New High-Power Fiber Laser Enables Cutting-Edge Research

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According to many in the laser industry, fiber lasers are a serious alternative to solid-state and carbon dioxide lasers for industrial material-processing applications. The recent commercial availability of high-power fiber lasers presented a timely opportunity for Gas Technology Institute to enhance ongoing research of laser applications for well construction and completion.

From 1997 to 1999, Gas Technology Institute (GTI – then operating as Gas Research Institute) assembled an exploratory research team to investigate fundamental research issues on a laser drilling applications concept. The GTI team, including the Colorado School of Mines and the U.S. Department of Energy (DOE), tested three military laser systems on more than 200 samples, including shale, limestone and sandstone. Lasers fired in the initial investigation included the U.S. Army mid-infrared advanced chemical laser, the U.S. Air Force chemical oxygen iodine laser and the laser hardening material experimental laboratory carbon dioxide laser (see *Lasers May Revolutionize Drilling and Completions in the 21st Century,* ***GasTIPS***, Winter 1998/1999, Vol. 5, No. 1, p. 11-15). The conventional wisdom regarding laser applications held by the industry at that time excluded their practical use for well construction and completion. This skepticism, however, was based on the technical limitations of rudimentary lasers from the 1960s and 1970s. Since that time, significant advances have evolved in laser power generation, efficiencies and transmission capabilities. Imagine forecasting the success of research activities based solely on state-of-the-art computer technology from 40 years ago.

GTI's initial study showed that current laser technology is more than sufficient to break, melt or vaporize any lithology encountered in the subsurface, and that the amount of energy required for spalling (melting or vaporizing) rock was significantly overestimated by previous industry sources. In addition, it was found that the energy required to remove and change the rock varies as much within lithologies as between them. Researchers did not quantify minimum power required to remove rock or factors that control power requirements.

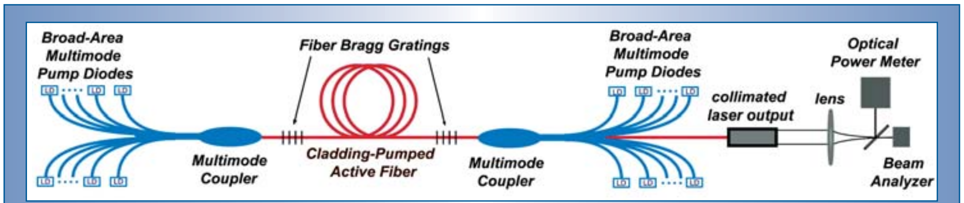

Figure 1. *In a fiber laser, a doped silica "active" fiber is excited by a diode source. Two Bragg gratings written into the fiber act like the mirrors of a normal laser cavity to generate the laser emission.*

Other observations from these experiments related to cutting ease and speed, as well as altering rock properties. It was observed that calculated penetration rates for all the rock samples, except salt, were faster than rates observed by most conventional rock-removing mechanisms. Although not performed under *in-situ* conditions, the cutting of hard rocks with close grain-to-grain contact was more easily accomplished than more porous rocks.

In addition, the thermal energy from the laser beam introduced some fundamental changes in rock properties. For example, the porosity of the rock surrounding the lased hole in a Berea sandstone sample actually increased. Also, the experiments indicated that at such high powers, there were harmful secondary effects that increased as hole depth increased. These effects included the melting and remelting of broken material, exsolving gas in the lased hole, and induced fractures, all of which reduced the energy's efficiency in rock removal and therefore the rate of mass removal.

It became clear from these experiments that through controlling the laser input parameters, rock removal and rock property alterations for various rock descriptions could be controlled. By doing so, the amount of material melted during the laser exposure could be determined, as could the minimum laser power necessary to drill rocks for oil and gas applications. From the results seen, the most powerful lasers available are able to quickly vaporize rock. However, an economic case for doing so would likely prove difficult to support.

Industrial lasers quantify results

If megawatt-sized lasers were technically capable but too costly to implement, would kilowatt-sized industrial lasers have enough punch to economically perform the same task? To find out, GTI shifted its investigation to include two lasers at the Laser Applications Laboratory at DOE's Argonne National Laboratory (ANL). These pulsed lasers were used to explore the basic scientific principles of interaction between laser and rock to determine the conditions required for an industry-supported drilling and completions concept.

