FORMATION OF OPTICAL COUPLING STRUCTURE BETWEEN SILICA GLASS WAVEGUIDES AND MOLTEN TELLURITE GLASS DROPLET

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Abstract

Several nano liters of tellurite glass melt ($x\mathrm{TeO_2}$-$(100-x)\mathrm{ZnO}$, $x = 80, 90, 100$ in mol%) were inserted and quenched between two ends of silica glass optical fibers to form a new optical coupling structure, whose length was several hundred microns. No visible precipitates were found even in the quenched melt of 100% $\mathrm{TeO_2}$. On the basis of reflection and insertion loss measurements and a bending test, it is proved that there's no micro crystals in the quenched melt segment which cause light scattering and/or stress concentration.

Few tens nano liters of the melt were also inserted into a silica glass capillary tube with the interior diameter of 126 μm, in order to examine their tolerance to the residual stress induced on cooling due to the large gap in thermal expansion coefficient between the two glasses. Neither fracture nor bubbles were observed in the quenched melt inside if its length is less than 2mm. This implies that tellurite melt can be introduced into voids of sub-mm in size to integrate hybrid lightwave circuits.

KEYWORDS: optical fiber, tellurite glass, insertion loss, thermal expansion coefficient

1 INTRODUCTION

Constructing integrated photonic circuit needs the technologies to connect various optical modules each other, such as light sources, modulators and detectors, via optical waveguides. One of the most important materials for optical waveguide is silica glass because its transmission loss is so low that it is used for optical fibers and planar lightwave circuit (PLC), which is made of deposited a-$\mathrm{SiO_2}$ thick film on Si substrate. The connection between PLC and semiconductor-based optical modules is easily accomplished, because their fabrication technique is common, i.e. deposition, lithography and etching.

As for the modules made of inorganic glasses, except silica glass, it is not so easy because these glasses are mainly fabricated via liquidus state at higher temperature. Recently, the authors succeeded to make an optical coupling structure between two ends of silica glass optical fibers by inserting several nano litters of tellurite glass melt (80$\mathrm{TeO_2}$-20ZnO in mol%)[1]. In spite of the large gap in thermal expansion coefficient among these glasses (table 1), no fracture and bubbles were observed in the tellurite glass segment. Since there is no waveguide structure in the glass segment, its insertion loss was about 10dB.

In this fabrication process, the melt is expected to be quenched very rapidly because the volume of the melt is only several nano litters and most of its surface is exposed to open air. Thus, this process may be applicable to the glasses which has poor stability against crystallization. Glass forming regions of binary zinc tellurite system are determined by Bürger *et al.*[2] as a function of cooling rate, which is shown in Fig. 1 on a phase diagram of this system[3]. From this figure, the stability of the melt is found to decrease drastically from 80$\mathrm{TeO_2}$-20ZnO to 100$\mathrm{TeO_2}$. In the first half of this study, we tried to make optical coupling structures with $\mathrm{TeO_2}$ melt and examined whether precipitation occurred or not through optical measurements.

In order to introduce non-silica glass materials into silica-based PLC by this fabrication method, small voids should be made inside the silica glass layer to be filled by the melt. In this configuration, the surface area of the glass melt exposed to air becomes smaller compared with the case for a fiber pair. This means that the stress induced at the interface between the two glasses is not negligible. In the latter half of this paper, we introduced the melt into a silica glass capillary tube to see under what condition the quenched glass is damaged.

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Table 1: Properties of the glasses used in this study. Data source: O.V. Mazurin *et al.*, Handbook of glass data.

	thermal expansion coefficient ($\times 10^{-7}/°C$)	refractive index
SiO_2	$\sim$6	1.46
80TeO_2-20ZnO (mol%)	170	2.08

