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Practical internal combustion engine laser spark plug development

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Abstract

Fundamental studies on laser ignition have been performed by the US Department of Energy under ARES (Advanced Reciprocating Engines Systems) and by the California Energy Commission under ARICE (Advanced Reciprocating Internal Combustion Engine). These and other works have reported considerable increases in fuel efficiencies along with substantial reductions in green-house gas emissions when employing laser spark ignition. Practical commercial applications of this technology require low cost high peak power lasers. The lasers must be small, rugged and able to provide stable laser beam output operation under adverse mechanical and environmental conditions. New DPSS (Diode Pumped Solid State) lasers appear to meet these requirements. In this work we provide an evaluation of HESP (High Efficiency Side Pumped) DPSS laser design and performance with regard to its application as a practical laser spark plug for use in internal combustion engines.

Introduction

The operation of internal combustion engines with lean gas-air mixtures, high cylinder head pressure and plasma spark ignition has been shown to increase fuel efficiencies and reduce green-house gas emissions by significant amounts. Advanced reciprocating engine research and development programs such as ARICE and ARES have reported fuel efficiency increases of greater than 45% and NOx-emission reductions of more than an order of magnitude when compared to standard spark-gap spark plugs [1,2,3]. The ARES-based engines are used for generating electricity. They are comprised of 16- and 20-cylinder configurations, operating at 1500 rpm/50 Hz, 1200 rpm/60 Hz or 1800 rpm/60 Hz, with ratings up to 2.1 Megawatts [3].

The use of laser ignition to improve gas engine performance was initially demonstrated by J. D. Dale in 1978 [4]. However, with very few exceptions, work in this area has for the last 20+ years been limited to laboratory experimentation employing large, expensive and relatively complicated lasers and laser beam delivery systems. More recently, researchers at GE-Jenbacher, Mitsubishi Heavy Industries, Toyota, National Energy Technology Lab and Argonne National Lab have obtained and/or built smaller high peak power laser spark plugs [5,6]. Unlike many earlier laboratory laser systems, these smaller lasers are now mounted directly onto the engine cylinder head so as to fire the laser beam directly into the chamber. The architectures now lead to designs that may become a direct replacement for the traditional high voltage electrical spark-gap plug. Further reductions in laser size, price and complexity will help the laser spark plug become a commercial reality and a viable competitor to the traditional high voltage spark-gap plug.

Practical Laser Sparkplug Requirements

The simplest and least costly laser ignition design architecture would consist of a compact high peak power laser transmitter head, and a sapphire window/lens delivery system. The sapphire window is a well proven and reliable method of providing a transparent bulkhead seal on high pressure combustion chambers such as gas engine cylinder heads and the breeches of 155mm howitzers [7,8]. BMLIS (Breech Mount Laser Ignition System) lasers, mounted directly on to the breech of large cannons, have over the last 20 years proven to be more reliable than fiber optic laser beam delivery systems [9]. In these laser applications the laser window "self cleaning" or "burning free" effect is well known [6]. This is a laser ablation effect where ignition residue that collects on the window surface is blown free and clear of the optical aperture with each laser pulse.

Many BMLIS, ARES and ARICE researchers are reaching the same conclusions about the attractiveness and dependability of direct fire laser ignition designs. Estimated basic cost and performance requirements for a practical laser spark plug are listed in table 1.

Mechanical	Laser and mounting must be hardened against shock and vibration
Environmental	Laser should perform over a large temperature range
Peak Power	Laser should provide megawatts raw beam output
Average Power	1-laser per cylinder requires 10Hz for 1200rpm engine operation
Lifetime	100 million shots – good, 500 million shots - better
Cost (ARES)	Laser cost less than $3,000 each (100M pulse life ~ break even)
Cost (Auto)	Laser cost less than $600 each

Table 1 - Laser spark plug cost & performance requirements

The cost values shown for the natural gas engine laser spark plug are based upon the estimated operational costs of an 800 Kilowatt 16-cylinder Waukesha engine operating at 1200rpm with 16 lasers (one for each cylinder). At 1200 rpm the laser operates 24 hours a day, 365 days a year at 10 Hz (1200 rpm/2 strokes x 60sec/min) for a total of approximately 315M pulses per year. The natural gas fuel consumption cost estimation for this engine is based upon $10MMBtu, $65.00/hr equal to approximately $569,000 per year [10]. Replacement of a standard spark plug with a laser spark plug provides an estimated 40% increase in fuel efficiency. Under these conditions, the laser spark plug requires $46.00/hr in fuel consumption. This translates into cost savings of approximately $174,000 per year. Laser replacement cost (materials only) is estimated at $144,000 (16 x $3000 each) x 3 times per year with an estimated 100M pulse lifetime. This spark plug cost analysis indicates that laser lifetime is a key issue with regard to the development of an economically viable (read practical) laser spark plug.

