Use of hollow core fibers, fiber lasers, and photonic crystal fibers for spark delivery and laser ignition in gases

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The fiber-optic delivery of sparks in gases is challenging as the output beam must be refocused to high intensity (∼200 GW/cm² for nanosecond pulses). Analysis suggests the use of coated hollow core fibers, fiber lasers, and photonic crystal fibers (PCFs). We study the effects of launch conditions and bending for 2 m long coated hollow fibers and find an optimum launch f# of ∼55 allowing spark formation with ∼98% reliability for bends up to a radius of curvature of 1.5 m in atmospheric pressure air. Spark formation using the output of a pulsed fiber laser is described, and delivery of 0.55 mJ pulses through PCFs is shown. © 2007 Optical Society of America

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1. Introduction

Initial demonstrations of the use of laser sparks to ignite combustible mixtures were performed in the late 1960s [1], and in recent years a relatively large number of studies have been performed [2–14]. By tightly focusing the beam from a high-power pulsed laser, a combustion-initiating spark can be created. While several modes of ignition are possible, our focus is on widely used nonresonant breakdown [2]. For commonly used nanosecond pulsed lasers (pulse duration ∼5–10 ns), the nonresonant breakdown sequence is initiated by initial seed electrons, which are accelerated by the electric field and create new electrons in collisions. The process is termed electron cascade and leads to avalanche growth [5,8] resulting in breakdown ionization. Following the initial breakdown, much of the remaining laser energy is absorbed by an electron-neutral or electron–ion (inverse bremsstrahlung) process providing a combustion initiating spark [11].

The first use of laser ignition for operation of an engine was performed by Dale et al. [15] using a CO₂ laser. Since then, a number of studies has investigated laser ignition for engine operation [13,16,17]. Laser ignition is of particular interest in stationary reciprocating gas engines [8,10,12,13], in turbine engines where igniter lifetime is a limitation, and in aircraft engines where flame extinction and relighting in adverse high-altitude operation can be problematic [18]. Our interest is primarily in large (megawatt class) stationary gas engines that are typically used for power generation and natural gas compression. Technology drivers include the need for increased efficiency and reduced pollutant emissions, which are trending advanced engines toward lean (reduced emissions) and high-pressure (increased efficiency) operation. Achieving this mode of operation is intimately connected to the ignition, and relatively high cost can be tolerated for an advantageous ignition system. Laser ignition is viewed as an attractive candidate technology as studies have shown the potential for increased lean limits [12,15]. Further, in contrast to conventional spark ignition (where the voltage requirement, dielectric breakdown, and erosion increase with pressure), laser ignition becomes easier at elevated pressures (the breakdown threshold intensity decreases) [19]. Briefly, the differences (potential benefits) of laser spark ignition stem from two sets of effects: The first is associated with the ability to freely locate the spark within the combus-
tion volume (by the selection of appropriate focusing optics) and the obviation of electrodes (which act as heat sinks and may provide catalytic chemistry), while the second is related to inherent physical differences between the two types of spark, for example, the higher pressure and temperature of laser sparks can lead to elevated (overdriven) early flame speed in laser ignition [11].

A key challenge for practical laser ignition systems is the need for fiber-optic delivery. The open beam paths used in most laboratory experiments are not considered practical for field (commercial) implementation owing to safety, maintenance, thermal, and vibrational issues. For gas engines of our interest several approaches are under investigation: (i) the use of a laser per cylinder [20], (ii) the use of a single laser per engine multiplexed through fibers to individual cylinders [21], and (iii) an intermediate approach in which (laser) pump light is fiber delivered from a single source to gain elements (amplifiers) located on each cylinder [22]. Our interest is in the second approach for which we require fiber delivery of high-peak-power (~megawatt) pulsed laser beams in a way that allows spark formation (in the gas phase) after exiting the fiber. This capability would have general application for the ignition of many other combustion devices in which laser ignition may have applicability (turbines and aircraft).

