Fiber optic cables for laser ignition applications

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Abstract

To fundamentally improve the combustion process for lean-burn natural gas compression engines, alternative ignition sources are considered. By use of a high power laser and fiber optic cables, a system is realized for the spatially complex high energy pulse transfer necessary for plasma spark formation inside the engine's combustion chamber. Given the multitude of styles of fiber optic cables available on today's market, considerations must be made to apply only the most suitable fibers capable of meeting this application's strict requirements. The following is an overview of the theory behind laser ignition and a review of the different styles of fiber optic cables considered for field application.

Introduction

Laser ignition is an ongoing area of research at Colorado State University aimed toward increasing the combustion efficiency and reducing the exhaust emissions of stationary natural gas internal combustion (IC) engines. The scope of this project aims to completely reengineer the ignition system of an IC engine by implementing the use of laser power to induce combustion instead of an electric arc from a spark plug.[1] Similar to how a potential difference in an electrical system will increase with poor terminal connection, the quality and loss of laser transmission is highly dependent upon the pathway and medium transitions the beam encounters within the optical circuit. High quality transmission for IC engine applications requires an extremely precise optical circuit to be resistant from environmental influences such as inconsistent vibration and heat. A solution to overcome these concerns is to incorporate a fiber optic cable where the optical alignment of an open beam is most likely to be compromised. The following is an overview of laser ignition theory and a review of the fiber optic cables considered for high intensity pulsed transmission.

Ignition is achieved within the combustion chamber be means of a high intensity pulsed laser being directed toward an optical distributor (rotating set of mirrors) known as a multiplexer. The multiplexer sequentially distributes the laser pulses to a desired fiber optic cable dependent upon firing order and crankshaft speed. The pulse is then transmitted down the length of the fiber toward its respective cylinder. Analysis and testing of fiber optic cables for laser pulse delivery has shown that high intensity pulses and low output beam divergence are required for spark formation. Each fiber is connected to an optical spark plug which uses a plano-convex lens to tightly focus the laser pulse to a desired location within the combustion cylinder of the engine. A specific location in the cylinder that the pulse is to be focused can be controlled via the focal length of the lens. This allows for a more complete and uniform burn to occur leading to higher fuel efficiency and a greater power output.[1] The range of focal lengths that can be applied to this system is fundamentally bounded by the power and beam quality considerations imposed by the

