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Then all the intersecting angles are equal to or greater than θ_{min} , and the total length of the crossconnecting section becomes

$$L_c = 2R \sin \phi + \{(N-1)(F-D) - 2R(1 - \cos \phi)\} / \tan \phi \quad (5)$$

Although the total length can be further reduced by optimising other intersecting angles, the effect is small. Thus, eqn. 5 gives the shortest length possible of the crossconnecting section having the waveguide curvature of R and the minimum intersecting angle of θ_{min} .

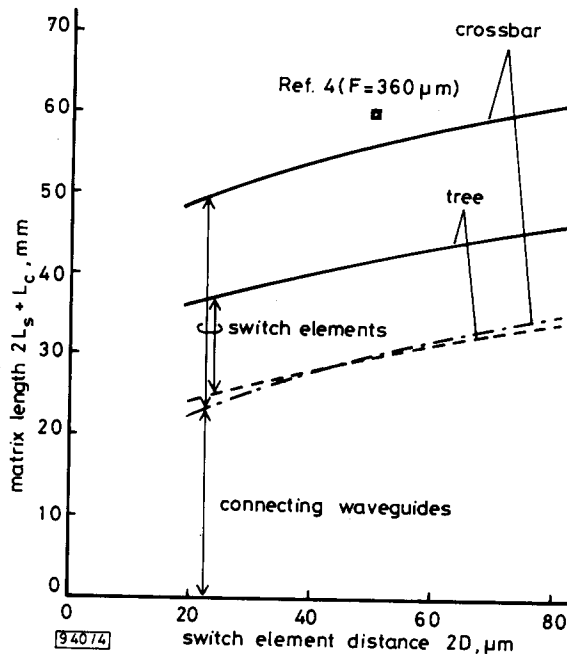


Fig. 4 Calculated matrix lengths as functions of adjacent switch element distance

$F = 200 \mu\text{m}$ is assumed in the crossbar. $R = 30 \text{ mm}$, $\theta_{min} = 7 \text{ deg}$, $L_{sw} = 2 \text{ mm}$

Calculations: The total length of the integrated 8×8 matrix is calculated from eqns. 1 and 5, and then compared with the length of the conventional crossbar matrix. The results are shown in Fig. 4. The minimum intersecting angle was assumed to be 7 degrees whereby crosstalk is negligible.⁵ The curvature of 30 mm and switch element length of 2 mm were used.³ The Figure shows that the required length of the connecting waveguides is almost the same for both the crossbar and the tree-structured matrices. However, the total length is shortened in the tree structure because this matrix requires only $6 (= 2n)$ -stage switch elements, whereas the crossbar matrix requires $15 (= 2N - 1)$ -stage elements. The total length of an 8×8 tree-structured matrix is 43 mm when the adjacent switch element distance is $60 \mu\text{m}$. Additionally, all the intersecting angles were calculated and confirmed to be equal to or greater than 7 degrees.

In the same way, the length of the 8×16 tree-structured matrix was calculated. In eqn. 1 the number of switch element stages was $n = 4$ for 1×16 splitters and $n = 3$ for 8×1 switches. The length of the crossconnecting section was almost the same as the length of $N = 12 (= (8 + 16)/2)$ in eqn. 5. The total length of 60 mm was obtained, and this length enables integration on a single substrate.

Conclusion: An integrated $N \times N$ tree-structured optical switch matrix has been proposed. The geometrical design considerations have been described. The required matrix length was shorter than that of the crossbar matrices, and 8×8 to 8×16 tree-structured matrices are possible on a single LiNbO_3 substrate.

K. HABARA
K. KIKUCHI

13th February 1987

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FOUR-PORT HOMODYNE RECEIVER FOR OPTICAL FIBRE COMMUNICATIONS COMPRISING PHASE AND POLARISATION DIVERSITIES

Indexing terms: Optical communications, Optical receivers

A new four-port homodyne receiver for optical fibre communications is proposed and studied experimentally. It comprises phase- and polarisation-diversity schemes, removing the need for phase locking and polarisation control. The bit-error-rate measurement is also reported.

Introduction: Among various coherent optical fibre communication schemes,¹ homodyne schemes are attractive because the required receiver bandwidth (highest detector response frequency) is equal to the signal baseband f_b , in contrast to typically $5f_b$ in heterodyne schemes.² This advantage will become increasingly important because the signal bit rate is now approaching the gigabit/s level, whereas the APD/PD response is still typically within a few gigahertz. However, in a conventional homodyne receiver, a phase match is required between the carrier and the local oscillator (LO), which is rather difficult to achieve. To overcome this difficulty, phase-diversity schemes^{3,4} have been proposed, offering practical countermeasures against the phase fluctuation.

