are employed. The signal processing chains were ac coupled, and so a definite offset frequency $(\sim B/100)$ allowed preservation of the carrier for ASK. A doubler was used to recover a twice-offset frequency carrier from the DPSK signal to enable frequency lock to be maintained. In each case, the recovered data stream is fed to a conventional clock extractor and regenerator. The experimental system uses HeNe lasers operating in the low-loss fiber window at 1.523 μm. Single-longitudinal-mode (SLM) operation is, of course, essential for both transmitter and local oscillator lasers. The test transmitter employs an integrated-optic phase modulator (made at STL) driven directly with the bit stream for ASK. The carrier is then added in a fiber Mach–Zehnder network to give the complete ASK transmission. For DPSK, the phase modulator is driven via a differential encoder, and the output is directly the DPSK signal. A full 180° phase reversal is employed.

A. Theory and Results (ASK)

To demodulate ASK the three phase-diverse signals are passed through linear full wave envelope detectors, and the outputs are added. We may identify two main ways in which the recovered data stream will differ from a direct-detected one. Firstly, the noise in the "zeros" will be the sum of three full-wave-rectified Gaussian noise processes, and hence will be non-Gaussian. Secondly, the "ones" will vary in amplitude by a factor of $2/\sqrt{3}$ at a rate of $6 \times f_{\text{offset}}$, due to the demodulation method. The noise in the "ones" will be essentially Gaussian. A theoretical study of these effects, and of other phase diversity systems, is in progress (21).

With the aid of the following simplifying assumptions, a first-order expression for the sensitivity may be derived. 1) Assume Gaussian noise in both "ones" and "zeros", with a mean square value equal to the sum of the mean square noises in the individual channels. 2) Consider the amplitude variation on the "ones" to be an impairment, and hence assume that the "one" amplitude is always at the minimum of the ripple, and that the detection threshold is one half of this.

The expected sensitivity with an ideal 3 × 3 coupler and identical signal processing paths is then

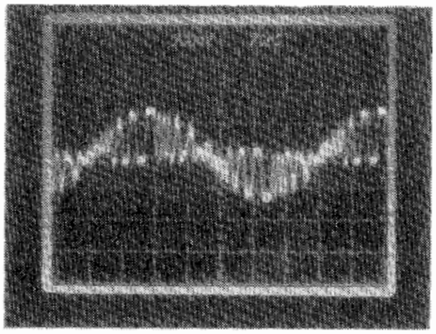
$$P_{\text{sig}} = 9Q^2B_n \frac{\left(\overline{i_a^2} + \frac{2}{3} e^2 \frac{\eta\lambda}{hc} P_{\text{LO}}\right)}{2\left(\frac{\eta e\lambda}{hc}\right)^2 P_{\text{LO}}}$$

where

P_{LO}	total LO power to three photodetectors,
Q	6 for a BER of 10^{-9},
B_n	system noise bandwidth after equalization ($\sim$0.5-Bd rate) (Hz),
$\overline{i_a^2}$	equivalent amplifier noise spectral density at photodetector (A^2/Hz),

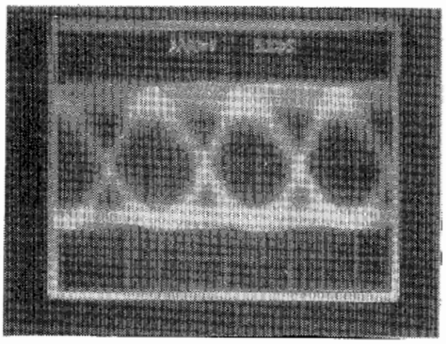
and the other symbols have their usual meanings.

The ASK receiver has been operated at 320 and 680 Mbit/s. The output from one receiver module in Fig. 13 clearly shows the nature of the signal, using a 24-bit fixed pattern at 680 Mbit/s. Patterning can also be seen, principally because the receiver bandwidth is less than desir-



680 Mb/s ASK

Fig. 13. One-channel receiver module output 24-bit pattern. Offset frequency 6.8 MHz.



680 Mb/s ASK

Fig. 14. Demodulated eye 2^{15}-1 pseudorandom pattern.

