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Amplified fibre delay line with 27,000 recirculations

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Abstract

An active recirculating-ring fibre delay line with 27,000 recirculations is reported, corresponding to a feedback coefficient of 0.99996 or a finesse as high as 150,000. This is the highest value ever reported and indicates the potential for long optical storage times in such devices.

Introduction

Recirculating-ring delay lines incorporating doped fibre amplifiers have been used to simulate ultra-long-distance optical guided-wave propagation [1,2]. The use of such a structure enables observation of transmission over several 100,000km of propagation [2] using much shorter fibre lengths of around 100km. Such devices have also been investigated for optical storage in signal processing applications [3], for finesse enhancement in spectral analysis [4] and can be used in ring resonator gyros [5].

For a number of applications such as in refs. 4 & 5 the resonator finesse sets a limit to the performance of the device. The finesse in this case is determined by the amplifier gain and is normally limited by the onset of lasing, which occurs when the gain and loss are equal. Note that lasing always occurs for the wavelength and polarisation state with highest round-trip feedback ($k=1$) and that these conditions do not necessarily coincide with the signal parameters. Typically, therefore, lasing occurs for some other wavelength and polarisation state and careful matching of the signal to the ring is required if the proximity to the lasing threshold is to be minimised. The maximum round-trip feedback previously obtained to our knowledge has been $k=0.9998$ [2]. Here we report an experimental investigation of the maximum round-trip feedback obtainable in such devices. We show that careful optimisation of a number of parameters, particularly signal wavelength and fibre birefringence, enables substantial improvement in the round-trip feedback over previously-reported results.

Experiment

Fig. 1 shows the experimental configuration used. The recirculating loop was formed by fusion- splicing a variable-ratio single-mode fibre coupler (VRC), a pig-tailed optical isolator, a WDM fused-tapered coupler, a 4.5m length of Er-doped fibre and a 380m length of single-mode fibre together. The optical isolator was nominally polarisation insensitive. The Er-doped fibre had a germania-silica core (emission peak at 1.536μm) with 80ppm Er^{3+} concentration, NA 0.17 and a second-mode cutoff wavelength of 950nm. The dichroic coupler was specified to allow 980nm pumping of the doped fibre with minimal loss to a 1.54μm signal propagating in the loop. In addition, polarisation controllers were incorporated both in the loop and in the signal input fibre to allow alignment of the ring polarisation eigenmodes and matching the input state to them. All exposed fibre ends were angle polished to minimise feedback from Fresnel reflection.

The total loss in the ring (dominated by splice losses) was estimated to be 7.5dB. The doped fibre was pumped in a copropagating signal/pump scheme through the WDM coupler using a 980nm laser diode (SDL 6301). A DFB laser diode at 1536nm (temperature tunable by $\approx$0.1nm/°C) was used as a diagnostic pulsed signal source. The DFB had a measured FWHM linewidth of 15MHz and a peak output power of 20mW. Pulses of 20ns duration from the DFB were injected into the loop at low repetition frequencies (20Hz - 130Hz). Note that each pulse from the DFB produces a pulse train at the loop output. The loop output was monitored with a DC-coupled InGaAs receiver with 50MHz bandwidth.

Fig 2 shows the longest pulse train we have obtained with the ring operating just below lasing threshold and with the DFB laser giving pulses at 20Hz. The VRC was set to give 95% cross coupling which minimises the loss and hence gain required to maintain long pulse trains whilst still allowing a reasonable signal to be obtained. Pulse recirculations totalling 27,000 are shown, although with only 2μs between successive pulses, individual pulses are not resolvable on such a time scale. The pulse train shows slight modulation at the relaxation oscillation frequency of the ring. The injected pulses were not of sufficient intensity to saturate the amplifier (as confirmed by varying the input pulse energy) and thus ASE fluctuations caused by feedback-induced pump power variations were believed to be the cause of the observed pulse-train modulation. This maximum delay was obtained by simultaneously optimising the signal wavelength (by temperature tuning the DFB), the loop birefringence and the input fibre birefringence. Tuning of the DFB was critical to within 0.01nm ($\approx$ 1GHz). This was to be expected as the accumulated gain on successive transits of the amplifier becomes very large and correspondingly the gain bandwidth becomes very narrow. Non-optimisation of any of these parameters resulted in much shorter pulse trains. Increasing the pump power above that corresponding to Fig. 2 caused the ring to lase, producing noise. Under non-optimised conditions the ring would reach laser threshold before long pulse trains could be obtained.

