Cent. Eur. J. Phys. • 8(2) • 2010 • 242-248
DOI: 10.2478/s11534-009-0146-1

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Central European Journal of **Physics**

Transportation of megawatt millijoule laser pulses *via* optical fibers?

Research Article

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Received 3 December 2008; accepted 17 September 2009

Abstract: Laser ignition is considered to be one of the most promising future concepts for internal combustion engines. It combines the legally required reduction of pollutant emissions and higher engine efficiencies. The igniting plasma is generated by a focused pulsed laser beam. Having pulse durations of a few nanoseconds, the pulse energy E_p for reliable ignition amounts to the order of 10 mJ. Different methods of laser ignition with an emphasis on fiber-based systems will be discussed and evaluated.

PACS (2008): 42.62.Cf, 42.81.Dp, 52.38.Mf

Keywords: optical fibers • high-power pulse propagation • laser-induced damage • laser ignition

1. Introduction

An essential fraction of the surge-current production is based on combined heat and power plants where the mechanical energy of internal combustion engines is employed to power electric generators and the exhaust gas is used for the exploitation of thermal energy. Consequently, the efficiency of such power plants, and therefore of the engines, must be as high as possible while the pollutant emissions should be kept low. Such requirements cannot longer be realized satisfactorily using conventional engine ignition techniques. For example spark plugs reach their limits at the necessary high ignition pressures required for excessively high voltages. However, there are several alternative ignition concepts for example plasma ignition, high-frequency ignition, Diesel micro-pilot ignition and laser ignition which may contribute to an improvement of the overall engine efficiency. To our knowledge, laser ignition represents the most promising future ignition concept for a number of reasons [1–4]. The main advantages of laser ignition, among many others, are performance enhancing high effective mean pressures in the combustion chamber as well as the feasibility of very lean mixtures lowering the flame temperature and consequently the NO_x emissions.

In general, the mechanism of laser ignition is based on non-resonant gas breakdown [5] of the tightly focused pulsed (nanoseconds) laser beam. Initial electrons absorb photons to gain energy *via* the inverse Bremsstrahlung process. These energetic electrons can ionize gas molecules *via* the electron avalanche process leading to the breakdown in the focal region. It is important to note that this process requires initial seed electrons [6]. These seed electrons may be produced from thermally heated or linearly ionized impurities like soot

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or dust in the gas mixture. In addition to the thermally generated seed electrons in the focal region multiphoton ionization (MPI) may also be a source of initial electrons, but at wavelengths around 1 µm the probability of simultaneous ionization of the atoms is very unlikely [7]. The optical thresholds for MPI for most gases (O_2, N_2, CH_4, *etc.*) are in the order of several 10^{11} W/cm^2 and decrease when the pressure in the combustion chamber increases. Furthermore, the breakdown threshold decreases by almost one order of magnitude when small particles or aerosols are present in the focal region [8, 9]. However, the required energy for plasma formation is in the order of 100 µJ at pulse durations of approximately 1 ns [1, 10]. For laser design considerations, the flame kernel energy is much higher than the required energy for plasma formation. Therefore, the minimum ignition energy rather than the plasma energy has to be considered when designing the laser ignition system.

The plasma formed by the mentioned ignition mechanism can ignite the combustible mixture. Plasma diagnostics revealing shock waves, ignition kernels and flame propagation were observed by high-speed Schlieren photography [11]. The different phases of laser ignition can be defined in chronological order [12]:

i. Electric breakdown and energy transfer from laser to plasma
ii. Shock-wave generation and propagation
iii. Gas dynamic effects
iv. Chemical induction of branching chain reactions of radicals leading to ignition
v. Turbulent flame initiation

Fig. 1 illustrates the plasma formation and the onset of combustion. Fig. 1a shows a multi-exposure image allowing the observation of a shockwave in 500-ns steps. The temporal expansion of the flame kernel is also illustrated using Schlieren photography (Fig. 1b) and PLIF imaging (Fig. 1c). For all of the images shown in Fig. 1 the laser pulse enters from the right with an energy of 140 mJ (E_p), the initial pressure of the mixture was 4.3 bar (p_{in}) and the relative air/fuel ratio (λ) was 1.3 [13].

