

## **Application of Fiber Lasers to Rock and Earth Materials**

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Over the past eight years, Gas Technology Institute (GTI) has advanced the use of high power lasers for cutting and breaking rock. A proof of concept study for natural gas well applications was recently completed using an IPG Photonics 5.34 kW Yb-doped multi-clad fiber laser, tunneling through siliceous and carbonate rock types at atmospheric and subsurface conditions. Results include drilling at least 12 inches through both sandstone and limestone with low energy requirements, improving near-tunnel fluid flow characteristics of sandstone, and drilling through a simulated wellbore at subsurface pressure conditions. Successful development of this laser/rock cutting application could be adapted for a variety of uses in several industries.

Initial GTI laser/rock research was conducted with high-powered military lasers. Although technically successful, megawatt lasers were unlikely to meet near-term economic thresholds for commercialization. As a result, GTI shifted the emphasis of its investigation to commercially-available industrial lasers. Results determined that industrial lasers were capable of removing rock with energy levels comparable to existing mechanical methods.<sup>1</sup>

Fiber lasers have become leading commercial candidates for on-site applications, including mining, tunneling, cutting and drilling of rock and concrete. They are fully capable of delivering sufficient rock cutting power with precision to distant targets via fiber optics; benefit from higher wall plug efficiency and improved beam quality with lower input energy requirements; and offer greater mobility and durability through a smaller overall size and solid state design (Figure 1). In addition, with projected diode failures exceeding 50,000 continuous hours, little or no maintenance is expected.<sup>2</sup>

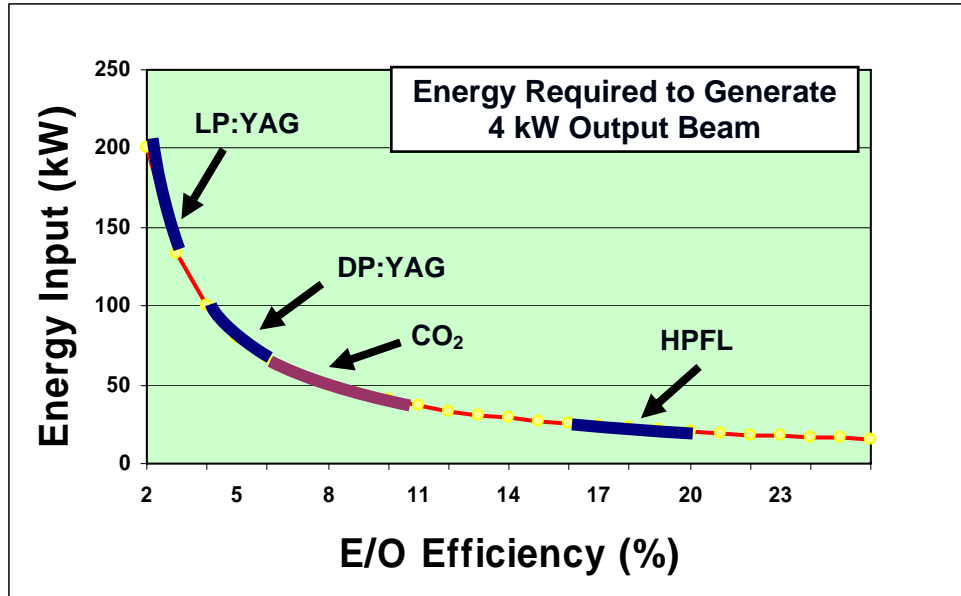


Figure 1. Comparison of Required Energy Required to Generate a 4.0 kW Beam from Lamp Pumped Nd:YAG (LP:YAG), Diode Pumped Nd:YAG (DP:YAG), Carbon Dioxide (CO<sub>2</sub>), and Yb-doped High Power Fiber Laser (HPFL).

