Fiber Optics for Remote Delivery of High Power Pulsed Laser Beams

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The work described here is focused on the technology to enable remote fiber optic delivery of high-power, pulsed laser beams for diagnostics used in combustion and flow-field characterization. Fiber delivery is desirable since it is not always practical to locate laser diagnostic equipment in close proximity to the harsh environment associated with propulsion test facilities (e.g., jet or rocket engine testing). In this study both one-dimensional hollow core waveguides and photonic bandgap fibers were investigated. Relatively large bore (~ 1000 μm) hollow waveguides were found to be the optimal fiber solution for their ability to deliver relatively high peak power pulses (5 ns duration at energies > 10 mJ/pulse) with an acceptable beam quality (M^2 ~ 10 to 20). Using such waveguides, a Coherent Anti-Stokes Raman Spectroscopy (CARS) system with fiber delivery of the laser beams was fully demonstrated in laboratory experiments. The technology is currently being applied to a field-ready CARS system, which will be initially demonstrated by mapping the temperature of exhaust products in a jet engine plume.

Nomenclature

CARS = Coherent Anti-Stokes Raman Spectroscopy
M^2 = laser beam quality parameter
BS = beam splitter
L = lens
ODL = optical delay line
MBDL = modeless broadband dye laser
ω = frequency of laser beam

I. Introduction

The ability to deliver relatively high-intensity laser beams via fiber optics would open up a range of diagnostics in combustion facilities that were previously unavailable due to harsh operating conditions and lack of accessibility. Coherent Anti-Stokes Raman Spectroscopy (CARS) is one specific example of a reliable laser-based temperature and species diagnostic used in combustion systems.[1] CARS is a 3rd-order, nonlinear wave mixing process in which laser beams are focused to a point where they interact with resonant molecules to produce a signal beam that is collected and measured with a spectrometer instrument (see Figs. 1 and 2). CARS Systems are typically built on large optical tables in dedicated laboratory areas due to such factors as (1) the high intensity of the laser beams needed to generate the nonlinear interaction in gas phase systems, (2) the requirements of beam formatting and dye pumping, and (3) the high spectral resolution required for the analysis of the CARS signals.

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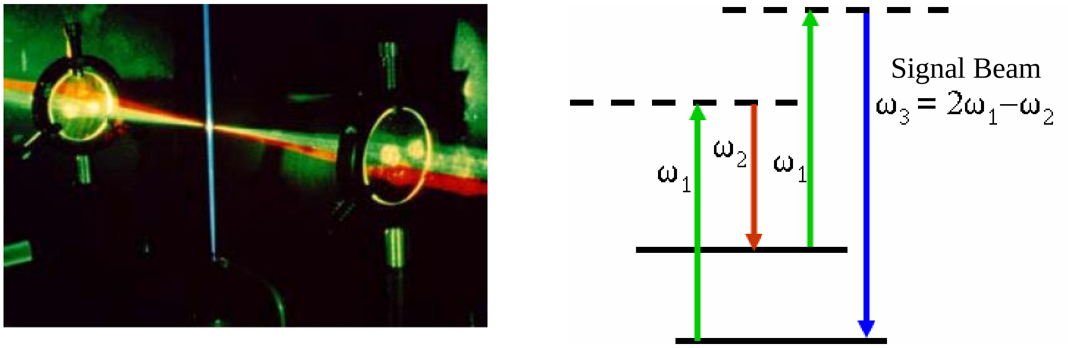
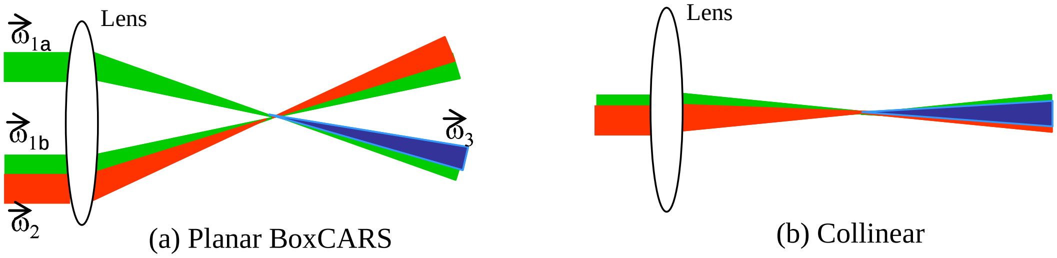


Figure 1. Image of CARS laser beams and energy level diagram. *CARS uses multiple laser beams, which interact with resonant molecules to form a signal beam. The signal beam can be analyzed to determine local temperature and species concentration in combustion systems.*



(a) Planar BoxCARS

(b) Collinear

Figure 2. Diagram of CARS beam geometries. *The phase-matched signal beam (shown here in blue) is generated in a direction that conserves momentum, such that* $\vec{\omega}_3 + \vec{\omega}_2 = \vec{\omega}_{1a} + \vec{\omega}_{1b}$.