As mentioned previously, non-resonant breakdown in gases requires intensities of several 10^{11} W/cm^2 in the focal region [1, 2, 10, 14–16] to be provided by a focused laser pulse with minimum energy $E_p = 0.1$ mJ and pulse durations $\tau_p \leqslant 10$ ns. For pulses down to several picoseconds the breakdown threshold increases according $\tau_p{}^{-1/2}$ [6]. Experiments revealing the minimum pulse energies (MPE) for ignition of different fuel-air mixtures (methane-air, hydrogen-air, methane-hydrogen-air) under

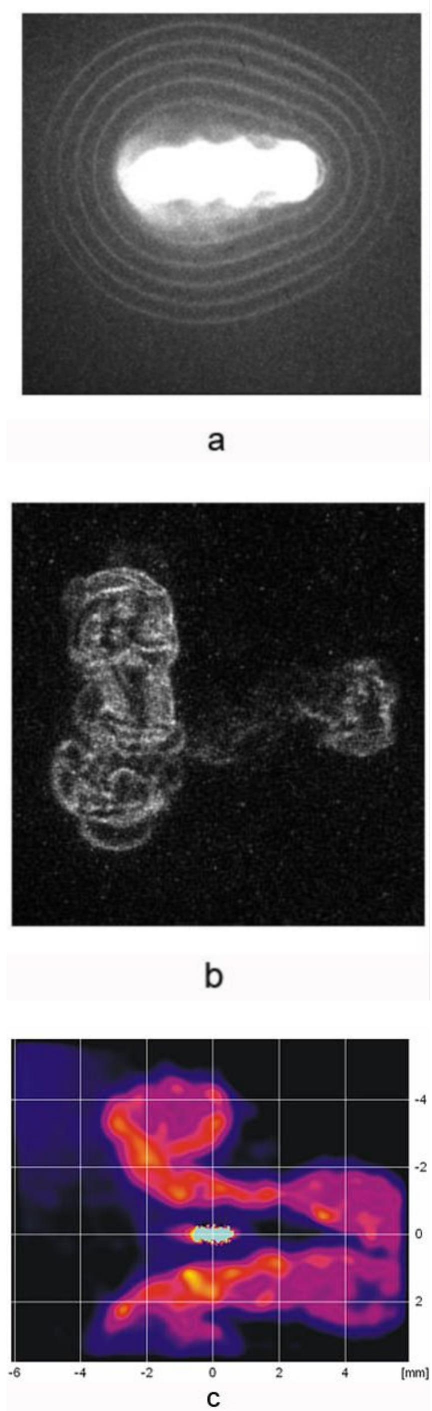

Figure 1. (a) Multi-exposure Schlieren image of shockwave emission around a plasma spark in air at 10 bar in 500-ns steps after ignition. (b) Schlieren image of a stoichiometric methane-air mixture at 10 bar, 500 µs after ignition. (c) Planar Laser-Induced-Fluorescence (PLIF) image of OH-radicals; in all cases, the laser beam enters from the right hand side [11, 13].

