

A LOW COST SUB-CARRIER MULTIPLEXED PPM FOR OPTICAL FIBRE TRANSMISSION SYSTEMS

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Abstract

Sub-carrier multiplexed (SCM) optical fibre distributed broadband services suffer from system non-linearity and are sensitivity to noise. Thus imposing stringent noise and linearity requirements and as a result their performance is limited. However, system performance can be improved by incorporating a second stage modulator. In this paper a SCM optical transmission system employing pulse position modulation (PPM) as a second stage modulator for transmission of video, audio and data channels is reported. System measurement and theoretical predictions obtained are in close agreement and the results show an improvement in optical receiver sensitivity compared to a conventional SCM.

1.0 Introduction

The advances made in computer and consumer electronic industries has stimulated a remarkable growth in the demand for new information services. Currently the communications industry is looking at different options for providing new services to the home and business environment. Ultimately the high bandwidth broadband services will be delivered by a broadband integrated digital services network (B-ISDN), but at present the high cost and immaturity of digital technology prohibit their wide spread deployment. In the interim, sub-carrier multiplexed systems offers an elegant and cost effective alternative to the conventional time division multiplexed systems for efficient

bandwidth utilisation of the fibre based networks for applications such as video, audio and data distribution services¹.

In SCM systems a number of baseband analogue or digital signals are frequency up converted before being combined to intensity modulate an optical source. A major advantage of SCM is the readily availability of the components required for systems implementation. Modulators, mixers and amplifiers employed in satellite, CATV and cable systems can be used thus allowing a realistic low-cost solution to the problem of exploiting the optical bandwidth. Potential application areas include: hybrid fibre coaxial²⁻³, CATV, telephony, data transmission and LANs⁴. SCM also has the ability to mix analogue and digital transmission which is very important for CATV networks since TV companies are now offering additional services such as telephony. Majority of existing SCM systems are based on analogue transmission techniques over optical fibres. These schemes have poor receiver sensitivities and as a result the optical power budget required is limited, thus restricting the transmission distance, the number of sub-subscribers and type of services delivered. They also require highly linear optical transmitter under large signal modulation. For laser light non-linearity introduce distortions that may severely limit the system performance⁵.

A technique employed by several authors in order to improve the power budget, the input dynamic range and non-linear distortion is based on introducing a second stage modulator prior to optical transmission. Grace⁶ has employed a

quantised sub-carrier multiplexing approach for the transmission of composite signals over optical fibre networks, but the applications of this method are limited by the speed of the A/D converter, cost and complexity of the digital modulator. Ohmoto⁷ and Sato⁸ have used frequency modulation (FM) as a second stage modulator to improve the signal-to-noise ratio (SNR) at output of the receiver. Savov⁹ have combined SCM with coherent detection in order to provide multi-channel and improved sensitivity. Both these schemes suffer from inter-modulation distortion.

Pulse time modulation (PTM) is an attractive alternative to both high cost digital and low performance analogue techniques, and recently it has seen a renewed interest in its applications for optical fibre communication systems. PTM is currently being used in cable TV transmission, deep space communication, optical wireless and in local area network applications¹⁰. The desirable features of PTM are, improved noise immunity, greater tolerance to non-linearity resulting in excellent receiver sensitivities, reduced circuit complexity and low cost.

We have already reported the system improvements achieved by implementing pulse frequency modulation (PFM) and square wave frequency modulation (SWFM), two of the PTM techniques, as a second stage modulator to deliver a broadband SCM signal¹¹. However, further improvement in performance can be achieved by employing a modulation technique which has the ability to exploit the available wide bandwidth of fibre based systems. Pulse position modulation (PPM), a member of PTM family, is an attractive technique of accomplishing this end. The goal of this paper is, by means of system implementation, to investigate and relate the performance of the proposed new scheme based on PPM, as a second stage modulator, to the performance of the a conventional SCM system. The following section describes the system implementation and the results obtained.