The ability to fiber optically deliver laser sparks (in the gas phase) would also advance practical laser-induced breakdown spectroscopy (LIBS) systems. Although fiber delivery and signal collection are routinely used for solid- and liquid-phase LIBS (where breakdown thresholds are orders of magnitude lower), gas-phase LIBS systems do not currently use fiber delivery. In this context we also mention that laser ignition of engines affords the possibility of a range of optical diagnostics including LIBS (with the combustion initiating spark), and optical emission spectroscopy (of the combustion light). The laser delivery inherently provides a window into the combustion cylinder. Further, while existing optical sensors in engines often suffer from window fouling, there is evidence that passage of the high-power beam through the window can maintain window cleanliness [23]. These in-cylinder diagnostics have the potential to monitor ignition vitality, knock formation, and air-to-fuel ratio formation of pollutant species [24–26].

Owing to the relatively high breakdown intensity in gases (100–300 GW/cm²) [5, 8, 17, 27–30], the required fiber delivery is optically challenging [16]. The essential problem is the need to deliver relatively high-power pulses with sufficient beam quality to refocus the light to the intensity required for breakdown. Solid core silica fibers have been investigated but without success in forming optical sparks in air (at atmospheric pressure) [16, 18]. As will be further discussed, photonic crystal fibers (PCFs) have been used for spark delivery at elevated pressure but only for low pulse energies (< ~1 mJ) that are insufficient for ignition of lean fuel–air mixtures. In our earlier work, we have shown what we believe to be the first fiber delivery of sparks in atmospheric pressure through the use of coated hollow core fiber optics [29].

The layout of this paper is as follows. In Section 2 we discuss the optical requirements (energy and intensity requirements) for ignition and present a figure of merit (FOM) analysis for assessing the intensity delivery capability of candidate fibers. Based on the analysis, we discuss the potential of candidate fibers. In Section 3 we present the results of experiments with 2 m long hollow core fibers including the effects of launch and bending. In Section 4 we consider PCFs for spark delivery including a study of energy delivery through a 25 μm large mode area (LMA) fiber. Section 5 shows the use of high-peak-power pulsed fiber laser for spark formation, and the last section presents conclusions including the outlook for use of solid core fibers at elevated engine pressures.

2. Optical Requirements for Fiber Delivered Ignition

We consider laser ignition using common Q-switched nanosecond laser sources (e.g., Nd:YAG lasers). For nanosecond optical pulses, the nonresonant breakdown of gases is generally an intensity limited process [5, 8, 17, 27–30]. In addition to achieving breakdown, successful ignition requires a minimum (ignition) pulse energy. The combination of delivered pulse energy and focused intensity is determined by the focusing optics and the beam’s energy, time duration, and spatial profile (M²). Figure 1 shows the minimum pulse energy required for ignition as a function of methane percentage [8]. In Fig. 1, the crosses are for high-pressure (3 MPa) ignition while the other symbols are for calculated or measured minimum ignition energies for atmospheric pressure. The results for other fuels are generally similar though methane is of primary interest as it is the dominant constituent of natural gas. As with conventional ignition, the minimum energy requirement occurs near the stoichiometric condition while leaner and richer mixtures require higher energy. Our interest (for advanced gas

![Fig. 1. Minimum pulse energy required for ignition for methane–air mixtures [8].](image-url)
engines) is generally lean operation, for which approximately 10 mJ of laser energy is required.

In the absence of fiber optics, it is straightforward to focus the output of a Q-switched (nanosecond) laser with pulse energy ~10 mJ (and reasonable beam quality) to form a gas-phase spark. However, spark formation after passage through a fiber is more challenging. The past approaches to this problem were summarized in Section 1. To ground the discussion, we frame the problem in terms of a standard solid silica fiber. In that case, owing to the damage intensity of the fiber material (~1–3 GW/cm²) [16,18,31], one requires a relatively large diameter multimode fiber (~300 µm) to transmit the needed ignition energy (~10 mJ). However, light exiting such a fiber is spatially multimode (M² ~ 100 from a simple estimation based on a waist of 150 µm and a base NA of 0.22) which limits the ability to focus to a small spot in order to reach the intensity required for breakdown. Indeed, experimental work (in gases at atmospheric pressure) using conventional fibers has failed to show delivery of nanosecond pulses to form sparks [16,18].

