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SECOND WORKSHOP ON
OPTICAL FIBRE COMMUNICATION

(14 - 25 March 1988)

COHERENT OPTICAL TRANSMISSION

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1. INTRODUCTION

At present all commercial optical fibre transmission systems are of the intensity modulation /direct detection type. In these systems no use is made of the coherence or spectral purity of the optical signal. However, it is now widely appreciated in telecom research labs throughout the world that coherent optical transmission, featuring either optical heterodyne or homodyne detection (FIG1), could offer significant improvements in optical receiver sensitivity and selectivity(G1-G7).

The improvement in sensitivity of between 5 to 20dB, which results from photomixing gain in the coherent receiver, could lead to:-

(a). Increased repeater separations- undersea and inland
(b). Higher transmission rates over existing routes without reducing repeater separations
(c). Increased budget available for optical multiplexers/ demultiplexers in distribution networks
(d). Improved sensitivity of optical test equipment,e.g-OTDR

Furthermore, by effectivily translating electrical filter bandwidths to optical frequencies using the coherent detection process it is possible to efficiently access vast latent optical bandwidth by frequency multiplexing (S13, S28). In fact there is over 50,000GHz available in the low loss fibre window between 1.2μm and 1.6μm which could be exploited within the framework of a future coherent wideband distribution network.

Although radio systems universally use heterodyne detection the application of this technique at optical frequencies has proved elusive until recently. This is mainly because it has been necessary to reduce the broad spectrum of several hundred Ghz which is characteristic of a conventional multimode semiconductor laser to a pure mode of MHz or kHz linewidth. This demanding requirement has now been achieved by recent semiconductor laser developments including the use of external cavities (L2, L3) ,injection locking (L1), and now by DFB lasers (L4). In addition there has been a need to develop a range of singlemode optical components, including external modulators and directional coupler combiners. Finally, since coherent detection is sensitive to the state-of-polarisation (SOP) of the received optical wave there has been concern over the polarisation stability of the transmission medium itself.

This lecture will discuss the potential performance of coherent transmission systems, examine the problems in achieving close to ideal performance, describe recent laboratory experiments and finally speculate on possible applications and the developments that will necessary.

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2. BASIC PRINCIPLES

2.1 Direct detection

The sensitivity of an ideal direct detection receiver containing a noiseless electronic pre-amplifier is determined only by the statistical distribution of the detected photons. For a binary ON-OFF keyed digital transmission system (considering Poisson statistics for the photocurrent) the required average number of received photons for a 10^{-9} bit-error-rate(BER) is 21; which represents a receiver sensitivity of -63dBm for a 1.5μm wavelength 140Mbit/s system. In practice it is only possible to come close to 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 1μm; the wavelengths of interest for fibre systems. For p.i.n diode receivers operating at wavelengths between 1.2μm and 1.7μm the amplifier noise dominates over the signal shot noise and in practice about 1000 photons per bit are required.

2.2 Coherent detection

With coherent detection the low level received signal is combined with a second, much larger signal from a local oscillator laser prior to detection(FIG.2). Because of the square law photodetection process the output from the photodiode contains an electrical signal at the difference frequency between the two optical signals. In Heterodyne detection the local oscillator is at a frequency offset from the input signal and therefore the electrical spectrum from the output of the detector is centred about an intermediate frequency (I.F). With homodyne detection the local oscillator is at the same frequency as the input optical signal and the signal current from the photodiode is at baseband. The conversion gain from both these mixing processes can be used to increase the signal photocurrent above the circuit noise in the following electronic preamplifier, thus improving the sensitivity of the receiver. In the ideal case when homodyne detection and phase-shift-key (PSK) modulation is used about 10 photons per bit are required at the input to the receiver.

For ideal coherent detection the wavefronts of the received signal and local oscillator must be perfectly matched before combination. This requirement, which was of great concern in early line-of-sight systems that used macro-optic components(G8), is neatly sidestepped in fibre systems by waveguide components.

