Application-specific Optical Fibres Manufactured from Multicomponent Glasses

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Introduction

Silica has been mostly used in special fibres because of its low loss transmission. However, some special fibres require short lengths for optimum performance. Among these are current sensors where the bandwidth is an important criterion, most nonlinear optical devices and rare-earth doped fibre lasers. Here, materials with properties optimized for short lengths of a few metres are favoured. These are typically multicomponent compound glasses. The composition of these glasses can be tailored to the application intended. By use of established glass melting, glass forming and fibre fabrication techniques, all optical devices can be made compatible with conventional monomode silica-based fibres. We have fabricated optical fibres from both commercially available and new component glass melts. Fibres with losses close to the intrinsic loss of the bulk glass precursors are obtainable using a rod-in-tube technique. The intrinsic loss is generally two orders of magnitude larger than silica. The objective of this presentation is to demonstrate the potential and practicality of using compound glass fibres for application in nonlinear devices, fibre sensors and fibre lasers.

Lead oxide glasses exhibit a combination of high refraction and high dispersion owing to the high polarizability of lead in silicate glasses. The consequences are much higher third-order nonlinear coefficients and larger Verdet constants than silica. F-series and SF-series glasses are lead silicate glasses containing up to 65 wt% PbO. Fibres for nonlinear devices and sensors have been fabricated from these glasses and the results are presented here.

In laser glasses where the host glass is doped with rare-earth ions, the lasing properties of a fibre can be modified by changing the composition of the host glass. Multicomponent silicate, phosphate, borate and chloride glasses have been investigated as potential host glasses for fibre lasers and amplifiers. We compare our results with silica MCVD fibres. Furthermore, the rod-in-tube method of fabrication lends itself to variations in fibre design to accommodate the availability of new laser sources such as high power multi-strip diode arrays for cladding pumped fibre lasers. We report here the first all glass cladding pumped Nd-doped fibre laser from compound glasses.

A brief description of the fabrication method is discussed below. Fibre testing and results follow. The details of the experimental set-up and procedures are not covered in this text. We refer the reader to the appropriate references.

Fabrication

A range of fibre types have been developed for many of the applications described here. For silica-based fibres, preform preparation involves the MCVD process and where necessary, in combination with solution doping[1]. The rod-in-tube technique is employed in the fabrication of multicomponent glass fibres. The process is briefly described below.

Both core and cladding glasses are drilled out from blocks of suitable glass with an ultrasonic drill. Inspection of the quality of the surfaces at this point is important. A rough surface can introduce losses of about 10dB/m. The important glass properties for matching core and clad glasses are thermal expansion coefficients and softening temperature (T_s). A difference of 40×10^{-7}/°C in thermal expansion is tolerable. The fibre is usually pulled 50°C above T_s of the component with the higher T_s. As the heating is from the outside to the inside, our experience shows that it is best that the T_s of the core be less than the T_s of the clad. This also allows air trapped in the core-to-clad interface to escape more readily. For low loss fibres, it is essential that the core glass be polished prior to drawing. This is done by drawing the initial rod into a cane. The clad tube need not necessarily be polished as it is polished in the drawing furnace during fibre pulling. For this, the rate at which the preform is feed into the furnace hot zone is important. The optimum feeding rate depends on the diameter of the rod and the change in viscosity with temperature about T_s. The preform is drawn into a fibre in a conventional tower equipped with a low temperature furnace. The diameter and length of the furnace hot zone are 20mm. For a lead silicate glass of diameter 10mm and a pulling temperature of 600°C, the optimum feed rate is 0.8mm/min. The pulling rate depends on the final diameter desired. For our application, this is typically around 3m/min.

Fibre testing and results

Nonlinear Devices

The very high power densities made available by lasers have enabled the observation of nonlinear optical effects in materials. The degree of nonlinearity is reflected in the nonlinear coefficients $\chi^{(2)}$ and $\chi^{(3)}$. The $\chi^{(2)}$ coefficient is responsible for the observation of SHG, parametric interaction which can lead to frequency up-conversion and linear EO effect in materials. The $\chi^{(2)}$ effect exist only in materials that do not possess inversion symmetry. Silica possesses a centre of symmetry. However, it has been demonstrated that second-order nonlinearities can be induced in germania-silica fibres by either defect excitation via high intensity blue light or optical fibre poling[2].

