It can be difficult to optimise the structure and operating point of gain levers for all-round performance, however, the calculated static light–current curves of Fig. 3 ($h = 0{\cdot}85$) are fairly typical, the general shape applying to most devices. The best link loss and noise figure are generally obtained close to point 'A' (indicated by the maximum separation of the plots at constant $i_{b2}$, however, bistability and hysteresis are also evident in this region. In Fig. 4 we show the dependence of the enhancement in modulation efficiency (over that with both contacts shorted) at 1 GHz, on the DC bias $i_b$. The current $i_{b2}$

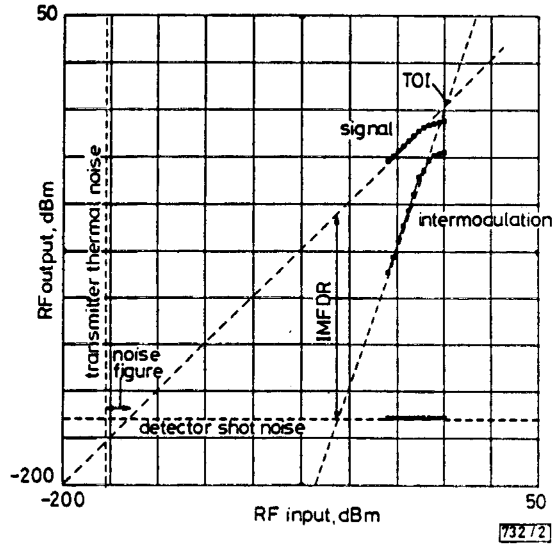


**Fig. 2** *RF transfer curves, showing noise figure and intermodulation-free dynamic range (IMFDR)*

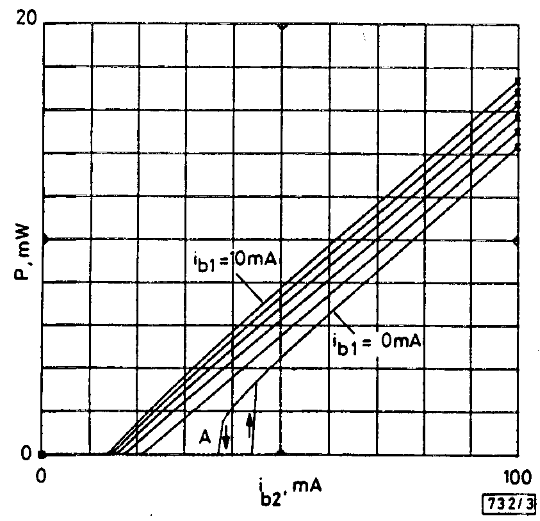


**Fig. 3** *Calculated static L–I curves for typical InGaAs gain lever*

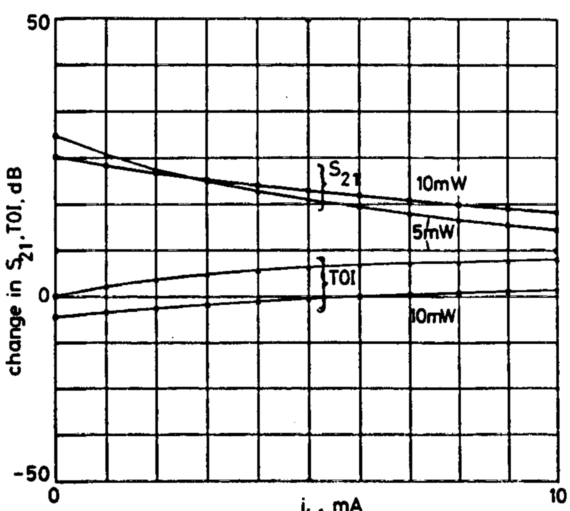


**Fig. 4** *Enhancement in $S_{21}$ and degradation in TOI as functions of $i_{b1}$*

was adjusted to maintain a constant optical output power. As expected from Fig. 3, the maximum modulation enhancement occurs closes to $i_{b1} \simeq 0$ mA. Also shown in Fig. 4 is the commensurate degradation in the TOI which is worst for $i_{b1} \simeq 0$ mA. This general trend is observed for different values of h and may be understood as resulting from the fact that the region of greatest modulation enhancement is also the region of greatest change in enhancement, and hence of greatest nonlinearity.