Therefore considering the case with perfect mixing (FIG2), the photocurrent is:-

$$i_T \propto [\, E_s \mathrm{Cos}\omega_s t + \phi) \; + \; E_L \mathrm{Cos}(\omega_L t) \;]^2 \quad \text{.........} (1)$$

where; E_s = signal field, E_L = local oscillator field
and ω_s = signal frequency, ω_L = local oscillator frequency

The useful peak signal photocurrent, ignoring d.c and 2ω terms and assuming the local oscillator signal is much larger than the input signal, is:-

$$i_s = 2\frac{\eta q}{hf}[\sqrt{P_s P_L}\ \mathrm{Cos}(\omega_s t + \phi - \omega_L t)] \quad \text{.........} (2)$$

where ; P_s = Input signal power
P_L = Local oscillator power
η = Detector quantum efficiency
h = Planck's constant
q = electronic charge

For Homodyne detection $\omega_L = \omega_s$; $i_s = 2\sqrt{P_s P_L}\,\frac{\eta q}{hf}\,\cos\phi$ ....(3)

For Heterodyne detection $\omega_L \neq \omega_s$; $i_s = 2\sqrt{P_s P_L}\,\frac{\eta q}{hf}\,\cos(\omega_{if}+\phi)$ ...(4)

The signal photocurrent is now proportional to the optical signal field, rather than intensity, and is effectively amplified by a factor proportional to the local oscillator field.

The combined optical power incident on the photodiode contributes to shot noise. When the local oscillator is much larger than the input signal the effective shot noise is :-

$$\bar{i}_{sh}^{2} = 2q\frac{\eta q}{hf}P_L B \qquad \text{......(5)}$$

Where B = bandwidth

The signal to noise ratio(SNR) of the coherent detection receiver is determined by both the amplifier noise and the shot noise:-

$$SNR = \frac{P_s P_L \left(\frac{\eta q}{hf}\right)^2 K}{\left(2q\frac{\eta q}{hf}P_L + \bar{i}_a^2\right)B} \qquad \text{......(6)}$$

where $\bar{i}_a^2$ = equivalent amplifier noise current and K=1 for heterodyne detection and 2 for homodyne detection.

For the case where the local oscillator power is large the SNR goes to :-

$$SNR = \frac{\eta P_s K}{hf\,2B} \qquad \text{......(7)}$$

This expression has effectively been given in terms of carrier to noise ratio. With coherent detection, phase or frequency modulation could be used instead of simple on-off keying. The final SNR at the signal decision point depends on the modulation scheme, and in the case of heterodyne detection the type of IF demodulator and baseband filter used.

The error probability(Tl) for a digital system with synchronous demodulation is given by:-

$$P_e = \frac{1}{2}\,\mathrm{erfc}\sqrt{\frac{1}{4}\frac{\eta P_s K M}{hf B}} \qquad \text{......(8)}$$

where M is a constant determined by the modulation scheme.

2.3 Modulation Choice

The use of coherent detection widens the choice of modulation that can now be considered for optical fibre transmission. For radio transmission it is well known that schemes, such as antipodal PSK ($\pm\pi/2$), which do not waste transmitter power in a large carrier component give better performance then simple on-off keying or ASK. In fact the use of PSK results in a 3dB improvement in receiver sensitivity over ASK in terms of mean received power and 6dB when peak power is considered. PSK modulation can be generated relatively easily at optical frequencies by use of the electroptic effect in waveguide devices made from either Lithium Niobate or semiconductor materials. A waveguide Lithium Niobate modulator has a typical fibre to fibre insertion loss of between 2 to 5dB and requires about 5volts drive for π phase shift. Modulation bandwidths well in excess of 10GHz are possible from travelling-wave structures.

FSK modulation is also of interest since it can readily be generated by direct modulation of laser injection current. Systems using 2FSK would usually be expected to produce inferior receiver sensitivity compared to PSK. However eliminating the external modulator reduces excess loss in the transmission path. Moreover, with FSK there is always the possibility of improving receiver sensitivity by increasing the choice of signalling frequencies. With an unlimited selection of signalling frequencies FSK would be about 7dB better than PSK and for a more realistic number, say 8FSK, sensitivity equivalent to 2PSK should be achieved- but at the expense of greater receiver bandwidth.

2.4 Performance comparison

FIG(3) compares the potential performance of ideal coherent detection receivers with the best direct detection receivers (both Pinfet and APD) over a range of bit/rates. In this comparison it should be noted that the low noise high impedance direct detection receiver has a rising frequency noise term,this results in the performance of the direct detection receiver degrading at 4.5dB for each doubling in bit rate whereas for ideal coherent detection a constant energy per bit is required,irrespective of data rate.

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.