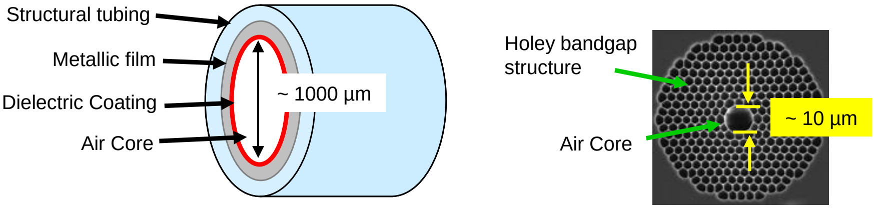
The difficulty with utilizing CARS and similar techniques outside of the lab is that the relatively complex optical systems required are susceptible to vibration and harsh environmental conditions, and due to space constraints such systems cannot often be located close to the test facility. Fiber delivery of the beams would enable the lasers and other sensitive components to be located an appropriate distance away from the harsh test stand, mitigating such issues. In addition, the ability to deliver beams through fibers would alleviate some of the safety and logistical issues with propagating high-energy beams through free space.

An example of one specific facility that could greatly benefit from a fiber-based CARS system is the Aerodynamic and Propulsion Test Unit (APTU) at the Arnold Engineering Development Center (AEDC). APTU is a blowdown facility designed for true temperature aerodynamic, propulsion, and material/structures testing. During a test, access to both the flow and a test model is severely limited, and the use of high-precision optical diagnostics proves to be a challenge. A dual-band CARS system is currently being developed for APTU, and fiber delivery of the beams would dramatically lessen the impact this system would have on the facility by making it much easier to install, accommodate, and operate.

The technological challenge with using fibers for a CARS system is that CARS requires relatively high peak power laser pulses to generate a significant signal, which prevents the use of standard fibers due to potential laser damage, breakdown at coupling, and poorly delivered beam quality. In terms of generating a CARS signal, the significant laser parameter is the intensity of the focused spot that can be achieved after the output of the fiber, which for CARS should be on the order of ~ 100 GW/cm^2 or higher.

II. Preliminary Fiber Investigation

Two different types of hollow fibers were investigated: hollow glass waveguides[2] consisting of capillary tubing coated with a metallic film and dielectric layer (Fig. 3a), and photonic bandgap fibers[3] consisting of a two-dimensional pattern of holes (Fig. 3b). Both types of fibers have an air core and can accept higher peak power laser beams than similar solid core fibers. The two major differences between the fibers, which are significant for this investigation, are (1) glass waveguides can have much larger cores, enabling much higher peak power and (2) the photonic bandgap fibers can operate in single mode and can deliver a beam with significantly better beam quality. This trade-off between peak power and beam quality is at the center of the investigation to determine appropriate fibers for laser combustion diagnostics.



(a) Hollow core waveguide

(b) Photonic bandgap fiber

Figure 3. Structure of different hollow core fiber options considered in this investigation. *(a) Hollow core waveguides used in this study have a relatively large core size and are produced by coating the interior of tubes (typically glass) with a dielectric coating over a metallic film. (b) Photonic bandgap fibers are produced using an assembly of much smaller core tubing to create a specific 2D pattern of holes.*

The specific goal of the investigation was to determine the optimal fiber solution for delivery of pulsed laser beams typically used for CARS. As an example, a compact CARS system[4] recently constructed by OKSI for use in rocket test stands served as a model for required beam parameters. This system is based around a 5-ns pulsed frequency-double ND:YAG laser at 532 nm. The output of this laser is split into multiple legs with two legs used directly in the probe volume and another leg used indirectly to pump one or more modeless broadband dye lasers. These dye lasers are essentially broad (FWHM ~ 10 nm) amplified fluorescence beams with a center wavelength in the range from 580 to 680 nm depending on the molecule that is to be probed. Typical energies per pulse at the probe volume for all of the beams (YAG and dye) are on the order of ~ 10 mJ/pulse; more significantly for fiber delivery, the peak power for each beam is on the order of ~ 2MW (this is similar to the peak power used in picosecond pulsed CARS systems, as discussed in Section V).