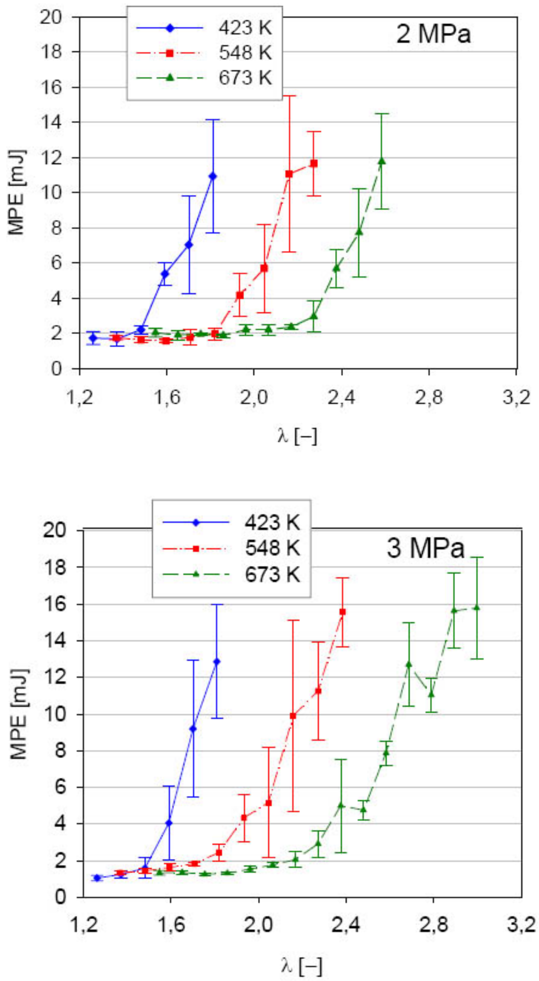

Figure 2. The minimum pulse energy (MPE) *versus* the relative air/fuel ratio (λ) for different temperatures (T) and initial pressures (p_{in}) of 2 MPa (=20 bar) (top) and 3 MPa (=30 bar) (bottom). The measurements were taken in a constant volume high-pressure vessel [22].

engine-like conditions have been reported in former work, partly by our group [1, 2, 10, 17–20]. Furthermore, laser ignition for biogas applications has also been successfully studied [21].

While a plasma can be formed by pulse energies of only a few 0.1 mJ at 8 ns, the development of a flame kernel requires more energy in order to ignite the mixture at higher λ and lower temperature (T) [22]. Fig. 2 clearly illustrates this concept. Moreover, for stoichiometric mixtures the MPE is independent of T, as also shown in Fig. 2. The higher p_{in} and λ are, the higher the engine efficiency and the lower the NO_x emissions, as illustrated in Fig. 3 and Fig. 4. Therefore a relative air/fuel ratio of $\lambda \geqslant 2$ is desirable.

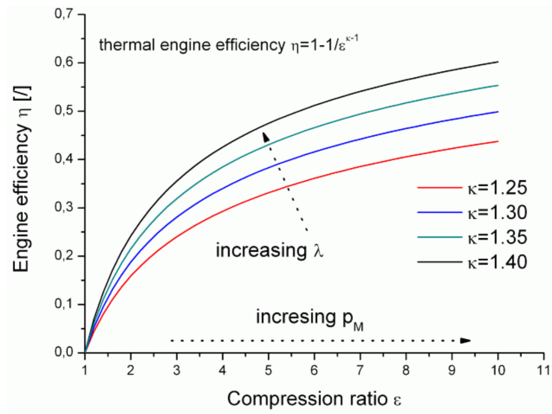

Figure 3. Theoretical engine efficiency as a function of the effective mean pressure p_{in} and the relative fuel/air ratio λ.

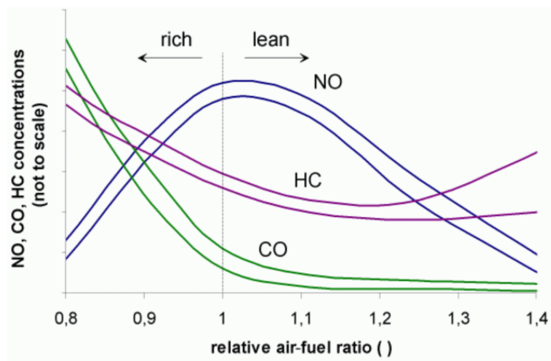

Figure 4. NO, HC and CO emissions as a function of λ [23].