3. PRACTICAL CONSTRAINTS

3.1 Limited local oscillator power

In a practical coherent system the theoretical performance will not be realised for several reasons. First, there may be insufficient local oscillator to achieve shot noise limited detection from a receiver with high circuit noise. This factor is highlighted by the need to ensure a low loss in the signal path by choice of a signal/local oscillator combiner with low coupling coefficient and also by the possible need to deliberately attenuate a high power local oscillator to reduce excess intensity noise (L6).

One solution to the problem of limited local oscillator power is to use a low noise photodiode /preamplifier combination, such as a PinFet hybrid, at the front-end of a coherent receiver. With this arrangement shot noise limited detection can almost be achieved using just 1μW local oscillator power at 140Mbit/s data rate (FIG4) (S1). The alternative is to use a balanced receiver (FIG5) (S26, S32, G8). In this scheme the local oscillator and input signal are combined in a 3dB directional coupler and connected to a pair of photodiodes. The two photocurrents are subtracted, which results in both the cancelling out of the large d.c term produced by the local oscillator as well as any excess local oscillator noise. Moreover, all of the local oscillator and input signal is efficiently used and therefore some of the constraints imposed by the previous need for wideband ultra-low noise preamplifiers are relaxed. However, some care is required to match the two arms of the receiver if good excess noise cancellation is wanted.

3.2 Polarisation control

With heterodyne or homodyne detection the polarisation states of the local oscillator and input signal must be well matched for efficient mixing. Unfortunately the received polarisation state after a long optical fibre transmission path cannot always be predicted because mechanical movement and temperature fluctuations of the fibre cable will alter any residual birefringence within the fibre and influence mode coupling. Therefore some concern must be given to the penalties incurred from polarisation misalignment and techniques to control polarisation.

The general expression for the performance penalty for any arbitrary input and local oscillator polarisation state is given in ref.(P5). One example, for misaligned linear polarisation states, is shown in FIG(6) for heterodyne detection. As can be seen, small fluctuations (such as might result from microphony) produce very minor penalties but larger unchecked fluctuations (such as cable strain relaxing) are catastrophic.

Ideally, to get round these problems polarisation holding fibre would be used for coherent transmission. Linear polarisation holding fibres apply strong built-in birefringence to swamp external pressure and bending induced birefringence. There have been a number of suitable designs(P1), one successful design is the bow-tie fibre (P2,P3). In this fibre, stress applying regions of Borosilicate glass are located on two opposite sides of the Silica core. However, although the performance of polarisation hol ding fibre is expected to improve, at present it has somewhat higher attenuation and higher cost than conventional fibre. Furthermore an extensive conventional singlemode fibre network is currently being installed by most major telecom administrations. Consequently it is expected that the first applications for polarisation holding fibre in coherent transmission will be for interconnecting components within equipments and not for the main transmission path itself. Conventional non-polarisation holding fibre can be considered for coherent transmission by including a polarisation control element within the receiver or by employing polarisation diversity reception.

In practice (P5) it has been found that fluctuations in polarisation state are fairly slow for cabled fibre installed in underground ducts; significant changes occuring over a cycle time measured in hours. Therefore the control element in the feedback system can also be slow acting which allows a wide choice of possible compensation techniques based on birefringent elements, including; manual and electromechanical devices based on the photoelastic effect (P6, P8), bulk electrooptic and waveguide electrooptic (P7), and the use of Faraday rotation (P9). The compensators, at least two are necessary for full control, can be placed in either the signal path or the local oscillator path although the latter is preferable if the device introduces significant signal attenuation. A present major concern is the development of polarisation control schemes which have sufficient range to cope with continuously ramping polarisation states.

The need for polarisation control can be eliminated by the use of a polarisation diversity receiver FIG(7). In this scheme the input signal is combined with a circular local oscillator signal, the composite signal is then passed through a polarising beam splitter. The two orthoganally polarised outputs are then detected on separate photodiodes and demodulated down to baseband before recombination. With this basic configuration there is the possibility of a performance degradation of 3dB for certain input polarisation states. This penalty can be reduced to less than 1dB with suitable post-demodulation processing.

3.3 The effects of laser phase noise (laser linewidth requirements)

The significance of laser phase noise on system performance will depend on the modulation and demodulation scheme used and the data transmission rate. Table(1) compares the laser linewidth requirements for a range of configurations.