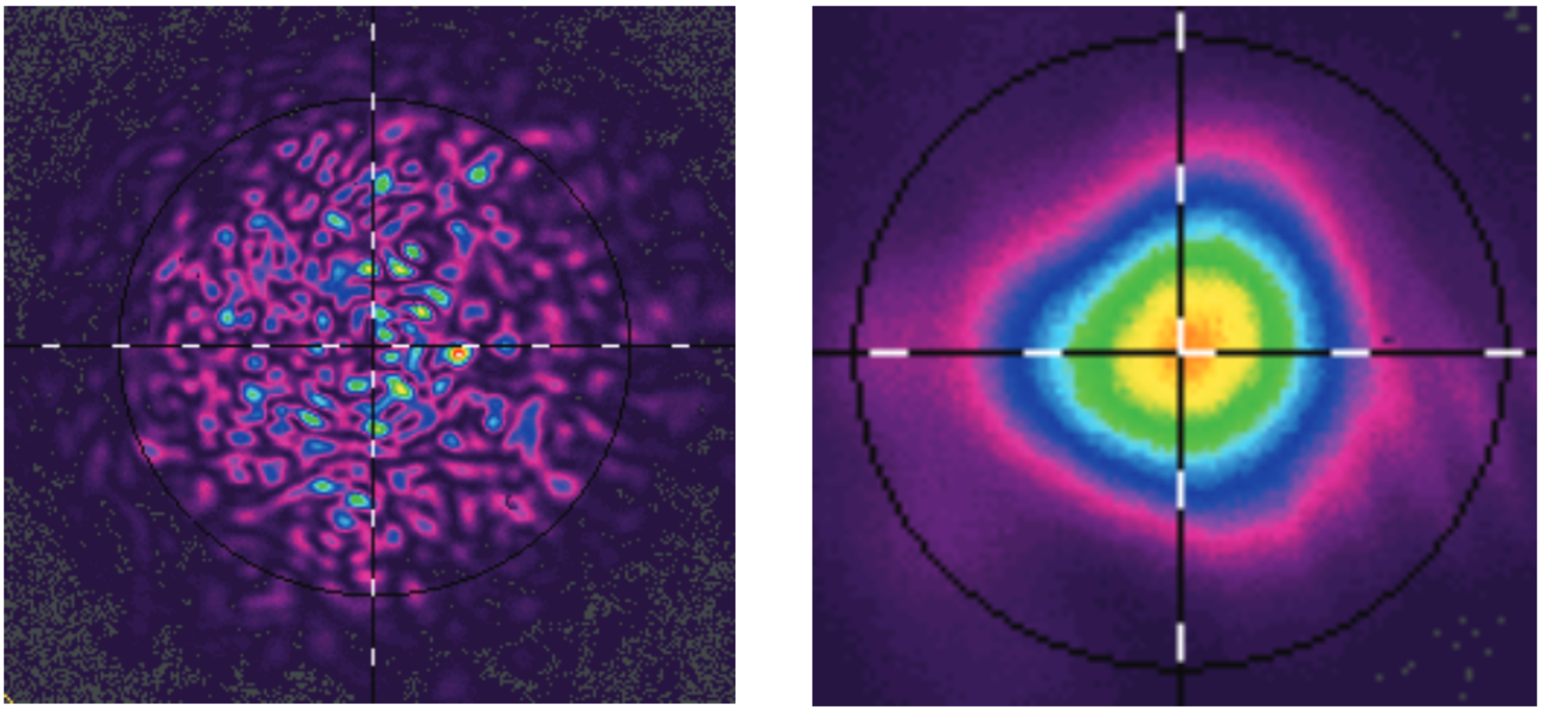

Figure 1. Output beam intensity profile due to mode coupling from externally induced stress (left), and desired beam quality output (right).

fiber. A longer focal length results in a larger spot size at the focal point of the lens requiring a greater laser power to initiate plasma formation.

Tightly focusing a high power laser pulse causes a high optical intensity at the focal point of the lens. If this local intensity is greater than the breakdown voltage of a given medium, multi-photon ionization will occur and release electrons onto the medium.[2] These new free electrons are accelerated by the electric field and collide with other atoms of the given medium. This further ionizes the atoms leading to an avalanche of electron release, referred to in this article as a plasma spark. At standard atmospheric pressure and temperature, the breakdown intensity of air for plasma formation is ~100-200 GW/cm^2.[1] A plasma spark is desirable in compression applications due to the decrease of a medium's breakdown intensity with increasing pressure.[1] This behavior will allow for the engine to be run at a higher compression ratio and a leaner air fuel mixture, effectively reducing the concentration of NO_X emission in the exhaust.

