CHARACTERIZATION OF OPTICAL FIBER PREFORMS BY LINE-FOCUS-BEAM ACOUSTIC MICROSCOPY

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ABSTRACT

An ultrasonic method of line-focus-beam acoustic microscopy is applied to an analysis of the mechanical properties of silica-based optical fiber preforms. A first-deposition-stage optical fiber preform with GeO_2 and F dopants and 80-mm outer diameter, fabricated by the vapor phase axial deposition (VAD) method, is used in the experiments. The leaky surface acoustic wave (LSAW) velocity profile along the radial direction is measured at 225 MHz and compared with that calculated from the chemical composition obtained by electron probe microanalysis. It is found that the LSAW velocity profile corresponds mainly to the dopant distribution, and the difference between the measured and calculated velocity distributions suggests that a residual stress distribution in the preform is detected in the measured profile.

INTRODUCTION

Optical fibers at present play a very important role in telecommunication as transmission lines. To realize the desired optical and mechanical properties, it is of fundamental importance to estimate and control the properties and qualities during the fabrication processes. Some dopants are distributed to form a refractive index profile of core and cladding for lightguide. The difference in the thermal expansion coefficient between core and cladding glasses introduces residual stresses, which influence both mechanical and optical properties. Several optical methods have been proposed to measure the structural parameters of optical fibers and preforms, such as core diameter, refractive index profile and residual stress distribution [1-3].

In this paper, we propose an ultrasonic method, using a line-focus-beam (LFB) acoustic microscope, to characterize the mechanical properties of optical fiber preforms and demonstrate its usefulness for resolving some scientific problems in research and development in optical fiber fabrication processes. LFB acoustic microscopy is a new and unique technology for characterizing quantitatively materials by utilizing leaky surface acoustic waves (LSAWs) excited on the water/sample boundary [4]. Characterization is performed by determining the LSAW propagation characteristics, viz., phase velocity and attenuation. The LFB acoustic microscope with perfect directionality is more useful than a point-focus-beam (PFB) acoustic microscope since the residual stresses introduce anisotropy to isotropic materials. The LSAW propagation characteristics are directly related to mechanical properties, reflecting the chemical compositions and residual stresses, and quantitative investigation has shown that LSAW velocity is closely related to the chemical and physical properties of materials [5-8].

The LSAW velocity profile is measured for a silica-based optical fiber preform at a frequency of 225 MHz with an LFB acoustic lens of 1.0-mm radius, and the result is compared with that calculated from the chemical composition distribution.

EXPERIMENTS AND RESULTS

Sample Preparation

A silica-based optical fiber preform, with a step index profile for a single mode fiber and which was fabricated by the vapor phase axial deposition (VAD) method [9], was used in the experiments. The preform was first-deposition-stage one, without mechanical cladding and with an outer diameter of 80 mm, and it was prepared into a sliced and optically polished sample 5 mm thick (see Fig. 2).

LSAW Velocity Measurement

Details of the LFB acoustic microscope system and the measurement principle were described in our previous paper [4]. The LSAW propagation characteristics are obtained through V(z) curve measurement and analysis. Figures 1 (a) and (b) show the typical V(z) curves for the preform measured at core and cladding, respectively. As indicated, the LSAW velocity at cladding is greater than that at core since the dip interval of the V(z) curve at cladding is slightly greater than that at core. According to the procedure for V(z) curve analysis [4], the LSAW velocities, V_{LSAW}, at

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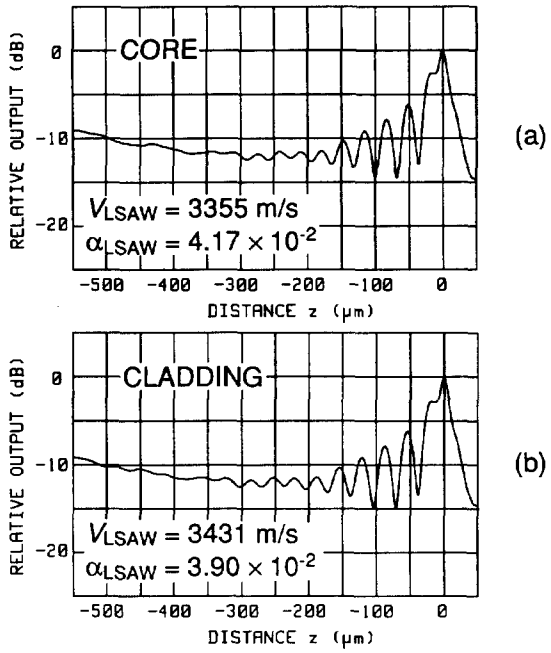

