Coherent optical fibre transmission systems

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Coherent optical fibre transmission systems, compared to those that use direct detection, offer increased transmission capacity and improved performance. In this paper the various coherent detection schemes, which include both homodyne and heterodyne techniques, are outlined and the performance of laboratory systems are discussed and compared with the best direct detection systems. Recently coherent optical detection has aroused interest worldwide and this work, which is still at the laboratory stage, is summarised.

1. Introduction

Currently all operational optical fibre transmission systems worldwide are of the intensity modulation/direct detection type; in other words no use is made of the coherence or spectral purity of the optical signal. However, it has been widely appreciated that coherent optical transmission, featuring either optical heterodyne or homodyne detection, could offer improvements in system performance of between 5 to 20 dB. This could lead to increased repeater separations for undersea and inland transmission systems or alternatively, it could allow the transmission capacity of long haul systems to be increased without reducing margins; for distribution networks the improved performance increases the power budget available for optical multiplexing/demultiplexing. In addition to the performance advantage the inherent selectivity of coherent systems could be used to access the vast optical bandwidth available from singlemode fibre (50,000 GHz in the low loss fibre window from 1.3—1.6 μm); one possible future application for this is wideband signal distribution.

Although the principles of coherent detection are not new — they are in fact well established at radio frequencies — there has been speculation since the development of the laser in the 1960s concerning the potential application of these techniques at optical frequencies [1,2]. However, it is only comparatively recently that coherent techniques have found application in optical fibre systems. The reasons are mainly threefold.

- The several hundred GHz wide, multimode spectrum characteristic of a conventional semiconductor laser, must be reduced to a narrow linewidth ($\leqslant$MHz) single mode spectrum. Recently this has been achieved using techniques such as external cavities [3] and injection locking [4]; for the future the DFB laser structure [5] may also satisfy this requirement.

- Research in the areas of singlemode fibre devices and lithium niobate integrated optic components has only recently produced components such as external modulators [6] and directional coupler combiners [7]; these devices have been essential for serious experimental work.

- The polarisation stability of the transmission media is an important consideration for coherent systems and early studies implied that polarisation holding fibre [8] would be necessary. However, recent polarisation measurements of conventional singlemode fibre have shown that this is not the case [9].

As a result of the advances in optical component and semiconductor laser technologies the past 3½ years has seen a period of intense experimental activity, especially in Europe and Japan, to demonstrate coherent optical fibre transmission. This paper briefly reviews the experimental work reported and discusses the potential of coherent detection, along with the constraints for present direct detection receivers. The problems associated with achieving close to ideal performance with coherent detection are also considered and recent British Telecom Research Laboratories (BTRL) state-of-the-art laboratory experiments are described.

2. Direct detection performance

The sensitivity of an ideal direct detection receiver (ideal assumes that the electronic preamplifier following the photodetector is noiseless) is determined only by the statistical distribution of the detected

photons. For a binary ASK transmission system (considering Poisson statistics for the photocurrent) the required average number of received photons for a bit-error-rate (BER) of 10^{-9} is 21 [10]; this represents a receiver sensitivity of -63 dBm for a 1.5 μm wavelength 140 Mbit/s system. In practice it is only possible to meet this quantum limit if the detector has noiseless internal gain. Photomultipliers and silicon avalanche photodiodes come closest to achieving this but their response declines rapidly beyond 1 μm. For pin diode receivers, operating at wavelengths in the range 1.2 to 1.7 μm, the preamplifier noise dominates over the signal shot noise and more than 400 photons per bit are required in a practical 140 Mbit/s system. At higher data rates the performance of the practical direct detection receiver deviates further from the quantum limited case since the electronic preamplifier usually has a rising noise versus frequency characteristic. Therefore, coherent detection will be of most benefit for high capacity systems working at the longer wavelengths.

3. Coherent detection principles

With coherent detection the low level received optical signal (e_s), see Fig 1, is combined, prior to

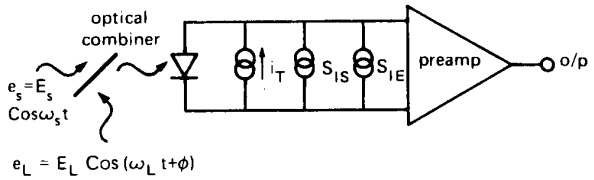


Fig 1 Basic coherent receiver model.

detection, with a second much larger optical signal (e_L) from a local oscillator laser; the angle ϕ is the phase relationship between these two fields defined at some arbitary point in time. Because of the square law photodetection process the signal photocurrent (i_T) is proportional to:

$$i_T \propto (e_s + e_L)^2 \qquad \text{.....(1)}$$

For ideal coherent detection the wavefronts of the received signal and local oscillator fields must be perfectly matched at the surface of the photodiode; to achieve this polarisation control and singlemode optical combiners are required in the receiver. Given perfect optical mixing the resulting photocurrent, from equation (1), is:

$$i_T = \frac{\eta q \lambda}{hc} \left(2\sqrt{P_s P_L}\ \cos(\omega_L t + \phi - \omega_s t) + P_s + P_L\right) \qquad \text{.....(2)}$$

where P_s is the input signal power in the absence of modulation
P_L is the local oscillator power
h is the detector quantum efficiency
h is Planck's constant
q is the electronic charge
λ is the optical wavelength
c is the velocity of light
ω_s is the signal frequency
ω_L is the local oscillator frequency
ϕ is the phase angle between the two optical fields at an arbitarily defined fixed point in time.

If the local oscillator signal is much larger than the input signal the expression for i_T can be replaced by the approximation (i_s) below:

$$i_s = \frac{\eta q \lambda}{hc} \left(2\sqrt{P_s P_L}\ \cos(\omega_L t + \phi - \omega_s t)\right) \qquad \text{.....(3)}$$

There are two types of coherent detection and they are homodyne and heterodyne. For homodyne detection ω_L and ω_s are equal and equation (3) reduces to:

$$i_s = 2\sqrt{P_s P_L}\ \frac{\eta q \lambda}{hc} \cos\phi \qquad \text{.....(4)}$$

When homodyne detection is used the output from the photodiode is a baseband signal and the local oscillator needs to be phase locked to the incoming optical signal.

For heterodyne detection ω_L and ω_s are not equal and equation (3) can be expressed as:

$$i_s = 2\sqrt{P_s P_L}\ \frac{\eta q \lambda}{hc} \cos(\omega_{IF} t + \phi) \qquad \text{.....(5)}$$

where ω_{IF} is the difference between ω_L and ω_s.

With heterodyne detection the output from the photodiode is centred about an intermediate frequency (IF) and this IF is stabilised by incorporating the local oscillator laser in an automatic frequency control loop (AFC).