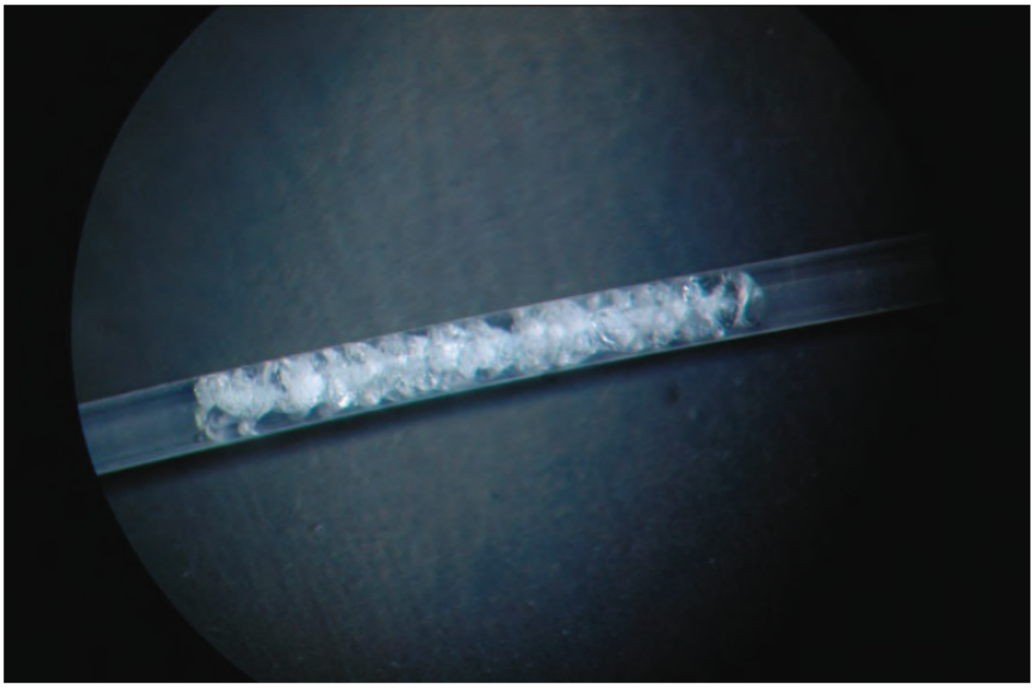

Figure 2. Solid core step index fiber with exceeded damage threshold of ~1-5 GW/cm^2.[5]

The amount of induced stress residing in the core and cladding of the fiber optic cable has been found to have a significant impact on the laser beam's intensity profile at the fiber's output. The quality of a beam is quantified by its M^2 value, dependent upon wavelength. It is a ratio of the actual beam parameters over the ideal Gaussian beam (TEM00) where the best possible beam quality has M^2=1.[3] A fiber in a relaxed state where external influence is minimized provides a more desirable M^2 value than a fiber influenced by a force (bending, surface load, etc.). An exception to this is a uniformly distributed bend or coil which will cause a reduction in transmission efficiency but will also cause the fiber to lose its higher order modes resulting in higher beam quality. Figure 1 shows the difference in output beam quality of a fiber induced with external stress compared to the desired output profile. The most stress occurring in a fiber oriented in a relaxed state is found to be localized in the connector. The connectorization of large core fibers for high intensity pulse transmission requires the proper epoxy selection and curing time to minimize these stresses allowing for less attenuation. An epoxy with a high thermal conductivity along with a 0% curing volumetric expansion rate is desired to minimize the induced mechanical and thermal stress transmitted to the fiber's core and cladding from the epoxy. Increasing the core and cladding stress in a fiber causes mode coupling to occur and will lead to local intensity peaks. If the intensity peak is greater than the damage threshold of the silica core, the fiber will suffer damage and be rendered useless.[4]

Preparation of the input and output ends of the fiber cable are very critical to obtain the best possible pulsed transmission. A uniformly spatial beam distribution across the fiber face is strongly desired and is obtained by having a perfectly flat surface polish. The polishing process is a laborious procedure which must be conducted with the utmost cleanliness and care to ensure the final quality of the fiber's face. A poor surface finish will lead to unwanted light scattering, Fresnel back reflection, a high M^2 value and may cause damage to the fiber via mode coupling and local intensity peaks.[4] The fiber shown in Figure 2 has reached its damage threshold due to undesired mode coupling near the fiber's input face. It is this silica to air medium transition that is most critical for high energy and high beam quality transmission.

In order for laser ignition to be applied to an IC engine, a means of transmitting a high energy laser pulse is required to be impervious to harsh engine conditions. Several styles of fiber optic cables are considered to accommodate the task of megawatt pulse transmission necessary for plasma spark formation. Fiber cables are attractive due to their flexibility, which is needed for routing from a remotely located laser and multiplexer to a designated engine cylinder. A durable exterior jacket on the fiber is also desired to absorb vibrations induced from the engine and to protect the core-cladding interface. The implementation of a fiber optic cable will provide the optical alignment necessary for the ignition system to function properly in field applications.

Fiber optic cable review

There are several styles of fiber optic cable which vary geometrically and in material composition to compliment a specific application. Only a select few have the necessary features to accommodate the requirements for laser ignition. These fibers must be able to transfer megawatt power laser pulses of adequate beam quality to allow for the breakdown threshold of gas to be reached at the fiber's focused output. For gases such as methane, the breakdown intensity of a reasonable air fuel mixture is ~100-200 GW/cm^2 which presents an optically challenging situation for pulsed laser delivery.[1,6,7] Breakdown has been achieved with energies as low as 4 mJ at 10 ns pulse durations, however ignition of most air/fuel mixtures is achieved with pulse energies of ~15 mJ.[5,8] The following discusses the styles of fibers that are considered for laser ignition applications.

