Fiber Lasers Launch into Medicine, Aerospace and Material Processing

by John D. Minelly

Techniques for power scaling and energy increases broaden nontelecom applications.

Optical fiber lasers appear to have come of age at last. More than 30 years after the initial demonstration of lasing in a neodymium-doped glass fiber,[1] and nearly ten years after the first erbium-doped single-mode fiber amplifier,[2] only now is there interest in rare-earth-doped fiber lasers as serious competition for other solid-state laser systems.

Telecommunications has been the driving force behind the technology. By 1985 single-mode fiber technology had developed to the extent that propagation losses in silica fibers were approaching the theoretical limit. Simple techniques were developed extending modified chemical vapor deposition (MCVD) technology[3] to incorporate rare-earth ions in the core of single-mode fibers. However, except for a fortunate coincidence of nature that places the attenuation minimum of silica at 1.55 µm, within the gain bandwidth of erbium-doped fibers, it is unlikely that the technology would have been developed much further.

New techniques enabling power scaling to average powers in excess of tens of watts, energy storage in the millijoule region and single-longitudinal-mode operation have boosted the scope of applications for fiber lasers. These extend beyond the telecommunications industry, with exciting new markets opening up particularly in medicine, aerospace and materials processing. Continuing efforts in materials research should lead to a second generation of long-wavelength fiber lasers within a few years.

Figure 1. *High-power semiconductor lasers with fiber delivery systems find use in laser surgery. Courtesy of Diomed Ltd.*

Benefits in medicine

The pioneering use of lasers in medical treatment has enabled the development of minimal access therapy (MAT). Much of the development in this area has been based on gas lasers and flashlamp-pumped solid-state lasers, both of which require complex and bulky power supplies and cooling systems. Compact and portable diode-pumped sources such as fiber lasers will not only reduce the purchase and running costs of the lasers themselves, but also reduce the cost of treatment because much of the therapy could be transferred away from the traditional operating theater to outpatient departments.

The 805-nm wavelength of a semiconductor laser is suitable for surgery of pigmented soft tissue in cases where a moderate amount of collateral thermal injury can be tolerated. For surgery of hard or unpigmented tissue or where collateral injury must be minimized, longer wavelengths with strong water absorption are required. Conversion of the diode light to 1.55 or 2.0 µm in

Figure 2. Schematic of the cladding-pumping technique. Double-clad fibers allow high-power diode pump sources to be converted to a diffraction-limited output beam in simple end-pumped fiber-laser cavities.

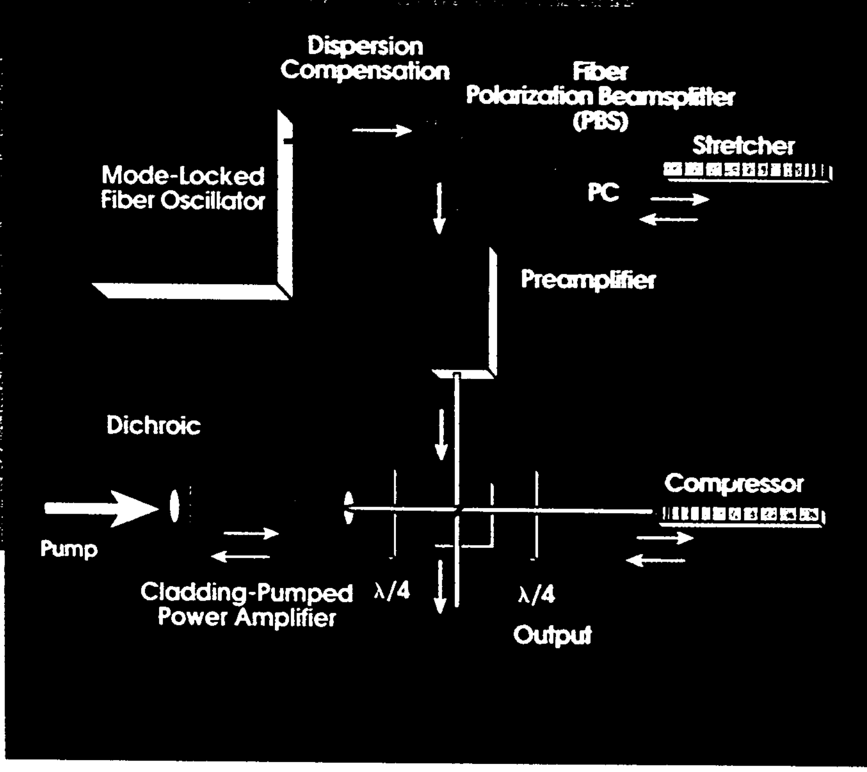

Figure 3. The chirped-pulse amplification scheme illustrates the many advantageous features of fiber lasers. High fiber nonlinearity passively mode-locks a low-power oscillator. Chirped fiber gratings stretch the pulse prior to amplification in a cladding-pumped power amplifier free of stimulated Raman scattering.

an Er^{3+} or Tm^{3+} fiber laser in which the power has been scaled by a technique known as cladding pumping is a very attractive means of increasing the versatility of fiber-coupled diode sources.