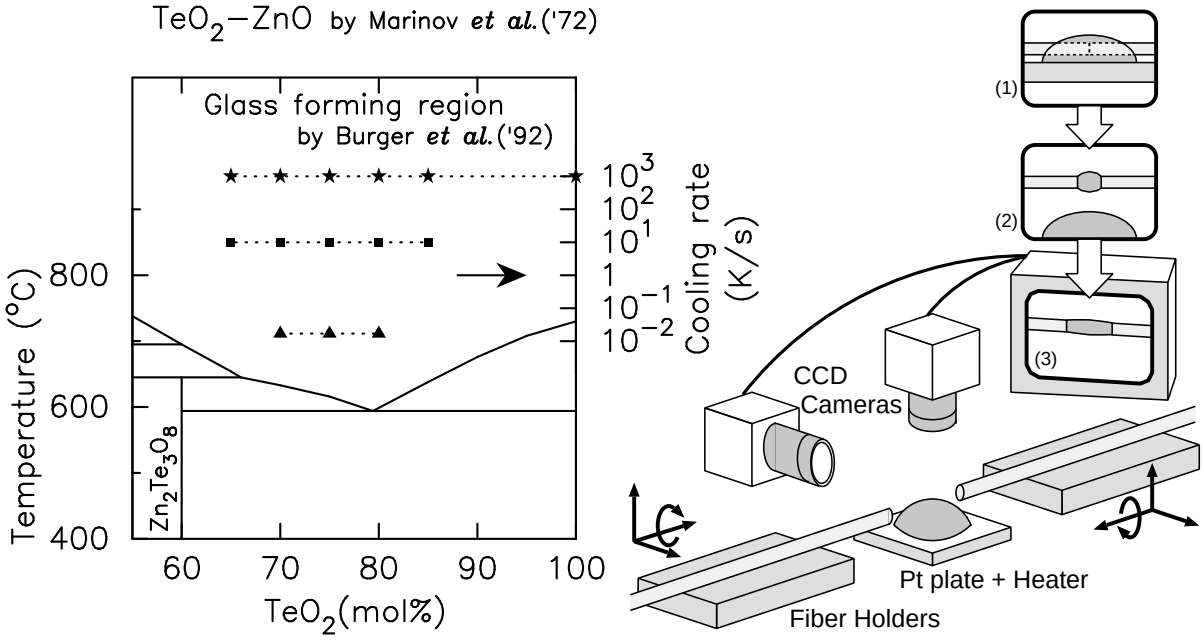


Figure 1: Phase diagram[3] and glass forming regions of TeO_2–ZnO system with different cooling rates[2]. ▲: cooled in a carbon mold, ■: cooled in a copper mold, and ★: quenched by pouring into a rotating twin roll.

Figure 2: Illustration showing an experimental setup and a procedure to make an optical coupling structure(see text).

2 EXPERIMENTAL

2.1 Fiber splicing

Commercial optical fiber cables (single mode, core diameter: 10μm, 3m-long with FC connectors) are used in this study. Bare fibers were cut by a fiber cleaver (York FK11-4). Two fibers were placed on fiber holders so that their ends face each other, as shown in Fig. 2. A Pt plate with a small heater (width: 10mm) was set between the two ends of the fibers. Their relative positions were controlled by a personal computer. The heater was kept at a constant temperature of about 440 °C which was monitored through a thermo couple placed on the back.

The glass melt was supplied by putting a small piece of glass ($x\mathrm{TeO_2}$-$(100-x)\mathrm{ZnO}$, $x = 80, 90$ in mol%) or a small amount of TeO_2 powder (5N, Shinko Chemical Co.,Ltd.) on the Pt plate. These glass pieces were prepared by the following procedures. The corresponding glass melt is melted in a Pt crucible heated at 800°C. Then the melt is sucked into a Pyrex glass capillary tube (inner diameter: 1.5mm) and cooled to room temperature[4, 5]. Finally, the inner glass bar is taken from the outer tube.

The droplet on the heater was observed through video cameras placed from its top and side. Two fibers were inserted into the droplet from its side((1) in Fig. 2). Then, the plate is lowered to leave a small amount of the melt between the two ends(2). Lastly, the fibers were immediately moved to an appropriate position before the melt was solidified(3). All the movements described above ends within few seconds.