Fig. 1 Typical V(z) curves for a preform measured at (a) core and (b) cladding at 225 MHz.

core and cladding are determined to be 3355 m/s and 3431 m/s, respectively, and normalized attenuation factors, α_{LSAW}, are determined to be 4.17×10^{-2} and 3.90×10^{-2}, respectively. In this study, velocity is used for characterization. Attenuation will be discussed elsewhere.

The LSAW velocity measurements were made at every 250 μm along the radial direction in two experimental procedures as shown in Fig. 2, where the shaded area represents the ultrasonic beam region linearly focused on the sample surface through water couplant (not shown in the figure). The LSAW propagates parallel to the radial direction in case (a), and perpendicular to it in case (b). Figures 3 (a) and (b) show the measured LSAW velocity profiles for both cases. The velocity variations along the radial direction were clearly measured. The velocity rapidly decreases at core, and the maximum difference between core and cladding is 90 m/s (2.7 %). However, while sharp variations at the boundary between core and cladding can be observed in case (a), this is not clear in case (b).

Here, let us consider the measurement models for each case. Figure 4 shows cross-sectional views of the lens and sample in case (a) and case (b), respectively. To obtain the V(z) curve, it is necessary to move the sample from a focal point (z = 0) toward the lens, a procedure called defocusing. In case (a), the LSAW propagates to the radial direction, and the propagation region used for measurement depends on the defocusing range, where θ_{LSAW} is the critical angle of LSAWs (see Fig. 4 (a)).

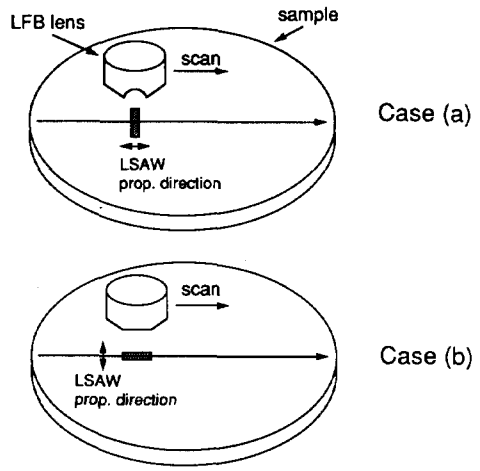

Fig. 2 Two types of experimental procedures: the LSAW propagates parallel, in case (a) and perpendicular, in case (b) to the radial direction. The shaded area shows the ultrasonic beam region linearly focused on the sample surface.

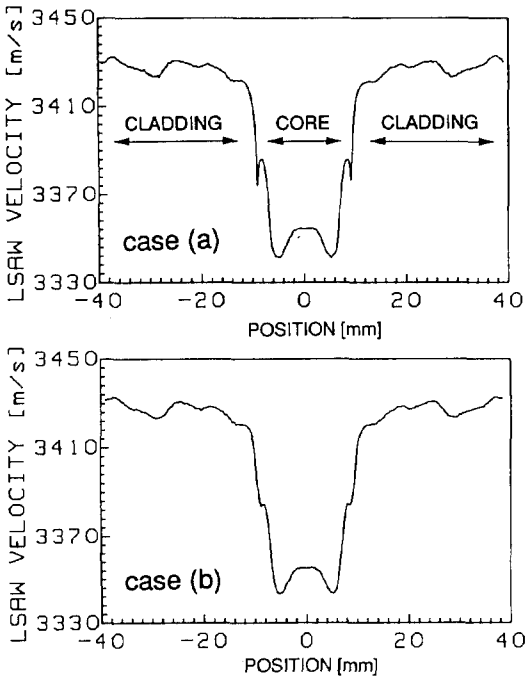

Fig. 3 LSAW velocity profiles measured by an LFB acoustic microscope

When the range of V(z) curves used for analysis is from -30 to -300 μm, the maximum propagation region is estimated to be approximately 290 μm at -300 μm for this sample. On the other hand, in case (b), the ultrasonic beam width along the radial direction is about 900 μm as the three-decibel width for the present LFB lens, which is independent of the defocusing range (see Fig. 4 (b)).

