PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Microwave-Frequency Carriers on Optical Fibres [and Discussion]

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Phil. Trans. R. Soc. Lond. A 1989 **329**, 23-36
doi: 10.1098/rsta.1989.0054

Phil. Trans. R. Soc. Lond. A **329**, 23–36 (1989)
Printed in Great Britain

Microwave-frequency carriers on optical fibres

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The use of microwave carrier frequencies in wideband optical-fibre networks is a promising new approach to the distribution of voice, data and video services to subscribers. This paper discusses the general features and design rules of microwave-multiplexed wideband optical-fibre systems and reports on several specific systems developed at GTE Laboratories. These include transmission of 60 frequency-modulated (FM) video channels multiplexed on carriers in the 2.7–5.2 GHz band, and the transmission of 20 frequency-shift-keyed (FSK) 100 Mb s^{-1} digital video channels in the 2–6 GHz band. A hybrid system is also described that transmits a 100 Mb s^{-1} baseband signal in addition to the 60 FM video channels. These transmission experiments illustrate the large bandwidth capability and design flexibility of microwave-multiplexed lightwave systems. As lightwave systems push towards larger and larger bandwidths, microwave-multiplexing may emerge as the more natural way to exploit the enormous bandwidth of lightwave components.

1. INTRODUCTION

A major objective of the telecommunications industry is the development of lightwave technology for cost-effective, broadband subscriber distribution networks. To justify the cost of an optical-fibre distribution system it is considered necessary to provide voice, data and video services. The video services transmitted over fibre are likely to include both broadcast television channels, similar to those presently available on cable television (CATV), and switched video services, not presently available.

An uncompressed digitized video channel requires a data rate of about 100 Mb s^{-1}. To compete with conventional CATV, which can provide 30–80 video channels, a subscriber distribution network based on conventional baseband digital fibre-optic transmission must either operate at multigigabit-per-second data rates or require extensive video switching capability. Researchers at Bell Communications Research (Linnell 1986; Linnell & Spears 1987) have proposed a fully switched video network for the subscriber loop. In this network, each subscriber would receive voice, data and up to four digitized video channels, all time-division multiplexed (TDM) at a total data rate as high as 500–600 Mb s^{-1}. To provide a full range of video services all video selections would be provided through remotely located video switches. As an alternative approach, Faulkner *et al.* (1988) have proposed a passive broadband network in which 30 channels, digitized at 70 Mb s^{-1} per channel, are time-division multiplexed to a data rate of 2.1 Gb s^{-1} and are passively distributed through a star-coupler to 32 subscribers. These 30 channels could include both broadcast and switched channels, but with all switching carried out at the central office.

Much research is also being devoted to the use of multichannel coherent transmission for a broadband subscriber network (see, for example, Stanley *et al.* 1987; Baack *et al.* 1987). While the potential of this approach is great, the complexity and cost is such that optically coherent subscriber networks are more likely to be implemented in later-generation subscriber networks.

This paper describes a new approach to broadband lightwave distribution systems that uses microwave-multiplexing. The combination of microwave electronics and fibre optics provides a method for building wideband, multicarrier systems that have many attractive features (Olshansky 1987; Darcie 1987). Microwave or lightwave systems can be designed to have a 4–8 GHz of bandwidth and to transmit dozens of independent channels. These systems accept a wide variety of modulation formats, including the analogue FM format used extensively for satellite transmission of video, and any number of digital formats including frequency-shift keying (FSK), phase-shift keying (PSK) and quadrature PSK (QPSK). The frequency assignments of the microwave carriers and the bandwidth allocation per channel are very flexible. Systems can be designed and built today that include digital channels for transmission of voice, data and digital audio signals, and also take advantage of the low-cost frequency-modulated (FM) video technology presently used for satellite video transmission. Subcarrier multiplexed (SCM) systems have sufficient flexibility and bandwidth capability to allow for the incorporation of high-definition video or digital video transmission, whenever these technologies are ready for the consumer market.

Microwave or lightwave systems are more properly called 'subcarrier multiplexed' (SCM) systems. This name emphasizes that multiplexing is done at microwave subcarrier frequencies rather than at optical carrier frequencies. The name SCM distinguishes the microwave-multiplexing from optical frequency-division multiplexing (FDM), a term that is more appropriately applied to wavelength-division multiplexed (WDM) direct-detection systems or to coherent systems multiplexed at optical frequencies.

This paper proposes design rules for SCM fibre-optic systems, and describes two multichannel SCM transmission experiments performed to verify these rules. In the first, 60 FM video channels are transmitted over 18 km of single-mode fibre (Olshansky & Lanzisera 1987), and in the second, 20 FSK channels carrying 100 Mb s^{-1} each are transmitted over 12 km (Hill & Olshansky 1988).

SCM systems have the further attractive feature that they are compatible with the simultaneous transmission of conventional baseband signals using the same laser, fibre and detector (Olshansky *et al.* 1988; Way & Castelli 1988). By using commercially available hybrid couplers, the baseband signal and microwave signals can be readily multiplexed and demultiplexed. A hybrid transmission experiment carrying 100 Mb s^{-1} at baseband and 60 FM video channels (Olshansky *et al.* 1988) will be described.

2. SUBSCRIBER-MULTIPLEXED MICROWAVE SYSTEMS

For a number of years the possibility of transmitting microwave signals over optical links has been discussed in the literature and a number of systems experiments have been carried out (Bechtle & Siegel 1982; Pan 1983; Blauvelt & Yen 1984; Stephens & Joseph 1985; Gee *et al.* 1986). Many of these early studies were directed toward narrowband military applications. More recently several studies have pointed toward commercial applications of microwave techniques in fibre-optic systems. Darcie *et al.* (1986) performed an SCM experiment in which three 45 Mb s^{-1} FSK channels were transmitted over 2 km of optical fibre. A later analysis (Darcie 1987) emphasized the application of SCM to multiple-access local networks. Bowers (1986) showed that microwave carriers could be used to transmit a 2 Gb s^{-1} PSK signal over a distance of 34 km.

