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An all fibre, diode-pumped recirculating-ring delay line

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ABSTRACT

A Nd^{3+}-doped optical fibre is used as an amplifier in a 35 m fibre recirculating delay line to overcome the round trip losses experienced by injected pulses. Dichroic fused-tapered couplers are used to couple light from a semiconductor source into the ring in order to pump the amplifier. Injected pulses have been maintained for more than 300 round trips.

<0.2dB and using fig 2 we see the maximum resonator finesse obtainable using this coupler will be approximately 30. The undoped fibre was characterised by a NA of 0.21, second mode cutoff of 800 nm and a loss of 10 dB/km at 1 µm. The doped fibre had nominally the same characteristics with the addition of 130 ppm Nd^{3+} dopant concentration. A second similar coupler was then fusion spliced onto the first providing separate ports for pump and signal input (Fig 1).

Theory

The power $P_s(t)$ of a recirculating intra-cavity signal pulse in a Nd^{3+}-doped ring-fibre laser at any time t can in general be written:

$$P_s(t) = P_s(0).\exp[nl/c \int_0^t -(1-(1-k).\exp \sigma \int_{l_1}^{l_2} N(x,t).dx.dt\ ]$$

where k = round trip loss, σ = stimulated cross-section, l = Cavity length, $l_2 - l_1$ = Length of doped fibre and assuming small ground-state depletion, the population inversion density N(x,t) is given by the rate equation:

$$\frac{dN(x,t)}{dt} = W_p(x).N_o - N(x,t).\left[\frac{P_s(t).\sigma.\Delta t.c/nl + P_l(t).\sigma}{hv_p.a} + \frac{1}{T_f}\right]$$

where $W_p(x)$=Pump rate, N_o=Total Nd^{3+} concentration, $h\nu_p$ =Photon energy at signal wavelength, T_f=Metastable-state lifetime, a_p=Effective core area and Δt = Input pulse width (assume square pulse). P_l is the power of the self oscillating laser mode that may be present within the ring resonator.

The pump power P_p required to overcome the losses at 1088 nm in the resonator can be obtained by solution of the above equations in equilibrium. Assuming small signal and loss this value of pump power will give the lasing threshold of the device and for complete pump absorption in the length of doped fibre will be approximately given by:

$$P_{pump} = \frac{k}{\sigma . \eta T_f} . h\nu_p . a$$

where η = Quantum efficiency and $h\nu_p$= Photon energy at the pump wavelength.

Incorporating typical values ($k=0.15$, $\sigma \approx 1.5.10^{-24}$ m^2, $\eta \approx 0.5$, $T_f \approx 350$ μs and $a=1.2.10^{-11}$ m^2) gives $P_p \sim 2mW$. Considering the losses incurred by the pump signal due to coupler loss and finite coupler splitting, this corresponds to approx 5mW of pump power launched into port 6 of the device.

Experiment

A dye laser was used as a source of 6 ns pulses at 1088 nm which were launched through a polariser into port 5 of the fibre device (Fig 1). Monitoring the output at port 3, without pumping of the amplifier, showed the intense throughput pulse followed by a decaying train of pulses corresponding to decay of the pulse fraction coupled into the resonator (see Fig 3). Comparison of the peak heights of the decaying pulses indicates a cavity round trip loss of ~15%. A semiconductor laser (Sharp LT015) was used to launch pump light at 825 nm into the ring via port 6 of the device. The maximum power coupled into the fibre was estimated to be ~12 mw and the lasing threshold was ~ 8 mW in good agreement with the theory.

Fig 3(a) shows the effect of diode pumping of the amplifier and clearly illustates the partial compensation of the loss by amplification. In this case the pulse polarisation was arbitrary. The modulation on the pulse envelope in both the pumped and unpumped cases is believed to be due to birefringence in the fibre ring along with slight polarisation sensitivity in the resonator coupler. By virtue of intrinsic birefringence and arbitrary bending of the fibre on the bench, the resonator fibre will have a cetain degree of birefringence. As a pulse of arbitrary polarisation makes successive transits around the ring its polarisation state will evolve periodically, so inducing a variation in the output coupling if the coupler is polarisation sensitive. From Fig 3(a) it would appear that ~4 cavity round trips, ie 190 m, corresponds to an integer number of polarisation beat lengths in the fibre. Aligning the polarisation state of the pulse input was seen to remove the modulation and gave rise to a maximum pulse delay of ~300 round trips, the maximum number being defined as the point at which signal~noise. This compares with approximately 800 round trips in a raman device [3]. Fig 3(b) shows the pulses after a delay of 35 μs, corresponding to approximately 200 round trips of the resonator.

