NEW FABRICATION TECHNIQUES FOR MULTIMODE INTEGRATED OPTICS (*)

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ABSTRACT — Ion exchange fabrication of low loss waveguides in glass has been demonstrated using $Li_2SO_4 - K_2SO_4$ eutectic. The process is extremely fast and the resulting distribution can be controlled by application of an electric field.

1 — INTRODUCTION

The present trend in optical communication systems towards multimode fibres has created a growing interest in the design of suitable deep integrated components. The thermal migration of ions in glass is one of the few fabrication techniques of low loss multimode waveguides. Ag/Na ion exchange from a silver salt melt [1] is a very widely used and convenient method, but it requires a very long immersion time and leads to a standard graded index profile which is difficult to modify. However the technique can be successfully extended to overcome these difficulties by using other melts, which are stable at higher temperatures and employing field assisted diffusion [2].

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This paper reports the fabrication and the characteristics of highly multimode planar waveguides made by Li/Na ion exchange, and describes the improvements and possibilities offered by an electric field assisted Ag/Na ion exchange technique.

2 — Li/Na ION EXCHANGE WAVEGUIDE FABRICATION

Small monovalent lithium ions can easily diffuse in a glass matrix where an exchange with the sodium ions of different polarisability takes place. The stability of lithium salts allows higher diffusion temperatures to be used. Their high melting points, which are unsuitable for soda lime glass, suggest the use of an eutectic melt, 80% mol Li_2SO_4 – 20% K_2SO_4, which brings the melting point down to 524°C [3]. Soda lime microscope slides were preheated and immersed in the eutectic for different immersion times *t* and temperatures T. The refractive index profiles were then determined by the WKB evaluation from the angular position of the m-lines. Figure 1

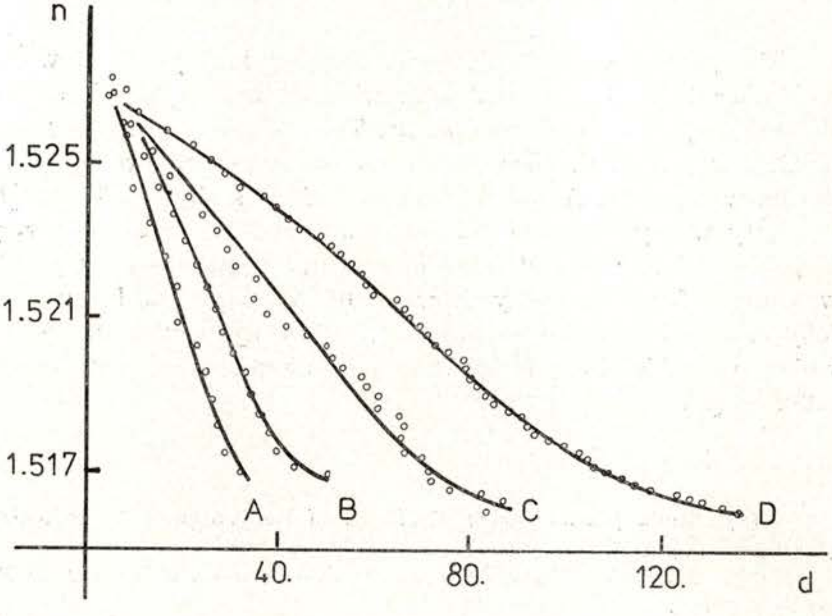

Fig. 1 — Index profiles n(d) obtained at T = 575°C for several immersion times t. The depth d is in microns. A: 1 min., B: 2 min., C: 5 min. D: 17 min.

shows the index profile of a number of waveguides with t as a parameter. By comparison with the Ag/Na technique, a 35 microns deep waveguide requires 50 hours at T = 250°C, whereas the Li/Na technique requires only 1 min. at T = 575°C, as shown by figure 1, curve B. The refractive index difference $\Delta n = 0.015$ between the surface index n_s and the substrate index is considerably smaller than in the Ag/Na case, but is even more compatible with the index characteristics of usual multimode fibers, as is the waveguide depth with the fibre core cross section.