Although a number of early authors (Tjhung *et al.* 1983, 1986) used RF multiplexing at lower frequencies to transmit FM video signals, Way *et al.* (1987) showed that a 10-channel signal from a C-band satellite, transmitting in the 3.7–4.2 GHz band, can be directly modulated onto a high-speed laser. A 35 km repeater spacing was achieved, and it was proposed that such a system would be useful as a satellite-station entrance link. In a similar experiment, a C-band satellite signal carrying FM video, 3 Mb s^{-1} QPSK and 60 Mb s^{-1} QPSK signals was transmitted over 20 km (Bowers *et al.* 1987).

In this paper it is shown that SCM techniques can be extended to transmission of very large numbers of information channels for a broadband subscriber network (Olshansky 1987). These systems have the ability to accommodate both analogue and digital signals, to handle voice, data, video, digital audio, high-definition video, and virtually any foreseeable combination of services. The flexibility in allocation of bandwidth, and indifference to the choice of modulation format, makes SCM very attractive for broadband applications where services may originate from a variety of different service providers, each preferring a different modulation format and requiring different signal bandwidths. The flexibility of SCM systems also enables them to accommodate anticipated developments in television technology, such as the emergence of either digital or high-definition television.

A basic SCM system is shown in figure 1. A large number of modulated microwave carrier frequencies f_i are combined in a microwave power combiner and the composite signal is used to modulate the intensity of a semiconductor laser, direct-current (DC) biased at about 5 mW. The intensity-modulated laser signal is transmitted over a single-mode fibre and directly detected with a wideband InGaAs PIN photodiode. For long-distance applications such as feeders or CATV supertrunks, a wideband InGaAs APD could be used to extend the link length.

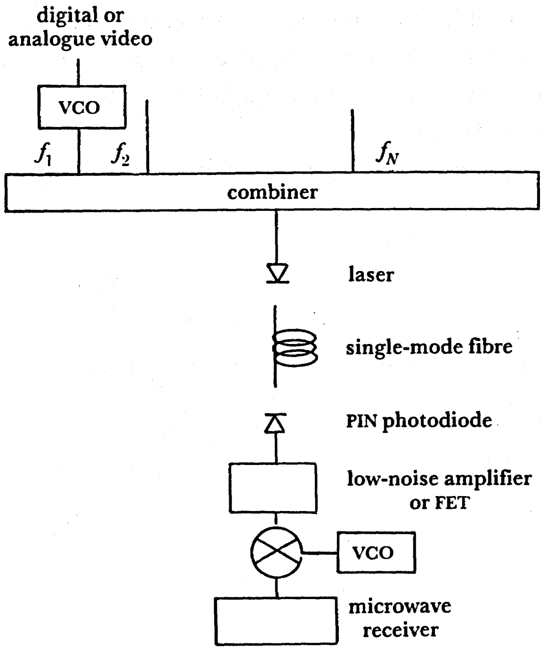

FIGURE 1. Block diagram of subcarrier-multiplexed lightwave system.

The received photocurrent can be amplified with either a wideband, low-noise amplifier or a wideband PIN–FET receiver. Commercial low-noise amplifiers with 2–8 GHz bandwidths have noise figures of about 3 dB. A wideband PIN–FET receiver with DC to 8 GHz response has been reported (Gimlett 1987) to have an average root mean square (r.m.s.) noise current of about 12 pA $\mathrm{Hz}^{-\frac{1}{2}}$. This is equivalent to an amplifier noise figure of 2.5 dB. The PIN–FET receiver would be an appropriate choice for a hybrid baseband digital or SCM system, such as the one described in §7.

For a subscriber distribution system, where only a single channel needs to be selected for demodulation, a tunable local oscillator, mixer and narrowband filter can be used to select simultaneously the desired SCM channel and down-convert it to a more convenient intermediate frequency (IF). The IF signal is then passed to an appropriate demodulator, which recovers the baseband signal.

An attractive feature of FM video transmission is that receiver electronics are already mass-produced for home satellite receivers. A low-noise block (LNB) consisting of an amplifier with a 1 dB noise figure, mixer and local oscillator can be purchased for $100. An FM video demodulator and channel selector that accepts a 12-channel 500 MHz signal spanning 950–1450 MHz can be purchased for as little as $150. These relatively low prices make it clear that at present FM systems have a significant cost advantage over digital transmission of video.

3. Optoelectronic components

High-speed InGaAsP *lasers*

The optical transmitter is a high-frequency, 1.3 μm, vapour-phase regrown, buried-heterostructure (VPRBH), InGaAsP laser (Olshansky *et al.* 1987*b*). The laser has a very simple mesa geometry that reduces the parasitic capacitance due to pn junctions and results in extremely good high-speed performance. A sample of 25 devices with 200 μm cavity lengths which were recently evaluated had an average small-signal modulation bandwidth of 11 GHz at a DC bias of 5 mW. The frequency response of a typical device biased at 5 mW is shown in figure 2. The fastest devices made to date have small-signal modulation bandwidths in excess of 20 GHz (Olshansky *et al.* 1987*a*).