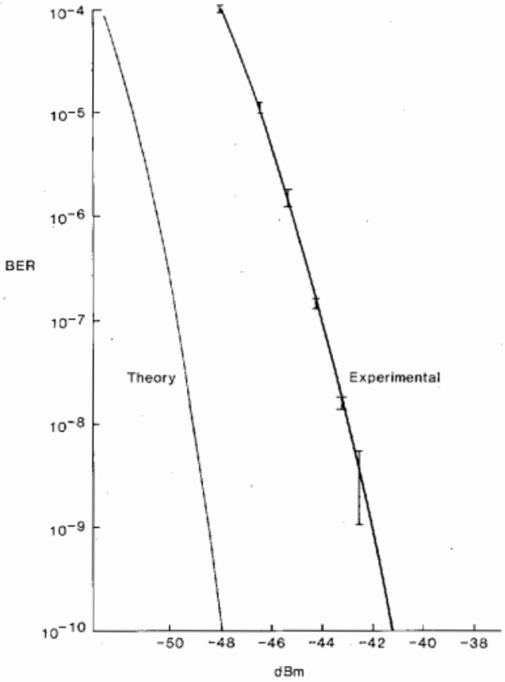


Fig. 15. 3 × 3 coherent receiver. 680-Mbit/s ASK, $\lambda = 1.52$ μm, $\eta = 0.8$, $i_n^2 = 9 \times 10^{-24}$ A^2/Hz, LO—injection locked, BH laser, $P = 61$ μW.

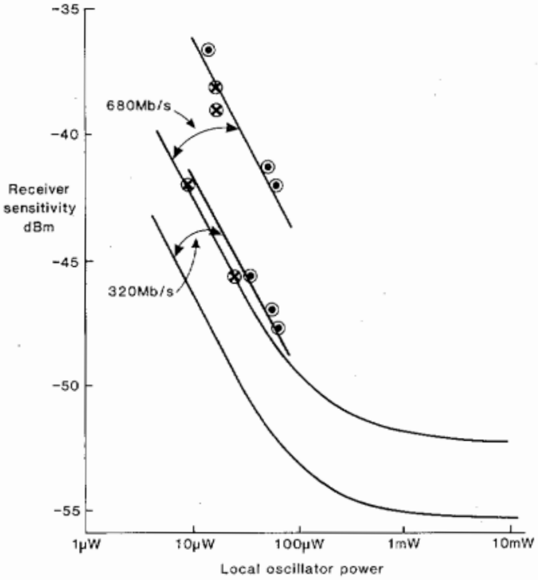


Fig. 16. ASK, BER = 10^{-9}, $\lambda = 1.52$ μm, $\eta = 0.8$, ⊗: HeNe local oscillator, ⊙ : injection locked semiconductor local oscillator, ——: theoretical.

able for the bit rate. Fig. 14 shows a demodulated eye for a 680 Mbit/s 2^{15}-1 pseudorandom bit stream.

Since only limited power was available from the HeNe LO, improved sensitivity was gained with an injection-locked semiconductor system. This consisted of an HeNe gas master laser operating at 1.523 μm coupled into a buried-heterostructure laser diode. Drive current and temperature were tuned to synchronize the dominant laser diode longitudinal mode and the HeNe output. Excess phase noise of the injection-locked output was negligible and amplitude fluctuations were reduced relative to the HeNe output. Ninety percent of the injection-locked output was in the amplified HeNe mode. The remaining power consisted of incompletely suppressed (broad linewidth) laser-diode modes, and this did not contribute to the coherent gain of the LO.

Error rate curves using a variety of local oscillator power were taken, and a typical plot showing no error rate floor down to a BER of 10^{-10} is shown in Fig. 15. It is also informative to plot expected and measured sensitivity against available LO power, as shown in Fig. 16. The equivalent noise of the (commercially available) transimpedance receiver modules used was measured at 2.8 pA$/\sqrt{(\text{Hz})}$ at 320 Mbit/s and 3 pA$/\sqrt{(\text{Hz})}$ at 680 Mbit/s. As usual with coherent optical system, sensitivity should improve with increasing LO power until limited by shot noise in the mean detector currents. With lower noise receiver modules, shot-noise-limited operation would be achieved at low LO powers. The available LO power (total at the three detectors) was 22 μW with the HeNe LO and 61 μW with the semiconductor injection-locked LO. Experimentally measured sensitivity, assessed as the total mean signal power at the three detectors, is shown for a number of LO powers at the two bit rates.