Another fluctuation phenomenon that makes homodyne (as well as heterodyne) detection difficult is the fluctuation of the state-of-polarisation (SOP) in the received signal. In a recent paper⁵ one of the present authors predicted that, among various countermeasures against the SOP fluctuation, polarisation diversity⁶ would become most attractive in the future when optoelectronic (OE)IC receivers become common, and that polarisation and phase diversity would eventually be unified in a multiport detection system.

In this letter we propose a new four-port homodyne receiver comprising phase and polarisation diversities, and report bit error rate (BER) measurements, which are the first for DPSK homodyne systems. The features of the proposed scheme are: (i) no need for phase locking and polarisation control, (ii) the requirement on the laser linewidth is approximately equal to the conventional heterodyne DPSK detection scheme (detailed discussion will be reported elsewhere), and (iii) the possibility of a complete OEIC version in the future.

Principle: The received signal light, which has an arbitrary SOP, is split into two branches by a Wollaston prism; the two lights thus split are vertically and horizontally polarised (see Fig. 1). Both of them are led to 90 degree optical hybrids.⁷ Thus we obtain two pairs of in-phase (I) and quadrature (Q) signal components for the vertical and horizontal polarisations with respect to the LO. In each of the two pairs, the

Then all the intersecting angles are equal to or greater than θ_{min} , and the total length of the crossconnecting section becomes

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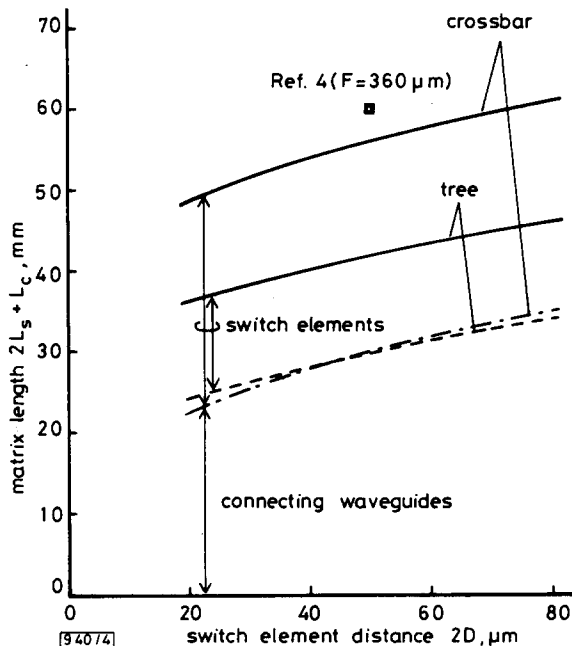


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the two polarisations. Thus the four combinations of the signal and LO are photodetected, amplified and DPSK-demodulated (i.e. multiplied with the signal itself delayed by T equal to a signal bit length), and finally, simply added algebraically.

The added output can be written, ignoring DC terms, as

$$V = \pm \{4K^2\alpha P_S P_L \cos^2 \phi(t) + 4(1-K)^2\alpha P_S P_L \times \cos^2 [\phi(t) + d_L - d_S] + 4K^2(1-\alpha)P_S P_L \times \cos^2 [\phi(t) + \theta] + 4(1-K)^2(1-\alpha)P_S P_L \times \cos^2 [\phi(t) + \theta + d_L - d_S]\} \quad (1)$$

where subscripts L and S denote LO and signal, respectively, P is the power at the input of the optical hybrid, K and α are power splitting factors of the 90 degree optical hybrid and in the Wollaston prism, respectively, $\phi(t)$ is the relative phase noise of the semiconductor lasers, θ is the phase difference corresponding to the ellipticity in the SOP of the signal, d is the phase difference between the vertical and horizontal field components, and the '+' sign corresponds to a DPSK mark signal (1, 1 or 0, 0) and a DPSK space signal (1, 0 or 0, 1), respectively.

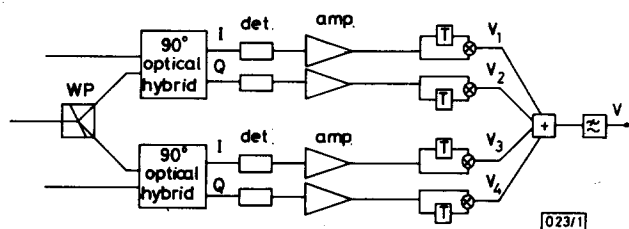


Fig. 1 Principle of proposed receiver

If we let $K = 1/2$ and $d_L - d_S = 90$ degrees in eqn. 1 because the system is so designed, eqn. 1 becomes independent of $\phi(t)$, θ and α , being simplified as

$$V = \pm P_L P_S \quad (2)$$

Thus, the complete DPSK signal can be restored by simply adding the four outputs.

