VERY LOW THRESHOLD SAGNAC SWITCH INCORPORATING AN ERBIUM DOPED FIBRE AMPLIFIER

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Indexing terms: Optical switching, Optical fibres

Fast, very low threshold optical pulse switching, in a nonlinear loop mirror incorporating an erbium doped fibre amplifier (EDFA) operating at 1·536 μm with a gain of 46 dB is reported. For a 336 m Sagnac loop the input switching power is 200 μW, which is 5×10^3 lower than the best previously reported.

Introduction: All optical switching devices based on an ultrafast nonlinear optical process, or processes, are of considerable interest for use in high speed optical signal processing and telecommunication systems. Several switching schemes utilising $\chi^{(3)}$ in optical fibres[1–4] have been reported. Although fast, they have large switching thresholds (100–1000 W) and suffer from environmental instability. Recently, work has concentrated on the fibre nonlinear optical loop mirrors (NOLM) (or nonlinear Sagnac interferometer),[5–7] since the device is inherently a balanced interferometer and therefore environmentally stable. Longer fibre lengths can be used and switching thresholds reduced to 10–100 W, a figure which is unfortunately still too high for practical applications. In the NOLM approach, a fibre Sagnac interferometer is constructed using a coupler of unequal splitting ratio at the operating wavelength. Pulses propagating in opposite directions around the loop have different amplitudes and therefore accumulate a net phase difference because of the optical Kerr effect. On recombination of the pulses at the coupler, they are routed to one the other of the NOLM outputs, depending on their acquired intensity dependent phase difference. Thus pulse switching between the NOLM outputs occurs as a function of the intensity of the input pulse. Unfortunately 100% amplitude switching is not possible because of the necessity for an unequal splitting ratio in the coupler.

A solution to the latter problem is to introduce a nonreciprocity into the loop by placing an optical amplifier close to one end (Fig. 1). A counter propagating pulse in the loop then differs in amplitude by the gain of the amplifier, since one of the pulses is amplified on entering the loop and the other on exiting. Consequently a 50 : 50 coupler can now be used and full contrast pulse switching is possible. In a recent demonstration employing an Nd^{3+} doped fibre amplifier with a gain of 6 dB, a switching threshold of a few Watts was obtained.[8] In this letter we have exploited the high gain available from an EDFA to construct an amplifying NOLM which can be switched with an input power of only 200 μW from a diode laser operating at 1·535 μm, a figure more than three orders of magnitude lower than the best previously reported. We believe this device makes nonlinear fibre switching and pulse shaping a practical reality.

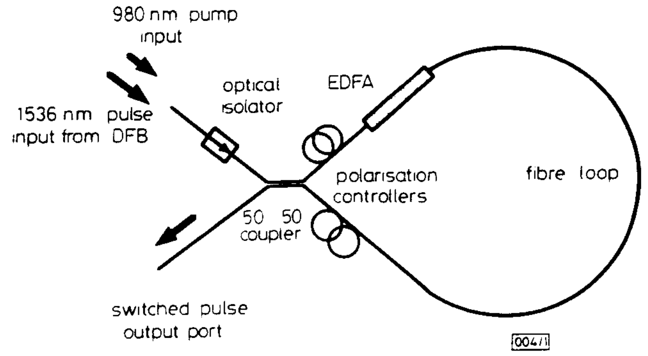

Fig. 1 *Experimental configuration*

Theory: Referring to Fig. 1, in a Sagnac loop operating at wavelength λ and incorporating an EDFA with gain G, the net phase difference accumulated between counter-propagating pulses on re-entering the coupler is

$$\Delta\phi(t + \delta) = \frac{\pi}{\lambda A_{eff}} n_2(G - 1)I_s(t)L \quad (1)$$

where $n_2 \approx 4 \times 10^{-20}\,m^2/W$ is the nonlinear refractive index of the fibre, L the loop length, A_{eff} the effective mode area, δ the loop transit time and $I(t)$ the amplitude of the pulse launched into the loop at time t. We have assumed the light to be plane polarised and the device to be polarisation preserving. An additional linear phase shift can be obtained by polarisation manipulation within the loop[9] and in this way the port from which the switched output is obtained can be reversed. The light transmitted from the loop output port is given by

$$I(t + \delta) = GI_s(t)\sin^2[\Delta\phi(t + \delta)/2] \quad (2)$$

100% amplitude switching is obtained for $\phi(t) = (2n + 1)\pi$, $n = 0, 1, 2, \ldots$. For $n = 0$ full amplitude switching is obtained for

$$I_s(t) = \frac{A_{eff}\lambda}{n_2 L(G - 1)} \quad (3)$$

Thus the high gain available with an EDFA ($G > 40$ dB) reduces input switching powers from the Watt to the micro-Watt regime.

Experiment: The experimental configuration used to investigate the switching properties of the NOLM incorporating an EDFA is shown in Fig. 1. The Sagnac loop was constructed from 306 m of nonpolarisation preserving fibre having a mode spot area of $40 \times 10^{-12}\,m^2$ at $1{\cdot}535\,\mu m$. Mechanical fibre polarisation controllers were used to adjust the reflection and transmission properties of the loop, although these can be dispensed with if polarisation preserving fibre is employed. Since it had a similar spot-size to the loop fibre, it was possible to splice the 30 m long EDFA (germano-silicate host glass, 100 ppm Er^{3+}, $\lambda_{co} = 930$ nm, $NA = 0{\cdot}19$) directly to the end of the loop. Up to 60 mW of pump at 980 nm was launched into the amplifier whose length was chosen to be optimal for high gain at 1535 nm. At a gain of 46 dB an ASE background of 2 mW was observed. A switching pulse of 5–20 ns duration with 1 ns rise and fall times was obtained from a $1{\cdot}535\,\mu m$ DFB laser diode. Fig. 2 shows the experimentally observed roll off in amplifier gain with increased mark-space ratio ($G = 43$ dB, amplifier input pulse $150\,\mu W$ peak and 10 ns width). No amplifier saturation effects are observed until a mark-space ratio of 10^{-4} is reached although this could be increased if higher levels of pump power were available. The loop will still switch with the amplifier operating in the saturation regime. Full amplitude switching at mark-space ratios as high as 10^{-3} should easily be possible with a suitable loop design.

