that of the deflected beam. Thus, the theoretical 100% efficiency predicted by the plane wave theory cannot be obtained with realistic beams of limited extension.

A deflection efficiency of 48% is expected as result of the computer simulation. Experimental investigation of the deflection efficiency using fibre coupling at the input and output of the modulator device yields values of about 40–45%. The electrical drive power required is 500 mW. Subtracting the transducer losses of about 3 dB and considering the unidirectionality of the IDT, the acoustic power in the interaction region is approximately 125 mW.

*Summary:* Work on a Ti : LiNbO$_3$ SSB modulator as a frequency shifter has been presented, and good agreement between simulation and experiment is obtained.

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## ALL-FIBRE, DIODE-PUMPED RECIRCULATING-RING DELAY LINE

*Indexing terms: Optical amplifiers, Delay lines, Fibre optics*

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, to pump the amplifier. Injected pulses have been maintained for more than 300 round trips.

*Introduction:* Re-entrant fibre loop devices have been fabricated for a number of applications including rotation sensors[1] and signal processing.[2] Raman,[3] Brillouin[4] and dye[5] gain media have been tried in these and similar fibre devices to compensate for the optical losses incurred in the resonator and to induce laser action. The development of rare-earth doped single-mode silica fibres[6] has given rise to an alternative amplifier for use in ring fibre devices with the added advantage of diode-pumped operation.

In this letter the fabrication and operation of an all-fibre, diode pumped recirculating ring delay line is reported in which a length of Nd-doped silica fibre was used as an amplifier. Fig. 1 shows the ring configuration with two dichroic couplers to direct the pump and signal wavelengths. A 31 m length of undoped fibre was fusion spliced to 3 m of mode-matched Nd$^{3+}$-doped fibre. This combination was then spliced onto two ports of one coupler to form a ring resonator containing the doped fibre. Fig. 2 shows the coupling characteristics of the fused tapered coupler fabricated from the undoped fibre. As can be seen, the coupler characteristic enables almost complete coupling of 825 nm pump light from port 1 to port 4, i.e. into the resonator, while still enabling relatively high resonator finesse at the 1088 nm gain wavelength. Measuring the coupler loss at 1088 nm to be $<0{\cdot}2$ dB 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 $\mu$m. 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).

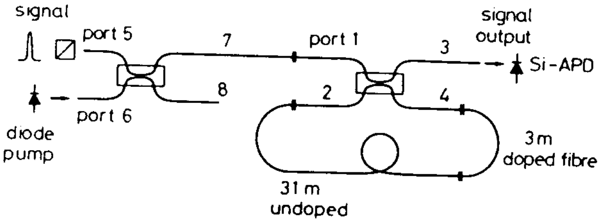

**Fig. 1** *Delay line configuration*

*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

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

where $k$ = round trip loss, $\sigma$ = 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

$$\frac{dN(x, t)}{dt} = W_p(x) \,.\, N_0 - N(x, t) \times \left[\frac{(P_s(t) \,.\, \sigma \,.\, \Delta t \,.\, c/nl + P_l(t) \,.\, \sigma)}{h\nu_p \,.\, a} + \frac{1}{T_f}\right]$$

where $W_p(x)$ = pump rate, $N_0$ = total Nd$^{3+}$ concentration, $h\nu_p$ = photon energy at signal wavelength, $T_f$ = metastable-state lifetime, $a_p$ = effective core area and $\Delta t$ = 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

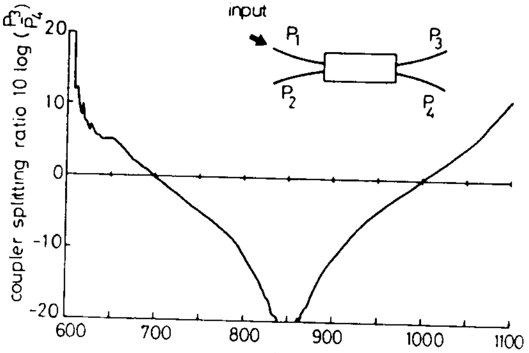

**Fig. 2** *Coupler splitting characteristics against wavelength*

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, it will be approximately given by

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

where $\eta$ = quantum efficiency and $h\nu_p$ = photon energy at the pump wavelength.

Incorporating typical values ($k = 0{\cdot}15$, $\sigma \approx 1{\cdot}5 \times 10^{-24}\,\mathrm{m}^2$, $\eta \simeq 0{\cdot}5$, $T_f \simeq 350\,\mu s$ and $a = 1{\cdot}2 \times 10^{-11}\,\mathrm{m}^2$) gives $P_p \simeq 2\,\mathrm{mW}$. Considering the losses incurred by the pump signal due to coupler loss and finite coupler splitting, this corresponds to approximately 5 mW 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.

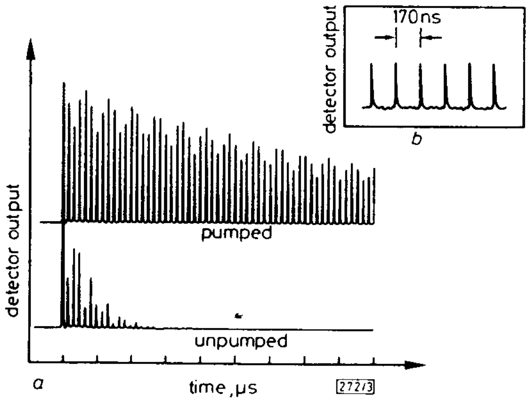

**Fig. 3**

*a* Pumped and unpumped pulse decay within cavity (input signal polarisation arbitrary)
*b* Pulse train after 35 μs delay (input signal aligned)

Fig. 3*a* shows the effect of diode pumping of the amplifier and clearly illustrates 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 certain degree of birefringence. As a pulse of arbitrary polarisation makes successive transits around the ring its polarisation state will evolve periodically, thus 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, i.e. 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 continuation 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 $\mathrm{Nd}^{3+}$-doped silica fibre in a completely fused fibre recirculating delay line has been shown. Pulses of 6 ns at the peak gain wavelength of 1088 nm 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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# VERY LOW THRESHOLD OPERATION OF 1·52 μm GaInAsP/InP DFB BURIED RIDGE STRUCTURE LASER DIODES ENTIRELY GROWN BY MOCVD

*Indexing terms: Semiconductor lasers, Epitaxy and epitaxial growth, Vapour deposition*

1·52 μm GaInAsP/InP DFB laser diodes with a buried ridge structure were fabricated entirely by MOCVD, with a second-order corrugation on the GaInAsP guiding layer. The 5 mA minimum threshold current achieved is believed to be the lowest yet reported for DFB lasers. Single longitudinal-mode operation with a side-mode suppression ratio greater than 35 dB was obtained from 20°C (up to 16 mW) to 90°C (up to 3 mW).

*Introduction:* We have shown previously that the low-pressure metalorganic chemical vapour deposition (LP-MOCVD) growth technique is very promising for production of GaInAsP/InP distributed feedback (DFB) lasers with the ridge waveguide structure developed by Kaminow,[1] and of buried ridge heterostructure lasers emitting at 1·5 μm[2] and at 1·3 μm.[3]

We have also demonstrated from statistical data and long duration life tests that this technique allows the manufacture of high performance devices with very uniform and reproducible characteristics.[4]