High-power fiber lasers and amplifiers

The development of a new fiber laser design—the double-clad fiber laser—has impacted the telecommunications, graphic arts, medical technologies, and materials processing industries. This article looks at the properties of these relatively new devices and explains their impact on current technologies.

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Fiber lasers have been the subject of considerable activity over the 25 years since they were first demonstrated. Researchers around the world have explored their power, or pulse properties, and their ability to generate light at different wavelengths. Fiber lasers have also been investigated for applications in areas such as telecommunications, laser ranging, materials processing, imaging, and medicine using combinations of different gain mediums, pumping schemes, and cavity designs.[1] Despite a detailed understanding of light coupling, generation, and propagation, fiber lasers are only now beginning to see commercial success. This is a result of the development of a new type of fiber device, the double-clad fiber laser. This article discusses the advantages of such lasers and the various applications that they will impact.

In principle, fiber lasers offer many advantages over diode or bulk devices.[2] Hair-thin glass fibers have extremely high damage thresholds and their high surface to volume ratio provides excellent heat dissipation. They can be virtually limitless in length—allowing efficient use of pump light—and exhibit excellent beam quality, and wavelength and temperature stability. However, conventional practical fiber lasers must be pumped with diode sources that couple light *directly into the single-mode core,* which is 8 μm in diamter. Since this *diode pump* power is currently limited to fractions of a watt, the power levels generated by fiber lasers have been relatively low and diode lasers continue to dominate

A critical weakness of diode lasers, though, is low brightness, which is the product of beam area and divergence. To increase output power, the diode facet area must be increased, because diode brightness is limited by the damage threshold of the semiconductor material. This curtails some industrial applications since light from large area diodes has poor beam quality and cannot be focused to small sizes. It is also a severe limitation for telecommunications applications, which use only light coupled into the single-mode core. The power of conventional fiber lasers can only be increased by combining multiple pumps into a single fiber. One method that was used early in the development of optical amplifiers for telecommunications was to polarization- and wavelength-combine multiple diodes onto a single fiber. But, practical implementation of this approach was limited by the complexity and losses of the components, which increase in number exponentially.

Double-clad fibers offer a clever solution to increasing the amount of pump power in a fiber laser.[3] By turning the entire glass cladding into a second waveguide surrounding a rare-earth doped core, low brightness pump light can be injected into a large area rather than into the small single-mode core. This construction is shown in Figure 1. Since the light overlaps with the core to some degree, it pumps the core as it propagates down the fiber. Therefore, laser emission generated in the core can have a brightness level thousands of times higher than that of pump diodes. This increased brightness is the significant advantage of double-clad fiber over both diodes and other types of fiber lasers. Additionally, powers exceeding 100 W have been efficiently coupled from two InGaAs diodes into high numerical aperture (NA) double-clad fibers only 200 μm in diameter, which is over two orders of magnitude higher than for single-mode guides. Using tens of meters of double-clad fiber, cw powers in excess of 50 W have been generated in a single-mode beam at 1100 nm, and devices approaching 10 W have run for thousands of hours.

Double-clad fiber design

The defining difference between double-clad devices and conventional active fibers is the provision of a cladding waveguide, often noncircular (see Fig. 2). is confined by the lower index of the outer cladding, and is absorbed by optically active dopants (Yb^{3+} or Nd^{3+}) in the core. The noncircular shape eliminates helical rays, which have poor overlap with the core. The scalloped and hexagonal shapes in Figure 2 combine good mode coupling with a fabrication and low-loss device assembly similar to that of standard fiber. This low loss is valuable because even small losses at fiber splices can lead to significant heating in multiwatt devices.

For high-power operation, the cladding's NA should be as high as possible so that light from the diodes is captured by a large facet area. For silica-based fiber, materials constraints limit the NA if both the inner and outer claddings are glass. Higher NA requires the use of a low index polymer to define the outer cladding. The low index polymer also protects the glass surface from mechanical damage. If fluorinated acrylate polymers replace the standard fiber coating, an NA from 0.45–0.60 is achieved with no compromise in mechanical properties.[4] Alignment tolerances in coupling to the large cladding are typically tens of microns rather than submicron for single-mode coupling. At the fiber exit, on the other hand, the beam is diffraction-limited, and the fiber can be spliced to other fibers using conventional techniques.

