Optical-fiber lasers exploit new techniques and materials

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Progress in fiber laser research around the world is accelerating as the implications of new materials and fabrication techniques begin to be felt. With the appearance of the fiber grating reflector the potential versatility of the spectrally broad emission characteristic of glass fibers can at last be exploited, in compact and rugged narrow linewidth sources at wavelengths precisely selected over a wide band. Fiber lasers are no longer restricted to low power operation; the cladding-pumping technique enables light from high power pump sources which are not diffraction-limited to be used efficiently, converted to output which may be multiwatt and enhanced in brightness by more than two orders of magnitude. Moreover, rare-earth-doped fluoride glass fiber is now commercially available from both Le Verre Fluoré, France, and Galileo Electro-Optics, MA; this is a "low-phonon-energy" alternative to silica, which offers many more metastable energy levels and laser transitions over a larger spectral range. Fluoride fibers have lased at blue and even ultraviolet wavelengths when pumped by longer-wavelength sources in upconversion lasing schemes.

The advantages of tight optical confinement of pump and signal light are well-appreciated for the optical amplifier, in which they confer an exceptionally large ratio of gain to pump power [1]. In a source, these advantages translate into low lasing thresholds and the ability to exploit relatively weak pumping and emission processes; an attractive feature is the robust fundamental spatial mode of the output, controlled only by the design of the fiber.

Fiber gratings

The fiber Bragg grating, written laterally into the photosensitive core by ultra-violet light from excimer laser pulses, or a frequency-doubled argon ion laser, has tremendously extended the potential of fiber laser sources. A good example of this is provided by the Yb-doped germanosilicate fiber laser with grating wavelength selection [2]. The Yb^{3+} laser ion is a particularly attractive candidate for operation in a guided-wave geometry, in which conditions of high population inversion are easily reached even for a three-level laser. Its simple energy level structure gives freedom from excited state absorption, concentration-quenching, and other parasitic processes which are responsible for limiting the efficiency of other dopant ions. The metastable level can be pumped over an unusually broad wavelength range, extending continuously from the domain of AlGaAs diodes at $\sim$800 nm at one extreme, to the 1064-nm Nd:YAG wavelength at the other. The fluorescence emission covers a range of more than 200 nm, including wavelengths of practical interest such as 980 nm for pumping the erbium-doped fiber amplifier, 1020 nm for pumping the 1300-nm Pr-doped fluoride fiber amplifier, and 1140 nm for pumping the blue Tm-doped fluoride fiber upconversion laser.

Without a strongly frequency-discriminating element in the laser cavity the high gain Yb-doped silica fiber laser will generally lase at wavelengths close to the 1030-nm gain maximum. In a cavity closed at one end by a fiber grating, however, efficient narrow linewidth operation at selected wavelengths which may be well away from the gain maximum can be realized [2]. In one such demonstration an 1140-nm laser operated with a slope efficiency of $\sim$66% with respect to launched power. The lasing threshold was only 6 mW, and an output of 330 mW was achieved for 500 mW launched power.

Fiber gratings have also been used to create fiber lasers oscillating in a single axial mode. A short cavity length is required, so that suitable transitions for this type of device must combine large pump absorption and laser emission cross-sections with the possibility of high dopant concentration, so as to achieve adequate pump absorption and gain in a fiber only centimeters long. A 1500-nm distributed-feedback laser has recently been demonstrated [3] in an $Er^{3+}:Yb^{3+}$ co-doped fiber 2 cm in length, with feedback provided by a single grating written directly into the doped fiber core. This device exhibited a 60-kHz linewidth.

Cladding pumping

The technique of cladding pumping overcomes the difficulty of coupling light efficiently from powerful pump sources of low spatial coherence, such as high-power diode lasers, into a laser waveguide which supports only a single spatial mode. A cladding-pumped fiber is fabricated with a rare-earth-activated single-mode inner core enclosed within a undoped multimode outer core of much larger area, designed to capture and guide the pump light. The reduced pump absorption coeffient of such fiber is compensated for via increasing the rare earth concentration and/or the length of the fiber. A Nd-doped fiber laser of this type has emitted 5W in a single transverse mode [4]; a similar device has been used to enhance the brightness of a fiber-coupled multi-diode-array by a factor of 150 [5].

