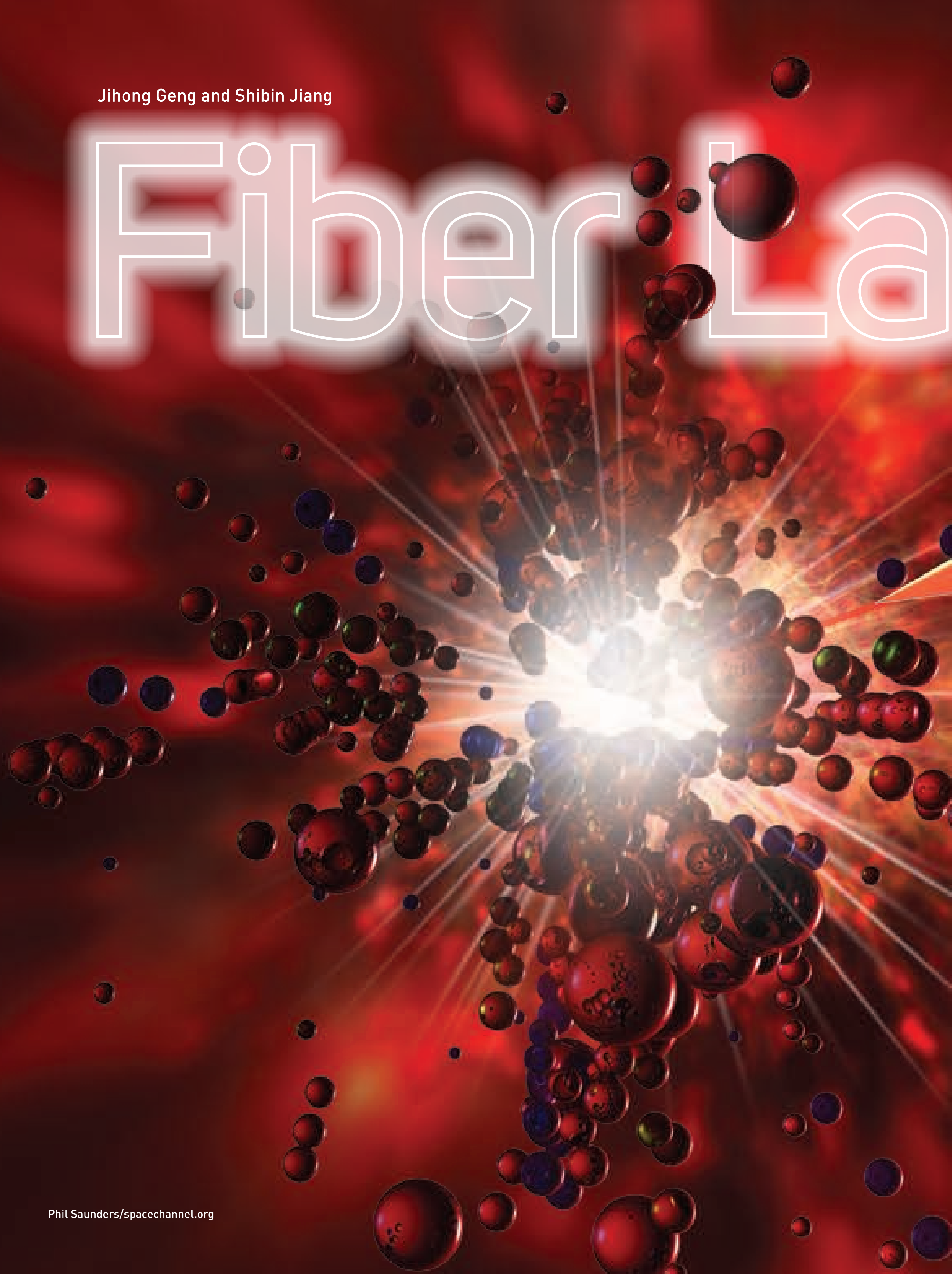
Jihong Geng and Shibin Jiang

Fiber La



Phil Saunders/spacechannel.org

The 2 µm Market Heats Up

Rapid gains in fiber laser technology, particularly in a key infrared wavelength band, are allowing these lasers to expand into a range of application areas.