The data were processed in order to find the function which best fits the experimental index profiles. Amongst the exponential, gaussian, error function, second order polynomial and linear profiles, the latter presents by far the smallest standard deviation, being the first order term of the solution of Fick's equation with a concentration dependent diffusion coefficient [4]:

$$n(x) = n_s - \Delta n \; x/d \tag{1}$$

Using the results of figure 1 it was shown that d depends linearly on $\sqrt{t}$, so that an effective diffusion constant D can be defined:

$$d = 2\sqrt{\mathrm{D}t} \tag{2}$$

D was determined by immersing several glass slides at different temperatures T for the same time. The linear dependence of the logarithm of D against inverse temperature shown by figure 2 suggests for D the standard expression:

$$\mathrm{D} = \mathrm{D}_0 \exp(-\mathrm{T}_0/\mathrm{T}) . \tag{3}$$

From our experimental data we found $\mathrm{D}_0 = 5.4 \times 10^{-3}\ \mathrm{m^2 s^{-1}}$ and $\mathrm{T}_0 = 1.6 \times 10^4\ ^0\mathrm{C}$. It follows for instance that a waveguide made at temperature T_1 can be made p times deeper by using a melt at temperature T_2 such that

$$\mathrm{T}_2 = \mathrm{T}_1 \mathrm{T}_0 / (\mathrm{T}_0 - 2\mathrm{T}_1 \, ln \, p) . \tag{4}$$

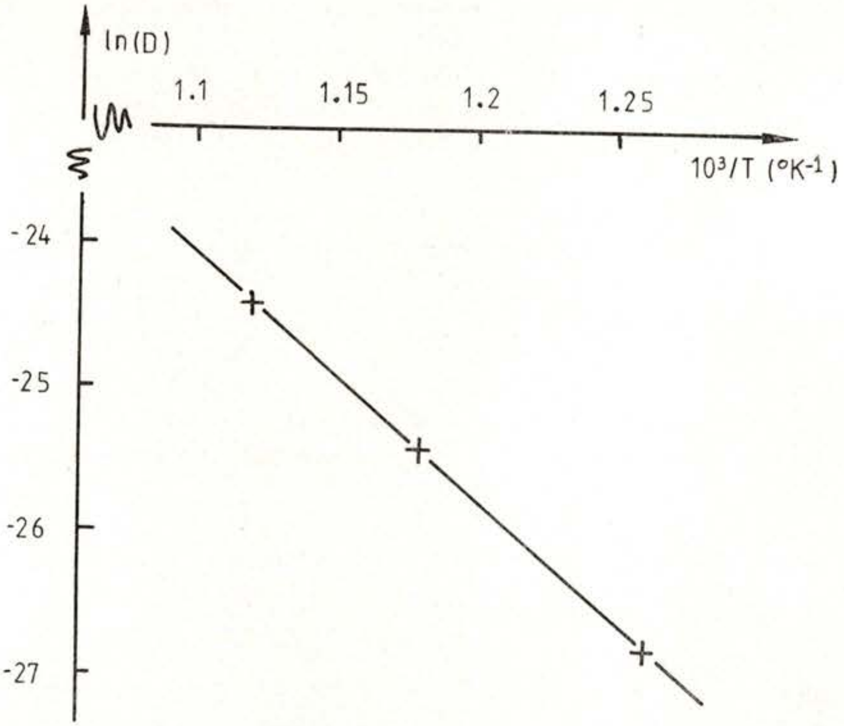

Fig. 2 — Temperature dependence of the diffusion constant D for 5 min. immersion time.

3 — FIELD ASSISTED Ag/Na ION EXCHANGE

An external electric field E may be used to enhance or modify the ion exchange rate and the penetration depth. Microscope slides were covered on one side by a negative aluminium electrode whereas the other side, which had been very carefully cleaned, was covered by a positive evaporated silver layer. An ionic current flows from the Ag anode to the Al cathode. The total charge is a direct measure of the waveguide depth. Waveguides were produced in the temperature and field ranges 170°C to 300°C and 0 to 2.10^5 V/m. Figure 3 shows the dramatic influence that can be achieved by varying the field. In the case of profile D, 13 well confined modes can propagate (only 2 without field). The dashed line H′ represents the guide profile