These examples used a highly multimode outer core, with area 1000x greater than that of the inner core, however, there are instances in which great benefits can be derived from using cladding-pumping with a near-diffraction-limited source in which the inner and outer core structures can be much closer in diameter. A cladding-pumped 1040-nm Yb fiber laser has been demonstrated [2] pumped by a Ti:sapphire laser, but with its beam-launch deliberately degraded to simulate a non-diffraction-limited source, of $M^2 \sim 2$. With an outer core area of 9x that of the inner core, this laser demonstrated a slope efficiency of 80% with respect to *incident* pump power, the highest slope efficiency reported. Besides the slope efficiency advantage, the launch alignment tolerance for this cladding-pumped fiber is significantly relaxed.

In an interesting extension of this technique, cladding-pumping was combined with fiber grating wavelength selection to create single-spatial-mode pump sources at 1020 nm and 1140 nm. The structure of the cladding-pumped fiber is shown schematically in Fig. 1. The NAs of the inner and outer guiding structures are ~0.16 and ~0.17 respectively, produced by light Ge_2O_3 doping in the outer core and stronger doping in the inner core, which is correspondingly more photosensitive and develops a stronger Bragg grating on exposure to excimer pulses. Yb-doping is within the inner core only at a concentration of ~500 ppm. Pump light is efficiently launched into the outer core, where the grating has high transmission for the pump. With 1020-nm gratings in the core, a lasing emission from the output end of the fiber exhibited a slope efficiency of ~42%, limited by the low reflectivity (~62%) of the grating at the launch end of the fiber. Taking laser power emitted at the launch end into account, the device had an overall conversion efficiency of ~70%. These devices clearly demand the development of more photosensitive fiber, in which highly reflecting gratings can be written, and this is a priority for future work.

Cladding-pumping offers exciting promise for enhancing the brightness of high power diode laser sources. For example, using a recently demonstrated beam-shaping technique to configure the diode beam into a near-circular shape [6], it should be possible to launch most of the light from a high power diode bar, array, or broad-stripe diode, into the outer core of the fiber and then extract most of this power via monomode (or low-order mode) lasing in the inner core. Such a fiber could be a pigtail attachment to the diode assembly, thus providing a very simple and convenient transformation from the planar geometry of diodes to the cylindrical geometry needed for most applications.

Upconversion lasers

Spatially coherent blue sources are in great demand for optical data storage, but the restricted lifetime of blue-emitting diodes so far precludes their practical use. Against this background, there may be a rôle for fiber upconversion lasers, which include some of the simplest solid-state green and blue laser sources developed to date [7]. The 480-nm Tm-doped fluorozirconate fiber laser depicted in Fig. 2 operates cw at room temperature when pumped at a single infrared wavelength in the range 1100 - 1140 nm, which could perfectly well in principle be supplied by a laser diode. The pumping scheme, which was first demonstrated by Grubb et al., involves three absorption steps in sequence, with substantial Tm ion populations stored in intermediate metastable levels, which are long-lived in the low-phonon-energy zirconium-fluoride-based glass host. Since the excitation spectrum of the blue fluorescence extends over ~ 40 nm, the spectral tolerance imposed on a pump diode for this blue laser could be extremely relaxed, in marked contrast to the highly stabilized single-frequency operation required of a diode used in a nonlinear frequency conversion scheme. In the fiber geometry this three-step pump mechanism becomes remarkably efficient, with thresholds of a few tens of mW and slope efficiencies of ~30% with respect to absorbed power being readily achievable [8].

The 480-nm upconversion transition is only one of the interesting possibilities offered by the trivalent Tm ion which, in a host of low or medium phonon energy, represents perhaps the richest and most complex laser system of any rare earth ion. Amongst the most surprising of these possibilities must be counted the 1470-nm laser pumped at 1064 nm, which is an upconversion laser in the sense that two pump photons are required to promote one ion to the upper laser level. Despite the extremely weak ground state absorption at the pump wavelength, it has been shown that high 1470-nm gain (19 dB) and output power (17 dBm) can be efficiently achieved (0.24 dB/mW) in a modest fiber length [9]. This could provide a useful extension of the EDFA gain window. Pumping at 1064 nm also offers high power performance, which could have interest for an "eye-safe" source at 1470 nm. The pump mechanism may involve energy transfer between Tm ions, presenting an interesting contrast with most earlier fiber upconversion lasers, which were distinguished from their bulk crystal counterparts by low dopant concentration and pumping by sequential excitation of single ions rather than energy transfer between ions. At high concentration energy transfer opens up many more channels for excitation and de-excitation some of which may be beneficial, as in this 1470-nm laser, while others may be detrimental. Characterizing and optimizing these energy transfer processes is an interesting future challenge.