2.0 System implementation

Figure 1 illustrates the proposed system block diagram of SCM-PPM. The SCM signal consists of

a baseband video channel (5.5 MHz), two audio channels frequency modulated at sub-carrier frequencies of 6 MHz and 7.2 MHz, respectively, an FSK modulated data channel at a sub-carrier frequency of 6.552 MHz, pre-emphasis networks and filters. Since signal quality can be affected by the laser non-linearity, resulting in higher noise power, therefore the frequency allocation was decided so that the effect of inter-modulation is minimised. The composite SCM signal is then converted into PPM pulse train before being applied to the optical transmitter. A semiconductor laser diode operating at 1300 nm, with a maximum output power of 1.5 mW is employed as a light source. At the receiver, a *p-i-n* photodiode, with a transimpedance amplifier configuration, is employed to convert optical signal back to an electrical signal. The recovered electrical signal, at ECL level, is then fed to the PPM/PWM convertor. The regenerated PWM frequency spectrum contains undistorted baseband component corresponding to the SCM signal which can be recovered simply by low pass filtering. Finally, PWM signal, containing the SCM channels, is applied to appropriate filters and demodulators in order to recover the desired channels. Full specifications of the proposed system are summarised in Table 1.

Table 1

Electrical Parameters			
Transmitter			
Input	B/W	Mod. format	M
video(1.0V _{pp})	5.5 MHz	baseband	0.4
audio*	15 kHz	FM1 @ 6 MHz FM2 @ 7.2 MHz	0.1
data (NRZ)*	500 kbps	FSK @ 6.5 MHz	0.1
* peak dev. 50 kHz, pre-emph 50 μs			
PPM:			
<ul style="list-style-type: none"> • format & frequency: ECL, 20.5 MHz • sampling ratio: ~ 2.8 • duty cycle: 4 % 			
Receiver filters:			
<ul style="list-style-type: none"> • video; 5.5 MHz (7th order LPF), SNR >40 dB • audio channels; 160 kHz (BPF), SNR >49 dB • data; 780 kHz (BPF), BER = 10⁻⁹ 			
Optical Parameters			
<ul style="list-style-type: none"> • Rise / fall times: 1.5 ns • Wavelength: 1300 nm • Power : 1.7 (max) dBm for LD -35.5 dBm (min) for PIN • Spectral width (FWHM): 3 nm • Responsivity: 0.75 A/W • Dark current noise: 100 pA • Receiver equivalent input noise current: 2.5 pA/√Hz • Load resistance: 14 k Ω 			

