FIBEROPTIC MATERIALS R&D

SINGLE-CRYSTAL FIBER APPLICATIONS INCLUDE NONLINEAR OPTICAL EFFECTS

By M. FEJER, J. NIGHTINGALE, G. MAGEL, and R. BYER

Single-crystal optical fibers offer a combination of material properties and waveguide geometry that is unavailable in either glass optical fibers or bulk single crystals. The broad transmission window, high melting point, and resistance to chemical attack of many crystalline media, (for example, sapphire), make them attractive for energy delivery, particularly in hostile thermochemical environments. The fluorescence and laser gain properties of crystals such as Nd:YAG and ruby are useful in sensor and miniature laser applications.

Single-crystal fibers are particularly well suited to nonlinear optical interactions, whose efficiencies can be greatly enhanced by the long interaction lengths and tight beam confinement available in guided wave structures. A variety of devices taking advantage of this effect have been demonstrated in glass fibers, notably Raman amplifiers and lasers. However, glasses have inversion symmetry, and thus can only support third-order nonlinear interactions. Crystal fibers, on the other hand, are suitable for second-order interactions like harmonic generation, frequency mixing, parametric oscillation and electro-optic modulation.

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The increase in nonlinear interaction efficiency can be significant. For example, the theoretical efficiency for second-harmonic generation of 532-nm radiation in a 2-cm long single-mode lithium niobate fiber is on the order of 1% per mW, three orders of magnitude larger than in a bulk interactions. The practical realization of such devices requires crystal fibers that meet stringent quality criteria. As is the case for bulk interactions, the fibers must be oriented single crystals of good optical homogeneity. In addition, the diameter of fibers must be kept constant in order to avoid scatter losses and to maintain phasematching along the entire fiber length. These losses are a complicated function of several parameters, but diameter control of 0.1–1% is adequate for a range of interesting devices.

Laser-heated miniature pedestal growth technique

A number of techniques to produce single-crystal optical fibers are currently being pursued. The approach that we have chosen to follow is laser-heated miniature pedestal growth (MPG)[1] of refractory oxide fibers. Other techniques of current interest include Bridgeman growth of organic crystals in glass capillary tubes,[2] extrusion of polycrystalline fibers followed by regrowth into single-crystal form,[3] and embedding unclad glass fibers in a single-crystal cladding.[3]

In MPG, the tip of a source rod of the material to be grown is melted by a focused laser beam. A seed crystal is dipped into the melt, then withdrawn at a constant rate while the source rod is fed in. If the seed is pulled faster than the source rod is fed in, conservation of mass dictates that the pulled fiber will have a