Hollow core

An attractive means of high power pulse transmission is by use of a hollow core fiber. The hollow core fiber is composed of an inflexible hollow quartz tube with a polymer coating and is typically covered with a highly reflective material such as silver or nickel.[3] This reflective material is the limiting feature for high intensity pulse transmission and has a relatively high damage threshold. Energies as high as ~35 mJ for ns pulse durations have been transmitted through the fiber's atmospheric medium producing an exit intensity of 2 GW/cm^2, proving them to be a viable candidate for spark production.[7]

For field applications, hollow core fibers are limited by their bending performance and fragility. A typical stationary natural gas engine can operate at frequencies anywhere from 300 to 500 rpm. Since the output of the fiber must be coupled to the cylinder head, the fiber will experience the frequency and amplitude at which the engine is operating. The brittle nature of these fibers makes them less than ideal for operating in parallel with the harsh conditions of an engine. As a hollow core fiber is bent, beam transmission dramatically decreases and exit beam divergence (M^2) value increases. Therefore, bending loss is a large limiting factor for hollow core fibers applied toward laser ignition and are not ideal for field use.

Photonic crystal fibers

Another fiber type considered for laser ignition is a photonic crystal fiber which typically has a hexagonal core pattern in structure. The patterned structure of the photonic crystal fiber is designed to modify the refractive index of the cladding. This is done to maintain a consistent relationship between the core and cladding, effectively allowing the fiber to operate in single mode transmission.[7] There are two main types of photonic crystal fibers that have the potential for spark delivery: hollow core photonic bandgap (PBG) fibers and solid core photonic crystal fibers (PCF). Since the output beam of a PCF is approximately single mode, the fiber can therefore deliver high intensity pulses. Single mode output allows for plasma generation to be achieved with ease. The structure of the PCF allows for bending and vibrational loss to be kept to a minimum which is ideal for field applications. Large mode area (40-80 µm) PCFs have been shown to be capable of delivering 1064nm, ns pulses with 0.55 mJ at the output and to have a higher damage threshold of ~3X than that of a PBG.[5,7] Due to the large energies required to create a plasma spark, PCFs are more desirable for plasma generation than PBGs.

Although the PCF operates in single mode and has low loss due to bending and vibrational influence, the amount of power that can be transmitted is comparatively limited. PCFs have been proven capable of creating plasma sparks in air but only at elevated pressures with low pulse energies of <~1mJ.[7] This is an insufficient amount of energy for the ignition of lean air/fuel mixtures and, therefore, use of these fibers is challenging for laser ignition applications.

Fiber laser

The output of a fiber laser is fundamentally fiber delivered and provides a means of integrating the desirable fiber delivery medium with a laser source. A fiber laser has a doped fiber as a gain medium and resonator and is a comparatively compact option. Recent developments in fiber laser technology have expanded to an increased core diameter, and due to the inherit integration of the source with the medium, have led to a relatively high beam quality output. It is this combination of large core area and high beam quality which makes fiber lasers highly beneficial for spark generation. Laser breakdown in air has been successfully accomplished using 0.7 ns duration with 2.4 mJ pulse energies.[7] This is an insufficient amount of energy to effectively ignite a lean air/fuel mixture, and further fiber laser improvements are required to better fit the application. Fiber lasers are a rapidly growing area of interest and have the potential to become an ideal component in laser ignition research.