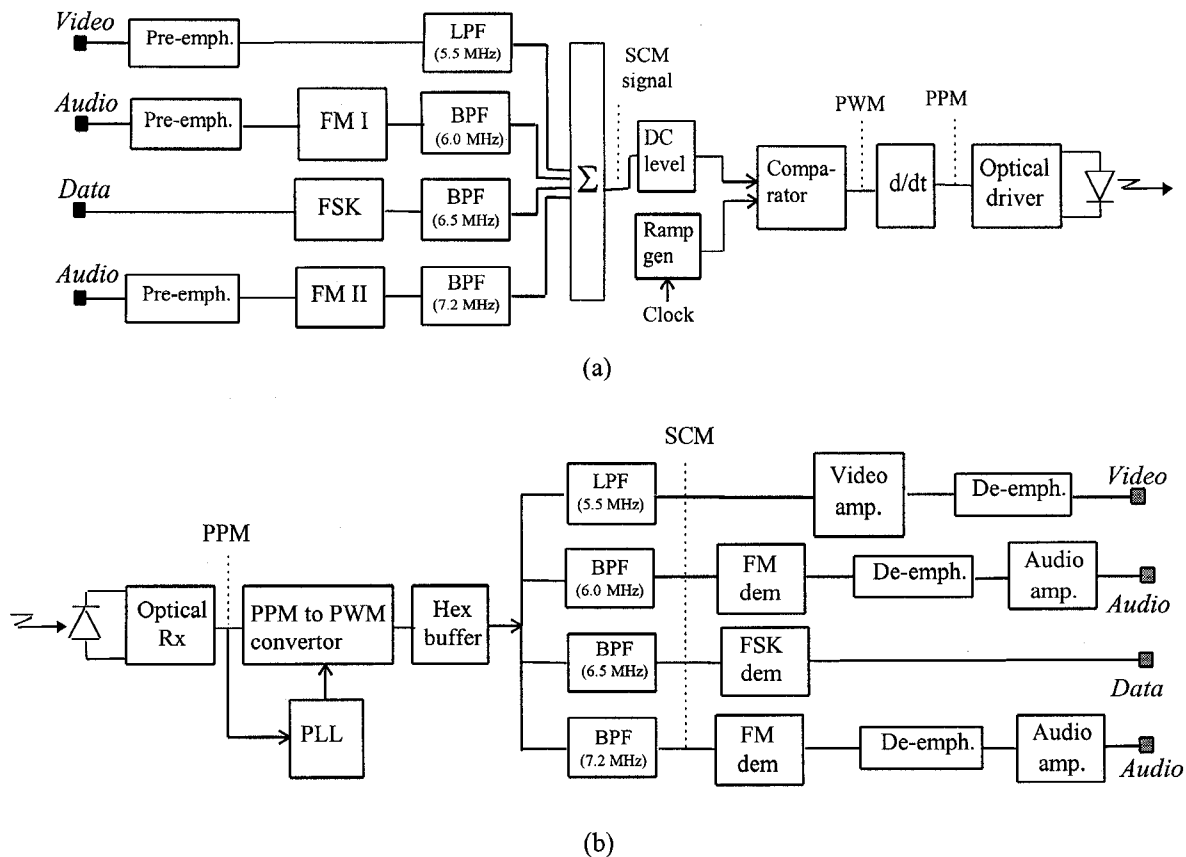


Fig. 1. SCM-PPM system block diagram: (a) transmitter and (b) receiver.

Circuit techniques used for implementation of the first stage, i.e. SCM stage, are well documented and no attempt is made to reproduce them here. Full details of the complete system circuit diagrams can be found in the work done by Wickramasinghe¹⁴. Therefore, the following section only describes the full implementation of the second stage (i.e. naturally sampled PPM). Naturally sampled PPM is preferable to uniformly sampled since it requires less complex circuitry, produce the required *SNR* and also have lower distortion when operated at low modulation index.

2.1 PPM modulator

The implemented naturally sampled PPM stage together with the optical link, shown in Fig. 1.a., is represented by circuit diagrams of Fig. 2. Direct comparison of the modulating signal, i.e. the SCM signal after dc-level shifting, and a high speed linear ramp waveform at the input of a fast comparator then produces trailing edge modulated PWM output signal. The modulating edge of the PWM signal is then differentiated to produce the desired PPM pulse train with a width of the order

of 1.9 ns, see Fig. 3. This results in a duty cycle of less than 4 percent, which is compatible with present laser devices. The PPM signal is then applied to the driver unite of an optical source employing a laser diode at 1300 nm wavelength. To compensate for temperature fluctuation a standard bias circuit is used with the laser driver circuit¹⁴. The fibre used is 50/125 μm multimode graded index.

It is vital that naturally sampled PPM modulator has a linear voltage-to-pulse position conversion characteristic. Failure to obtain linearity can result in harmonic distortion which could lead to poor system performance. Therefore, the need for generating a linear ramp waveform. There are various techniques of generating ramp signal, but the approach adopted here is based on charging a capacitor with a constant current source and discharging it through a high frequency switch, see Fig. 2.a. In order to maximise the input dynamic range of the PPM modulator, very short reset times are desired. A *n-p-n* RF transistor with a gain bandwidth of 8 GHz was used as a high frequency switch, achieving reset times in the order of 4 ns.