In addition to modulation bandwidth, the other important characteristics of InGaAsP laser

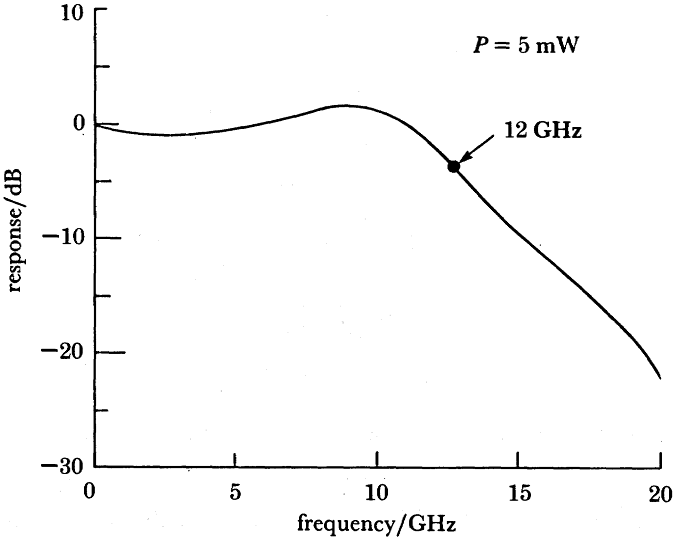

Figure 2. Typical frequency response of 1.3 μm InGaAsP VPRBH laser biased at 5 mW.

sources for SCM systems is the noise due to laser intensity fluctuations and intermodulation products (IMPS). As a basis for comparison, the thermal noise current i^2_{th} of the receiver is given as

$$i^2_{\mathrm{th}} = N_{\mathrm{F}}kT/R_{\mathrm{L}}, \tag{1}$$

where N_{F} is the amplifier noise figure, kT is the thermal energy, and R_{L} is the 50 Ω load resistance. For a 3 dB noise figure the corresponding thermal noise current is $1.6 \times 10^{-22}\ \mathrm{A^2\,Hz^{-1}}$. Best system performance is obtained if the laser intensity noise and the cumulative noise due to intermodulation distortion lies 5–10 dB below this value.

Laser intensity noise

Relative intensity noise (RIN) is defined as the square of the ratio of intensity fluctuations to the mean:

$$N_{\mathrm{R}} = \langle \delta P^2 \rangle / \langle P \rangle^2. \tag{2}$$

For a 30 μA received photocurrent, typical of the SCM systems described in the following, the resulting noise is $3 \times 10^{-23}\ \mathrm{A^2\,Hz^{-1}}$ for $N_{\mathrm{R}} = -135\ \mathrm{dB\,Hz^{-1}}$. This is 7.5 dB below the noise level of the microwave amplifier. For this example, the penalty in signal-to-noise ratio is less than 1 dB. Figure 3 shows the measured relative intensity noise for a high-speed InGaAsP lasers at several different bias currents.

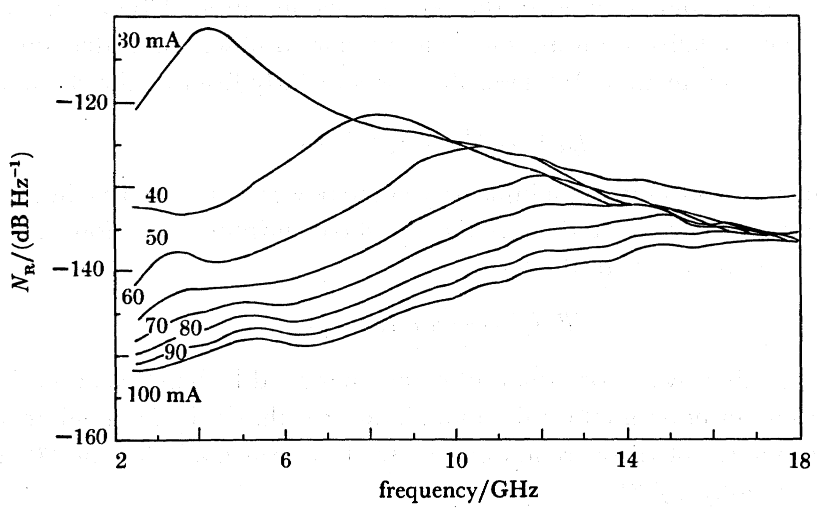

FIGURE 3. Measured relative intensity noise of InGaAsP VPRBH laser at several different bias currents.

Laser intermodulation products

A second source of noise originating at the laser is intermodulation distortion. Second- and third-order IMPS are created by intrinsic nonlinearities of the laser. Third-order IMPS arise when modulating signals at frequencies f_j, f_k and f_l mix together to produce a weak signal at the composite frequencies $f_j \pm f_k \pm f_l$. Within each subcarrier channel there are a maximum of $\frac{1}{2}N^2$ third-order IMPS (Daly 1982). The ratio of the third-order IMP, δP_{jkl}, to the total optical power P, is given by the expression

$$\delta P_{jkl}/P = m^3 F_3, \tag{3}$$

which varies as the third power of m, the modulation depth/channel, and depends on a function F_3, which is a function of the ratio of the frequency of the IMP to the laser's resonant frequency f_{r}, and other laser parameters.

Expressions for F_3 have been given in the literature (Lau & Yariv 1984; Darcie *et al.* 1985; Iannone & Darcie 1987). Even for the worst case, in which the frequency of the IMP corresponds to the resonant frequency, the function F_3 has the value of about 0.3. The $\frac{1}{2}N^2$ IMPS within a signal band add incoherently and the carrier-to-noise ratio (CNR) resulting from third-order IMPS alone is given as

$$S^{(3)} = 2/\{m^4 F_3^2 N^2\}. \tag{4}$$

A 60-channel system with $m = 0.03$ gives a worst case $S^{(3)}$ of 38 dB, greatly in excess of the 16 dB required for high-quality transmission. In general, third-order IMPS do not contribute to system noise for SCM transmission. A detailed theoretical and experimental analysis of the IMPS of an 8-channel system has been made (Iannone & Darcie 1987).

If the SCM system operates over a bandwidth of more than one octave, then second-order IMPS at frequencies $f_j \pm f_k$ are also present. The noise power in a second-order IMP is proportional to the fourth power of the modulation depth/channel, but for the worst case there are no more than N second-order IMPS within a single SCM channel (Daly 1982). Both theory and experiment (Olshansky 1987; Hill & Olshansky 1988) have shown that if care is taken in designing the system, the noise due to second-order IMPS is sufficiently small that bandwidths greater than one octave can be used.

