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 : LiNbO₃ SSB modulator as a frequency shifter has been presented, and good agreement between simulation and experiment is obtained.

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References

Fig. 1 Delay line configuration

Theory: The power \( P(t) \) of a recirculating intra-cavity signal pulse in a Nd⁺⁺ doped ring-fibre laser at any time \( t \) can in general be written

\[
P(t) = P_0 \exp \left[ \frac{n_l/c}{l} (1 - (1 - k) \sigma \int_{t_0}^{t} N(x, t') \, dx' \right]
\]

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

\[
\frac{dN(x, t)}{dt} = W_0 \cdot N_0 - N(x, t)
\]

\[
\times \left[ \frac{[P(t) \cdot \sigma \Delta t \cdot c/(nL + P(t) \cdot \sigma \Delta t \cdot c)]}{\hbar \nu_p \cdot a \cdot T_p} + \frac{1}{T_p} \right]
\]

where \( W_0 \) = pump rate, \( N_0 = \) total Nd³⁺ concentration, \( \hbar \nu_p = \) photon energy at signal wavelength, \( T_p = \) metastable-state lifetime, \( a = \) effective core area and \( \Delta t = \) input pulse width (assumed square pulse). \( P_i \) 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

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

Indexing terms: Optical amplifiers, Delay lines, Fibre optics

A Nd⁺⁺ 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 over 300 round trips.

Introduction: Re-entrant fibre loop devices have been fabricated for a number of applications including rotation sensors and signal processing. Brillouin and dye 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 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 moded-matched Nd⁺⁺ 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 <0.2 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 µm. The doped fibre had nominally the same characteristics with the addition of 130 ppm Nd³⁺ dopant concentration. A second similar coupler was then fusion-spliced onto the first providing separate ports for pump and signal input (Fig. 1).
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

\[ P_{\text{pump}} = \frac{k}{\sigma} \eta \frac{h}{\eta} a \]

where \( \eta \) = quantum efficiency and \( h / \eta \) = photon energy at the pump wavelength.

Incorporating typical values (\( k = 2.15, \sigma \approx 1 \times 10^{-24} \text{m}^2, \eta = 0.05, T_{\text{f}} \approx 350 \mu\text{s} \) and \( a = 1 \times 10^{-11} \text{m}^2 \)) gives \( P_{\text{pump}} \approx 2 \text{mW} \). 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 \( \approx 15\% \). 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 \( \approx 12 \text{mW} \) and the lasing threshold was \( \approx 8 \text{mW} \) in agreement with the theory.

**References**


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**References**


**References**