For this investigation, researchers at GTI, the DOE's National Energy Technology Laboratory,

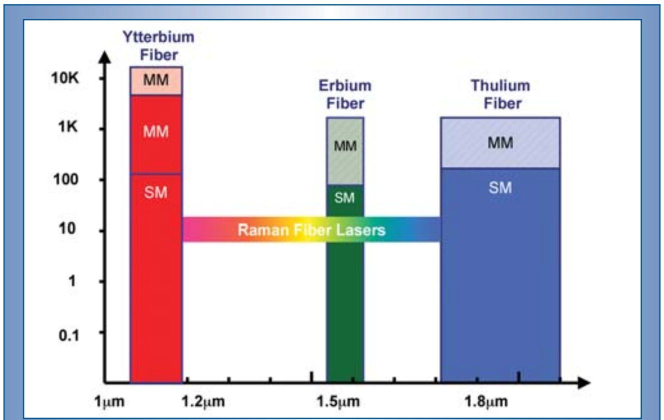

Figure 2. *This figure shows fiber laser spectral ranges. The solid areas represent output levels and shaded areas represent planned output levels. Power (in Watts) is plotted on the y-axis, and wavelength is plotted on the x-axis. SM = single mode; MM = multimode.*

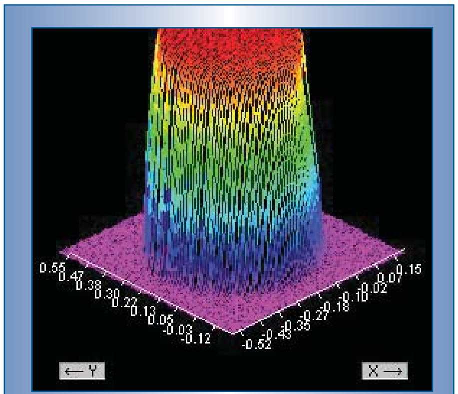

Figure 3. *This figure shows a 3-D beam profile of a fiber laser emission.*

Petroleos de Venezuela-Intevep SA, Halliburton Energy Services, the Colorado School of Mines and ANL explored some key issues:

- how much energy is needed to remove a unit volume of rock;
- does pulsing the laser increase the rate of penetration; and
- can a laser beam operate in the presence of drilling fluids, or will too much laser energy be wasted vaporizing mud rather than penetrating rock.

Although some of the work was conducted with ANL's 6-kW carbon dioxide laser, most was performed with the 1.6-kW neodymium yttrium aluminum garnet (Nd:YAG) high-power pulsed laser operating at 1.06 microns. During this phase of study, tests were carried out to measure the amount of energy required to remove material under various laser conditions. The focus was on trying to minimize the secondary effects that absorb much of the laser's power and establish an intrinsic specific energy value for each sample. Specific energy is the amount of energy needed (in kiloJoules) to remove a unit volume (1 cu cm) of rock.

To this end, laser parameters, such as duration and power, were controlled such that the lased holes' diameters were larger than the depths. This, in combination with a gas purging system designed to quickly remove exsolved gases and spalled particles, provided what the team judged to be a reasonably good measure of the specific energy for each sample.

Studies of the effects of various Nd:YAG laser parameters on the samples of shale, limestone and sandstone revealed that:

- measured specific energy increases quickly with beam exposure time, indicating the effects of energy-consuming secondary processes;
- shale samples recorded the lowest specific energy values as compared with limestone and sandstone samples;
- as laser pulse repetition rate and pulse width increase, the specific energy decreases; however, pulse width is a more dominant mechanism for reducing the specific energy than is the pulse repetition rate;
- each rock type has a set of optimal laser parameters to minimize specific energy;
- rates of heat diffusion in rocks are easily and quickly overrun by absorbed energy transfer rates from the laser beam to the rock. As absorbed energy outpaces heat diffusion, temperatures rise to the minerals' melting points and quickly increase specific energy values;
- sandstones saturated with water cut faster. More power can be applied before melting commences; and
- a laser is able to spall and melt rock through water.

(See *Laser Drilling: Understanding Laser/Rock Interaction Fundamentals*, ***GasTIPS***, Spring 2002, Vol. 8, No. 2, p. 4-8.)

The cutting edge: high-power fiber lasers

Since the time GTI and its partners explored laser application issues at ANL, significant developments were made in creating and commercializing high-power fiber lasers. The principle for the laser is similar to an amplification unit used in fiber-optics systems. The design brings with it many advantages that result in high reliability and long life. IPG Photonics (IPG), a leading global designer and manufacturer of high-performance fiber lasers and amplifiers in Oxford, Mass., had been turning up the power and made an early entrance to the market.

In a fiber laser, a doped silica "active" fiber is excited by a diode source (Figure 1). Two Bragg gratings written into the fiber generate the laser emission, resulting in an efficient, compact laser source with excellent beam quality. IPG found a way to "bundle" its ytterbium-doped fiber lasers together efficiently. It also produced systems that emit up to 6 kW of continuous-wave power at 1.08 microns through the integration of standard sub-assemblies. The number of sub-assemblies used determines the maximum power from the system. At the heart of IPG's technology are proprietary active fibers and a patented pumping technique allowing the utilization of broad-area multimode diodes rather than diode bars. This leads to a projected diode lifetime of more than 100,000 hours of operation. The diode pump energy is delivered to the active medium through multimode fibers spliced to the multiclad coil. The laser cavity is created directly in the active fiber. The laser emission leaves the fiber laser through a passive single-mode fiber, typically with a core diameter of 6 microns.

