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## On-chip fabrication of air-bubble-containing Nd<sup>3+</sup>-doped tellurite glass microsphere for laser emission

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We fabricated an air-bubble-containing glass microsphere on a substrate by using localized heating technique. Nd<sup>3+</sup>-doped tellurite glass cullets on a substrate were melted by a CW-Ti:sapphire laser at the wavelength of 810 nm and with the power density of more than 4.8 MW/cm<sup>2</sup> to obtain tellurite glass microspheres with the diameter of 5 to 200  $\mu$ m. The localized heating technique using laser is useful to form a bubble at a certain place in the microsphere. Both air-bubble-containing and bubble-free spheres showed lasing actions at around the wavelength of 1065 nm. The average laser thresholds of the air-bubble-containing and bubble-free microspheres with the size of 20-50  $\mu$ m were 0.78 mW and 5.25 mW, respectively. Copyright 2012 Author(s). This article is distributed under a Creative Commons Attribution 3.0 Unported License. [<http://dx.doi.org/10.1063/1.4769888>]

Micrometer-size spheres have received considerable attentions for many years mainly because of their versatility in micro-optical system for microlasers,<sup>1-3</sup> microamplifiers,<sup>4</sup> nonlinear optical devices<sup>5,6</sup> and chemical/bio sensors.<sup>7,8</sup> The microspheres for optical resonators with high-quality factor were prepared by heating the end of a glass fiber<sup>1-8</sup> and glass cullets in an air.<sup>9</sup> However, it is difficult to fabricate micrometer-size spheres having high sphericity and very smooth surface on silica glass or silicon substrate, which are commonly used for optical devices, because the shape of glass droplet on substrate is strongly affected by the wetting property of the substrate by the molten glass. Nowadays, complex processes to prepare intricate structures are the most effective way for the on-chip fabrication of micrometer-size spherical part with smooth surface.<sup>10,11</sup>

In this study, we developed a new fabrication technique of glass microspheres with good sphericity and smooth surface on a substrate. This technique employs a very simple process using localized heating with laser. By using this technique, we can also make an air bubble into the microsphere and control its position. Their characteristics as microlasers were demonstrated.

We used tellurite glass having low softening temperature for the localized heating technique. Tellurite glasses have great potentiality to be utilized as the resonator matrix materials because of their wide optical window, high linear and nonlinear refractive index and relatively low phonon energy.<sup>3,12</sup> A glass sample with the composition of 10K<sub>2</sub>O-10WO<sub>3</sub>-80TeO<sub>2</sub> containing 1.0 Nd<sub>2</sub>O<sub>3</sub> (in mol%) was prepared by the conventional melt-quenching method. The glass transition temperature and refractive index at a wavelength of 633 nm of the glass were found to be 310°C and 2.05, respectively. The Nd<sup>3+</sup> ion acts not only as a luminescent center for lasing action, but also a heating source for the localized heating. The glass was crushed and classified by using sieves in ethanol in order to obtain glass cullets. Figure 1 schematically illustrates the setup of the localized heating technique. The Nd<sup>3+</sup>-doped tellurite glass cullet on a silica glass substrate was placed on an XY translation stage under an optical microscope in an air. Subsequently the glass sample was irradiated by a CW-Ti:sapphire laser at the wavelength of 810 nm and the power of 150-300 mW through an objective lens (x100, NA:0.80). The diameter of laser spot was 2  $\mu$ m. During the laser irradiation,

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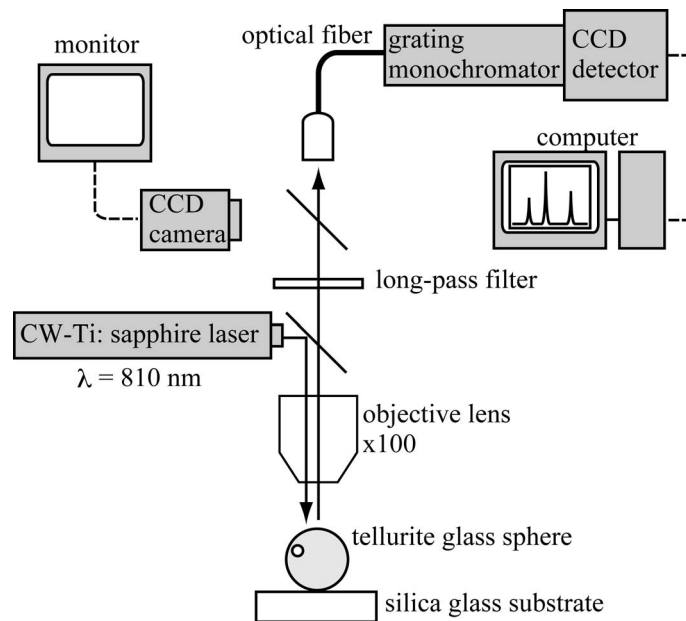


FIG. 1. Schematic illustration of setup for localized heating technique and emission spectra measurement of  $\text{Nd}^{3+}$ -doped tellurite glass sphere.