To explore potential fiber delivery candidates we have developed a FOM approach to assess the intensity achievable after refocusing the light. The FOM is (approximately) equal to the achievable optical intensity (at the desired spark location downstream of the fiber) divided by the breakdown intensity requirement for atmospheric pressure air (for typical 5–10 ns pulses of Q-switched lasers). Therefore a candidate fiber should have a FOM exceeding approximately unity for spark formation in air. The achievable intensity is found from the intensity at the fiber exit and the magnification of the postfiber optical (imaging) system. The relevant parameters are shown in Fig. 2. The diameter and intensity of light at the fiber exit face are represented by dexit and Iexit, respectively, while the corresponding quantities at the (intended) spark location are given by dspark and Ispark. The angular divergence of light exiting the fiber and converging at the spark location is represented with Oexit and Ospark respectively.

Ray tracing (geometric optics) or the Lagrange invariant gives the magnification of the imaging system as Oexit/Ospark so that the dimension of light at the spark location is

\[ d_{\text{spark}} = d_{\text{exit}} \left( \frac{\theta_{\text{spark}}}{\theta_{\text{exit}}} \right). \]  

Assuming negligible loss through the lenses, the corresponding intensity at spark location becomes

\[ I_{\text{spark}} = I_{\text{exit}} \left( \frac{\theta_{\text{spark}}}{\theta_{\text{exit}}} \right)^2. \]  

We define the FOM as the optical intensity at the spark location divided by the breakdown intensity for atmospheric pressure air, IBD,atm:

\[ \text{FOM} = \frac{I_{\text{spark}}}{I_{\text{BD,atm}}} = \frac{I_{\text{exit}}}{I_{\text{BD,atm}}} \left( \frac{\theta_{\text{spark}}}{\theta_{\text{exit}}} \right)^2. \]

The FOM expression in Eq. (3) shows that, in order to achieve a high intensity at the intended spark location, one requires a high intensity at the fiber exit (Iexit) as well as low divergence Oexit at the fiber exit. The latter requirement corresponds to a high beam quality (low M²). Further one wants highly converging light at the spark location corresponding to high Ospark (a low f/# final lens or imaging system). For fiber comparison we fix the fiber-independent parameters as IBD,atm = 200 GW/cm² [5,8,17,27–30] and assume a (relatively low) final f/# = 2(Ospark = 0.25). These parameters are selected somewhat conservatively in the sense that somewhat lower intensities may provide breakdown, and higher Ospark may be possible (ultimately limited by aberrations). Under these assumptions we compute the FOM for candidate fibers by using representative values for achievable exit intensity and exit divergence angle (fiber NA) from the literature. Table 1 shows the resulting FOM values for multimode solid core fibers [16], coated hollow core fibers [29] PCFs [32], and fiber lasers [33]. We emphasize that the values in Table 1 are initial values for rough assessment and should not be viewed as exhaustive. Outlook and comments for each fiber type are given below.

FOM values are proportional to the intensity achievable after refocusing laser pulses exiting the candidate fibers. For a given fiber, the magnitude of the FOM is indicative of the ability to spark at atmospheric pressure (requiring FOM > ~ 1). The analysis is somewhat idealized in terms of effects such as spatial mode distribution and hot spots; however, the FOM can also be found from M² concepts by using embedded Gaussian method concepts to determine the beam waist at the spark location [34]. If one assumes an initial beam waist located at the fiber exit and equal to the fiber radius and a second waist located at the spark location and equal to the spark radius, the

<table>
<thead>
<tr>
<th>Fiber</th>
<th>Iexit (GW/cm²)</th>
<th>θexit (rad)</th>
<th>FOM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solid core silica fiber</td>
<td>3</td>
<td>0.05</td>
<td>0.34</td>
</tr>
<tr>
<td>(base NA)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coated hollow fiber</td>
<td>2</td>
<td>0.01</td>
<td>5.6</td>
</tr>
<tr>
<td>Fiber laser</td>
<td>8</td>
<td>0.02</td>
<td>4.9</td>
</tr>
<tr>
<td>Photonic crystal fiber</td>
<td>12</td>
<td>0.04</td>
<td>2.8</td>
</tr>
</tbody>
</table>

