Characterization of single-crystal sapphire fibers for optical power delivery systems

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Sapphire single-crystal fibers with diameters of 110 μm and lengths of over 2 m have been grown by the laser-heated pedestal growth method. The fibers are free of imperfections such as voids and bubbles. The minimum loss of 0.5 dB/m was measured in the near infrared at 1064 nm. Absorption loss at 2936 nm was 0.88 dB/m with a damage threshold higher than 1.2 kJ/cm^2 for 110-μs-long pulses making tissue ablation feasible with fibers several meters in length.

Sapphire (α-Al_2O_3) has long been recognized as a good material for optical components due to its wide transparency range (240–4000 nm), high melting temperature (2053 °C), low solubility in water, and favorable mechanical and chemical properties. Sapphire single-crystal fibers are well suited for sensor applications in high temperature or chemically hostile environments,[1] as well as for use in medical power delivery systems operating at the 2936 nm Er:YAG wavelength[2] where silica glass fibers are highly absorbing.

In this letter we report on the optical properties of single-crystal sapphire fibers prepared with the laser-heated pedestal growth method (Fig. 1).[3] The fibers are grown by dipping an oriented single-crystal seed into a molten droplet produced above a feed rod[4] by CO_2 laser heating (Fig. 1). By carefully controlling the ratio of the speeds at which the source rod is pushed into and the fiber is pulled out of the molten zone, a reduction ratio of source rod to fiber diameter of 3.5 is typically obtained. A 6-cm-long, 0.4-mm-diam source rod generates a 70-cm-long, 110-μm-diam fiber. The sapphire fibers were typically grown in air at a speed of 4 mm/min. The cross section of the *c*-axis fibers is roughly circular with slight deviations reflecting the trigonal symmetry.

Longer fibers were grown by using a two-step reduction. A fiber grown from an 800-μm-diam source rod was used as the source material for a second step with a diameter reduction ratio of 3.5. The resulting 120-μm-diam fibers were as long as 2.5 m (Fig. 2). For the remainder of this letter, data given are for *c*-axis fibers with a diameter of 110 μm.

The fibers grown are unclad (core index = 1.78) and therefore highly multimode. Despite the large numerical aperture, the measured modal power distribution after propagating a laser beam through a 0.71-m-long fiber has a full angle at half intensity of only 11°. This distribution was only weakly sensitive to bends in the fiber and input launching conditions.

Low propagation loss is necessary for optical applications of sapphire fibers. Two effects, scattering and absorption, contribute to the total loss. Absorption can arise from point defects in the crystal and from impurities. Since there is no contact of the liquid zone with crucibles or dies during the growth process, contamination of the crystal with metallic impurities during growth is not a problem, suggesting that impurities in the source material, gaseous species (H_2O), or color centers are responsible for extrinsic absorption. Inclusions, inhomogeneities, and surface irregularities increase the scattering losses. We could not detect any inhomogeneities in the volume of the fibers with optical microscopy, nor were any scattering centers apparent under laser illumination, which suggests that diameter variations are the most important factor influencing the scattering loss.

Variations in diameter can be caused by several sources. Heating power fluctuations and variations in the diameter of the source rod or the feed rate affect the molten zone volume which in turn affects the diameter of the fiber. A diameter measurement system[5] recorded the variations in the diameter of the fiber during growth. The diameter variations, which typically have a maximum at a spatial period of 5 mm for 110-μm-diam fibers, roll off rapidly for shorter periods. This is fortunate, since short-period variations efficiently couple power to higher order modes and ultimately lead to scatter loss.[6] The rms diameter variation is 2–3% for spatial periods shorter than 15 mm. Even though an active stabilization loop kept the laser power constant to within 0.5%, we believe that the main source for diameter variations are laser power fluctuations, amplified by the resonant response of the molten zone.[7] Further studies of the growth dynamics are in progress.

Scatter losses were measured by launching laser light into the fiber and measuring scattered radiation along the

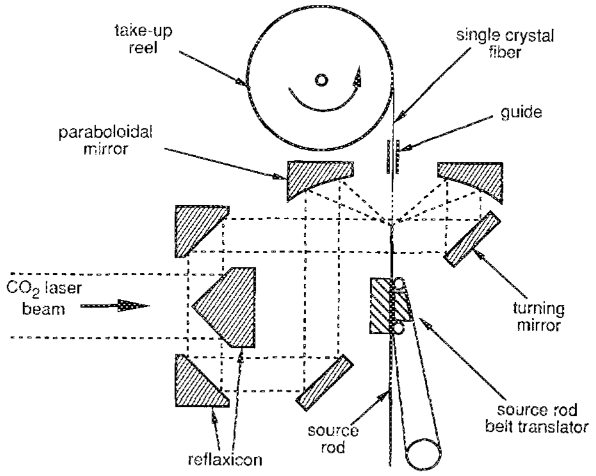

FIG. 1. Cross-sectional diagram of focusing optics and translators used to grow single-crystal fibers.