In order to ensure reliable ignition for various operational conditions of the gas engine, a ns-laser pulse with $E_p = 5 \div 10$ mJ is necessary. Furthermore, we could prove that shorter ns-pulses ($\approx$1 ns) are more effective than long ns-pulses ($>$ 10 ns) as the transmission of a plasma decreases with τ_p down to several 100 ps.

2. Fiber delivery-based laser ignition systems

The concept of an optical ignition system emerged in the late 1960s and has been successively studied and improved by several groups [6, 12, 15, 24, 25]. The coupling of laser radiation into the combustion chamber can be realized by various approaches [25], two of the most promising are:

- A separate ignition laser is mounted on every cylinder head each of which is supplied by an external

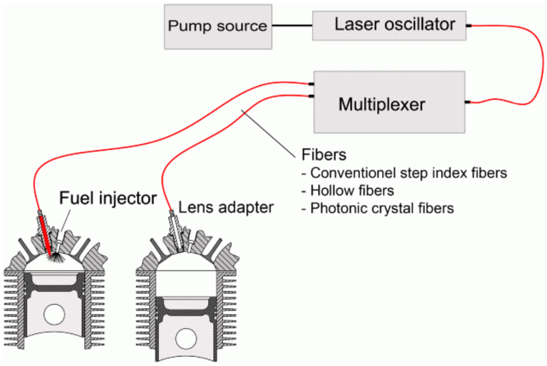

Figure 5. Scheme of laser ignition *via* optical fibers.

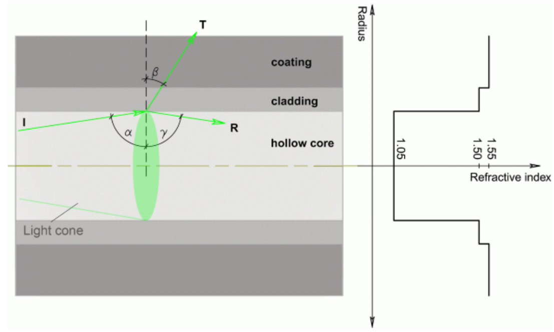

Figure 6. Scheme of propagation in a hollow core capillary. The higher the incoupling angle, the higher is the coeffi-cient of reflection according Fresnel's equation; Acronyms: I - initial; R - coefficient of reflection; T - coefficient of trans-mission (=1-R).

pump source (laser diode). This is termed a laser spark plug.

- The laser unit and engine are separated and the ignition pulses are transported *via* optical fibers to the cylinders.

The conceptual ideas and experiments dealing with the development of a compact ignition laser can be found in our recent publication [26]. Unfortunately, such a laser system is exposed to parasitic influences like temperature and vibration on the engine head. Therefore, the idea of fiber transportation of the ignition pulse becomes the most plausible solution. Potential fiber candidates for ignition pulse propagation are:

- conventional step index fibers (SIF),
- hollow-core fibers (e.g. photonic band gap fibers, hollow dielectric capillaries).