Since only limited LO power was obtainable (61-μW maximum), shot noise limited operation was not approached. Results at both baud rates follow the expected

[2] S. Yamakazi, K. Emura, M. Shikada, M. Yamaguchi, I. Mito, and K. Minemura, "Long span optical FSK heterodyne single-filter detection transmission equipment using a phase tunable DFB laser diode," *Electron. Lett.*, vol. 22, pp. 5–7, 1986.

[3] D. J. Malyon, "Digital fiber transmission using optical homodyne detection," *Electron. Lett.*, vol. 20, pp. 281–283, 1984.

[4] T. G. Hodgkinson, "Phase locked loop analysis for pilot carrier coherent optical receivers," *Electron. Lett.*, vol. 21, pp. 1202–1203, 1985.

[5] H. K. Phillip, A. L. Scholy, E. Bonek, and W. R. Leeb, "Costas loop experiment for a 10.6-μm communications receiver," *IEEE Trans. Commun.*, vol. COM-31, pp. 1000–1002, 1983.

[6] A. W. Davis and S. Wright, "Coherent optical receiver for 680 Mbit/s using phase diversity," *Electron. Lett.*, vol. 22, pp. 9–11, 1986.

[7] N. G. Walker and J. E. Carroll, "Simultaneous phase and amplitude measurements on optical signals using a multiport junction," *Electron. Lett.*, vol. 20, pp. 981–983, 1984.

[8] T. G. Hodgkinson, R. A. Harmon, and D. W. Smith, "Demodulation of optical DPSK using in-phase and quadrature detection," *Electron. Lett.*, vol. 21, pp. 867–868, 1985.

[9] D. W. Stowe and T.-Y. Hsu, "Demodulation of interferometric sensors using a fiber-optic passive quadrature demodulator," *J. Lightwave Technol.*, vol. LT-1, no. 3, pp. 519–523, Sept. 1983.

[10] K. P. Koo, A. B. Tveten, and A. Dandridge, "Passive stabilisation scheme for fiber interferometers using 3 × 3 fiber directional couplers," *Appl. Phys. Lett.*, vol. 41, no. 7, pp. 616–618, Oct. 1, 1982.

[11] I. A. W. Vance, "An integrated circuit VHF radio receiver," *Radio Electron. Eng.*, vol. 50, no. 4, pp. 158–164, Apr. 1980.

[12] I. A. W. Vance, "Fully integrated radio paging receiver," *Proc. Inst. Elec. Eng.*, pt. F, vol. 129, no. 1, pp. 2–6, Feb. 1982.

[13] A. R. L. Travis and J. E. Carroll, "Possible fused fiber in-phase/quadrature measuring multiport," *Electron. Lett.*, vol. 21, pp. 954–955, 1985.

[14] G. Nicholson, "Probability of error for optical heterodyne DPSK system with quantum phase noise," *Electron. Lett.*, vol. 20, pp. 1005–1107, 1984.

[15] S. Wright and P. R. Couch, "Some receiver considerations for coherent systems," in *Tech. Dig. IEE Colloq. Coherence in Optical Fiber Syst.*, May 1982, Dig. no. 1982/59.

[16] G. L. Abbas, V. W. S. Chan, T. K. Yee, "A dual detector optical heterodyne receiver for local oscillator noise suppression," *J. Lightwave Technol.*, vol. LT-3, no. 5, pp. 1110–1122, Oct. 1985.

[17] L. G. Kazovsky, "Balanced phase locked loops for optical homodyne receivers: Performance analysis, design considerations, and laser linewidth requirements," *J. Lightwave Technol.*, vol. LT-4, no. 2, pp. 182–195, Feb. 1986.