Finally, it should be noted that in addition to the IMPS predicted by the laser rate equations, IMPS also can arise from nonlinearities in the power–current curve of InGaAsP lasers. These nonlinearities can be modelled by using the widely reported observation that the differential quantum efficiency η_{ex} of an InGaAsP laser decreases linearly from its threshold value η_{th} as

$$\eta_{ex} = \eta_{th}[1 - c(I_b - I_{th})], \tag{5}$$

where c is a parameter expressing the sublinearity of the power–current curve in the 0–10 mW range, I_b is the DC bias current and I_{th} is the threshold current. Equation (5) leads to an expression for second-order IMPS of the form

$$\delta P_{jk}/P = -m^2 c(I_b - I_{th}). \tag{6}$$

For a system operating over more than an octave bandwidth these second-order IMPS can contribute to the system noise if either the modulation depth, or the laser sublinearity is too large. A detailed analysis of these second-order IMPS has been made for the 20-channel FSK system (Hill & Olshansky 1988).

High-speed InGaAs *photodiodes*

The photodetectors used in the receiver are rear-illuminated InGaAs mesa PIN photodiodes with average bandwidths greater than 15 GHz and responsivities of 0.7 A W^{-1} at 1.3 μm (Schlafer *et al.* 1985). Wide photodetector bandwidths are obtained by reducing the junction capacitance, by reducing the diameter of the mesa to 30 μm, and by reducing the transit time of holes across the depletion layer by limiting the depletion width to 1 μm (Schlafer *et al.* 1985; Burrus *et al.* 1985). The optical receiver is completed with a bias tee, an electrical isolator to reduce reflections, and a 50 Ω microwave amplifier with a 2–8 GHz bandwidth and 3 dB noise figure.

Microwave packages

Microwave packages have been developed for both lasers and detectors (Schlafer & Ulbricht 1988) by modifying standard packages to include a high-frequency SMA connector and a length of microwave stripline which joins the centre pin of the connector at one end and contacts the device at the other end through a short bondwire. Such microwave packages can give frequency responses to 20 GHz that are flat to ±1 dB.

4. CARRIER-TO-NOISE RATIO FOR VIDEO TRANSMISSION

The CNR requirements of SCM systems depend on the modulation format. For FM video transmission, the format widely used for satellite transmission has been chosen (Siocos 1984; Way *et al.* 1987). A peak frequency deviation of 8.5 MHz is used. The filter bandwidth is taken as 30 MHz and the separation between microwave carriers is 40 MHz. A 16.5 dB CNR yields a studio quality video signal with a 56 dB weighted signal-to-noise ratio (SNR). The 39.5 dB improvement comes about from three factors. The use of wide deviation FM gives a 22 dB improvement (Clayton 1976). The use of preemphasis and deemphasis to reduce high-frequency noise gives a 12 dB improvement. And the use of the standard NTSC weighting factor adds an additional 6 dB. Because a 16 dB CNR is a typical requirement of digital optical communication systems, FM video signals are no more prone to degradation from laser noise and nonlinearities than conventional lightwave systems. This is in contrast to VSB-AM video transmission, which requires 40–50 dB CNRs, values that are very difficult to achieve.

For a typical SCM system, the noise is dominated by the thermal noise of the receiver and thus,

$$S = (mI)^2 R/(2N_F kTB), \tag{7}$$

where m is the modulation depth of the microwave carrier relative to the DC photocurrent, R is the 50 Ω load, and B is the 30 MHz filter bandwidth. The r.m.s. photocurrent/channel, $mI/\sqrt{2}$, needed to achieve a 56 dB SNR is then 0.47 μA. For a 30 μA DC photocurrent, which would be reasonable for a 10–15 km system with 5 dB system margin, this corresponds to a modulation depth of only 2% channel (Olshansky 1987; Olshansky & Lanzisera 1987).

For digital systems the CNR required for a 10^{-9} bit error rate (BER) is a 12.6 dB for either binary PSK (BPSK) or QPSK and 15.6 dB for synchronously detected FSK.

The data rate required for transmission of video signals generally varies from about 70 Mb s^{-1} to 140 Mb s^{-1} depending on the encoding scheme. In the following analysis, a 100 Mb s^{-1} data rate is taken as typical and the receiver bandwidth as 120 MHz (Hill & Olshansky 1988) for a frequency deviation of 100 MHz. For FSK modulation with differential detection, equation (4) gives a 0.94 μA r.m.s. photocurrent. This corresponds to a modulation depth of 4.3% per channel for a 30 μA DC photocurrent.

The comparison between digital and analogue transmission of video is summarized in table 1. Overall, digital transmission requires four times the bandwidth and twice the signal

TABLE 1. SOME OF THE SALIENT FEATURES OF FM AND FSK TRANSMISSION OF VIDEO SIGNALS ARE COMPARED

	analogue	digital
format	FM	100 Mb s^{-1} FSK
receiver bandwidth	30 MHz	120 MHz
signal quality	56 dB weighted SNR	10^{-9} BER
CNR	16.5 dB	16 dB
r.m.s. photocurrent/channel	0.5 μA	1.0 μA

level per channel. Because the FM equipment is already mass-produced for the consumer market and is relatively inexpensive, FM transmission appears to have a significant advantage in the near term.

5. Sixty-channel FM video transmission experiment

To verify the analysis of the previous section, a 60-channel FM video transmission experiment (Olshansky & Lanzisera 1987) has been carried out. The 60-channel video source is shown in figure 4. Eleven channels are taken from a C-band satellite transmitting in the 3.7–4.2 GHz band and a twelfth channel is combined with this for transmission of video test patterns. The 12-channel signal is then power divided into three branches. One propagates straight through and the other two are shifted ±500 MHz and ±1000 MHz using two balanced mixers. The three branches are then recombined to form a 60-channel signal spanning the 2.7–5.2 GHz band. The composite signal is used to modulate directly a 1.3 μm VPRBH laser biased at 5 mW.