The most restrictive factor with respect to fiber use is the damage threshold of the material. Peak intensities beyond 10 GW/cm^2 may cause significant damage of the fiber material since the laser-induced damage threshold (LIDT) for ns-pulses is the order of several GW/cm^2 [27]. Therefore, using conventional solid-core step-index fibers (SIF) the diameter of the core where the beam is guided, has to be enlarged in order to reduce the intensity of the laser pulse. An enlargement of the diameter of the fiber at a fixed wavelength implies multimode beam profiles. The focus of the ignition pulse depends strongly on the beam profile and therefore multimode radiation would enhance the MPE and more laser energy would be necessary. Several investigations in high-power pulse propagation have been performed [28–30], for example ignition pulses with 45 mJ at a pulse duration of 6 ns have been successfully transported over a 940 µm–SIF [28]. However, no plasma formation after focusing at atmospheric conditions was noticed. More powerful laser pulses (20 MW) have been propagated over a 1500 µm–SIF [29] and plasma formation at a target and not in air has been reported. The measured damage threshold was around 4.4 GW/cm^2, which is in agreement with that reported in the literature. An appropriate method for determining the LIDT can be found in recent publications [31, 32]. For fused silica, which is one of the most common material for fibers, the LIDT behaves according $(\tau_P)^{1/2}$ and is around 5 GW/cm^2 for ns-pulses [27]. Moreover, the LIDT also depends on the focal spot size since the damage mechanism is mostly due to defects somewhere in the material. With a smaller spot size the probability of meeting a defect is lower and consequently the the value for LIDT is higher [33]. In [31] values for the damage threshold between 14 and 24 GW/cm^2 (1064 nm, 15 ns) in multimode fibers (diameter 180...600 µm) have been reported. Nevertheless, pulse propagation *via* optical fibers is theoretically possible, but appropriate focusing causing efficient plasma formation remains unlikely. In this paper, efficient plasma formation is associated with good beam quality and consequently lowest energies for plasma generation. One way decreasing core damage is using fibers with a hollow core and guiding the beam *via* partial reflection. The simplest type of hollow-core fibers are hollow capillaries where the propagation is based on partial reflection at the boundary layer between the core and the cladding material.

Considering the simplest case, as illustrated in Fig. 6, where the total energy of the laser beam is concentrated on the surface of the light cones, the fiber transmission, T, depends firstly on the number of reflections, ψ.

The fiber transmission, T, can be calculated by Eq. (1)

$$\mathrm{T} = \frac{E_{OUT}}{E_{IN}}, \qquad (1)$$

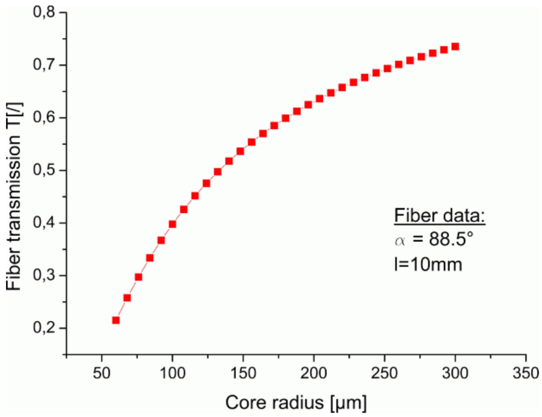

Figure 7. Simulation of the fiber transmission *versus* the core radius. The transmission increases as the diameter increases. This is due to the lower number of reflections at higher core diameter.

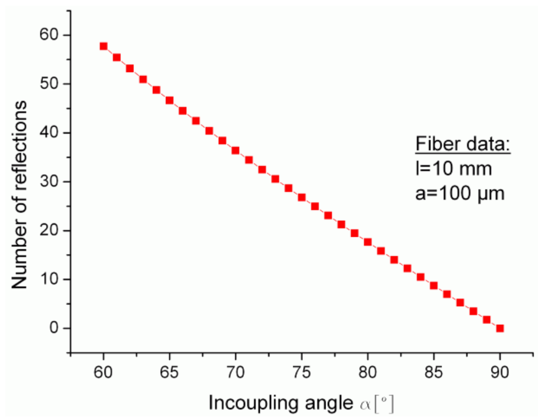

Figure 8. The number of reflection per unit length decreases when the incoupling angle increases. Therefore incoupling angles close to 90° (corresponding to focal lengths > 200 mm) are desirable.

where E_{IN} is the input energy and E_{OUT} the output energy. Assuming a single reflection (one cladding layer) the number of reflections over the fiber length can be derived by geometrical aspects (Eq. (2)).