Fig. 2. Schematic of light exiting fiber.
FOM can be equivalently expressed as

\[
\text{FOM} = \frac{I_{\text{spark}}}{I_{\text{BD,atm}}} = \frac{I_{\text{exit}}}{I_{\text{BD,atm}}} \left( \frac{\pi d_{\text{exit}} \theta_{\text{spark}}}{2M_{\text{exit}}^2 \lambda} \right)^2 . \tag{4}
\]

The adopted values of \( I_{\text{BD,atm}} \) and \( \theta_{\text{spark}} \) are also somewhat problematic as the published data for the intensity breakdown threshold have considerable scatter \((\pm 50\%) \) \([5,8,17,27–30]\), and the minimum achievable \( \# \) will vary with the details of the light’s spatial mode and focusing optics (ultimately limited by aberrations). Despite these limitations we find that the FOM analysis provides a useful framework for fiber assessment and the interpretation of experimental results.

In terms of the outlook for various fiber candidates for gas-phase spark ignition at atmospheric condition we summarize as follows: The FOM for solid fibers with base NA of 0.22 is considerably less than unity showing them to be unsuitable for atmospheric pressure fiber delivery, an outlook that is consistent with experiments \([16] \). On the other hand, the FOM does suggest the potential utility of solid fibers when operated with lower output NA \([18] \). Further discussion on this approach is given in Section 6. Coated hollow fibers differ from solid fibers primarily with regard to having lower exit divergence (lower \( M^2 \)) resulting in FOM > 1 and showing potential for spark delivery, as has been demonstrated \([29] \). For both hollow and solid fibers, the intensity limit is related to optical damage thresholds. For solid silica fibers, the upper limit of intensity is due to laser-induced damage of bulk fused silica, though as discussed in Ref. 35 (and the references therein), the measured damage intensities for multimode fibers are generally lower. The intensity limit for coated hollow fibers is generally due to optical damage of the reflective coating \([36] \). Fiber laser and PCFs both have FOM > 1 indicating their utility for high intensity delivery, and spark formation has been demonstrated with fiber lasers (this work) at atmospheric pressure and with hollow core PCFs at elevated pressure \([37] \). We note that these demonstrations have been for delivered energies in the range of \( \sim 1 \) mJ, which is not sufficient for ignition of lean mixtures. These issues are further discussed in Sections 4 and 5. In principle, fiber lasers can have different types of fiber as output, but for initial FOM assessment we used parameters from published reports of high-power fiber lasers \([33] \).

3. Hollow Core Fiber Testing

Initial research on the use of hollow fibers for laser spark delivery proved unsuccessful \([16] \). Our past work showed that with an appropriate fiber launch we were able to deliver sparks through the cyclic olefin polymer coated hollow fiber shown in Fig. 3 \([29] \). From our initial experiments with 700 \( \mu \)m core fibers, we found that for launch \( \#s \) of \( \sim 72 \), we were successful in spark formation \((\sim 97\%) \) at atmospheric condition. In this case, the exit beam divergence was measured at 0.011 corresponding to \( M^2 \) of 11 and a focal intensity of approximately 300 GW/cm\(^2\) at the spark location. A similar setup with 1 m long fiber was also used on a single cylinder of an engine demonstrating (what we believe to be the first) successful fiber delivered ignition of a gas engine \([38] \).

To develop more flexible systems suitable for engine environments, longer fibers are required. For example, the cylinders of modern megawatt-class gas engines are typically separated from one another by as much as 2 m. In this work we build upon our past results and report investigation of a 2 m long cyclic olefin polymer (COP) coated hollow core fiber with a core diameter of 1 mm. The experimental setup is shown in Fig. 4. The light source is the fundamental 1064 nm beam of a \( Q \)-switched Nd:YAG laser (Big Sky) with a pulse duration of 8 ns, a repetition rate of 10 Hz, and a spatial beam quality of \( M^2 < 2 \). The light is focused into the fiber with a single plano-convex lens. To understand the effect of input launch \( \# \) on the beam properties of the fiber, we experimented with three input \( \#s \): 35, 55, and 85. In some cases, air breakdown was observed at the input face of the fiber owing to high intensity at the input focal area. A weak helium purge was used to prevent sparking at the input of the fiber. It is well understood that the launch condition has a significant impact on mode coupling, transmission, and the output beam quality of the hollow core fiber \([29,39,40] \). A five-axis fiber holder was used to optimize the launch alignment. For initial tests, the fiber was kept relatively straight. The exit beam was focused using a pair of lenses with focal lengths of 120 and 8 mm empirically found to be an effective focusing combination. The first (longer focal length) lens was placed at approximately 300 mm \( (l_1) \) downstream of the fiber exit, with the final focusing lens approximately 20 mm \( (l_2) \) down-
stream of the first focusing lens. Spot diameters were calculated using a Spiricon beam profiler.