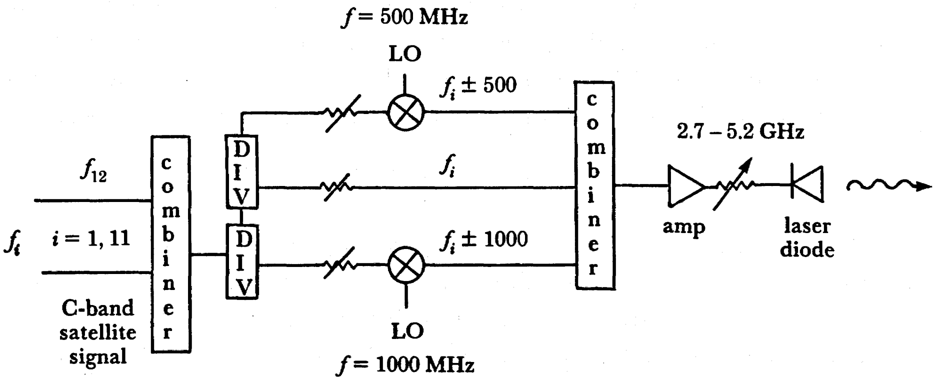

Figure 4. Diagram of 60-channel FM video transmitter for SCM system experiment.

A power level of about 700 μW is coupled into a single-mode fibre, and the signal is propagated over an 18 km length of standard single-mode fibre, containing four GTE elastomeric splices (Melman & Carlsen 1982). The total optical loss of the fibre is 8 dB. An additional 4 dB of loss in intentionally introduced at the photodetector to give a received photocurrent of 30 μA. The measured CNR and weighted SNR are shown in figure 5 as a function of the modulation depth per channel. A 56 dB weighted SNR is obtained with a 2% modulation depth per channel and a corresponding 16.5 dB CNR.

While these numbers suggest that the total modulation depth is 2% × 60 or 120%, it should be recognized that the 60 carriers operate with random relative phases and thus the r.m.s. modulation depth $m\sqrt{N}$ or 15% is a more appropriate measure of the laser modulation depth. In other system experiments r.m.s. modulation depths of 25% have been achieved while still maintaining the 56 dB SNR.

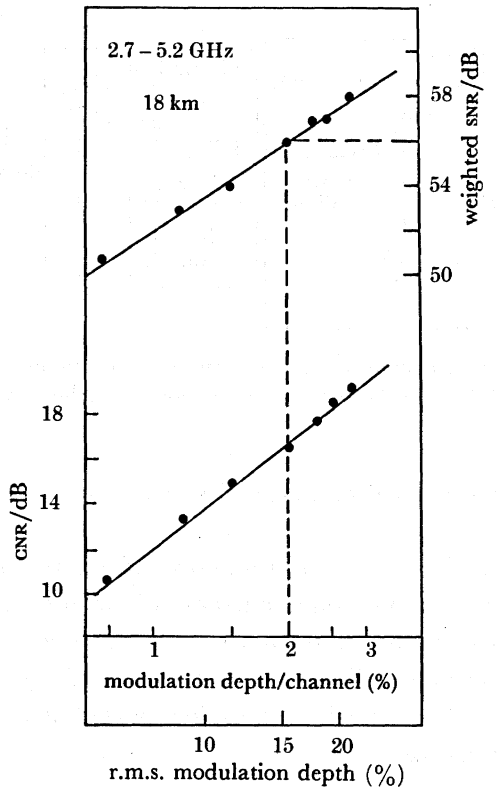

FIGURE 5. Weighted SNR and CNR against modulation depth per channel for the 60-channel FM video transmission experiment over 18 km of single-mode fibre.

6. TWENTY-CHANNEL FSK VIDEO TRANSMISSION

To verify the analysis for SCM digital video transmission, a 20-channel FSK system has been built (Hill & Olshansky 1988). The 20 carriers span the 2–6 GHz band with a 200 MHz spacing between carriers. The carrier frequencies were chosen as 2.1, 2.3, ..., 5.9 GHz. This selection places all the second-order intermodulation products at frequencies, $f_i \pm f_j$, which lie between the carriers. The frequency deviation of each carrier is 100 MHz.

Each subcarrier is generated by a voltage-controlled oscillator (VCO) and multiplexed by using microwave power combiners. Each VCO is followed by an isolator to prevent distortion which could be caused by interactions between VCOs and by electrical reflections. Filters are used where appropriate to eliminate second harmonics from the VCOs that would fall within the 2–6 GHz band. The optical link consisted of a 1.3 μm InGaAsP VPRBH laser, 12 km of standard single-mode fibre, and an InGaAs PIN photodetector. The laser biased at 5 mW per facet has a resonant frequency of 9 GHz, and has a flat frequency response and a RIN of less than -135 dB Hz^{-1} over the 2–6 GHz band. The noise contributed by the largest second-order intermodulation distortion has been measured to be at least 10 dB below the thermal noise of the microwave amplifier for modulation depths of 5.5% per channel or less.