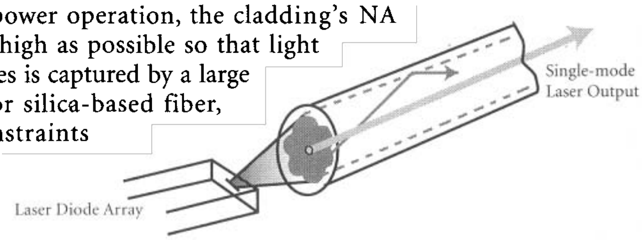

Figure 1. Double-clad fiber laser structure. Light from an area diode is launched into a noncircular inner cladding to pump Nd or Yb into the single-mode core. Fiber lases from the core at a high brightness level.

Double-clad laser operation

A fiber laser can be configured by defining a resonant cavity using Bragg gratings written directly into the core of the fiber, or by using mirrors deposited on or attached to the fiber ends.[5] Since the pump energy is distributed across the inner cladding, pump intensity is relatively low. To allow population inversion, the absorption of the core at the lasing wavelength must be low. This limits operation to four-level laser systems, and also diminishes the amount of pump absorbed per unit length, which scales with the core to clad area ratio. However, because the core absorption at the pump wavelength is typically several dB/cm, laser lengths are less than 100 m. Nd-doped lasers pumped at 810 nm with GaAlAs diodes have generated over 30 W at 1060 nm.[6] Typical slope efficiencies are around

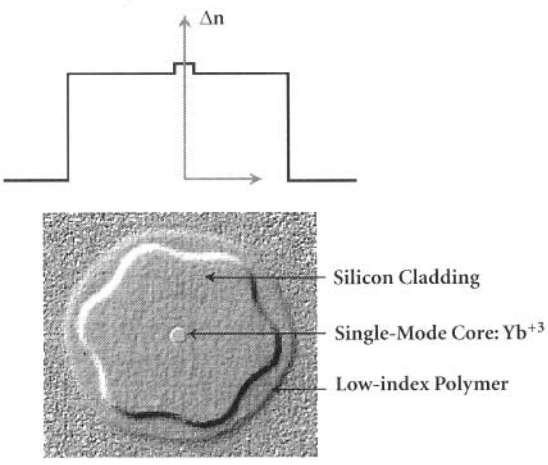

Figure 2. Cross-sectional view of a double-clad fiber with a Yb-doped single-mode core (about 7-μm-diameter),

levels limited only by the available pump power. Yb-doped lasers may be pumped from 900–975 nm using InGaAs diodes. Given the broad Stark splitting in Yb, quasi-four-level operation allows lasing from 1060–1120 nm, though this range can be extended with effort. Slope efficiency approaches 70% and, again, output power is limited only by the pump. In practice, coupling losses reduce the total efficiency to about 40% of the diode facet power.

Applications in telecom

High-power amplifiers are of great interest as communications networks expand in capacity and distance. The explosion of Internet traffic has fueled the development of WDM systems with an ever-increasing number of channels, each with around 1 mW of power. Moreover, as components such as dispersion compensators and gain equalizers are added to cope with system impairments, power budgets continue to increase. Double-clad fiber lasers are obviously compatible with fiber devices used for optical communication. However, an intermediate stage must be used to convert laser light (typically from 1060–1120 nm) to the wavelengths of interest for telecom, 1300–1600 nm. This can be accomplished using rare-earth doped or Raman devices and can be either a complication or a benefit, as discussed below.

Rare-earth doped systems

Conventional Er-doped optical amplifiers are limited by the amount of power coupled from highly reliable single-mode diodes with wavelengths in the pump bands of erbium, namely 980–1480 nm. An early effort to exploit diode-pumped solid-state (DPSS) lasers such as Nd:YLF at 1060 nm required removal of the constraint on wavelength. This was accomplished using energy transfer from Yb to Er through co-doping.[7] The high absorption cross-section of Yb allows pumping from 800–1100 nm with subsequent transfer of this energy to Er for signal amplification. A suitable glass host, such as p-doped Si, ensures efficient transfer. Slope efficiencies from pump to signal of 40% are typical.