$$\psi = \frac{l}{a \times \tan \alpha}. \tag{2}$$

In the Eq. (2), l denotes the length of the fiber, $2a$ is the fiber diameter and α the incoupling angle. Neglecting the simplicity of this model, it is obvious that the fiber transmission decreases as its length increases since every reflection causes an additional loss. The coefficient of single reflection$r$ can easily be derived by the Fresnel equations and the fiber transmission (1) can be rewritten as

$$\mathrm{T} = r^{\psi}. \tag{3}$$

It is important to note, that the losses (more or less the coefficient of transmission of a single reflection) cannot be avoided and can only be reduced e.g. by the use of dielectric multilayers. In other words, the light is reflected by many layers acting as a dielectric mirror for the designed wavelength. By applying such a multilayer structure, the coefficient of reflection r grows very close to 1. As illustrated in Fig. 7, the thicker the core of the fiber the higher the transmission since the number of reflections decreases. Moreover, the number of reflections can be reduced by incoupling angles close to 90° which can be realized by long focal distances of the incoupling optics, as illustrated in Fig. 8. Fig. 9 and Fig. 10 show a simulation for the resulting fiber transmission as a function of the incoupling angle and the fiber length, respectively.

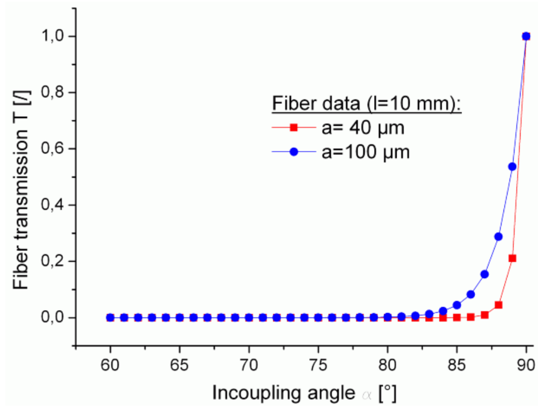

Figure 9. The fiber transmission as a function of the incoupling angle. As predicted, high fiber transmission can only be achieved at angles close to 90°C.

Our experimental investigations covered transmission measurements of single layer capillaries with diameters up to 200 µm and lenses with an effective focal length between 50 and 200 mm. The experimental results are in good agreement with the theoretical predictions shown in Fig. 10. In Fig. 11 the theoretical and experimental results are compared. Surprisingly, the experimental values for fiber transmission are higher than those of the simulation. This may be due to the assumption in the model that the whole energy is accumulated in the light cone instead of aGaussian distribution of the energy. However, the transmission decreases with increasing length which for laser pulse transportation is not optimal.
Several publications on coated hollow capillaries have been reported by A. Yalin and B. Willson and coworkers [34–38]. They have successfully demonstrated the

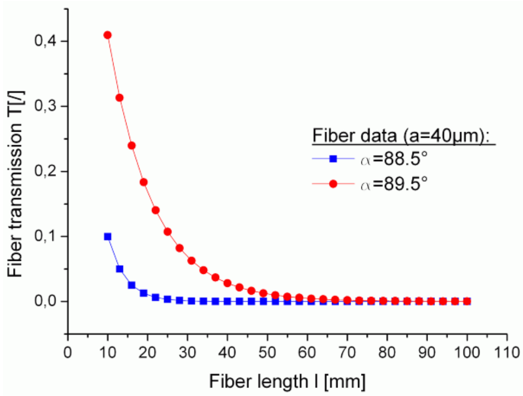

Figure 10. Fiber transmission *versus* fiber length. For this type of fiber, the transmission decreases strongly with the length of the fiber. An enhancement of the transmission can only be achieved by high reflecting coatings inside the capillary.

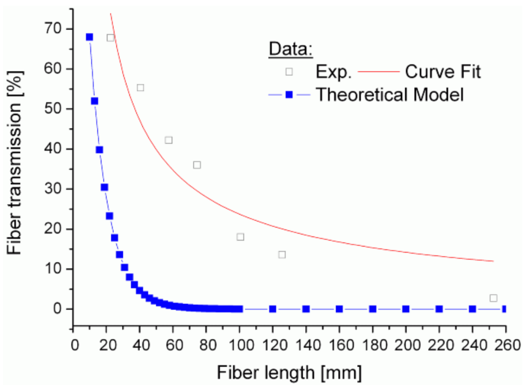

Figure 11. Theoretical *vs*. experimental results for fiber transmission. The experimental values are somewhat higher than their theoretical prediction. This may be explained by the assumption that the energy of the laser pulse is accumulated on the light cone.

propagation of intense laser pulses as well as the application of laser ignition on an engine using such hollow fibers.