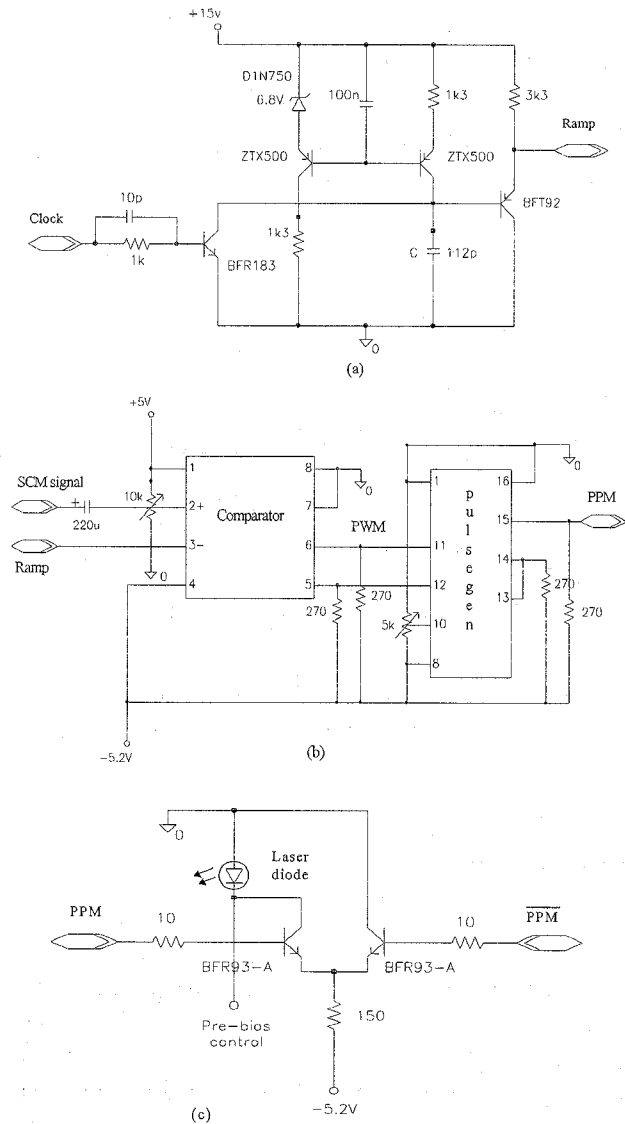


Fig. 2. PPM modulator circuit diagrams: (a) ramp generator, (b) PWM and PPM and (c) optical drive.

One of the main advantages of PTM schemes, compared to digital schemes, is the ability to operate at low sampling ratio $R_s = f_c / (f_m)_{max}$, where f_c and $(f_m)_{max}$ are the carrier frequency and the maximum modulating frequency, respectively, and still result in relatively good performance. This is best seen by considering the signal-to-noise ratio characteristics of PPM which is inversely proportional to the carrier frequency. Assuming that the noise performance is determined by jitters alone and the recovered PPM pulses have a Gaussian shape, the SNR defined in terms of peak

and average received optical powers are given in Eqs. 1 and 2, respectively

$$SNR = \frac{18}{25} M^2 \left(\frac{B_t}{f_c} \right)^4 \frac{(R_o G P_p)^2}{N_i} \quad (1)$$

$$SNR = \frac{72}{25} M^2 \left(\frac{B_t}{f_c} \right)^4 \frac{(R_o G P_{av})^2}{N_i} \quad (2)$$

where, R_o is the photodiode responsivity, M is the PPM modulation index, G is the optical gain, P_p and P_{av} are the peak and average received optical power, respectively, and N_i is the input rms noise power, and $B_t = 1/2(\text{PPM pulse width})$. However, if sampling ratio is too low, then lower side tones components, generated around the carrier fundamental frequency, can overlap with baseband signal, thus resulting in baseband distortion, see Figs 6 & 7. An improved baseband distortion performance for a given sampling ratio can only be achieved by reduced the modulation index, but at the cost of lowering the SNR performance¹². For this system a carrier frequency of approximately 20 MHz corresponding to sampling ratio of ~ 2.8 is used in order to achieve a baseband distortion level and SNR of -40 dB and > 40 dB, respectively.

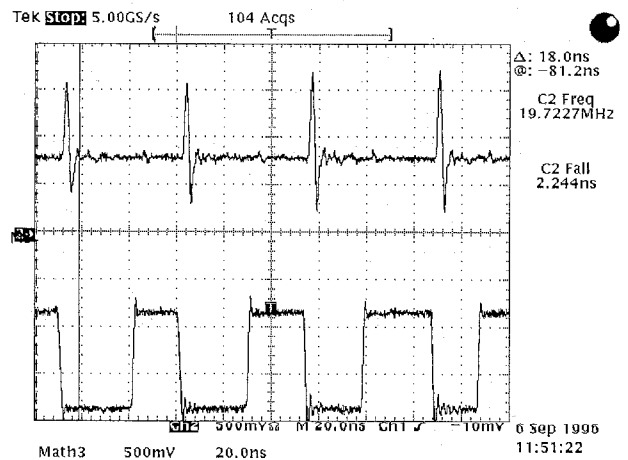


Fig. 3. PTM waveforms; upper trace PPM & lower trace PWM.