The SCM receiver is shown in figure 6. It consists of circuit for frequency selection and a delay-line discriminator which demodulates the FSK signal. The frequency selection is accomplished with a band-pass filter centred at 6.5 GHz, a mixer and a tunable VCO operating over

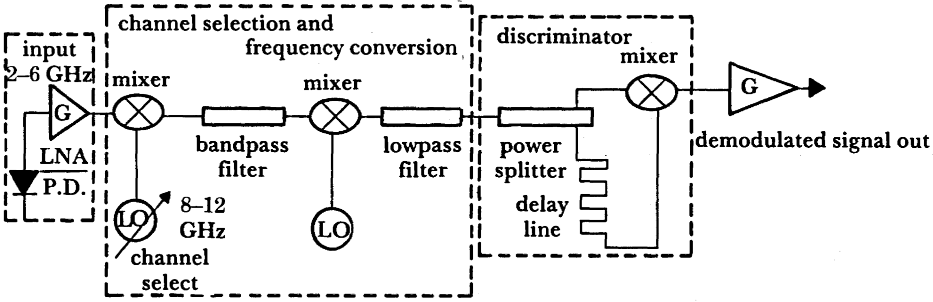

FIGURE 6. The SCM receiver for the 20-channel FSK video transmission experiment showing channel selection, down-conversion to intermediate frequency and delay-line discriminator.

8–13 GHz. A second mixer and local oscillator downconvert the signal to a 1.2 GHz intermediate frequency.

The measured BER is shown in figure 7 as a function of the modulation depth per channel. Results were obtained with a DC photocurrent of 50 μA. A modulation depth of 3.3 ± 0.3 %/channel was required to obtain a 10^{-9} BER. The corresponding CNR of 17 dB is within 1 dB of the theoretical value. The system was successfully operated with modulation depths of up to 5 %/channel. This is the first example reported of an SCM system operating over a bandwidth exceeding one octave.

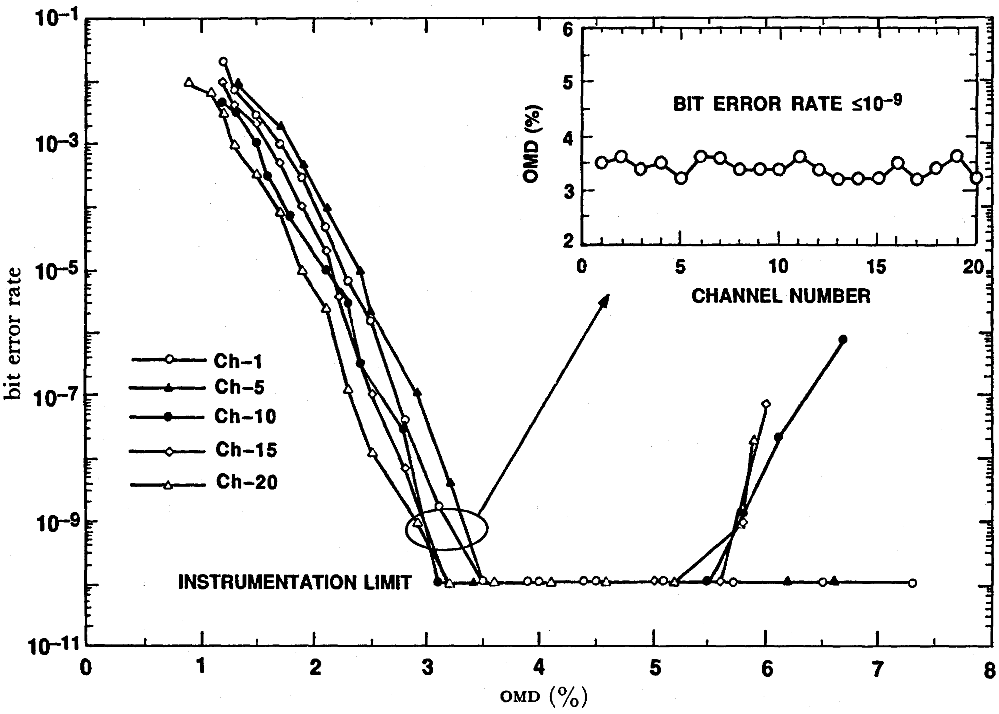

FIGURE 7. Measured BER against modulation depth per channel for a selection of the 20 FSK 100 Mb s^{-1} channels transmitted over 12 km.

7. Baseband digital plus 60-channel FM transmission

An additional feature of SCM transmission is that microwave and baseband signals can be transmitted simultaneously from a single laser source (Olshansky *et al.* 1988; Way & Castelli 1988). To demonstrate this concept a commercial hybrid coupler has been used to combine a 100 Mb s^{-1} baseband signal generated by a BER test set and the 60-channel FM video signal described in §5. The block diagram for the system experiment is shown in figure 8. Following the photodiode and bias tee, a second hybrid coupler separates the baseband and high-frequency signals.

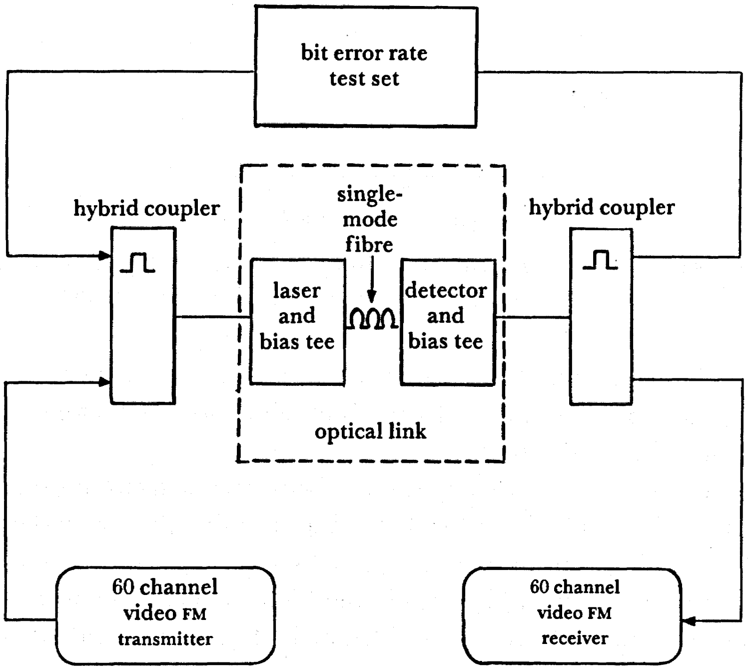

Figure 8. Block diagram for hybrid SCM experiment combining a 100 Mb s^{-1} baseband signal and 60 FM video channels.

