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Lasers and Beam Delivery for Rock Drilling

by

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Abstract

High power laser beams have been demonstrated to be effective in ablating or drilling rocks. Natural gas wells are typically greater than 5000ft (1524m) ft deep. Consequently, the laser beam has to be delivered to great depth for the drilling to progress. In addition to the logistics /difficulties of delivering the requisite energy and guidance technologies to depths of several thousand feet, the pressure and temperature at those depths also present challenging engineering considerations.

This report is an analysis of commercially available high power lasers, laser beam delivery methods and their suitability for gas well drilling. This initial analysis focuses on the requirements to deliver the beam to depths of a few kilometers. The viability of different laser systems and beam delivery methods are examined. The energy levels and subsidiary systems needed for the ablation or rock drilling process are also discussed. Research and development activities are recommended to develop the required capabilities for deep-hole drilling with lasers.

The availability of high power lasers is evaluated, the process of laser beam-material interaction and the properties of laser beams required for efficient drilling of rocks are examined, and beam delivery systems suitable for high power laser beams are evaluated for drilling to depths of several thousand meters.

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Executive Summary

This report finds that beam delivery for laser drilling is feasible but is subject to constraints and requirements. Fiberoptic beam delivery is an attractive option because of the complexity of sending a laser head downhole. Improvements in fiber transmission are needed for more efficient delivery to deeper depths. Currently available silica fibers are capable of delivering multikilowatt beams over long distances but the beam power is attenuated by mechanisms depending on the wavelength, purity, and quality, of the fiber. For a Nd:YAG laser beam, transmission through 1 km length of a standard silica fiber that is available today, results in approximately 50% loss in power. Current fibers, screened for quality, may have lower attenuation losses of only 2.0 dB/km for a Nd:YAG beam, which means a 1 km fiber would deliver approximately 63% of the power injected at the surface. Furthermore, for a COIL beam, the fiber length increases to 3km for a 50% loss. Attenuation sets the practical length of the fiber that can be used and still have sufficient beam power for processing.

A promising fiber technology for the delivery of multi-kW fibers is currently being commercialized by OmniGuide Communications Inc. (www.omni-guide.com, Cambridge, MA). OGCI's hollow-core photonic bandgap fibers will guide the laser beam in their hollow core. According to the company, their technology can be used to make fibers for guiding high power Nd:YAG lasers as well as fibers for guiding CO_2 lasers. For both, they claim losses will be under 1 dB/km, and power handling will be in the multi kW regime. The technology was developed at MIT and OGCI has an exclusive license for it.

Diode and fiber lasers can be designed to be inserted downhole but require development of power and cooling systems. Presently available diode lasers have limited beam irradiance. Although rapid near term improvements in the beam quality of diode lasers are expected, diode laser beam quality will not approach that of Nd:YAG or fiber lasers. However, beam quality is not nearly as important if the laser is acting directly on the rock face, compared to that required for launching into a fiber.

Preliminary tests indicate that laser beams will have difficulty drilling through water or mud. Engineering solutions to this problem of providing a clear path for the laser beam from the drill head to the rock face are scheduled to be investigated in more detail in the 2003 test plan.

The industrial laser business is currently in a downturn while the telecom industry is substantially worse. Companies are seeking or redirecting efforts to more viable markets and are also more receptive to collaborative efforts. An example is IPG Photonics which has redirected their product development to high power fiber lasers from low power fiber telecommunication products after the telecommunication downturn. Laser and beam delivery manufacturers contacted have already expressed interest. This would be an opportune time to collaborate with the industrial community to develop the necessary technologies for laser drilling of gas wells.

If one of several possible fiber manufacturers is engaged, improvements in preform material and fiber drawing technology may lead to substantial improvements in transmission, enabling longer fibers and lower losses. This finding is in agreement with an earlier analysis by the petroleum industry [16].

To advance the development of laser-based technology for downhole drilling, improvements in current technology have to be developed and innovative designs must be engineered to address the hostile environments encountered in deep drilling. Four tasks are identified to address the findings of this report:

Develop and Test High-Power Fiber-Optic Beam Delivery

To develop fiber-optic beam delivery cables with low power losses, the Team should establish and carry out a fiber-optic cable test program to identify and improve the limits of fiber beam delivery. This effort builds on our previous work in [5]. Collaborative subcontracts should be established with one or two of the most forward-thinking fiber cable vendors under which we jointly develop high power cables to be tested with lasers available at ANL and at laser manufacturers.

Clear Beam Path Design and Testing

Minimizing beam losses from the end of the beam delivery system to the rock surface is critical. The next steps should go well beyond liquid absorptivity and pulsed-versus-steady-state testing. The effort should evaluate, design and test the possibility of using a transmissive flowing liquid or pressurized gas purging system to provide a clear beam path. A viscous inert transmissive liquid offers an improved shield for optics compared to fast flowing gases.

Compact Downhole Laser Head Concept Development

Problems with beam delivery losses can be eliminated if the laser head itself can be inserted downhole. In this Task, the Team should survey advanced laser system performance issues and develop novel designs of advanced semiconductor pumped and other compact high performance laser systems which have the possibility of functioning downhole. The latter task should be performed in collaboration with one or more laser manufacturers.

Downhole Processing Head Concept Development

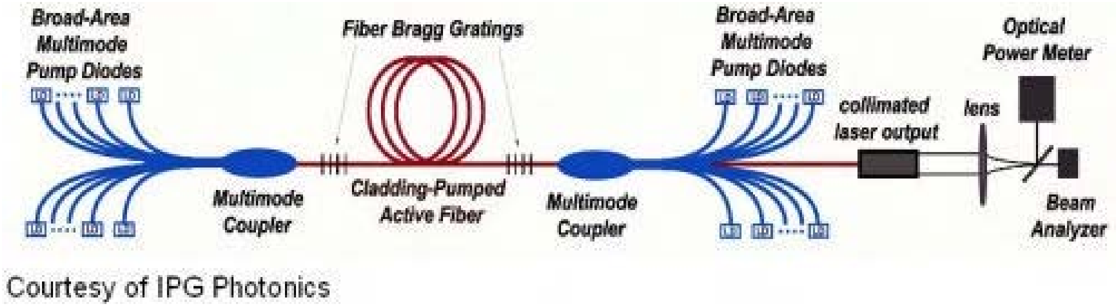
A special processing head is necessary to utilize laser beams for drilling. The laser beam has to be shaped and manipulated to create a large hole. Optical components have to be protected against flying particles and rock fragments. Rock particles and fragments have to be removed and the head translated downward for rock removal to proceed. For this task, the Team should design, engineer, fabricate, and demonstrate a prototype processing head to address the requirements for laser drilling downhole. An initial design should be conceived, engineered and demonstrated in a laboratory environment to validate the different methods and concepts. The device should then be improved to handle the higher temperatures and pressures typical of downhole environments.

Background and High Power Lasers

Lasers are commonly used in research and industry. The applications are numerous and diverse and include both material analysis and material modification. Examples of research applications include laser induced plasma spectroscopy, isotope separation, fusion studies and laser assisted materials processing. Laser processed components permeate many fields. Turbine blades in aircraft engines have cooling holes that are laser drilled with a pulsed Nd:YAG laser. Human corneas are sculpted with laser beams to improve vision. The plastic headlight covers of automobiles are trimmed with CO_2 lasers. The inner door panels of late model cars are laser cut and welded with CO_2 lasers for lower cost and improved performance. Razor blades are spot-welded with pulsed Nd:YAG laser beams. The valve seats of high performance automobile engines are laser cladded for improved performance. Lasers are used in stereolithography to produce 3-D prototype models for engineering components. Plastic bags containing food may come with easy tear features that are enabled by laser beam processing. Low power red laser beams from diode lasers are used to scan bar codes at the checkout counter and as laser pointers. The above industrial applications are listed in order of decreasing laser beam irradiance. It is the tailoring of the beam irradiance to a particular process that enables the flexibility of laser processing.

Lasers have been developed with a wide range of output power, wavelength and beam characteristics. Laser pointers generate a beam with a few milliwatts (mW), lasers for micromachining are a few watts (W) and industrial lasers range from several hundred watts to several kilowatts (kW) for cutting and welding. Lasers developed for military purposes are in the 100kW to 1 megawatt (MW) range. Wavelengths of available lasers range from the ultraviolet wavelengths generated by excimer (gas) lasers and frequency tripled or quadrupled solid state YAG lasers to infrared wavelengths of CO_2 (gas) lasers or quantum cascade (solid state) lasers. High average powers greater than1kW are generally available for near infrared and infrared wavelengths with multikilowatt outputs from CO_2, Nd:YAG and diode lasers. A recent development is the high power ytterbium fiber laser (Fig.1). Diodes are used to pump a single mode fiber to obtain up to 100W output at 1.07 µm. The output from several fiber lasers can be combined or launched into a multimode fiber to obtain multi-kilowatt outputs. The Chemical Oxygen Iodine Laser (COIL) is capable of generating up to 20kW. The free electron laser (FEL) is also capable of generating kilowatt beams but require a large particle accelerator facility to be feasible. Lasers developed for military applications that generate greater than100kW of average power do so over a short time interval (<1min) by exciting a large volume of gas that is expelled to the environment after excitation. Most types of lasers can be operated in a pulse or continuous wave (CW) mode although a particular configuration, i.e. the mode of excitation of the lasing medium may restrict the laser to either pulse or CW.

There has been recent interest in the use of high power lasers for drilling rocks. Potential benefits include self-casing by the formation of a vitrified layer, higher and more consistent drilling rate and improved perforation capabilities [1]. Previous studies examined the efficacy of high power laser beams in drilling different rock materials [1]. High specific energy (energy/volume of rock removed) was required to melt, vaporize or eject the rock material to form a hole. Later work used a lower intensity to thermally crack the rock with ejection of the fragmented material aided by high pressure gas jets [2, 3]. As a result, substantially lower and more competitive specific energies for laser rock drilling were obtained.



Courtesy of IPG Photonics

Figure 1. Schematic of diode-pumped ytterbium fiber laser.

The laser drilling of rock to several thousand meters requires:

1. a high average power and robust laser,
2. a beam delivery technique to convey the laser beam to the rock material, and
3. extraction/removal of the drilled material.