Double-clad fiber lasers enable an almost 50-fold power to more than 10 W at 1550 nm. In addition to pumping a single-mode Er/Yb fiber amplifier with a discrete double-clad laser, an amplifier may be configured directly in a double-clad fiber with an Er/Yb doped core.[8] Though double-clad amplifiers have fewer components and higher efficiency, coupling of both the pump into the cladding and the signal into the core is a complication.

One-watt amplifiers are of immediate interest for broadcast analog transmission where the signal power per channel must be high enough (around 1 mW) to maintain adequate carrier-to-noise power across 80 channels. Meanwhile, the amplifier's cost must be kept very low to create a financially viable local loop network that penetrates to the home. High-output power allows massive power splitting so that the cost of an amplifier may be shared by many users.

Multiwatt amplifiers are of interest for laser-based satellite communication. As data capacity increases, microwave, the current mode of transmission, becomes prohibitively large and costly. A fiber-based alternative combines the benefit of high-speed electronics developed for terrestrial applications (greater than 10 Gb/s) with low weight and power consumption. In the proposed schemes, up and down links to the ground may be optical or microwave while optical signals are passed satellite-to-satellite in an orbiting constellation. For this application, immunity to ionizing radiation must be considered in addition to high efficiency.

Raman devices

Interaction of high optical intensity with vibrational modes of the glass results in stimulated Raman scattering. The light generated is downshifted in frequency by about 450 cm^{-1}, with a very broad spectrum caused by the random nature of the glass host. Although the nonlinear cross-section is small, low-loss fiber allows use of long interaction lengths, and amplification of a signal can exceed 40 dB over fiber distances less than 1 km. Lasers and amplifiers using this phenomenon have been explored since the mid-1980s, but suffered from the lack of practical pump sources. The advent of double-clad fiber lasers has altered this situation. Laser output at 1120 nm can be Stokes shifted over five orders to 1500 nm.[9]

The efficiency of wavelength conversion can be greatly increased by capturing the intermediate orders within a resonant cavity defined by Bragg gratings or fiber couplers. The configuration and output spectrum of such a cascaded Raman resonator (CRR) is shown in Figure 3. Through the careful design of the resonant structure, conversion efficiency to 1480 nm can exceed 50%, which is remarkable for a nonlinear device.[10] Given the broad gain spectrum, CRR output can range from 1200–1600 nm, with linewidths around 2 nm, controlled by the gratings.

An obvious use of high-power at 1480 nm is to pump conventional Er-doped fiber. With an appropriate fiber design, output powers can exceed several watts without rollover, due to excited state absorption. A more interesting application is to locate the Er-doped fiber remotely, say 100 km offshore in an unrepeatered submarine link.

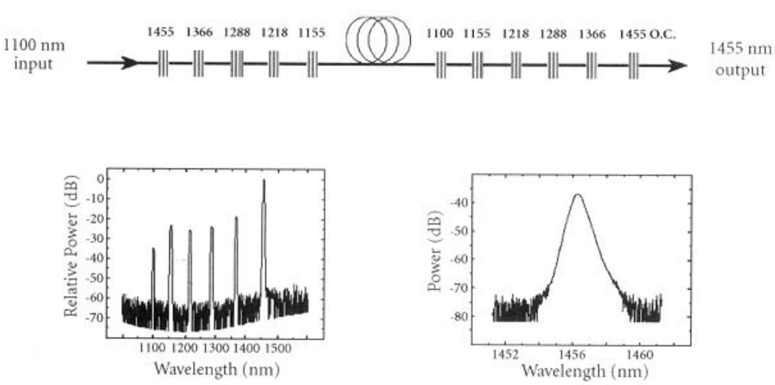

Figure 3. A cascaded Raman resonator composed of up to 1 km of optical fiber between nested sets of fiber Bragg gratings. Light generated by Raman scattering is confined by gratings and resonantly enhanced. The graphs show the residual light at intermediate Stokes frequencies (left) and laser emission (right).

cation over 529 km without amplification. The availability of high-power from 1200–1600 nm opens many possibilities for optical amplification, which is timely since the demand for capacity is doubling every two years or so. Demand is being met by increasing the bandwidth and transmission rate as high as fiber nonlinearities allow. To ease these limits, Raman gain can be developed within the transmission fiber itself by injecting fractions of a watt at 1450 nm to amplify signals at 1550 nm. In this configuration, lab demonstrations have indicated that Raman gain can quadruple system capacity.[11]