Since the number of sub-carrier channels used are small, then the overall modulation index can be

expressed as a linear quantity. For SCM-PTM system it may be defined as a rms quantity M_{rms} :

$$M_{rms} = \sqrt{\sum_{i=1}^N M_i^2} \quad (3)$$

where M_i is the modulation index per channel and N is the number of channels. For quality reason, video channel has been allocated the highest modulation index of 0.4.

2.2 PPM demodulator

At the receiver, the light carrier is first converted back to an electrical signal by an optical receiver. The regenerated electrical PPM pulse train is then converted back to PWM waveform for SCM signal recovery. PPM to PWM conversion requires an access to an accurate clock reference signal, see Fig. 1.b. One simple solution would have been to transmit the clock signal with information pulses, thus making clock recovery unnecessary. However, the drawback of this scheme is that the optical source is turned on and off at twice the rate, compared to the system proposed in this paper. Here, we investigate an alternative technique based on employing a phase locked loop (PLL) to recover the clock component directly from the incoming PPM pulse train, see Fig. 4.

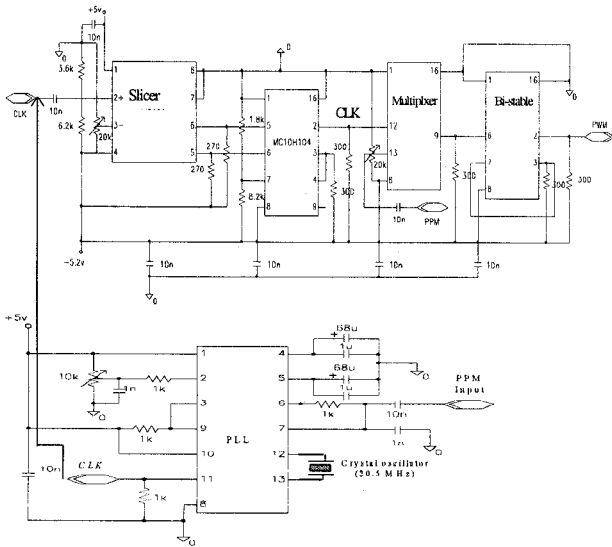


Fig. 4 PPM demodulator circuit diagram.

This is best described by investigating the spectra for single tone input naturally sampled PPM waveform which may be expressed as¹³:

$$f(t) = \frac{A\omega_c\tau}{2\pi} + AM \cos(\omega_m t) \sin(\omega_m \tau / 2) + \frac{2A}{\pi} \sum_{k=-\infty}^{\infty} \sum_{n=1}^{\infty} J_k(n\pi M) \frac{\sin[(n\omega_c + k\omega_m)\tau / 2]}{k} \times \cos[(n\omega_c + k\omega_m)t] \quad (4)$$

where A is the pulse height, ω_c is the carrier frequency, ω_m is the modulating frequency τ is the width of PPM pulses, M is the modulation index (equivalent to $2\Delta t/T_c$, where Δt is the peak time deviation and T_c is the pulse period), $J(\cdot)$ is the Bessel function of the first kind and k and n are integers. In Eqn. 4, the first term is the dc component and the second term represent a differentiated version of the baseband component. In the latter the amplitude decreases as the PPM pulse duration is reduced. The final term represent the clock fundamental, its harmonics and a set of diminishing side tones around them. The amplitude of the clock component is:

$$A_c = \frac{2A}{\pi} J_0(\pi f_c M) \sin(\pi f_c M) \quad (5)$$

Equation 5 normalised to the unmodulated carrier amplitude versus modulation index is plotted in Fig. 5. It shows a presence of a strong clock component at low modulation indices decreasing to lower levels at higher values of M . Although the amplitude of clock component may drop down to a low level at higher modulation index, see Figs. 5 and 6 but it is still possible to recover it by employing a PLL.