In recent years, remarkable advances in fiber laser technology have rapidly changed the game for these lasers in the marketplace. The advantages of fiber lasers—compactness, high average power, high beam quality, high efficiency and low cost of ownership for maintenance and operation—have allowed them to make inroads against conventional solid-state lasers (and, increasingly, CO_2 lasers) in many areas. Fiber lasers are finding wide use in applications ranging from materials processing and medicine to free-space optical communications, fiber optic sensing, precise frequency metrology, 3-D lidar and high-energy laser weapons. And the trend seems likely to continue in the foreseeable future.

One factor driving these expanding applications, beyond superior performance, is the continual extension of fiber lasers to new wavelength bands. Development of new glass hosts and use of a variety of rare-earth dopants in the gain fibers of these lasers are pushing fiber laser operation into different wavelength regions; moreover, nonlinear frequency conversion techniques can offer still more options for operating wavelength.

A wavelength of considerable current interest is the 2 µm area. Particularly because of their absorption characteristics in liquid water and other important substances, fiber lasers at these “retina safe” wavelengths have potential applications ranging from ground- and space-based lidar measurement of atmospheric patterns, to biomedicine, to pump sources for lasers in the mid-infrared. And 2 µm fiber lasers fill a spectral gap between the visible/near-infrared region, for which many laser systems are well-developed and commercialized, and the mid-infrared region, which has seen dramatic advances in quantum cascade laser (QCL) technology.

This unique spectral position could make 2 µm fiber lasers an essential part of many industrial and scientific applications. This article briefly reviews some of the operating principles of fiber lasers, and then overviews some interesting application areas for continuous-wave (CW) and pulsed fiber lasers in the 2 µm range.

Fiber laser basics

In fiber lasers, a length of optical fiber, doped with one of several rare-earth ions, serves as the laser gain medium. Commonly, this active fiber core sits at the center of a double-clad fiber architecture, consisting of an outer glass or polymer coating; an inner cladding or pump core, which acts as a waveguide for pump light; and the active doped core, which carries the signal light and which absorbs pump light carried in the inner cladding to amplify the laser signal. This fiber geometry allows the lasers to be easily coupled to high-power, commercially available multimode diode lasers (with relatively low beam quality) as pump sources. Indeed, it was the development of cladding-pumped lasers using double-clad fiber, first demonstrated in 1988, that has led to the vast increase in fiber laser power demonstrated over the past several decades.

Commercial fiber lasers commonly use fiber Bragg gratings (FBGs) as resonators, which avoids the use of free-space mirrors and eliminates the need for realignment during the fiber laser’s lifetime. The result is a simple, compact and robust setup.

Fiber lasers can operate in CW or pulsed modes. Pulsing can be accomplished by passive or active mode-locking or Q-switching (using, for example, saturable absorbers such as SESAMs), or gain switching, in which the pump source itself is pulsed. In the 2 µm wavelength area, mode-locked Tm/Ho-based fiber lasers have achieved pulse widths approaching 100 fs, and Q-switched fiber lasers have achieved pulse widths in the tens of nanoseconds.

Considerable research has focused on developing glass host materials for fiber lasers.

A note on “eye safety”

While wavelengths longer than 1.3 to 1.4 µm are sometimes colloquially referred to as “eye-safe” wavelengths—because the eye’s cornea and lens tend to absorb light at those wavelengths, thereby protecting the sensitive retina from them—it does not follow that lasers at these wavelengths are necessarily “eye-safe lasers.” At the power levels of mid-infrared fiber lasers in particular, substantial eye damage is still possible from these lasers, and all relevant safety precautions apply.

In recent years, remarkable advances in fiber laser technology have rapidly changed the game for these lasers in the marketplace.

1047-6938/14/07-08/34/8-$15.00 ©OSA

For wavelengths below 2.2 µm, silica glasses have proved most successful, owing to their good mechanical and thermal properties for this use and their relatively low nonlinearities. Much of the development of silica glass fibers for fiber lasers has focused on chemical additives and fabrication techniques to increase the solubility of rare-earth ions in the glass host. For wavelengths longer than 2.2 µm, development has focused on fluoride glasses of various compositions (e.g., ZBLAN glass, a mixture of zirconium, barium, lanthanum, aluminum and sodium fluorides).