Ranging applications

Over the last decade, rapid advances in laser technology have led to growing interest in the use of lasers for ranging applications. Historically, laser transmitters based on carbon dioxide lasers operating at 10.6 µm have been the choice for most applications. Fiber lasers offer the prospect of significant advantages over CO_2 lasers including higher efficiencies, smaller size and weight, longer lifetimes and the absence of consumables. In addition, the shorter operating wavelengths should allow [illegible] velocity-resolution measurements, improved transverse spatial resolution and better atmospheric transmission. Possible applications include simple ranging and altimetry, windshear detection and avoidance systems for aircraft and satellite-based LIDAR and wind-monitoring systems.

[illegible] power required depends on a number of factors, such as the range of the target under investigation, atmospheric attenuation and the efficiency of the detection system employed. For lasers operating in the continuous wave (CW) or high pulse-repetition-frequency (PRF) regime, an average output power in the range of 5 to 10 W is considered sufficient for most applications. Alternatively, for low-PRF systems, a pulse energy in the range of 1 to 10 mJ is sufficient. If, in addition to range data, target velocity is required via measurements of the Doppler shift of backscattered light, the transmitter output needs to be single-frequency. A 1-MHz linewidth corresponding to velocity resolution of 1m/s for a source in the 1.5- to 2.0-µm region is sufficient for most applications.

Fiber laser systems are expected to be deployed in hospitals and aircraft at least on a trial basis within two years. Other applications include laser printing and marking, imaging in turbulent media where high-power broadband sources (>5-nm linewidth, >1-W output) are required and as special wavelength sources for spectroscopy (e.g., a single-frequency

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laser at 1.083 µm for helium isotope spectroscopy).

The waveguiding nature of the optical fiber means that very high power densities can be achieved in the fiber core for moderate power levels. (Gain coefficients around 10 dB/mW of pump power can be achieved in erbium-doped fiber amplifiers.) The high surface-area-to-volume ratio of the fiber geometry virtually eliminates thermal problems. This enables glass lasers in fiber form to lase readily in CW mode, unlike bulk glass lasers.

In design, there is always a compromise.

The broad absorption band of the glass host facilitates the choice of pump source and eliminates the need for stabilization of the pump wavelength with power-consuming thermoelectric coolers. Broad emission spectra means that fiber lasers are broadly tunable (over a range of 100 nm in the case of ytterbium) and ideal for ultrashort pulse generation. The technology has benefited greatly from the development of side-writing techniques for photorefractive fiber gratings,[4] which enable precise wavelength selection and line-narrowing.

Power scaling

The key to power scaling of fiber lasers is a technique known as cladding pumping. Specially designed double-clad fibers convert pump radiation from high-power, but low-brightness, semiconductor diodes into highly intense diffraction-limited laser light (Figure 2). Useful for applications requiring average powers from a few hundred milliwatts to several tens of watts, the technique was pioneered by groups at Polaroid, Southampton University, the Institute of Radioengineering and Electronics (Moscow), Rutgers University, and, more recently, by Laser Zentrum (Hannover) and the University of Bern.

The essential difference between a cladding-pumped fiber laser and a conventional core-pumped device is that, despite the higher pump powers available, the pump intensity is actually reduced. This is because, for reasons of thermal management, the emitting area of high-power diodes scales faster than power, and coupling the pump light into the fiber further degrades brightness.

In designing a cladding-pumping fiber, there is therefore, always a compromise between launch efficiency, which improves with increasing cladding-waveguide dimensions, and pump rate, which is better for smaller-cladding waveguides. The characteristic pump absorption length will scale with the area of the cladding waveguide, but also depends on the shape of the cladding waveguide and the position of the fiber core.[5] A rectangular waveguide gives the highest pump absorption for a given cladding-to-core-area ratio.