A major design criteria for the PLL is to have an extremely narrow lock-in range in order to prevent the PLL locking onto sidetones components, spaced around the carrier (clock) fundamental frequency components, and it should also have a minimise frequency drift.

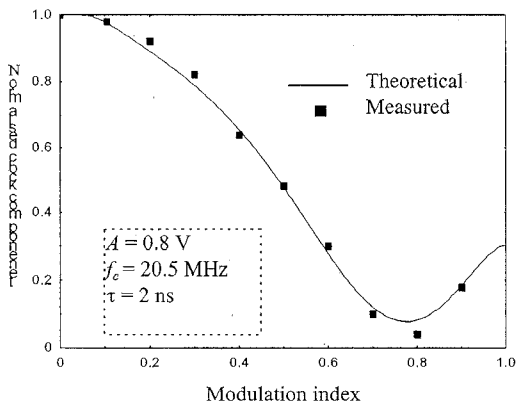


Fig. 5 Normalised clock component vs. modulation index.

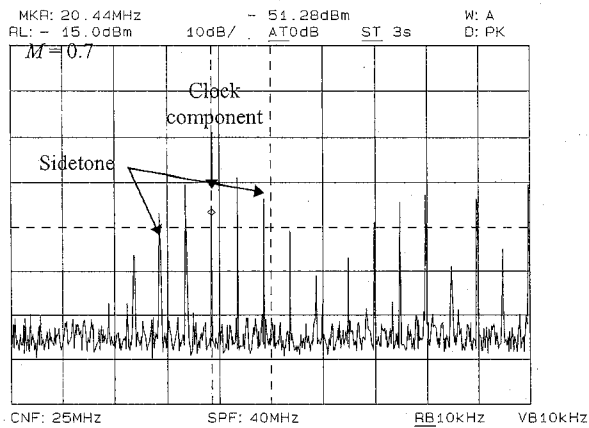


Fig. 6 PPM spectrum.

The transfer function of the loop filter has a considerable influence on the properties of the loop such as: capture range, lock acquisition time, transient response *etc.* The lock-in range of a PLL, defined as the frequency range centred about the free running frequency of the VCO over which the loop can acquire lock with the input signal, is in fact equivalent to the loop bandwidth. Since a narrow lock in range is desired, then loop bandwidth must be made very small, which ensures good noise performance and can tolerate large frequency variations without losing lock. The longer lock acquisition times are a drawback of narrow bandwidth loop filters, but is of no concern in the PPM implementation. A monolithic IC, with a frequency operation of up to 50 MHz was employed as the PLL together with a first order loop filter having a cut-off frequency of

approximately 6 Hz. To design a small loop bandwidth PLL and to ensure good locking, a crystal controlled VCO is highly desirable. The VCO frequency drift should be controlled to be less than the lock-in range in order to prevent the PLL from un-locking. Using a similar crystal, to generate the clock signal, at the transmitter will result in low frequency offset which in turn allows VCO frequency drift to be within the lock-in range of the PLL.

The recovered clock signal after being passed through a slicer and A TTL-to-ECL convertor is then multiplexed with received PPM pulse train in order to trigger a bi-stable to regenerate the PWM signal, see Fig. 4. Since the spectrum of the PWM signal contains in its baseband region the SCM signals, as illustrated in Fig. 7, then simple filtering should recover the desired SCM channels. A high order low pass filter followed by an amplifier and a de-emphasis network were used to recover the video signal. Data and audio signals were recovered by employing bandpass filters followed by FSK and FM demodulators. For audio channels de-emphasis networks and further amplification are also required, see Fig. 1.b.

