$MgO:LiNbO_3$ single-crystal fiber with magnesium-ion in-diffused cladding

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A Mg-ion in-diffusion process was applied to form an optical guiding structure in $LiNbO_3$ single-crystal fibers. A parabolic refractive-index profile was formed in a 56-μm-diameter, c-axis $MgO:LiNbO_3$ fiber, yielding quasi-single-mode (two modes) propagation.

$LiNbO_3$ single-crystal fibers have potential applications to devices such as second-harmonic generators, optical modulators, lasers, and optical parametric oscillators.[1–3] To achieve the application of $LiNbO_3$ single-crystal fibers to efficient nonlinear and laser devices, the fibers must be provided with a core–cladding structure. Cladding the fiber reduces both scattering loss and the number of propagating modes. To date, however, little investigation of cladding for single-crystal fibers has been conducted.[4]

There are several methods of lowering the refractive index of $LiNbO_3$, such as Mg-ion in-diffusion[5] and proton exchange.[6] Another possible approach is to coat a suitable material onto the fiber surface. We believe, however, that the Mg-ion in-diffusion is the most promising cladding method for $LiNbO_3$ fibers. First, Mg-ion in-diffusion lowers both the ordinary and the extraordinary refractive indices; second, it reduces the effective core size; third, the diffusion process naturally increases the interface smoothness as the depth of diffusion is increased.

In this Letter we report on a $MgO:LiNbO_3$ single-crystal fiber with Mg-ion in-diffused cladding and the realization of quasi-single-mode propagation in this fiber.

The as-grown $LiNbO_3$ fiber was c axis, 56 μm in diameter, and had approximately 5 mol % MgO concentration. The cladding was achieved by the following steps. First, we annealed the fiber at a temperature of 1050°C for 2 h. The fiber was placed upon a platinum boat in an electric furnace and suspended above Li-rich powder to prevent excessive Li out-diffusion. This first step is called vapor transport equilibration. Second, a thin MgO layer was deposited onto the fiber surface in an evaporator. The MgO layer thickness was 200 nm. Third, the Mg-ion in-diffusion process was carried out using the same setup as for the annealing step. The diffusion interval was 10 h at a processing temperature of 1050°C. Based on the diffusion coefficient data, $D = 10^{-11}$ cm^2/sec, indicated in Ref. 5, we estimated that the Mg ions diffuse around 25 μm, taking into account the cylindrical shape of the fiber.[7]

After this cladding process, the cladded fiber was mounted with UV-cured epoxy in a glass capillary tube to allow both end surfaces of the fiber to be polished.

Figure 1 shows an optical microscope photograph of the end face of the c-axis, 56-μm $MgO:LiNbO_3$ fiber with Mg-ion in-diffused cladding. The three ridges, indicating the trigonal symmetry of c-axis $LiNbO_3$, can be clearly seen in this photograph. This end face has some edge chipping that could be avoided with a more careful polish.

The MgO concentration distribution of the fiber was measured with a JEOL Model 733 microprobe within an accuracy of 0.1 mol %. The end face of the fiber was scanned with a 1-μm spot-size microprobe electron beam. Analysis of the MgO concentration was conducted at 2-μm intervals. Figure 2 indicates the ratio of Mg to (Mg + Nb) concentration versus the fiber radius. It can be seen from the profile that Mg ions diffused to the center of this fiber. This confirms the above value for the Mg-ion in-diffusion coefficient. In addition, the concentration profile has a parabolic shape, fitted well by the expression $C = 5.35\,\% + 4.2 \times 10^{-3}\, r^2$. The MgO concentration difference ΔC be-