Rare-earth dopants: getting to 2 µm

The rare-earth elements used to dope the active fiber core, and the energy-level transitions of those rare-earth cations, determine the wavelength of fiber laser operation. While numerous elements have been investigated in the quest for new wavelengths, three have emerged as the most common dopants in fiber lasers at present:

Yb^{3+}. Ytterbium doping offers the highest output power among fiber-based lasers. Commercial Yb laser units can deliver more than 100 kW of CW power at 1 µm from a single optical fiber port. However, the 1 µm wavelength of these lasers is shorter than the region of interest for retina safety (> 1.3 µm), which limits the use of these lasers in many applications.

Er^{3+}. Erbium-doped fiber lasers, owing to the fluorescence transitions of the Er^{3+} cation, can provide output at both 1.55 µm and 2.9 µm. These wavelengths are in the region of interest for retina safety. Compared with Yb-doped fiber lasers near 1 µm, however, power levels for Er-doped

A QUICK GUIDE TO

DOPED FIBER OPTIC LASERS

CREATING THE DOPED ACTIVE CORE

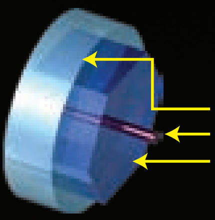
A tube of purified silica glass is rotated gently and maintained at a constant temperature. During this process rare-earth-ion doped silica glass is deposited inside the glass tube.

When this is completed, the doped fiber core and surrounding undoped cladding glass is placed at the top of a five-story drawing tower. Here it is gently heated to melting temperature.

The melting glass falls slowly through a channel in the tower, cooling as it does so. This fiber includes a tiny core, rare-earth doped for laser gain.

DOUBLE-CLAD FIBER STRUCTURE

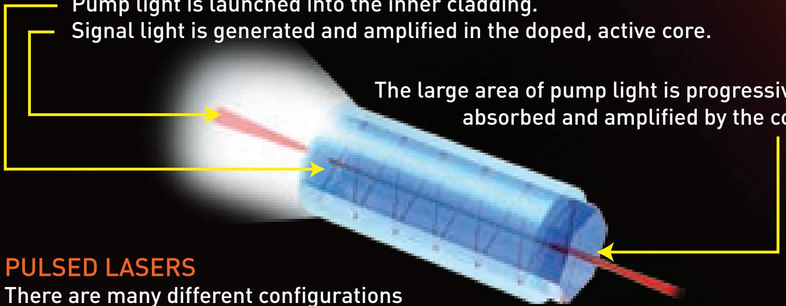
There are three principal components to the structure:



A low-index polymer or glass outer cladding.
An active core doped with rare-earth ions, where lasing occurs.
An inner pump core that acts as a multimode waveguide for pump light.

THE BASIC PRINCIPLES

Pump light is launched into the inner cladding.
Signal light is generated and amplified in the doped, active core.



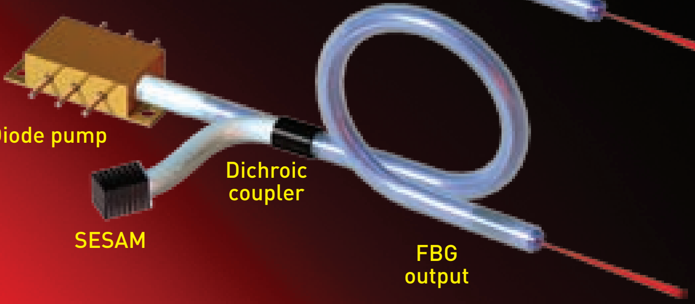
The large area of pump light is progressively absorbed and amplified by the core.