Reflection from the optical coupling structure was measured by a high-resolution reflectometer (AQ7410A, Ando Electric Co.,Ltd.) which consists of a Michelson interferometer and a laser of 1.31 μm. Its resolution is 20 μm. Transmittance of the laser light through the optical coupling structure was measured by an optical multimeter (AQ-2140, Ando Electric Co.,Ltd.). These measurements also performed on an empty fiber pair varying

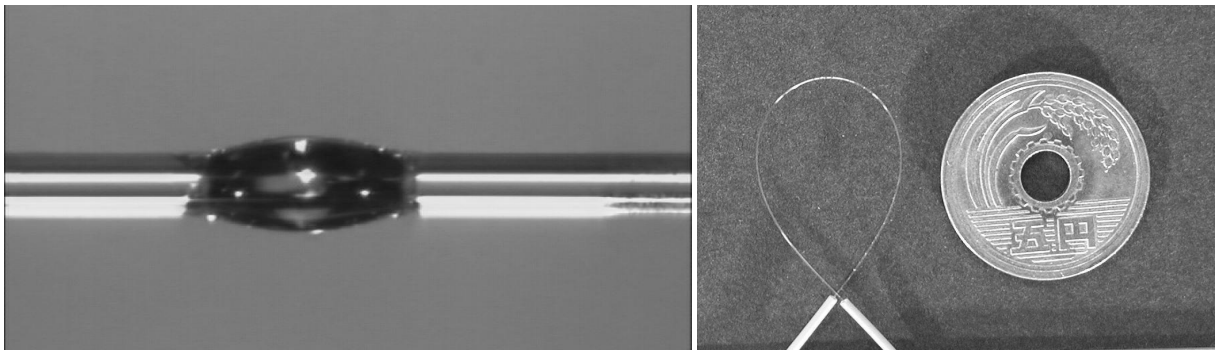


Figure 3: Photographs of an optical coupling structure, in which the composition of the quenched melt is 100% TeO_2. (a, left) The diameter of the fiber is 125 μm and the distance between the two fiber end is about 0.4mm. (b, right) The fiber is bended in order to test its toughness. The diameter of the coin is 22mm.

the distance of two fiber ends.

2.2 Capillary filling

A silica glass capillary tube (OD 1.8mmϕ $\times$ ID 0.126mmϕ $\times$ 20mm) is placed in a vertical ring furnace kept at 800°C after an silica glass optical fiber (OD 0.125mm) is inserted into the capillary from its lower hole. A small Pt crucible containing tellurite glass melt (80TeO_2-20ZnO) is also placed beside the capillary in the furnace. A Pt wire is dipped into the melt and then a droplet of the melt at the top of the wire is placed over the upper hole of the capillary tube. Next, the inserted fiber is pulled and removed from the capillary in order to introduce the melt inside. Then, the capillary is taken from the furnace to cool it.

3 RESULTS

3.1 Fiber splicing

For each of the melt compositions, optical coupling structure was made without any apparent precipitation. Fig. 3(a) shows a side view of the structure in which TeO_2 melt was quenched. The diameter of the fiber is 125 μm and the distance between the two fiber end is about 0.4mm. This structure is not so fragile if properly treated that the fiber segment can be bended without fracture as shown in Fig. 3(b).

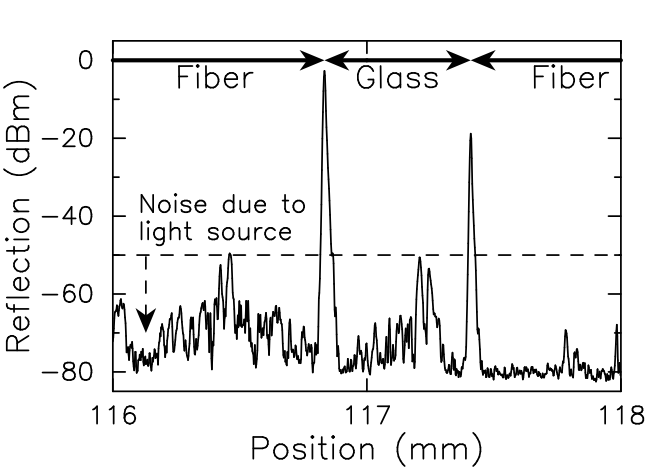
Fig. 4 is a typical example of the distribution of reflected light along the light path of the optical coupling structure. There are only two sharp peaks which correspond to the reflection from the fiber ends. The fine structure below -50dB is due to the noise of light source. No sample is found to exhibit extra peaks other than these two peaks. Since this measurement assumes the refractive index of the whole path to be 1.5, the distance between the two peaks, d_{nominal}, is not correspond to its true value, d. The relation between the two lengths is described as $d/n = d_{\mathrm{nominal}}/1.5$, where the refractive index of the glass segment is about $n \sim 2.1$.