[18] L. G. Kazovsky, "Decision driven phase locked loop for optical homodyne receivers: Performance analysis and laser linewidth requirements," *J. Lightwave Technol.*, vol. LT-3, no. 6, pp. 1238–1247, Dec. 1985.

[19] T. Bricheno and A. Fielding, "Stable low-loss single mode couplers," *Electron. Lett.*, vol. 20, pp. 230–232, 1984.

[20] T. G. Hodgkinson, "Costas loop analysis for coherent optical receivers," *Electron. Lett.*, vol. 22, pp. 394–396, 1986.

[21] A. Hadjifotiou, unpublished.

*

Anthony W. Davis was born in London, England, in 1937. He gained the Diploma in electrical engineering from the Institution of Electrical Engineers in 1965 after study at the Hatfield Polytechnic.

He then joined Standard Telecommunication Laboratories where he worked initially on free-space optical communication. After spending several years on signal processing and radar projects, he returned to optical communication in 1976. He has worked on analog optical systems and optical receivers for digital systems, and now has a special interest in coherent optical transmission.

*

Martin J. Pettitt was born on May 25, 1958. He received the B.Sc. degree in electrical engineering from Imperial College, London, in 1979.

He then joined STL to work in the optical communications systems group. Since then his work has included studies of semiconductor laser coherence, polarization properties of fibers, nonlinear effects in fibers, and integrated optics components. He is currently involved in the development of coherent systems employing phase diversity techniques.

*

Jonathan P. King was born in Chelmsford, England, in November 1959. He gained the B.Sc. Honours degree in physics from Bristol University, England, in 1981.

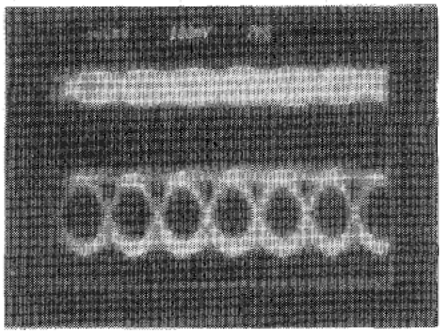
He joined STL in 1981 where he has enjoyed working on a wide variety of optical systems related subjects. These have included photon counting photodiodes, optical fiber modulators, laser-diode amplifiers and injection locked oscillators, and a study of fading effects in coherent OTDR. He is currently interested in 'noninvasive' components for optical fiber networks.

*

Stephen Wright was born in Sheffield, England, in 1950. He received the B.A. degree in electrical sciences from the University of Cambridge in 1971, and the Ph.D. degree from the University of London in 1975, for research in integrated optics carried out at University College London.

He joined the Integrated Devices division of Standard Telecommunication Laboratories (STL—now STC Technology Ltd.) in 1974, to work on integrated optic and surface acoustic wave devices in $LiNbO_3$. In 1979, he was appointed a Lecturer in the Department of Electronics at the University of Glasgow, where he initiated research in coherent optical systems. In 1981, he returned to STL to work in the Transmission Networks division. He is currently a Laboratory Manager responsible for work in coherent optical technology.

Dr. Wright is a member of the Institute of Electrical Engineers.



320Mb/s DPSK

Fig. 17. Top—modulated offset frequency signal. Bottom—recovered eye.