PULSED LASERS

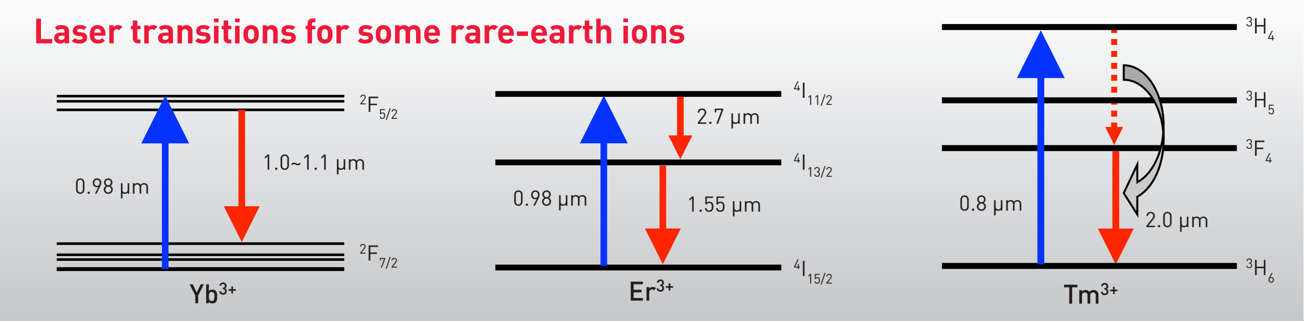
There are many different configurations and these are two examples:

Gain-switched fiber laser

Q-switched fiber laser



Phil Saunders/spacechannel.org


Laser transitions for some rare-earth ions

fiber lasers at 1.55 μm are still quite limited; the highest laser power at 1.55 μm has been ~300 W. One reason lies in the relatively low quantum efficiency from the pump wavelength, at 0.98 μm, to signal wavelength, at 1.55 μm, when a high-power Er-doped fiber system is pumped using the best-developed, high-power InGaAs diodes.

Tm^{3+}/Ho^{3+}. Thulium- and holmium-doped fiber lasers operate in 2 μm wavelength area. In particular, Tm-doped fiber lasers at 2 μm offer the highest output power to date in the wavelength region of interest for retina safety. That strong output power rests on the very high quantum efficiency of Tm-doped laser systems, and also on the mature technology of high-power GaAlAs diodes at 0.8 μm. In particular, Tm-doped fiber lasers can benefit from the phenomenon of cross-relaxation: because the energy of the pump light is more than twice that of the laser transition, a single pump photon, at 0.8 μm, can lead to the excitation of two ions and generate two signal photons at 2 μm. With a sufficiently high doping concentration of Tm^{3+} ions (greater than 2 weight percent) in the gain medium, Tm-doped fiber lasers have shown quantum efficiency exceeding 100 percent in some experiments.

The highest CW output power from a single Tm-doped fiber laser demonstrated thus far is about 1 kW, the second-highest power among fiber lasers. Highly coherent 2 μm fiber lasers have also reached more than 600 W power with a single-frequency diffraction-limited output beam, which can allow further power scaling up to multiple kilowatts using advanced beam combining technology.

In addition to operation in the retina-safe wavelength region, lasers near 2 μm exhibit strong absorption attenuation in liquid water, animal fat issue, polymer materials and some atmospheric greenhouse gas species. This is opening up a range of applications for these lasers, including clinical medicine (such as laser surgery, laser lithotripsy, laser angioplasty and ophthalmic procedures), materials processing, atmospheric measurements and lidar, and longer-wavelength laser pumping. The rest of this article reviews some of those applications.

Some surgical applications

High absorption in liquid water and biological tissues makes lasers in the 2 μm region of particular interest for laser surgery. Tm:YAG lasers ($\lambda = 2.01$ μm) and Ho:YAG lasers ($\lambda = 2.12$ μm) have featured in clinical laser surgery for years. But high-power, Tm-doped 2 μm fiber lasers—compact, rugged, energy efficient, and with the beam already generated from fiber, thereby allowing for flexible beam delivery—are emerging as a strong alternative. Pulsed 2 μm lasers, including modulated CW lasers, gain-switched lasers and Q-switched lasers, may be even better for laser surgery because they allow for better temporal control of how heat and energy are delivered to the surgical location and, thus, more precise cutting to minimize excessive heat damage to peripheral tissue.

Particular success has been seen in use of 2 μm lasers for treatment of stones, or calculi, that form in the urinary tract. More than 10 percent of the U.S. population, particularly in the southeastern and central southern United States, may experience this painful condition at

Lasers near 2 μm exhibit strong absorption attenuation in liquid water, animal fat issue, polymer materials and some atmosphere greenhouse gas species.

some point in their lifetimes. Treatment for this disease goes under the general name of lithotripsy, and involves the fragmentation of the stone into pieces small enough to be passed out of the urinary tract. Lithotripsy is done using a range of techniques, including fragmentation of the stone using externally applied sound waves as well as endoscopic techniques using electrohydraulic, electromagnetic and piezoelectric lithotripters.