Synchronous detection places greatest demands on laser phase stability. With homodyne detection the optical local oscillator must be phase locked to the transmitted signal and with heterodyne detection an electrical oscillator must be phase locked at the IF. For PSK transmission, since the carrier is normally suppressed, it is necessary to either transmit a low level pilot carrier or locally generate a phase reference from the modulation sidebands by either a squaring circuit or Costas loop. Any phase error in the reference will produce eye closure and a degradation in performance, which in the limit results in a saturation of the bit-error-rate. The reference phase error is a function of the laser linewidth, the power available for phase locking and the parameters of the phase lock loop; in fact there is an optimum phase lock loop bandwidth to minimise the phase error FIG(8). In practice, for a homodyne pilot carrier receiver operating at 140Mbit/s laser linewidths of kHz values are required. (T2, T9).

ASK modulation with heterodyne detection, featuring non-synchronous demodulation of the electrical IF (i.e envelope or square-law demodulation) is least effected by laser phase noise. Here it is only of significance because the IF bandwidth of the heterodyne receiver must be made broader to allow for laser frequency jitter expanding the IF spectrum. This increased IF bandwidth results in increased shot noise power at the input to the demodulator. This extra noise cannot be totally removed by baseband filtering following the square-law demodulator. This is because, unlike synchronous demodulation, the SNR does not transfer linearly through the demodulation process and higher order noise terms are produced. The detailed calculation of the resultant performance penalty is quite complicated, a solution is outlined in ref(T4). In general it is expected that laser linewidth values of between 10% to 40% of the modulation rate are required. FSK signals can also be demodulated non-synchronously by either a limiter-discriminator or by using separate IF filters for the mark and space channels followed by envelope detectors. For very large frequency deviations between mark and space channels the analysis is similar to ASK (this is particularly so when receiver bandwidth limitations dictate single filter detection). For narrow frequency deviation cases where both frequencies are detected it is also necessary to estimate the probability of wrong slot errors.

4. LASERS FOR COHERENT TRANSMISSION

4.1 Spectrum of semiconductor lasers

The linewidth of single mode lasers is predicted by the Schawlow-Townes relationship, which in the case of semiconductor lasers must be modified by a factor, α, (L7). α describes the coupling between fluctuations in the carrier density and refractive index. One form of the expression for the half power linewidth (assuming a Lorentzian lineshape) is:-

$$\Delta f_L = \frac{A_o hf\ (\Delta f_c)^2 \cdot (1+\alpha^2)}{P_o} \qquad \text{.........................}(9)$$

where Δf_c= 'cold cavity bandwidth' and P_o= output power and A_o is the spontaneous emission factor.

The 'cold cavity ' bandwidth is determined by the Q of the laser cavity which in the case of a Fabry-Perot laser is a function of the cavity length and the losses from the cavity (internal loss and coupling from the output mirrors). The linewidth of a single mode 0.85μm wavelength GaAlAs Fabry-Perot laser of 300μm cavity length is typically from 3 to 30MHz. The linewidth of solitary devices at 1.3 and 1.5μm wavelength is usually somewhat broader.

In practice the solitary Fabry-Perot diode laser will not be reliabily singlemode and a more complex wavelength selection mechanism is required. This can be achieved by either the use of compound cavities (C^3) or distributed feedback (DFB) and distributed Bragg reflector structures (DBR). The relationship between linewidth and output power for a 1.5μm DFB laser is presented in FIG(9)(L12). Although the linewidth so far achieved from DFB lasers is satisfactory for the non-synchronous demodulation schemes, such as ASK and FSK, considerable improvements are necessary before they can be considered for PSK.

4.2 Reduction of laser linewidth

For experiments using phase modulation a considerable linewidth reduction has proved necessary. In early system demonstrations this was achieved by injection locking a diode laser to a narrowline reference source. Sub-MHz linewidths have been obtained in practice by coupling a small amount of light (0.75μW) from a 1.52μm HeNe laser into a InGaAsP diode laser (L1).

For field installation the use of a gas laser may be considered undesirable and an all-semiconductor solution is to be prefered. An alternative method of reducing the linewidth of a semiconductor laser is to increase the 'Q' of the cavity, as implied in equation 9. For the Fabry-Perot laser this can be achieved by increasing the effective length of the resonator. An extended cavity can be achieved by reflecting the collimated output beam, after some distance, back on itself with either a plane mirror or a diffraction grating (the latter is better as it both helps to ensure the laser oscillates in single cavity mode and makes the laser tunable) (L2,L3)(FIG10). In fact a cavity of about 10cm can reduce the linewidth sufficiently that the dominant phase noise is no longer quantum limited but determined by mechanical vibration to the cavity. In practice kHz linewidths have been measured over millisecond intervals but measurements over longer periods have shown LF jitter with MHz deviations. In principle this LF jitter can be tracked out by the receivers electronic AFC loop.