These simulations demonstrate that, although gain levers are attractive for reducing SCM link loss and noise figures, in this configuration at least, reduced noise figure is obtained at the expense of dynamic range.

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# VERY LOW LOSS ION IMPLANTED PLANAR WAVEGUIDES IN LEAD GERMANATE GLASS


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*Indexing terms: Ion implantation, Optical waveguides, Glass*



Ion implantation has been used to produce very low loss optical waveguides in lead germanate glass samples. There is an increase in the refractive index of 0·35% for the given ion beam parameters. The loss can be as low as 0·15 dB/cm after thermal annealing.


*Introduction:* Ion implantation has been used to form waveguides in many different insulators (especially crystalline insulators) [1]. The variety of different substrates and applications have made ion implantation a widely accepted technique. Losses of ~1 dB/cm, which are reasonably good for many applications, have made ion implantation competitive with other techniques, except where extremely low losses <0·1 dB/cm are required.

An essential step toward lower losses using ion implantation is the production of a very low loss planar waveguide in a lead germanate glass substrate. The loss in this waveguide is ~0·15 dB/cm, which is the lowest yet reported using $He^+$ ion implantation and is comparable with the best from other techniques.

*Results and discussion:* The waveguides used for the experiments were implanted with $^4He^+$ and $^3He^+$ at 77 K. The implant doses were, $4 \times 10^{16}$ ion/cm$^2$ and $5 \times 10^{16}$ ion/cm$^2$, respectively, at an energy of 2·5 MeV. Refractive index profiles were determined from the mode spectra which were measured using a prism coupler in the dark mode configuration. Analysis of the mode data was performed using the reflectivity method [2].

Fig. 1 shows the refractive index profile of the $^4He^+$ implanated waveguide. The index increases by ~0·34% near the surface region, and decreases by a small amount (~0·12%) at the end of the ion range, producing in this way a small barrier. In general, nuclear damage domination (at the end of the ion range) leads to a decrease of the refractive index, and a combination of damage ionisation and diffusion may lead to either increase (silica glass) [3] or decrease (some multicomponent glasses) [4]. The optical well type waveguide resulting from refractive index enhancement has better mode confinement as there are nontunnelling modes. Thus, the loss due to leaky modes is completely eliminated.

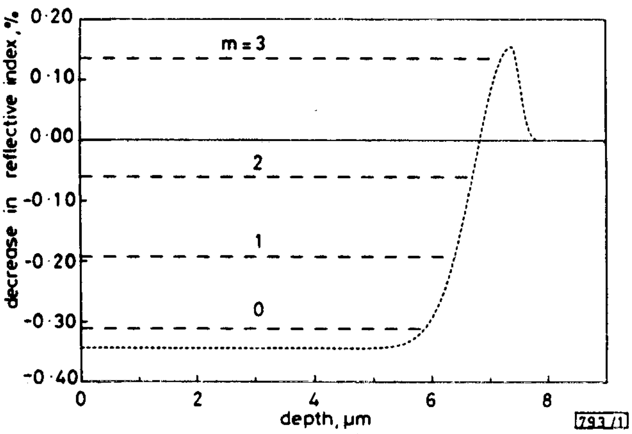


**Fig. 1** *Refractive index profile of lead germanate glass after $^4He^+$ at 2·5 MeV and dose of $4 \times 10^{16}$ ion/cm$^2$ at 77 K*

Mode values were measured at 633 nm

During ion implantation, ionisation energy may produce colour (absorption) centres which sometimes give high propagation losses within the waveguide. Fortunately, these defects are unstable and they are found to anneal out between 200 and 300°C in this glass.

Loss measurements were performed using the end-coupling configuration. A ×20 microscope objective lens was used to focus an He–Ne (633 nm) laser beam on one polished edge of the sample, and the output light from the waveguide was focused onto a silicon detector connected with a power meter.

