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High numerical aperture multicomponent glass fiber

S. Shibata, S. Mitachi, and S. Takahashi

High-numerical-aperture (N.A. 0.53) multicomponent glass fibers with 20 dB/km optical loss have been obtained. Glass containing BaO is most promising for fabrication of high-N.A. low-loss optical fibers over a wide wavelength region. The BaO-core glass/multicomponent-clad glass fibers show the following notable characteristics: relatively low optical loss in the 0.6–1.3-μm region, small N.A. wavelength dependence, high effective N.A., large bandwidth due to mode coupling, and high coupling efficiency to LED.

I. Introduction

High-numerical-aperture (N.A.) optical fibers are particularly well suited for short-distance transmission of incoherent light from light-emitting diodes (LEDs) because of a high coupling efficiency between an incoherent light source and such fibers.

Several kinds of high-N.A. optical fibers have been studied: silica-core/plastic-clad fibers,[1] GeO_2-doped silica-core/silica-clad fibers made with the MCVD technique,[2] and multicomponent-(alkali-lead-silicate) glass core/multicomponent-clad fibers made with the double crucible technique.[3] These fibers, however, are unsatisfactory for a short-distance transmission system. For example, the effective N.A. of the plastic-clad fibers is different from the value calculated from the refractive indices of core and clad glasses because of the high absorption loss of the plastic cladding layer. The MCVD technique also involves difficulty in preparation of preforms without cracks, which usually occurred due to the large difference in the thermal expansion coefficients of heavily doped core glass and silica-clad glass.

Multicomponent glass is well suited for the preparation of high-N.A. optical fibers because of its large variety of optical and thermal properties. As a light guide a few meters long, high-N.A. fibers with losses of several hundred decibels per kilometer have already been developed. The transmission loss in alkali-lead-silicate glass fibers with 0.47 N.A. has been lowered to 50–60 dB/km at 0.8–1.1 μm. Unfortunately, the optical loss in the fiber cannot satisfy the requirement for a transmission medium. Moreover, it is not tolerable that these fibers showed an optical loss of a few hundred decibels per kilometer in the 0.6–0.7-μm wavelength region.

This paper describes the development of high-N.A. multicomponent glass fibers with 20-dB/km optical loss and their transmission properties. We discuss glasses with high refractive indices for high-N.A. fibers and the fabrication of low-loss high-N.A. fibers and their characteristics.

II. Glasses with High Refractive Indices

The core glass for low-loss high-N.A. fibers should meet the following requirements:

(1) The core glass should have a high refractive index induced by a small quantity of additives to avoid mismatch in the thermal expansion coefficient with clad glass.

(2) It should be melted and drawn at low temperature to keep contamination from crucible material at a minimum.

(3) A large shift of the UV absorption edge of the core glass to a longer wavelength should not be induced by the additives.

(4) The transition metal impurity content in the glass should be lowered to the parts per billion level.

(5) The glass should be stable against devitrification during fiber drawing.

In order to obtain the most promising additives for high-N.A. optical fibers the properties of the glass containing additives for high refractive index were examined.

A. Sample Preparation and Measurements

It is well known that PbO, BaO, and La_2O_3 additives make glasses with high refractive index. PbO, BaO, or La_2O_3 was added to the mixture of matrix glass starting

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Table I. Matrix Glass Composition[4]

SiO_2	GeO_2	Na_2O	Li_2O	CaO	MgO
		(wt. %)			
55	18	15	5	6	1

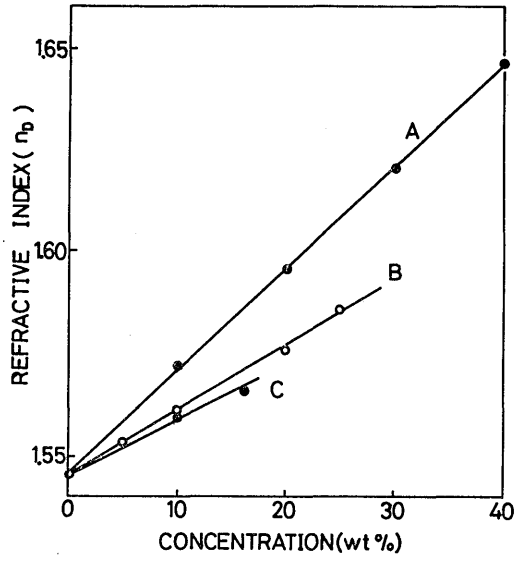

Fig. 1. Additive concentration dependence of refractive indices. (A) Glass containing PbO; (B) glass containing BaO; (C) glass containing La_2O_3.