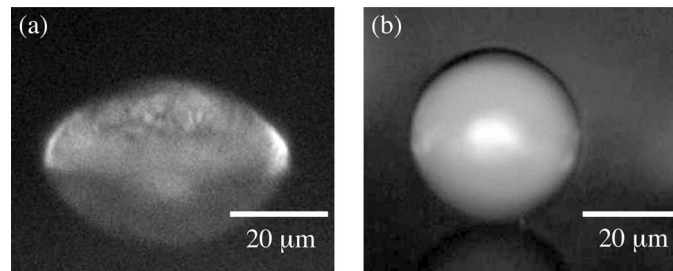


FIG. 2. Side-view optical microphotographs of the tellurite glass particles on silica substrate. (a) Heat treatment at  $390^{\circ}\text{C}$  for 30 minutes using an electric furnace and (b) Localized heating technique using the CW-laser.

small bubbles were formed in the molten glass, and they were gathered into a large bubble at the place of the laser spot. The formation and position of the bubble can be controlled by changing the laser power, irradiation time and laser spot.

The samples were observed by an optical microscope (OM) and a scanning electron microscope (SEM) in order to know their shape and surface roughness. The emission spectra from the sample were measured by using the same optical system as shown in Fig. 1. The pumping light source was the CW-Ti:sapphire laser with the wavelength of 810 nm. The laser power for the emission spectrum measurement was ranging from 0.01 to 30 mW. A long-pass filter was inserted to remove the emission at shorter wavelength than 835 nm. The emission from the sample were sent to monochromator (JASCO, CT-25C) through an optical fiber and analyzed by a CCD detector (ANDOR, iDus DU401A).

Figure 2(a) and 2(b) show the sample heat-treated on a silica glass substrate at  $390^{\circ}\text{C}$  for 30 min in an electric furnace and the sample fabricated on the same substrate by the localized heating technique, respectively. The glass cullet of the conventional heat treatment had a plano-convex-lens shape, and that of the localized heating technique had a sphere. The average contact angles of the samples were measured from side-view OM photos; they were found to be  $71^{\circ}$  for the conventional technique and  $180^{\circ}$  for the localized heating technique. This means that the wetting was suppressed in the case of the localized heating. The most likely cause for the suppression of the

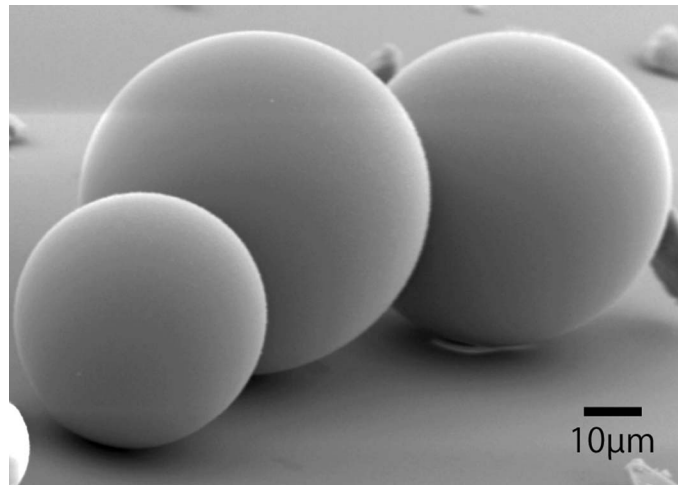


FIG. 3. SEM image of the  $\text{Nd}^{3+}$ -doped tellurite glass microspheres fabricated by the localized heating technique.

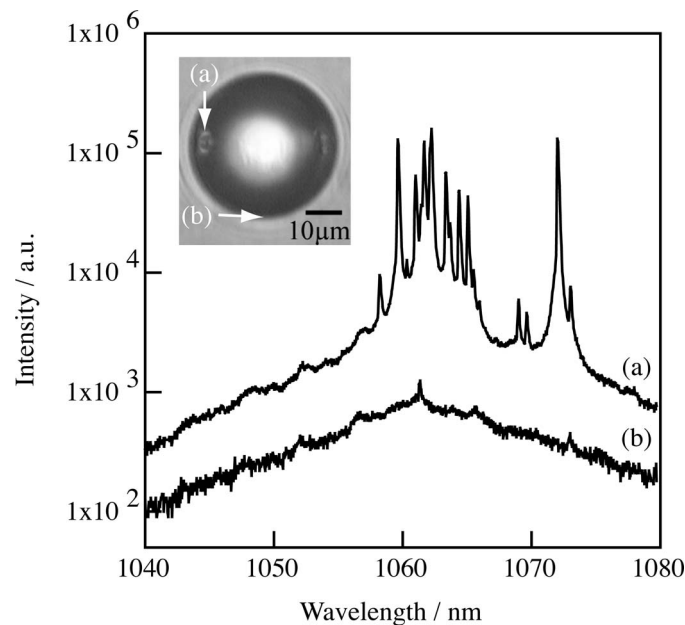


FIG. 4. Emission spectra from the air-bubble-containing  $\text{Nd}^{3+}$ -doped tellurite glass microsphere. The insets show the OM photo of the microsphere. The white arrows indicate the pumping spots: (a) air bubble, (b) near the edge of sphere. The pumping power was 2.2 mW.

wetting is the temperature gradient between glass droplet and substrate.<sup>13,14</sup> We observed the same phenomena for the glass droplet on silicon, soda-lime silicate glass and tellurite glass substrates.

