COMPARISON OF DIRECT AND EXTERNAL MODULATION FOR CATV LIGHTWAVE TRANSMISSION AT 1·5 μm WAVELENGTH

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The use of a high-power 1·5 μm DFB laser and a linearised Ti : $LiNbO_3$ Mach–Zehnder modulator as a transmitter in a CATV lightwave system is reported. The performance is compared with directly-modulated 1·5 μm-wavelength DFB lasers in 60 channel transmission over 16 km of conventional singlemode fibre. The transmission of 52 high-frequency channels is demonstrated (450–750 MHz) in anticipation of future CATV upgrades.

Amplitude-modulated vestigial-sideband (AM-VSB) CATV lightwave systems impose strict requirements on the optical transmitter. Directly-modulated DFB lasers suffer poor yield due to the high degree of linearity needed [1]. Direct modulation also produces frequency 'chirp' which causes nonlinear distortion when combined with fibre chromatic dispersion [2], wavelength-dependent variations in optical-amplifier gain [3], or multipoint reflections [4]. In addition, the relaxation resonance of laser diodes may make it difficult to extend linear response to the higher frequencies (up to ~1 GHz) which are envisioned for future systems [5].

External modulation using an $LiNbO_3$ Mach–Zehnder modulator may be an attractive alternative to direct modulation if sufficient laser power is available to accommodate the modulator insertion loss. Composite second order distortion (CSO) products are extremely low when the modulator is biased at the half-transmission point [6], and chirp can be eliminated [7]. Composite triple beat (CTB) distortion products are unacceptably large, but can be reduced by several methods. These include electronic predistortion [8] and feed-forward compensation [9]. Here we report 1·5 μm-wavelength 60 channel transmission over 16 km of conventional singlemode fibre using external modulation and electronic predistortion. We compare the results with those obtained using directly-modulated 1·5 μm-wavelength DFB lasers. In anticipation of future CATV upgrades, we also demonstrate transmission of 52 high-frequency (450–750 MHz) channels.

A schematic diagram of our predistortion circuit is shown in Fig. 1. The diode pair is a commercial beam-lead device using wafer-matched medium-barrier microwave diodes. When the diodes are forward-biased at ~0·30 V, and the input signal level is properly adjusted, a substantial third-order term is generated. This is added to the main drive signal to cancel the third-order distortion produced by the Mach–Zehnder modulator.

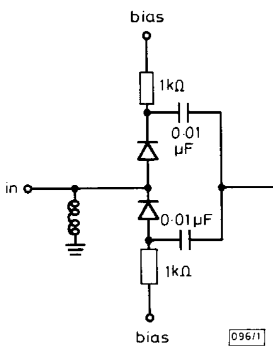

Fig. 1 *Diode-pair predistortion circuit*

An experimental system, shown in Fig. 2, was set up for transmission measurements. The signal source was either of two Matrix Test Equipment multiple-frequency signal generators: 60 channels ranging from 55·25 to 439·25 MHz, or 52 channels ranging from 445·25 to 751·25 MHz. The carriers were unmodulated. A high-power 1·56-μm DFB laser, running continuous-wave, launched +9·0 dBm of optical power into a lensed singlemode fibre. The Mach–Zehnder modulator was a commercial device from AT&T. It exhibited an insertion loss of 2·9 dB, an extinction ratio of 30 dB, and a switching voltage of 3 V. The modulator was biased at the inflection point, resulting in an additional optical loss of 3·0 dB. Therefore, +3·1 dBm of modulated optical power was available for transmission experiments. Frequency-response measurements indicated a rolloff of 1 dB over the range 100–450 MHz. This was partially compensated for by a slope equaliser placed in the main signal path (see Fig. 2). The modulator response was flat from 450 to 750 MHz, so that slope equalisation was not necessary in this band. The required predistortion signal was ~40 dB down in power from the undistorted drive signal to the modulator. Consequently, attenuators were required on each side of the predistortion circuit. This had the advantage of making impedance matching unnecessary. The 16 km optical fibre was a conventional depressed-cladding type with total loss of 3·0 dB and dispersion of ~270 ps/nm at 1·56 μm wavelength. For baseline measurements, the fibre was replaced with a variable optical attenuator.