Large bore (~ 1000 µm) hollow core glass waveguides were found to be the optimal fiber solution for their ability to deliver extremely high peak power at adequate beam quality. For example, nanosecond pulsed beam energies as high as 100 mJ with M^2 ~ 10 at the fiber output have been achieved by others through such hollow core waveguides.[5] In addition, the coupling of light into such fibers is best achieved with slow optics (i.e., large f# ~ 20) that produce a relatively weak focus, making the coupling of light much more robust and less susceptible to vibrations than the smaller core (~ 10 µm) photonic bandgap fibers that require a much tighter focus. This is particularly important in a large-scale propulsion facility, where even remotely located optical tables can experience significant vibrations that could affect the beam coupling into the fiber. In other words, precise focusing is not needed to couple into larger core fibers, and thus they are much less likely to be adversely affected (e.g., decrease in coupling or even destruction of fiber) due to vibrations than a smaller core fiber is.

In related work, Professor Azer Yalin and his group from Colorado State University studied the use of fibers to deliver high-intensity laser pulses for laser ignition applications.[6-7] For this work, the power per unit area (i.e., the irradiance) is the key parameter, which needs to be above a certain threshold to initiate ignition. Therefore, it is not just a matter of how much energy/pulse can be delivered, but also how tight the pulses can be focused after exiting the fiber (this is the same criterion for CARS). The results of these studies indicate that hollow core waveguides are the best option compared to hollow core photonic bandgap fibers, large mode area Photonic crystal fibers, solid core silica fibers, and fiber lasers. Using the hollow core glass waveguides, Yalin and his group achieved spark formation with the transmission of nanosecond pulsed beams at energies on the order of 50 mJ/pulse with moderate beam quality.

Others have studied the use of photonic bandgap fibers for laser ignition, but the highest energy values we found in the literature for the transmission of nanosecond pulses in photonic bandgap fibers was just 0.6 mJ/pulse in 20 micron core fibers,[8] and this was achieved only for fibers residing within an evacuated chamber to prevent breakdown in air at the fiber input. In addition to the delivered beam intensity being too low for applications such as CARS, a vacuum shroud is not practical in most practical circumstances.

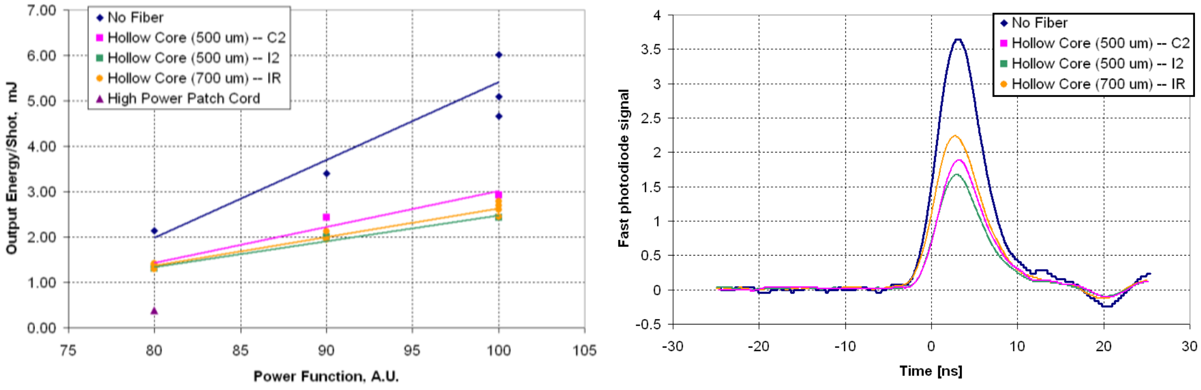
The basic result of the preliminary investigation concluded that relatively large core hollow glass waveguides are the superior choice for achieving high-intensity focused spots. The main drawback with using a larger core waveguide is decreased beam quality (i.e., a larger spot size at the focus); however, the ability to couple in much higher peak power more than compensates for this disadvantage. Furthermore, the modeless broadband dye lasers that are often used in CARS systems have a relatively poor beam quality to begin with, which means that (A) the beam quality is not significantly degraded by the larger fibers, and (B) such beams can only be effectively coupled into larger fibers since their focused spot size is relatively large. In other words, not only are the hollow core waveguides better for the relatively high-quality YAG beams, but they are also basically the only option for the relatively poor quality MBDL beams.

III. Test Results

A. Basic Tests of Hollow Core Waveguides

Based on the above considerations hollow core waveguides were further investigated by conducting basic tests using a 7-ns pulsed YAG laser operating at 1,064 nm. These tests included measured transmission vs. input energy, temporal profile, and beam waist. As a baseline with which to compare the hollow core waveguides, a high-power solid core patch cord from Newport Corporation part No. F-MTC-C-2SMA was also used. This fiber has a core diameter of 350 µm, a length of 2 m, and a numerical aperture of NA = 0.22.