Figure 3 shows the SEM image of the samples prepared by the localized heating technique. Samples showed the good spherical shape and very smooth surface. We have confirmed that the microspheres with the size ranging from 5 to 200  $\mu\text{m}$  can be obtained by this technique. The ellipticity of equatorial plane in the spheres was less than 1%, which was estimated from top-view OM photographs. These results indicate that the localized heating technique has the potential to realize on-chip fabrication of microspheres for integrated optical devices.

Figure 4 gives the laser emission spectra from a  $\text{Nd}^{3+}$ -doped tellurite glass microsphere, which is shown in inset of Fig. 4. The 40- $\mu\text{m}$ -diameter sphere contains an air bubble of 6  $\mu\text{m}$  in diameter, which is placed at the vicinity of the sphere surface. The corresponding laser spots are shown in the

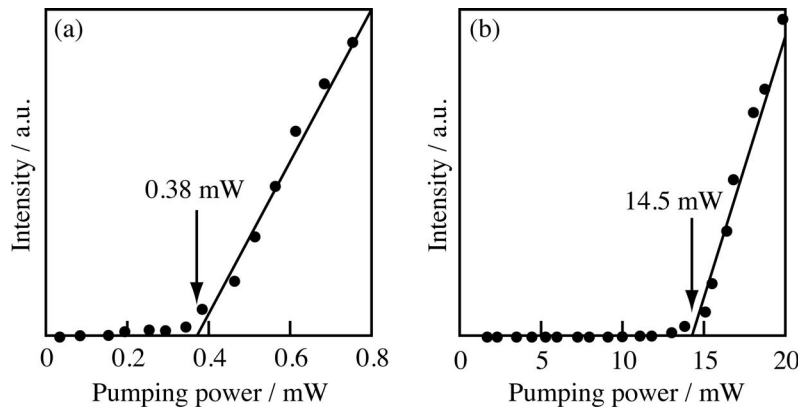


FIG. 5. The peak intensity at the wavelength of 1065 nm plotted against the pumping power for the air-bubble-containing microsphere (a) and bubble-free microsphere (b).

inset of the Fig. 4: (a) at the air bubble and (b) near the edge of the sphere surface. The pumping power was 2.2 mW. When the point (a) was pumped, the sphere showed the noteworthy increase of the emission intensity, as shown in the Fig. 4. Generally in bubble-free spheres the excitation at the tangent line (edge of sphere) is suitable to achieve resonant condition. However, the emission intensity at the air bubble was higher than those at any other spots in the air-bubble-containing microsphere.

In Figure 5, the emission intensities from the air-bubble-containing microsphere, which is the same sample in the Fig. 4, and the bubble-free microsphere with the diameter of 40  $\mu\text{m}$  were plotted against the pumping power. The pumping spot of the former sample was at the air bubble, and that of the latter sample was near the edge of the sphere surface. The slopes of the plots for air-bubble-containing and bubble-free microspheres increased clearly at 0.38 and 14.5 mW, respectively. The thresholds for bubble-free and air-bubble-containing samples with the diameter of 20-50  $\mu\text{m}$  were ranging from 2.00 to 14.5 mW and 0.03 to 2.29 mW, respectively. The average thresholds were 5.25 mW for bubble-free and 0.78 mW for air-bubble one. The reason for the improvement of the lasing action due to the air bubble is not well understood at this time but may be related to resonant modes in the hole-containing spherical cavity structure. The air bubble is located at the vicinity of sphere where the light propagates by repeated total internal reflection at grazing incidence on the surface, so the modes could be limited or changed by the bubble. More detailed analyses are in progress to characterize the novel cavity structure. Air bubbles in conventional optical devices such as lenses, fibers and displays are regarded as defects degrading their optical properties, but the air bubble in the sphere improves the lasing action. These results demonstrate that the air-bubble-containing glass sphere has a potentiality of a unique cavity structure for a low-threshold micro-laser.

In summary,  $\text{Nd}^{3+}$ -doped tellurite glass microspheres were fabricated on a substrate by a simple technique using localized heating. By using this technique, air-bubble-containing microspheres can be obtained. Both the air-bubble-containing and bubble-free microspheres worked as microlasers. The laser threshold of the air-bubble-containing sphere was lower than that of the bubble-free sphere.

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