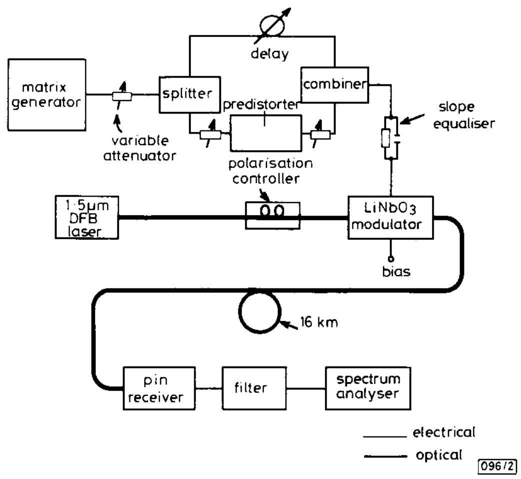

Fig. 2 *Experimental transmission system with linearised modulator*

In the 60 channel experiment, the channels ranged from 55·25 to 439·25 MHz. The optical modulation depth (OMD) was set to 3·0% per channel. The received optical power was adjusted to −1·0 dBm. The carrier-to-noise ratio (CNR) in a 4 MHz bandwidth, the CSO distortion, and the CTB distortion were measured at channels 3 (61·25 MHz), 11 (199·25 MHz), 40 (319·25 MHz), and 60 (439·25 MHz). Results are shown in Table 1. For all channels, the CNR was ~51 dB, the CSO was less than −68 dBc, and the CTB was less than −61 dBc. These results were unaffected by 16 km of optical fibre. It is worth noting that without predistortion the CTB was ~−45 dBc. Thus, the use of our circuit reduced the CTB distortion by ~16 dB.

For comparison, a 1·5 μm DFB laser was directly modulated with the 60-channel signal at an OMD of 3·0% per channel. The frequency chirp of the laser was 0·41 GHz/mA. The CSO distortion was measured both before and after transmission over 16 km of fibre. As predicted by Reference 2, chromatic dispersion acting on the chirped signal led to a

Table 1 PERFORMANCE IN 60 CHANNEL CATV LIGHTWAVE SYSTEM

Channel	Frequency	CSO	CTB	CNR
	MHz	dBc	dBc	dB
3	61·25	−74·0	−63·1	51·5
11	199·25	−74·0	−61·7	51·6
40	319·25	−75·0	−64·4	52·0
60	439·25	−68·2	−62·5	51·1

severe impairment. At channel 60, the most affected channel, the CSO was increased by 12·5 dB, to −41·0 dBc. Similar results were obtained with a second DFB laser which exhibited chirp of 0·56 GHz/mA. In this case the CSO was degraded by 15 dB, to −37·5 dBc.

The bandwidth of our external modulator is 4·5 GHz. The predistortion circuit should have a bandwidth of greater than 1 GHz. Consequently, the linearised modulator may be useful in extending the CATV band to higher frequencies. In the 52 channel experiment, the channels ranged from 445·25 to 751·25 MHz. The OMD was 3·2% per channel. Second-order products do not fall within the band, and consequently CSO distortion is absent. Results for CNR and CTB measurements are shown in Table 2 for channels 63 (457·25 MHz), 70 (499·25 MHz), 87 (601·25 MHz), 116 (703·25 MHz), and 122 (739·25 MHz). For all channels, the CNR was greater than 51 dB, and the CTB was less than −60 dBc. As before, there was no degradation after transmission over 16 km of fibre.

Table 2 PERFORMANCE IN 52 CHANNEL HIGH-FREQUENCY CATV LIGHTWAVE SYSTEM

Channel	Frequency	CTB	CNR
	MHz	dBc	dB
63	457·25	−62·9	52·0
70	499·25	−60·8	52·5
87	601·25	−60·9	53·4
116	703·25	−62·7	53·2
122	739·25	−62·4	51·8

Results obtained over both frequency bands, ranging from 55·25 to 751·25 MHz, demonstrate the advantage of the simple high-speed beam-lead diode pair as the nonlinear predistorter element. This broadband capability has not yet been demonstrated for more complex circuits consisting of multiple diodes [8] or analogue multipliers [5].

In conclusion, we have reported CATV transmission experiments which uses a CW DFB laser and linearised $Ti:LiNbO_3$ Mach–Zehnder modulator as a transmitter. Predistortion of the modulator drive signal with a simple diode-pair circuit resulted in a reduction of CTB distortion by ~16 dB.

Multichannel operation at frequencies of up to 750 MHz was demonstrated. Transmission at 1·5 μm wavelength over 16 km of conventional fibre resulted in no degradation in system performance.