Table 2 summarizes the effect of launch condition on the performance of the fiber. The focal length of the launch lens and input f/# are represented by $f_{\text{launch}}$ and $f_{\#}$, respectively, while the angular beam divergence at the fiber exit is given by $\theta_{\text{exit}}$. The measured focal spot size at the waist and final focused (spark) location are represented by $w_{\text{launch}}$ and $w_{\text{focus}}$. The intensities at the fiber exit and final focused (spark) location are represented by $I_{\text{exit}}$ and $I_{\text{focus}}$ (where the former is computed based on the fiber area and the latter based on $w_{\text{focus}}$). We also report the $M^2$ of the beam exiting the fiber ($M^2_{\text{exit}}$), fiber transmission, and the percentage of delivered sparks resulting in spark delivery.

Of the conditions tested, we find optimal spark formation (~98% of laser shots) and exit beam parameters for input f/# ~55. This launch configuration resulted in the lowest beam exit divergence ($\theta_{\text{exit}} \sim 0.014$) corresponding to $M^2$ of ~15 at the fiber exit. With a pulse energy of ~35 mJ for this condition, the focal intensity was as high as ~470 GW/cm² well above the breakdown threshold intensity [5,8,17,27–30]. The occasional (2%) misfires are thought to be attributable to varying multimode spatial profile (hot spots) in the exit beam [29,41]. We found that as the f/# was increased (f/# ~85) or decreased (f/# ~35) in relation to this condition, the fiber transmission and the exit beam quality degraded suggesting an optimum launch f/#. This behavior is consistent with past findings for hollow fibers [39] and is associated with the mode coupling and mode distribution of light in the fiber.

We have also explored the effects of fiber bending on the fiber performance. Tests were conducted for the input f/# of 55, which provided the highest sparking at straight configuration. In these experiments, the first 100 cm of the fiber was kept straight while the remaining 100 cm was bent into arcs of different radii of curvature (R). As shown in Table 3 and consistent with past research [29,40], we found that, as the fiber was bent, the transmission of the fiber dropped, and the exit beam divergence and corresponding $M^2$ increased. We found that for small bending ($R = 1.5$ m) the performance remained comparable to that of straight configuration and provided enough spatial beam quality at fiber output to give a high sparking rate (~98%). With further bending (i.e., $R = 1$ m), the sparking reduced to zero owing to an increase in the exit beam divergence (~0.019) and corresponding increase in $M^2$. While moderate fiber bending is possible, we identify bending loss (transmission and beam quality) as a limitation of hollow fibers in this application.

### 4. Photonic Crystal Fiber Testing

PCFs constitute a rapidly developing fiber technology, which may have potential for spark delivery (Table 1). The output beams for these fibers are approximately single mode giving the potential to deliver high intensity. Recent research has investigated the use of both LMA solid core PCF and hollow core photonic bandgap (PBG) fibers for delivery of high power nanosecond pulses [32,42]. Konorov et al. [43] delivered a sequence of picosecond pulses with a total energy in the pulse train of approximately 1 mJ through a hollow core PBF with a core diameter of approximately 14 μm [43].

