incident wave. An even more dramatic change can be seen for temperatures below \( T_c / 2 \). A phase shift and an accompanying change in pulse shape are also identified. This is a direct result of the presence of superconducting electrons.

From the measured transmission function (in this case the frequency response of the film on substrate divided by the response of the substrate alone) and the standard thin-film transmission formula, the complex index as well as the complex conductivity were obtained. A plot of the normalised complex conductivity against frequency for a sample temperature above and below the critical temperature is shown in Fig. 3. The small undulations in some of the values is an artifact due to the noise present in the time domain waveforms (see Fig. 2). The conductivities were normalised to the normal state conductivity just above \( T_c \). A number of dramatic effects can be seen. The imaginary part of the conductivity \( \sigma_i \) nearly zero in the normal state, increases greatly at low frequencies exhibiting a 1/\( \omega \) frequency dependence as expected from theory. The behaviour of \( \sigma_i \) primarily comes from superconducting pairs. The real part of the conductivity \( \sigma_r \) decreases below the normal state value for low temperatures. This is mainly due to the reduction in quasi-particles. Despite these expected behaviours, some anomalies exist. There is a small nonzero value of \( \sigma_2 \) in the normal state which increases slightly with frequency. This dependence is not understood at this time. Also the reduction in \( \sigma_r \) is not as great as would be expected, a sign of residual loss which is associated with the depressed \( T_c \) of the film. Future experiments will have a larger signal-to-noise ratio allowing full advantage to be taken of the bandwidth available \( \sim 2\,\text{THz} \).

Also a more detailed comparison to theory will be made.

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Fig. 3 Complex conductivity obtained from transmission function above and below critical temperature

{\begin{tabular}{|c|c|}
\hline
Transmission function above critical temperature & Transmission function below critical temperature \\
\hline
(ii) & \( \sigma_{r,0}(30\,K) \) \\
(iii) & \( \sigma_{r,0}(80\,K) \) \\
(iv) & \( \sigma_{r,0}(30\,K) \) \\
(v) & \( \sigma_{r,0}(80\,K) \) \\
\hline
\end{tabular}}

CHANNEL OPTICAL WAVEGUIDES DIRECTLY WRITTEN IN GLASS WITH AN ELECTRON BEAM

A new channel waveguide fabrication process for use in glass is described. The new technique uses an electron-beam induced effect to directly alter the refractive index of the glass.

Introduction: The effects of electron bombardment on glass were first apparent as a glass 'browning' failure mechanism in electronic valves. This failure mechanism was subject to a number of investigations and in 1980 Gossink et al. performed measurements of electron-beam bombardment on soda-lime glasses where Auger emission spectroscopy (AES) was used, in situ, to measure any compositional changes at the glass surface as they happened. These experiments confirmed that a chemical 'migration' process is set up within the glass by the deposited electrons and that the rate of migration for a particular element may be altered by the electron beam current and the addition/removal of other elements to the glass compound. Gossink et al. showed that a glass of composition 20% NaSO, 10% CaO, 70% SiO_2 has its surface changed to a composition of 20% CaO, 80% NaSO due to the sodium/calcium migration process. For this glass the refractive index values have been calculated from Huggins & Sun's data to be: \( n \) (initial) = 1.5212, \( n \) (after bombardment) = 1.528, \( \Delta n \) (bombardment) = 0.0068. Therefore it would appear that the electron radiation can cause the refractive index at the glass surface to increase by \( \sim 0.007 \) (K^+Na^+) ion-exchange waveguides can produce a maximum \( \Delta n = 0.009 \) which is sufficient for channel optical waveguides at wavelengths of 633 nm and using a suitable accelerating voltage for the electrons, waveguides may be written to depths of a few microns.

Electron beam bombardment has previously been used in pure silica to produce slab waveguides but was ascribed to a compaction mechanism rather than chemical migration (Houghton & Townsend). Our experimental results suggest that single-mode electron-beam waveguides are formed by the chemical migration process described by Gossink et al.

Fabrication: The first glass investigated had a composition close to that of 20% NaSO, 10% CaO, and 70% SiO_2, as used by Gossink et al. This is Chance-Proppe's 'Blue-Star' microscope slide glass of composition 14% NaSO, 7-1% CaO, 72% SiO_2 with 6-9% impurities. The glass slides were polished to give an optical quality finish and coated with a 10 nm layer of NiCr to give a conductive surface for use in the electron beam microscope. Each glass blank is loaded into a scan-
The SEM employed had been adapted for electron-beam lithography. The typical beam currents employed were 26 nA. The maximum dwell time of the electron-beam on a particular spot is set by the electron beam lithography and is not long enough to deliver the charge necessary to produce sufficient refractive index change for waveguiding. Therefore each spot along the line is exposed several times to deliver a charge density of typically 1000-17000 C/m² which is sufficient to produce waveguiding.