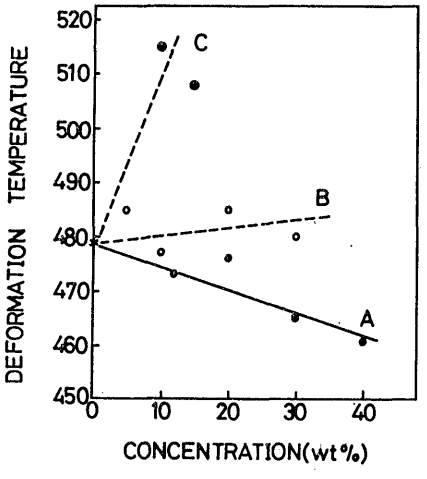

Fig. 2. Deformation temperature concentration dependence. (A) Glass containing PbO; (B) glass containing BaO; (C) glass containing La_2O_3.

materials (Table I) with which low-loss multicomponent glass fibers have been obtained.[4] Concentrations of these additives were within the area of glass formation: 0–50 wt. % for PbO, 0–25 wt. % for BaO, and 0–15 wt. % for La_2O_3. Melting of these glasses was carried out in a SiC resistance furnace using a platinum crucible at 1400°C for 1–2 h. Refractive indices (n_D) of the glasses were measured with Abbe's refractometer. Thermal properties were measured by a differential dilatometer using a silica glass rod as a standard sample. Absorption spectra for the glass samples (0.5-mm thickness) were also measured in the UV-wavelength region from 0.21 to 0.36 μm.

B. Properties of High-Refractive-Index Glasses

1. *Refractive Index (n_D)*

The concentration dependence of the refractive index of additives is shown in Fig. 1. The refractive index increases proportionally with the concentration. The slope of the lines was 2.7×10^{-3} (PbO glass), 1.5×10^{-3} (BaO glass), and 1.4×10^{-3} (La_2O_3 glass). If a N.A. of more than 0.5 is desired, the core-glass refractive index should be more than 1.60, provided that the clad-glass refractive index is 1.52. (The refractive index for the clad glass in low-loss fiber was about 1.52.) This means that more than 21, 33, and 40 wt. % PbO, BaO, and La_2O_3 should be added, respectively. Concentrations of additives other than PbO are higher than the glass formation limit.

2. *Thermal Properties*

There are two important factors in obtaining low-loss fibers by the double crucible technique: relatively low drawing temperature and stability of glass composition against devitrification during fiber drawing. The deformation temperatures T_d for glasses containing PbO, BaO, or La_2O_3 are shown in Fig. 2. Although La_2O_3 addition caused a large increase in T_d, PbO and BaO influences were tolerable. The transformation temperature T_g was similarly changed to T_d. Thermal expansion coefficients for the glasses decreased with increasing concentration of additives. The stability of glasses with a large amount of additives, except for PbO, was far from satisfying the requirement for core glass: For example, core glass containing 30 wt. % BaO showed severe devitrification during fiber drawing over only 100–200-m length.

3. *Absorption Losses*

Absorption losses for PbO, BaO, and La_2O_3 glasses in the UV-wavelength region are shown in Fig. 3. The effect of additives can be estimated on the tailing of the

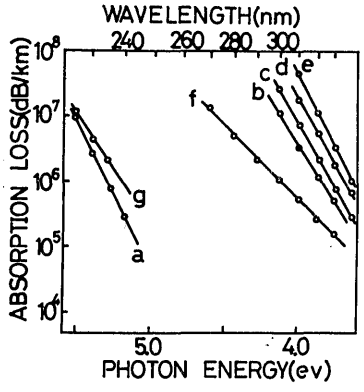

Fig. 3. PbO, BaO, and La_2O_3 glass absorption losses in UV-wavelength region. (a) Glass without additives; (b) glass containing PbO 10 wt. %; (c) PbO 20 wt. % glass; (d) PbO 30 wt. % glass; (e) PbO 40 wt. % glass; (f) La_2O_3 10 wt. % glass; (g) BaO 25 wt. % glass.