For near term (approximately 5 years) applications, the high power military (chemical) lasers have the following problems:

1. high cost
2. low duty cycle (not designed to operate continuously)
3. the large volumes of expelled gas after each laser firing are hazardous to the operators and the environment, and
4. not robust for industrial applications.

The COIL has been an interest for defense applications but has seen little commercial feasibility. A niche application has been its development to 10kW by Kawasaki Heavy Industries for fiberoptic beam delivery at 1.3 µm for the decommissioning of nuclear power plants. The COIL system uses large pumps for supersonic gas flow and chemical reaction of iodine and oxygen for excitation. The bulkiness, cost and need to dispose of a hazardous waste stream from the open-cycle process have been major deterrents to commercialization. Furthermore, the 10kW COIL has been demonstrated for run times of only approximately1 hour. The FEL is also not currently practical because it is not transportable and is cost prohibitive to build (greater than $100M) and operate. Multikilowatt industrial CO_2 laser systems are priced from $50/W to$100/W and Nd:YAG systems are $95-$200/W (Fig. 2). The cost of high power diode lasers is similar to CO_2 systems. High power fiber lasers are a recent development and currently are greater than $170/W. Consequently, for near term considerations, multikilowatt industrial lasers are the most appropriate. Robust lasers at reasonable cost include CO_2, Nd:YAG, diode and fiber lasers. A list of high power industrial lasers is given in Table 1. Up to 40kW CW is commercially available for the CO_2 laser, 6 kW for the Nd:YAG, 4kW for diode lasers, and 6 kW for fiber lasers. Near term, outputs of 10kW are achievable for both the Nd:YAG, diode, and fiber lasers and the extrapolated costs are indicated in Fig. 2.

Although medium powers (around1kW) can be delivered through hollow waveguides for the CO_2 laser, multikilowatt beams require conventional fixed optics using mirrors or the development of improved hollow fiber/waveguide systems. The near infrared beams of the Nd:YAG laser (1.06 µm), diode laser (750nm to 980nm) and fiber laser (1.07 to1.09 µm) can be delivered using fiberoptic cables. The better beam quality of the Nd:YAG and fiber lasers allows launching into fibers that are less than1mm in core diameter with less than10% power loss whereas the poor beam quality of the diode laser results in approximately 60% transmission into the fiber.

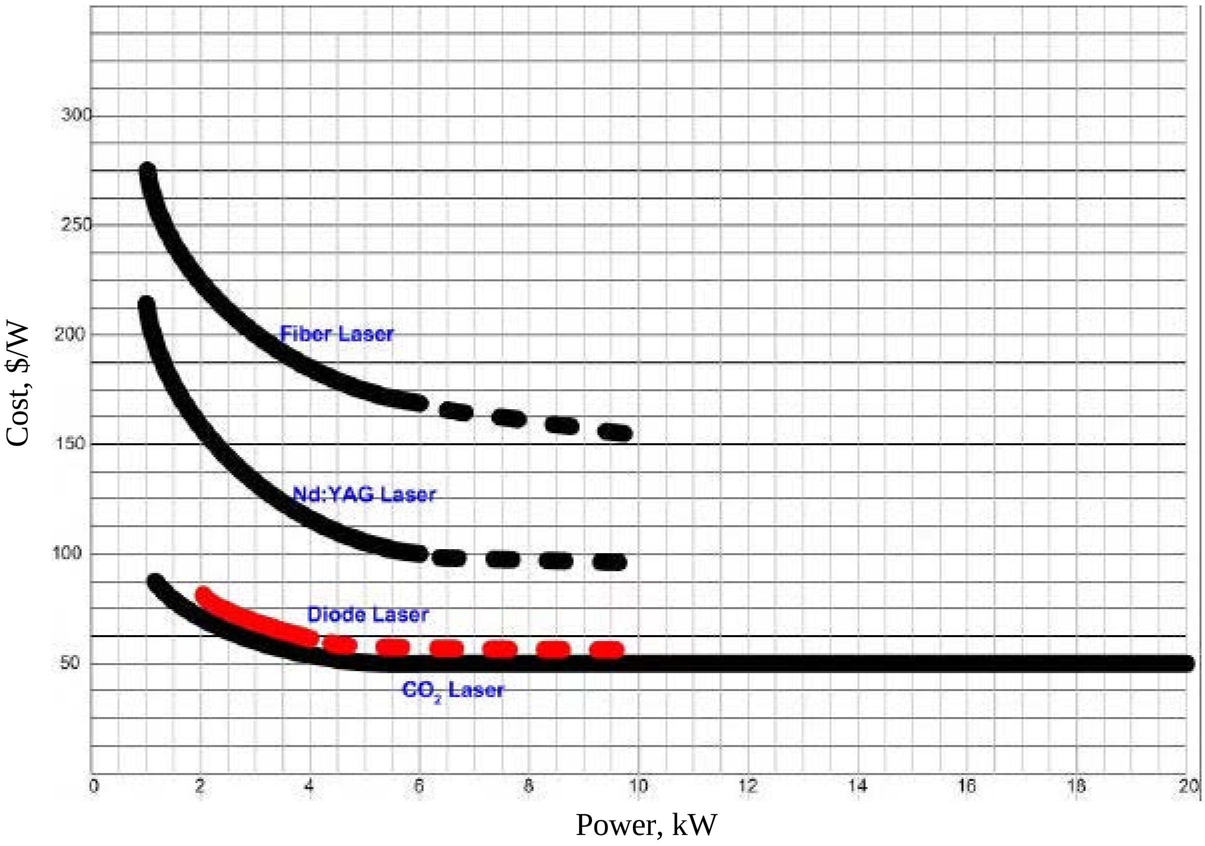


Figure 2. Approximate cost of current industrial high power lasers and extrapolated cost at higher powers.

Manufacturer	CO_2 Laser	Nd:YAG Laser	Diode Laser	Fiber Laser
Convergent Prima 1 Picker Road Sturbridge, MA 01566 www.convergentprima.com	40kW CW	250W average, 50kW peak		
Fraunhofer Institut f. Lasertechnik Steinbachstr. 15, D-52074 Aachen, Germany www.ilt.fhg.de		1kW CW, 800W pulsed mode with 400 kW peak		
GSI Lumonics 22300 Haggerty Road, Northville, MI 48167 www.gsilumonics.com		2kW CW, 4.5kW peak 400W average, 30kW peak		
IPG Photonics Corporation 50 Old Webster Road Oxford, MA 01540 www.ipgphotonics.com				6 kW diode pumped ytterbium fiber laser
Nuvonyx Inc. 3753 Pennridge Dr. Bridgeton MO. 63044 www.nuvonyx.com			4kW CW, 1-100% duty cycle	
PRC LASER N. Frontage Rd. Landing, NJ 07850 www.prclaser.com	6kW CW, 15kW peak with hyperpulse			
ROFIN-SINAR, Inc. 40984 Concept Dr. Plymouth, MI 48170 www.rofin-sinar.com	20kW CW	6kW CW	3kW CW	
TRUMPF Inc. 111 Hyde Rd Farmington, CT 06032 www.trumpf.com	20 kW CW	6 kW CW		
U.S. Laser Corporation 825 Windham Court N. Wyckoff, NJ 07481 www.uslasercorp.com		2kW CW		

Table 1. List of commercial suppliers of high power industrial CO_2, Nd:YAG, diode, and fiber lasers.

Laser Beam-Material Interaction

The optimal use of lasers in the present application requires the understanding of the primary parameters pertinent to laser beam-material interactions. Basically, the laser beam is a heat source that can be controlled to deliver a wide range in intensities and power. When interacting with a material, reflection at the surface, and transmission and absorption through the material occur. The material interaction process is governed by the irradiance (power/unit area) of the incident beam and the interaction time resulting in an amount of heat /energy absorbed by the material. The product of the irradiance and the interaction time gives the amount of energy applied per unit area.

Beam Parameters

Since laser beam properties impact a process, their understanding will help to determine how a particular beam can be utilized. A laser beam can be propagated continuously (continuous wave or CW) or intermittently (pulsed). Power is a straightforward parameter for CW beams. For pulsed beams, the average power is the product of the pulse energy and the pulse repetition rate. The peak power for a pulse is the ratio of the pulse energy to the pulse width and can be several orders of magnitude higher than the average power. High peak powers are attractive for many applications like drilling or thick section cutting or welding. The average power drives the speed of the process.

The intensity of a beam may vary over its cross-section. The beam may be single-mode, i.e. Gaussian for a circular beam with the maximum intensity in the center or multi-mode with several peaks. The cross-sectional profile of a Gaussian beam is shown in Fig. 3. The size of the beam is often defined at the $1/e^2$ intensity level, i.e. when r=w. This is also the radius that contains 86.5% of the beam power.

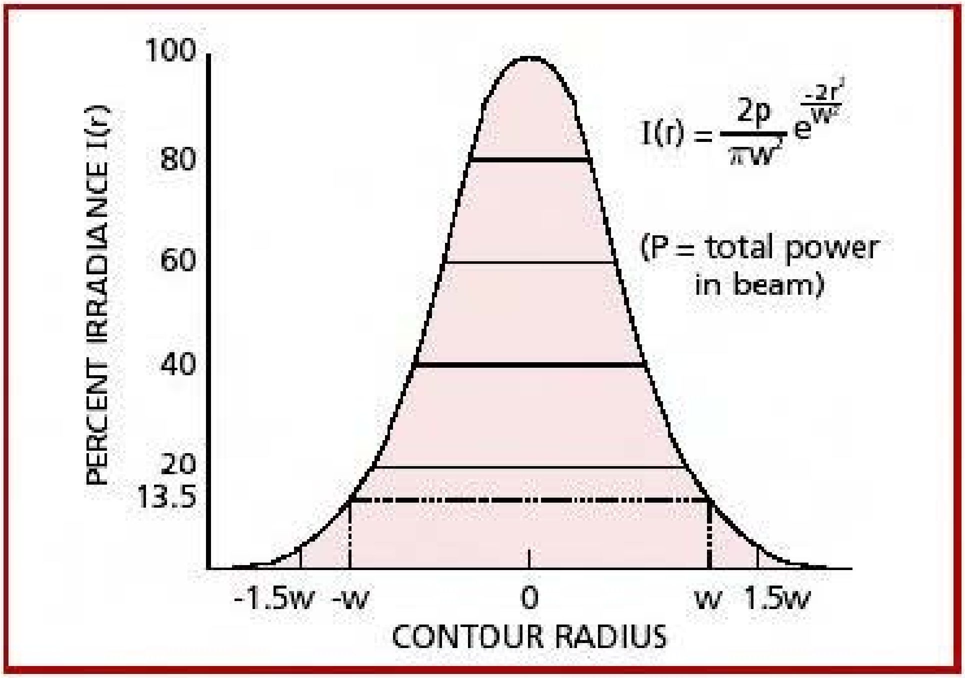


Figure 3. Intensity profile of a Gaussian beam. From www.mellesgriot.com

Optical elements are used to tailor the beam irradiance for a particular processing need (see beam delivery section). Often, a higher irradiance is needed and the beam is focused or down-collimated to a smaller size. The spot size of a beam at the focus of an optic is affected by its quality. A Gaussian beam has the highest beam quality with a beam quality factor $M^2=1$ (see equation (1) in the beam delivery section). Multimode beams have $M^2>1$. M^2 is then a factor indicating the focusability of a beam where a Gaussian beam with $M^2=1$ has the smallest spot size. In general, multi-kilowatt beams are multimode as a larger resonator is more efficient in generating higher power.