Although at present the airpath external cavity laser has been the most useful technique for linewidth reduction it is, never the less, a fairly complex construction. It is possible that more compact solutions will result from composite cavity lasers featuring either fibre waveguide or planar waveguide cavities (S39, L5). It is also anticipated that a combination of improvements to DFB/DBR lasers and a trend towards higher data rates, where linewidth requirements are proportionally not so severe, will ultimately enable single chip lasers to be used for PSK transmission.

5. EXPERIMENTAL SYSTEMS

5.1 Heterodyne systems using DFB lasers

The most straightforward heterodyne systems are those using single frequency DFB or DBR lasers with ASK or FSK modulation and non-synchronous IF demodulation. Large deviation FSK is particularly attractive to use with DFB lasers because it can be produced by direct modulation of the laser injection current, typically by between 100MHz to 2GHz per mA. The sensitivity of the spectral characteristics of DFB lasers to optical reflections are particular problems and it is essential to include non-reciprocal isolation between the transmitter laser and the transmission path and between the local oscillator and the photodetector. At present this requirement can only be achieved using discrete magnetooptic devices and sometimes it has proved necessary to use two isolators in tandem for satisfactory operation.

Experimental transmission systems using DFB lasers have now been reported from a number of laboratories (S7, S19, S21, S25). The performance of these systems in terms of receiver sensitivity is either just equivalent or slightly better than the best direct detection results. Some of the present problems include: reflection induced noise, non-linear direct FM characteristics of DFB lasers, imperfect demodulation resulting from a low IF to bit-rate ratio, low bit-rate to laser linewidth ratio, excess intensity noise and the use of single rather than dual filter detection. Consequently it is expected that these systems will improve as lasers are improved and receiver bandwidths increased to enable gigabit operation.

5.2 Heterodyne experiments using external cavity lasers

FIG(11) shows an experimental PSK system using a Lithium Niobate phase modulator and external cavity lasers for both the transmitter and local oscillator laser. After the fibre transmission path the received signal and local oscillator are combined in a fused fibre directional coupler. The combined signal is detected using a PINFET module. Manual polarisation control and automatic control of the laser local oscillator frequency is used. To demodulate the PSK signal synchronously, it is necessary to have a carrier recovery circuit within the receiver, or alternatively DPSK transmission can be considered, which requires a simpler delay demodulator. Experiments using synchronous demodulation have achieved a performance of -59dBm at 140Mbit/s (S4) and a performance of -52dBm has been reported at 400Mbit/s with an experiment featuring a balanced receiver(S26).

5.3 Homodyne detection

Homodyne detection offers 3dB better receiver sensitivity and baseband receiver bandwidths. The latter is particularly important for future multigigabit systems, for although heterodyne detection has been demonstrated at 1Gbit/s (S26) its comparative performance with lower bit-rate measurements (on a photons per bit basis) is significantly inferior. However, homodyne reception requires a local oscillator laser which is phase locked to the incomming signal. Because of the difficulties of optically phase locking a remote local oscillator laser to a weak input signal most of the initial optical fibre homodyne experiments have featured a common laser to generate both the transmitter signal and the local oscillator. Using this simple arrangement receiver sensitivites within 2dB of the quantum limit have been reported for a 1010 word and 4dB away for a PRBS (S3). But for a laboratory demonstration of homodyne detection over a long fibre link this approach is unsatisfactory and it has been necessary to develop an optical phase lock loop (S8, S9, S33, S34, S35).

FIG(12) shows a recent realisation of an optical homodyne receiver using an external cavity laser incorporating an electrooptic modulator. If we assume the loop is initially locked the operation is as follows:-

The 3dB directional coupler and balanced detectors is used to measure the phase difference between the optical carrier and the local oscillator ($\Delta\phi$). The output of the difference amplifier is proportional to Sin$\Delta\phi$ (or just $\Delta\phi$ for small angles) and is coupled, via a loop filter, to the phase modulator located within the laser cavity. Variation of the voltage applied to the modulator controls the effective laser cavity length and hence its frequency to maintain phase lock. In this form the optical phase lock loop is directly analogous to the classical second order electronic phase lock loop. This type of homodyne receiver requires a c.w carrier component in quadrature phase to the local oscillator signal. Since with ideal ($\mp\pi/2$) PSK the carrier is suppressed, it is necessary instead to use a slightly reduced depth of phase modulation to ensure a suitable residual pilot carrier with the correct phase relationship. In practice it has been possible to achieve phase locking with pilot carrier powers as low as 100pW (S8). The need for a low level pilot carrier along with d.c coupling within the receiver, and associated drift problems, is avoided in the Costas loop receiver (T3, S34).

