An Optical Fibre Switch Employing a Sagnac Interferometer

M. C. Farries*and D. N. Payne

Introduction

Local area networks and high-bit-rate telecommunications demand fast switches for modulators, re-routing and demultiplexing. Optically-driven nonlinear optical switches based on intensity- dependent phase shifts in an optical fibre have been demonstrated at femtosecond switching speeds[1]. An all optical switch has the benefit of compatibility with the rest of the optical network and its availability would considerably enhance the capabilities of optical transmission systems. An optical fibre switch which exploits the non-linearity in silica fibre may be polarimetric[2] or interferometric[1]. However, most configurations are very environmentally unstable and suffer large phase shifts due to temperature and vibration. The exception is the Sagnac interferometer (Figure 1), which uses the same path for both interfering beams and is therefore only sensitive to perturbations that occur in a time less than the loop transit time[3].

Figure 1: Experimental Sagnac switch configuration.

We describe here the basic theory of operation of the Sagnac fibre switch, followed by an experimental demonstration of a stable switch operating on a picosecond time scale.

Theory of Sagnac Switching

Self-switching of one beam by itself has already been reported[4,5] in a Sagnac loop. The effect relies on counter-propagating pulses of different amplitudes and is similar to the Kerr effect in the optical fibre gyroscope[6]. Because of the unequal pulse magnitudes, the switch contrast ratio is limited. In a balanced interferometer, no self-switching occurs. However full contrast can be obtained at a lower power level by switching a signal at one wavelength with a pulse at another. In this case the Sagnac interferometer is arranged to be balanced at the signal wavelength in order to obtain 100% contrast, and unbalanced at the switching pulse wavelength to obtain a low switching threshold.

In our switch the Sagnac interferometer is made from a fused taper coupler, with the two output ports spliced together (Figure 1). The coupler has a 50:50 splitting ratio at the signal wavelength and less than 5% at the pump wavelength. In the unperturbed fibre the phase difference m between the two counter-propagating paths is zero.

The pump induced phase shifts in the co-propagation and counter-propagation signal are mC and mA respectively. These are written as:

$$\phi_C(t) = \frac{2\pi l n_2 I_p(t)}{\lambda_s A \xi_0 c n} \qquad (1)$$

$$\phi_A = \frac{2\pi c n_2 E}{\lambda_s 2 n A \xi_0 c n} \qquad (2)$$

I_p = pump pulse power

n_2 = nonlinear refractive index = $2.5 \times 10^{-22}\mathrm{m/V^2}$

l = length of Sagnac loop.

A = pump spot area.

E = pump pulse energy.

λ_s = signal wavelength.

c = velocity of light.

n = refractive index of the fibre.

ξ_0 = permitivity of free space.

We have assumed for simplicity that the pump and signal spot areas are equal and that no group velocity walk-off occurs.

In order to quantify the shape of the switched signal we must take account of the pump pulse shape. We have taken this to be a Gaussian pulse from a mode-locked laser. The co-propagating phase shift ϕ_C follows the pump pulse profile as shown in Figure 2. The counter-propagating phase shift ϕ_A has the form of a pedestal with a width equal to the loop transit time. For short pulses where the pump pulse width T is less than half the loop transit time, ϕ_C is larger than ϕ_A. In this experiment ϕ_A was small enough to be neglected.

The intensity modulation of the signal output from the Sagnac loop may be expressed as

$$I_s = I_{so}\sin^2((\phi_C - \phi_A)/2) \qquad (3)$$

The switched signal pulse shape is a function of pump intensity as shown in Figure 2. Maximum modulation is obtained for a π phase shift (solid curve). For higher pump levels, where the phase is driven through more than π, the signal is split into multiple shorter pulses; here two are shown (dotted curve).

An important parameter for characterising a fast optical switch is the energy switched (i.e. the integral of the

*Plessey Research Ltd, Caswell, Towcester, Northants, NN12 8EQ

Figure 2: Calculated co-propagating, counter-propagating and total phase shifts for full modulation with a Gaussian pump pulse (lower 3 curves). Calculated signal modulation pulse shapes for π (upper solid curve) and 2π (dotted curve) phase shifts.

signal modulation for a given pump power.) This parameter can be obtained by numerical integration of the switched signal and is shown in Figure 3. In this experiment the measurements are instrument bandwidth limited so it is necessary to characterise the experiment with the switched energy rather than the amplitude. It is noted that full amplitude switching of the signal occurs at a lower pump intensity than maximum energy switching.