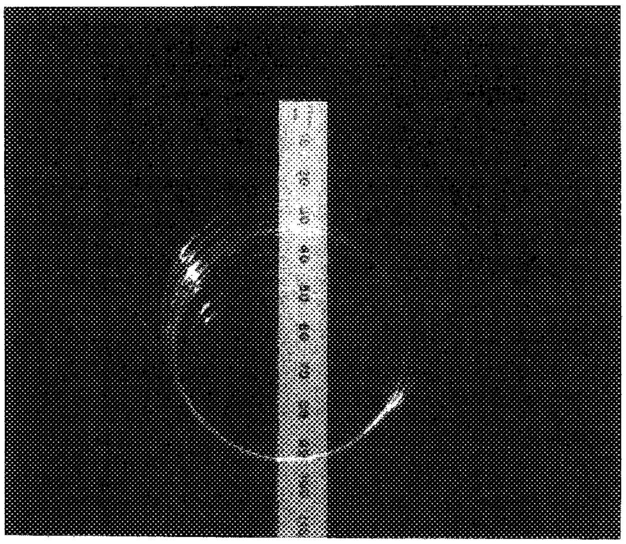

FIG. 2. Photograph of 120-μm-diam c-axis single-crystal sapphire fiber. The ruler unit is mm.

fiber with a photodiode in a 6-cm-diam integrating sphere.[8] As the scatter losses are dependent on the modal power distribution,[6] there is no unique loss figure for a given wavelength. Since the angular distribution of the output light was found to be largely insensitive to moderate fiber bending, we expect the loss measurements, taken near the output end of the 0.71-m-long fiber, to be representative of those for actual applications. Results of scatter loss measurements at wavelengths ranging from 458 to 2936 nm are shown in Table I. The scatter losses for all the wavelengths measured are the same, 0.16 dB/m, within experimental accuracy. The change in throughput of a fiber bent in a loop with a radius of 13 mm was found to be less than 1%.

Calorimetry was used to measure absorption losses in fibers.[9] The calorimeter consisted of two identical capillary tubes each 30 cm long, one containing the sample and the other serving as a reference. The absorbed laser light heated the fiber, and the resultant temperature difference between the two capillary tubes was measured with six thermocouple junctions in series. The responsivity of the calorimeter was measured with a heating wire in place of the fiber. The guided power was calculated from the measured output, taking into account the Fresnel reflection loss and attenuation as the light travels from the point of measurement to the end of the fiber.

The results of the absorption measured by calorimetry at six different wavelengths for a fiber grown in air are shown in Table I. A lower absorption loss of 0.88 dB/m for 2936 nm light was measured for a fiber grown in an atmosphere of pure oxygen, probably due to reduced OH incorporation.[10] From the data in Table I, it can be seen that absorption dominates scattering losses in the visible and the mid-infrared. In the near-infrared, absorption is small and comparable in magnitude to the scatter losses.

The absorption in the UV-visible region of the spectrum was measured using an arc lamp. The arc was imaged by a lens onto the plane of an aperture which let pass light from a small section of the arc that had a well-defined spectral emission. One end of the fiber was positioned in the aperture; the other end was placed inside an integrating sphere. The wavelength dependence of the ouput of the sphere was measured with a 1 m spectrometer and photomultiplier detector. The wavelength dependence of the throughput of the measurement system was removed by normalizing the data to the signal obtained by directly imaging the aperture onto the input of the integrating sphere. The overall scale factor was set by comparison with the 633 nm data point in Table I.

TABLE I. Scattering and absorption losses for a fiber grown in air. The data point in parentheses is for a fiber grown in an oxygen atmosphere.

Wavelength (nm)	Scattering loss (dB/m)	Wavelength (nm)	Absorption loss (dB/m)
458	0.16 ± 0.03	458	17.4 ± 0.8
488	0.17 ± 0.03	488	6.30 ± 0.1
515	0.16 ± 0.03	515	4.6 ± 0.15
633	0.13 ± 0.03	633	1.3 ± 0.2
1064	0.18 ± 0.035	1064	0.28 ± 0.08
		2936	1.7 ± 0.2 (0.88 ± 0.2)

The resulting curve for the attenuation constant α in a c-axis fiber is shown in Fig. 3, along with the absorption losses measured at the laser wavelengths. There is a broad absorption band centered at 400 nm (corresponding to a photon energy of 3.1 eV) with a peak absorption of 18 dB/m (0.04 cm^{-1}). An absorption band centered at 3 eV with a full width at half maximum of 1.5 eV, similar to the observed band, has previously been reported in γ-irradiated sapphire crystals.[11,12] The type of color center responsible for the absorption has been attributed to hole (or V-type) centers. Two hole (V^-), one hole (V^{2-}), and V_{OH} centers[13] all absorb near 3.0 eV.[14] Bauer and Whitmore[15] propose a hole trapped on an anion which is adjacent to a substitutional divalent iron impurity. The absorption bands of all of these centers were reported to be bleached when the samples were annealed at a high temperature. We are currently investigating annealing as a means of reducing the 3.0 eV absorption in the sapphire fibers.