Early examples of remote fiber laser systems have been successfully deployed. The U.S. Army developed and deployed self-contained Humvee-mounted laser units to destroy unexploded ordnance in Afghanistan.<sup>3</sup> Edison Welding Institute designed a fiber laser concrete drill-assist system for use in an earthquake retrofit of a California hospital.<sup>4</sup>

### Rock Removal Processes with Lasers

Initial fiber laser experiments results determined rock removal energy requirements and were compared with previous laser/rock data. Of primary interest were limestones and sandstones, as both types are likely reservoir targets for completion practices. Results determined the fiber laser was more efficient in drilling both rock types when compared to previous data from COIL, CO<sub>2</sub> and Nd:YAG lasers (Figure 2).<sup>5</sup>

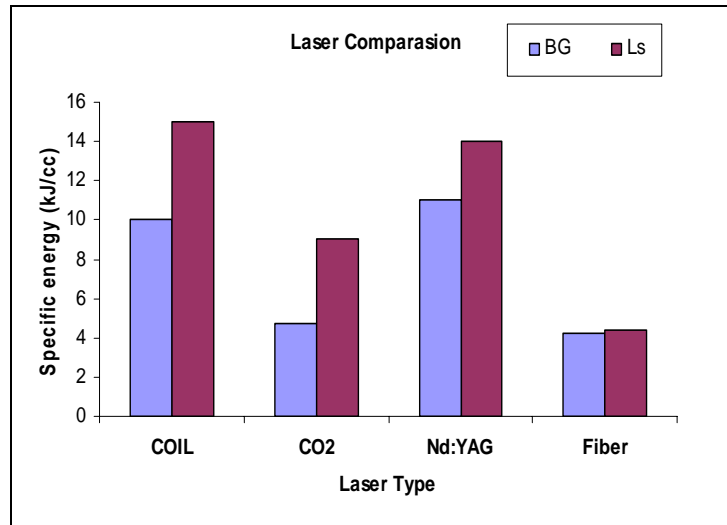


Figure 2. Lowest SE values obtained from laser/rock interaction experiments using COIL, CO<sub>2</sub>, Nd:YAG and Yb fiber lasers on Berea sandstone (BG) and limestone (Ls) at lowest SE conditions.

Beam penetrations of at least 12 inches were made in a quarry limestone using a focused CW beam. The tunnel is created by calcination, the thermal dissociation of CaCO<sub>3</sub> into CaO and CO<sub>2</sub> at about 825°C. Fluid flow restriction in CaO due to melting is not likely as the melting point is 2570°C.

Similar penetration depths were made in Berea sandstone, a sedimentary rock composed predominately of quartz grains (SiO<sub>2</sub>), using collimated CW beams. The most energy efficient process observed for laser cutting Berea is thermal spallation, which occurs in sandstone between 400 – 800°C.<sup>6</sup> Thermal stresses produced by a high temperature gradient from the beam and differential thermal expansion of minerals break the grains and their bonds.

Unlike limestone, mineral melting occurs in Berea quartz grains as temperatures exceed 1610°C, redirecting beam energy from spalling, and significantly decreasing cutting efficiency. To avoid this, thermal accumulation in the rock can be limited by altering the energy transfer rate to the rock face and beam exposure to cuttings. Energy

transfer rates can be controlled through average measured power applied, irradiance, or exposure time. Optimal beam power and irradiance levels were previously determined for fiber laser applications to Berea.<sup>7</sup>

Efficient cuttings removal is also important for limiting thermal accumulation. For example, moving the beam in various geometric patterns increased the hole-to-beam diameter ratio allowing cuttings to exit the hole with limited or no exposure to the beam.<sup>1</sup>

### **Fiber Laser Perforation in Berea**

A demonstration of an alternative perforation method was performed on a one-foot cubic block of Berea sandstone. Perforation is a well completion procedure that pierces through steel well casing into fluid-filled reservoir rock, creating a path for oil, gas and water production. Conventional perforation methods introduce considerable flow restrictions by irreparably damaging the rock structure and fluid path.

In the demonstration, a beam collimator converted the raw beam from a 300 micron fiber into a 1.0 inch diameter collimated beam. Compressed air at 75 psig was directed through a 0.25 inch stainless steel nozzle set approximately 1.0 inch from the target. The optics and purge nozzle were both attached to a robot arm moving in a 1.0 inch circle at 22.6 RPM. The purge nozzle moved toward the hole as it deepened.