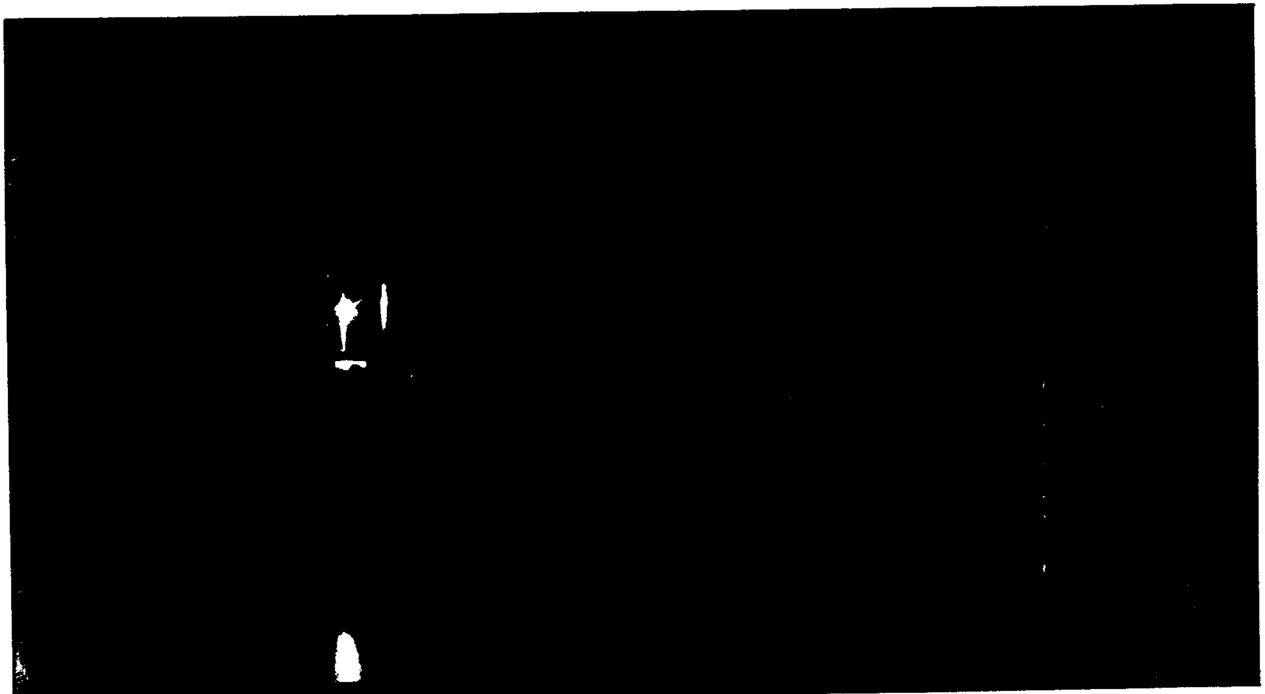

FIGURE 1. The apparatus used in laser-heated miniature pedestal growth. The optical system is based on a 15-W waveguide CO_2 laser and diamond-turned copper focusing optics.

smaller diameter than the source. This process is significantly different from glass fiber pulling, in that the abrupt solid-liquid phase transition characteristic of crystalline media precludes the existence of a gradual viscous drawdown region. MPG is thus susceptible to high spatial-frequency-diameter variations not present in glass fibers. Control of these diameter variations requires that the growth process be thermally and mechanically stable, and is facilitated by maintaining a thermally symmetric growth zone.

The apparatus illustrated in Fig. 1 was designed to implement these stability criteria.[1] Fiber and source rod translation is accomplished with a continuous belt drive that slides the fiber through a V-groove guide. This arrangement maintains the relative position of the source and feed rods while allowing arbitrary lengths of fiber to be pulled. The belts are driven by phase-locked dc motors for accurate speed control.

The optical system is based on a 15-W waveguide CO_2 laser and diamond-turned copper focusing optics. A CO_2 laser is an excellent heat source for MPG. The 10.6 μm output is strongly absorbed by all the refractory oxide materials of interest, and can be tightly focused to produce the short molten zones necessary for stable growth. The copper optics are designed to provide near diffraction limited f/2 focusing, and to heat the fiber in an azimuthally symmetric pattern to provide the necessary thermal symmetry. The entire apparatus is enclosed in a sealed chamber to isolate the growth zone from environmental perturbations and to allow the introduction of oxidizing or reducing atmospheres.

Several characteristics of MPG make it an attractive materials processing technique. Temperatures in excess of 2000°C can be reached with moderate laser power in a controlled atmosphere, completely crucibleless environment. Thus, reactive or high melting point materials can be grown without contamination. Growth rates are rapid and only a small amount of starting material is necessary, making laser-heated MPG ideal for many material survey and characterization applications.

MPG technique offers promise with several materials

A number of refractory oxides have been grown with this system. Emphasis has been on the growth of sapphire and ruby, Nd:YAG, and lithium niobate as examples of materials suitable for energy transmission, fluorescence and laser devices, and nonlinear interactions, respectively. Other materials grown include terbium gallium garnet, Ti: sapphire, and potassium niobate.

The initial source rods are generally 0.5-mm diameter rods of either single-crystal or pressed-powder material. Stable growth is feasible for diameter reduction of up to three or four to one. Thus two or three passes through the system are nec-

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essary to produce 20–50 μm diameter fibers. Fibers with diameters ranging from 500 μm down to 20 μm have been grown. The laser power required is 5–10 W for larger diameters and hundreds of milliwatts for small fibers. Lengths up to 20 cm have been achieved at typical growth rates of 1–10 mm per minute, orders of magnitude faster than bulk crystal growth.

Fibers grown open-loop, that is, with no feedback stabilization, show diameter variations of several percent over centimeter lengths. In order to reduce these unacceptably large variations, a noncontact diameter measurement system with kilohertz measurement rate and sub-10-nm resolution was installed to monitor the fiber diameter at the liquid-solid interface.[4] The diameter deviation signal can be fed back to the pull rate or the laser power to stabilize the growth process. With closed-loop control, fibers with diameter variations as low as 0.1% have recently been obtained.

Growth morphology and etching studies indicate that properly grown fibers are oriented single crystals with no visible grain boundaries. Scatter losses of 150-μm diameter unclad sapphire fibers measured at 633 nm are on the order of 0.01 dB/cm. Similar results have been obtained in Nd:YAG and lithium niobate.

Fibers with losses in the 0.01 dB/cm are adequate for a number of applications. Monolithic Nd:YAG oscillators with mW thresholds[5] and single-transverse mode output have been demonstrated, as have monolithic ruby fiber lasers. A thermometer based on the blackbody emission from a doped tip guided through a sapphire fiber has achieved mK resolution in a 10-Hz bandwidth.

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