The possibility of laser surgery using sapphire fibers was

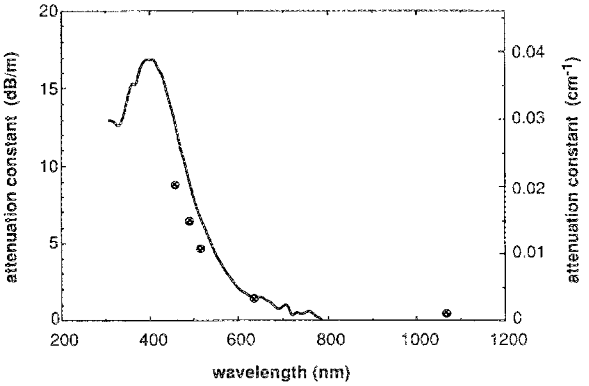

FIG. 3. Loss coefficient in 110-μm-diam fiber. The solid line depicts the attenuation constant measured with the arc lamp apparatus. Circles are absorption losses from Table I measured by laser calorimetry.

investigated with a Quantronix model 294 Er:YAG laser operating at 2936 nm with a pulse duration of 110 μs and a repetition rate of 3 Hz. To establish the damage threshold, the flash lamp energy was slowly increased. The energy incident on the input end of the fiber was estimated by recording the ouput of the fiber and correcting for propagation losses. No damage was observed for 130 mJ pulses falling on the 110-μm-diam input face of the fiber. Assuming uniform intensity across the end face yields a damage threshold in excess of 1.2 kJ/cm^2 (an intensity of 11 MW/cm^2). Ablation of post-mortem human arterial tissue was observed with 6 mJ per pulse at the output of the fiber. Assuming a fiber delivery system 4 m in length with a loss coefficient of 1 dB/m, reflection losses of 8% at each end, and with an output energy of 6 mJ per pulse, the incident fluence on the fiber would be at least seven times below the damage threshold. We conclude that sapphire single-crystal fiber power delivery systems are feasible for medical applications.

Because the Er:YAG laser exhibited spiking and operated in multiple transverse modes, the local damage threshold of the sapphire fiber surface is probably higher than the average value of 11 MW/cm^2. Furthermore, the surface damage threshold of sapphire has been shown to depend strongly on absorbing defects or impurities in the surface layer.[16] We believe that the surface absorption could be reduced by improving the polishing techniques and by annealing the polished surface,[16] leading to a considerable increase in damage threshold. Alternatively, the damage threshold could be increased by tapering the fiber to increase the endface area.

The tensile strength of sapphire fibers is ten times that of fluoride or silver halide fibers and is adequate for practical applications.[17–19] A bend radius of 4 mm has been demonstrated in a 150-μm-diam fiber,[20] and 50-μm-diam fibers are easily handled without breakage. For many delivery system applications, highly flexible fibers are necessary. To compare sapphire fibers with fused silica, we note that the force required to bend a long rod into a certain shape is proportional to Ed^4/l^3, where E is the Young's modulus, d is the diameter, and l is the length of the fiber.[21] Because sapphire fibers have a Young's modulus of 4.95×10^{11} Pa along the c axis,[22] seven times larger than fused silica, seven times as much force is necessary to bend a sapphire fiber as is required to bend a glass fiber of the same dimensions. If the same flexibility is required for a sapphire fiber as for a glass fiber, meaning that Ed^4 is kept constant, the diameter of the crystal fiber should be reduced to 62% that of the glass fiber.

To summarize, high quality single-crystal sapphire fibers of lengths over 2 m were grown and evaluated. Measured scatter losses were less than 0.2 dB/m. The loss was dominated by absorption, with a broad absorption band centered at 400 nm. Laser light at 2936 nm was guided with a total loss of 1 dB/m, and a damage threshold of 1.2 kJ/cm^2 for a 110-μs-long pulse. Ablation of post-mortem arterial tissue was demonstrated with incident fluences at the fiber surface well below the damage threshold. Power handling might be improved by reducing impurities in the fiber and improved end polishing techniques or by tapering the fiber. The sapphire fibers are well suited for medical applications due to their nontoxicity, chemical inertness, and mechanical strength.

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