Figure 4. *Researchers prepare to shoot a laser beam at the small cylindrical rock sample (lower left) in the Gas Technology Institute's new laser laboratory for exploration and production applications. The IPG Photonic 5-kW ytterbium fiber laser is in the vertical cabinet in the center background. (Photo courtesy of GTI)*

The resulting laser beam is essentially diffraction-limited and, when outfitted with an integral collimator, produces a beam that is extremely parallel. For example, a 100-W single-mode fiber laser has a full angle divergence of 0.13 milliradians at half-angle when collimated to about 0.2-in. diameter.

The maximum power from an industrial single-mode IPG fiber laser module is 200 W – higher powers are produced using multiple modules. The emissions from lasers are collected using a proprietary beam combiner, resulting in a single high-quality beam. For example, a 1-kW unit would be made up of 10 individual fiber lasers integrated into a common cabinet. Although the beam is no longer single-mode, the resulting M2 value of 7-10 is better than high-power solid-state lasers (M2 is a measure of beam quality; M2=1 for a pure Gaussian beam). The beam from a 6-kW fiber laser can be delivered using a 200-micron to 300-micron fiber. Different output beam profiles, including a near-perfect rectangular shape, can be produced.

The ytterbium fiber laser has a wall-plug efficiency of 16% to 20%. Erbium and thulium fiber lasers demonstrate lower wall-plug efficiency but are more efficient than typical YAG lasers (Figure 2). There are certain applications where these wavelengths are the best choice. Erbium lasers are being developed because of demand for a laser with the performance of Nd:YAG and eye safety better than carbon dioxide (CO_2) types.

Single-mode continuous-wave systems can be modulated to 50,000 Hz with pulse durations as short as 10 microsec. Three super-pulsed versions with pulse durations as short as 1 nsec or pulse energies up to 1 milliJoule in a 100-nanosecond (nsec) pulse and multimode continuous-wave versions from 300 W to 6 kW are available.

Fiber laser technology offers several benefits from other industrial lasers. The footprint of a 4-kW fiber laser unit is 5.4 sq ft vs. 118 sq ft for a conventional lamp-pumped Nd:YAG, and there is no requirement for a chiller. They are essentially maintenance-free during their lifetime because there is no need to replace flashlamps or diodes. The high electrical efficiency reduces operating costs. Better beam quality (Figure 3) allows the user to produce spot diameters substantially smaller than conventional lasers, producing high fluence and/or longer working distances (1 kW can be focused to 50 microns with a 4-in. lens).

The cost for fiber laser technology, up to 1 kW output power, is below or comparable to that of lamp-pumped YAG lasers. The acquisition cost of a fiber laser greater than 1 kW is higher. However, when all factors – floor space, chillers, maintenance – are accounted for, these lasers should be more cost-effective than equivalent power rod-type Nd:YAG lasers.

The fiber laser system solves many of the application issues posed by the industry for years. Conceptually, the fiber laser represents the industry's initial candidate for well completion applications in the field, with the laser unit remaining at surface and beam energy directed downhole through an optic fiber to the target. Other laser systems may also be applicable; however, they were not considered near-term options because of technical or economic constraints.

Aside from their numerous technical advantages, it is the cost of ownership of fiber lasers that may turn out to be the key economic factor. It has been estimated that during the typical lifetime of a source, the total cost of ownership of a fiber laser is about one-third that of a similar CO_2 or solid-state device. This calculation includes the slightly higher initial purchase cost of a fiber laser compared with other lasers, and it highlights the low maintenance cost.

GTI focused on fiber lasers

Although fiber lasers were invented in 1963 and used widely at low power-levels throughout the 1980s and 1990s as optical amplifiers, their use in high-power applications was theoretical and remained years from commercial reality. IPG technology accelerated theory into reality, and GTI saw a promising opportunity to integrate high-power fiber lasers into its applications research.

In 2003, GTI formed an alliance with IPG as part of its ongoing laser applications research. At that time, GTI acquired and is operating a 5-kW IPG fiber laser (Figure 4) at its Des Plaines, Ill., research center, which is the largest available for research in the United States. The device is made from coils of ytterbium-doped multiclad fiber with an emission wavelength of 1.07 microns. Expectations are to complete proof-of-concept investigations for perforation applications with the fiber laser by this fall, to be followed by field experiments at GTI's Catoosa Test Facility in Tulsa, Okla. ◇

All graphics and photos courtesy of IPG Photonics unless otherwise noted.