A laser lithotripter, however, offers a more precise fragmentation technology, in which a laser beam comes into direct contact with the urinary stones for fragmentation. A laser beam is directed at urinary stones, preferably by fiber delivery, and the high absorption of the stones and surrounding water at 2 µm increases the temperature of the irradiated volume. Following the laser irradiation, high-energy laser pulses can directly ablate the urinary stones, causing the ejection of fragmented breakdown products. In addition, absorption of laser energy by water around stone can induce vapor bubble formation and collapse with shock wave generation. Shock waves generated by the laser pulses also help the process of stone fragmentation.

Currently, a flash-lamp-pumped Ho:YAG laser is the most efficient and versatile tool for laser lithotripsy. High-power, pulsed 2-µm fiber lasers, however, have been replacing Ho:YAG lasers for this application, once again due to their compactness, ruggedness, flexible beam delivery and energy efficiency.

Materials processing

Many industrial sectors have used lasers to process plastic materials for decades—using many types of lasers, including CO_2 lasers for cutting, diode lasers for welding, and solid-state and fiber lasers for marking. For clear plastic materials, however—which commonly are transparent from near UV to near infrared—applications such as laser welding, marking and drilling sometimes require the addition of an extra absorbent material to the plastic to allow for laser processing. Most visible or near-infrared lasers are not efficient in all these processing applications for transparent plastics materials without the help of absorbent. On the other hand, CO_2 lasers cannot penetrate plastics materials for laser welding, due to strong absorption at the surface of plastics. Although CO_2 lasers have been efficiently used in laser cutting, marking and drilling applications, they remove plastic materials through intense local heating, resulting in carbonization and residue around the local heat zone.

AdValue Photonics Inc.

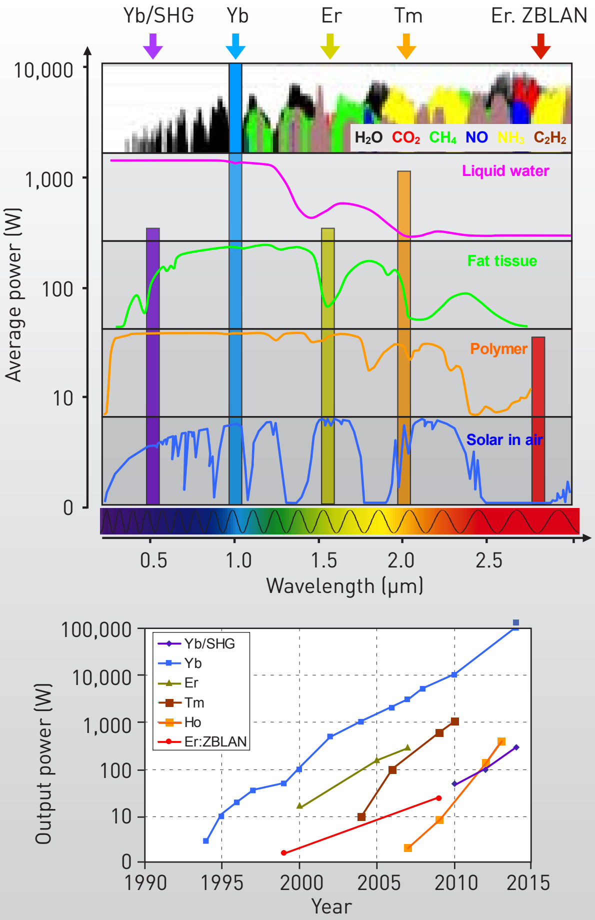
Laser marking on transparent plastic materials with a Q-switched 2 µm fiber laser.

In contrast to visible/near-infrared and CO_2 lasers, a 2 µm laser experiences moderate absorption by plastic materials. This could make Tm- and Ho-doped fiber lasers ideal for plastic material processing. High-average-power CW 2 µm fiber lasers are an ideal tool for laser welding of transparent plastics, without the requirement of any added absorbent material, an essential requirement for fabricating medical devices. Pulsed 2 µm fiber lasers—particularly high-peak-power Q-switched, Tm-doped fiber lasers—can remove materials with much less carbonization or color change, because of the lasers' high peak power and short pulse duration compared with the thermal diffusion rate of most plastic materials. This could make them a natural choice for plastic engraving and marking applications.