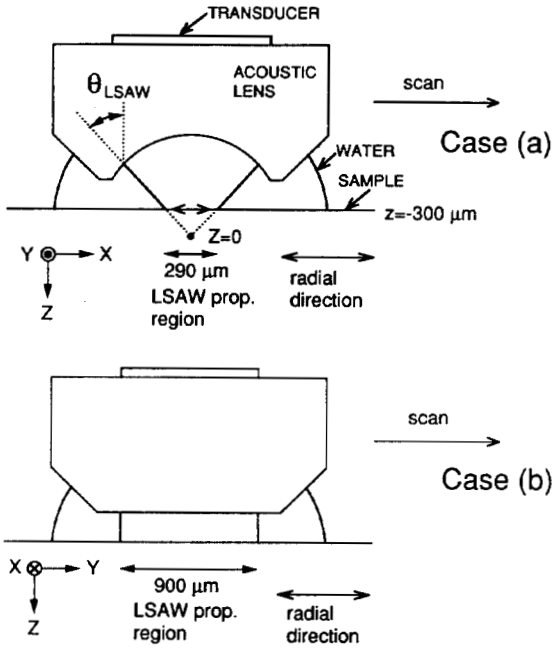

Fig. 4 Cross-sectional views of the lens and sample explaining the measurement models.

Thus, it can be said that a higher spatial resolution is expected in case (a) than in case (b) and that this is the main cause for the difference in the velocity profile between the two cases in Fig. 2.

DISCUSSION

In order to investigate the causes of the velocity variation along the radial direction, the chemical composition distribution was measured by electron probe microanalysis, as shown in Fig. 5. Germanium oxide (GeO_2) and fluorine (F) are doped to silica glass (SiO_2) to control the refractive index profile and thermal expansion coefficient. It is well known that GeO_2 increases the refractive index of pure silica glass, while F decreases it [10]. Chlorine (Cl) is incorporated into the preform since chlorine gas is used in the dehydration process for the preform fabrication [11].

GeO_2 and F dopants decrease the LSAW velocity of silica glass, and it is possible to calculate the velocity of doped silica glass from the velocity variation versus the dopant concentration for silica glass [8]. The LSAW velocity profile, calculated from GeO_2 and F dopant concentrations for SiO_2 obtained from the chemical composition distribution in Fig. 5, is shown in Fig. 6 as a solid line. The measured profile in case (a) is also shown as a broken line for comparison. The velocity value of 3431.84 m/s measured for a synthetic silica glass specimen (T-4040, Toshiba Ceramics Co.) was used as a reference velocity for undoped silica glass in calculation.