Figure 4(a) shows the energy transmission through the fibers measured as a function of the input power control on the laser. Results for different hollow core fiber samples are shown designated by a core size and internal coating. Three coating types were tested: cadmium sulfide deposited over silver (designated as C2), silver iodide (designated as I2), and bare silver (designated as IR). The energy output is linear with the input energy, and the upper limit was due to experimental design and not a limit due to the fibers themselves. The hollow core samples that were tested all behaved roughly the same delivering from 50 to 70% of the input power. For comparison the energy through the solid core fiber was only about 20%; however, note that this measurement could only be done at the lowest power setting tested since damage began to occur at higher power (i.e., a hollow core is needed for higher power). Much of the energy loss for the hollow core waveguide tests is actually due to the coupling, which was not optimized. Since there are no reflections at the input (i.e., since the core is hollow), with the proper lens selection the coupling efficiency can in practice be well above 90%. Out of convenience we used a 75-mm lens to couple into the fiber, whereas Yalin found that longer focal length lenses (higher f#) on the order of 200 mm (f/20) or more give better results[6].



(a) Fiber Output Engery VS Input Power Function

(b) Temporal response of output pulse

Figure 4. Measurements of pulsed beams through sample hollow core waveguides. *(a) Energy at the output of the fiber as a function of the power control function on the laser and (b) temporal profile of the beam exiting the fiber. In both plots, the measurements through the fibers are compared to those without the fiber.*

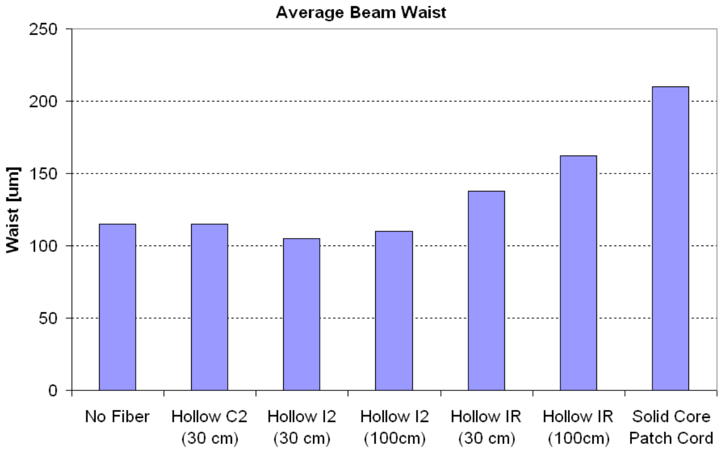


Figure 5. Measurement of beam waist. *Beam waist measured at the focus of a 50-mm lens using a knife edge technique demonstrating that the hollow core fibers do not substantially degrade a moderate quality pulsed beam.*

To check for temporal spreading, which can reduce the peak power, the beams at the output of the fibers were characterized with a fast photodiode with a 1-ns rise/fall time connected to a 100-MHz oscilloscope. Curves of the temporal beam profile with and without coupling through a hollow core fiber are shown in Fig. 4(b). The data show that the fibers do not cause any appreciable spreading of the pulse in the temporal domain.

The laser beam profile coming out of the fibers was measured in two ways: (1) a razor blade (knife-edge) was translated through the beam focused to the spot while measuring the energy and (2) an image a given distance from this focus was taken with a camera. Results of the former are shown in Fig. 5 for different fiber samples and fiber lengths. Unfortunately, the beam quality from the 1,064-nm laser was rather poor to begin with, making the tests less than ideal; however, the results can still be used to qualitatively demonstrate that the hollow core waveguides are able to deliver moderate beam quality without further degradation to the focused spot size.

B. Demonstration of Fiber CARS

A full demonstration of a fiber-delivered CARS system was conducted with hollow core waveguides. This consisted of measurements of the temperature of O_2 in room air using two fiber-delivered beams in a collinear CARS geometry (see Fig. 2b). Visible wavelength 5-ns pulsed beams at 532 (doubled-YAG) and 580 nm (modeless broadband dye laser) with energies on the order of 10 mJ/pulse each were used. A schematic of the setup used is shown in Fig. 6, and pictures of the optical table with the fibers are shown in Fig. 7.