Lidar mapping of greenhouse gases

A large number of strong molecular transitions, including fundamental vibrational bands and their overtones, fall in the mid-infrared spectral region from 2 to 20 µm. Even the small portion of the spectral region from 1.5 µm to 3 µm shown in the figure on p. 40 includes numerous molecular absorption bands that can be used as spectroscopic "fingerprints" in remote sensing of chemical species.

One of the most important greenhouse gas species in the atmosphere is CO_2, the concentration of which has been rapidly increasing in the recent decades owing to human industrial activity and has raised concern about global climate change. A better understanding of the role of CO_2 in the global carbon cycle requires tools for monitoring the global spatial distributions of atmospheric CO_2 in the long term. NASA scientists have proposed doing this tracking using lidar operating on an airplane,



Laser power output

(Top) Average output power and relevant absorption bands in selected media, for fiber lasers at different wavelengths based on selected rare-earth dopants. (Bottom) Power scaling of several fiber-based lasers at different wavelengths, showing the exponential growth in output power over the past two decades.

J. Geng and S. Jiang

a satellite, or both, which in turn requires a high-energy coherent pulsed laser source.

One of the lidar approaches would use joule-level-energy single-frequency pulses at a wavelength near 2.05 μm, which matches a specific absorption line of atmospheric CO_2. Such high-energy laser pulses have been demonstrated in conventional crystal-based (Ho:Tm:YLF and Ho:YLF) laser systems. However, the optical system design of these conventional solid-state lasers commonly includes many free-space optical components, which in turn raises concerns about their bulkiness and their long-term reliability for these lidar missions. Such a system, in a fiber-based format, would eliminate these disadvantages and thus be very attractive, particularly for airborne and spaceborne platforms for which weight and bulkiness are such a significant consideration. One immediate opportunity for fiber laser technology here is to replace the crystal-based seed laser in the existing system with a single-frequency fiber laser at 2.05 μm, taking advantage of the fiber laser's high reliability, compactness and robustness.

2 μm fiber lasers as pump sources

Since the first Ti:sapphire-based frequency combs were demonstrated more than a decade ago (and attracted the Noble Prize in Physics for 2005), this revolutionary advance has attracted enormous interest in both scientific and industrial communities. Optical frequency combs have quickly emerged as an enabling tool for applications ranging from the calibration of astronomical spectrographs to frequency/timing standards to high-precision molecular spectroscopy.

For molecular spectroscopy in particular, the substantial number of strong vibrational transitions for molecules of interest that fall in the mid-infrared (2 to 20 μm) spectral region creates a significant need for frequency combs in that band. The emerging QCL technology offers direct laser access to the mid-infrared spectral region, but mode-locking—the common method for comb generation—poses challenges for these lasers. QCLs are intrinsically difficult to passively mode-lock, and although active mode-locking has been demonstrated for QCLs, it offers only a very limited bandwidth for mid-infrared combs.

A more routine way to generate frequency combs in the mid-infrared is nonlinear frequency down-conversion using frequency combs in the near-infrared, which are more readily available. Currently, the best-developed frequency combs are based on near-infrared solid-state lasers, such as femtosecond Ti:sapphire lasers, or near-infrared fiber lasers, such as femtosecond Er-doped or Yb-doped fiber lasers. Many efforts have been made

Mode-locked 2 μm fiber lasers may provide a better option as a pump source for nonlinear frequency down-conversion further into the mid-infrared.

under this approach to extend the spectral coverage of frequency combs from near-infrared to longer-wavelength mid-infrared combs, using nonlinear methods including difference frequency generation (DFG), optical parametric oscillator (OPO) and supercontinuum generation.