5.4 Multiport detection

Baseband coherent detection without the need for optical phase locked loops is possible by the application of multiport detection. This technique, used in microwave engineering and recently applied to optics (S37,S38, S11), features a local oscillator operating at a frequency close to the signal carrier but not phase locked to it. The local oscillator is combined with the input signal in various phase combinations within a multiport network to achieve phase diversity. Schemes have been demonstrated using either 3X3 fibre couplers (S38) or 90 degree optical hybrids based on polarisation selective elements (S11). However, although the multiport receiver requires only baseband bandwidth its performance at best is only comparable to normal heterodyne detection. Moreover, the overall complexity is higher and the performance, in the 90degree optical hybrid case, rather more sensitive to polarisation fluctuations.

5.5 Homodyne detection using Brillouin carrier amplification

Very recently a new detection scheme has been proposed which although a form of homodyne detection does not require local oscillator laser phase locking and furthermore could be polarisation insensitive (S10). The principle is based on selective amplification of a residual carrier component using the narrowband Brillouin gain process (15MHz at 1.5µm wavelength in silica fibre). The composite signal containing both the amplified carrier, which now becomes the effective local oscillator, and the message sidebands is photodetected at the receiver and homodyne conversion gain is produced. In initial experiments a colour centre laser has been used as the pump source located at the receiver but it is anticipated that this could ultimately be a single mode semiconductor laser. Substantial homodyne gain has been achieved in early laboratory experiments with milliwatt pump powers although system BER measurements have yet to be reported.

5.6 Optical frequency multiplexing and wideband coherent networks

There is increasing interest in the possible application of coherent transmission in local area networks and wideband distribution applications (S13, S28, S29, S30). FIG(13) shows one possible arrangement of a distribution system based on these principles. In this network the improved sensitivity resulting from coherent detection is used to allow the number of teminals that can be served by a passive distribution network to be greatly increased and the selectivity of coherent detection allows many separate channels to be transmitted. Clearly, although FIG(13) is essentially a distribution network other configurations could be developed to enable both way transmission. At present experiments have been limited to 2 and 3 channels, but already it has been shown that channel spacings less than 1GHz are possible (S13). The channel spacing is determined by consideration of image band and intermodulation products (R9).

The ultimate number of channels that can be transmitted using optical frequency multiplexing for long haul transmission is likely to be limited by non-linear effects, in particular Raman crosstalk (R5, R6).It is less likely that Raman crosstalk will limit the capacity of a local distribution scheme because the power in individual channels will be much smaller and interaction lengths shorter. Additional non-linear crosstalk resulting from Brillouin gain and 3 wave mixing has been observed at sub-mW values (R3,R10) but its effects may be reduced by suitable channel spacing and/or choice of modulation.

6. SUMMARY OF COHERENT SYSTEMS RESEARCH

Table 2 is a summary of systems experiments at 140Mbit/s using a range of modulation and reception techniques and table 3 indicates the current status of coherent optical system research around the world.

7. FUTURE PROSPECTS AND CONCLUSIONS

The recent demonstrations of coherent optical fibre transmission in laboratories around the world have verified the large predicted improvements in receiver sensitivity that accrue from heterodyne and homodyne detection. This improvement in receiver sensitivity has lead to long haul transmission experiments carried out over 200km and greater fibre paths (S6, SS21, S22). However, to realise these systems in a future field environment several engineering developments are now needed; in particular improved narrow linewidth lasers, wideband receivers and automatic control schemes (including polarisation control).

As coherent optical systems further evolve more use will be made of the selectivity of coherent detection for close packed multiplexing. For these potential local network application, the complexity of the coherent receiver must be reduced to achieve a realistic cost. Here integrated optics should be expected to play a role (S12).