Fibres fabricated with F7 glass using F2 glass for cladding have been fabricated to demonstrate the nonlinearities in flint glasses. A minimum attenuation of about 300dB/km is attainable which is comparable to the bulk loss of the glasses. A D-shaped fibre with a hole running parallel to the core was used for testing[3]. The longitudinal hole was filled with gallium to act as an electrode, the other being an external plate placed against the fibre section. For

Figure 1: Electric-field induced SHG in F7 fibre

SHG, a pulsed beam from a Nd/YAG laser was launched into the fibre, then the fibre was poled with an applied DC field across the core and the development of the SHG signal was observed. Figure 1 shows the result of poling the F7 fibre. There is a slow rise in generated signal followed by a levelling off. When the DC field is removed, there is also a slow return to initial conditions. The SHG is not preserved. For the same poling field of 1500kV/cm, the result is opposite that observed for Ge/Si fibres. Here, defect centres are induced permanently. In F7, the field induces polarization of the lead oxide because of its high polarizability. There is an orientation of the molecules by the field which causes the slow rise. Without the field, it relaxes back to its original state. The field does not introduce a permanent non-centro symmetry. Another indication of the difference in mechanism is the absence of an induced linear EO or Pockels effect in F7 fibres. In Ge/Si, the effect is not only induced but is found to remain permanently. The non-permanent nonlinearity may be exploited for use in tunable SHG devices.

The $\chi^{(3)}$ coefficient is responsible for optical THG, second order EO or Kerr effect, and optical frequency Kerr effect. We observed THG signal in the F7 fibre. However, the conversion efficiency was masked by the high loss of the fibre at 354nm. The Kerr coefficient at 633nm of the F7 fibre was measured. The value is 2.15 times higher than that reported for a Ge/P-doped silica MCVD fibre[3]. The estimated Kerr constant is 4.5 times that of silica[4]. The slow response to the electric field, as above, will restrict its practical application as an EO modulator but the larger Kerr or $\chi^{(3)}$ coefficient makes it ideal for optical switching devices.

In optical frequency Kerr effect, the refractive index change is brought about by an applied optical field. A twin core fibre (TCF) using F7 for cores and F2 for clad was fabricated to demonstrate optical switching. We found that with the rod-in-tube technique, it was difficult to fabricate core rods to the necessary degree of uniformity. MCVD prepared TCF showed the same problem of nonuniformity. For efficient switching both a large Kerr constant and coupling length are desirable to keep to a minimum the laser power required for switching. To resolve our difficulty, we introduced resonant perturbations in combination with applying a load to the TCF to offset the effect of nonuniformity[5]. For switching an F7 TCF with a YAG laser, power densities greater than $0.1GW/cm^2$ is required. This power is less than the critical power for switching as we still observed coupling to the other core. The damage threshold of an F7 single core fibre was determined to be $5GW/cm^2$. This required a very pristine fibre end. Any defects in the fibre end resulted in heating and fibre damage. We are currently limited by this difficulty. One of the problems encountered with fibres from multicomponent glasses is the difficulty in getting a good cleave. This apparently is a bigger problem in a TCF configuration.

Fibre Sensors

The use of fibres to measure electrical current employs the principles of the Faraday effect. The sensor consists of a number of fibre coils wound around a current carrying conductor. The response of the fibre coil is proportional to the Verdet constant and the length of the fibre. Because the fibre has to be wound, the fibre must also have a low linear birefringence. The Verdet constant of an F7 fibre has been measured previously[6]. It is 2.5 times larger than that of a Ge/Si fibre. As a current sensor, the minimum current that can be received is limited by the receiver noise. At the optimal length, the noise equivalent current is proportional to the ratio of the attenuation to the Verdet constant. Curves of current sensitivity against fibre length from Reference 6 indicate that the performance of an F7 fibre will be superior to silica fibres for all lengths up to 50 metres.

SF57 shows the greatest sensitivity up to lengths of 15 metres. SF57 has the advantage of exhibiting a transition from negative to positive stress-optic coefficient with increasing wavelength, whereby the passage through zero is at 568nm. This potentially makes SF57 a good material for current sensors because it will have an inherently low linear birefringence. Spinning the fibre during the fabrication can be omitted. A single mode fibre was fabricated with SF57/SF6 glasses (core/clad). The fibre loss was excessively high. This is attributed to an interfacial problem. The glasses showed volatilization at low temperatures. To make this fibre work a better understanding of the glass behaviour at the pulling temperature is required. Also, a higher index cladding material will be appropriate.