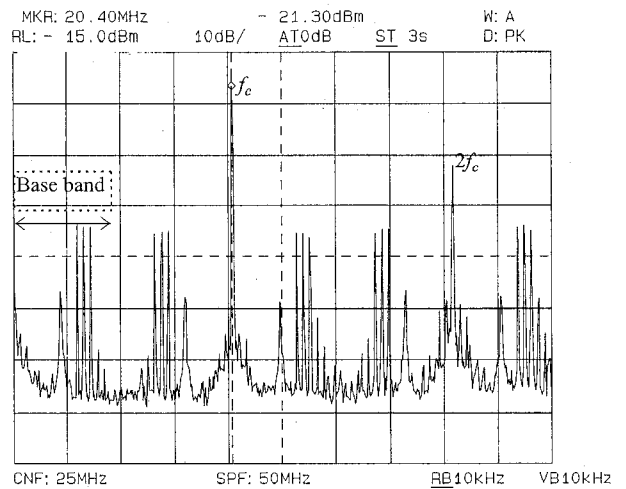


Fig. 7 Regenerated PWM spectrum.

3.0 Results & discussions

The prototype system was designed and built to evaluate the performance potential of the SCM-

PPM technique. The performance of the video and audio channels are measured in terms of unweighted *SNR* and the results are plotted against peak received optical power in Figs. 8 and 9, respectively. The measured values are lower only by a few dB compared to the calculated results, thus showing quality of the system. The calculated *SNR* performance for a conventional SCM system is also shown in the figures for comparison. *SNR* performance exhibits a marked threshold effect, a characteristics common to all PTM schemes, below which the performance deteriorate rapidly. To deliver 40 dB *SNR* for video channel, the approximate receiver sensitivity improvement offered by the SCM-PPM compared to SCM is 8.5 dB. For audio channels delivering 49 dB *SNR* the improvement factor is about 7 dB. The increase in receiver sensitivity, compared to SCM is quite significant which could be utilised to extend the transmission distance and the number of channels. 8.5 dB improvement in PPM will result in an increased transmission link of 17.2 km and 28.6 km when operating at wavelengths of 1300 nm and 1550 nm, respectively.

For data channel to achieve a bit error rate of 10^{-9} , as was specified in Table 1, the measured receiver sensitivity was ~ -35 dBm which is 5.5 dB better than the SCM system.

Since conventional SCM systems imposes strict linearity requirements, therefore any non-linearity associated with the optical source will result in inter-modulation distortions (IMD). IMD can be reduced by limiting the sub-carrier frequencies to a single frequency octave, so that second order IMD products fall outside the pass band and therefore has no bearing on the system, leaving only the third order IMD to deal with. In SCM-PTM techniques the overall system linearity is mainly determined by the modulator and demodulator and the associated electronics, provided the constraints on the optical sub-system specification is relaxed. In naturally sampled PPM the amount of non-linear distortion is primarily determined by the voltage-to-pulse characteristics of the PPM transmitter. Figure 8 shows the measured voltage-to-pulse characteristics of the PPM transmitter approximated by a second order polynomial. For an

input signal of 1V, the predicted the second harmonic distortion relative to the fundamental component is about -75 dB, far exceeding the required -40 dB. For analogue channels full system linearity tests were carried out, and the result for video channel is shown in Fig. 11, illustrating high linearity and low distortion characteristics of the proposed scheme. The second harmonic and third distortions measured at the output for video channel were below -47 dB and -50 dB, respectively, and for audio channels the harmonic distortion were -44 dB and -48 dB, respectively, an acceptable figures for adequate signal performance⁶. As for IMD no significant third order IMD could be measured.

Finally For video channel the measured differential phase and differential gain of 2.5% and 1.6°, respectively were well within the CCIR recommendations

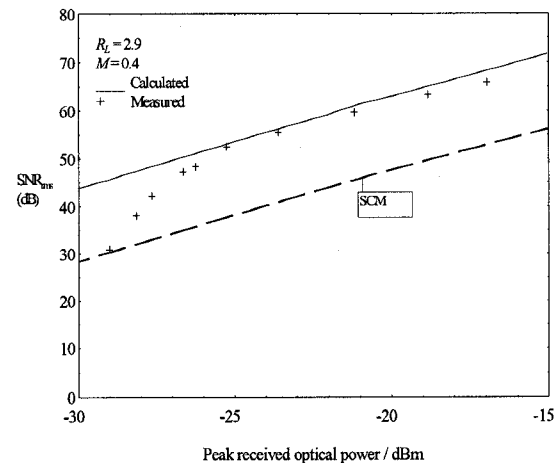


Fig. 8. SNR performance of the video channel.