Figure 3: Signal energy switched for various peak pump powers (points are experimental measurements and curve is calculated).

Results

Pump pulses where obtained from a frequency-doubled, Q-switched, mode-locked, Nd:YAG laser and were launched into the Sagnac loop with a dichroic beamsplitter (Figure 1). The peak intensity and pulse width were independently measured after propagating through the fibre as 42W and 350ps respectively. A single mode fibre (NA = 0.17 and X_{co} = 420nm) formed the Sagnac loop. A controlled twist was applied to the loop to counteract the fibre birefringence and this ensured full reflection of the signal from the unpumped loop[7]. The signal was detected via a beam splitter with a silicon A.P.D. and is also shown in Figure 4. The secondary pulse on the oscilloscope trace is an artefact of the detector.

The variation of integrated signal modulation with pump power is compared with the theoretical plot in Figure 3. From this we calculate that full signal modulation was obtained for a pump power of 24W. Note that the energy switched saturates above full modulation power. This provides some stabilisation against pump intensity fluctuations at the expense of signal pulse distortion. Higher pumping levels are limited by the onset of competing nonlinear effects and this may be responsible for the poor correlation of measured results with theory at pump powers over 30W (Figure 3).

Discussion

Using a two-wavelength technique the Sagnac loop configuration appears attractive as an optical switch structure. Our measurements indicate that the switch was stable against environmental fluctuations, a decrease in loop reflection of only 10% occurring due to movement of the fibre in the loop. This could be corrected by applying a twist to a 5cm section of the loop. The switching power shows good agreement with theory which assumes that the signal and pump are parallel plane-polarised. The loop stability and switching intensity may be improved by utilising polarisation holding fibre and a polarisation maintaining coupler.

A considerable reduction in switching intensity to levels obtainable from semiconductor diodes may be obtained by increasing the loop length, although the maximum loop length is limited by group velocity walk-off between pump and signal. This may be minimised by correct fibre design and choice of the pump wavelength. In our experiment the switching time was limited by the pump pulse to 350ps fwhm. However, the loop switching time would be less than 10ps with a shorter pump pulse[1]. A possible application of the Sagnac switch demonstrated here is as the output coupler of a fibre or external-cavity diode laser. Optically driven mode-locking or Q-switching would then be an attractive possibility.

Acknowledgements

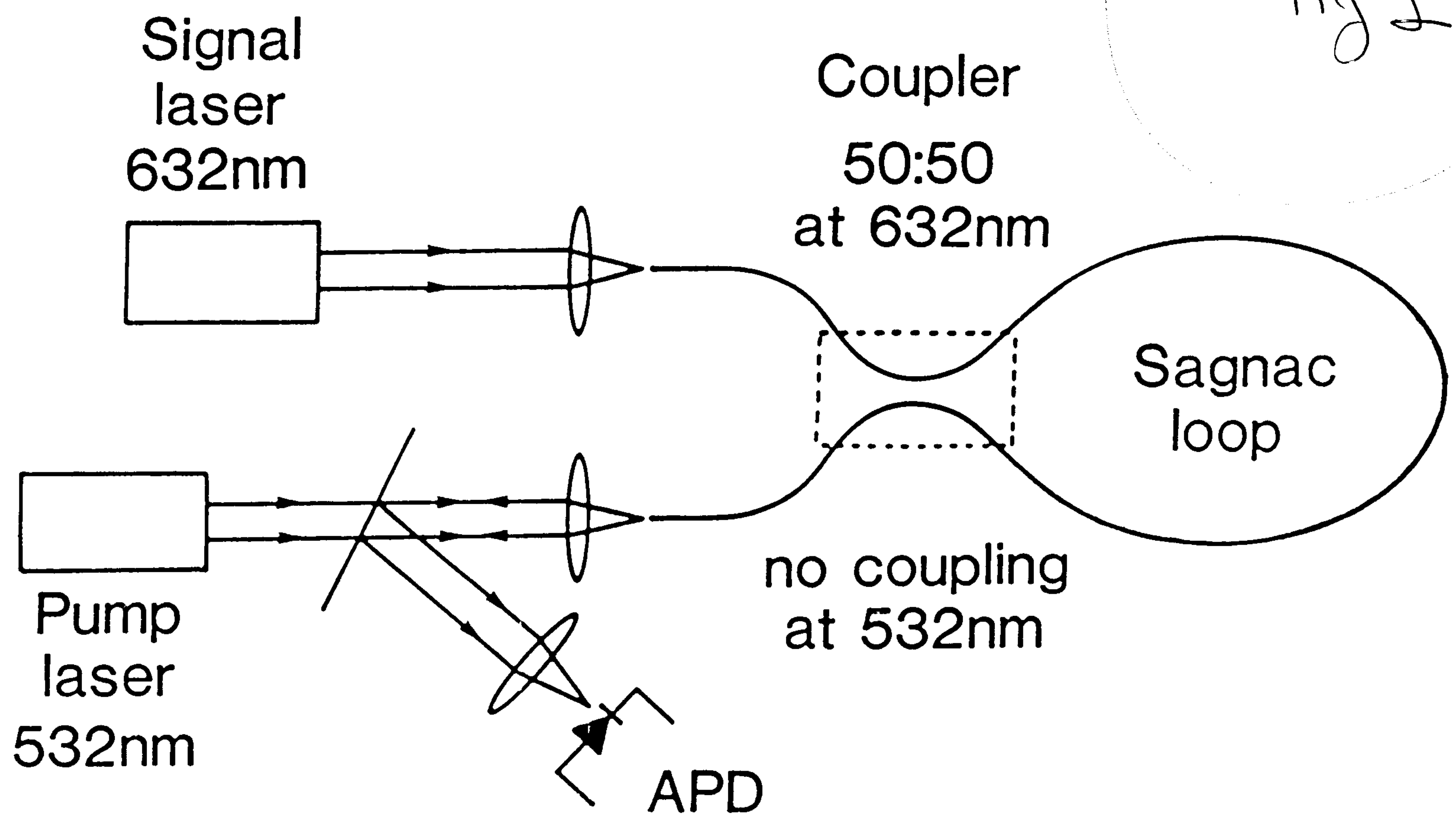
The authors would like to thank T. Birks, C. Tsao and P. Morkel for their assistance. This work is supported by the SERC/DTI JOERS. Dr. D. N. Payne receives a Readership from Pirelli.