Cladding pumping is particularly suited to four-level laser systems (where the unpumped fiber is essentially transparent at the lasing wavelength), such as the 1.06-µm transition in Nd^{3+}, because the reduced pump rate degrades performance only slightly as a result of an increase in background loss associated with longer cavities. The group at Polaroid has demonstrated >5W output power with a slope efficiency of 55 percent and a threshold of only a few tens of milliwatts.[6]

Cladding pumping is not as easy to implement for three-level systems such as the 1.55-µm transition of Er^{3+} because the unpumped fiber absorbs strongly at the lasing wavelength. Because this absorption must be bleached before gain can be achieved, the threshold power is higher. The first demonstration used an Yb^{3+} co-dopant and an energy-transfer pumping scheme to compensate for the reduction in pump rate because of the double-clad geometry.[7] A range of high-power amplifiers and lasers based on $Er^{3+}Yb^{3+}$ technology are now commercially available from ATx Telecom Systems Inc. of Naperville, Ill., and IRE Polus International Inc. in Chicago.

In cases where co-doping is not possible or convenient, cladding pumping of three-level systems

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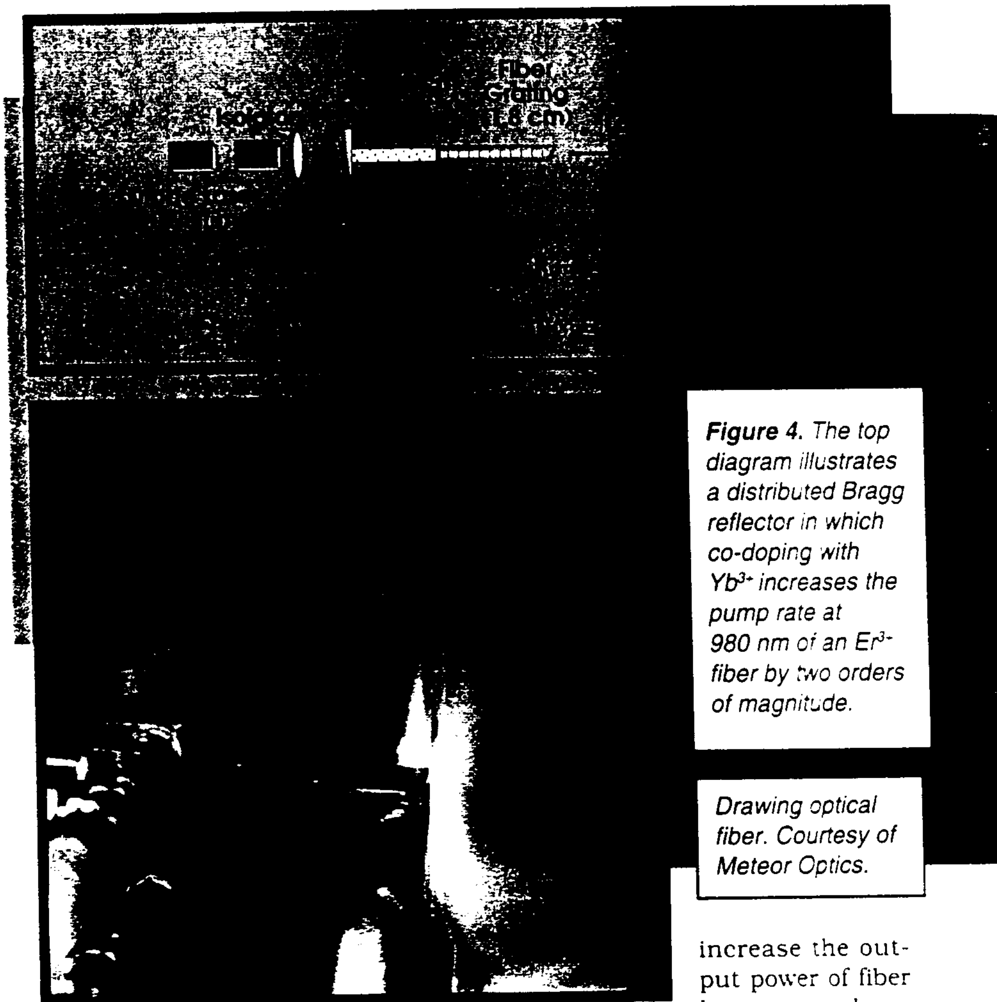

Figure 4. The top diagram illustrates a distributed Bragg reflector in which co-doping with Yb^{3+} increases the pump rate at 980 nm of an Er^{3+} fiber by two orders of magnitude.