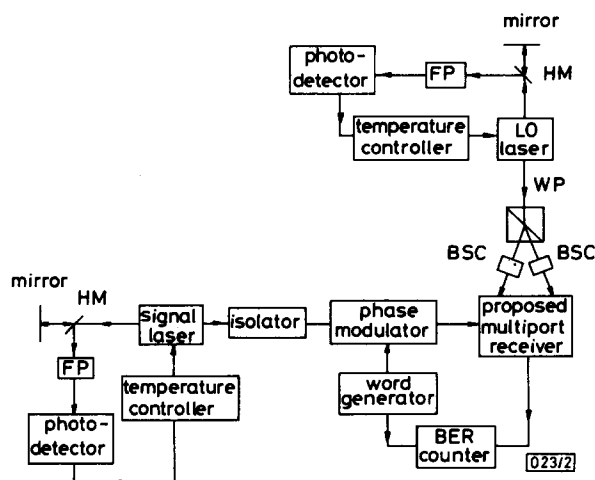


Fig. 2 Experimental set-up for BER measurement

HM = half-mirror, WP = Wollaston prism, FP = Fabry-Perot interferometer, BSC = Babinet-Soleil compensator

Experiment and results: The experimental set-up is shown in Fig. 2. Two $1.3 \mu\text{m}$ DFB external cavity semiconductor lasers are used as the signal and LO, which are frequency-stabilised by temperature control and an AFC loop. The beat frequency between the two lasers is less than 30 MHz, and the linewidth of the beat frequency is narrower than 1 MHz. An LiTaO_3 waveguide phase modulator is used to give the DPSK signal. The LO power at the photodetector surface is -8.2 dBm . The four front-end circuits consist of InGaAs PINs and GaAs FETs.

A detected eye pattern for the 200 Mbit/s, $2^{15} - 1$ pseudo-random sequence used in the experiment is shown in the inset of Fig. 3, where the measured BER (curves d, e) and theoretical curves (a, b, c) are also shown. In the calculation of the theoretical curves, the actual baseband amplifier bandwidth (200 MHz) is used, which is twice the Shannon limit. Curves a, b and c show the shot-noise-limited state without phase noise, that with a 1 MHz linewidth of the beat frequency, and the BER for finite LO power (-8.2 dBm), respectively. Curves d and e show the measured BER as a function of signal source power, and that as a function of the total signal power incident on the detectors (2.8 dB below d), respectively. Fig. 3 shows that the achieved sensitivity is -48.8 dBm for $\text{BER} = 10^{-7}$, which is about 5 dB worse than theory. The difference is attributed to the imbalance of the receiver, imperfect phase modulation and wavefront mismatch between signal and LO on the detector surface; efforts are being made to reduce these. The variation of the receiver sensitivity due to the fluctuation of the deflection angle of a linearly polarised signal was within $\pm 0.6 \text{ dB}$.

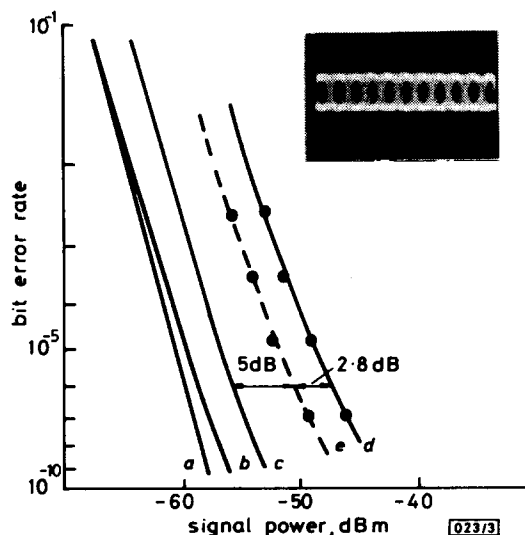


Fig. 3 Error rate against received signal power

See text for details

Discussion and conclusions: A new four-port homodyne receiver has been proposed and the BER has been measured. The results of experiment show that the proposed scheme is technically feasible, removing the need for phase locking and polarisation control.

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3rd March 1987

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