We may also envision smaller and less costly laser spark plugs for use in common automobile and truck engines [11]. These applications may make use of very small low cost single emitter laser diodes to significantly reduce the laser spark plug component cost. An eye-safe erbium glass version of this type of laser is shown in figure 1 [12]. Diode laser pumps are the most costly element employed in traditional side and end pumped DPSS Lasers. The diode lifetime is the limiting factor in the laser lifetime.

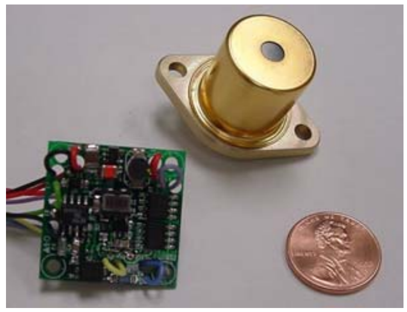

Fig. 1 – Kilowatt class mil-spec high peak power diode pumped Er:glass laser

Mechanical

Laser spark plug designs must perform under engine mount shock and vibration conditions. Testing to shock and vibration specifications for engine mounted products will help to validate the durability and design life of the laser spark plug. It appears that large stationary ARES engines will most likely subject the laser spark plug to substantial long term vibration and limited shock. Military lasers are designed for use under adverse environmental conditions. The HESP lasers are designed with an exoskeleton optical bench and to comply with military environmental standard MIL-STD-810. This includes Altitude-method 500.2, Humidity-method 507.2, Acceleration-Method 513.3, Vibration-method 514.3 and Shock-method 516.3. It appears that military standard test specifications are tougher than the vibration test specifications for engine mount automotive products [13]. The mil-spec calls for shock and vibration compliance of random vibration frequency testing at 20 to 40 g's while the automotive requirements are limited to less than 15 g's. Other exoskeleton optical bench lasers such as the BMLIS and MK-367 have withstood shock and vibration testing in excess of 1000 g's [14,15].

Environmental

Lasers and optical instrumentation designed for outdoor use are typically hermitically sealed backfilled with dry inert gas. DPSS lasers are most sensitive to environmental temperature fluctuations as the diode pump wavelength changes with temperature. This can be especially troublesome in Nd:YAG and other crystal host DPSS lasers as their pump band width tends to be narrow. Glass host DPSS lasers provide broad pump band widths allowing them to traverse through -30 to +50 ^{o}C mil spec temperature operating range without the need diode thermal conditioning. A typical specification for diode wavelength drift with temperature is 0.25nm/ ^{o}C. Figure 2 illustrates the difference in pump band width and how it affects the thermal stability of neodymium doped crystal and glass host lasers.

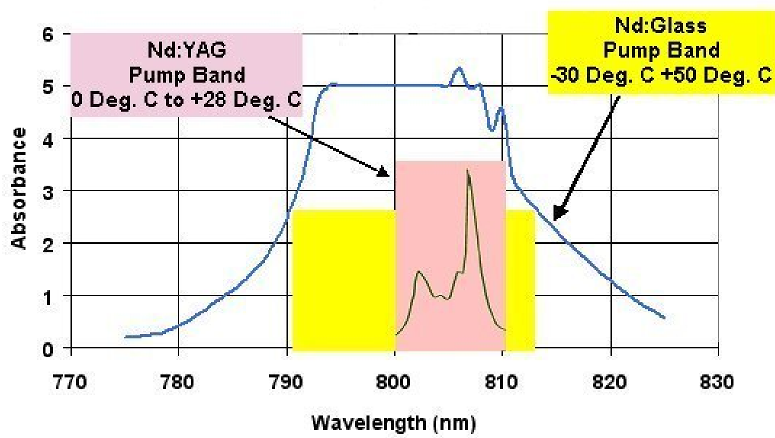

Fig.2 – Effective diode drift range for Nd:YAG and Nd:Glass pump bands

The ideal laser spark plug requires maximum performance over large temperature ranges with minimum thermal conditioning. Decreasing the laser's thermal conditioning requirements makes the laser design less complicated and less expensive to build and maintain.