The collimated beam was applied continuously at 1.0 minute intervals for 6.0 minutes total laser time. Beam power was 3.2 kW, determined as optimal in previous studies for this rock type and beam size.<sup>7</sup> When the beam penetrated half the length of the block, it was turned such that the beam could penetrate from the opposite direction and meet in the block's center. The resulting hole passed through the full 12-inch length of the sample creating the deepest tunnel in Berea reported to date.<sup>7</sup> The tunnel diameter was

approximately 2.0 inches at the entry points on either face and 1.1 inches at the center of the block (Figure 3).<sup>8</sup> The resulting volume of material removed was 210 cc.

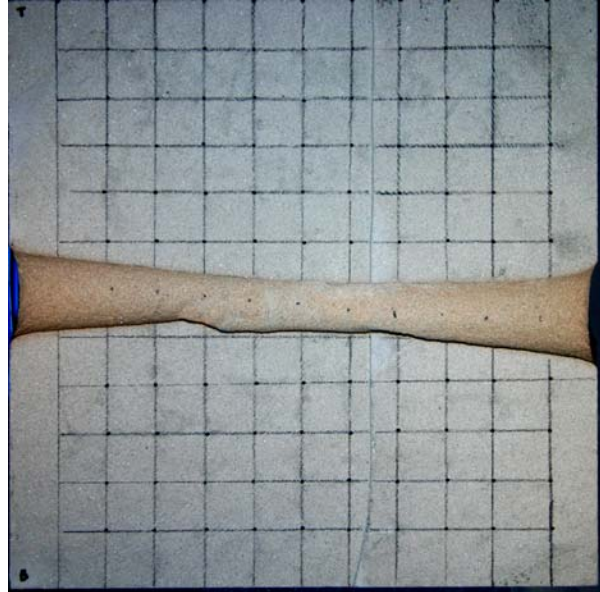


Figure 3. Cross section of lased tunnel 12 inches across measuring 2.0 inches in diameter on each end.

The procedure of cutting from opposite ends reduced the influence of boundary effects, and best simulated an infinite reservoir rock. Berea blocks were also lased from only one direction and boundary effects were observed, including changes in thermal diffusion characteristics and increased energy consumption as the beam approached full penetration.<sup>7</sup> This phenomenon was observed in past experiments and is likely an artifact of the experimental design and sample geometry.

### **Demonstration Results**

Specific Energy (SE), the energy required to remove a unit amount of rock (kJ/cc), was determined for all laser/rock exposures. The SE value observed to create the 12- inch

Berea tunnel was 5.5 kJ/cc. laser energy used for spallation was about 1155 kJ, or 0.32 kWh.

The lowest observed SE values in Berea from previous experiments ranged from 4.3 to 5.2 kJ/cc for 0.5 second surface exposures.<sup>9</sup> Later tests involving multiple, overlapped 0.5 second exposures resulted in larger, deeper holes (about 1.0 inch in diameter and 1.0 inch deep) with SE values ranging from 9.2 to 13 kJ/cc.<sup>10</sup>

Comparisons of pre- and post-lased permeability measurements along the rock face perpendicular to beam entry were inconclusive. A heat-altered zone extended about 2.0 mm radially into the rock from the tunnel wall.<sup>8</sup> This indicated, along with the low SE value, that much of the energy directed at the sample was efficiently used for spallation, not thermal alteration of near-tunnel rock properties.

A similar comparison was made along the bisected length of the tunnel. There was no evidence of mineral melt on the tunnel wall. Post-lased permeability readings showed increases along the wellbore of between 15 and 30 percent.<sup>8</sup> Although enhancement to the rock's fluid flow characteristics is limited, the process of lasing perforation tunnels caused no noticeable damage, a significant improvement over conventional perforation methods.

### **Looking Ahead**

Additional investigations are in process, including liquid purging techniques and in-situ pressure experiments in excess of 2000 psig. Next steps include designing an initial downhole prototype tool, lab and field trials, and subsurface field demonstration in a production well. The expected dividends from this work will become integrated into more complex well construction and completion applications. Other drilling and cutting

applications of Earth materials may soon result across a variety of industries, including energy, mining, military, homeland security, space, construction, and demolition.

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