Table II. Core-Glass and Clad-Glass Composition and Physical Constants

	SiO_2	B_2O_3	GeO_2	Na_2O	Li_2O	CaO	MgO	BaO	Refractive index (n_D)	Thermal expansion coefficient	Transformation temp. (°C)	Deformation temp. (°C)
				(wt.%)								
Core	30.8	10.0	15.1	2.8		3.5	1.0	36.7	1.614	89×10^{-7}	586	635
Clad	65.0	15.0		13.3	0.7	5.0	1.0		1.516	67×10^{-7}	554	622

UV absorption loss α in the longer-wavelength region by extrapolating $\log(\alpha)$ against the photon energy.[5] Although glass containing 10 wt. % PbO and that containing 10 wt. % La_2O_3 showed 70- and 40-nm shifts of absorption edge to longer wavelengths, respectively, glass containing BaO (5–30 wt. %) showed little edge shift of absorption. This means that BaO would be the most desirable additive to obtain low-loss optical fibers for use in the visible and near-IR wavelength regions.

To lower the absorption loss due to impurities, especially transition metal elements, they should be removed from the starting materials by purification. The difference in physical and chemical properties between Pb^{2+}, Ba^{2+}, La^{3+}, and transition metal ions decides the purification possibility. When the ion-exchange technique with chelate ion-exchange resin is adopted, Pb and La salts in solution cannot be purified because of the small difference in chelate formation constants. Ba salts, however, can be readily purified. Other purification techniques, involving separating the impurities from Pb^{2+} and La^{3+}, may also be difficult for the same reason.

C. Appropriate Core-Glass Additive

For low-loss high-N.A. fibers, the most important factor is that the absorption losses due to UV absorption tailing and impurities be lowered. Although glass containing PbO has good enough refractive-index and thermal properties, it has harmful absorption loss. La_2O_3 is a useful additive for high-refractive-index glass, while it cannot meet the other requirements for core glass. Glass containing BaO is most favorable, because of a small shift in the UV absorption edge and the availability of ultrapure starting material. The deficiency of glass containing BaO, its instability against devitrification, was improved by adopting the other matrix glass.

III. Optical Fibers with High N.A.

Low-loss high-N.A. fibers with core glass containing BaO were prepared by the double crucible technique and were examined extensively to reveal their transmission characteristics.

A. Fiber Fabrication

Glass composition resistant to devitrification was studied in the SiO_2–B_2O_3–BaO–Na_2O system. (These data will be presented in more detail elsewhere.[6]) Stable core-glass composition and its physical constants are summarized in Table II. Clad-glass composition, which is suited for core glass, and its properties are also shown.

Purified starting materials were mixed in a closed system and melted in a fused-quartz crucible at 1400°C for 0.5 h. Then the molten core glass was stirred repeatedly to avoid inhomogeneity and cast into the inner crucible of a platinum double crucible. The clad glass was melted in an alumina crucible at 1400°C for 2–3 h and poured into the outer crucible. High-N.A. optical fibers were drawn at 25–35 m/min, with 100-μm core diam and 150-μm outer diam. The drawing temperature was 700–800°C. For the coupling efficiency experiment, core diameter and fiber diameter were changed from 100 to 300 μm and 150 to 460 μm, respectively.

B. Measurements

The optical loss spectrum (0.35–1.7 μm) for high-N.A. fibers was measured by using a monochromator and a solar cell or an InSb detector under N.A. 0.25 launching conditions. To examine N.A. dependence on attenuation, optical losses at 0.63 μm (He–Ne laser) were measured under different N.A. launching conditions and fiber lengths.

The refractive indices of core glass and clad glass at wavelengths from 0.4 to 1.1 μm were measured by the minimum deviation method, using a modified spectrometer.[7] N.A. values for fibers were calculated from these refractive-index data.

N.A. values, after transmission over fibers of different lengths, were measured by far-field patterns from 0.1 to 0.55 launching N.A.

The baseband frequency response for this 100-m long fiber was determined by the swept-frequency technique using a GaAlAs laser (0.82 μm) as a light source.

Light coupling to high-N.A. fibers with different core diameters was examined using a LED with 0.7475-μm wavelength and 25-mW emitting power.

C. Transmission Characteristics

1. *Optical Losses*

The optical loss spectrum for the high-N.A. fiber (0.53 N.A.) from 0.35- to 1.7-μm wavelength is shown in Fig. 4 (solid line). Losses as low as 20 dB/km are observed at 0.75 μm. Small absorption bands due to OH radicals are achieved by using dry gas flow during glass melting.[8] The BaO effect on the absorption edge was less than the PbO effect (Fig. 4,[3] dashed line), which agrees well with the result of the experiment using bulk glass. The relatively flat spectrum, from 0.7 to 1.3 μm, is caused by scattering loss due to inhomogeneity in the glass fiber and absorption loss due to Fe^{2+} ions.