The maximum delay was limited by parasitic lasing action of the resonator, indicated by the onset of relaxation oscillations as the pump was increased. The start of laser oscillation appears to inherently limit the maximum number of round trips obtainable (for a given pulse input energy). As soon as the resonator begins to self oscillate the gain becomes clamped to the threshold value and any injected pulses will tend to saturate the gain to below the threshold value so preventing continued maintenance of the pulses. This implies a fixed number of recirculations and for a longer delay the resonator would have to be fabricated from a longer length of fibre.

Conclusions

The implementation of Nd^{3+}-doped silica fibre in a completely fused fibre recirculating delay line has been shown. Pulses of 6ns at the peak gain wavelength of 1088nm have been maintained in the ring for ~300 round trips, the limiting factor being parasitic self-oscillation of the resonator. The incorporation of several hundreds of metres of low loss fibre into such a device should enable delays ~ 1 ms to be obtainable, comparable to Raman devices of similar length [3].

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References

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Figure captions

Fig 1. Delay line configuration

Fig 2. Coupler splitting characteristics vs wavelength

Fig 3. (a) Pumped and unpumped pulse decay within cavity. Input signal polarisation arbitrary.
(b) Pulse train after 35 μs delay. Input signal aligned.

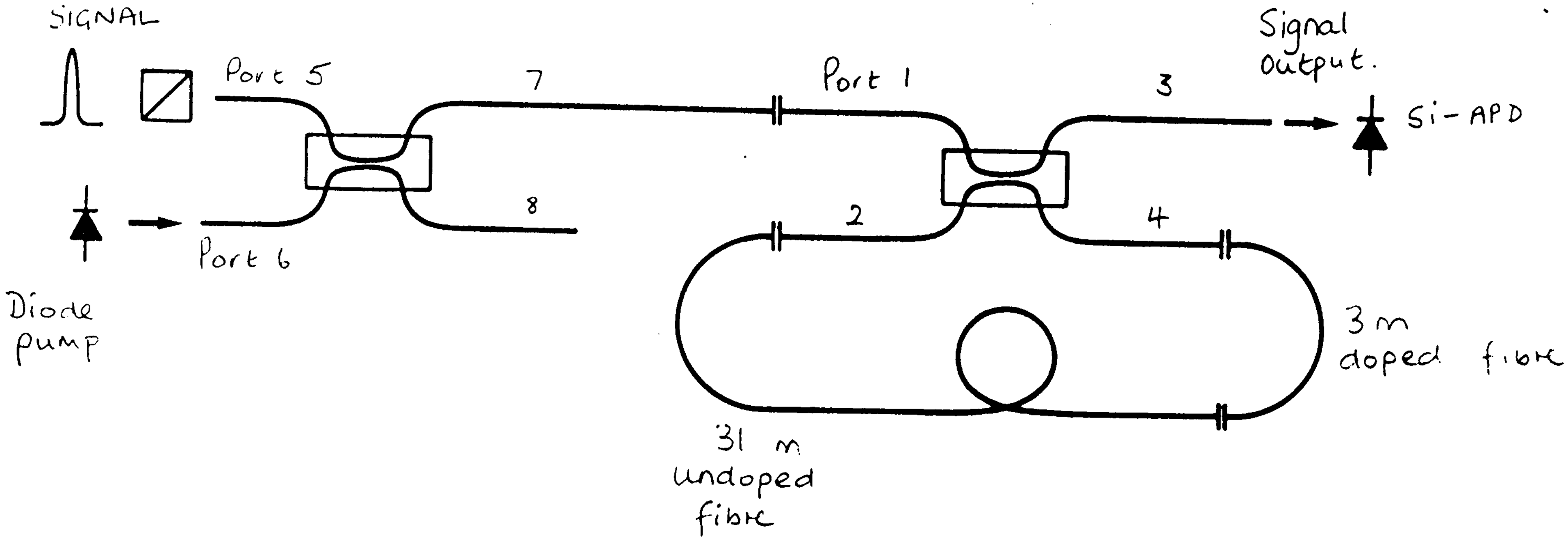
SIGNAL
Port 5
7
Port 1
3
Signal output.
Si-APD
8
2
4
Port 6
Diode pump
3 m doped fibre
31 m undoped fibre

Fig 1.