Finally, there is the prospect of long haul fibre systems operating in the 2-10μm waveband range where reduced Rayleigh scattering from non-silica fibres would make transoceanic crossings theoretically possible. The likelyhood of poorer direct detection receivers at these longer wavelengths could lead to coherent reception as the natural choice.

AKNOWLEDGEMENT

The author wishes to thank the Director of Research for British Telecom PLC for permission to publish this lecture.

REFERENCES AND BIBLIOGRAPHY

See Appendix

TABLE 1

LASER LINEWIDTH REQUIREMENTS

MODULATION	DETECTION	BEAT LINEWIDTH/ BITRATE	REFERENCES
ASK	Heterodyne Square law & envelope	10%-40%	T4-T5
FSK wide deviation	I.F filter with envelope	similar	
DPSK	Heterodyne with delay demod.	0.3%	T6
PSK	Heterodyne	0.1%-0.5%	T2,T3 T8,T9,T10
	Homodyne: pilot	0.05%	
	Homodyne: Costas	0.1%	

TABLE 2

140Mbit/s EXPERIMENTAL COHERENT SYSTEMS (BTRL)

(direct detection = -45dBm)

SYSTEM	TRANSMITTER		RECEIVER		SENSITIVITY	
	modulator	laser	demodulator	laser	theory (dBm)	measured (dBm)
HETERODYNE	ASK (direct)	LEC	Synchronous	LEC	-60	-54
	FSK (direct)	LEC	delay	LEC	-60	-56
	FSK (direct)	DFB	single filter	LEC	-57	-50
	PSK ($LiNbO_3$)	HeNe	Synchronous	LEC	-63	-59
	DPSK ($LiNbO_3$)	HeNe	delay	LEC	-62	-57
HOMODYNE	ASK (inj. lock)	HeNe	self homodyne	....	-63	-59
	PSK ($LiNbO_3$)	HeNe	self homodyne	....	-66	-62/-64*
	PSK ($LiNbO_3$)	HeNe	optical PLL	HeNe	-66	-57
MULTIPORT	ASK ($LiNbO_3$)	LEC	I&Q square law	LEC	-60	-52
	DPSK ($LiNbO_3$)	LEC	I&Q delay	LEC	-62	-52

LEC = long external cavity diode laser; * = 1010 pattern

TABLE 3

RECENT REPORTED COHERENT TRANSMISSION EXPERIMENTS WORLDWIDE
(See proceedings IOOC/ECOC 1985, Venice)

SYSTEM	BITRATE	RECEIVER SENS.dBm	FIBRE LENGTH	LABORATORY
FSK using external cavity lasers. Direct modulation. Heterodyne	400Mbit/s	-49	270km*	NTT (Japan)
FSK using DFB lasers (split contact). Single filter heterodyne	140Mbit/s	-49	343km	NEC (Japan)
FSK using DFB lasers Heterodyne	565Mbit/s	....	....	Bellcore (USA)
DPSK using external phase mod. LEC.Het.	400Mbit/s 1Gbit/s	-53 -44.5	150km	AT&T (USA)
ASK, Multiport(3phase)	320Mbit/s	-48	....	STL (U.K)

* latter result

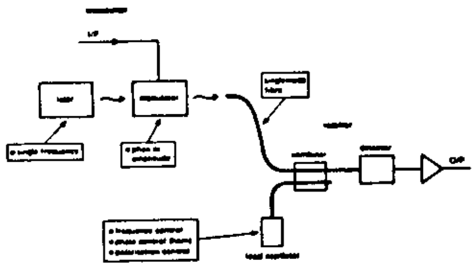


Fig. 1 Coherent optical transmission

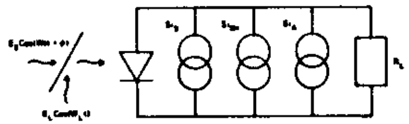


Fig. 2 Coherent detection

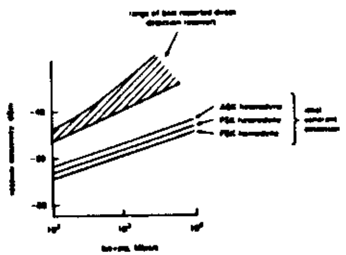
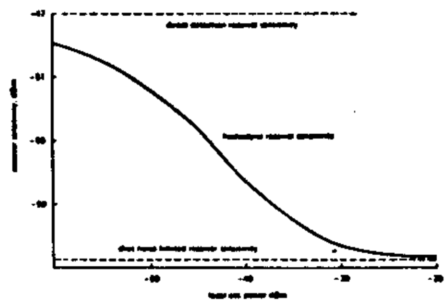
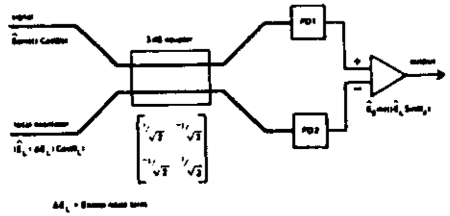


Fig. 3 Performance comparison of ideal coherent detection with practical direct detection at a wavelength of 1500 nm.