Beam-Material Interaction

The laser beam is a flexible heat source where its intensity and interaction with materials can be controlled by varying the power and size of the beam or the interaction time. For any material, a minimum amount of energy has to be absorbed for the material to be ablated by the laser beam, i.e., a solid has to be heated to liquefy and then vaporize. Under certain conditions, the photon energy may be able to break the molecular bonds of the material directly. In general, the energy absorbed is needed to vaporize the material and account for any heat that may be conducted away. Consequently, the interaction is a heat transfer problem. The relevant parameters are the heat flux and total heat input to the material. The corresponding parameters for the laser beam-material interaction are the irradiance of the beam and the interaction time. The product of these two parameters is the energy applied per unit area. A high irradiance beam may be able to ablate a material rapidly without significant heat transfer to surrounding areas.

For drilling or cutting materials, a high intensity beam is required for laser ablation with minimal heat lost to the surrounding areas. However, at high beam irradiance (greater than1 GW cm^{-2} for Nd:YAG beams), the intense plasma formed from ionization of gases and vapor will partially absorb or diffract the beam. Reduced penetration of the material results. Similarly, in welding using CO_2 lasers where the beam irradiance is approximately1 MW cm^{-2}, the plasma plume formed decreases penetration. A high velocity jet of inert gas is usually used to blow away the plasma.

Conventionally, a high irradiance beam is used in drilling to melt and vaporize or eject the melt. Recent data indicate that an alternate method can be used to drill rock. At relatively low irradiance, a laser beam can cause fragmentation of the rock. The specific energy required to drill sandstone and shale by fragmentation is less than 1 $kJcm^{-3}$ [2, 3]. For the process to remain efficient, i.e. minimal melting or vaporization, the rock fragments formed from the interaction process will have to be removed to expose new solid rock for processing. If we start at an irradiance and interaction time regime to avoid melting for rock fragmentation, increasing the power, i.e. the irradiance may move the process into the melting regime. The same will also occur if the interaction time is increased. This deduction is consistent with the experimental results obtained where the interaction or pulse times for both CO_2 and Nd:YAG lasers were restricted to less than 1s to avoid melting of the sand at irradiances of approximately 1 $kWcm^{-2}$[2,3].

The major types of rock considered in tests to date are limestone, sandstone and shale. Each of these rock types has a different mineral and chemical composition [2, 6]. Limestone is essentially calcium carbonate with some magnesium impurities. The Berea Gray sandstone used in tests at Argonne National Laboratory consists of quartz (85%), feldspar (10%) and other minerals while one of the shales tested is similar with quartz (35%), feldspar (20%) and clays (45%). In addition to the minerals, rocks, particularly shale, may contain varying amounts of adsorbed water. The porosity varies from 0.6% for limestone, 3% for shale to greater than 20% for the Berea Gray sandstone. The thermal diffusivity for these representative rocks is 7.5×10^{-3} cm^2s^{-1} for shale, 8.1×10^{-3} cm^2s^{-1} for limestone and 11.3×10^{-3} cm^2s^{-1} for Berea Gray sandstone. To determine the effect of laser irradiance on a rock sample, the absorption coefficient of the rock constituents and their temperature stability need to be examined. Knowing the thermophysical properties of each of the rock constituents is necessary to predict the effects of a laser beam on a rock material. Computing the volatility of the minor constituents of a rock illuminated by a laser beam will help to predict the fragmentation behavior. A model of the laser-rock interaction process is needed to help determine the best and most efficient approach to drilling the material.

Methods of Laser Beam Delivery

Laser beams can be delivered using refractive optics, reflective optics, fiberoptics and waveguides [see 4, 5]. A general goal of beam delivery optics is the transmission and shaping of the laser beam without substantial loss in power and degradation in beam quality. Consequently, important considerations are the absorptivity and reflectivity of the material used, the quality of the optical surface and the ability of the optics to transmit or reflect the beam without introducing aberrations or degradation to the beam quality.

Conventional Fixed Optics

Refractive optics

Refractive or transmissive optics are generally used to shape low power beams. They are lenses made with the appropriate transmissive material and are frequently coated with an anti-reflective (AR) coating to avoid Fresnel losses of approximately 4% at a surface. For high power beams, the absorptivity of the lens substrate determines the maximum power a lens can handle without substantial distortion as only edge cooling can be easily applied. The more complex cooling technique of flowing air across the lens surface may allow higher power to be transmitted as for the case of zinc selenide lenses. A lower absorptivity AR coating will also allow the same.

Most applications use a focused beam and the spot size or diameter of the beam at focus, d_s is given by

$$d_s = M^2 \, [4f\lambda/(\pi d_b)] \tag{1}$$

where M^2 is the beam quality factor, f is the focal length of the lens, and λ and d_b are the wavelength and diameter of the collimated beam respectively [4]. Alternately, the beam quality is also expressed in units of millimeter-milliradian (mm-mrad) where

$$d_b\Theta = M^2 \, (2\lambda/\pi) \tag{2}$$

where Θ is the far field divergence of the beam. The depth of focus of the beam where the spot size does not vary by more than 5% is given by

$$z_f \sim 1.48\, F^2 \lambda \tag{3}$$

where F is the ratio of the focal length to the beam diameter at the lens [4]. This parameter is important in processing as it represents the region where the maximum beam irradiance is maintained.

Refractive optics use zinc selenide for high power CO_2 (10.6 µm) beams and fused silica (or BK7 glass for lower power) for Nd:YAG (1.06 µm) and near IR diode beams. For zinc selenide, the absorption coefficient for CO_2 beams is 0.0005/cm. For fused silica, the value is 10×10^{-6}/cm at 1.06 µm. The slight absorptivity of zinc selenide for 10.6 µm wavelength restricts its use for high power beams to a few kilowatts average power. When used for kilowatt beams, zinc selenide optics are usually edge-cooled. Higher beam power increases the thermal distortion of the lens affecting the beam quality transmitted. The low absorptivity of fused silica for near IR beams allows operation without active cooling. An industrial beam delivery component using refractive optics for focusing is shown in Fig. 4. The laser beam enters the beam delivery component from the top right and is deflected downwards by a 90° turning mirror. A slide-in lens holder provides ease in lens replacement and holds the focusing lens. The nozzle shown is used for cutting with a coaxial flow of assist gas to protect the lens from debris and aid in the cutting process. An optical flat can be placed in front of the focusing optic for protection.

A variety of refractive optics can be used for beam shaping. They include spherical lenses for beam focusing and defocusing, cylindrical lenses for asymmetric beam shaping, and multi-faceted optics for beam integration, i.e. to obtain a tophat profile. Other optical shapes and combinations can be used for custom beam shaping. Focal lengths shorter than 125mm usually introduce distortion or aberrations to the beam but can be minimized using gradient index (such as Gradium lenses from LightPath Technologies) or aspheric lenses.

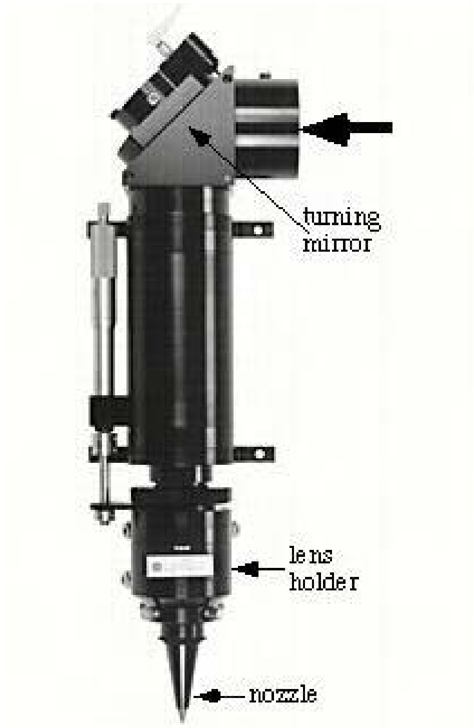


Figure 4. Beam delivery for laser cutting from Laser Mechanisms

Reflective optics

Reflective optics is more suited than refractive optics for handling multikilowatt beams particularly for the CO_2 wavelength. Reflective optics generally use a multilayer reflective coating with less than 0.2% absorption on a metallic or silica shape or a highly reflective (greater than 97%) metallic surface. Reflective coatings are generally tailored for a particular wavelength but can be extended to two or more wavelengths. Highly polished unoxidized metal surfaces have high reflectivity for a wide range of wavelengths from the visible to the infrared. It should be noted that 3% absorption of a 5kW beam generate 150W. Hence, such optics require cooling.

Delivery of high power beams require turning and focusing of collimated beams. These functions are accomplished with water-cooled flat and parabolic mirrors. Examples of such optics are shown in Fig. 5, an engineering drawing of an industrial focusing head for high power beams. The schematic shown on the right side of the figure is a side view of the assembly with the flat turning mirror on the left hand side and the parabolic mirror on the right between the arrows. Fittings on the back of the copper mirror mounts allow water to flow through for cooling. The dashed lines indicate a collimated laser beam propagating down on the turning mirror, reflected 90° to the right and then focused downwards by the parabola. A 90° parabola is difficult to align perfectly and tends to give a larger spot size compared to a refractive lens of the same focal length. Table 2 lists several suppliers of optics and components for high power laser beam delivery.

