CONFIGURATION OF INTERFEROMETER USING SINGLE-MODE SLAB OPTICAL WAVEGUIDE

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1. Introduction

A number of planar optical waveguides are being developed for optical sensors and optical information processing systems based on optical fibers[1]. The primary methods of fabrication for such waveguides are sputtering and thermal ion exchange[2)~5)]. The latter method can be carried out on soda-lime glass substrates to form singlemode waveguides. The sodium ion in the glass is interchanged with potassium or silver ions. Exchanging sodium ions with potassium ions produces smaller refractive index differences in comparison to the case of silver ions and produces lower loss single mode waveguides[6].

The sodium-potassium ion exchange method was applied to microscope glass slides and low loss (<0.2 dB/cm) single-mode waveguides were produced. The refractive index distribution and the potassium ion density distribution (i. e. waveguide layer thickness) were measured. A simple interferometer was constructed with this single-mode waveguide and the relation between the refractive index of the waveguide surface and the magnitude of the fringe displacement was experimentally determined. The experimental results were also analyzed theoretically. Based on the results obtained a pressure sensor was designed and experimentally evaluated[7)~8)].

2. Fabrication of Single-Mode Optical Waveguides and Their Characterization

potassium nitrate crystals were heated to their melting point (340°C) and glass substrates were immersed into the molten potassium nitrate for specific lengths of time. Partial replacement of sodium ions in the glass substrate with potassium ions resulted in the formation of a single-mode slab optical waveguide. The fabrication process is outlined in Fig. 1.

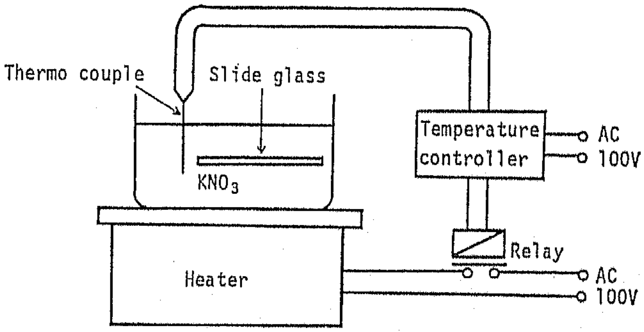


Fig. 1 Schematic diagram for fabricating optical waveguide

Microscope slide glasses from Matsunami Glass Industries and Fisher Scientific and "Tempax" glass slides from Jena Glassworks were used as substrates. The "Tempax" glass has a low sodium content. The ion exchange was carried out at a temperature of 350°C~390°C over a time interval of 10 min. ~640 min..

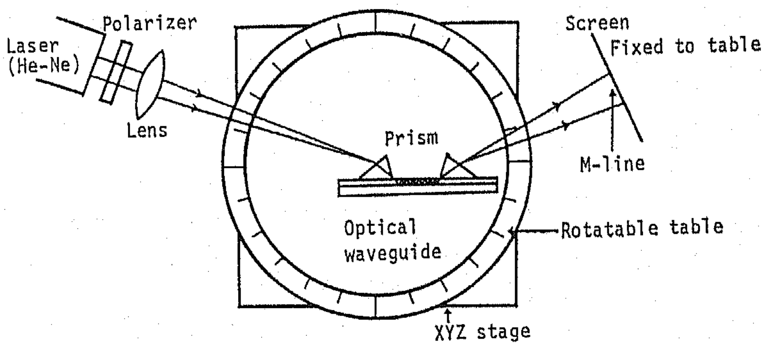


Fig. 2 Arrangement of prism coupler

Figure 2 shows the experimental arrangement for observing the propagating waveguide modes using a prism coupler.

Figure 3 shows the mode-line of a single-mode waveguide produced by ion exchange at 370°C for 64 min. on a Fisher Scientific slide glass.

Figure 4 shows the relation between the number of waveguide modes in a waveguide and the time interval of ion exchange at specific temperatures for a Fisher Scientific slide glass.