From the above expressions it can be seen that the signal photocurrent is proportional to $\sqrt{P_s}$, rather than P_s as in the case of direct detection, and that it is effectively amplified by a factor proportional to $\sqrt{P_L}$. This gain factor increases the optical signal without changing the preamplifier noise term (S_{IE}) and this is the reason why coherent detection gives better receiver sensitivities than direct detection.

Figure 1 shows two receiver noise sources, S_{IS} and S_{IE}. S_{IS} is the shot noise spectral density and S_{IE} is the

equivalent current noise spectral density for the pre-amplifier. Ideally the shot noise term should be the dominant noise source and provided that the local oscillator power is large enough this condition can always be satisfied. The shot noise power in a coherent receiver is dependent on the resultant optical intensity at the surface of the photodiode, but when the local oscillator is much larger than the received signal the shot noise spectral density can be taken as being equal to that generated solely by the local oscillator. Given this condition, the double sided shot noise spectral density is:

$$S_{IS} = P_L \frac{\eta q^2 \lambda}{hc} \qquad \text{.....(6)}$$

If the previous signal terms and the above noise expression are used to derive the shot noise limited signal-to-noise ratio (SNR) the result below will be obtained:

$$\text{SNR} = \frac{\langle P_s \rangle}{KB} \frac{\eta\lambda}{hc} \qquad \text{.....(7)}$$

where K has a value determined by the modulation/demodulation combination used, (see Table 1),

B is the double sided noise bandwidth for the receiver,

$\langle P_s \rangle$ is the mean value of P_s with the modulation present.

Table 1 Table of K values to be used in the $\langle P_s \rangle$ expression for the various modulation/demodulation combinations.

	SYNC DEMOD	
MOD	HOM	HET
PSK	0.25	0.5
FSK	0.5	1.0
ASK	0.5	1.0

The performance of a digital system is usually expressed as the value of $\langle P_s \rangle$ needed to give a specific BER, 10^{-9} is a typical value used for this purpose. To derive the BER the normalised Gaussian variable Q is used [11]; this has the following relationship with equation (7):

$$Q^2 = \frac{\langle P_s \rangle}{KB} \cdot \frac{\eta\lambda}{hc} \qquad \text{.....(8)}$$

Transposing this expression for $\langle P_s \rangle$, using the following substitutions and the assumption that the equalisation used gives a raised cosine output pulse spectrum, the shot noise limited receiver sensitivity expression is as given below:

$Q = 6$, this corresponds to a BER of 10^{-9}
$h = 6.626 \times 10^{-34}$
$c = 2.998 \times 10^{8}$
$\eta = 100\%$
$\lambda = 1.5 \times 10^{-6}$
$B = 1.128/T$ where T is the bit time

$$\langle P_s \rangle = 5.4 \times 10^{-18} \cdot \frac{K}{T} \qquad \text{.....(9)}$$

4. Coherent system performance

The expression for $\langle P_s \rangle$ shows that the shot noise limited receiver sensitivity is determined by the modulation/demodulation combination used. Table 2 shows the advantage of the various combinations when compared with an ASK heterodyne system [12]. The system performance given by binary PSK is better than that given by binary ASK because optical power is not wasted in a continuous wave carrier component. Furthermore with PSK and FSK systems, for peak-power limited sources, there is an additional 3 dB of transmitter power available. M-ary transmission is also possible, either for spectral conservation (M-ary ASK, M-ary PSK) or to improve receiver sensitivity by spectral expansion (M-ary FSK). In radio there is often pressure to achieve the former whereas the rationale in optical systems may lean to the latter and for some applications the use of M-ary FSK to improve sensitivity could have merit.

Of the demodulation schemes synchronous detection gives the best performance but is more demanding on laser linewidth requirements than the non-synchronous schemes. Homodyne detection by definition is a synchronous detection scheme but heterodyne detection can employ either synchronous or non-synchronous IF demodulation schemes. Any variants of homodyne detection where the local oscillator laser is not phase locked to the incoming signal should be considered as a form of heterodyne detection, an example of which is multiport detection [13,14].

Table 2 Performance advantage of the various modulation/demodulation schemes referenced to the performance of an ASK heterodyne receiver.

Synchronous demodulation	Modulation	Improvement on ASK HET (dB)
Homodyne	ASK	3
	PSK	6
Heterodyne	FSK	0
	PSK	3
	DPSK	2

5. Comparison of direct and coherent detection performance

In Fig 2, the performance of ideal coherent detection is compared with the best practical PINFET and APD direct detection receivers over a range of bit-rates. In this comparison it should be noted that because the best low noise preamplifier designs have a rising noise versus frequency characteristic, the performance of the direct detection receiver degrades by 4.5 dB for each doubling in bit rate; whereas for ideal coherent detection it is only 3 dB. In practice the improvements in sensitivity from using coherent detection may not, ultimately, be so large because improvements in direct detection receivers are still possible and perfect coherent detection may not always be achievable.

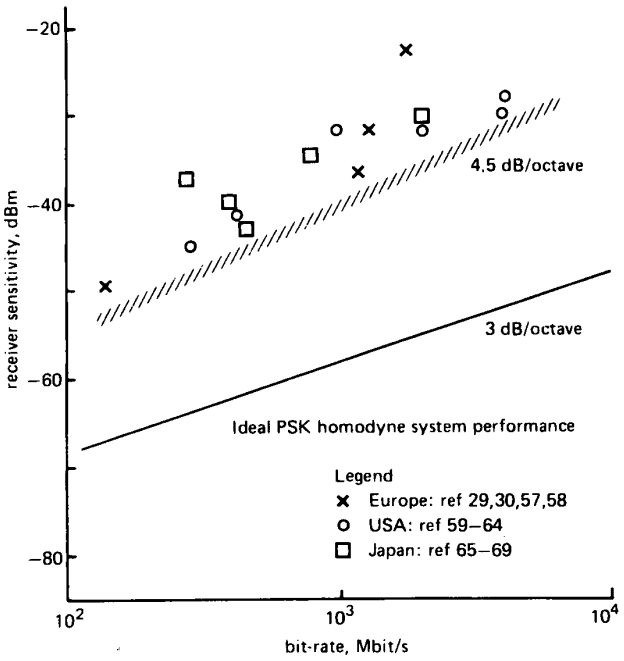


Fig 2 Performance comparison of ideal PSK homodyne with practical direct detection at a wavelength of 1.5 μm.

6. Practical coherent system constraints

6.1 *Effects of laser phase noise*

The significance of laser phase noise on system performance will depend on the modulation and demodulation scheme used, with homodyne detection and synchronous IF demodulation placing the greatest demands on laser phase stability. To meet the phase stability required for synchronous detection, the local oscillator laser must be phase locked to the incoming signal for homodyne detection; for heterodyne detection the electrical oscillator in the IF demodulator must be phased locked to the IF. Table 3 compares the laser linewidth requirements for the various modulation/demodulation schemes and indicates which laser sources meet these requirements at present.