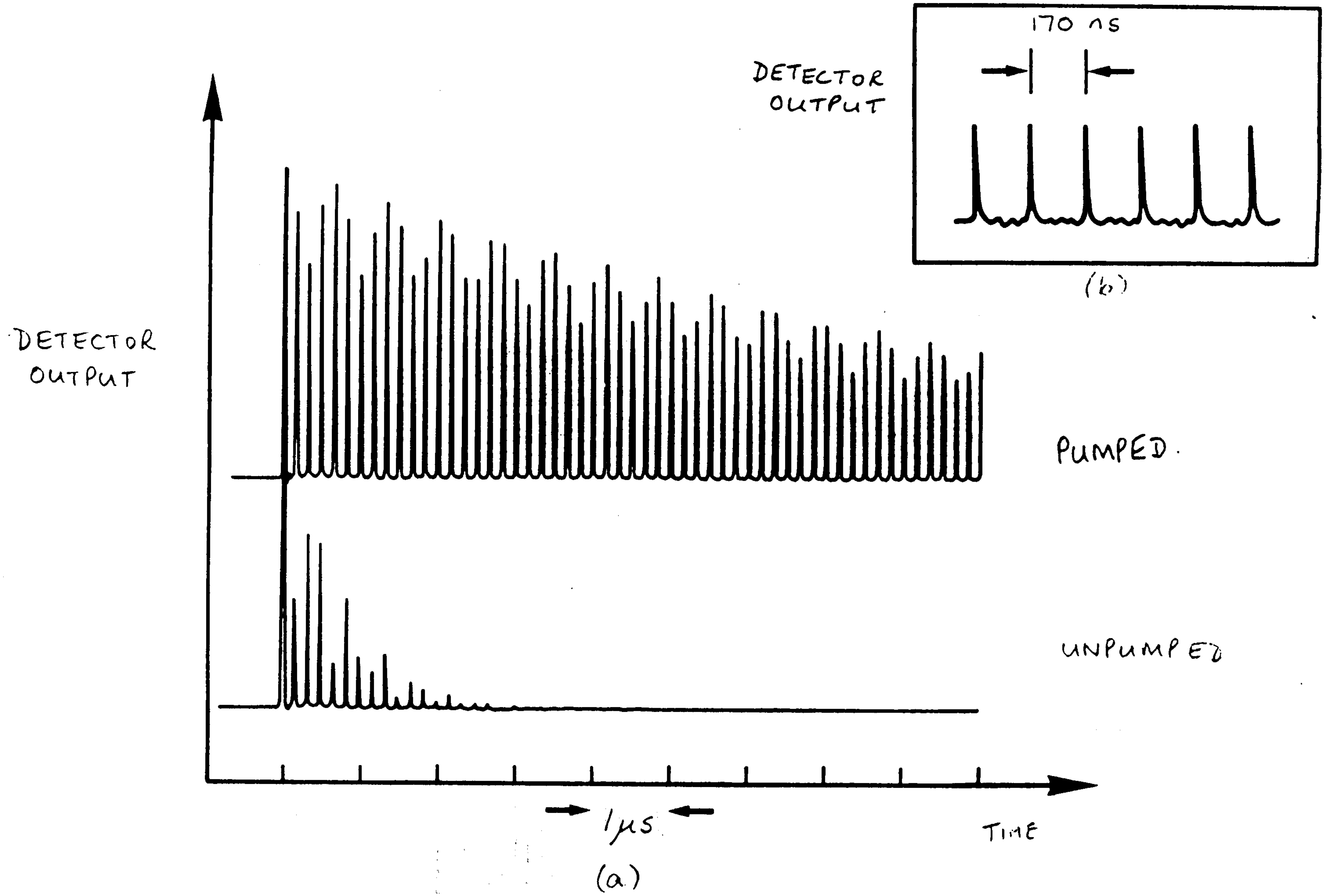
DETECTOR OUTPUT
PUMPED
UNPUMPED
1μs
TIME
(a)
DETECTOR OUTPUT
170 ns
(b)

FIG 3.