Successful delivery of energy of 0.37 mJ for 1064 nm 65 ns pulses through hollow core PBG fibers has been demonstrated [42]. Transmitted pulse energies of 0.15 mJ through a hollow core PBG fiber have been reported to run rich methane–air mixtures at high pressures [37]. However, in all the published cases, the transmitted energy is well below the target of ~10 mJ required for lean mixture operation in engines. Our interest, therefore, is to seek delivery of high-energy pulses with sufficient fiber exit beam quality for spark delivery. To this end, we have investigated LMA PCFs (Fig. 5). While PBG fibers are also of interest, we are guided by the published work indicating that, as the core diameter is increased to transmit higher energy, PCFs can (in practice) sustain higher damage threshold than PBG fibers [32]. The periodic hole-silica structure in the PCF (Fig. 5) modifies the refractive index of the cladding and maintains an appropriate relationship between the

<table>
<thead>
<tr>
<th>$R$ (m)</th>
<th>$w_{\text{launch}}$ (μm)</th>
<th>$\theta_{\text{exit}}$ (rad)</th>
<th>$M^2_{\text{exit}}$</th>
<th>$I_{\text{exit}}$ (GW/cm²)</th>
<th>$w_{\text{focus}}$ (μm)</th>
<th>$I_{\text{focus}}$ (GW/cm²)</th>
<th>Transmission (%)</th>
<th>Sparking (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>39</td>
<td>0.01</td>
<td>15</td>
<td>0.6</td>
<td>17</td>
<td>470</td>
<td>86</td>
<td>98</td>
</tr>
<tr>
<td>0.66</td>
<td>39</td>
<td>0.011</td>
<td>16</td>
<td>0.58</td>
<td>21</td>
<td>300</td>
<td>83</td>
<td>98</td>
</tr>
<tr>
<td>1</td>
<td>39</td>
<td>0.019</td>
<td>29</td>
<td>0.5</td>
<td>49</td>
<td>53</td>
<td>80</td>
<td>0</td>
</tr>
</tbody>
</table>
refractive index of the core and the cladding so as to operate it in a single mode.

We have conducted experimental investigation of LMA PCF of length 2 m and core diameter of 25 μm. The fiber used has a relatively low input NA of 0.04–0.07. The ends of the fiber were connectorized with high-power SMA connectors. A spatial filter setup was used to improve the beam quality of the laser \( M^2 \approx 1.4 \) after the spatial filter. A variable attenuator allows controlled attenuation of the beam from a few millijoules down to microjoules of energy without displacing the beam. The beam was launched with a 50 mm focal length lens onto the fiber input, which was held with a five-axis fiber holder.

Figure 6 shows the fiber transmission measured as a function of the input pulse energy. We attribute the discontinuous behavior to slight shifts in the beam position or profile between measurements. We found that, as the pulse energy increased, the fiber transmission decreased from \( \sim 97\% \) to \( \sim 45\% \). In these tests, the maximum achievable input energy was 1.3 mJ corresponding to an output of 0.55 mJ. This output energy is still too low for the ignition of lean mixtures but is among the highest reported for PCFs and is more than 3 times higher than that achieved in past PBG experiments showing ignition of rich methane–air mixture [37]. Ongoing efforts include the use of larger mode area fibers (40–80 μm) to increase pulse energies (even at the expense of some degradation in the exit beam quality, since a somewhat elevated \( M^2 \) would still allow spark formation).

5. Fiber Laser Testing

Because the fiber laser output is inherently fiber delivered, the fiber lasers provide a means of integrating the laser source with the fiber delivery medium. The recent development of pulsed fiber laser technology has led to a demonstration of state of the art systems producing megawatt peak power/multimillijoule energy pulses in the nanosecond duration range. This includes generation of 2.4 MW peak power for 4 ns pulses [33]. The main technological development that enabled this scaling is associated with fiber core size increase. This core-size scaling has also enabled spark production in atmospheric air using output from a nanosecond-pulsed fiber laser, with energy and peak power characteristics suitable for laser ignition of combustible mixtures. Here we describe our experiments showing the ability to form optical sparks at the output of a pulsed fiber laser.

In our work we used a multistage fiber amplifier system, seeded with electronically controlled nanosecond diode pulses, similar to the one described in Fig. 7. In the current system, however, the last amplification stage has been constructed with an 80 μm diameter core Yb-doped fiber, producing output beam quality of better than \( M^2 \approx 1.5 \). This combination of large core and high beam quality was highly advantageous for achieving spark generation with nanosecond-long and few-millijoule energy pulses.