Table 3 Coherent system linewidth requirements.

Modulation	Demodulation		Linewidth to bit rate ratio	Suitable lasers
	HET	HOM		
ASK, FSK, PSK	SYNC	YES	<0.1% [39]	Gas and Ext Cav
DPSK	DELAY	NO	<0.3% [40]	Gas and Ext Cav
ASK, FSK	NON-SYNC	NO	<20% [41,42]	Gas, Ext Cav and DFB

With PSK transmission, since the carrier is normally suppressed, it is necessary to either transmit a low level pilot carrier or locally generate a carrier from the modulation sidebands by either a squaring circuit or Costas loop [15]. To achieve a given BER target without incurring a significant power penalty it is necessary to limit the maximum phase error between the recovered carrier and the signal to be demodulated. Clearly the bandwidth of the phase lock loop, irrespective of whether it is optical or electrical, must be sufficiently broad to track the phase noise (linewidth) of the beat spectrum generated by combining the transmitter and local oscillator signals. However, if the tracking circuit is made excessivily wideband the additional phase noise associated with the quantum phase fluctuations of the local oscillator shot noise will dominate. Clearly, for a given required performance there is a maximum laser linewidth which can be tolerated by this scheme. Similar constraints also apply for synchronous demodulation of ASK and FSK modulation, but for these two cases the received carrier component is much larger.

Non-synchronous demodulation can, in principle, be made insensitive to phase noise by ensuring that the IF bandwidth of the heterodyne receiver is large enough. However, practical constraints restrict the maximum bandwidth that can be used; as the bandwidth is increased the extra shot noise power reduces the signal-to-noise ratio at the input to the demodulator and at some threshold value the demodulation process can no longer be assumed to be linear. If the bandwidth is increased beyond this point the system performance is rapidly degraded.

For ASK modulation, square-law or envelope detection are the demodulation choices; they can also be used with FSK modulation provided that a bandpass filter and associated IF demodulator are used to detect each of the transmitted frequencies. Alternatively, a limiter-discriminator can be used to demodulate an FSK signal but the conversion of phase noise to amplitude noise limits its applications.

6.2 *Limited local oscillator power*

In practice the amount of local oscillator power incident on the photodetector may be insufficient to achieve shot noise limited detection. Apart from the power available from the laser being limited this situation may arise as a result of other receiver design considerations.

- To ensure there is low loss in the signal path it is often necessary to use a combiner with a low coupling coefficient; this results in a high loss in the local oscillator path. With a coupling ratio of 10:1 the losses are 0.5 and 10 dB for the signal and local oscillator paths respectively.

- If excess intensity noise [16] is present at the output of the local oscillator better performance can be achieved by attenuating the output of the local oscillator laser. In the presence of local oscillator excess intensity noise, optimum performance is achieved by operating the laser at a high output power to reduce it's excess noise factor (χ), then attenuating it's output by employing a combiner with a low coupling ratio (α) (see Fig 3). An alternative approach is to use a balanced receiver [17].

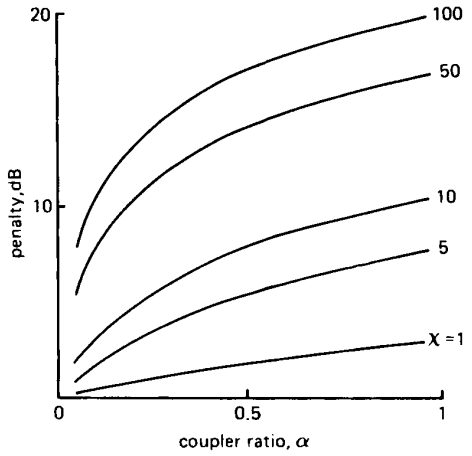


Fig 3 System penalty as a function of the parameters χ and α.

NB The above curves assume that the local oscillator power incident on the photodiode is large enough to give shot noise limited performance irrespective of the value of α.

When the local oscillator power is limited, irrespective of the reason for this, a low noise preamplifier is a significant asset if performances close to the shot noise limit are to be achieved. This is illustrated by Fig 4 which shows, theoretically, that the performance of a coherent system will be within 1 dB of the shot noise limit if the local oscillator shot noise spectral density (S_{IS}) is at least four times larger than the equivalent current noise spectral density (S_{IE}) of the receiver [12]. The curves in Fig 4 are slightly dependent on the value of S_{IE} so they were derived using a value of 10^{-26}; this value is typical for a PINFET preamplifier designed for operation at 140 Mbit/s. If this type of preamplifier is used in a 140 Mbit/s homodyne receiver 1 μW of local oscillator power will give a performance within 1 dB of the shot noise limit.

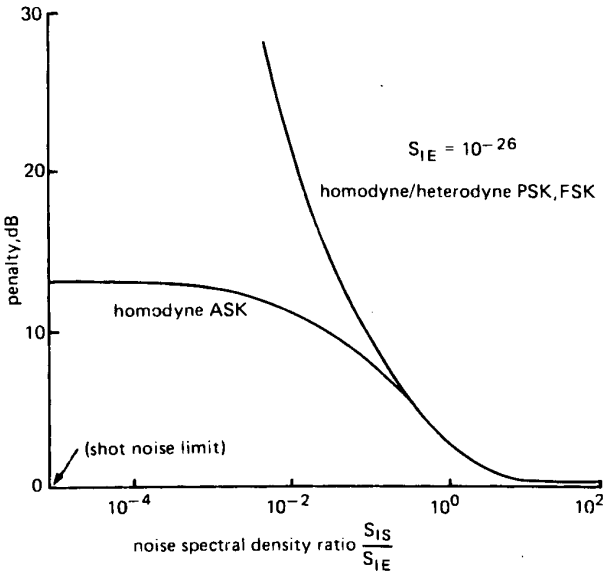


Fig 4 Effect of preamplifier noise on system performance when the shot noise is not dominant.

6.3 *Polarisation penalty*

With heterodyne or homodyne detection the polarisation states of the local oscillator and input signal must be well matched for efficient mixing otherwise larger performance penalties can be incurred. These penalties, along with possible polarisation control techniques, have been reported in detail in an earlier publication [9].

7. Coherent optical communication experiments

Coherent optical communication is now being given serious consideration by numerous research laboratories worldwide and work published during the period 1981 to 1983 [18], along with that reported up until the present time [19], is summarised in Table 4. Recent publications include: heterodyne systems using external cavity semiconductor lasers and/or DFB lasers at both the transmitter and receiver [20,21,22]; heterodyne detection used in conjunction with optical frequency division multiplexing [23,24]; the feasibility of optical phase locked loops [25,26,27]; and the use of multiport detection [13,14], as an alternative to homodyne phase lock loop detection. To illustrate some of the differences between the different types of system the following four sections describe some of the most recent BTRL 1.5 μm coherent system experiments [20,21,23,25].