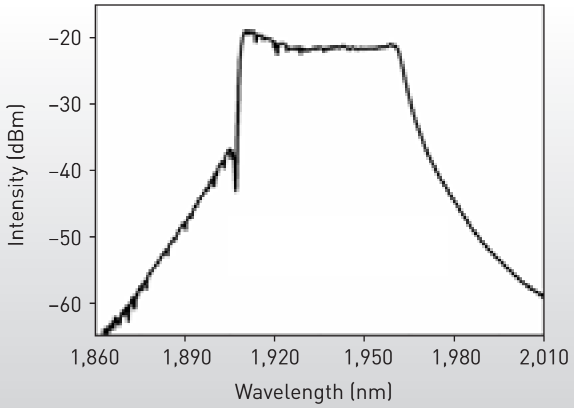
Tm/Ho-doped fiber lasers in particular have strong characteristics for helping to address this need. Tm^{3+} and Ho^{3+} ions doped in glass/fiber media exhibit wide gain bandwidths covering from 1.7 µm to 2.1 µm. The wide gain bandwidth means that Tm- and Ho-doped fiber lasers can deliver femtosecond frequency combs when operated in a mode-locking regime. Mode-locked 2 µm fiber lasers, in turn, may provide a better option as a pump source for nonlinear frequency down-conversion further into the mid-infrared—both because of low theoretical quantum defect, and for some specific reasons tied to specific nonlinear techniques.

For example, 2 µm lasers are more favorable pump sources than short-wavelength lasers such as at 1 µm and 1.55 µm for nonlinear frequency down-conversion using OPO and DFG. That's because some nonlinear optical crystals used for mid-infrared comb generation under these techniques are not transparent, or have a high propagation loss, at the shorter wavelengths, but behave fine at 2 µm. In addition, for some nonlinear optical crystals with large amounts of dispersion, phase-matching cannot be obtained for these nonlinear frequency conversion processes when the pump wavelength is too short (e.g., 1 µm).

Lasers at 2 µm are also favorable pump sources for mid-infrared supercontinuum generation. To obtain efficient mid-infrared supercontinuum generation, the nonlinear media must first have a low propagation loss at both pump wavelength and supercontinuum wavelength. Some nonlinear media (including nonlinear crystals and glass fibers) for mid-infrared generation are not transparent at short wavelengths, such as 1 µm. Another requirement is that the pump laser wavelength be close to or longer than the zero-dispersion wavelengths of nonlinear media, which gives preference to a longer pump wavelength for efficient spectral broadening in the mid-infrared region.

The outlook

As the discussion above suggests, the 2 µm wavelength area is a key one for a wide variety of interesting applications—many of them ideally suited to the characteristics of fiber lasers. Over the last decade, fiber laser technologies have gained tremendous progress. With their demonstrated, remarkable average power scalability and their increasing acceptance in the industrial market, high-power 1 µm fiber lasers have attracted the most attention. A similar roadmap can be envisioned for 2 µm fiber lasers, if some of current technical challenges can be overcome. One such obstacle seems to lie in the GaAlAs pump diode commonly used for 2 µm fiber lasers, which is not as efficient or reliable as the InGaAs diodes used to pump Yb-doped fiber lasers at 1 µm. As technical progress continues in these and other areas, however, 2 µm fiber lasers should continue to emerge as a strong alternative in a variety of markets, helping to fill the spectral gap between the visible/near-infrared region and the mid-infrared region. OPN



Frequency comb at 2 µm

Frequency comb at 2 µm from a mode-locked Tm-doped fiber laser.

J. Geng and S. Jiang

Jihong Geng (jgeng@advaluephotonics.com) and Shibin Jiang (sjiang@advaluephotonics.com) are with AdValue Photonics Inc., Tucson, Ariz., U.S.A.

References and Resources

- N.M. Fried. Lasers Surg. Med. **37**, 53 (2005).
- J. Yu et al. Opt. Lett. **31**, 462 (2006).
- Y. Jeong et al. IEEE J. Sel. Top. Quantum Electron. **13**, 573 (2007).
- G.D. Goodno et al. Opt. Lett. **34**, 1204 (2009).
- Y. Jeong et al. J. Opt. Soc. Korea **13**, 416 (2009).
- P.F. Moulton et al. IEEE J. Sel. Top. Quantum Electron. **15**, 85 (2009).
- D.J. Richardson et al. J. Opt. Soc. Am. B **27**, B63 (2010).
- B.J. Eggleton et al. Nat. Photonics **5**, 141 (2011).
- S.D. Jackson. Nat. Photonics **6**, 423 (2012).
- A. Schliesser et al. Nat. Photonics **6**, 440 (2012).
- C. Jauregui et al. Nat. Photonics **7**, 861 (2013).