Experimental investigations in [39] reported fiber transmissions greater than 80% using a 2 m-long and 700 µm-core diameter straight fiber and incoupling lens with an effective focal length between 135 and 315 mm. Bending of the fiber causes a drastic reduction of the fiber transmission and poor beam quality which leads to misfires. Although such hollow core fibers are able to transport significantly more pulse energy compared to conventional SIF, fiber damage remains a serious problem. In standard silica fibers, damage tends to occur in the core, either as damage on the end face or as a result of non-linear self-focusing effects within the core. Regarding hollow core waveguides, damage may occur before any measurable change in the output is noticed. Generally, the damage tends to occur close to the first bend [40].

In summary, dielectric hollow core waveguides are promising candidates for high power pulse propagation, especially for laser ignition as shown by the first engine demonstration by Yalin, Wilson *et al.* several years ago. Since the presence of radial losses of the hollow core, the overall efficiency of this type of waveguiding is somewhat lower compared to conventional pulse transportation mechanisms. Moreover, the drastic reduction of fiber transmission due to bending is disadvantageous especially for engine applications. However, even when these problems are taken into account, our colleges have demonstrated successful engine operation with a multiplexer (2-cylinder operation with one laser source) applying laser ignition with hollow-core waveguiding of the ignition pulse.

One way to minimize the radial losses of dielectric hollow-core waveguides are to use photonic band gap fibers where the pulse is trapped inside the hollow core by a surrounding 2-dimensional honeycomb structure. Similar to a semiconductor, these photonic band gap (PBG) fibers have a photonic band structure. Incident light with a photon energy inside this gap cannot propagate and is reflected by the structure [41]. Recent research investigations using PBG fibers for delivery of high power ns–pulses are demonstrated in [42]. Pulse trains with a total energy of 1 mJ have been transported *via* a 14 µm hollow-core PBG fiber. Successful delivery of 0.37 mJ for 1064 nm 65-ns pulses through a hollow-core PBG fiber has been shown in [43]. Using a 15-µm hollow–core PBG fiber we achieved transmitted pulse energies of nearly 0.8 mJ at pulse durations of 10 ns [44]. An incoupling efficiency greater than 80% has been yielded. It has been observed that at higher pulse energies damage of the honeycomb structure occurs. This damage may be due to the tails of the Gaussian beam incoupled into the fiber. However, in all published cases, the transmitted energy is well below the target of > 10 mJ required for lean mixture operation in engines.

3. Conclusion

We summarized the status quo in higher power pulse delivery with respect to laser ignition. In addition to the propagation of the laser beam the focusability of the output beam is of great interest. For this reason, conventional step index fibers are not appropriate for ignition pulse delivery. Hollow-core fibers are a promising candidate for ignition pulse propagation even if the overall efficiency of propagation is lower compared to conventional fibers.

The radial losses of the dielectric hollow capillaries due to partial reflection on the multilayer boundary between the core and the cladding cannot be avoided but can be minimized. Apart from the loss mechanism, hollow core capillaries have been successfully tested for ignition pulse propagation.

Considering fiber transportation, photonic band gap fibers allow the reduction of the loss propagation with a good beam quality of the output beam. Unfortunately, the transmitted energies are far below the required energy of approximately 10 mJ needed for ignition. In conclusion, laser ignition is one of the most promising candidates for a new ignition system, however,the realization of laser ignition in engines contains several problems which require to be solved – no matter which laser ignition system is applied.

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