References

1. Friberg, S. R., Weiner, A. M., Silberberg, B. G. and Smith, P. S., Opt. Lett., Vol. 13, 1988, pp. 904–906.
2. Trillo, S., Wabnitz, S., Stolen, R. H., Assanto, G., Seaton, C. T. and Stegeman, G. I., Appl. Phys. Lett., Vol. 49, 1986, pp. 1224–1226.

Figure 4: Instrument limited switched signal pulses.

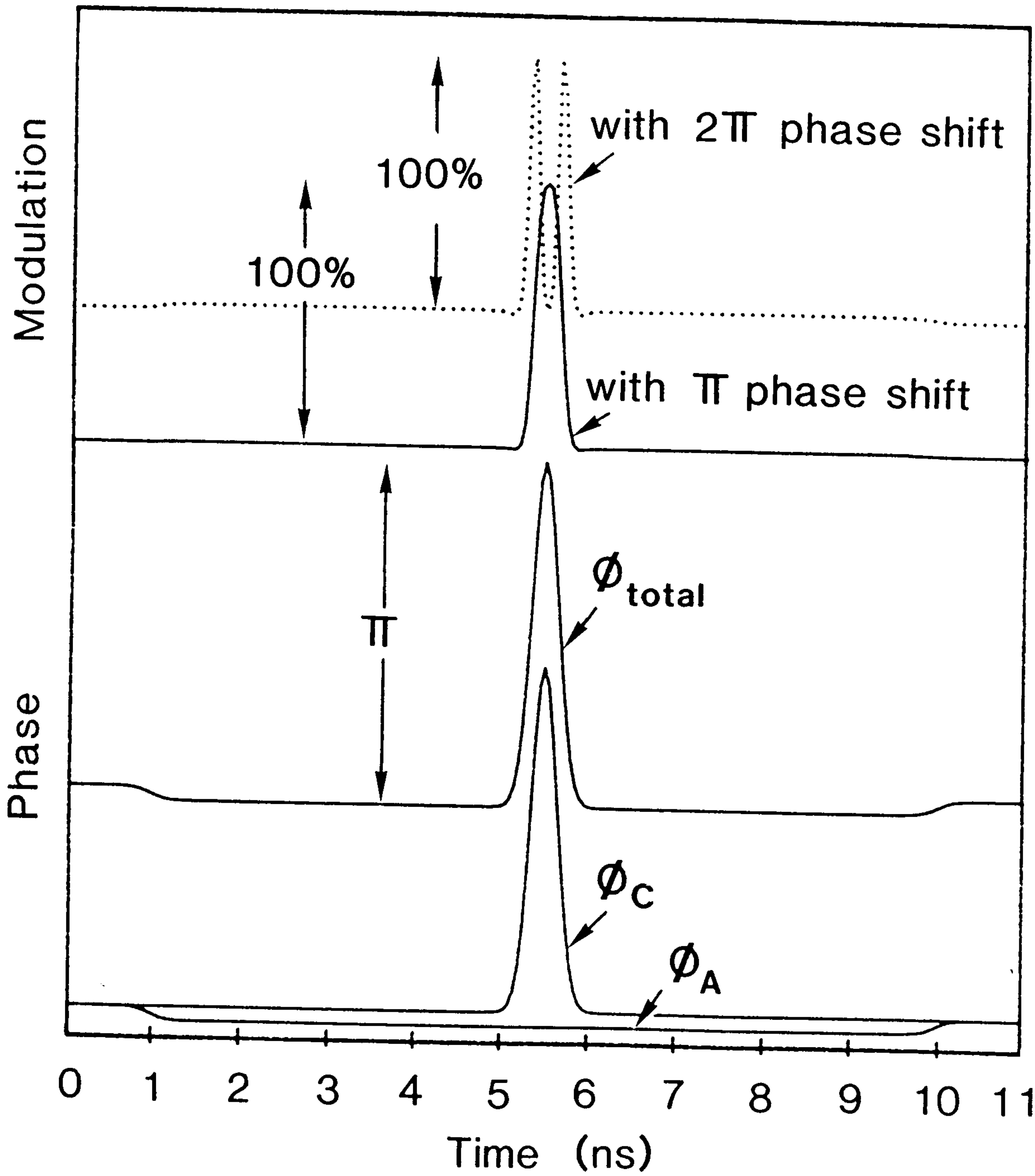
3. Shupe, D. M., Appl. Opt., Vol. 19, 1980, pp. 654–655.
4. Doran, N. J. and Wood D., Opt. Lett. Vol. 13, 1988, pp. 56–58.
5. Doran, N. J., Forrester, D. S. and Nayar, B. K., submitted to Electron. Lett. 1989.
6. Ezekiel, S., Davis, J. L. and Hellwarth, R. W., Opt. Lett. Vol. 7, 1982, pp. 457–459.
7. Birks, T. A., Morkel, P. R., "Jones Calculus analysis of single-mode fibre Sagnac reflector", Appl. Opt., Vol. 27, 1988, pp. 3107–3113.