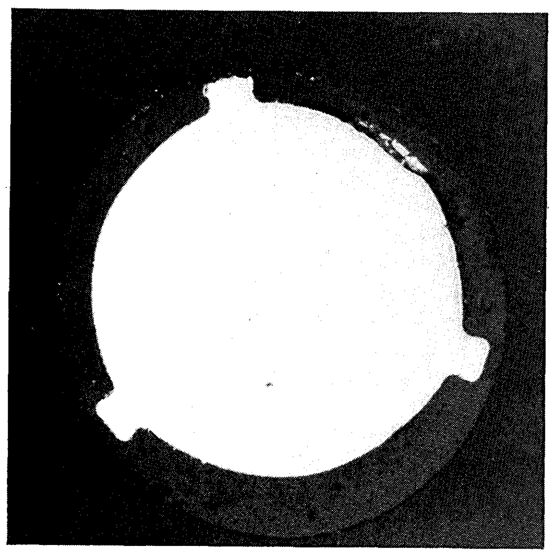

Fig. 1. Photograph of the end face of the c-axis, 56-μm $MgO:LiNbO_3$ single-crystal fiber with Mg-ion in-diffused cladding. This photograph was taken under reflected light.

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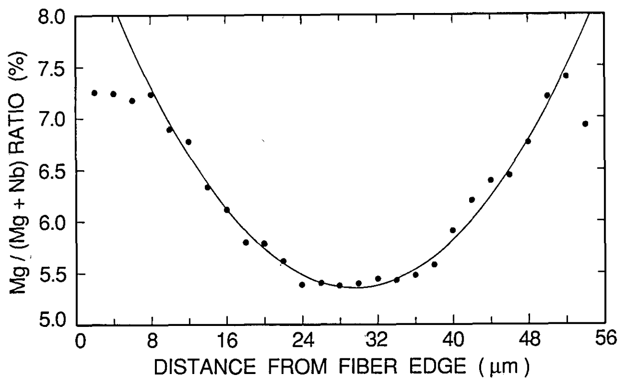

Fig. 2. The ratio of Mg to (Mg + Nb) concentration versus the distance from the fiber edge measured with a microprobe.

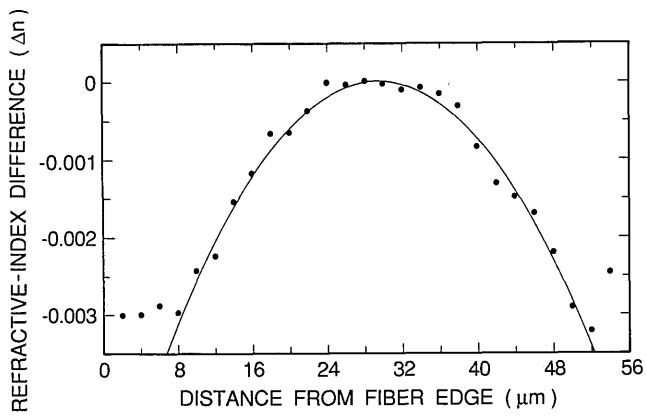

Fig. 3. Refractive-index profile of the c-axis, 56-μm $MgO:LiNbO_3$ single-crystal fiber with Mg-ion in-diffused cladding.

tween the central part and the surrounding is 1.8 mol %. We find that a concentration difference ΔC of 1.8 mol % corresponds to a refractive-index difference Δn of 0.0032, based on experimental results to be reported elsewhere.[8] This correspondence between ΔC and Δn agrees with the data of Ref. 9. Figure 3 shows the refractive-index profile of this fiber calculated from the correspondence between ΔC and Δn. This index profile has a Δn of 0.0032 and a well-fitted parabolic shape.

It should be noted that this fiber also has a thin MgO-rich layer near its surface. We are investigating the properties of this layer. Our results will be submitted for publication.