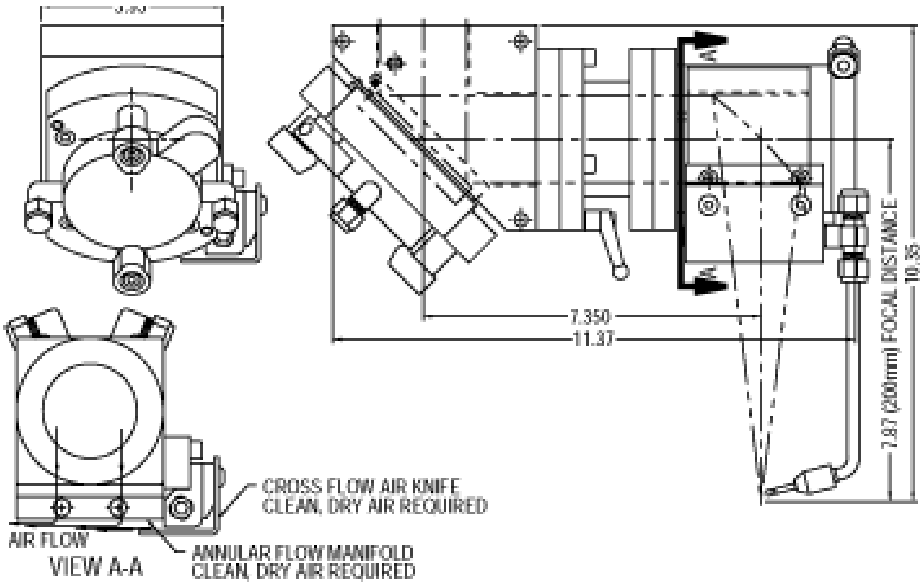


Figure 5. A reflective focusing head assembly from Laser Mechanisms, Inc.

For safety and elimination of inadvertent scattering, absorption or deflection by particles or objects, high power beams should be enclosed along its propagation path. For a fixed location, beam tubes provide an easy solution. A more flexible method is the use of an articulating arm where optics are placed at each hinged position as shown in Fig. 6. The articulating arm consists of beam tubes hinged together with reflective optics and 3-D motion of the terminating point can be carried out. The segments in the middle usually require a flexible support to hold up the assembly and the end of the arm can be attached to a robot arm or multi-axis motion system.

Although the articulated arm provides flexible delivery of high power beams for many industrial cutting and welding operations, its applicability for downhole drilling needs to be evaluated. In order to effect processing, the collimated laser beam needs to be delivered to a processing head where the beam irradiance and the point of interaction with the rock surface are controlled. For short distances of several meters, the use of articulated arms appears to be relatively easy. As the hole depth increases, the segments would have to be increased in both number and length by perhaps a telescoping tube. In addition, each mirror at the junction of the segments has to be cooled. The cost and complexity rapidly increases with length and the need for lengths of greater than1km makes articulating arms a difficult choice.

Manufacturer	CO_2	Nd:YAG
Haas Laser Technologies, Inc. 37 Ironia Road, Flanders New Jersey, 07836 www.haslti.com	x	x
Laser Mechanisms, Inc. 24730 Crestview Ct. Farmington Hills, MI 48335 www.lasermech.com		x
Precitec Inc. 55820 Grand River Ave., Suite 250 New Hudson, Michigan 48165 www.precitec.com	x	x
Preco Laser Systems 500 Laser Drive Somerset, Wisconsin 54025 www.precolaser.com	x	x
Spawr Industries Inc. - Optics Division 2051 Spawr Circle Lake Havasu City, AZ 86403 www.spawrindustries.com	x	x

Table 2. Manufacturers and suppliers of optics and components for high power laser beam delivery.

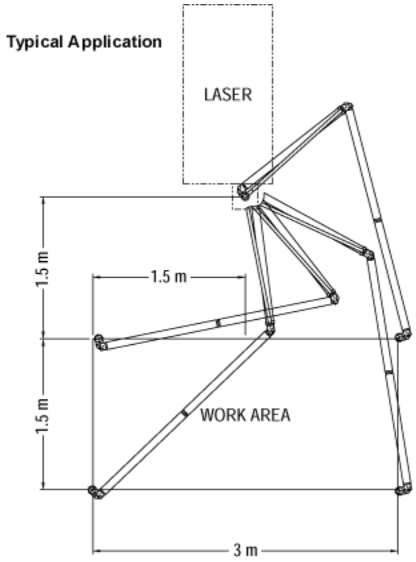


Figure 6. Different positions of an articulating arm for flexible laser beam delivery.
Schematic from Laser Mechanisms, Inc.

Galvanometer Scanners

For drilling rock or any other process, the laser beam needs to be shaped or its irradiance modified to suit the process. Irradiance tailoring is generally carried out near the processing point. For example, in the previous section, a focusing head is used to increase the irradiance. However, this method is based on a fixed interaction point. For rock drilling, the requirement of a 1 kW cm^{-2} irradiance (for fragmenting) implies that a 10 kW beam must have a diameter of approximately 3.6cm. Consequently, the point of interaction needs to be translated to produce an 8in diameter hole. Since it is not feasible to move the rock, the beam has to be rastered to produce a larger hole or multiple beams must be used.

Galvanometer scanners are typically used for precision positioning of laser beams. Examples of commercially available systems are shown in Fig. 7. A typical galvanometer uses a moving magnet to create high torque for rotation of the shaft with the attached mirror. Positioning information is by optical or capacitive sensors. A closed loop system is capable of exceeding milliradian accuracy. For the x-y positioning system on the left side of Fig. 7, the beam enters from the right and is deflected by the bottom mirror to the top mirror. The angular positions of the mirrors determine the position of the outgoing beam. The schematic in Fig. 8 illustrates a standard 2-D scanning system. Two scanners each with an attached mirror are placed orthogonal to each other. An F-theta lens is used to obtain a flat image field. The beam at the point of application may need to be shaped or focused to obtain the optimal irradiance and shape for the application. This can be achieved by selecting an appropriate reflective optic for the last mirror in the scanner system.

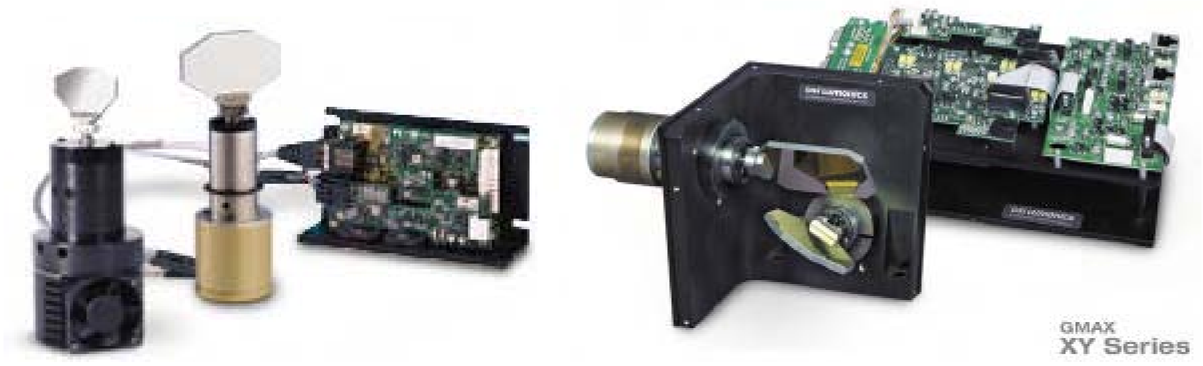


Figure 7. Galvanometer scanners from GSI Lumonics. The left side shows individual galvanometers and the right is an assembly of two galvanometers for x-y control.

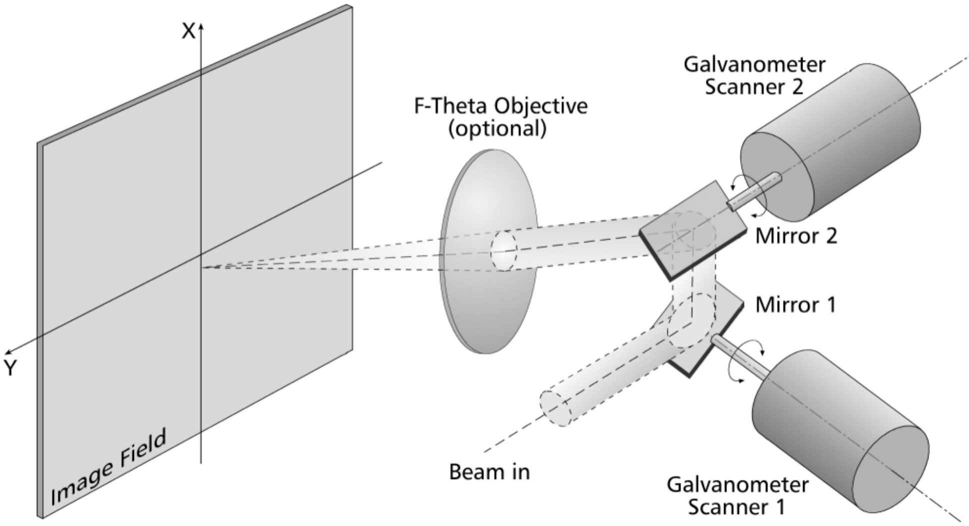


Figure 8. Schematic of 2-D beam scanning using two scanners and a F-theta lens. Courtesy of SCANLAB AG.

A commercially available 3-D scanning system for multikilowatt laser beams is shown in Fig. 9. The input collimated laser beam enters from the left into a dynamic controlled-defocusing optics system to vary the focus in the z-axis. Two galvanometer driven mirrors provide the x-y positioning of the beam. The second mirror focuses the beam through an F-theta lens for a large flat field in the x-y plane. A 1 cm diameter beam with an irradiance of 10^4 $kWcm^{-2}$ is capable of penetrating sandstone or shale at a rate of 13 cm s^{-1}. A collimated beam of the required irradiance can be scanned rapidly across a larger area to effectively drill a shallow but large square hole in the rock.