In order to observe the long decay period and resolve individual pulses, the repetition rate of the DFB laser was increased to 130Hz. This caused the pulse trains as shown in fig. 2 to overlap in time and thus sampled pulses from several trains could be observed on a much shorter time scale. Fig 3a shows the detector output in this case as observed on an oscilloscope. The two pulses labelled "O" in fig 3a are the first two pulses in one pulse train separated by the loop transit time ($\approx 1.86\mu s$). The pulses labelled 1,2...5 belong to the five preceding pulse trains, the smallest distinguishable (5) having travelled around 20,700 times through the ring. The delay in this case was slightly lower than that shown in fig. 2, although the modulation was substantially reduced. The noise floor shown in fig. 3a was dominated by detector noise, although a small component of amplifier noise was observable. In fig 3b the amplitudes of the pulses in fig. 3a are plotted against their respective time delays. A double decay is observed (as in fig. 2) which we attribute to slight loss differential between the orthogonal eigenstates of the ring [2] which are both excited to some degree. For the fast and slow decay components shown in fig 3a the round trip feedback k is determined to be 0.99953 and 0.99996 respectively, a difference of only 0.043% Such a differential could easily be imparted by components such as the couplers or isolator. The power feedback figure of 0.99996 can be translated to a finesse as high as 150,000 ($F = \pi\sqrt{A}/(1-A)$ where A is the field feedback coefficient [6])

Although the polarisation controllers were nominally optimised, a degree of excitation of the higher loss eigenstate is inevitable which explains the double decay. Deliberate non-optimisation of the input polarisation state caused a decrease of the decay time until it corresponded to only the fast decay component. Additionally, non-optimisation of the polarisation controller in the loop caused a periodic modulation of the pulse train. The period of the modulation is determined by the beatlength between the orthogonal states and has been described theoretically by Giles et al [2]. Longest decays were obtained by minimising the modulation to obtain to an integer number of beatlengths per round trip of the loop.

Removal of the optical isolator prevented such high feedback coefficients from being obtained. In this case the highest feedback coefficient we were able to obtain was $k \approx 0.993$ corresponding to 300 recirculations. Such a characteristic has previously been identified to be due to coupling of counter-propagating ASE modes [1] and is fundamental to a bidirectional device. With the isolator incorporated, only ASE modes travelling in one direction are allowed and this problem is obviated.

Conclusions

We have investigated the maximum feedback or finesse obtainable in a recirculating fibre loop incorporating a fibre amplifier. With an optical isolator incorporated in the loop, we have shown round-trip coupling coefficients as high as 0.99996, which is substantially greater than the highest previously reported. We have found that optimisation of the signal wavelength is critical for obtaining high coupling coefficients as well as optimisation of the loop birefringence and the signal input polarisation state. We believe our results are also applicable to much longer loop lengths, thus enabling storage of optical pulses for time periods in excess of 1s.

5. R.E.Meyer, S.Ezekiel, D.W.Stowe & V.J.Tekippe, "Passive fiber-optic ring resonator for rotation sensing", Opt. Lett., Vol.8, pp.644, 1983.

6. A.E.Siegman, *Lasers*, University Science Books, Mill Valley, California, 1986.

Figure captions.

Fig. 1 Experimental setup. WDM=wavelength division multiplexer, PC=polarisation controller, ISO=optical isolator. S1-S5 are fused splices. Si filter transmits 1.536nm and blocks 980nm.