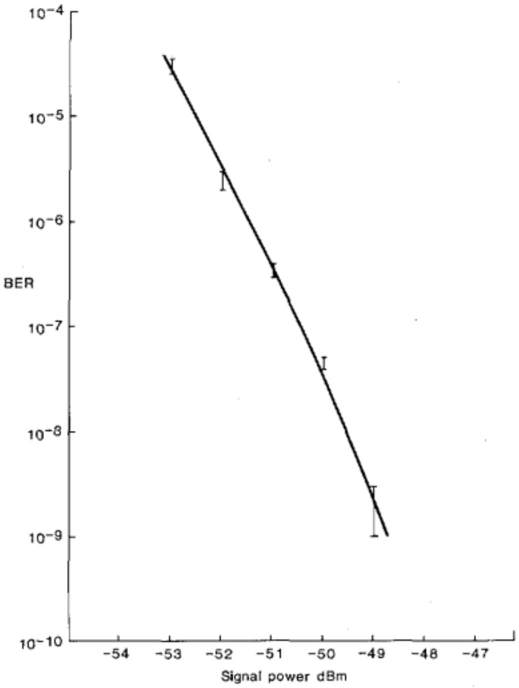


Fig. 18. 3 × 3 coherent receiver, 320-Mbit/s DPSK, 24-bit pattern, $\lambda = 1.52\ \mu\text{m}$, $\eta = 0.8$, $i_n^2 = 9 \times 10^{-24}\ \text{A}^2/\text{H}$, LO: 12 μW.

trend, with the best sensitivities of −47.5 dBm at 320 Mbit/s and −42 dBm at 680 Mbit/s being achieved with the highest LO power. Penalties are due to a number of factors: equalization, optical receiver module patterning penalty (at least 2 dB at 680 Mbit/s due to limited bandwidth) and the difficulty of obtaining and maintaining complete extinction with the type of transmitter used. Extinction ratio penalties are more severe for coherent ASK than for direct detection of intensity modulation.

B. Results (DPSK)

Again considering an ideal coupler, we expect from simple considerations that the sensitivity will be some 2 dB better than for ASK on a mean power basis. (This gives, of course, a 5-dB system advantage with a peak-power limited laser transmitter).

The DPSK system has so far been operated only at 320 Mbit/s, with a maximum available LO of 12 μW. An offset frequency signal and recovered eye are shown in Fig. 17, and error rate plot in Fig. 18.

At this LO power, the system is some 8.5 dB from shot noise limited operation, but nevertheless sensitivities of −47.5 dBm (2^{15}-1 pseudorandom pattern) and −48.5 dBm (24 bit pattern) have been recorded. The penalties in the pseudorandom pattern measurement are due largely to the differential encoder employed.

V. DISCUSSION AND CONCLUSIONS

We have shown that phase diversity operation has real advantages when compared with heterodyne or either of the homodyne (CPLL or Costas loop) techniques. In particular, baseband operation without phase locking not only eases design requirements, but also means that the very severe linewidth requirements for phase-locked operation are avoided. Sensitivity is ideally equal to that of a heterodyne system and laser linewidths needed are compatible with measured line-narrowed DFB sources. DPSK, FSK, or ASK modulation can be used in the system. Baseband operation also ensures that such receivers are evolutionary in that they can use optical receivers and other modules developed for direct detection systems.

Of course, phase diversity operation has its own disadvantages. At least two channels of signal processing are required, although they are baseband and potentially realizable in integrated circuit form. Depending on whether a two or three-phase system is used, photodiode amplifier noise becomes twice or three times as significant as for a single channel system, and more LO power is needed to reach shot noise limited operation. On the other hand, the usual heterodyne receiver approach using an asymmetric coupler typically needs 10 times the expected LO power to keep signal loss to 0.5 dB.

The ideal eight-port 90° coupler is not yet available in a form which allows long term operation without a control system, but the six-port 120° coupler provides a very realistic option, losing only a further 1.8 dB of potential sensitivity. Our experimental work demonstrates that successful high bit rate phase diversity receivers can be built using such couplers, and we have demonstrated operation with both ASK and DPSK modulation. Since FSK operation should also be feasible, all proposed modulation schemes can be accommodated and the advantages of baseband signal processing are available to system designers for coherent receivers at all proposed bit rates.

ACKNOWLEDGMENT

The authors would like to thank R. E. Epworth and A. Hadjifotiou for valuable discussions, T. Bricheno for the 3 × 3 coupler, M. Grant for the phase modulator, and the Directors of STC Technology Ltd for permission to publish this article.

REFERENCES

[1] R. A. Linke, B. L. Kasper, N. A. Olsson, and R. C. Alferness, "Coherent lightwave transmission over 150-km fiber lengths at 400 Mbit/s and 1 Gbit/s data rates using phase modulation," *Electron. Lett.*, vol. 22, pp. 30–31, 1986.