Energy transfer also plays a crucial rôle in the blue-green Pr:Yb fluoride fiber laser for which impressive results have recently been reported from Los Alamos National Laboratory [10]; 2 mW at 493 nm have been obtained from a diode-pumped device. The energy level diagram of the trivalent Pr ion (Fig. 3) illustrates its most attractive feature which is the existence of blue-green, green, orange and red laser transitions originating from the same initial metastable level [11]. In fiber doped only with Pr two infrared pump wavelengths are required to populate this level; co-doping with Yb as a sensitizer which can transfer energy to Pr allows the laser to be pumped at a single wavelength anywhere in the range 840 - 860 nm, thus compatible with AlGaAs diode pumping as the Los Alamos results demonstrate.

Research groups continue to report interesting new upconversion laser transitions in fluoride fibers, with cw room temperature operation of the Tm 455-nm transition [12], and 381-nm operation of Nd [13] most recently added to the list. Fluoride fibers do appear to offer the prospect of shorter wavelength operation, and the challenge of optimizing these complex systems, and establishing the ultimate limits to their performance, poses an important problem for modeling.

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Figure 1. Structure of cladding-pumped Yb-doped germanosilicate fiber with grating in the inner core.

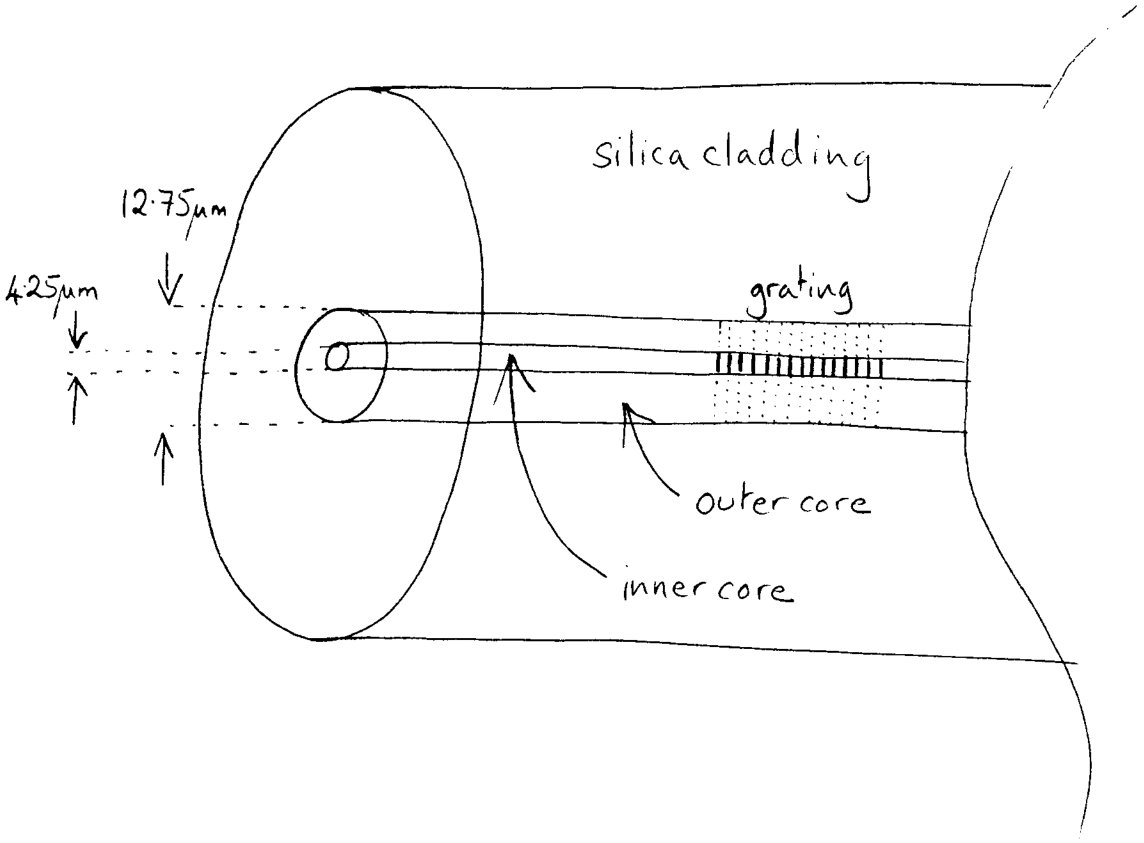

Figure 2. 480-nm Tm-doped fluoride fiber laser pumped at 1140 nm.