Table 4 Summary of recently reported coherent detection experiments that quote BER measurements.

Research Labs	MOD/DEMOD Combination	Wavelength μm	Transmission path	Year
BTRL UK	HET: ASK [55], FSK [20,21], PSK/DPSK [23,56] HOM: ASK [54], PSK [6,25]	1.5	Operated over distances up to 200 km	1982—85
STL (UK)	Multiport: ASK [14]	1.5	Transmission distance <1 km	1985
CNET (France)	HET: DPSK [46]	0.8	3.9 km of fibre used	1982
HHI* (W Germany)	HET: FM/PM [24,51]	0.8	Transmission distance <1 km	1983—85
TUW (Austria)	HOM: PSK [53]	10.6	Line-of-sight system	1984
UNIV Tokyo (Japan)	HET: ASK [44,45],PSK [43]	0.8	Transmission distance <1 km	1981—83
NEC (Japan)	HET: ASK [49], FSK [22], DSPK [50]	1.3/1.5	Operated over distances up to 105 km	1983—84
NTT (Japan)	HET: FSK [47,48]	0.8	Transmission distance <1 km	1982—83

*This experiment used polarisation holding fibre; all of the others used conventional non-polarisation holding single mode fibre.

8. Homodyne system experiment using gas lasers

The experimental arrangement for this system is shown in Fig 5. The output from the transmitter laser was modulated at a data rate of 140 Mbit/s by an external $LiNbO_3$ phase modulator [6]; the polarisation required at the input to the phase modulator was set by the manual fibre polarisation controller [28]. To satisfy the beat linewidth to bit rate ratio requirement HeNe gas lasers were used at both the transmitter and receiver. The modulated signal was transmitted over 30 km of conventional monomode fibre prior to being combined with the local oscillator signal in the 1:1 fused fibre coupler [7] at the receiver. To align the polarisation of the local oscillator with that of the received signal a manual fibre polarisation controller was inserted in the local oscillator path. A balanced receiver [17], constructed from two standard direct detection type PINFET receiver modules [29], was used to detect the signal at each output port of the coupler. With homodyne detection any phase variations on the received optical carrier need to be tracked so the local oscillator laser is incorporated in an optical phase lock loop. The balanced receiver design ensures that the phase lock loop is insensitive to intensity fluctuations, especially those associated with the local oscillator. The phase lock loop design used in this experiment maintains a 90° phase difference between the received carrier and local oscillator fields. When the phase difference between these two fields is 90° the two outputs from the balanced receiver are equal, but if the phase difference changes from 90° one output from the balanced receiver increases and the other decreases. These level variations cause the output from the comparator to vary and this controls the frequency of the local oscillator laser to bring it back into phase quadrature with the received signal. To control the frequency of the local oscillator a PZT mount was used for one of the laser mirrors. To generate the carrier component needed for the control loop, the level of the modulation signal was set to give less than 180° peak to peak phase deviation; in this particular experiment the deviation was 170°. To avoid the need for a carrier component other techniques such as the Costas loop [15] can be considered.

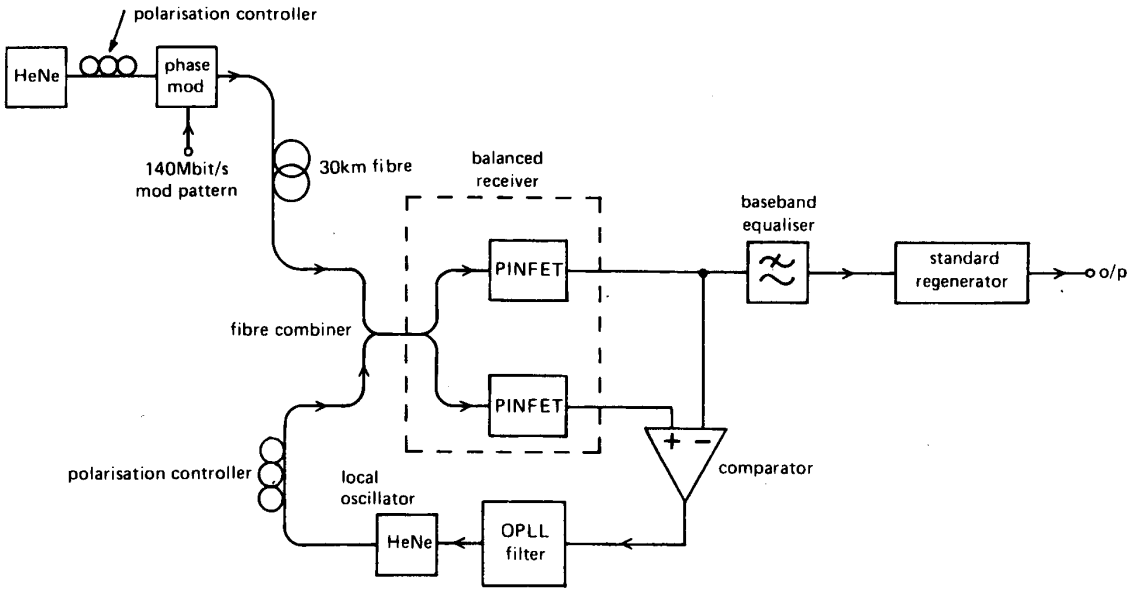


Fig 5 140 Mbit/s PSK homodyne system experiment.

Figure 6 shows both the theoretical (A) and measured (●) BER versus mean received signal power incident on the photodiode; the discrepency between these two curves is attributed to limited local oscillator power, modulation pattern length and phase noise [6,25]. The measured result also shows further degradation at higher receive powers due to the onset of error rate saturation; this was caused by the limited bandwidth of the local oscillator PZT mirror mount in conjunction with the microphony-induced phase noise caused by laser mirror vibration. Despite this saturation effect the measured performance is still 7 dB more sensitive than that achieved with the best direct detection systems [30]; 14 dB is the best improvement measured so far but this was for a self homodyne system experiment [6]. To overcome the phase lock loop bandwidth limitation experienced in this experiment, the possibility of controlling the frequency of an external cavity semiconductor laser with an intracavity electro-optic device, is at present being studied. Recently a local oscillator laser of this type has been successfully phase locked to a HeNe laser but the homodyne system performance that can be achieved is yet to be assessed.