4.0 Conclusions

An analogue - pulse modulation format, SCM-PPM, has been proposed to transmit a video signal, two audio signals and a data channel over multimode graded index fibre link, with a 1300 nm laser diode source and PIN based optical receiver. The performance of PPM technique together with its self synchronising property for transmitting a broadband SCM signal has been evaluated both

theoretical and experimentally. The performance of video, audio and data channels were compared to a conventional SCM system showing major improvement. The results obtained for SNR indicated that by employing PPM, as a second stage modulator, optical power budget can be improved by up to 8 dB, for video channel, compared to conventional SCM. For the data channel the improvement in the receiver sensitivity is about 6 dB. These results illustrates the attractiveness of SCM-PPM scheme for applications such as local CATV networks or a private office communication networks.

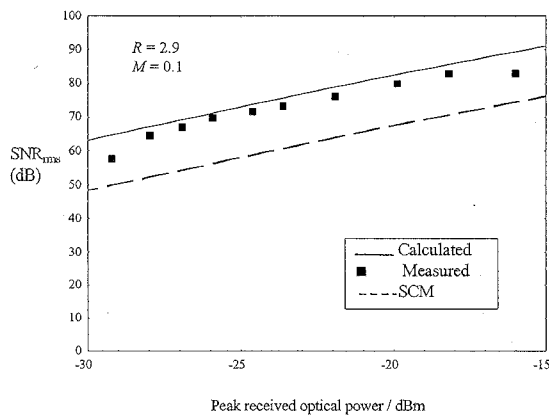


Fig. 9 SNR performance for the audio channel.

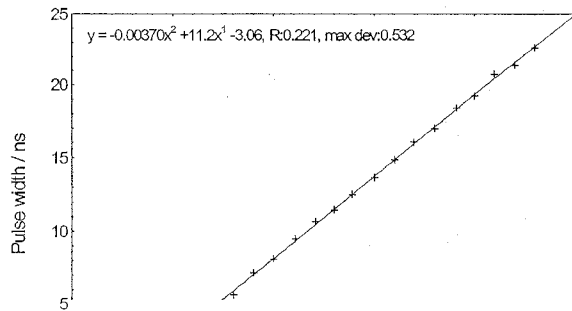


Fig. 10 Voltage to pulse position conversion characteristic of the PPM modulator.

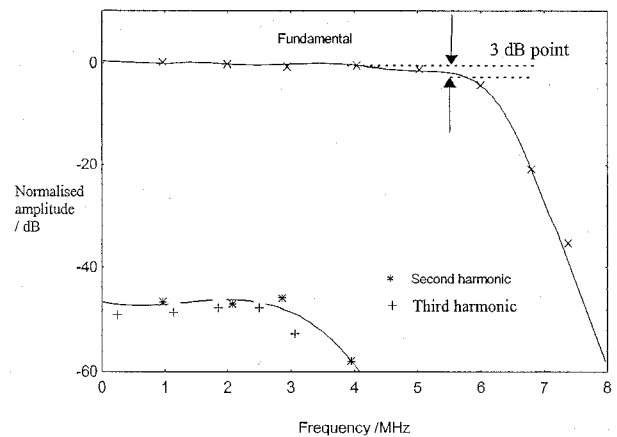


Fig. 11 Harmonic distortions for the video channel.

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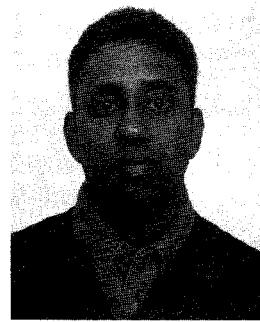
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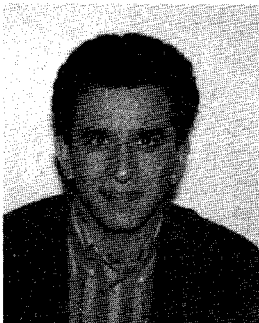
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