Peak Power

The peak power requirements for the laser spark are relatively high. Formation of a plasma or "laser spark" in free space air is not difficult if you start with Megawatt class (nanosecond pulse width - millijoule energy level) laser pulses. Simple optics may be used to focus a Q-switched laser pulse and breakdown air if sufficient peak power is contained within the laser pulse. Megawatt (raw beam) laser pulse power densities are readily focused to form a plasma spark at distances of 20 to 50mm using a single lens. More complicated lens systems may be employed to focus the laser spark at longer distances. As the engine cylinder head pressure increases, the required laser pulse peak power level for air breakdown decreases. With a multiple lens focusing system it is plausible that one could reliably project a laser spark into a high pressure cylinder head utilizing lower Kilowatt class pulse power densities. High peak power pulses are obtained from a laser by spoiling the Q-factor of the resonator cavity. A passively Q-switched laser contains a saturable absorber or passive Q-switch. This passive Q-switching method provides for smaller, simpler and less expensive high peak power laser devices than alternative means of intra-cavity modulation.

Passive Q-switched lasers also allows for generation of a multiple laser pulse output or "pulse train." The first pulse of a pulse train initiates the plasma and successive pulses feed more energy into the plasma causing the plasma to expand. For neodymium lasers the pulses are typically separated by a few 10's of microseconds. The net result of pulse train operation is a longer sustained plasma containing higher energy. The substantial increase in plasma energy with pulse train operation is illustrated in figure 3.

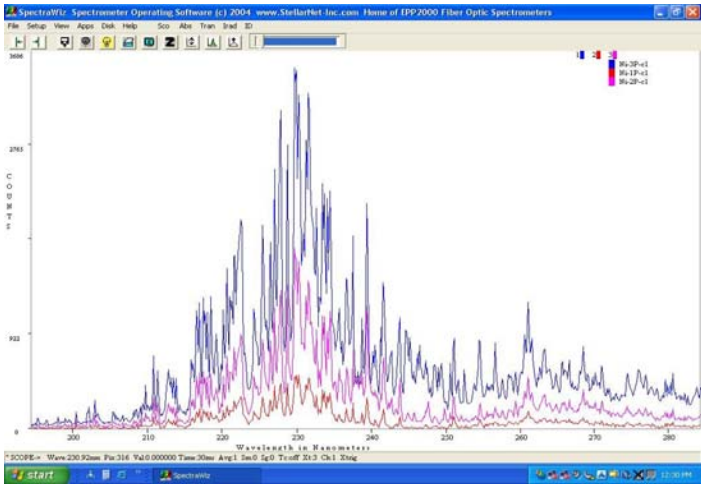

Fig. 3 – Increase in laser plasma induced line spectra signal strength resulting from 1, 2 and 3-pulse train operation

Average Power

The average power requirements for a laser spark plug are relatively modest. A four stroke engine operating at maximum of 1200 rpm requires an ignition spark 10 times per second or 10Hz (1200rpm/2x60). For diode pumped neodymium lasers pumping at ~ 800nm and lasing at 1000nm the quantum defect (~200nm) is relatively low and the quantum efficiency high. With for example 1-Joule/pulse electrical diode pumping levels we are readily able to generate high millijoule levels of Q-switched energy. This provides us with an average power requirement for the laser spark plug of say approximately 1-Joule times 10Hz equal to approximately 10 Watts.

Lifetime & Cost, New Micro-Laser Designs

With funding support from DARPA, Kigre developed core technology for a new generation of micro-lasers [16]. These megawatt class laser devices utilize a unique pumping architecture that provides a foundation for compact reliable high power/high gain laser devices an order of magnitude lighter, smaller, more efficient and less expensive than the existing state-of-the-art. The significant performance improvement in these High Efficiency Side Pumped (HESP) DPSS lasers is due in large part to the invention of a new generation of athermal high-gain laser glass materials and innovative conduction cooled packages (patents pending) that portends long diode lifetime at high power levels with minimal thermal conditioning requirements. Lifetime testing of pre-production HESP laser devices designed for applications in eye-safe laser surveillance and detection systems is currently underway. Figure 4 illustrates improvement in laser life. These improvements include implementation of unique conductive cooling designs and the use of lower diode pump amperage settings. Further improvements and life testing is currently underway.