The advantages of using homodyne detection, compared to heterodyne detection, are that it gives a better receiver sensitivity and requires less receiver bandwidth, which is a significant advantage of homodyne detection especially at Gbit/s data rates. At present, however, these advantages are offset by the need for an optical phase lock loop. Multiport detection [13,14], a technique that detects the in-phase and quadrature components of the received signal, removes the need for an optical phase lock loop without increasing the receiver bandwidth requirement; however the choice of modulation is restricted and, at best, the performance is only equivalent to that of heterodyne detection.

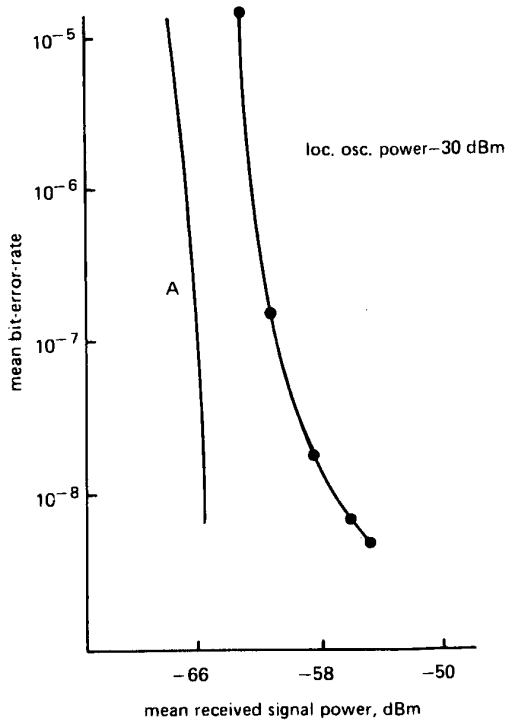


Fig 6 140 Mbit/s PSK homodyne system performance.

9. Heterodyne system experiment using external cavity lasers

The experimental arrangement for a 140 Mbit/s FSK system is shown in Fig 7. The significant differences between this and the previous homodyne experiment are that long external cavity semiconductor lasers [3] were used, there is no need for an optical phase lock loop, and the FSK modulation was obtained by directly current modulating the transmitting laser. The unwanted amplitude modulation produced by direct modulation was minimised by biasing the transmitter

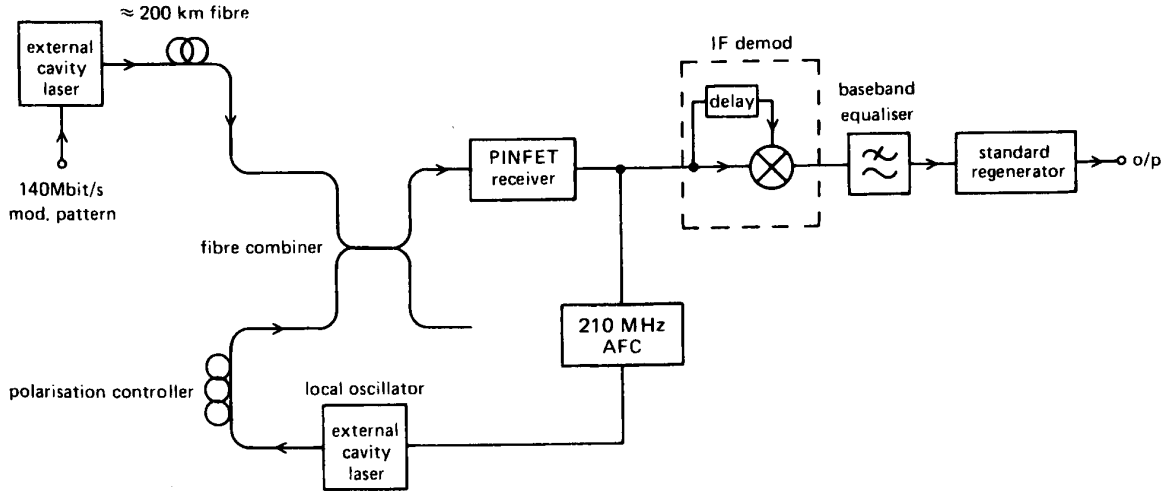


Fig 7 140 Mbit/s FSK heterodyne system experiment.

laser well above threshold at a current where the output power began to saturate. The residual amplitude modulation depth with 32 mA peak to peak modulation current was 20%; the associated frequency deviation was 84 MHz. The output from the transmitter was coupled directly into the transmission fibre which was conventional non-polarisation holding monomode fibre [9]. At the receiver the received signal was combined with the local oscillator in a 10:1 fused fibre coupler. Only one output port from the coupler is used and this was connected to a standard direct detection type PINFET receiver [29]. The output from the PINFET receiver was bandpass filtered and then demodulated using a delay line discriminator. The baseband signal from the discriminator was filtered and regenerated as in the homodyne experiment. To maintain a stable 210 MHz IF the local oscillator laser, which could be tuned electromechanically, was incorporated in an AFC loop.

The measured BER for fibre path lengths of 10 km (□), 186 km (X) and 199.7 km (○) are shown in Fig 8 for a 2^4-1 PRBS modulation pattern; the second 186 km result (△) is for a $2^{10}-1$ PRBS modulation pattern.

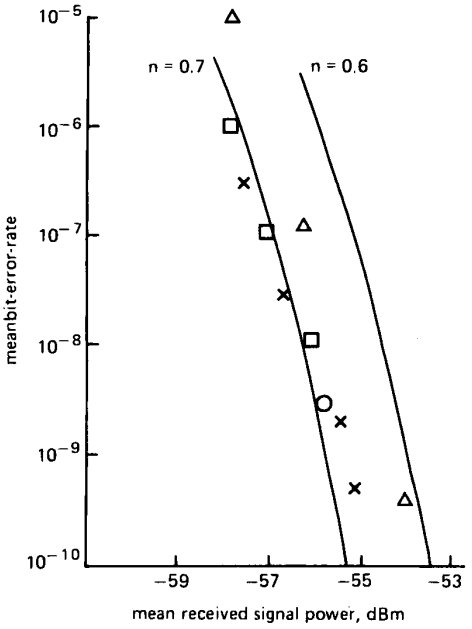


Fig 8 140 Mbit/s FSK heterodyne system performance.

The solid curves in Fig 8 are the theoretical plots for frequency deviations to bit rate ratios (h) of 0.7 and 0.6. It can be seen from the plotted results that the system performance was unaffected by the length of the transmission path but it was affected by the length of the modulation pattern; changing the pattern length from 2^4-1 to $2^{10}-1$ degraded the system performance by 1.2 dB. The performance of this system, when using the short modulation pattern, is 6 dB better than has been achieved by direct detection systems [30]; also it is only 1 dB worse, at a BER of 10^{-8}, than the previous homodyne system result. Table 5 summarises the loss budget for this experimental system.