Results: Transmitted pulse shapes obtained at the Sagnac-loop output port for 20 ns square input pulses at 1 kHz are shown in Fig. 3. For convenience, the loop was tuned to

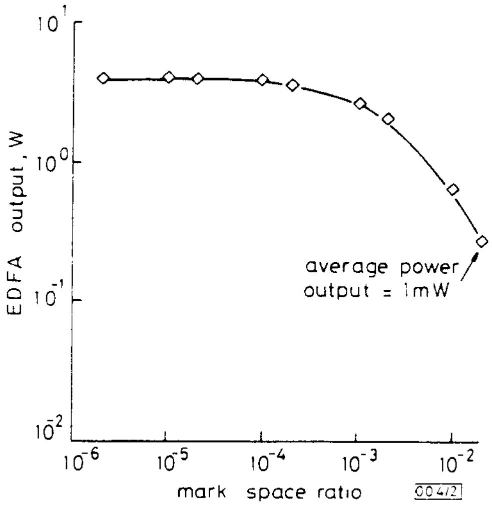

Fig. 2 *EDFA output against mark-space ratio*
Gain = 43 dB
Average power output = 1 mW

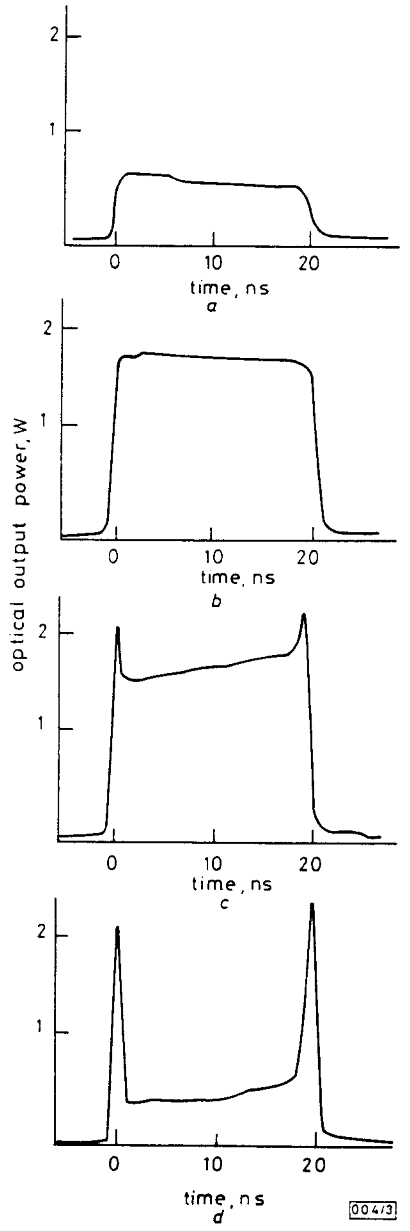

Fig. 3 *Loop mirror output*
a Input pulse power = $15\,\mu W$
b Input pulse power = $60\,\mu W$
c Input pulse power = $120\,\mu W$
d Input pulse power = $200\,\mu W$

reverse-switching using the polarisation controllers.[9] The effect of the phase bias is to cause the switch to transmit low level signals and block (route to the other port) high levels, rather than the reverse. Thus the rising edges of the pulses in Fig. 3 are linearly transmitted to the switching level, where the pulse intensity falls as power emerges from the other port once the nonlinear regime is entered. The centre of the pulse is therefore sliced out and appears at the other (input) port. The effect is dramatic and can be used to convert the rising edge of a square pulse into a short pulse. Fig. 3*d* shows 1 ns pulses sliced from the rising and falling edges of a 20 ns square pulse.

Fig. 4 shows the experimental and calculated power input/output transfer characteristics of the loop, normalised to account for the 3 dB loss of the loop. It can be seen that the agreement is excellent and that maximum output extinction (95%) is obtained for only 200 μW of input pulse power. For 100 μW input the switch output is 2 W.

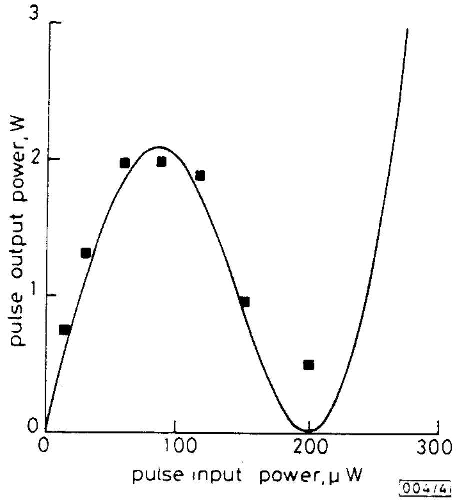

Fig. 4 *Input/output power transfer function for amplifying nonlinear loop mirror*

Gain = 46 dB

Conclusion: We have demonstrated that the high-gain characteristics of the EDFA can radically improve the characteristics of previously impractical nonlinear devices and allow full amplitude switching using diode lasers at input power levels of around 200 μW. This is an improvement of 5×10^3 in input switch power over the best previously-reported fibre switch. The amplified Sagnac switch has potential as an amplifying pulse discriminator and shaper, as well as an amplifying MUX/DEMUX if used in a two wavelength mode.

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