Figure 4(a) shows the setup for mode-propagation experiments. The beam from a vertically polarized He–Ne laser was focused into the fiber with a lens having a 20× magnification and a 0.4 N.A. The fiber length was 3 mm. A polarizer was used to analyze the output beam from the fiber. Figures 4(b) and 4(c) show the output-beam patterns from the polarizer: in Fig. 4(b) the polarization is vertical, that is, the same polarization direction as that of He–Ne laser; in Fig. 4(c) the polarization is horizontal. A quasi-single-mode pattern was obtained without the polarizer, and this pattern seemed to include two modes, namely, LP_{01} and LP_{11}. After the polarizer was put in the output beam, those two modes were separated, with the fundamental mode in the vertical polarization as can be seen in Fig. 4(b) and the higher-order mode in the horizontal polarization as can be seen in Fig. 4(c). Small fractions of the light pattern shown in Figs. 4(b) and 4(c) seem to be in cladding modes or leaky modes that have not been stripped out because of the short fiber length. We measured the relationship between the output-beam size for the fundamental mode and the distance from the end fiber face. From this measurement, the output-beam size at the end face was calculated to be 13.8 μm in diameter according to the Gaussian-beam equation $\omega \cong \lambda/\pi \tan\theta$.

Since we used a 20× lens (N.A. = 0.4) to launch the light into the fiber, the spot diameter at the focusing point was 8 μm, and the diameter of such a beam could have reached 50 μm within a 1.0-mm propagation distance. Thus the 3-mm fiber length should be sufficient to produce guided modes. Therefore the results suggest that two modes could propagate as guided modes or that this single-crystal fiber can be operated

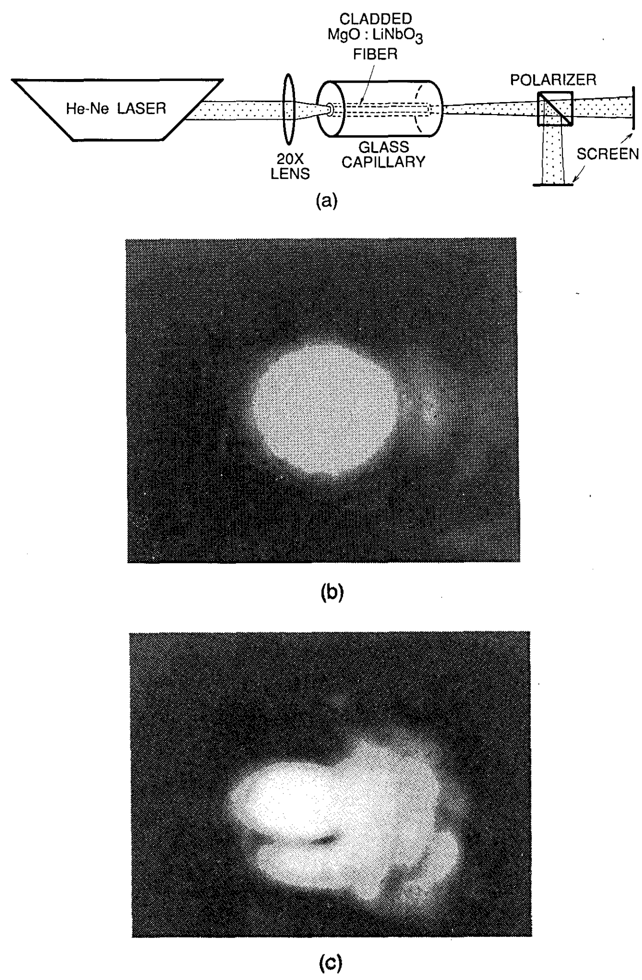

Fig. 4. Setup for mode-propagation experiment and output-beam patterns. (a) Experimental setup. (b) Output-beam pattern for the vertical polarization. (c) Output-beam pattern for the horizontal polarization.

as a quasi-single-mode fiber. Further investigation is necessary to clarify the mode-propagation characteristics in such cladded $LiNbO_3$ fiber.

This fiber has a large core diameter of approximately 45 μm and a Δn of 0.0032. Thus the current $LiNbO_3$ fiber has a very large V value, and consequently such two-mode propagation seems not to be a steady state. However, single-mode propagation along the short length is possible, and this length should be sufficient to demonstrate nonlinear devices of interest.

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