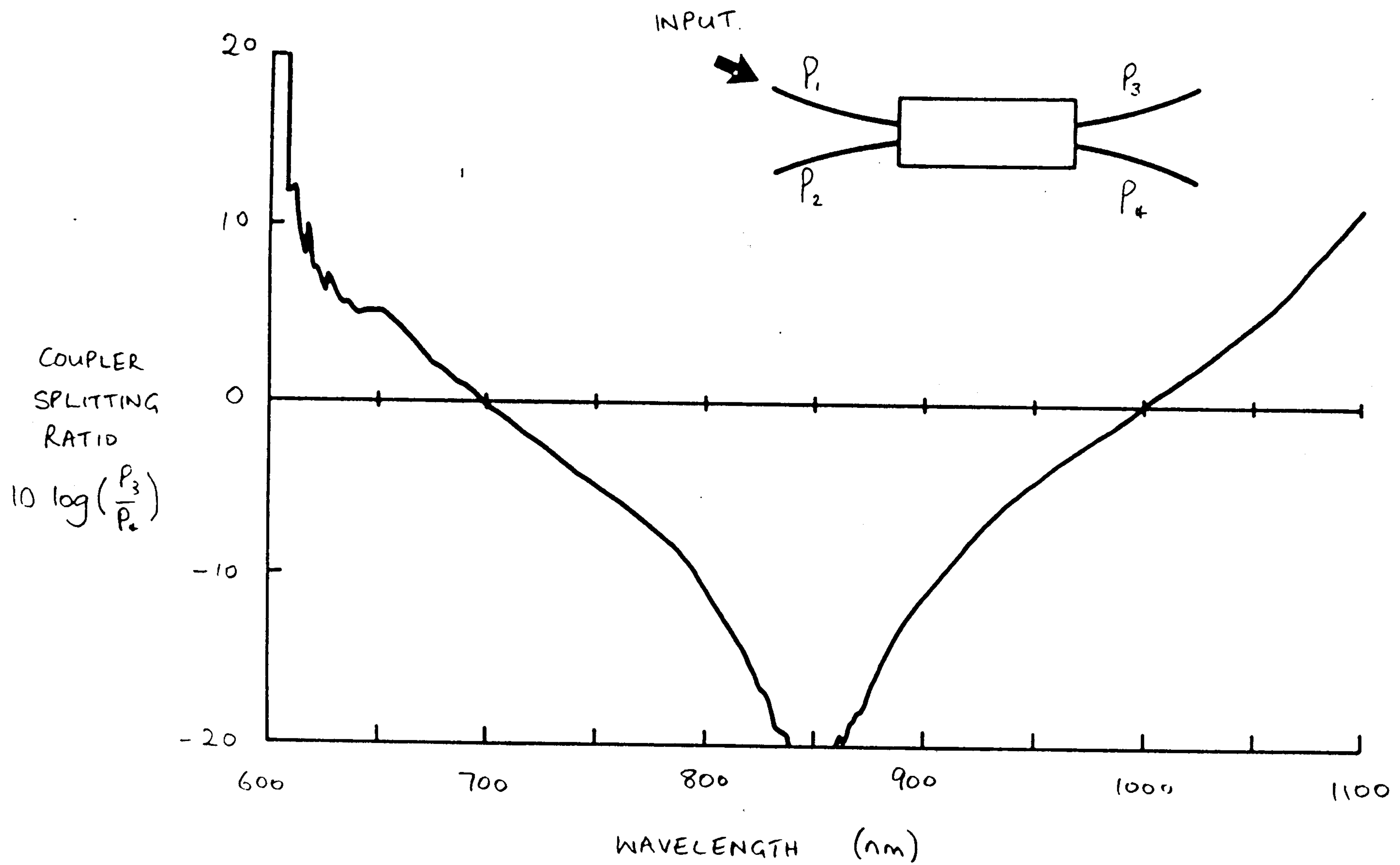
INPUT
P_1
P_2
P_3
P_4
20
10
0
-10
-20
COUPLER
SPLITTING
RATIO
$10 \log\left(\frac{P_3}{P_4}\right)$
600
700
800
900
1000
1100
WAVELENGTH (nm)

FIG 2.