Figure 2: Fluorescence spectra of samarium glass host: (a) Ge/Si (b) Ge/Si (c) P/Al/Si (d) P/Al/R, [Sm] in 10^{19} ions/cm^3: (a) 0.8 (b) 2.1 (c) 9.0 (d) 8.6

Fibre Lasers

Examples of compositional dependence of rare-earth doped glasses are illustrated in Figures 2 to 3. Laser

emission of Sm in the visible has been reported[7]. Samarium shows a markedly strong dependence to host glass as reflected in changes in its fluorescence branching ratios as shown in Figure 2. Plots (a), (b) and (c) are MCVD fibres. All transitions originate from the same metastable state. The 565nm transition is to the ground state. There is an apparent influence of electron-phonon coupling as the branching ratios between adjacent states with separation less than the silicate stretching vibration are affected. When Sm is doped in P/Al/R compound glass, where R is an alkali modifier, then the transitions that are affected have a separation closer to the phosphate stretching vibration and almost resonant to it, plot (d). A further study of Sm under different conditions may help in our understanding of the complex relationship between dopant and host glass.

Figure 3: Fluorescence in Nd-doped fibre

We observed a shift in fluorescence wavelength in Nd-doped compound melt with 50 mol% $ZnCl_2$, Figure 3. The peak maximum is at 1038nm versus 1054nm in phosphate glass. The shift is accompanied by narrowing. There is a corresponding shift to lower wavelength in the $^4F_{3/2}-^4I_{13/2}$ transition which occurs around 1290nm in the chloride glass. The modifier components of the glass are KCl – NaCl – $PbCl_2$. It is fairly reduced in hygroscopic tendency relative to $ZnCl_2$–KCl binary system. The glass forming ability on addition of Nd is low, only up to 0.01wt% and even markedly less for Er. The Nd fluorescence lifetime is 205μs. This is comparable to the radiative lifetimes reported[8] for $50Z_nCl_2 \cdot 50KI$ and $60BiCl_3 \cdot 40KCl$. The glass is interesting in effecting a shift in optical transitions and may be further modified to give transitions closer to 1.30nm. We had limited success in finding a suitable cladding material for this glass due to its very high thermal expansion. Also, we have been unable to preserve the fibre ends from hygroscopic attack during testing. Clearly, this is an area that will require more work.

We also report observing dramatic reduction in fluorescence lifetime in a 0.5 mol% Er_2O_3 in 80 mol% borate glass. The lifetime is 279μs. We observed the broadening as expected of borate glasses. The short lifetime is associated with increase in nonradiative decay rate due to the large phonon energy of borate. The short lifetime makes it unacceptable for Er amplifier application. However, the short lifetime is ideal for passive Q-switching of Er-doped fibres.

The high cross-section values and low concentration quenching associated with phosphate glasses make them ideal host for fibre lasers. We have recently reported laser emission at 1.363μm from a Nd-doped compound phosphate glass fibre[9]. Normally, this transition is strongly suppressed in oxide glasses due to excited state transition effects. However, the spectral gain in this fibre exhibits gain starting at 1360nm. When pumped with a Ti:sapphire laser at 850nm, a threshold of 5mW absorbed power and slope efficiency of 10.8% was obtained. This is the lowest lasing threshold and highest slope efficiency reported to date for this transition.

The increasing availability of higher powers in multi-strip diodes have made them attractive multimode pump sources for fibre lasers. We have fabricated a double clad offset core fibre to test the performance of compound glasses for cladding pumped fibre lasers[10]. The advantage of using compound glass is that different glasses can be matched to obtain the desired refractive index differences. The disadvantage is that the length is a limiting factor because of fibre loss. The core glass is 2 wt% Nd_2O_3 in F7. The inner clad is F2 glass and the outer clad is LF8 glass. The Nd*F7/F2 fibre has an NA of 0.125, an absorption length of about 2mm at 805nm and a loss of 1.7dB/m at 1060nm. The higher loss in the doped fibre comes from inhomogeneity and small bubbles present in the prepared bulk Nd-doped glass. The F2/LF8 fibre NA is 0.41 and the loss at 805nm is 0.5dB/m. This is comparable to the bulk loss of the glasses. The configured double clad fibre has a core/clad area ratio of 1/437. The fibre was placed in a Fabry-Perot cavity for testing the performance of the fibre. The fibre was pumped with a 10-strip laser diode array at 805nm. The laser emission was at 1064nm. The characteristics of the fibre laser are shown in Figure 4. A fibre length of 1.5 metre is optimum. A threshold of 50mW and a slope efficiency of 47.6% was obtained. This is a very favourable result. We can expect to improve on this efficiency by minimizing the fibre loss and reconfiguring the fibre design.