Fig. 5 shows the insertion loss values of the optical coupling structures (closed stars for TeO_2 glass and open polygons for 80TeO_2-20ZnO glass) and an empty fiber pair (open circles) as a function of the distance between the two fiber ends. Each distance is calculated from the reflection measurement described above. The refractive indices of 80TeO_2-20ZnO and 100TeO_2 glasses are assumed to be 2.08 and 2.19(extrapolated value)[6], respectively. 0 dB of the insertion loss corresponds a configuration where two fiber ends are physically contacted to give a minimum transmission loss. There are variations in insertion loss because of an error in disalignment of facing fibers which is due to an accumulated displacement of fiber holders during their motion in fabrication[7].

Since the transmitted light between the fibers is not collimated, the insertion loss values increase with d. The loss values of the optical coupling structures are smaller than that of the fiber pair because the transmitted light refract more strongly in the glass melt compared with in the air[7].

3.2 Capillary filling

In the quenched melt inside the capillary, some fractures and/or bubbles were observed if the length of the melt is larger than 2mm. Figure 6 shows a typical damage-free glass segment, in which residual stress is found by the



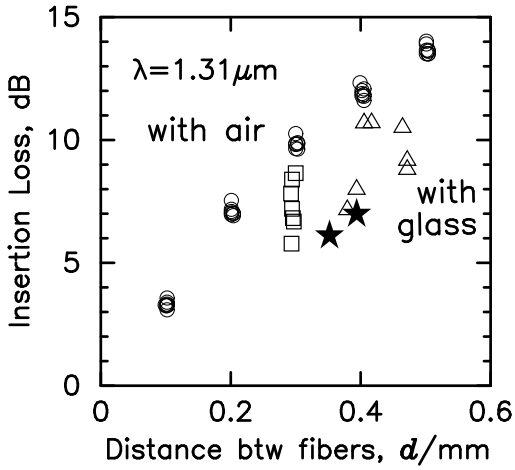
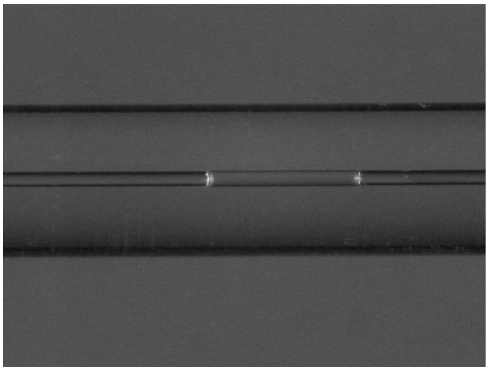


Figure 4: Distribution of reflection along the light path of a coupling structure shown in Fig. 3(a), in which the composition of the quenched melt is 100% TeO_2.

Figure 5: Insertion loss vs. distance between the two fiber ends for the coupling structure (open polygons for $80TeO_2$–20ZnO glass and closed stars for TeO_2 glass) and an empty fiber pair (open circles).