Figure 5 shows the relation between the theoretical effective wave-

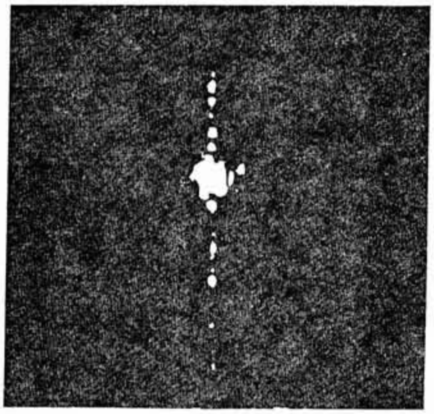


Fig. 3 Typical output m-line of a potassium-ion exchanged guide
Diffusion temperature 370°C
Dffusion time 64 min.

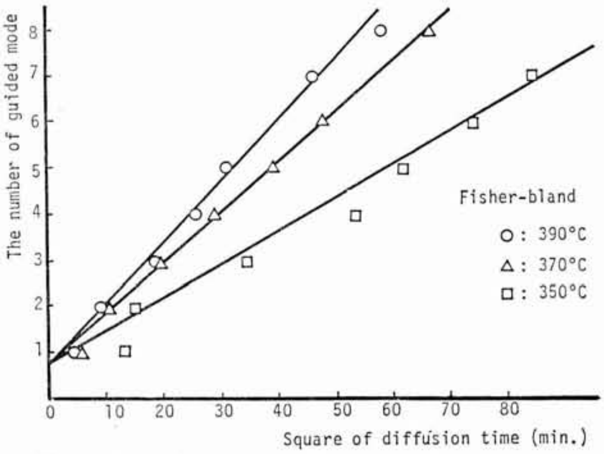


Fig. 4 Relation between the number of guided mode and square of diffusion time

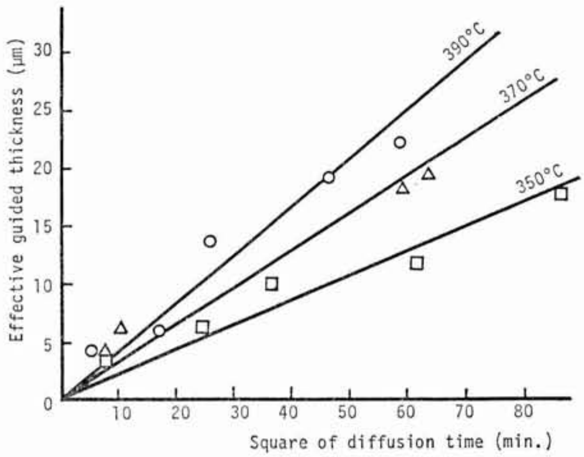


Fig. 5 Relation between effective guided thickness and square of diffusion time

guide thickness (depth of ion-exchange diffusion) and the time interval of ion exchange at specific temperatures for a Fisher Scientific slide glass. The calculation assumed a gaussian cross-section for the waveguide. Effective indices of refraction for each mode was calculated first and the effective waveguide thickness was the obtained from the modal dispersion curve by numerical methods. Figure 5 shows that the effective waveguide thickness obviously depends on the temperature and time interval of immersion of the substrate. A waveguide of approximately 4 μm thickness which supports only a single mode, can be fabricated by immersing the substrate for 64 min. at 370°C. This theoretical result agreed approximately with the result for the potassium density distribution using an X-ray micro-analyzer.

Table 1 shows the measured characteristics of one of the experimentally fabricated waveguides.

Table 1 Character of single-mode slab waveguide

		Mesured value
Diffusion depth (Waveguide layer thickness)	d	3μm
Substrate index	n_s	1.522
Maximum index of refraction	n_f	1.526
Normalized frequency	v	3.290

3. Application to Pressure Sensors

3.1 Interferometer Structure

The structure of an interferometer based on a singlemode slab waveguide is outlined in Fig. 6. optical beam from a 632.8 nm He-Ne laser was coupled into the waveguide through a beam expander and a cylindrical lens. The input-face of the slab waveguide was shaped as a prism with a peak angle of 178° and the face was polished flat to precision of 1/4 of a wavelength. At the output end of the waveguide, interference fringes are created according to the principle of the Fresnel bi-prism. The separation of the fringes depends on the peak angle of the prism and a small angle produces small fringe separations. The prism had a peak angle of 178° which gave a fringe separation of about 38 μm. Since this separation was difficult to measure directly, the fringe pattern was enlarged through a microscope objective. If a peak angle of 179° is used, the fringe separation will be about 50 μm.