Progressively higher loss with increasing cone angle of the injected beam (launching N.A.) were reported in the FEP-clad silica fiber.[1] This kind of loss was also observed to increase for multicomponent glass fibers with high N.A. Excess losses in a 100-m long fiber as a function of launching N.A. are shown in Fig. 5, where the excess loss is defined as the loss difference between value at N.A. 0.1 launching and the value at higher launching N.A. Excess losses increased with increasing the launching N.A. and reached a steady value when the launching N.A. exceeded the fiber N.A. To determine the excess loss origin, the fiber-length dependence of losses (dB) under different launching conditions was measured at 0.63 μm (Fig. 6). Within a 200-m length, the slope of the lines for loss vs fiber length was increased with increasing launching N.A. Beyond a 200-m length, however, they were constant at each launching N.A. condition. This result can be explained as follows. The initially narrow beam was widened due to mode coupling, narrowed by preferential losses at higher modes, and subsequently reached a steady state. The steady state was achieved beyond a 200-m long region in this fiber.

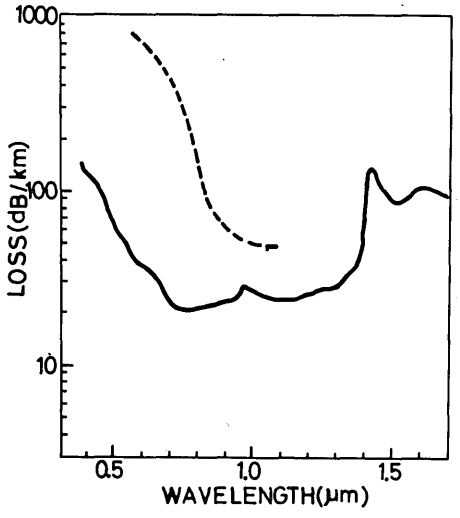

Fig. 4. Optical loss spectrum for high-N.A. fibers. Solid line shows the loss value of the fiber whose core glass contains BaO (prepared in this experiment). Dashed line shows PbO-core glass fiber.[3]

2. *N.A. Wavelength Dependence*

N.A. values for high-N.A. fibers at wavelengths from 0.4 to 1.1 μm are shown in Fig. 7. The N.A. variation is $\leq$0.01 in the 0.6–1.1-μm wavelength region. Since the refractive-index dispersion curve for core glass containing BaO shows the same shape as that of clad glass with no BaO additive, the wavelength dependence for the refractive-index difference between them is very small. At the wavelength region, N.A. depends on the change in refractive index, which is caused by the shift in UV absorption bands. Thus, the N.A. small wavelength dependence is one of the particular properties of glass containing BaO.

3. *Effective N.A.*

The effective N.A. is associated with a steady-state transmission condition. The N.A., measured using the far-end pattern of the fiber, reached steady state at more than 200-m length, which agrees well with the result of fiber-length dependence on losses (dB). When the launching N.A. was small (for example, 0.1), the far-end N.A. increased with increasing fiber length and reached a 0.4–0.5 steady-state value at a 200-m length. When the launching N.A. was nearly equal to the fiber N.A., the far-end N.A. at each length was not changed. Therefore, it can be said that the effective N.A. for this high-N.A. fiber is nearly equal to the fiber N.A. calculated from refractive-index data.

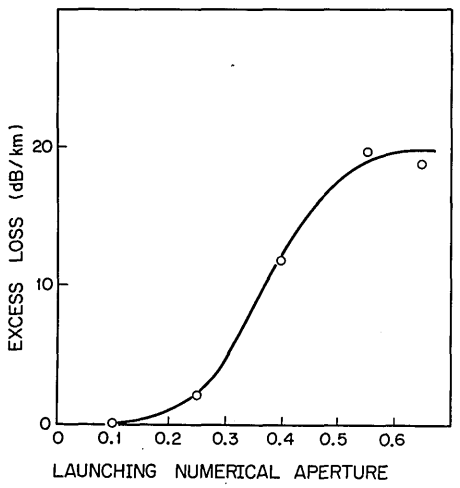

Fig. 5. Excess losses at 0.63 μm as a function of launching N.A.s.