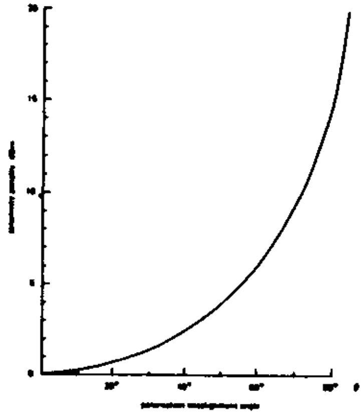
Effect of local oscillator power on receiver sensitivity at 140 Mbit/s

FIG 4



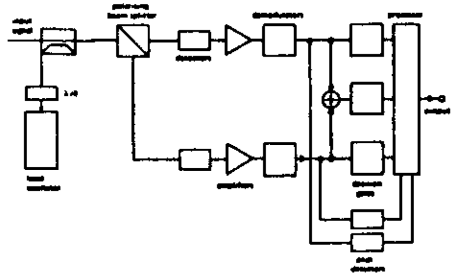
Balanced receiver

FIG 5



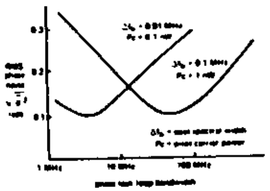
Dependence of coherent receiver sensitivity on polarisation alignment.

FIG 6



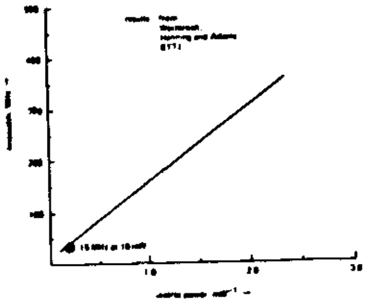
Polarisation diversity receiver

FIG 7



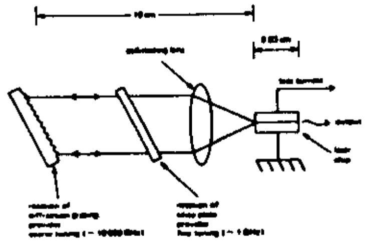
Relationship between phase noise and phase-lock loop bandwidth

FIG 8



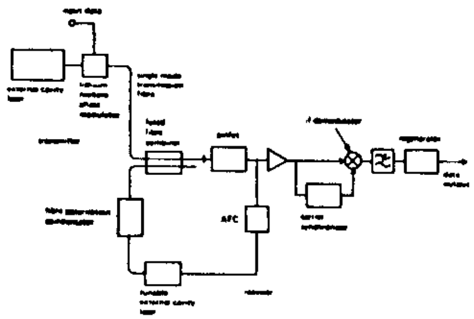
DFB laser linewidth against inverse power

FIG 9



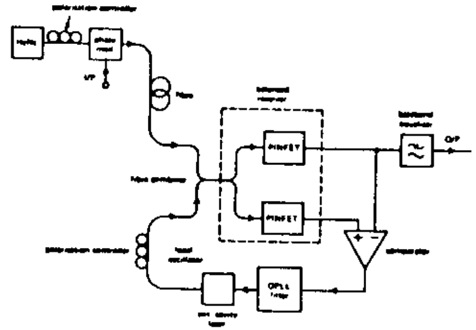
External cavity semiconductor laser

FIG 10



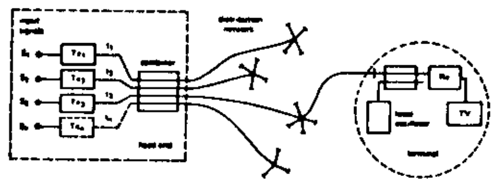
PSK heterodyne detection experiment

FIG 11



PSK homodyne system experiment

FIG 12



Coherent wideband distribution system

FIG 13

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