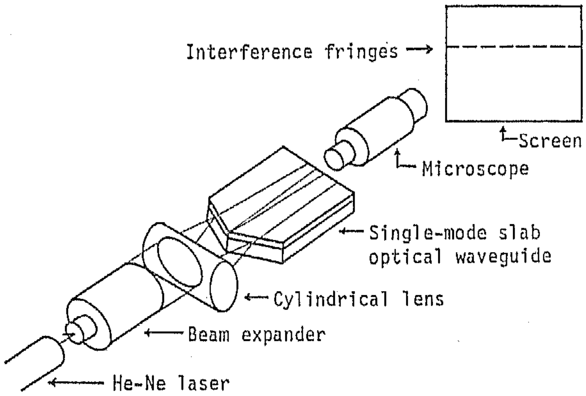


Fig. 6 Experimental arrangement for obtaining interference fringe

3.2 Movement of Interference Fringes with Changes in the Cladding Index of Refraction: Theoretical Analysis

The dependence of the movement of the interference fringes on the index of refraction of the top-side of the waveguide was calculated theoretically. The top-side is normally exposed to the atmosphere but in this case, an extra cladding layer was assumed to be present. Figure 7 shows the model used for the calculation based on the rayapproximation method. An optical ray traces out a propagation path in the form of an arc when the waveguide index distribution is graded. The phase shift caused by total internal raflection at the surface $x=0$ is given by the expression,

$$\phi_1 = -2\tan^{-1}\sqrt{\frac{N^2-n^2_{clad}}{n^2_f-N^2}} \tag{1}$$

where N=effective index of refraction,

n_{clad}=index of refraction of the extra cladding layer,

n_f=maximum index of refraction of $n(x)$.

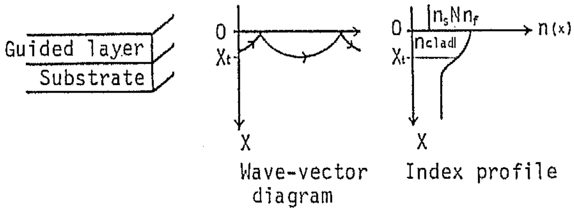


Fig. 7 Analysis model of ray-approximation method

Hocker et al.[9] used $n_{clad}=1.0$ for air and obtain $\Phi_1=-\pi$. Since we assume the presence of an extra cladding layer, $n_{clad}=1.0$ and it follows that $\phi_1\neq-\pi$, and equation (1) can be used to calculate the variation in phase according to the change in n_{clad}.

The measure of asymmetry, a of a step index waveguide is given by the expression[10],

$$a=(n^2_s-n^2_{clad})/(n^2_f-n^2_s) \tag{2}$$

where n_s=index of refraction of the substrate. Also, the normalized guided mode eigen value equation is given as,

$$2V\int_0^{xt}\sqrt{f(x)-b}\,dx=2\tan^{-1}\sqrt{\frac{b+a}{1-b}}\left(2m+\frac{1}{2}\right)\pi \tag{3}$$

where $m=0,\ 1,\ 2,\ \cdots\cdots$

$$V=k_0d\sqrt{n^2_f-n^2_s} \tag{4}$$

V=normalized frequency,
K_0=wave number in vacuum,
d=effective waveguide thickness,

$$b=(N^2-n^2_s)/(n^2_f-n^2_s) \tag{5}$$

b=normalized waveguide index of refraction,

$$x_t=f^{-1}\ (b) \tag{6}$$ and

f(x)=index of refraction distribution function.