Single mode solid core fibers

The applicable solid core fibers for laser ignition intentions come in several styles and constructions. A solid core fiber optic cable is only capable of supporting a discrete set of modes which is a strict function of the transmission wavelength, refractive index profile and geometry of the fiber. Modes which are not supported by the fiber will either leak out of the fiber resulting in an increase in overall transmission loss or be canceled out due to interference effects.[3] Regardless of the wavelength at which a pulse is to be transmitted, there is a certain amount of radiation that will not be totally internally reflected and will leak out of the core and into the cladding. This produces an isolated radiation mode which may cause loss to the signal at the fiber output. How the radiation modes affect the output is a function of the cladding size. A properly sized core/cladding ratio will allow for maximizing the transmission peaks in the spectra of fiber modes allowing for ultimate transmission to be achieved. Alteration of the fiber's structure also allows for the modification of the transverse distribution of radiation intensity within the fiber's core. This allows for waveguide transmission to occur for the fundamental mode of the fiber.[5]

Perhaps the most common types of solid core fibers are single mode fibers with core diameters of ~8 µm. These fibers are most widely used for telecommunication applications and are designed to transmit low energy signals over long distances. Although the single mode output is ideal for plasma generation, these fibers are limited by the amount of energy they can transmit without reaching their damage threshold. The small cross sectional core size is the limiting feature in a single mode fiber since the fiber's damage threshold is quickly reached at high input powers.

Multimode gradient index solid core fibers

A more useful fiber for high intensity transmission is a solid core fiber with a graded core index. The graded core has the highest refraction index at the center of the core and decreases radially as the core approaches the cladding interface with a parabolic distribution. The gradient of the index change has a profound impact on not only the power distribution throughout the fiber but also on the overall optical loss and the velocity at which various modes propagate as well. The effect of this graded index is that each mode is gradually refracted as the beam traverses the fiber. It is this property that ensures only the highest order modes reach the core cladding interface. The graded core allows for a better output beam quality and a peak intensity at the focal point of about five times that of a step index fiber of similar core size.[3] This makes the graded core fiber a highly viable candidate for high intensity pulsed transmission. The steep intensity peak is ideal for cutting and drilling applications but may be harmful to sensitive optical setups and equipment. Although a graded core fiber can allow for higher peak intensity to be achieved at the focal point compared to that of a step index fiber, the peak power that may be transmitted through a graded index is less than the peak power that may be transmitted through that of a step index due to tighter focusing that occurs within the fiber's core.

Also to be considered is the alteration of radial index profile as a bend in the fiber is introduced. A bend causes stress to be induced on the fiber's core, leading to an effective non-symmetric radial index profile. The latter has been shown in uniform index fibers as well. The index change is more significant in a graded core fiber, and when influenced by stress will result in a skewed parabolic index contour and rather unpredictable mode coupling.

Multimode step index solid core fibers

Step index fibers are perhaps the most ideal fibers for high intensity pulse transmission.

Their construction is of a constant refractive index across the core of the fiber followed by an abrupt index increase at the cladding interface. A coating and jacket layer surround the cladding to make the fiber more resistant to external influence such as stress, bending and heat. The core/cladding ratio is available in several different configurations dependent upon wavelength and application and can be fabricated to nearly any size desired (~50-1000 μm core). Under ideal fiber operation, total internal reflection will occur at the core cladding interface for all of the modes the fiber supports. The consistency of the core's refractive index results in a more uniform intensity profile at the step index fiber's output. It is this quality which makes step index fibers attractive for laser ignition applications.

Recent advances in the research of step index fibers (core/clad=400/720) have shown that the transmission of 3mJ at 10 ns pulse durations using 1064nm light is capable of producing 100% plasma spark generation in air at atmospheric pressure.[8] Although this energy is below the minimum energy required for ignition of applicable gases, much higher transmission energies can be achieved at longer laser pulse durations. This presently makes the solid core step index fiber optic cable the most applicable style of fiber for laser ignition applications.

Conclusions

Prior to the full implementation of a laser based ignition system, more testing is required to understand fully how a fiber optic cable will behave in a harsh engine environment for high power transmission. The transition between air and the fiber's silica core is the most critical aspect of pulse transmission through a fiber and is a significant limiting factor for laser ignition applications. Future experimentation will be focused on minimizing the back reflection and local intensity peaks by selective fusion splicing and investigating the use of index matching fluid for high power applications. The effects of beam quality output from externally induced vibrations are to be considered as well. Proven to be the most applicable candidate for laser ignition, these tests are to be performed primarily on multimode step index solid core fibers. A better understanding of how these fibers respond under specific design conditions is a major stepping stone to practical application. This study and implementation of a laser ignition system is constantly progressing and is sure to be a revolutionary aspect in the future development of internal combustion engines.

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