Fig. 2 Delay line response to a 20ns input pulse. The round-trip feedback in the ring is very close to unity, this being the laser threshold condition. Ring round-trip delay time $\tau=1.86\mu s$.

Fig. 3 a) Response to 20ns input pulses injected at 130Hz repetition rate, causing overlap between succeeding pulse trains. Two pulses labelled "0" are the first two pulses in one pulse train and their separation represents the round-trip delay time τ. Pulses labelled 1,2....5 belong to the five preceding pulse trains, the smallest distinguishable pulse (5) having travelled 20 700 times through the ring.

b) The amplitudes of the pulses in a) plotted vs. their respective total time delays. The decay is fitted as a sum of two exponential decays, representing high and low loss modes of the ring.

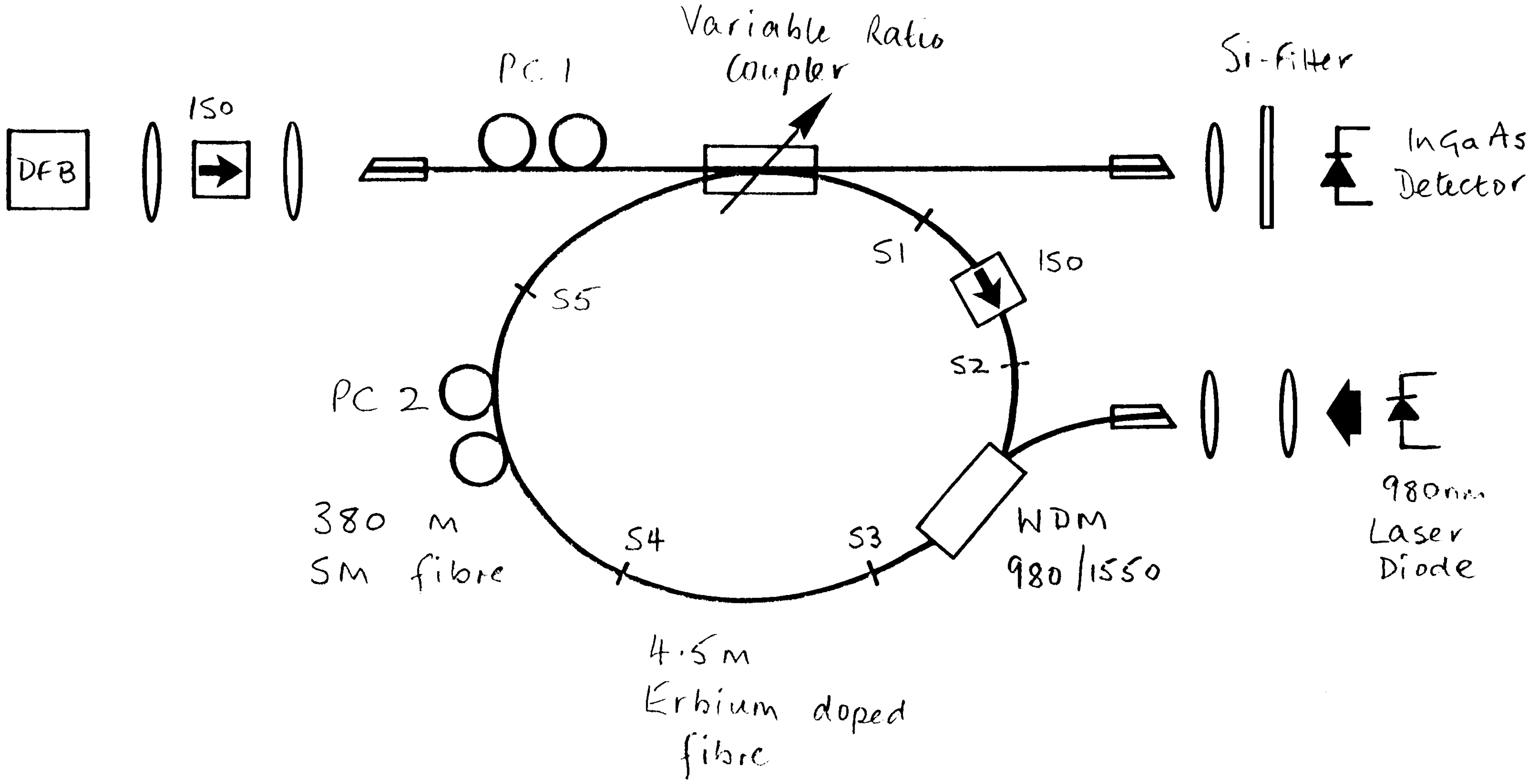

DFB
ISO
PC 1
Variable Ratio Coupler
Si-filter
InGaAs Detector
S1
ISO
S5
S2
PC 2
380 m SM fibre
S4
S3
WDM 980/1550
980nm Laser Diode
4.5m Erbium doped fibre