Fig. 2 shows the loss reduction with annealing temperature for two waveguides. The first one (solid line) was implanted with $^4He^+$ (2·5 MeV, $4 \times 10^{16}$ ion/cm$^2$), and the second one with $^3He^+$ (2·5 MeV, $5 \times 10^{16}$ ion/cm$^2$). The $^3He^+$ isotope, because it is lighter, gives a longer range, and thus a wider waveguide and better mode confinement. The loss in the $^3He^+$ implanted guide is lower for most of the annealing temperatures. The spot size of the focused laser beam is ~10 μm, which is larger than the 6·4 μm width of the waveguide, resulting in a launch efficiency of less than 100%. Nevertheless, assuming a 100% launch efficiency the loss, at 200°C for the $^3He^+$ implant, is as low as 0·15 dB/cm. The lowest loss for the $^4He^+$ implanted waveguide is 0·3 dB/cm after the 300°C annealing temperature. For both of the cases we can assume a reproducibility error of ~±0·05 dB/cm. After it reaches its minimum value, for both waveguides, the loss increases due to destruction of the waveguide.

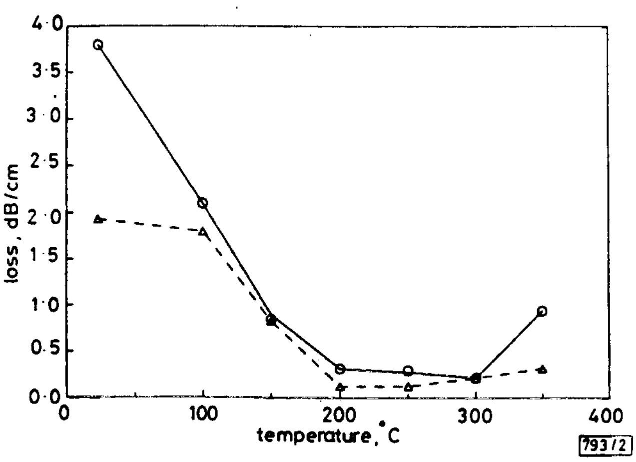


**Fig. 2** *Multimode losses for planar waveguides of $^4He^+$ and $^3He^+$ implanted lead germanate glass, after thermal annealing*

○ $^4He^+$
△ $^3He^+$

*Conclusions:* We have demonstrated the first example of an ion implanted waveguide in lead germanate glass. Furthermore, these guides have the lowest loss ever reported for He ion implanted waveguides in either glass or crystalline substrates. Further optimisation of the edge polishing and minimisation of the surface scattering should lead to even lower propagation losses. This should readily allow lower pumping thresholds and better waveguide laser performance for the rare earth doped lead germanate glass.

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## INTERPOLATOR FILTER STRUCTURE FOR ASYNCHRONOUS TIMING RECOVERY LOOPS

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*Indexing terms: Synchronisation, Digital signal processing*

A novel structure for the interpolation filter used as a timing-correction element in asynchronous timing recovery loops is introduced. Multirate techniques are employed in an algorithm to institute both bulk and fractional delays in the loop. The performance of the new algorithm is illustrated by generation of the S curves for a two-point NDA tracker and a four-point DD tracker.

*Introduction:* The generic asynchronous timing-recovery loop is shown in Fig. 1. The input analogue waveform is sampled to give *B* samples per symbol although the phase of the sam-

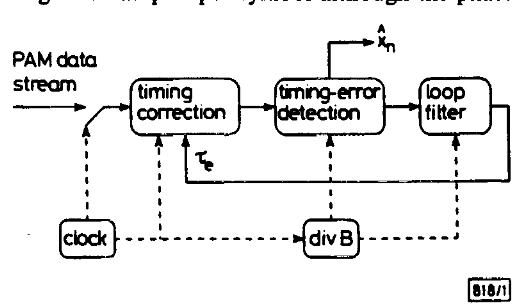


**Fig. 1** *Generic model of asynchronous timing-recovery loop*