The hybrid coupler introduces a 0.5 dB insertion loss in the baseband channel and a 3 dB loss for the high-frequency signals. On the transmitter side, the insertion loss is unimportant as the power of the input signals can be easily increased to achieve the desired modulation depth. At the receiver, the insertion loss represents a degradation of the signal before amplification, and the CNR becomes

$$S = \eta(mI)^2R/(2N_F kTB) \tag{8}$$

where η is the insertion loss of the hybrid coupler. A DC-6 GHz PIN-FET receiver would eliminate signal degradation due to the hybrid coupler's insertion loss.

A 65 MHz baseband filter follows two 500 MHz video amplifiers with noise figures of 1.5 dB which provide a total of 65 dB power gain. The baseband SNR is measured with a power meter following the two amplifiers. Figure 9 shows the BER measured for the 100 Mb s^{-1} baseband signal as a function of the measured SNR for transmission over 12 km of fibre. A 20 dB SNR is required to obtain a BER of 10^{-9}. This is somewhat higher than the theoretical value of 15.6 dB due to electrical reflections between the photodetector and the amplifier which

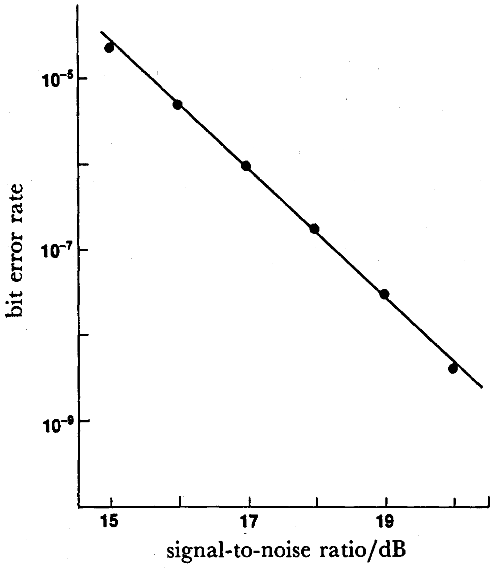

FIGURE 9. Measured BER (●) against SNR for the 100 Mb s^{-1} baseband signal transmitted over 12 km of fibre. The same BER is obtained whether or not the 60 channels are present.

produce intersymbol interference. The measured BER is the same whether or not the 60-channel FM signal is transmitted. Similarly, a 56 dB SNR is obtained for the 60 FM channels whether or not the baseband signal is transmitted.

This experiment demonstrates the compatibility between SCM transmission and conventional baseband signalling. The results indicate that subscriber distribution systems could be built with 140–565 Mb s^{-1} being transmitted to each subscriber at baseband for switched services (Linnell 1986; Linnell & Spears 1987), while the high frequency band could be used as an overlay to provide conventional broadcast video or high-definition video services.

8. SUMMARY

This paper has described the use of microwave subcarriers to transmit multichannel video signals over single-mode fibre. These systems provide an alternative method of using the wide bandwidth of single-mode fibres, InGaAsP lasers and InGaAs PIN photodiodes. Subcarrier multiplexed systems make use of available microwave components and take advantage of well-developed microwave transmission techniques. The basic design rules of multichannel SCM lightwave systems have been described and verified with several system demonstrations. Sixty FM video channels, 20 FSK 100 Mb s^{-1} channels, and a hybrid system combining a 100 Mb s^{-1} baseband signal and 60 FM video channels have all been demonstrated. These systems perform either at or near the levels predicted by the SCM design rules. It is clear that the same basic multiplexing techniques can be used to include many additional information channels or as a method for multiplexing multigigabit-per-second data rates.

The history of telecommunications in the twentieth century has been primarily based on the use of RF carriers to transmit multiple information channels. The microwave subcarrier multiplexing techniques described in this paper demonstrate that the same principles can be effectively applied to lightwave systems. As lightwave systems push to greater and greater transmission bandwidths, it is possible that subcarrier multiplexing rather than baseband digital modulation will emerge as the more natural method for exploiting the enormous bandwidth of lightwave systems.

The author is grateful to Dr R. B. Lauer and Dr B. A. Shortt for their strong support and encouragement. Special thanks are due to my colleagues, Mr P. Hill and Mr V. Lanzisera, for their extensive contributions to the development of the SCM systems, and to the many people in the Optoelectronic Device Department of GTE Laboratories who have contributed over the years to the development of high-speed lasers and photodiodes.