Figure 4: Cladding pump laser characteristics

Conclusion

We have confirmed the high nonlinearity and large Verdet constants of flint glasses in fibre form, in particular F7 fibres. These properties make them suitable fibres for fibre devices and sensors. The rare-earth dopant level in compound glasses can be orders of magnitude larger than in silica. Thus, for shorter lengths of fibre, compound glass laser fibres can be as efficient as silica laser fibres.

References

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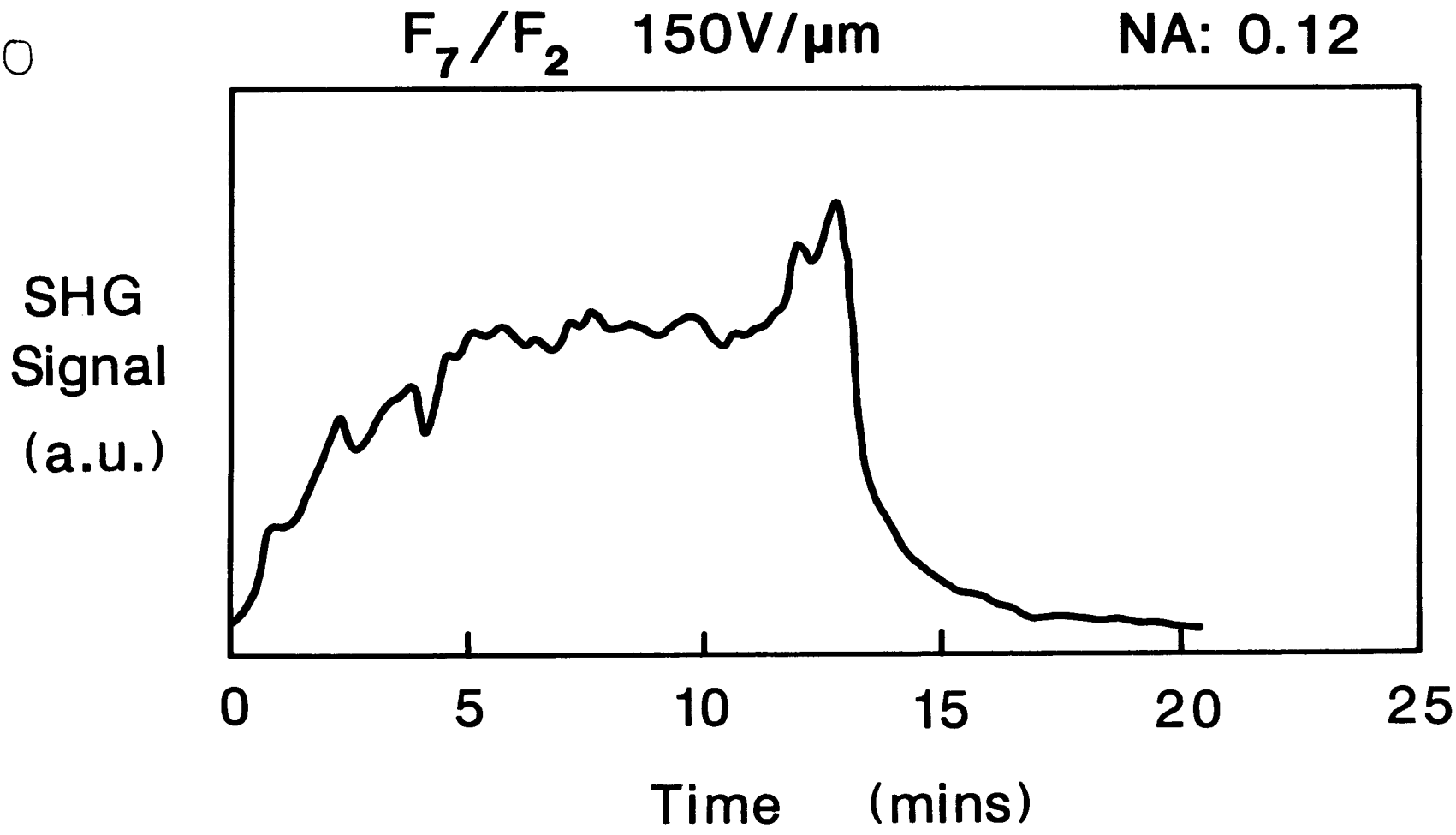
456.1