To open other spectral windows for optical amplification, Raman devices can be configured as discrete amplifiers. For example, by truncating the nested gratings shown in Figure 3 to 1240 nm, signals at 1310 nm—the next Stokes shift—can be amplified by more than 40 dB. Amplifiers using this principle have been demonstrated for both analog[12] and digital systems[13] and at wavelengths of 1310 nm and 1400 nm. Given the broad spectral response of Raman scattering and the flexibility of fiber gratings, the entire low-loss window of silica—from 1300–1620 nm—can be exploited using Raman devices. The combination of a double-clad fiber laser pumping a cascaded Raman resonator in either a discrete or distributed amplifier has tremendous potential for increasing transmission capacity.

Applications in industry and medicine

Double-clad fiber lasers have characteristics and capabilities that uniquely qualify them for several industrial and medical markets, including

- a very high diffraction-limited cw power
- high gain and high average power in amplifier configurations
- wavelength agility, reliability, efficiency, and economy.

Graphic arts

Double-clad fiber lasers represent an enabling technology for the new advanced thermal media that are becoming available in the graphic arts industry. Presently, most graphic arts houses (including publishers of magazines, newspapers, and books) produce their prepress images and printing plates using wet photographic techniques. Virtually all of the major graphics media suppliers, however, are now developing instant, thermally exposed, digital media for proofing and platesetting. The lack of chemical processing makes these "dry" media much more convenient for the user, as well as more environmentally benign. Widespread agreement exists in the graphics industry that the long-term trend is toward an all-digital workflow using this type of media.

In this process, images are formed on a dry substrate by scanning and modulating a laser across the substrate's surface, exposing individual pixels down to about 10 μm in size. In one approach, called laser-ablative transfer (LAT), pigments or sensitizing agents from a donor sheet are ablated by the laser and deposited on a receptor sheet or plate (see Fig. 4). Alternatively, the laser may modify the adhesive properties of imaging agents in a multilayered sandwich that is pulled apart after exposure, sepa-

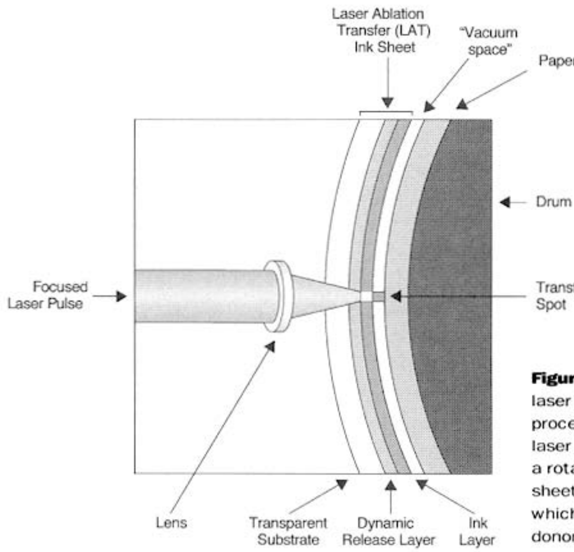

Figure 4. Schematic of the laser ablation transfer (LAT) process in which a fiber laser pulse is focused onto a rotating pigment donor sheet ablating the pigment, which is deposited on a donor plate or sheet.

For exposure, thermal processing requires a much higher threshold fluence than photographic techniques—typically on the order of 100 mJ/cm^2. Moreover, thermal conduction makes the threshold intensity dependent; exposures in excess of tens of nanoseconds become progressively less efficient. In order to expose a standard-sized image (44" × 32") in a few minutes, cw laser powers on the order of 10 W are required. The double-clad fiber laser is close to ideal for this application. The fiber laser's higher brightness allows the use of hardware similar to that used in most current reproductive systems (the "internal drum" architecture, in which only a scanning mirror moves). Because of the low brightness of laser diodes, diode-based machines require an alternative architecture, namely an external drum, in which the entire workpiece spins. There is considerable inertia to staying with internal-drum machines, thereby making fiber lasers the preferred choice.