Fig 1

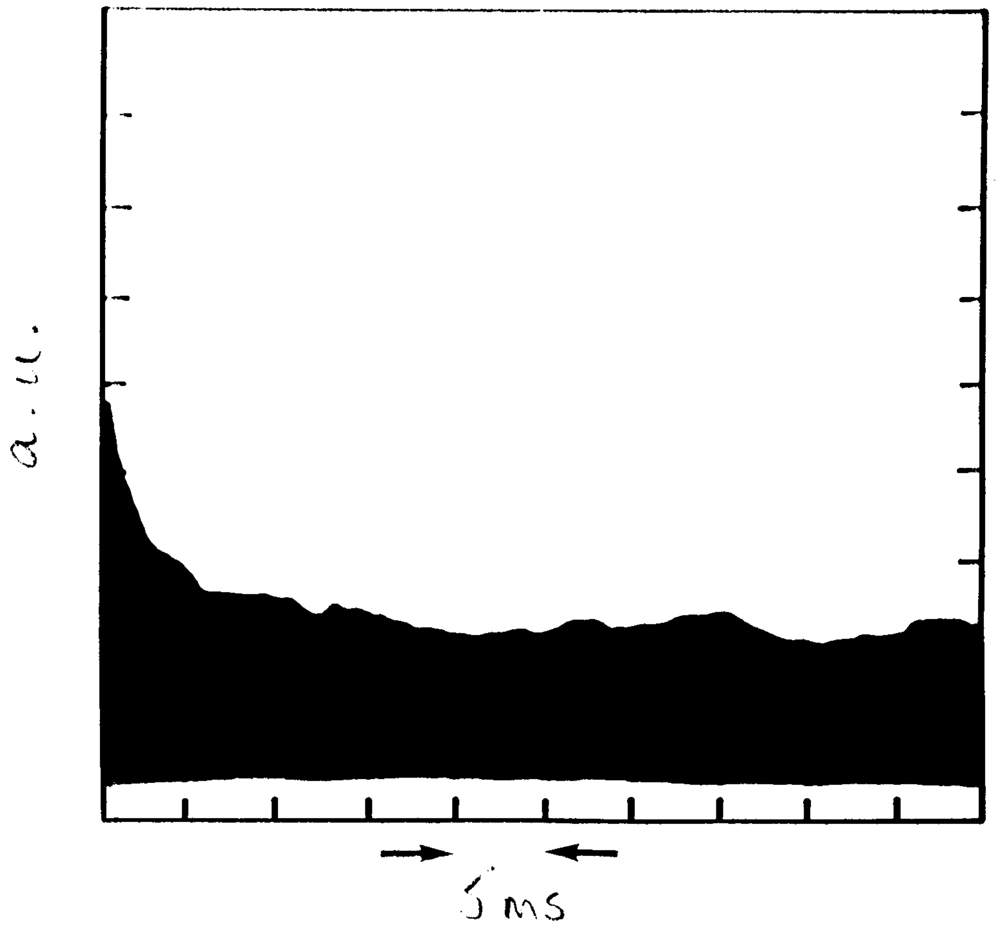
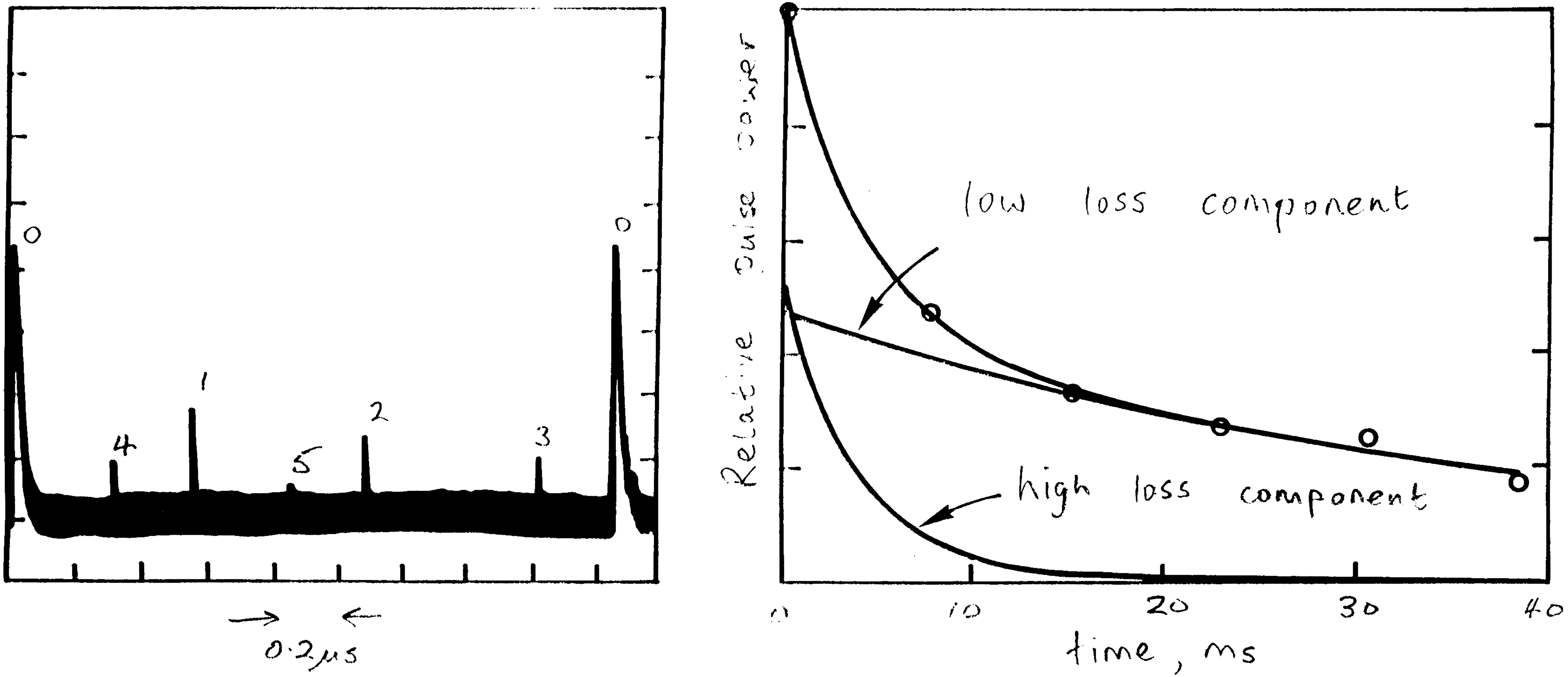


Fig 7


0
4
1
5
2
3
0
0.2μs
Relative pulse power
low loss component
high loss component
0
10
20
30
40
time, ms

(a)

(b)

Fig. 3