Figure 3. Energy level diagram of the trivalent Pr ion

Note to Editor: energy scale on left not essential if the relative level spacings can be preserved – nor are all the level labels. It would be nice if the downward arrows could be coloured appropriately:
491nm – blue-green; 520nm – green, 605nm – orange
635nm – red.

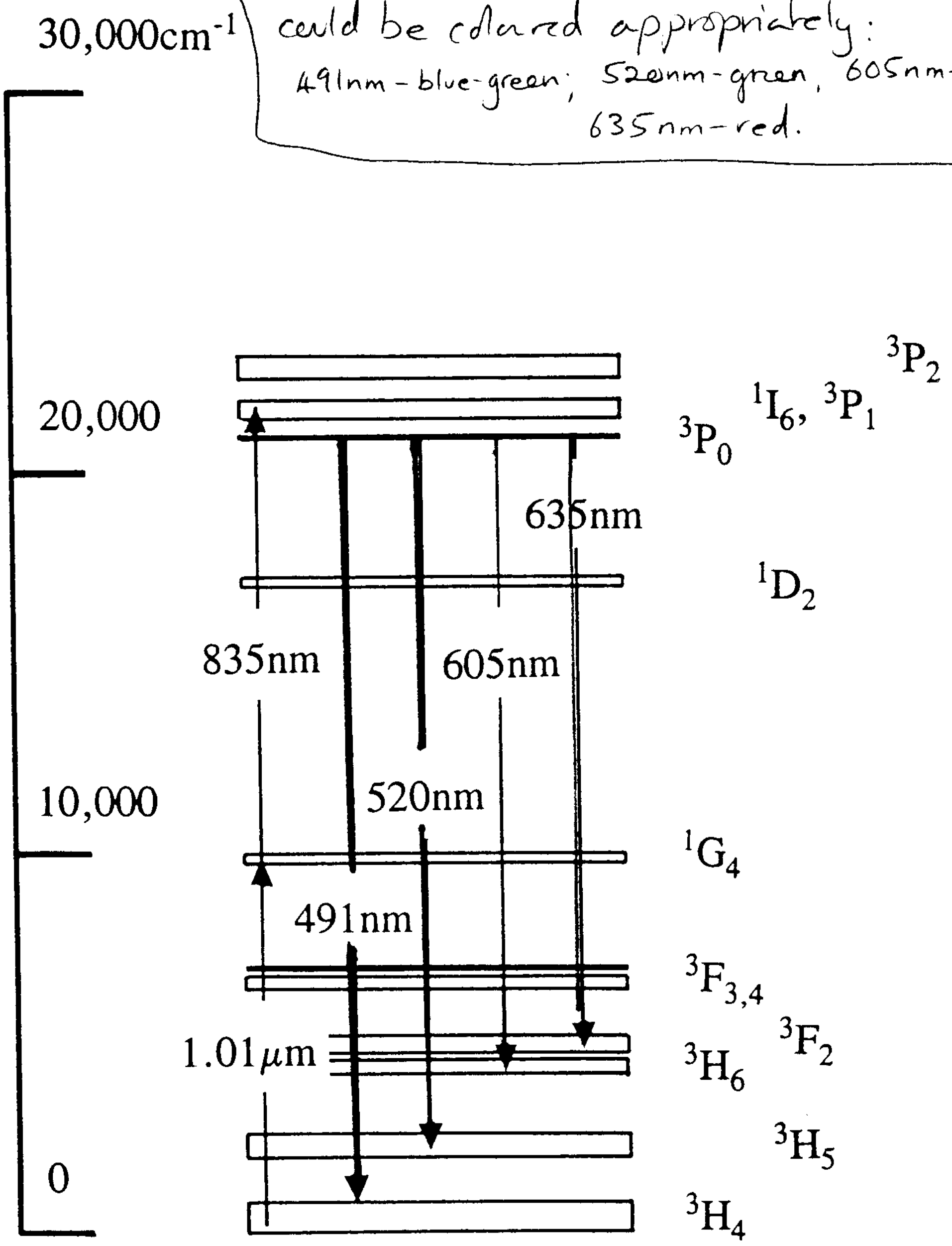

Figure 3