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References

1 SUSAKI, W.: 'Recent progress in superlinear InGaAsP laser diodes'. OFC '91, Paper WG5, San Diego, CA, 1991

2 PHILLIPS, M. R., DARCIE, T. E., MARCUSE, D., BODEEP, G. E., and FRIGO, N. J.: 'Nonlinear distortion from fiber dispersion of chirped intensity modulated systems', *IEEE Photonics Technol. Lett.*, 1991, **3**, pp. 481–483

3 KUO, C. Y., and BERGMAN, E. E.: 'Erbium-doped fiber amplifier second order distortion in analog links and electronic compensation', *IEEE Photonics Technol. Lett.*, 1991, **3**, p. 829

4 DARCIE, T. E., BODEEP, G. E., and SALEH, A. A. M.: 'Fiber reflection-induced impairments in lightwave AM-VSB CATV systems', *J. Lightwave Technol.*, 1991, **LT-9**, pp. 991–995

5 DARCIE, T. E., and BODEEP, G. E.: 'Lightwave subcarrier CATV transmission systems', *IEEE Trans.*, 1990, **MTT-38**, pp. 524–533

6 BODEEP, G. E., and DARCIE, T. E.: 'Comparison of second and third order distortion in intensity modulated InGaAsP lasers and $LiNbO_3$ external modulators'. OFC '89, Paper WK2, Houston, TX, 1989

7 KOYAMA, F., and IGA, K.: 'Frequency chirping in external modulators', *J. Lightwave Technol.*, 1988, **LT-6**, pp. 87–93

8 CHILDS, R. B., and O'BYRNE, V. A.: 'Predistortion linearization of directly modulated DFB lasers and external modulators for AM video transmission'. OFC '90, Paper WH6, San Francisco, CA, 1990

9 DERIDDER, R. M., and KOROTKY, S. K.: 'Feedforward compensation of integrated optic modulator distortion'. OFC '90, Paper WH5, San Francisco, CA, 1990

SOLVING THE GATE PACKING PROBLEM USING A CONCURRENT NETWORK

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Indexing terms: Computer aided design, Neural networks

The layout problem of gate matrices and one-dimensional logic arrays is composed of two major tasks: to find a permutation of gates which minimises the number of tracks required and to layout/pack gates based on the ordering. A parallel algorithm is presented in the Letter which can pack n gates within O(1) time, whereas the conventional near-optimum algorithm needs $O(n^2)$ time. The simulation results show that the increase of the problem size does not degrade the solution quality.

Introduction: Digital design is an exploration of the space of possible choice and a justification of time constraints. The layout design problem of large-scale integration circuits was introduced by Weinberger in 1967 [5]. Minimum track placement can be analogous to the general layout compaction problem. The problem is known as NP-complete [3]. The layout problem can be divided into two tasks. The first task is to find a permutation of the columns which minimises the number of tracks to pack the gates. Several algorithms for ordering the gates have been reported in References 1, 2, 6 and 7. The second task is to pack and lay out gates to minimise the area of the chip. Hashimoto and Stevens [4] proposed the left-edge first algorithm in 1971 which needs $O(n^2)$ time. No parallel algorithm for packing gates has been reported since then.

In this Letter a parallel algorithm is presented which can lay out and pack n gates within O(1) time. The algorithm uses a few processing elements. The processor network is the implementation of the Hopfield computation network. The network consists of m clusters where each cluster is composed of n processing elements (PEs). The proposed algorithm applies a two dimensional $m \times n$ processor network where m and n are the number of tracks and the number of gates, respectively. The output of the x_ith PE in the two dimensional processor network follows the binary function

$$V_{x_i} = \begin{matrix} 1 & \text{if } U_{x_i} > 0 \\ 0 & \text{otherwise} \end{matrix}$$

and (1)

$$U_{x_i} = \max(U_{k_i}) \qquad \text{for } k = 1 \ldots m$$

where U_{x_i} and V_{x_i} are the input and output of the processing element x_i, respectively. All the PEs are running concurrently to calculate their Us and Vs.

Gate packing problem: In one-dimensional logic arrays, the gates are arranged horizontally with each gate occupying a vertical strip. When the horizontal size of an array is fixed, the vertical spacing determines the total chip area which should be minimised. The vertical spacing is equivalent to the number of tracks. The existing algorithms provide a near-optimum ordering of the columns and determine the necessary minimum number of tracks. After the column assignment the gates must be placed on tracks. Our algorithm places and