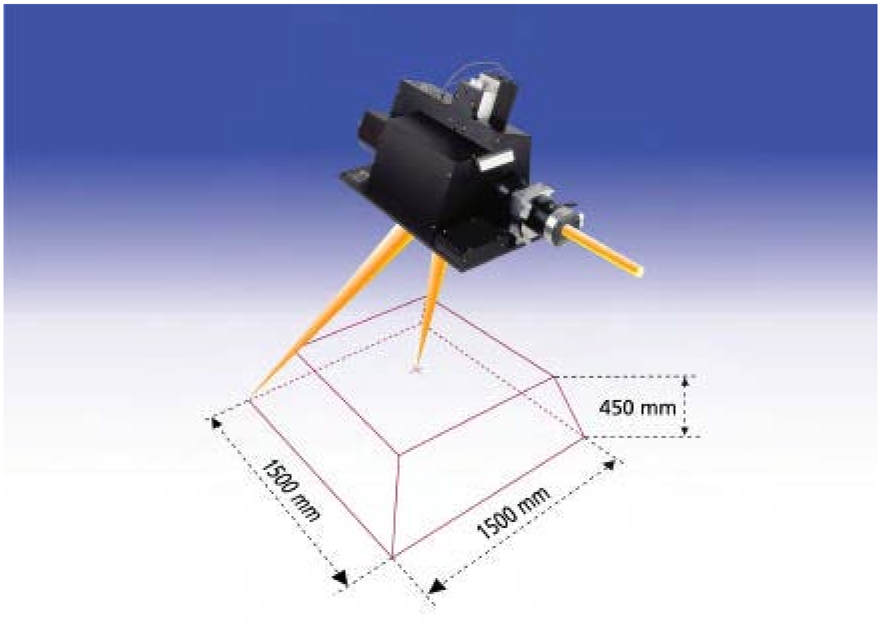


Figure 9. A high power 3-D scanning system from SCANLAB AG with a large flat field and z-axis focus position control.

Manufacturer	Product
Cambridge Technology, Inc. 109 Smith Place Cambridge, MA 02138 www.camtech.com	Scanner components
GSI Lumonics 22300 Haggerty Road Northville, MI 48167 www.gsilumonics.com	Scanner components and systems
SCANLAB AG Benzstrasse 28 82178 Puchheim / München Germany www.scanlab.de	Application oriented scanner systems and components

Table 3. Suppliers of galvanometer components and systems for positioning laser beams.

A list of suppliers is included in Table 3. For high power beams, cooled mirrors, larger than the input beam diameter, are required. Large mirrors with cooling will have a large inertia limiting the speed of the positioning. The scanning speed can be improved by using custom lightweight mirrors that are available from high power beam delivery component suppliers like Spawr Industries (see Table 3).

Fiberoptics and Waveguides

Solid optical fibers and hollow waveguides offer flexible delivery of multikilowatt beams. They are basically flexible cables or tubes that contain the beam through internal reflection. Silica fibers are often used for delivery of high power Nd:YAG beams offering flexibility and insignificant power loss over several hundred meters but have high losses for CO_2 beams. Hollow waveguides are available for CO_2 beams [9]. We will discuss flexible optics suitable for high power beam delivery of CO_2 and near IR beams. Special glass fibers like chalcogenide are available for low power CO_2 beams but are not suitable for high power.

A promising fiber technology for the delivery of multi-kW fibers is currently being commercialized by OmniGuide Communications Inc. (www.omni-guide.com, Cambridge, MA). OGCI's hollow-core photonic bandgap fibers will guide the laser beam in their hollow core. According to the company, their technology can be used to make fibers for guiding high power Nd:YAG lasers as well as fibers for guiding CO_2 lasers. For both, they claim losses will be under 1 dB/km, and power handling will be in the multi kW regime. The technology was developed at MIT and OGCI has an exclusive license for it.

Fibers

Fused silica fibers are manufactured by drawing from a preform with one end heated to the melting temperature. Standard continuous lengths of 200-250m are available for multimode high power beam delivery fibers (greater than 600µm) from several manufacturers (Table 4). Custom lengths of 500m are available if the core size precision is relaxed slightly. Longer lengths are possible but may require some development. Shorter lengths can be connected together with couplers with a few percent power loss. Longer lengths of approximately 1km are available for smaller diameter fibers.

Fibers transmit light through total internal reflection where the critical angle is given by:

$$\alpha = \sin^{-1}(n_{clad}/n_{core}) \tag{4}$$

where n is the refractive index. Core refers to the silica fiber core and clad is the material used on the wall of the fiber core. There is a maximum angle between the ray of light and the optical axis normal to the fiber end surface where all light entering the fiber within that cone angle will be guided through the fiber. The numerical aperture (NA) of a fiber is the sine of this angle and can be computed by

$$NA = (n^2_{core}-n^2_{clad})^{1/2} \tag{5}$$

From equations (4) and (5), it can be deduced that if $n_{clad}=1$, i.e. bare fiber with no clad, the NA is a maximum but the fiber tends to be lossy particularly at bends because the critical angle is small. Consequently, a cladding material with a refractive index close to that of the core is used.

For low and medium powers, plastic or polymer clads are used whereas silica clad is preferred for high power applications. Polymer cladded fibers tend to be more lossy than silica cladded fibers and the power transmitted into the cladding material would tend to produce heat and may create problems. The silica cladding used is doped to reduce the refractive index and forms an integral bond with the silica core unlike an adhered layer of plastic or polymer. This type of fiber with a uniform refractive index core and a clad layer is called a step index (SI) fiber. A gradient index (GI) fiber is manufactured by varying the doping (germanium) in the core radially with the maximum at the wall of the fiber. No clad layer is necessary. The difference in the two types of fibers is that the SI fiber tends to give a tophat-like output beam profile whereas the GI fiber results in a Gaussian-like profile. Fig. 10 illustrates the NA of a fiber and the different types of fibers in regards to the output beam profile. A single-mode fiber is also shown for reference. Both SI and GI fibers manufactured for high power applications have a standard NA=0.22. The refractive index of the clad is lower than the core by approximately 1%. The minimum bend radius for this NA value is approximately 200 times the core size. Fibers subjected to smaller bend radii will suffer leakage of the light into the cladding. Custom NA's of 0.12 and 0.26 are available. Smaller minimum bend radii are possible with lower NA values but is constrained by the flexibility of the fiber. For applications in the field, fiber cables have a buffer layer and jacketing surrounding the silica core. Silica is a high temperature material. Hence, the operating temperature of a fiber cable is constrained by these jacketing materials used.

A launch optic is used to focus the laser beam into the fiber. The optic is selected such that the spot size is less than 0.8 of the fiber core size and cone of light produced is less than 0.8 NA of the fiber. The focus of the optic is positioned at the surface of the fiber end. The beam quality of the output beam is determined by the product of the core diameter and the NA (equation 3). For multikilowatt Nd:YAG laser beams, fiber core sizes of 0.6mm to 1mm are used. This large core size is multimode and will degrade the beam quality. To maximize beam quality, the smallest core size that the beam can be launched into is used. Although a larger NA makes beam launching into the fiber easier, the larger NA degrades the beam quality. For example, a 25 mm-mrad 6 kW beam can be launched into a 600 µm fiber that has a numerical aperture of 0.2 which is also the far field divergence of the output of the fiber. From Equation (2), the beam quality from a 600 µm fiber with an NA=0.2 is less than120 mm-mrad. This value of beam quality occurs when all modes of the fiber are filled. Generally, the beam launched into the fiber is at NA<0.2 and not all modes are filled for fiber lengths of several meters.

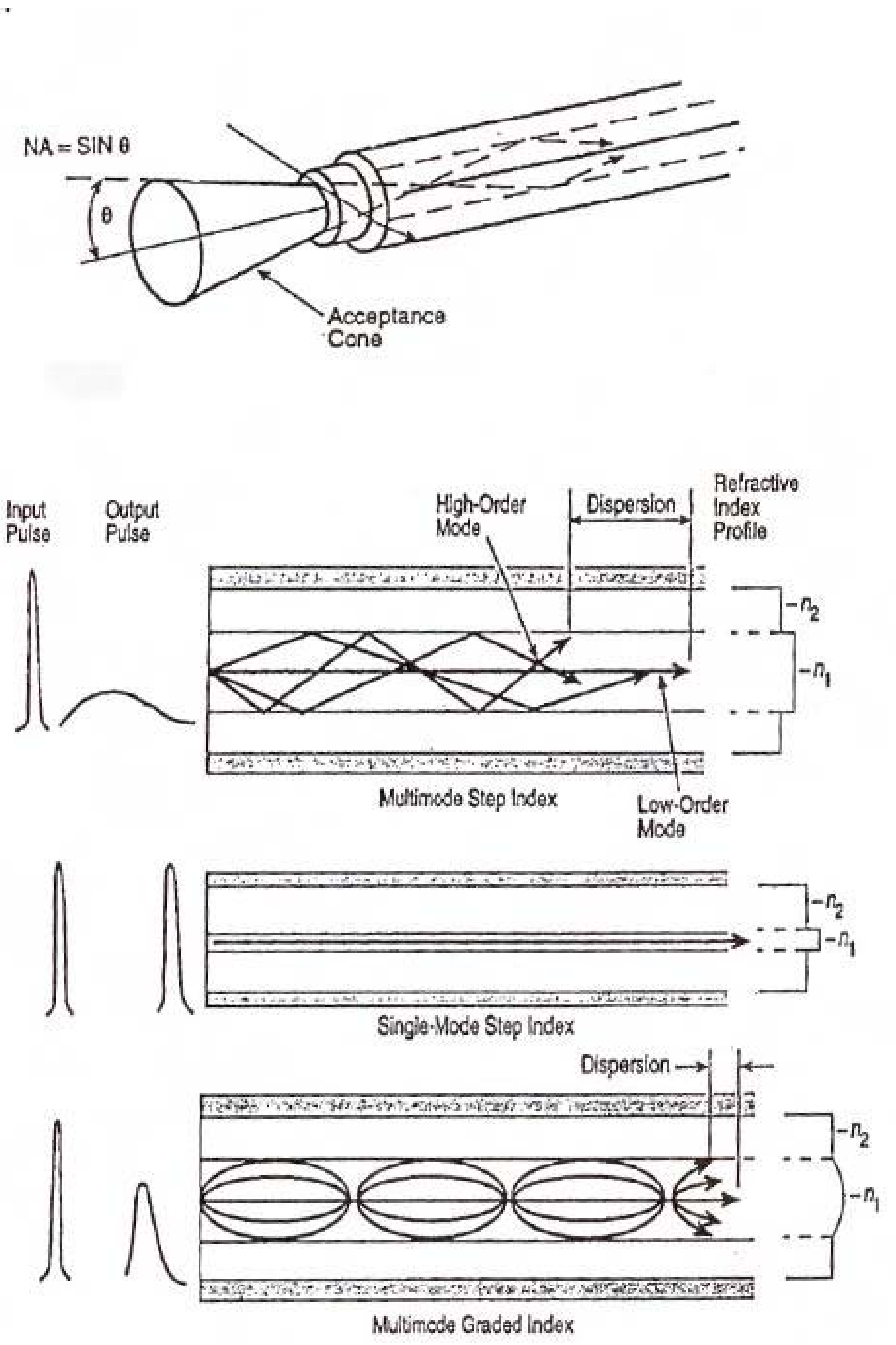


Figure 10. Light propagation in different types of fibers. From [17].