Table 5 System budget for the 140 Mbit/s FSK heterodyne system.

Transmit power	−2.5 dBm
Fibre loss (199.7 km)	45.5 dB
Joint loss	4.0 dB
Signal loss through coupler	1.0 dB
Receiver sensitivity (10^{-9} BER)	−56 dBm
System margin	2.3 dB

The best binary heterodyne system performance is given by PSK modulation, but when FSK modulation is used the transmit laser can be directly modulated; this avoids the insertion loss of the external modulator needed for PSK systems. However, if the appropriate IF demodulation is used in conjunction with MSK modulation [31] (i.e. FSK modulation with a frequency deviation equal to half the bit rate), a performance similar to that given by PSK modulation should be possible. A further advantage of narrow deviation FSK modulation is its compact IF spectrum (see Fig 9); this could be of significant importance for Gbit/s heterodyne systems where receiver bandwidth is at a premium. The main limitation of the external cavity semiconductor laser transmitter is that the external cavity length limits both the FSK frequency deviation and bit-rate. Apart from this they are, at present, relatively complex devices and the possibility of replacing them with DFB lasers has been considered [21,22]. The advantages of the DFB laser are that it is a compact device capable of being directly modulated, but it has the disadvantages of having a relatively broad spectral linewidth along with a non-linear modulation characteristic. The non-linear modulation problem can be overcome using techniques already reported [22,32,33] and to overcome the linwidth problem non-synchronous IF demodulation must be used, but at the expense of system performance.

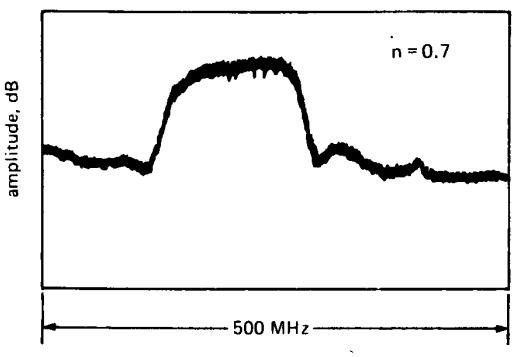


Fig 9 Measured IF spectrum for 140 Mbit/s narrow deviation FSK.

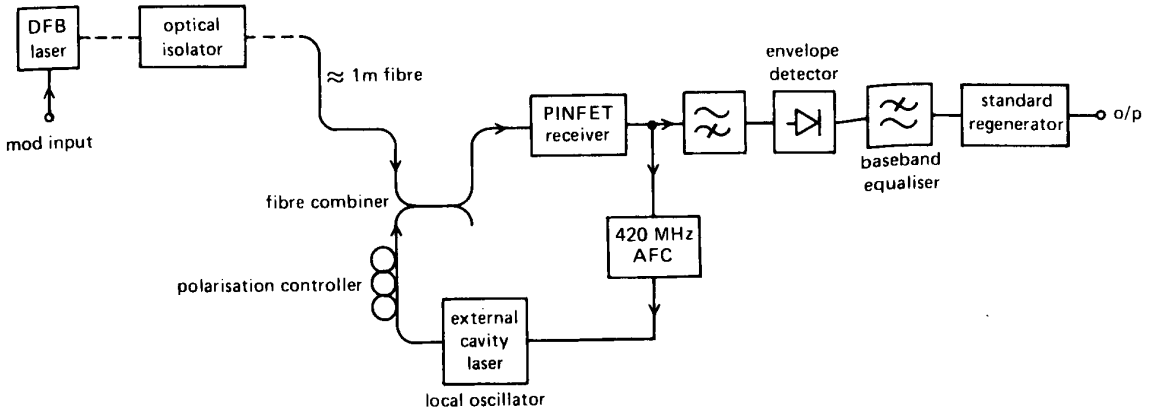


Fig 10 140 Mbit/s FSK heterodyne system experiment using a DFB laser transmitter.

10. Heterodyne system experiment using a DFB laser transmitter

To assess the effect of laser linewidth on system performance the experimental arrangement shown in Fig 10 was used. The transmitter laser, a 1.5 μm ridge waveguide distributed feedback laser diode [5], was biased above threshold and the current was adjusted to give either a 30 MHz or a 60 MHz FWHM linewidth. FSK modulation of the DFB laser was achieved by directly modulating the bias current; a modulation current of 1 mA was used and this gave a FSK frequency deviation of 1.4 GHz. Due to the sensitivity of the DFB laser to optical reflections more than 40 dB of optical isolation was needed at the laser output. The local oscillator laser was a 10 kHz linewidth tunable external cavity semiconductor laser and this gave 20 μW of power at the photodiode. The highpass filter, PINFET receiver combination gave an IF bandwidth of 300 MHz centred about 420 MHz. Due to limited receiver bandwidth it was necessary to use single filter detection in this experiment; this technique degrades the system performance by 3 dB because half of the received signal is ignored. When using single filter detection the IF spectrum is equivalent to that for ASK modulation and this is why envelope detection can be used to demodulate the IF. The envelope detector used consisted of a half wave rectifier followed by a lowpass 100 or 50 MHz bandwidth filter. The baseband signal at the output of the IF demodulator was then regenerated as in the previous experiments. The AFC loop was identical to that used in the previous experiments except that it maintained the IF constant at 420 MHz instead of 210 MHz.

Figure 11 shows the measured BER versus mean received signal power for 140 and 70 Mbit/s modulation rates and different IF linewidths. The onset of error rate saturation has degraded the 60 MHz linewidth result and as yet the reason for this is not fully understood. The remaining bit error rate curve is the 30 MHz IF linewidth, 70 Mbit/s result. Due to insufficient local oscillator power the measured performances should only be 2 dB worse than the theory lines; the remaining 5 dB is attributed to the combined effects introduced by the value of the bit rate to IF, IF linewidth to IF and IF bandwidth to bit rate ratios. However, most of the penalty is thought to be associated with the first ratio.

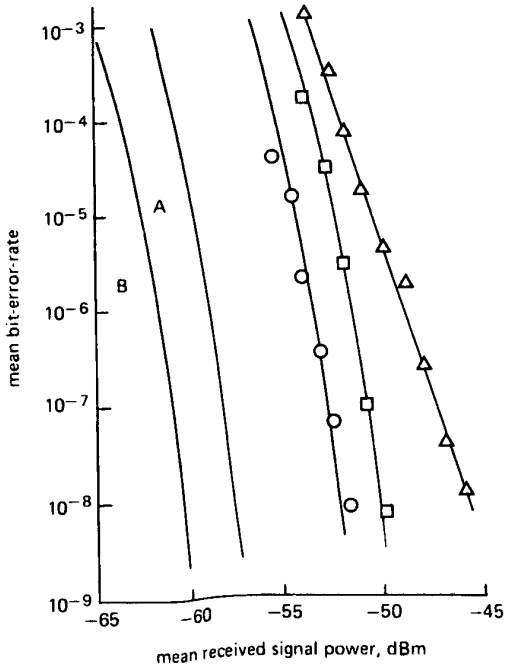


Fig 11 140 Mbit/s FSK heterodyne system performance with a DFB laser transmitter.