Compared with competing high-brightness sources, such as diode-pumped crystalline solid-state lasers (*e.g.*, Nd:YAG and Nd:YVO), the fiber laser offers superior thermal stability and efficiency, as well as the potential for internally modulated output using a master-oscillator/power-amplifier (MOPA) architecture. Presently, fiber lasers are used in the proofing and platesetting machines made by most graphic arts hardware manufacturers. Several hundred high-power fiber lasers are in commercial operation in this market today.

Marking

Significant numbers of fiber lasers are also being used commercially in marking applications. In these applications, the laser's output is modulated then scanned across a surface. Fiber lasers have been especially effective in making small or micron-scale inscriptions on semiconductor chips and packages. They are also used for marking plastic and metal. The particular benefits of fiber lasers here are their beam quality and pointing accuracy.

Generation of pulses

promise in generating pulses at high average power levels. They may become an efficient, versatile alternative to some Q-switched or mode-locked crystalline lasers, and may also be a key to realizing commercially viable ultrafast systems.

Double-clad devices can have high average powers with moderate pulse energies. This is because the energy that can be stored in a gain medium before self-lasing begins is proportional to the gain cross-sectional area rather than the volume. A typical Yb-doped fiber, with a core area of 5×10^{-7} cm^2, can only store up to about 100 μJ. While the use of fibers with larger gain regions has raised the attainable pulse energy somewhat, it is clear that single-mode fiber devices will be limited to pulse energies below approximately 1 mJ. On the other hand, attainable average powers are still in the 10–100 W range, so repetition rates are typically on the order of MHz.

This new regime of moderate energies and high repetition rates is currently adequate for some pulsed applications. Double-clad devices are a particularly good match with ultrafast lasers, using the technique of chirped-pulse amplification to amplify nanojoule, femtosecond pulses by 30 dB or more. Ultrafast lasers are superior in materials-processing applications because they ablate material rather than melt it. Efficient and inexpensive double-clad amplifiers may finally make ultrafast systems competitive.

Generation of desired wavelengths in the IR and the visible

The broad gain bandwidth of rare-earth doped glasses, coupled with the high gain of fiber devices, makes double-clad devices well suited for tunable operation and generation of specific wavelengths. Fiber Bragg gratings can enforce laser operation at desired wavelengths for use in pumping other laser mediums such as Pr:fluoride fibers (lasing at 1.3 μm), Tm:fluoride fibers (480 nm), and Tm- and Ho-doped materials (2 μm).

Nonlinear frequency conversion can greatly extend the wavelength coverage. As mentioned above, Raman shifting can efficiently convert Yb-fiber laser output to longer wavelengths. Additionally, direct frequency doubling of Yb-fiber lasers has yielded several hundred milliwatts at yellow and green wavelengths, while narrow-line tunable radiation at 585 nm has been demonstrated by mixing the output of a 1060-nm double-clad fiber amplifier with the output of a 1.3 μm Nd crystal laser in a periodically poled nonlinear crystal. Both pumps were about 5W.

Medical applications

Double-clad fiber devices are well suited to medical applications because they are compact, relatively inexpensive, and free of gases, dyes, solvents, and special utility needs. Researchers have used an inexpensive, low-power fiber laser for confocal microscopy; even at only 1–2 W, such a laser has enough headroom in power that low-power imaging and higher-power therapeutic functions might be integrated in one device. Small fiber devices may also prove useful for optical coherence tomography. Multiwatt, narrow-line 1083-nm Yb^{3+} medical imaging of low-density tissue such as lungs.[14] High-power 2-μm fiber sources may prove useful in microsurgical applications. Finally, medical spectroscopic applications in areas such as dermatology, diagnostic imaging, and cancer therapy should benefit from doubled fiber lasers serving as a replacement for 1–10 W dye lasers in the visible range. There are doubtlessly a host of medical diagnostic and therapeutic applications for fiber lasers that remain to be explored.

The future

Although the technique of cladding pumping is not new, commercial lasers and amplifiers are now available. Fiber lasers offer advantages over diode lasers for applications in which spot size and beam quality are important. For telecom applications, interest is mounting rapidly as optical networks require greater power to handle greater capacity. A significant hurdle for telecommunications devices has been the requirement of high reliability. As long-term testing is completed, these devices will begin to be deployed and will become a significant component of the next generation of optical networks. Applications of fiber lasers in graphic arts are well established, and work is proceeding rapidly on the development of fiber lasers as alternatives to existing lasers and as enablers for new applications.

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