20·5 to 8·0

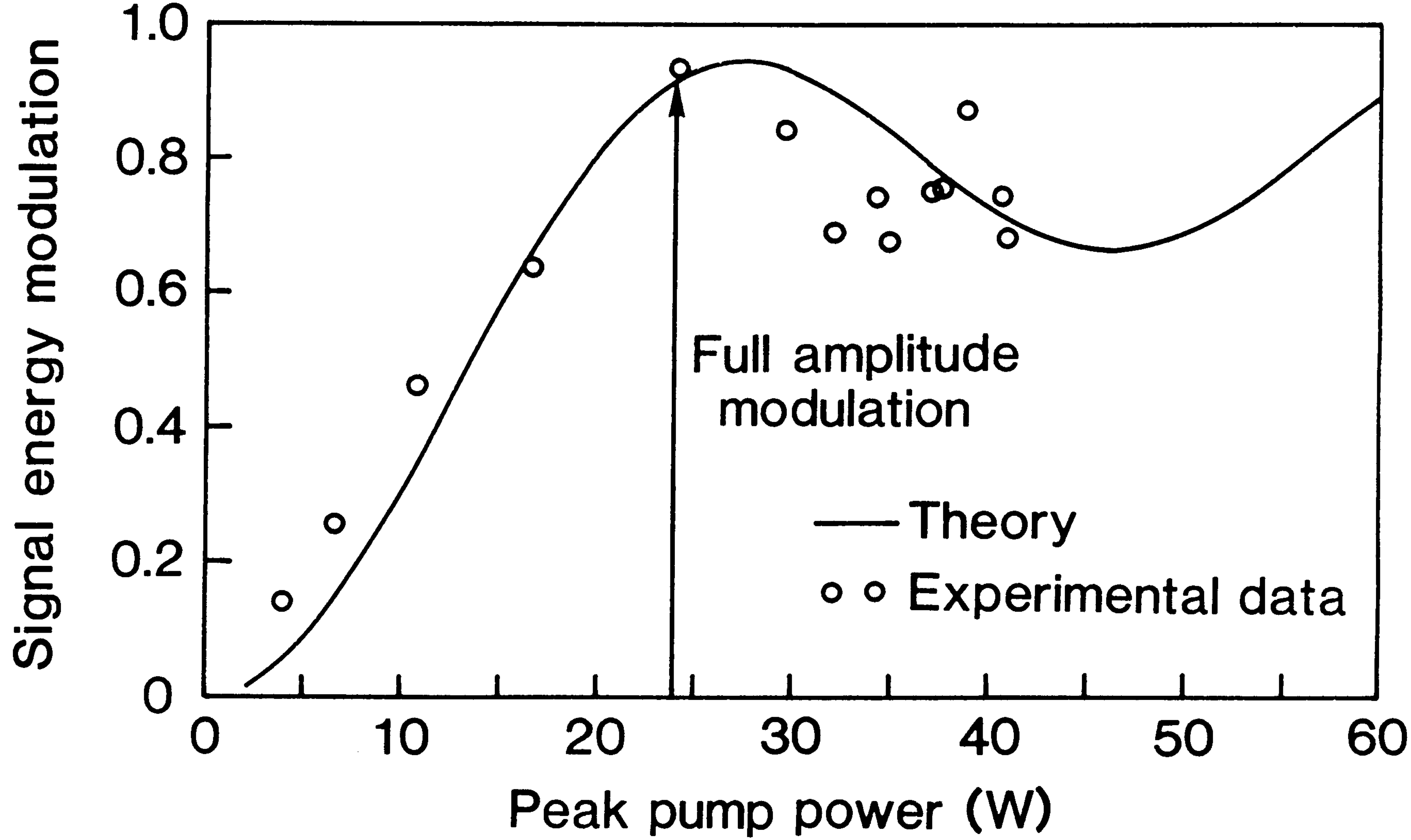
Fig 1

412 fig 2



Modulation
100%
100%
with 2π phase shift
with π phase shift