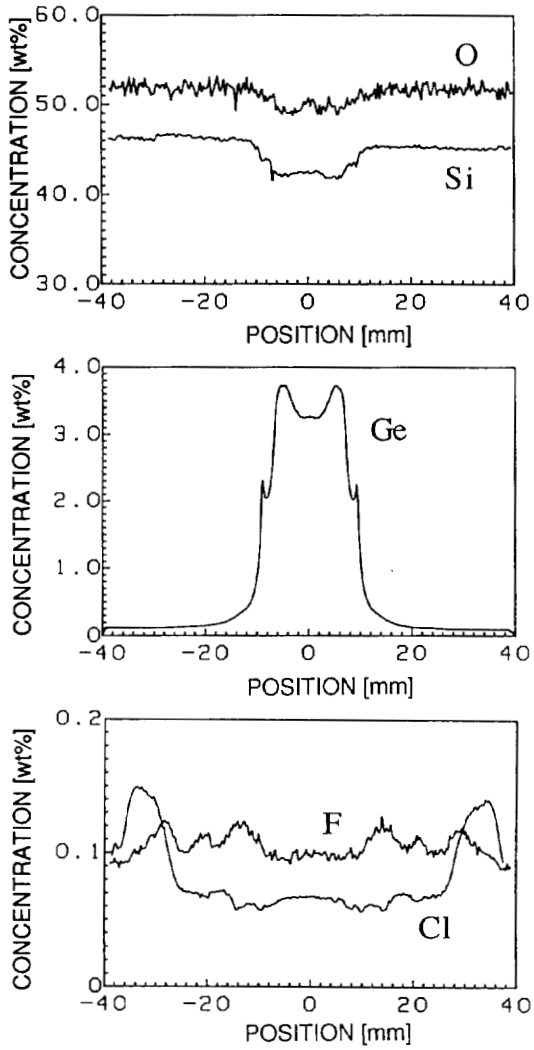

Fig. 5 Chemical composition distribution measured by electron probe microanalysis.

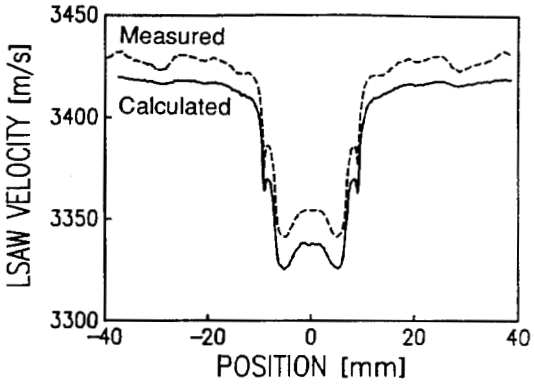

Fig. 6 LSAW velocity profile calculated from GeO_2 and F dopant concentrations for SiO_2 in comparison with the measured profile as shown in Fig. 3 (a).

The relative variation of the calculated profile is in good agreement with the measured profile. Hence, it is indicated that the LSAW velocity profile corresponds mainly to the dopant distribution.

However, the calculated LSAW velocities are about 10 m/s greater than the measured velocities at every position. This difference could be caused by such factors as the difference between the LSAW velocity of undoped silica glass fabricated by the VAD method and that of T-4040 and the lack of consideration in the calculations of the influence of Cl on LSAW velocity. Furthermore, a greater relative variation at cladding is found in the measured profile than in the calculated profile. It seems that the residual stress distribution in the preform can be detected in the measured profile. This suggests that the LFB system can estimate the residual stress distribution in the preform. Further investigation should be carried out to separate the residual stress information from the velocity profile.

The refractive index profile can also be calculated from the index variation versus the dopant concentration for silica glass [10]. Figure 7 shows the refractive index profile calculated from GeO_2 and F dopant concentrations for SiO_2. The relative refractive index difference between core and cladding is estimated to be 0.31 %.

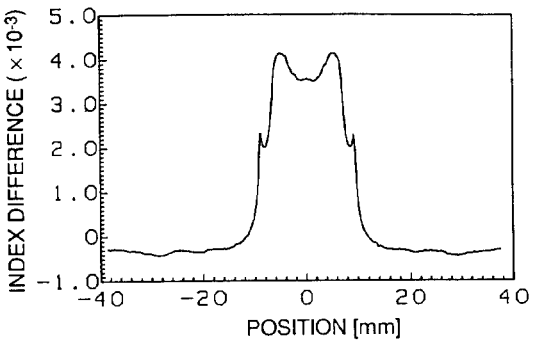

Fig. 7 Refractive index profile calculated from GeO_2 and F dopant concentrations for SiO_2.

CONCLUDING REMARKS

We have applied LFB acoustic microscopy to characterize optical fiber preforms. The LSAW velocity profile has been clearly measured and compared with that calculated from the chemical composition distribution. The measured LSAW velocity profile corresponds mainly to the dopant distribution and includes information on the residual stress distribution. It is concluded that LFB acoustic microscopy is very useful in evaluating the mechanical properties of preforms for research and development in optical fiber fabrication processes.

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