Theory: 140 Mbit/s (A); 70 Mbit/s (B)

Measured: 30 MHz linewidth
140 Mbit/s (□); 70 Mbit/s (○)
60 MHz linewidth
140 Mbit/s (△)

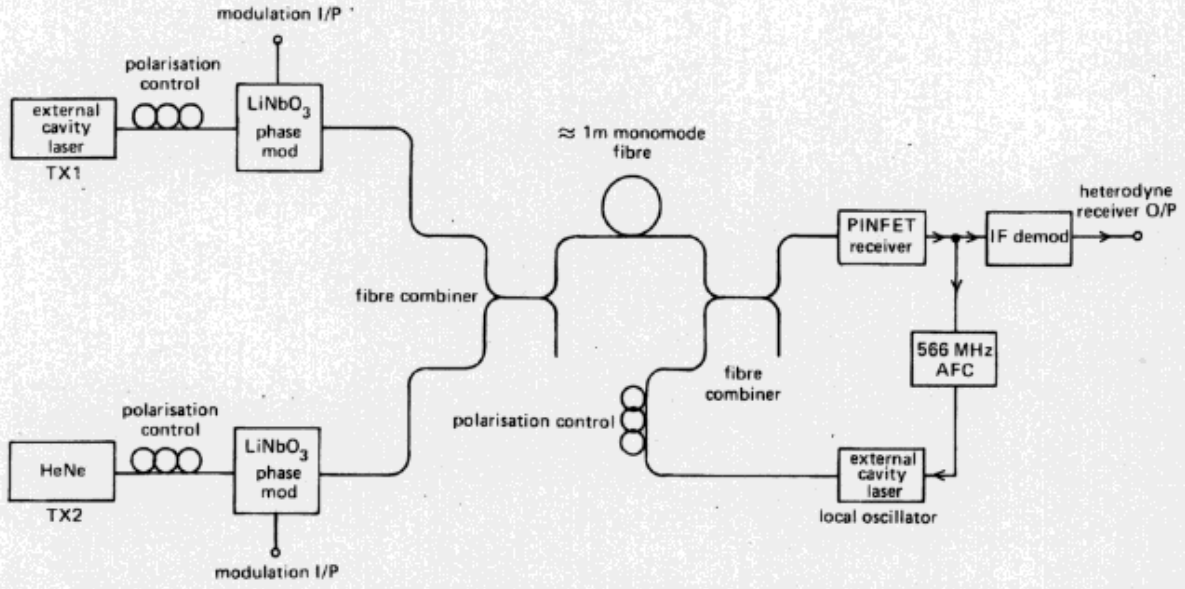


Fig 12 Experimental 2-channel frequency multiplexed transmission system.

Penalties associated with the non-linear modulation characteristic of the DFB laser were minimised by using a $2^3 - 1$ PRBS modulation pattern; had this effect been significant the demodulated waveforms would have exhibited noticeable patterning effects.

Even though the measured performances for this experiment are no better than can be achieved by good direct detection systems [30] they do have the potential of giving a 7 dB improvement. Most of the performance degradation observed is thought to be due to the envelope detector being sensitive to phase noise; a condition that does not exist with ideal envelope detection. Further practical improvements should be possible when receiver bandwidths large enough for dual filter detection become available.

Now that coherent optical systems have been shown to be feasible future research will be concerned with applications such as multi-Gbit/s long span unrepeatered systems, local area networks and frequency multiplexing. Some preliminary frequency multiplexing experiments have already been carried out at BTRL [23] and these are dealt with in the following section.

11. Frequency multiplexed coherent system experiment

Using early research components the possibility of utilising heterodyne detection in conjunction with optical FDM transmission has been demonstrated using the experimental arrangement shown in Fig 12. Transmitter Tx 1 was a packaged external cavity semiconductor laser [34] and Tx 2 was a HeNe laser; both transmitters were modulated by external $LiNbO_3$ phase modulators. Subsequent to modulation the two optical channels were combined in a fused fibre coupler which had one of its outputs connected to the heterodyne receiver by a short length of conventional non-polarisation holding fibre. At the receiver the local oscillator was a packaged external cavity semiconductor laser, the IF was 566 MHz, and synchronous IF demodulation was used. A modulation depth smaller than ± 90° was used so that there was a carrier component present in the IF spectrum; this was extracted using a bandpass filter and then used as the phase reference for the synchronous IF demodulator. A 60 MHz sub-carrier PFM [35] was used for transmitting video over the link because the lack of modulation components in the vicinity of the IF allowed the design requirements for the IF extraction filter to be relaxed. This is illustrated by Fig 13 which shows the structure of the IF spectrum when using this type of modulation in conjunction with PSK modulation of the transmitter.

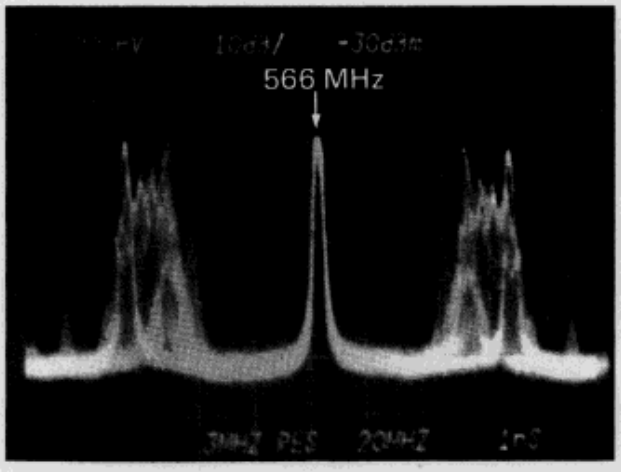


Fig 13 Intermediate frequency spectrum when using a PFM system modulated by baseband video.

To demonstrate the tunability of the receiver the optical frequency of Tx 1 was adjusted to be approximately 0.01 nm away from Tx 2, this gives a separation of 1 GHz between the two optical carriers. By tuning the local oscillator in the receiver to be 566 MHz away from Tx 1, channel 1 was selected, demodulated and a colour picture displayed on a video monitor; stable operation was achieved and the AFC loop maintained the IF frequency at 566 MHz. Next, the AFC loop was temporarily disconnected and the local oscillator tuning was adjusted to be 566 MHz away from Tx 2. The second channel now appeared on the video monitor and stable operation was achieved with the AFC loop again maintaining the intermediate frequency at 566 MHz.