The maximum length of the waveguide is determined indirectly by the spot size of the electron beam. For 1 μm and 0.5 μm diameter spot sizes, the SEM scanning area limits the waveguide length to 3 mm.

The depth of electron penetration is determined by the accelerating voltage. According to the empirical formula of Schmidt and Glueck³ the depth, \( L (A) \), is given by

\[
L = 218E^{1.33}
\]

where \( E \) is electron energy in keV. The voltage used was typically 25 kV which implies an electron penetration depth of 1.6 μm.

Characterisation: A frequently employed technique for waveguide characterisation is prism coupling. This requires large planar waveguides. However, the SEM employed in the fabrication had limitations on beam current which made the fabrication of large area planar waveguides impractical and we can only present a comparison of the electron-beam waveguides with ion-exchanged waveguides.

Once the glass blanks have been exposed, the NiCr top layer is removed and the glass is tested for evidence of waveguiding using an HeNe laser, operating at 633 nm, and an end-fire rig. The mode profiles of the guides were recorded in the far field. A comparison of mode profiles from electron-beam and ion-exchanged waveguides is shown in Fig. 2.

Three different glasses have been used in these experiments. They are: 'Blue Star' transparent glass (commercial soda lime), Corning CS 2-62 red filter glass (commercial borosilicate semiconductors doped glass), and Schott #7183 red filter glass (special melt soda-lime semiconductors doped glass). Fig. 3 shows the percentage optical transmission of each of the 3 mm long E-beam guides as a function of the charge density used for waveguide writing. The results are for both double and single-mode waveguides. For the Blue Star glass waveguides written with the 1 μm spot size beam, the three largest exposures produce double-moded guiding conditions. Below 3310 C/m² the waveguides are single-mode. For the 0.5 μm spot size only the largest exposure of 18335 C/m² gives a double-moded waveguide.

The lowest loss single-mode electron-beam waveguide is written with a 0.5 μm spot size and an exposure of 9167 C/m²; it has a loss of 75% in 3 mm or 20 dB/cm. This compares with 1.5 dB/cm for single-mode ion-exchanged waveguides. The electron-beam waveguides' relatively large loss may be associated with the reduced sodium which gives rise to the 'browning' effect.

Fig. 3 also includes results on a Corning Ltd. colour filter glass (CS 2-62). We include this to show that the waveguiding results are glass composition dependent. However the exact composition of the CS 2-62 glass was not available.

The Schott glass results are not included in Fig. 3 because no appreciable guiding was observed in this glass. Table 1 compares the composition of the 'Blue Star' and the Schott glass. The most significant difference is the calcium content. In the Schott glass the calcium is replaced by zinc. This is evidence that the presence of calcium is crucial for the formation of waveguides by electron-beam writing.

**Table 1** COMPARISON OF COMPOSITION OF BLUE STAR GLASS AND SCHOTT GLASS

<table>
<thead>
<tr>
<th>Element</th>
<th>Blue Star</th>
<th>Schott 7183</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si</td>
<td>33.66</td>
<td>31.66</td>
</tr>
<tr>
<td>Na</td>
<td>10.38</td>
<td>9.42</td>
</tr>
<tr>
<td>K</td>
<td>0.49</td>
<td>3.57</td>
</tr>
<tr>
<td>Ca</td>
<td>5.07</td>
<td>0</td>
</tr>
<tr>
<td>Mg</td>
<td>2.48</td>
<td>0</td>
</tr>
<tr>
<td>Al</td>
<td>1.01</td>
<td>45.52</td>
</tr>
<tr>
<td>O</td>
<td>46.71</td>
<td>45.52</td>
</tr>
<tr>
<td>Zn</td>
<td>0</td>
<td>6.56</td>
</tr>
</tbody>
</table>

Quoted figures are by percentage weight content

Note that Schott glass contains no calcium

Conclusions: The evidence that the mechanism for producing the waveguides is the same electron-beam assisted chemical migration as reported by Gossink et al.¹ is as follows: The observation that calcium is required in the glass and by comparison with ion-exchanged waveguides, we infer that Δn is around 10⁻³ which is the value expected from the Gossink et al. and Huggins and Sun results.² This evidence is good but not absolutely conclusive. A microprobe of the chemical content of the glasses is required for further confirmation.
The lowest loss E-beam waveguides produced so far were double-mode waveguides with a loss of 10 dB/cm. Clearly this is a problem which requires further investigation; it may be associated with the reduction in the alkalis which gives rise to the "browning" effect.