Fiber cable assemblies for high power applications are terminated with proprietary high power connectors that hold the bare end of the fiber recessed in a rugged metal tube that provides alignment for connection and a protective heat sink. An example of a high power fiber cable assembly is shown in Fig. 11. Several sources of high power fiber cable assemblies are available commercially and some are listed in Tables 4 and 5. The ability of a fiber to handle high power is determined by the purity of the core material and the quality of the polish on the end faces. A submicrometer smoothness and freedom from microcracks and contamination are required for damage free operation at multikilowatt power levels. CW Nd:YAG beams of 6kW can be handled by high quality 600 µm silica fibers. Q-switched pulses exceeding 1 $GWcm^{-2}$ can be transmitted without damage to the end faces or the fiber [10].

Figure 11. High power fiber cable assemblies from Richard Losch, Inc.

In addition to beam quality degradation through a fiber, reduction in power will also occur. For uncoated end faces, there are Fresnel losses of approximately 4% at each surface, i.e. input and output faces. AR coatings can be used to reduce the 8% loss to less than 1%. Although silica is essentially transparent to 1.06 µm radiation, there is sufficient absorption that reduction in the output power will occur over long distances. The absorptivity of the fused silica material although low is dependent on the impurities present and the quality of the fiber. Fibers with high OH content have substantially higher absorption than low OH (<2ppm) fibers. The OH molecule has absorption bands at 950nm and greater than1100nm. However, the absorption at 1.06µm is not affected significantly. The spectral attenuation characteristics of a low OH silica fiber are shown in Fig. 12. The attenuation at 1.06 µm is nominally less than 3dB/km indicating less than 50% loss in power per km. The attenuation increases for shorter wavelengths (<1µm) because of molecular scattering losses and for longer wavelengths (>1.7µm) from absorption. In addition, micro-indentations on the fiber surface and any micro-bubbles or contamination will contribute to the attenuation. The attenuation curve in Fig. 12 is for an actual fiber and hence includes the characteristics of the preform used and losses from the quality of the fiber drawn. A selected preform may reduce the overall attenuation to less than 2dB/km i.e., less than 37% loss in 1 km. Furthermore, each AR coated optical surface used in the beam delivery train will cause small losses (approximately 0.5%) and will have to be accounted for in arriving at a power delivered to the surface being irradiated.

The beam emanating from the output end of a fiber is divergent with an angle approaching the NA of the fiber. After collimation the beam is like a conventional laser beam. Refractive or reflective optics can then be used to tailor the beam for processing applications.

Manufacturer	**Silica fiber**	**Sapphire fiber**	**Hollow waveguide**
CeramOptec Industries, Inc. 515A Shaker Rd. East Longmeadow, MA 01028 www.ceramoptec.com	SI fibers, assemblies and bundles		
Fiberguide Industries 1 Bay St Sterling NJ 07980 www.fiberguide.com	SI fibers, custom assemblies, and bundles		
Mitsubishi Cable America Inc New Products Div 411 Hackensack Ave Hackensack NJ 07601 www.mcausa.com	SI and GI fibers and assemblies		
OFS 2000 N.E. Expressway Norcross, GA 30071 www.ofsoptics.com	SI fibers		
Photran LLC 13 Columbia Dr, Unit 7 Amherst NH 03031 www.photran.com		Fibers and assemblies	
Polymicro Technologies LLC 18019 N 25th Ave Phoeniz AZ 85023 www.polymicro.com	SI fibers and assemblies		Waveguides

Table 4. Manufacturers of multimode fibers and waveguides for delivery of high power laser beams. (SI – step index, GI – graded index)

Manufacturer	**High power fiber assemblies**
Multimode Fiber Optics Inc 9A Great Meadow Ln East Hannover NJ 07936 www.multimodefo.com	Assemblies and bundles
Optical Fiber Systems Inc 6 Boston Road Chelmsford MA 07824 www.opticalfibersystems.com	Assemblies and arrays
Richard Losch Inc 340 SW Columbia St Bend OR 97702 www.richardloschinc.com	assemblies

Table 5. Suppliers of custom fiberoptic assemblies for high power laser beam delivery.

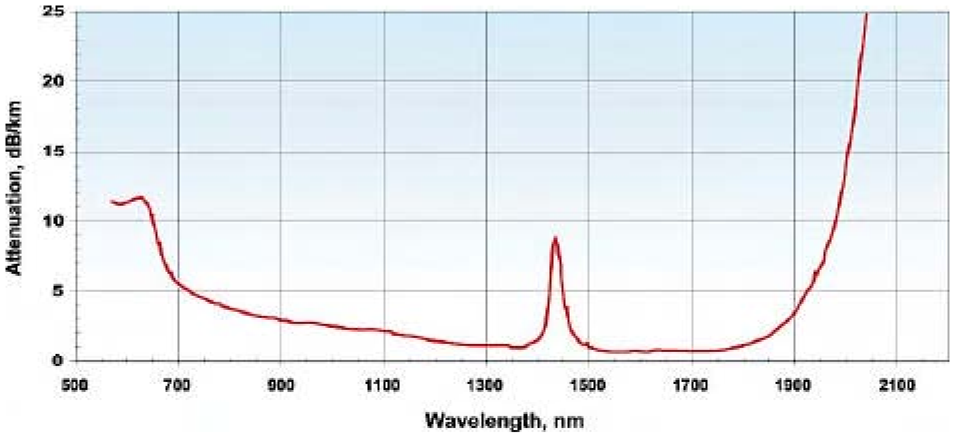


Figure 12. Attenuation of a low OH silica fiber manufactured by Polymicro Technologies.

Waveguides

Since plastic and silica have a high absorption coefficient for 10.6 µm radiation, hollow flexible waveguides were developed as an alternative. Hollow waveguides can have either an inner wall with the refractive index n greater than 1 or a wall material with n less than 1. The former is a leaky reflector and the latter, with an air core of n=1, is similar to the case of the silica fiber where $n_{core} > n_{wall}$. A number of different methods have been developed to produce hollow waveguides [9]. We will restrict our discussion to commercially available waveguides. They include hollow glass waveguides (HGW) that have silver and silver iodide coatings (n>1) and hollow sapphire fibers (n<1). The attenuation of hollow waveguides is inversely proportional to the cube of the bore radius. In addition there is a bending loss that is inversely proportional to the bore radius. For large core waveguides of 1mm, the attenuation is less than 1 dB/m (Fig. 13) and bending loss is approximately 1dB for a curvature of 10/m. This relatively high attenuation is the consequence of the slight absorptivity of the reflecting surface unlike the total internal reflection property of a silica fiber. In addition, any imperfection of the coating process for HGW and smoothness of the wall increases the attenuation.

Current methods of manufacturing HGWs restrict it to lengths of a few meters. Hollow sapphire fibers are also only available in similar lengths. The leaky nature of the waveguides require a small NA (<0.1) to minimize power loss. Laser beams can be launched into these waveguides using the same technique for silica fibers. An advantage over silica fibers is that there is no interface, being an air core. Hence, there is no Fresnel loss and problems with the core material at high irradiance. In fact, hollow fibers have been demonstrated as a viable flexible beam delivery for Q-switched pulses [11]. However, the lossy nature of the waveguide requires active cooling for delivery of kW beams. Greater than 1 kW beam delivery has been demonstrated for a water jacketed HGW. The beam quality is more sensitive to bending effects which can severely distort the original beam.

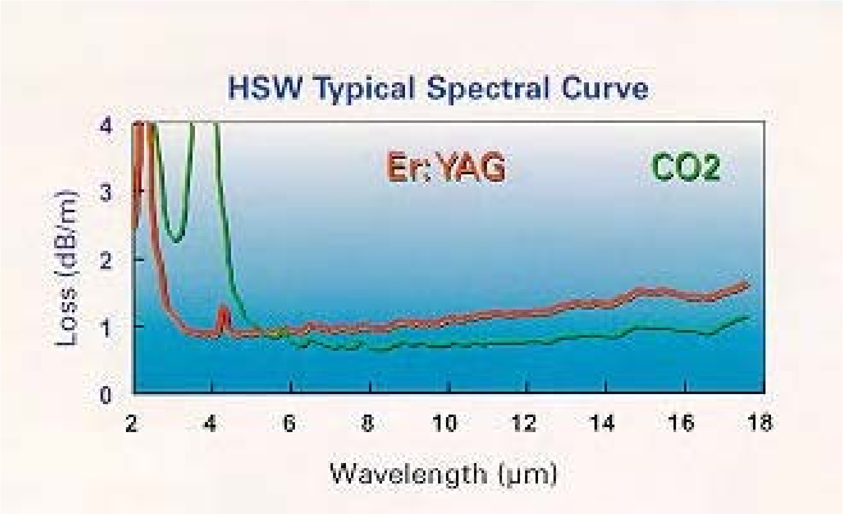


Figure 13. Attenuation characteristics of hollow silica waveguides from Polymicro Technologies. The curves show the characteristics of the waveguides designed for Er:YAG and CO_2 laser beams.