Figure 8 shows the relation between a and b using V as a parameter. The refractive index distribution function f(x) was assumed to be gaussian in form and numerical methods were used to obtain the results. The effective index of refraction N is

$$N=\beta/k_0$$

and from equations (2) and (5) we see that Fig. 8 represents the variation of the propagation constant as function of n_{clad} The interference fringe

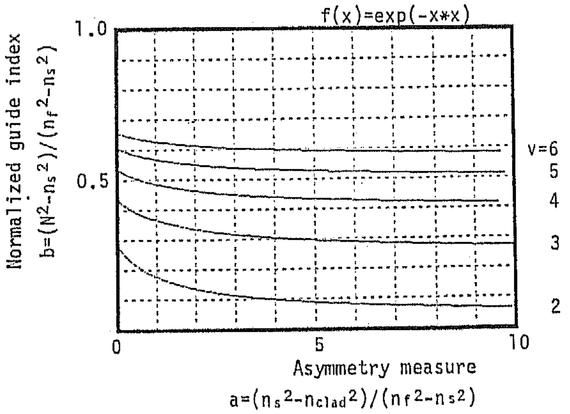


Fig. 8 Relations between normalized guide index and asymmetry measure

pattern moves as the propagation constant changes.

Since the fringe pattern moves through one fringe with a change of 2π in phase, if we define the length of the extra cladding layer as L, from $N=\beta/k_0$ and Eqs. (2) and (5), the number of fringe displacements $m=\Delta\beta L/2\pi$ is given by,

$$\frac{\Delta\beta L}{2\pi}=-\frac{1}{2\pi}\frac{k^2{}_0 n_{clad}}{\beta}\cdot\frac{db}{da}\cdot\Delta n_{clad}L \qquad (7)$$

The sensitivity of the pressure gauge is proportional to the number of fringe displacements.

According to Fig. 8, the variation of b (i. e. β) is large when the value of a is closest to 0 (i. e. $n_{clad}\cong n_s$) and the sensitivity is large. Furthermore, according to Eq. (4), V is proportional to d and the variation of b is largest when V is smallest. This means that in order to maximize the sensitivity $m=\Delta\beta L/2\pi$ the value of n_{clad} should be close to that of n_s, and the thickness of the waveguide should be such that only a single-mode is supported.

3.3 Movement of Interference Fringes with Changes in The Length of Cladding Material: Experimental Analysis

Cladding layers of PMMA were formed on the waveguide substrates with ethyl acetate solutions of PMMA. The index of refraction of the layers were found to be $n_{clad}=1.49$. The length of the cladding layer was

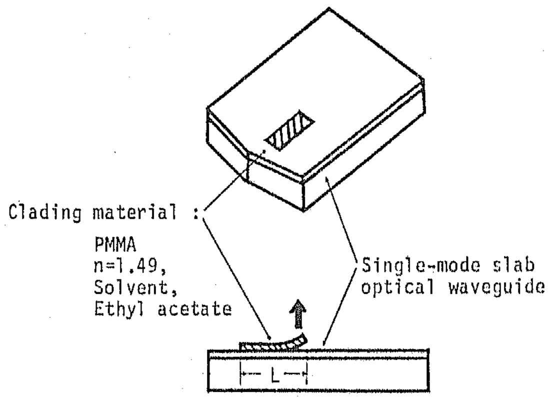


Fig. 9 Configuration of fringe displacement for clading material

shortened by gradually peeling off the PMMA layer starting from the opposite side of the input facet. Figure 9 schematically shows the process. The peeling process is effectively changes the index of refraction of the cladding layer from $n_{clad}=1.49$ to $n_{clad}=1.00$. This change is reflected as a change in the propagation constant and causes the fringe pattern to shift.

When the degree of fringe shift is measured as a function of cladding layer length, a measure of the dependence of the fringe shift on the index of refraction of the cladding layer is obtained.