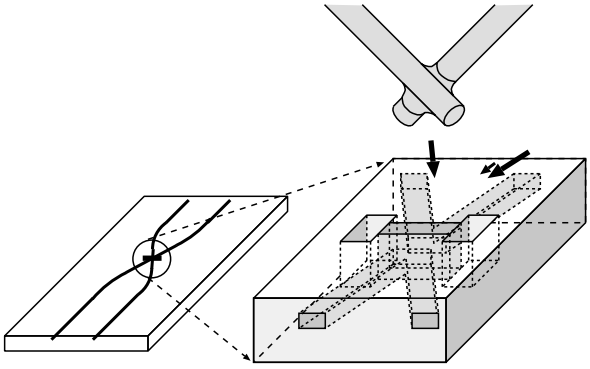


Figure 6: Sideview of quenched melt ($80TeO_2$–20ZnO) inside a silica glass capillary. The outer diameter of the capillary is 1.8mm.

Figure 7: An idea to utilize the present fabrication technique to make a hybrid PLC(see text).

observation of a strain inspection scope.

4 DISCUSSION

4.1 Quenching rate

There seems to be no precipitates in the quenched melt of TeO_2. Although the absence of crystals is not proved by XRD measurement, it is possible to conclude that there's no precipitate which scatter the incident light in this structure. In fact, since the insertion loss values for TeO_2 glass are comparable to those for $80TeO_2$–20ZnO glass, attenuation factors for light transmission among them are much the same. Moreover, considering that fractures of glass fibers are generally caused by a stress concentration at a micro crystal precipitated on their surface[8], the bending test shown in Fig. 3(b) also supports to be free of precipitates. Thus, there's no precipitation which is harmful to optical devices.

The quenching rate of the melt in this fabrication technique is considered to be as large as that in twin-roller quenching method, which corresponds to be 10^3 K/s[2] (see Fig. 1). This implies that even the melts with poor stability which can vitrify only by twin roller quenching method can be spliced to silica fibers without precipitation. This means that we can use considerably wider range of glass compositions to make these optical coupling structure

compared with the range for making optical fibers, in which glasses have to survive heating process for a long time without precipitation.

4.2 Possible applications

The present fabrication technique has a potential to be applied to form a hybrid PLC. For example, a hybrid PLC may be fabricated by the following procedure illustrated in Fig. 7. A small amount ($\sim$nℓ) of hot melt is captured at the top of two fibers and to is transmitted to an appropriate void on the PLC in order to be coupled with embedded waveguides. Since the void in PLC is rigid compared with the void between the ends of the fiber pair, the variation in insertion loss value is expected to be small[7]. Tellurite glasses are appropriate for hybrid PLC because their softening temperature is about 350 °C, much lower than that of silica glass, and is known to show active properties such as non-linear optical effect[9], acousto-optics effect[10] and broad band amplification for 1.55 μm band when Er^{3+} ions are doped[11].

Although the thermal expansion coefficient of tellurite glass is 2-orders bigger than that of silica glass (table 1), the capillary filling test in this study suggests that the fracture due to residual stress can be suppressed if the void size is in the order of sub-mm.

Another possible application is to make microcavity devices, in which lasing with ultra-low threshold is possible. For example, Spillane *et al.* demonstrated recently that Raman lasing with 60μW pumping is possible in a system of silica glass microspheres attached with a thin silica glass optical fiber[12]. It will have a considerable impact on this field if microcavity devices made of non-silica glasses are realized. Some methods of making non-silica glass microspheres are already proposed such as re-heating raw glass powder in a furnace[13] and pouring glass melt into liquid nitrogen[14]. By these methods, however, it is very hard to control the cavity size and to connect the microsphere to existing optical waveguides.

Since the present fabrication method provides a technique to sample nano liters of hot melt and to quench it rapidly, it can help to make microcavities with further controllability. Moreover, high refractive index of tellurite glass enables to capture light into microcavities efficiently. We are now planning to make such microcavities connected with optical fibers.

5 SUMMARY

Several nano liters of tellurite glass melt is captured between the ends of silica glass optical fibers and quenched it in order to make optical coupling structures. The quenching speed is found to be so fast that even TeO_2 glass melt is solidified without any visible precipitation, light scattering and stress concentration leading to fracture. Although a large gap in thermal expansion coefficient among these glasses bring about some residual stress at the interface, fractures can be prevented if the cavity size is within sub-mm. This fabrication technique can be applied to make hybrid planar lightwave circuit and microcavity devices.

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