SHG INDUCED BY DC ELECTRIC FIELD

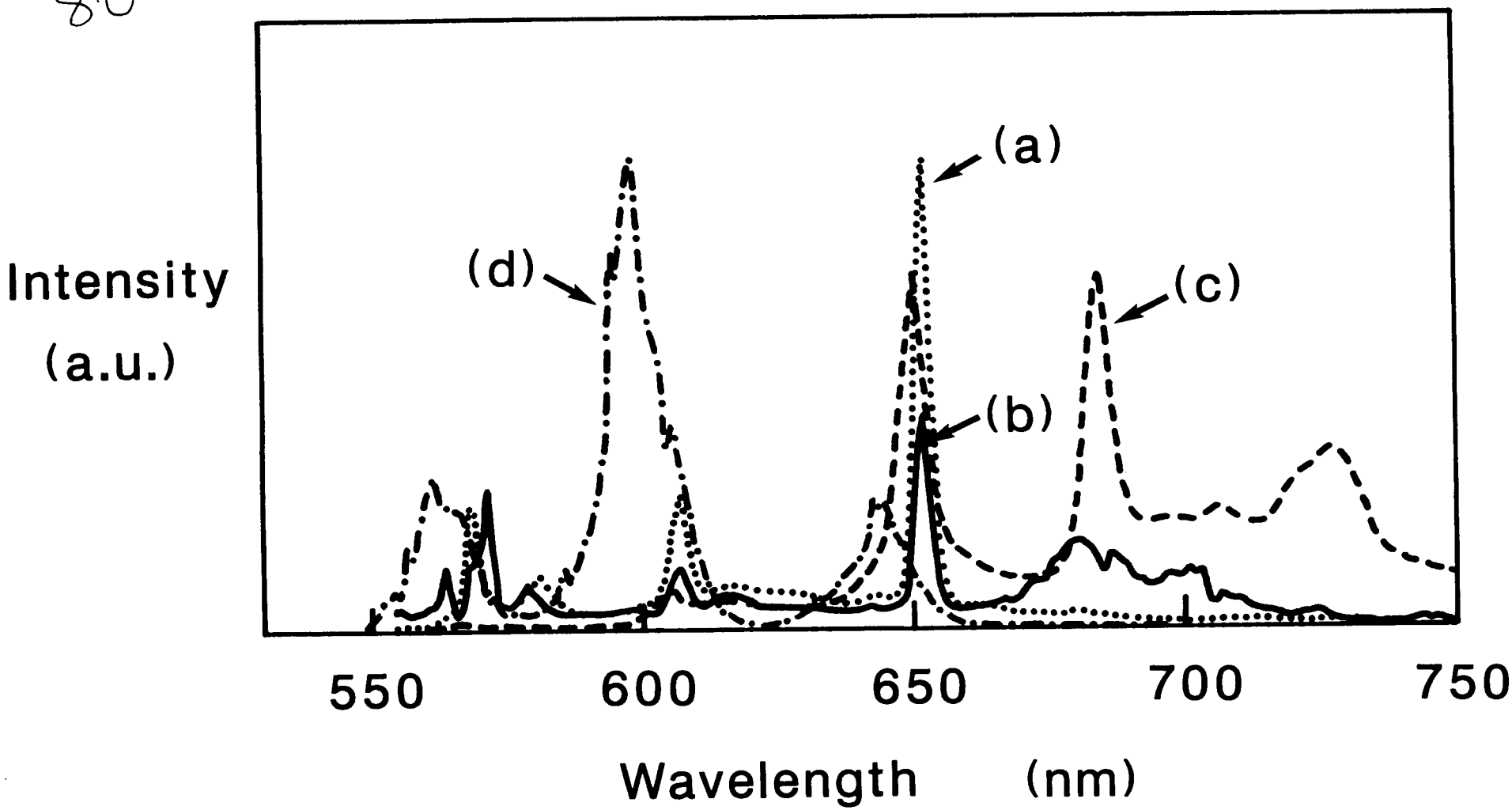
22.0 TO 8.0



FLUORESCENCE SPECTRA OF SAMARIUM FIBRES

25·0 TO 8·0