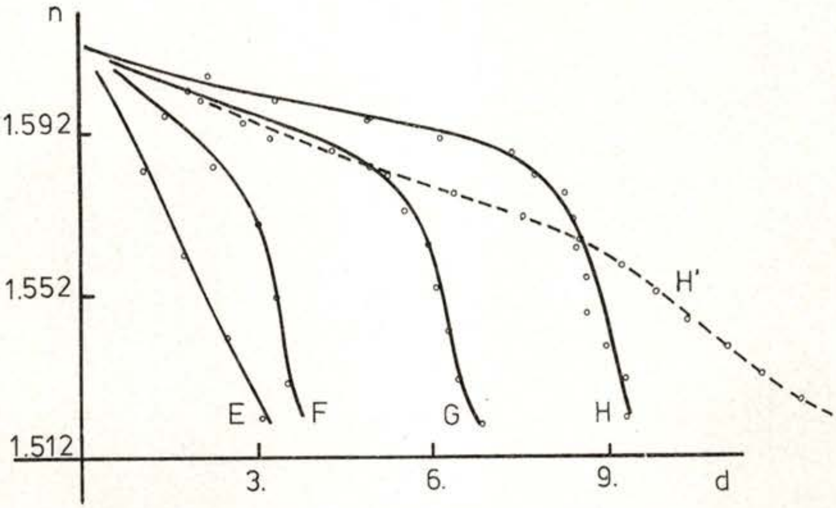

Fig. 3 — Influence of the applied field on the index profile n(d). The depth d is in microns. Immersion time t = 30 min. Temperature T = 250°C.

E: V = 10 V, F: V = 30V, G: V = 50V, H: V = 100V
H': t = 330 min.,T = 250°C, V = 0 V

which, by passive diffusion during $5^1/_2$ hours, also propagates 13 modes.

The diffusion process can be described here by a Fick's equation with an extra term $-\mu E\ \partial c/\partial x$ involving the gradient of the concentration, $c(x, t)$, an effective mobility μ and E. Although its coefficients are concentration dependent, as is the electric field, the solution for constant coefficients was used to fit approximately the experimental profiles [5]:

$$n(x, t) = n_s - {}^1/_2\,\Delta n\,[\mathrm{erfc}\,((x - \mu E t)/2\sqrt{Dt}) + + \exp\,(\mu E x/D)\ \mathrm{erfc}\,((x + \mu E t)/2\sqrt{Dt})] \qquad (5)$$

by adjusting D and μ. Despite some minor discrepancies, some values of the mobility were determined and confirmed by resistance measurements during the experiments. Figure 4 shows the linear dependence of the logarithm of the mobility against inverse temperature, which can be written [6]:

$$ln\ \mu = A + B/T \qquad (6)$$

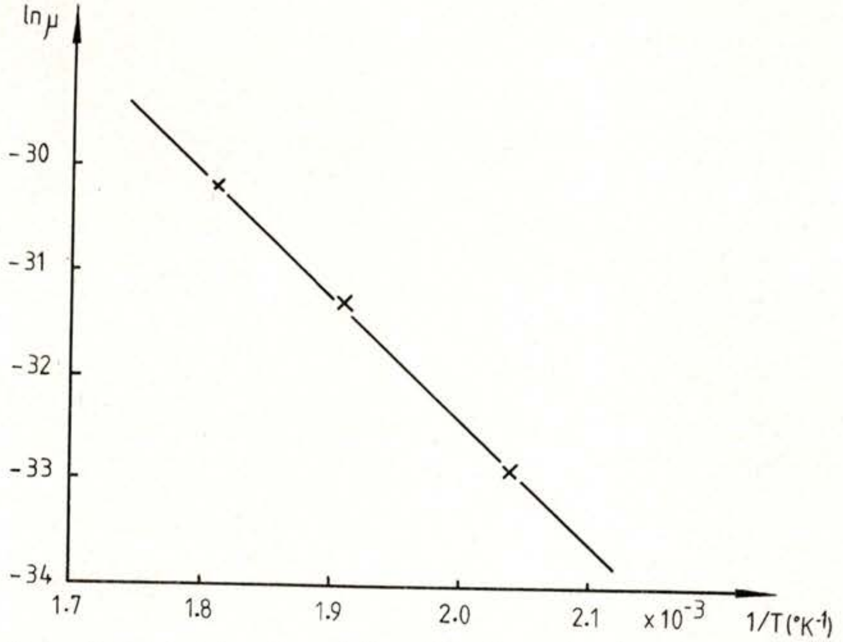

Fig. 4 — Temperature dependence of the mobility for t = 30 min., voltage 50 Volts, at various temperatures (217, 250, 280°C).

where the constants A and B are found to be -9 and -1.2×10^{-4} respectively.

4 — CONCLUSION

The present development of fibre optic systems ascribes an important role to multimode integrated optics. One major problem in this new field is to realise waveguides presenting a satisfactory geometrical and electromagnetic match to multimode fibres. These requirements are fulfilled by the waveguide fabrication techniques presented in this paper. Sufficient depth and an additional control of the index distribution by an electric field can be achieved in very short times.

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