As in the PCFs, the energy extraction in a fiber laser is ultimately limited by the bulk damage intensity threshold in fused silica, which scales inversely proportionally to the square root of pulse duration, \( I_{\text{damage}} = \Phi_{\text{damage}} / \tau \), where \( \Phi_{\text{damage}} \) is a damage fluence for 1 ns pulse, and \( \tau \) is a pulse duration in nanoseconds. Then if pulsed fiber laser output is focused into a spot size \( d_{\text{spark}} \) and fiber mode field diameter (MFD) \( d_{\text{MFD}} \), achievable intensity in a focused beam in \( I_{\text{spark}} \) is related to \( I_{\text{damage}} \) in a fiber through

\[
I_{\text{spark}} = I_{\text{damage}} \left( \frac{d_{\text{MFD}}}{d_{\text{spark}}} \right)^2.
\]

The exact damage fluence \( \Phi_{\text{damage}} \) value for fused silica is not known yet. Our recent studies indicate that it must significantly exceed 100 J/cm². Figure 8 shows the theoretical plot of achievable focused...
intensity in air as a decreasing function of pulse duration using 80 μm core fiber (60 μm MFD for fundamental mode) and assuming 20 μm diameter focus in air, which is possible with a low M^2 value of the exiting beam. For pulse durations up to 6 ns achievable intensities in focus exceed the 300 GW/cm^2 value, above the published breakdown intensities for air at atmospheric pressure. It is important to emphasize that these intensities are achievable with high multi-millijoule pulse energies. Indeed, Fig. 8 also shows theoretically extractable pulse energy as a function of pulse duration (upper sloping curve) calculated assuming 100 J/cm^2 pulsed fluence (at 1 ns), compared with experimentally demonstrated pulse energies for various pulse durations (solid black bullets).

We have experimentally verified that laser breakdown in air is indeed achievable with 0.7 ns duration fiber laser pulses from 80 μm core fiber amplifier (corresponding to 2.4 mJ pulse energy and 3.4 MW peak power) at 50 Hz repetition rate. We believe that this demonstration is the first proof that fiber lasers are well suited for formation of optical sparks and confirms the findings of the FOM analysis in Section 2. Current parameters should readily allow the ignition of gas engines operating at near-stoichiometric conditions. The further optimization of laser pulse parameters, including further pulse energy increase (as shown in Fig. 8) is anticipated. Such an increase in parameters would then lead to parameters allowing the ignition of targeted lean fuel engines.

6. Conclusions

Fiber-optic delivery of laser sparks is generally viewed as a requirement for practical laser ignition systems and may also enable other applications such as fiber-delivered gas-phase LIBS. We have developed a figure of merit analysis to identify candidate fibers from the point of view of intensity delivery as is required for spark formation. The analysis shows that high intensity and low divergence (M^2) at fiber exit are required characteristics. For the initial comparison of different fiber types, we calculate representative FOM values based on published values and find favorable FOM values for hollow core fibers, fiber lasers, and PCFs.

We have reported an investigation of spark delivery using 2 m long coated hollow core fibers (a reasonable length for practical laser ignition systems on multicylinder engines). We found an optimum launch condition (f# ~55) for fiber transmission and exit beam quality, which allows reliable (98%) spark formation with transmission of pulses of ~35 mJ. Owing to the decrease in breakdown threshold with pressure (~P^−0.4) [19] such a configuration is expected to provide 100% reliability at engine pressure conditions. We described what we believe to be the first demonstration of spark formation at the output of a pulsed fiber laser having parameters of ~0.7 ns, 2.4 mJ, and we show output energies of 0.55 mJ from LMA PCFs. We discuss approaches to increase transmitted pulse energies for both fiber laser and PCFs, as needed to ignite lean mixtures in gas engines.

According to our FOM analysis, solid core fibers (with base NA) are incapable of laser spark formation at atmospheric conditions. However, their use may become feasible with a reduction in output NA and at higher pressure conditions. For example, if the output NA could be reduced by a factor of 2 (e.g., by tailoring the launch or refractive indices) and the ignition pressure were 10 atm (as is the case in some engines) then the FOM (referenced to 10 atm) would improve by ~10(= 2/10^0.4), and such a configuration could be expected to spark. Indeed, laser spark formation using solid core fibers with reduced output NA and at higher elevated pressure has been demonstrated by Gaborel [18] with 90% reliability at 6 atm pressure.

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