Currently available hollow waveguides are an inferior alternative to silica fibers as they are limited to a few meters, less flexible and have substantially higher attenuation. They are suited only for applications of moderate power and short distances for IR wavelengths where silica fibers are a disadvantage.

OmniGuide Fibers - Photonic Bandgap Fibers for Delivery of Multi-kW Laser Beams

A promising fiber technology for the delivery of multi-kW fibers is currently being commercialized by OmniGuide Communications Inc. (www.omni-guide.com, Cambridge, MA). OGCI's hollow-core photonic bandgap fibers will guide the laser beam in their hollow core. According to the company, their technology can be used to make fibers for guiding high power Nd:YAG lasers as well as fibers for guiding CO_2 lasers. For both, they claim losses will be under 1 dB/km, and power handling will be in the multi kW regime. The technology was developed at MIT and OGCI has an exclusive license for it.

MIT researchers have recently published an article on OmniGuide Fibers with exciting experimental results [18]. The OmniGuide Fiber features a hollow core, a dielectric mirror wrapped around it and an outer cladding for mechanical stability. By choosing materials for the dielectric mirror which are highly dissimilar optically, the authors have been able to guide light not using conventional index-guiding, but rather using a photonic bandgap. As a result, the fibers they analyze have losses that are 30,000 times lower than the effective bulk losses of the materials these fibers are made of. Reported measured attenuation for an OmniGuide CO_2 fiber with a 700 µm hollow core is 0.9 dB/m; as stated above, OmniGuide claims, based on their extensive modeling and simulation work, that they can reduce this loss figure by a factor of 1000. Unlike other hollow-core fiber approaches, OmniGuide Fibers seem to be flexible and to have low bending losses: one of the exhibits in the publication shows transmission through a 360 degree bend of this fiber with approximately 1 cm diameter, and low losses.

The manufacturing process for photonic bandgap fibers is very similar to the manufacturing process for silica fibers: First, a preform is made that has the same structure as the desired fiber, however on a much larger scale. Then, the preform is drawn into a fiber. The length of the fiber is determined by the size of the preform. Therefore, very long lengths of these fibers can be manufactured, a major advantage over other hollow waveguide approaches, which to date have not been able to deliver length of more than 3 meters of fiber.

OGCI is launching its first product: a fiber for guiding CO_2 laser beams. This first product will not be able to guide kilowatts of optical power. However, OGCI is working on technical improvements that would dramatically increase the power handling capability and reduce the losses of these fibers.

While this new technology is not yet capable of filling all the needs for rock drilling, there is a lot of potential. Unlike hollow waveguides, photonic bandgap fibers are highly flexible and can be made in long lengths. Unlike silica fibers, they are capable of transmitting CO_2 laser light, and at least in theory can go well below the loss limitations of silica at the Nd:YAG wavelength. The major obstacle for photonic bandgap fibers in high-power applications is their high attenuation. There is substantial development work in progress to reduce the fiber attenuation. If this work proves successful, OmniGuide Fibers will be the beam delivery method of choice for multi-kW Nd:YAG and CO_2 lasers.

Lasers and Beam Delivery for Deep-Hole Drilling

A pragmatic path to the near term deployment of laser technology for gas well drilling is to engineer a prototype demonstration system using proven and robust components. Industrial components are available for such a system that includes a laser, beam delivery, and processing head. Multikilowatt industrial laser systems are available, but each type has different characteristics and none is presently suited for downhole deployment without specific development efforts with this objective in mind. Table 6 is a summary of the relevant characteristics of the 4 types of high power industrial lasers. All the lasers listed are CW lasers. Some can be modulated for pulse output but the peak power is the same as in the CW mode. There are no industrial multikilowatt pulse Nd:YAG lasers available currently. The CO_2 laser has the highest power and best beam quality (at comparable powers) available, but has the largest displacement in terms of volume or footprint. Flexible beam delivery in excess of 10m is not feasible with existing technology. The Nd:YAG, diode, and fiber lasers can be delivered through silica fibers. The higher beam quality of the Nd:YAG and fiber lasers allows the use of a smaller fiber core size without significant power loss. The poorer beam quality of the diode laser results in approximately 50% power loss using a 1mm fiber. Nevertheless, the electrical to optical efficiency after the fiber delivery is still better than or comparable to the Nd:YAG. The electrical to optical efficiency (not including cooling) of the high power lamp-pumped Nd:YAG laser is 2-4%, the diode pumped Nd:YAG is approximately10%, the diode is approximately 45%, the fiber laser is approximately17%, and the CO_2 is 6-10%.

Characteristic	CO_2	Nd:YAG	Diode	Fiber
Power, kW	20	6 (diode pumped)	4	6(diode pumped)
Beam quality, mm-mrad	<25	<25 (<120 from 600 µm fiber)	>300 (<200 from 1mm fiber)	<22
Size of resonator	large	medium	small	small
Flexible beam delivery	<10m	>100m	>100m	>100m
Overall electrical to optical efficiency including cooling, %	5	8	30	16

Table 6. Characteristics of high power industrial lasers relevant to gas well drilling.

The CO_2 and Nd:YAG lasers are proven technologies that have decades of industrial use. Industrial high power diode lasers are a recent introduction and have only been used in manufacturing for several hundred hours. High power fiber lasers are an even more recent development with beta-testing currently ongoing. Current developments in diode technology may result in the production of diodes with beam quality that is an order of magnitude better than current diode bars in two to three years [12]. In addition, the cost of diodes is expected to decrease with more efficient production at higher demand. Consequently, we can expect the cost ($/W) of diodes and diode pumped systems to decrease.

For beam-material interactions, the beam can be collimated, focused or defocused. A focused beam is used for conventional (not rock) drilling where high irradiances are required to melt and vaporize the material. A focused beam is constrained by the focal length of the optics used and has a small spot size (see equation 2). Increasing the focal length increases the spot size and decreases the beam irradiance. The depth of effective beam irradiance is governed by the depth of focus that increases with the focal length of the optic used. Even if a collimated beam (which has an infinite depth of focus) is used, the aspect ratio (hole depth to diameter) will progress to a point where ejected material from the point of interaction will accumulate on the wall and not be ejected outside the hole. The above considerations point to the fact that the point of interaction of the beam with the rock surface has to be translated both laterally and in depth.

A 2-D scanner system is well suited for lateral control of a high power beam. Limited depth control of the focus can also be incorporated as in the SCANLAB system (Fig. 9) described previously. For the large depths necessary in well drilling, either the laser head has to be moved down the hole created or a long flexible beam delivery method used with a moveable processing head. The CO_2 laser appears to be unsuitable for either, as the resonator is too large (approximately 1m in width) to fit into a 8in (203cm) hole and no flexible beam delivery method is currently available. The Nd:YAG, diode, and fiber lasers can be delivered through silica fibers. However, the power is attenuated by approximately 50% over a fiber length of 1 km. The beam quality of the Nd:YAG and fiber laser beam after the beam delivery fiber is slightly better as a smaller core fiber can be used whereas the use of the same size fiber by the diode laser will increase the power loss. Nd:YAG laser cavities are not suited for downhole use. A special design using a linear array of rods may meet the cross-sectional requirement but the necessity for maintaining alignment of the optics and the resonators may make the system susceptible to shock and vibration. The high power diode laser consists of many semiconductor diode bars that operate with high efficiency. It is less susceptible to alignment and vibration problems as each diode bar consist of many semiconductor laser emitters that are grown in the bar substrate. The laser is compact and can be configured for a small cross-section to fit into the drilled hole. The disadvantage of the diode laser with fiber delivery is that the available beam quality is lower and the irradiance is limited to $<10^5$ Wcm^{-2} at a focal length of 10cm. Expected near term improvements in diode beam quality will increase the irradiance. The diode pumped ytterbium fiber laser is also very compact using fibers as the resonators. Consequently, the diode and fiber lasers are the best candidates for downhole applications. But note that the diode and fiber lasers are the newest systems on the market, and thus have the most unknown about them.

Temperature and Pressure Characteristics

Current industrial components are designed to function in conventional manufacturing environments, i.e. room temperature and pressure, and access to the system for ease in servicing. At depths of 2km, the pressure exceeds 2000 psig (134 bars) and temperature increases by 20 to 40C. At depths over 5 km, temperatures will exceed 100C. The elevated pressure and temperature presents a challenging environment not only for the components but also for the process. Diode lasers operate efficiently at temperatures less than 50C and heat generated during the electrical to optical conversion for lasing has to be removed. Silica fibers can be jacketed with materials that withstand temperatures to 200C. Metal mirrors and holders can easily operate at temperatures greater than 200C. However, galvanometers are limited to 100C. Cooling is likely to be required.

Effect of Water in the System

Studies have been carried out on laser welding in underwater and hyperbaric conditions with CO_2 and Nd:YAG lasers [13]. Water is highly absorptive for CO_2 (10.6 µm) wavelength and partially absorptive for near IR (see Figure 14). For high power focused CO_2 beams, the vaporization of the water along the beam propagation path creates a water free channel for the beam to reach the workpiece surface and effect welding. For Nd:YAG beams, the water partially absorbs and diffuses the beam. For rock fragmentation where lower irradiances than those required for welding are desired, the water absorbs and diffuses the laser beams. ANL's preliminary studies indicated that although both CO_2 and Nd:YAG beams can penetrate a few mm of water, the overall effect of water is deleterious to the processing. For water that is particle-laden, more of the beam energy will be absorbed. Consequently, a liquid-free surface is preferred for efficient rock drilling.