Phase
π
ϕ_{total}
ϕ_C
ϕ_A
0
1
2
3
4
5
6
7
8
9
10
11
Time (ns)

23·0
to
8·0
Fig3



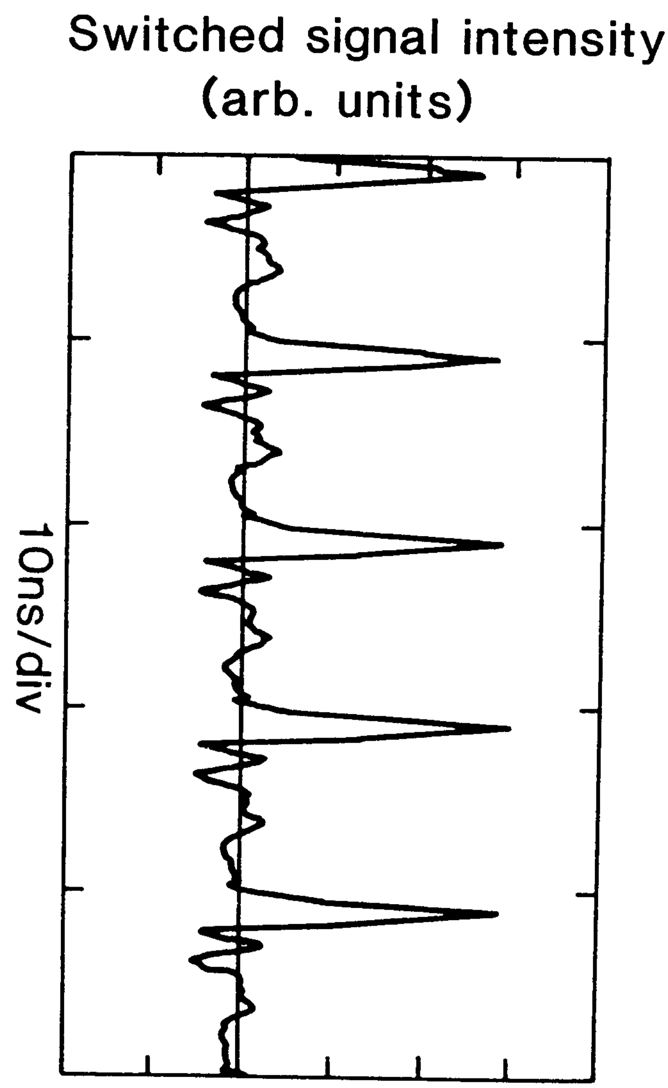


Fig4