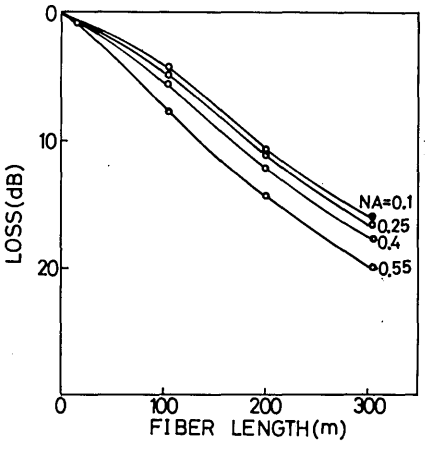

Fig. 6. Fiber-length dependence of optical losses (dB) at different launching conditions.

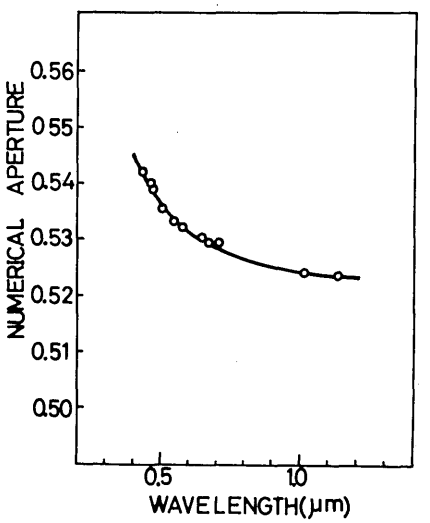

Fig. 7. N.A. wavelength dependence calculated from refractive-index data.

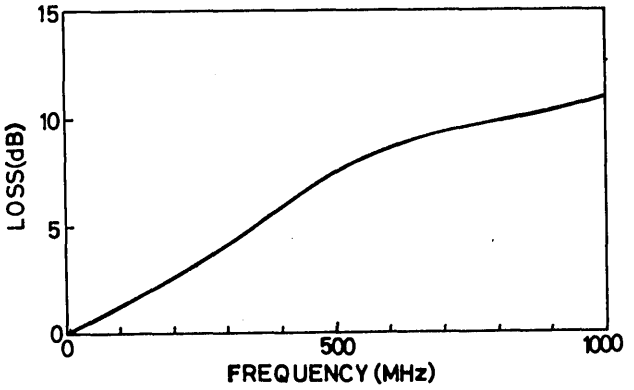

Fig. 8. Baseband frequency response for 100-m long high-N.A. fiber (at 0.82 μm).

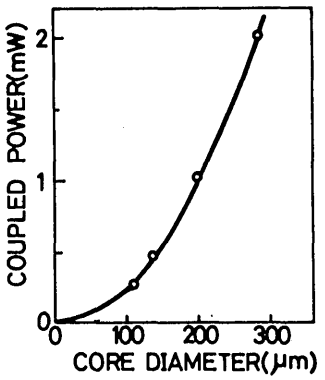

Fig. 9. Core-diameter dependence for coupled power launched from LED to the high-N.A. (0.53) fibers (LED can emit 25-mW power at 0.7475 μm).

4. *Baseband Frequency Response*

The baseband frequency response for a 100-m long high-N.A. fiber is shown in Fig. 8. The 6-dB down-transmission bandwidth is ~400 MHz. This value is much larger than the calculated one, in which mode coupling is neglected. Large mode coupling is also expected from the effective N.A. and the excess loss measurements.

5. *Coupling Efficiency*

The coupling efficiency between a light source (LED) and a fiber is proportional to the square of the N.A.[9] This causes a sevenfold coupling efficiency increase if the high-N.A. (0.53) fiber is compared with a typical-N.A. (0.2) fiber.

To make a further improvement in coupling efficiency, large-core-diameter fibers were prepared. The coupled power from the LED to the high-N.A. fibers is shown vs core diameter in Fig. 9. The coupled power is increased with increasing core diameter proportionally to the square of the core diameter. The improvement in coupling efficiency by increasing the N.A. or core diameter is essential to short-distance application.

IV. Conclusion

High-N.A. (0.53) multicomponent glass fibers with 20-dB/km optical loss have been obtained. To fabricate high-N.A. low-loss optical fibers over a wide wavelength region, the use of glass containing BaO is most promising. The fibers have the following transmission characteristics:

(1) relatively low optical loss in the 0.6–1.3-μm wavelength region;
(2) small fiber N.A. wavelength dependence;
(3) high effective N.A.;
(4) large bandwidth due to mode coupling; and
(5) high coupling efficiency between LED and fiber.

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