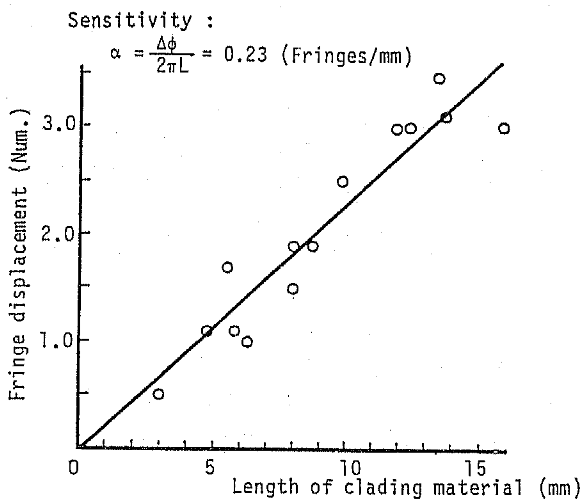
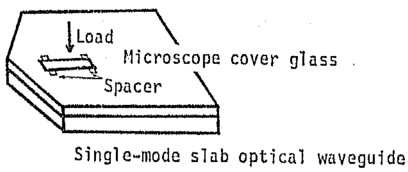


Fig. 10 Length of clading material vs fringe displacement

Figure 10 shows the experimental result when the cladding layer length is changed from 3.00 mm to 16.00 mm. The result shows that the movement of fringes is 0.23 fringes per mm. The theoretical result obtained from sensitivity (α) gives 0.27 fringes per mm which is in reasonable agreement with the experimental result.

3.4 Application to Pressure Sensors

Figure 11 shows the structure of the experimental pressure sensing



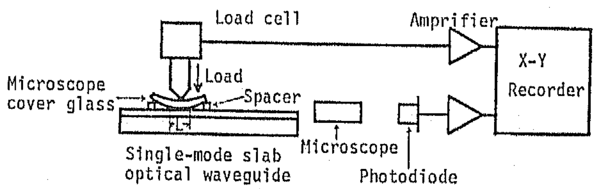


Fig. 11 Configuration for measuring of load

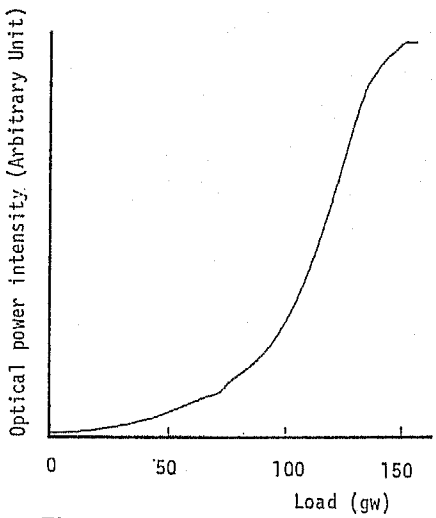


Fig. 12 Measured optical power intensity vs load

system schematically. A microscope cover glass of thickness 0.15 mm was placed above the waveguide substrate by using 16.00 mm thick spacers made from PET material. A load was applied to the cover glass through a load cell. As the load was increased, the area of physical contact between the cover glass and the waveguide became larger. The increase in contact area is equivalent to an increase in the cladding layer length and as a result, a shift in the fringe pattern is generated.

The shift in fringe pattern was detected by a photodiode arrangement and the degree of shift was measured as a change in detected optical power. Figure 12 shows the experimental result for the optical power variation with the load that was applied. Clearly, the apparatus can serve as a pressure sensor. Higher sensitivities can be expected if the thickness of the cover glass is reduced.

4. Conclusios

The process of replacing the sodium ion in the glass slide with potassium ion was carried out by immersing the glass slide in molten potassium nitrate. A 4 μm thick single-mode waveguide with comparatively low loss (<0.2 dB/cm) was obtained after immersion for 64 min. at a temperature of 370°C.

The single-mode slab waveguide layer thickness depends on the temperature and time internal of immersion of the substrate. Relatively simple pressure sensors with can be constructed by using slab waveguides produced in microscope glass slides through an ion exchange process.

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