Drawing optical fiber. Courtesy of Meteor Optics.

requires a restriction in the dimensions of the cladding waveguide. Dimensions of approximately 20 µm are appropriate for pumping with master-oscillator power amplifier (MOPA) pump sources that are essentially diffraction-limited or beam-shaped high-brightness broadstripe diodes. These are diodes of typically 100- to 400-µm × 1-µm emission area that are optically reshaped prior to focusing to reduce the asymmetry and enable coupling to smaller-diameter fibers. Cladding pumping of fibers of this type has been successfully applied to the development of Yb^{3+} fiber lasers at 1020 nm and to singly doped Er^{3+} fibers at 1.55 µm.

New applications open up

Improvements in the brightness of high-power diode lasers and further development in beam-shaping and -combining techniques will further increase the output power of fiber lasers to perhaps 100 W, opening up a range of applications in material processing.

For many applications, short pulses are desirable. Widths can vary from a few femtoseconds in mode-locked fiber lasers to hundreds of nanoseconds in Q-switched or pulse-amplifier systems. Single-mode fibers are ideal for situations requiring modest pulse energies — up to ~10µJ — at moderate-to-high repetition frequencies. The pulse energy is limited by the active-ion density, self-saturation by amplified spontaneous emission and nonlinear effects such as Raman scattering. Amplifier chains with a final stage comprising either a large-mode-area (low-NA) single-mode fiber[11] or a section of doped multimode fiber[12] can achieve higher energies. A final stage comprising a cladding-pumped amplifier can achieve high average powers and high pulse energy simultaneously.[13] Chirped pulse amplification, in which ultrashort pulses are stretched with

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fiber gratings to widths of ~100 ps prior to amplification and subsequently recompressed to their original duration, can overcome nonlinear effects such as stimulated Raman scattering (SRS) (Figure 3).[14]

Keeping it to single-frequency

Single-frequency fiber lasers are being developed as sources for telecommunications, spectroscopy and coherent lidar. Under normal conditions, multilongitudinal-mode operation results from a combination of spatial holeburning (periodic modulation of the optical intensity and gain saturation by forward- and backward-propagating signals) and the relatively long length of fiber laser cavities. Two principal techniques are used to suppress this tendency to multimode oscillation.

One is operating the laser in a traveling-wave configuration to eliminate spatial holeburning, and the other is incorporating a narrow-band fiber grating reflector within a short cavity. While the ring-laser approach can yield very narrow linewidths of ~20 kHz, difficulties in selection of a precise wavelength and a tendency to mode hop have made the grating feedback method the favorite.

The initial devices comprised several centimeters of Er^{3+} fiber with a narrow-band fiber grating spliced to the output end.[15] The performance of these devices was somewhat limited because concentration-quenching of the laser metastable level at Er^{3+} concentrations above 1000 ppm limits pump absorption to about 10 dBm^{-1}. In a length of fiber short enough for single-frequency operation, only a small fraction of launched pump light is actually absorbed, so the efficiency is very low, typically less than 1 percent. Although the unabsorbed pump light can be used to amplify the output from such a source, the oscillator power is usually too low to achieve adequate noise levels.

Researchers have created much more efficient single-frequency sources by using energy transfer in $Er^{3+}Yb^{3+}$ co-doped fibers (Figure 4). The presence of Yb^{3+} increases the pump absorption at 980 nm by around two orders of magnitude compared with singly doped Er^{3+} fiber, thus enabling efficient pump absorption in a few centimeters of fiber. Distributed Bragg reflector (DBR) and distributed feedback (DFB) fiber lasers[16,17] that have threshold powers around 1 mW and slope efficiencies as high as 55 percent have been demonstrated.

As devices based on silica reach the development stage, we can speculate on the next generation of fiber lasers. Just as much of the progress described above resulted from investment in silica-based 1.55-μm Er^{3+} amplifiers, the next generation will benefit from the extensive research into low-phonon-energy glasses carried out in the quest for an improved Pr^{3+}-doped 1.3-μm fiber amplifier, which provides the lowest signal dispersion and thus the best-quality transmission.

The next generation will benefit from this research.

Although this search has been of limited success so far, an important spinoff has been the development of purification and fiber-manufacturing techniques in glasses capable of long-wavelength transmission and generation. Impressive results have already been achieved at 2.7 μm in Er^{3+}-doped fluoride fiber,[18] a wavelength important for medical procedures requiring precise cutting and ablation of tissue. There are exciting prospects for longer-wavelength sources based on new glasses such as gallium lanthanum sulfide. These include gas and environmental sensing in the 3- to 5-μm range.[19] □

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John D. Minelly graduated in physics from Strathclyde University and received his PhD from the University of Southampton in Southampton, UK, where he works as a senior research fellow.