This two channel experiment has shown that stable demodulation of one PFM video channel spaced just 1 GHz away from an adjacent channel is possible. One channel of this system was operated for 12 hours a day over a period of a week and after resetting the control loops each morning the system operated throughout the rest of the day without any need for further adjustment. The stable operation observed from this system is a direct result of the packaged lasers having a better frequency stability [36] than early laboratory versions of the external cavity semiconductor laser.

To assess inter-channel interference the transmitters were modulated by two independent 70 Mbit/s PRBS to give a DPSK signal, and a DPSK IF demodulator was used in place of the previous one. Figure 14 shows these two channels at the output of the PINFET receiver. The receiver was tuned to channel 2 and the BER was monitored as the channel spacing was varied; this was achieved by altering the frequency of Tx 1. Figure 15 shows the measured BER degradation as a function of channel separation.

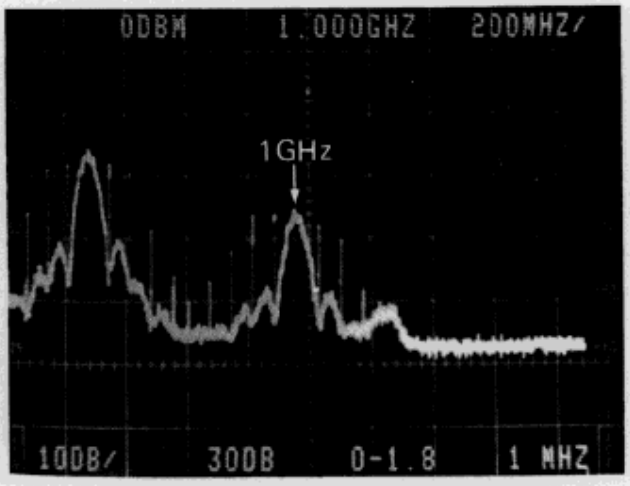


Fig 14 Simultaneous detection of two frequency multiplexed 70 Mbit/s phase modulated channels.

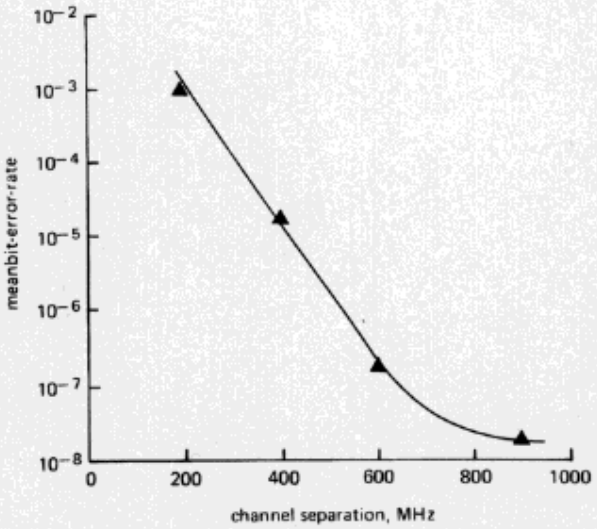


Fig 15 Effect of channel separation on BER.

For multi-channel transmission, the channel spacings should be large enough to place intermodulation products and image band signals outside the receiver bandwidth; recent theoretical work [37] has reported that the minimum spacing should not be less than $5 \times$ BW (BW is the bandwidth of the modulated carrier [37]. However, for some specific cases, provided the local oscillator output is placed in the optimum position channel spacings as small as $3 \times$ BW should be possible; further experimentation is needed to verify this. Transmission of frequency multiplexed channels over long fibre lengths is still to be demonstrated and an area that needs further study is the variation in the received states of polarisation for the different channels. In addition if a large number of optical channels are to be combined for transmission over a single fibre the effect of fibre non-linearities will need to be considered of which Raman crosstalk [38] could be one of the more troublesome.

12. Conclusion

The predicted benefits of coherent optical detection, in terms of improved receiver sensitivity, have been verified in preliminary 140 Mbit/s systems experiments at a wavelength of 1.5 μm. It is expected that the concepts used in these experiments can be extended to Gbit/s operation provided that suitable receiver designs are available. To develop coherent transmission systems for field deployment a key area that will require further attention is line narrowed lasers and at present there are two main lines of approach: the external cavity laser and the DFB laser. For the time being the former approach is offering the best initial gains in terms of system performance but the more compact DFB laser could prove attractive in the longer term.

Interest is now increasing in the application of coherent transmission in future wideband optical networks; this is an application that would make particular use of the wavelength selectivity of coherent transmission. The basic principle of using wavelength multiplexing and coherent detection was demonstrated in the 2 channel experiment. The future prospects of coherent techniques in this area will depend on cost reduction, where it is hoped that the wider application of integrated optics will play a role.

The ultimate transmission capacity of a network based on coherent optical principles may be restricted to less than the potential 50,000 GHz, by the onset of channel crosstalk introduced by non-linear propagation effects; this is yet to be verified in practice. However, it is already clear that the transmission capacity is likely to be larger than achievable with any other closed transmission medium.

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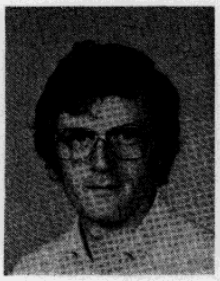
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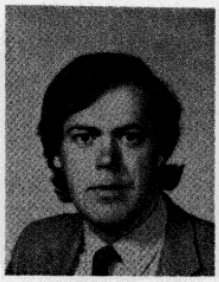
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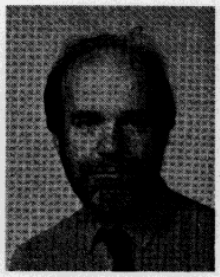
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Richard Wyatt received his BSc in Electronics from the University of Southampton in 1972, and his PhD in Quantum Electronics in 1976 from the same university. He then carried out 2 years postdoctoral research at Southampton, before moving to the Department of Laser Physics at the Max-Planck Institute for Biophysical Chemistry in 1978. He joined British Telecom in 1981 to work on coherent systems, with particular emphasis on design and construction of narrow linewidth semiconductor and gas lasers. He is currently head of novel lasers and picosecond phenomena group. He is a Member of the Institute of Physics, and a Chartered Physicist.



Derek Malyon joined British Telecom in 1965 and graduated in electrical and electronic engineering from Portsmouth Polytechnic in 1973. He joined the optical communications division in 1974 and has worked on fibre measurement techniques and long span monomode fibre systems. He is currently investigating coherent transmission techniques using homodyne detection.

FOOTNOTE:- In 1984 the authors of this article received a joint award from the Rank prize funds for their work on coherent optical transmission.