The fabrication of waveguides by direct electron-beam writing does not require the production of photolithography masks which, in a research context, means that a large amount of time is taken for the fabrication of novel waveguide configurations can be considerably reduced. Also submicron resolution may well become available and could be important in some applications such as Y junctions and defraction grating fabrication.

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STEERING OPERATION OF OPTICAL BEAM SCANNER WITH SEMICONDUCTOR WAVEGUIDES

Indexing terms: Semiconductor devices, Waveguides, Optics

An optical beam scanner which is capable of high speed random steering has been fabricated. The device consists of two AlGaAs/AlGaAs rib waveguides prepared on a GaAs substrate. The deflection angle obtained was 3° by applying a reverse bias of 9 V to the pn junction in one of the waveguides. This angle almost agrees with the value designed.

Introduction: Optical beam steering is one of the important fundamental techniques in optoelectronics fields. Practical devices at a commercial level, however, consist of a mechanically rotating polygon mirror or hologram. Those devices have merits of large deflection angle and high dot resolution. The steering speed of those devices is, however, extremely low, and steering direction cannot be changed randomly; for these reasons, their fields of application are limited only to laser printers or bar-code readers. Moreover, they are not reliable when subjected to vibration and mechanical shock.

To realise high speed random steering, various kinds of electronic optical beam scanners, e.g. acousto-optic scanners, laser scanners, electro-optic prism scanners, thermo-optic scanners, and photoelectrode scanners have been proposed and studied. We proposed an optical beam scanner with multiple semiconductor waveguides, in which the phase of the optical wave can be controlled by the electro-optic effect. Moreover, an optical beam shape emitted from the device is relatively stable during operation in contrast with that emitted from a laser array. This is because the transverse mode in this device does not change so much by steering operation, but super modes in a laser array may be changed easily by varying the injection current for steering. The proposed device has an advantage of being able to be monolithically integrated with a laser diode. In our previous report, the deflection angle measured was only 0.6°, and is very small compared with that calculated. This is mostly attributed to bad electrical isolation. This Letter describes improvement of the device structure and the deflection angle of 3° realized by applying a reverse voltage of 9 V.

Structure and fabrication: The present device consists of two phase variable waveguides. The phase of the lightwave introduced into the waveguides is modulated by changing the refractive index in the waveguides. The direction of effective wavefront emitted from the output facet can be changed into the required direction. A relatively large deflection angle can be obtained with phase shift of less than 2π. The maximum deflection angle which is defined by the angle between main beam and sub-beams varies with the spacing between the two waveguides, i.e. that angle increases with decreasing the spacing. A dot resolution increases with increasing the number of waveguides. These relations are shown in Table 1.

<table>
<thead>
<tr>
<th>Maximum spacing of waveguides (μm)</th>
<th>Maximum deflection angle (degrees)</th>
<th>Number of waveguide</th>
<th>Dot resolution (dots/scan)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>4</td>
<td>2</td>
<td>14</td>
</tr>
<tr>
<td>5</td>
<td>9</td>
<td>10</td>
<td>68</td>
</tr>
<tr>
<td>3</td>
<td>15</td>
<td>20</td>
<td>14</td>
</tr>
<tr>
<td>1</td>
<td>50</td>
<td>100</td>
<td>68</td>
</tr>
</tbody>
</table>

There are several effects that can be used to produce the change in the refractive index in a semiconductor, e.g. the electro-optic effect, plasma effect of free carrier and quantum-confined Stark effect. We used the electro-optic effect induced by applying reverse electric field to a pn junction, because optical absorption at the depletion region is relatively low.

In the previous device the electric field applied to one of the waveguides affected the other, because the electrical isolation between waveguides was poor. Therefore, a 0.4-μm thick undoped cladding layer is inserted between undoped core and p-type upper cladding layer as shown in Fig. 1. The mole fraction of Al in the core is 0.25 and that in the cladding layer is 0.3. The concentration of acceptors or donors in the doped cladding layers is 5×10^17 cm^-2. The core thickness is 0.6 μm. The wafer was prepared using metalorganic chemical vapour deposition (MOCVD). The width of the waveguides is 4 μm, the spacing between the waveguides is 10 μm, and the device length is about 2 mm. These rib waveguides are fabricated by chemical etching using a mixed solution with composition of H_2SO_4 : H_2O_2 : H_2O = 6 : 1 : 18.

Fig. 1 Schematic diagram of fabricated optical beam scanner

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