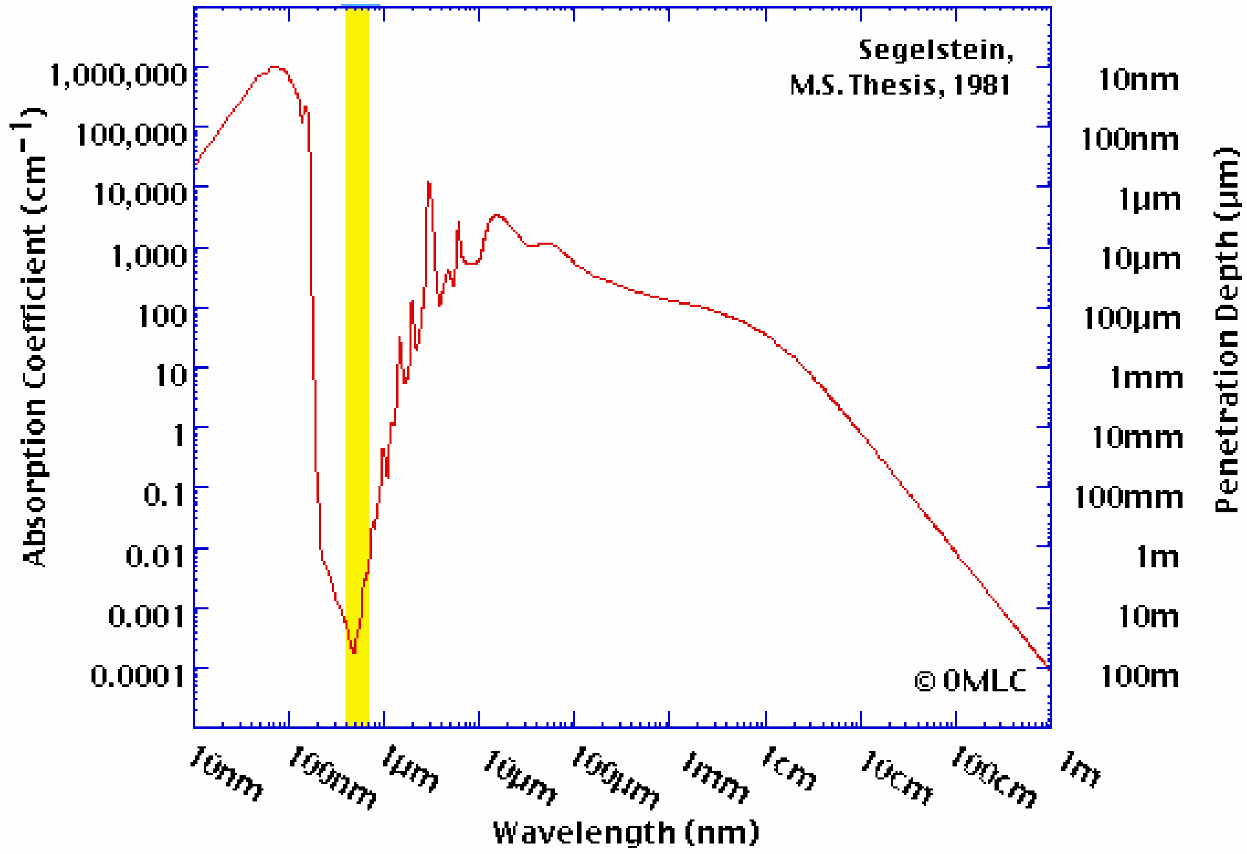


Figure 14. Absorption Coefficient of water

Plasma formation at High Irradiances

The beam irradiance that will cause ionization of a gas is inversely proportional to the square of the wavelength and inversely proportional to the pressure of the gas [14]. For particle-free air at 1 atmospheric pressure, the irradiance for breakdown exceeds 10^{11} Wcm^{-2} for 1.06 µm radiation.

The presence of particles and contaminant gases from the laser-rock interaction will lower the breakdown irradiance substantially to $<10^7$ Wcm^{-2} [15]. At 100 atmospheres, the irradiance for breakdown will be $<10^5$ Wcm^{-2}. This lowering of the breakdown irradiance results in the formation of a high intensity plasma during the beam-rock interaction that tends to shield the beam and decreases the processing effectiveness. The effect can be ameliorated greatly by using an inert gas (argon or helium) jet to blow the plasma away from the region of interaction. This gas jet can also serve a dual purpose by helping to eject the fragmented rock.

Solid Material Removal

During the beam-rock interaction process, particles and rock fragments are ejected at a high velocity away from the surface towards the processing optics. These particles may deposit on the surfaces of any mirrors and optics used. The particles scatter and absorb the beam and decrease the power and irradiance delivered. A high velocity gas flow is needed to deflect the particles away from the mirrors and optics.

Summary and Conclusion

Rock drilling at depths of several kilometers presents a challenging environment for the use of lasers. The analysis carried out above indicates that laser drilling is feasible but is subject to constraints and requirements.

1. Silica fibers are capable of delivering multikilowatt beams over long distances but the beam power is attenuated by different amounts depending on the wavelength and the purity or quality of the fiber. For an Nd:YAG beam, transmission through 1 km length of a standard silica fiber results in approximately 50% loss in power. However, for a COIL beam, the fiber length increases to 3km for a 50% loss. This attenuation property limits the practical length of the fiber that can be used and still have sufficient beam power for processing.
   a. Improvements in preform material and fiber drawing technology may substantially improve transmission to allow for longer fibers and lower losses. This finding is in agreement with an earlier analysis by the petroleum industry [16].
   b. Current fibers screened for quality may have attenuation losses of only 2.0 dB/km for an Nd:YAG beam, which means a 1 km fiber would deliver about 63% of the power injected at the surface.

2. A promising fiber technology for the delivery of multi-kW fibers is currently being commercialized by OmniGuide Communications Inc. (www.omni-guide.com, Cambridge, MA). OGCI's hollow-core photonic bandgap fibers will guide the laser beam in their hollow core. According to the company, their technology can be used to make fibers for guiding high power Nd:YAG lasers as well as fibers for guiding CO_2 lasers. For both, they claim losses will be under 1 dB/km, and power handling will be in the multi kW regime.

3. Diode and fiber lasers can be designed to be inserted downhole but require power and cooling to function.
   a. Long electrical cables and coolant lines will be necessary. Comparisons will have to be made to determine if the power losses associated with, particularly, electrical cables are less than the losses in optical fibers.
   b. The use of a thermoelectric cooler may be more feasible and may negate the need for cooling lines but an effective means of ejecting the heat from the cooler to the environment will be needed.

4. The use of diode lasers limits the beam irradiance available. Although rapid near term improvements in the beam quality of diode lasers are expected, they will not approach the beam quality of Nd:YAG or fiber lasers. The available beam quality will impact the processing flexibility such as the irradiance required for perforation. However, beam quality is not nearly as important if the laser is acting directly on rock, compared to launching into a fiber.

5. The processing head, which may include a scanner for rapid beam positioning, requires power and pressurized gas to function. In addition, high temperature galvanometers are needed to function without cooling. The fragmented rock that will be created by the laser drilling process will have to be removed to the surface.

6. Preliminary tests indicate that laser beams will have difficulty drilling through water or mud. Engineering solutions to this problem of providing a clear path for the laser beam from the drill head to the rock face are scheduled to be investigated in more detail in the 2003 test plan..

7. Laser drilling and perforation offer many of the benefits of conventional rotary drilling and completing wells using shaped charges, while potentially avoiding many of the drawbacks. The above analysis indicates that current industrial laser technology is directly applicable to drilling and completing oil and gas wells, but the application of this power to the depths of a normal well offer several challenges.

8. The complexity of sending a laser head downhole makes fiberoptic beam delivery an attractive option. Improvements in fiber transmission are needed for more efficient delivery to deeper depths. Innovative engineering solutions need to be developed to overcome the challenges posed. Research and development to date has demonstrated the viability of laser drilling at ambient temperature and pressure conditions. Further development and demonstration of the technology at more prototypic conditions that are representative of downhole conditions are the next phase in the development.

9. The industrial laser business is currently in a downturn. The telecom industry is substantially worse. Companies are seeking or redirecting efforts to more viable markets and are also more receptive to collaborative efforts. An example is IPG Photonics which has redirected their product development to high power fiber lasers from low power fiber telecommunication products after the telecommunication downturn. Laser and beam delivery manufacturers contacted have already expressed interest. This would be an opportune time to collaborate with the industrial community to develop the necessary technologies for laser drilling of gas wells.

Recommended Tasks

To advance the development of laser-based technology for downhole drilling, improvements in current technology have to be developed and innovative designs engineered to address the hostile environments encountered in deep drilling. The tasks listed below are identified to address the findings of this report:

Develop and Test High-Power Fiber-Optic Beam Delivery

To develop fiber-optic beam delivery cables with low power losses, we would establish and carry out a fiber-optic cable test program to identify and improve the limits of fiber beam delivery. This effort builds on our previous work in [5]. Collaborative subcontracts would be established with one or two of the most forward-thinking fiber cable vendors in which we jointly develop high power cables to be tested with lasers available at ANL and at laser manufacturers. Issues to be investigated include:

c. continuous fiber length and core diameter limitations,
d. effects of core diameter variations on beam quality and transmission,
e. improvements in fiber transmission through improved fiber purity, addition of dopants, and refinements in the fiber pulling process

Clear Beam Path Design and Testing

Minimizing beam losses from the end of the beam delivery system to the rock surface is critical. The work described here aims to go well beyond the presently planned liquid absorptivity and pulsed-versus-steady-state testing. We will evaluate, design and test the possibility of using a transmissive flowing liquid or pressurized gas purging system to provide a clear beam path. A viscous inert transmissive liquid offers an improved shield for optics compared to fast flowing gases. Issues to be addressed include:

a. identification and tests of transmissive liquids with low vapor pressure and high boiling points,
b. tests of different inert gases at high pressure for plasma suppression and shield for optical components.

Compact Downhole Laser Head Concept Development

Problems with beam delivery losses can be eliminated if the laser head itself can be inserted downhole. In this Task, we will <u>survey advanced laser system performance issues and develop novel designs</u> of advanced semiconductor pumped and other compact high performance laser systems which have the possibility of functioning downhole. The latter task would be performed in collaboration with one or more laser manufacturers. We will examine downhole cooling techniques, and approaches to reducing unit size.

Downhole Processing Head Concept Development

A special processing head is necessary to utilize laser beams for drilling. The laser beam has to be shaped and manipulated to create a large hole. Optical components have to be protected against flying particles and rock fragments. Rock particles and fragments have to be removed and the head translated downward for rock removal to proceed. For this task, we will design, engineer, fabricate, and demonstrate a prototype processing head to address the requirements for laser drilling downhole. An initial design will be conceived, engineered and demonstrated in a laboratory environment to validate the different methods and concepts. The device will then be improved to handle the higher temperatures and pressures typical of downhole environments.

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