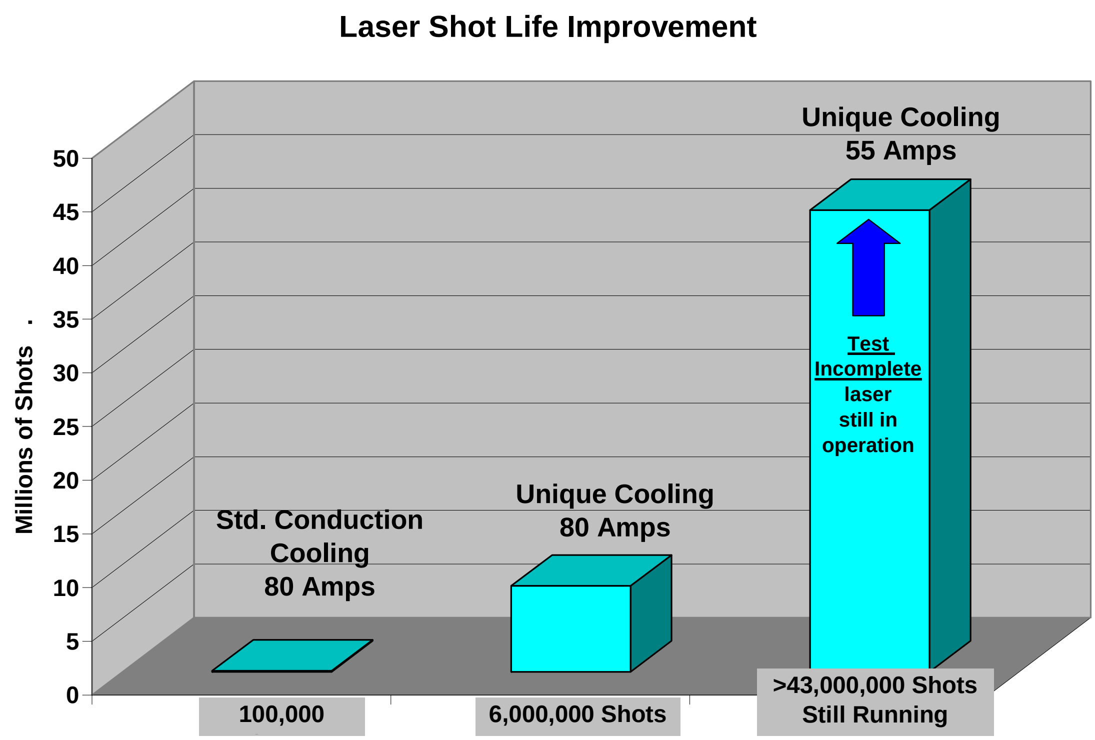

Fig. 4 – Laser life improvement with lower amperage levels and unique cooling

Conclusion

Small, low cost, long life, conductively cooled mil-spec HESP DPSS lasers may be fitted with threaded bulkhead seal sapphire focusing lens beam delivery optics to form a practical laser spark plug. The unit is mounted directly into the cylinder head and cooled via a small fan or other modest temperature controls including water to air and thermo-electric. Laser spark plug prototypes may be packaged into housings similar to that used for the erbium glass HESP DPSS lasers as shown in figure 5 below.

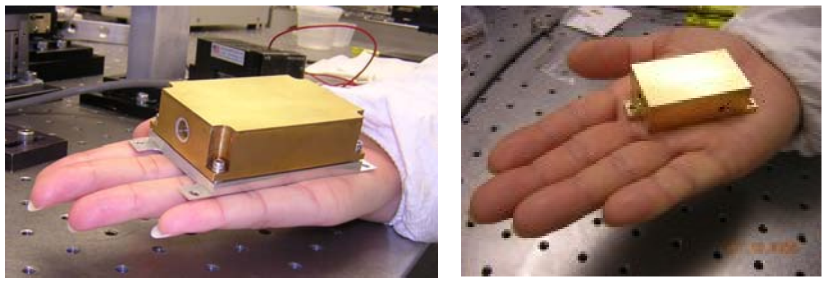

Fig. 5 - Erbium glass HESP DPSS laser conduction cooled packages

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