REFERENCES

Baack, C., Bachus, E.-J. & Heydt, G. 1987 *Tech. Dig. of 13th European Conf. on Opt. Commun.* III, pp. 79–88. Helsinki, Finland.
Bechtle, D. W. & Siegel, S. A. 1982 *RCA Rev.* **43**, 277–309.
Blauvelt, H. & Yen, H. 1984 *SPIE Proc. Opt. Technol. Microwave Appl.* **477**, 44–49.
Bowers, J. 1986 *Electron. Lett.* **22**, 1119–1121.
Bowers, J., Chipsloski, A. C., Boodaghians, S. & Carlin, J. W. 1987 *IEEE J. Lightwave Technol.* **LT-5**, 1733–1741.
Burrus, C. A., Bowers, J. E. & Tucker, R. S. 1985 *Electron Lett.* **21**, 262–263.
Clayton, L. 1976 *IEEE Trans. Cable Television* **CATV-1**, 25–30.
Daly, J. C. 1982 *IEEE Trans. Commun.* **COM-30**, 1954–1958.
Darcie, T. E. 1987 *IEEE J. Lightwave Technol.* **LT-5**, 1103–1110.
Darcie, T. E., Dixon, M. E., Kasper, B. L. & Burrus, C. A. 1986 *Electron. Lett.* **22**, 774–775.
Darcie, T. E., Tucker, R. S. & Sullivan, G. J. 1985 *Electron. Lett.* **21**, 665–666.
Faulkner, D. W., Russ, D. M., Douglas, D. & Smith, P. J. 1988 *Electron. Lett.* **24**, 655–656.
Gee, C. M., Newberg, I. L., Thurmond, G. D. & Yen, H. W. 1986 *Tech. Dig. IEEE, MTT-S Int. Microwave Symp., CC*-1.
Gimlett, J. 1987 *Electron. Lett.* **23**, 281–283.
Hill, P. & Olshansky, R. 1988 *Tech. Dig. Conf. Lasers and Electro-Optics*, Anaheim, California, pp. 128–130.
Iannone, P. & Darcie, T. 1987 *Electron. Lett.* **23**, 1361–1363.
Lau, K. Y. & Yariv, A. 1984 *Appl. Phys. Lett.* **45**, 1034–1036.
Linnell, L. 1986 *IEEE J. selected Areas Commun.*, **SAC-4**, 612–618.
Linnell, L. & Spears, D. 1987 *Tech. Dig. of 13th European Conf. on Opt. Commun.*, II, pp. 132–136. Helsinki, Finland.
Melman, P. & Carlsen, J. W. 1982 *Electron. Lett.* **18**, 320–321.
Olshansky, R. 1987 *Tech. Dig. of 13th European Conf. on Opt. Commun.*, II, pp. 122–125. Helsinki, Finland.
Olshansky, R. & Lanzisera, V. 1987 *Electron. Lett.* **23**, 1196–1197.
Olshanky, R., Hill, P., Lanzisera, V. & Powazinik, W. 1987*a* *J. quant. Electron.* **QE-23**, 1410–1418.
Olshansky, R., Powazinik, W., Hill, P., Lanzisera, V. & Lauer, R. B. 1987*b* *Electron. Lett.* **23**, 839–841.
Olshansky, R., Lanzisera, V. & Hill, P. 1988 *IEEE MTT-S Symposium. Dig.* II, pp. 901–903.
Pan, J. J. 1983 *Tech. Dig. Opt. Fiber Commun. Conf.*, New Orleans, Louisiana. TuK2.
Schlafer, J., Su, C. B., Powazinik, W. & Lauer, R. B. 1985 *Electron. Lett.* **21**, 469–471.
Schlafer, J. & Ulbricht, L. 1988 *Tech. Dig. Opt. Fiber Commun. Conf.*, New Orleans, Louisiana, pp. 185–186.
Siocos, C. A. 1984 *Space Commun. Broadcast* II, 363–369.
Stanley, I. W., Hill, G. R. & Smith, D. W. 1987 *IEEE J. Lightwave Technol.* **LT-5**, 439–451.
Stephens, W. E. & Joseph, T. R. 1985 *IEEE J. Lightwave Technol.* **LT-3**, 308–315.
Tjhung, T. T., Lim, T. K. & Mendis, F. C. V. 1983 *Electron. Lett.* **19**, 106–107.
Tjhung, T. T., Selvan, B., Haldar, M. K. & Mendis, F. C. V. 1986 *Electron. Lett.* **22**, 507–509.
Way, W. I. & Castelli, C. 1988 *Electron. Lett.* **24**, 611–612.
Way, W. I., Wolff, R. S. & Krain, M. 1987 *IEEE J. Lightwave Technol.* **LT-5**, 1325–1332.

Discussion

P. A. KIRKBY (*STC, Harlow, U.K.*). Has Dr Olshansky done any work to study the problems of using more than one laser source on the same passive network to study interference effects if the laser optical frequencies coincide? Does he agree that microwave on optics is an alternative to TDM rather than WDM?

R. Olshansky. Yes, I have done some theoretical analysis on the use of more than one laser source on the same passive network. These are noise problems caused by the beating of two lasers whose frequencies have drifted too close. The severity of the problem depends on the linewidth of the lasers and the bandwidth of the signal being transmitted. Whether such systems are practical or not will depend on the details of the system.

I agree with Dr Kirkby's second point, but I feel that it is more accurate to say that SCM is an alternative to baseband digital signalling. I make the distinction because TDM and SCM are compatible in the sense that if we want to build an 8 Gb s^{-1} system, we could use four microwave carriers, each carrying a 2 Gb s^{-1} TDM signal. As he points out SCM is completely compatible with WDM.

H. S. Hinton (*AT&T Bell Labs, Naperville, U.S.A.*). Has Dr Olshansky experimentally demonstrated the optical amplification of a subcarrier multiplexed signal? Will there be problems with crosstalk as a result of the nonlinearities of optical amplifiers?

R. Olshansky. We have not yet carried out the demonstration of optical amplification of an SCM signal. I do not expect any crosstalk or four-wave-mixing problems because the modulation depth m of each SCM channel is so small that this reduces nonlinear effects by factors such as m^3 or m^4.

W. J. Stewart (*Plessey Research & Technology (Caswell) Ltd, Towcester, U.K.*). Dr Olshansky claimed that second-order intermods would be small if less than one octave was used; but his example used 2–6 GHz, more than one octave. Is he happy that this will be satisfactory in use (e.g. ageing, etc.)?

R. Olshansky. Second-order intermods at $f_i \pm f_j$ are completely out of band if the SCM bandwidth is less than one octave. Second-order intermods do fall in-band in the FSK system which spans the 2–6 GHz band. A detailed analysis, supported by measurements, shows that the second-order IMPs are only a problem if one operates too close to the laser resonant frequency. In the experiment reported, the laser resonant frequency is at 8–9 GHz and there is no intermod problem. A more detailed discussion of this appears in the published proceedings.