Pumped at 488nm

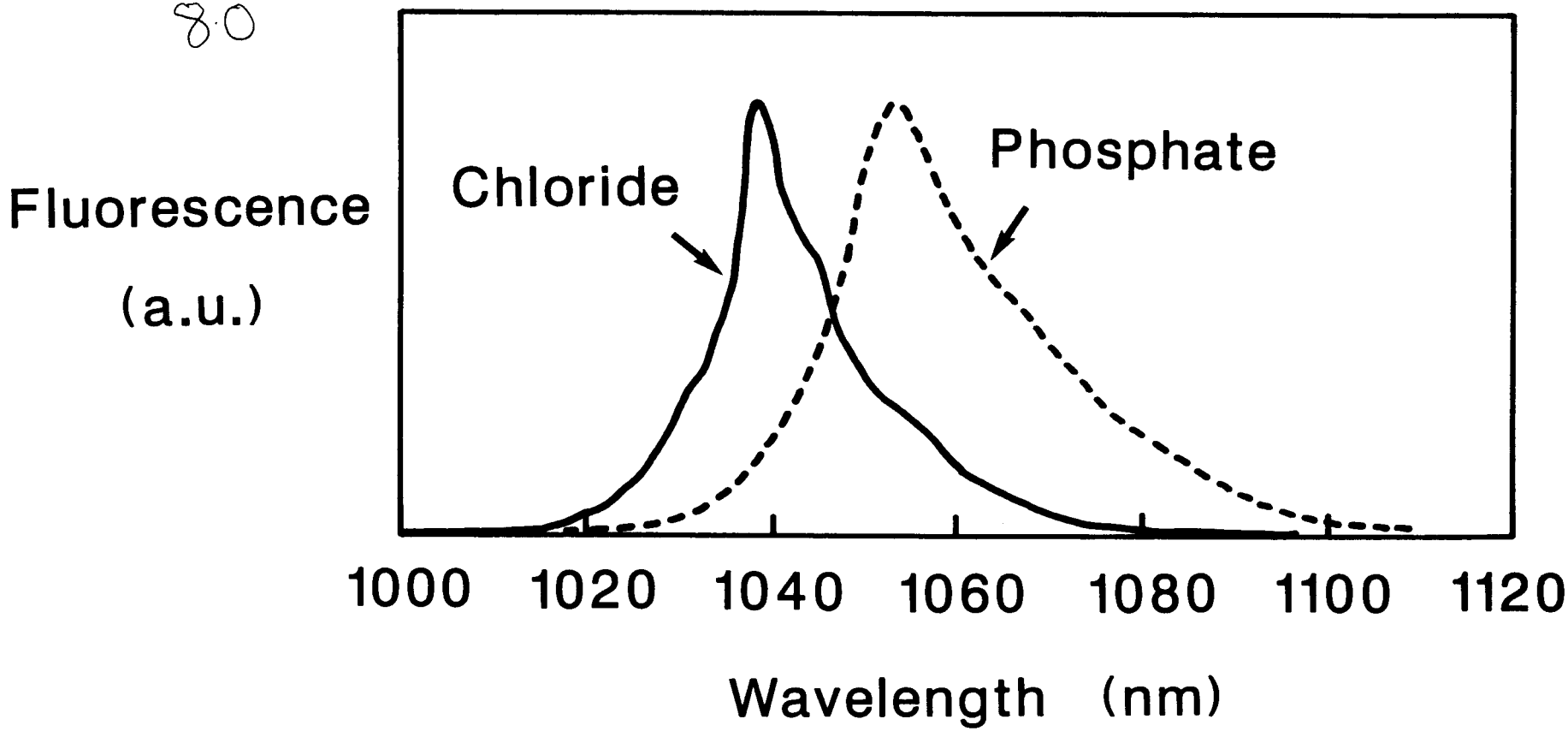


1.42 in

456.3

FLUORESCENCE IN Nd-DOPED FIBRE

240 TO 80



1.58"

24.3
TO
8.0

456.4