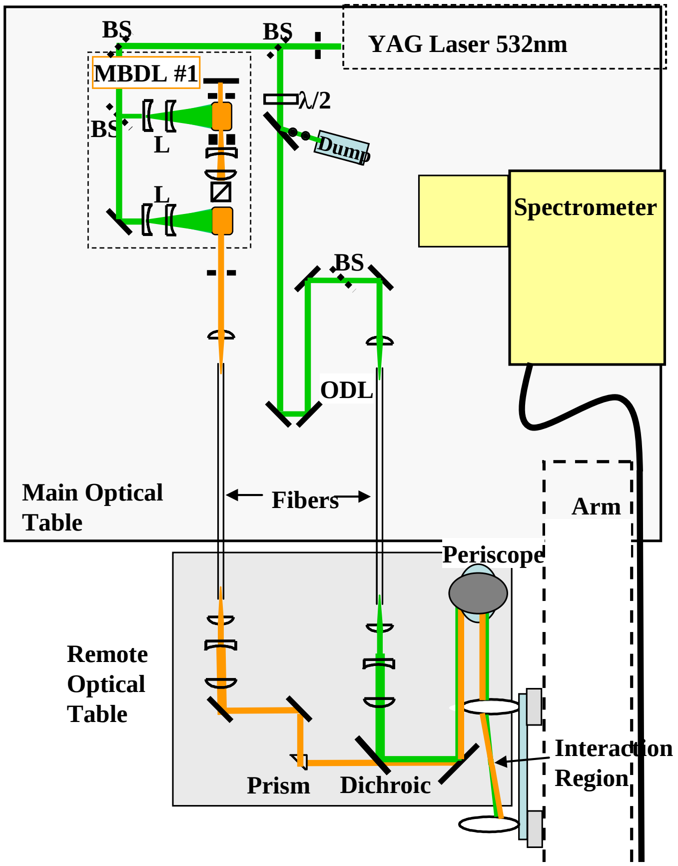


Figure 6. Optical schematic of test system used for demonstration of fiber-delivered CARS. *High-power hollow core fibers move the laser beams off the main optical table and onto a separate "remote" optical table where they are combined on a dichroic filter. Using mirrors, the beams are then directed to an "arm" where they are focused to generate a collinear CARS signal in the probe volume (i.e., interaction region). The CARS signal beam is then focused into a standard (low-power) fiber optic leading to a high-resolution spectrometer.*

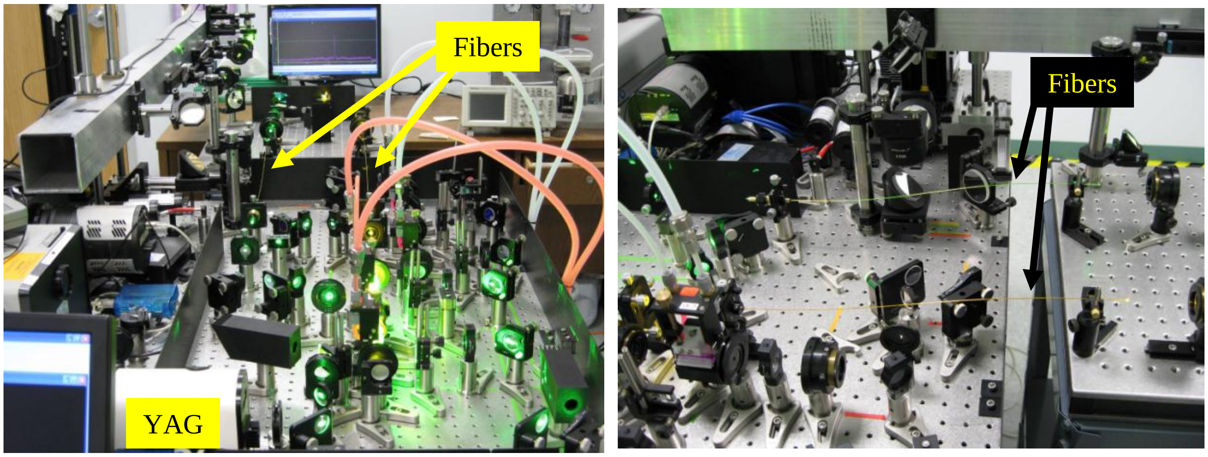


Figure 7. Pictures of optical setup for demonstration of fiber delivered CARS. *The fibers used to move the laser beams from one optical table to another are pointed out in the two pictures, which were taken from two different angles.*

Sample spectra were measured and compared with a theoretical spectra obtained with the CARSFT[9] software (see Fig. 8). The results provide a proof of the overall concept demonstrating the use of the hollow core waveguide for delivery of beams of sufficient peak power and beam quality to enable generation of a CARS signal. Due to availability, the fibers used in the laboratory demonstration were only 50 cm long each. While it is true that longer fibers will have more loss, the transmitted energy/pulse will still be well above that needed for relevant experiments.

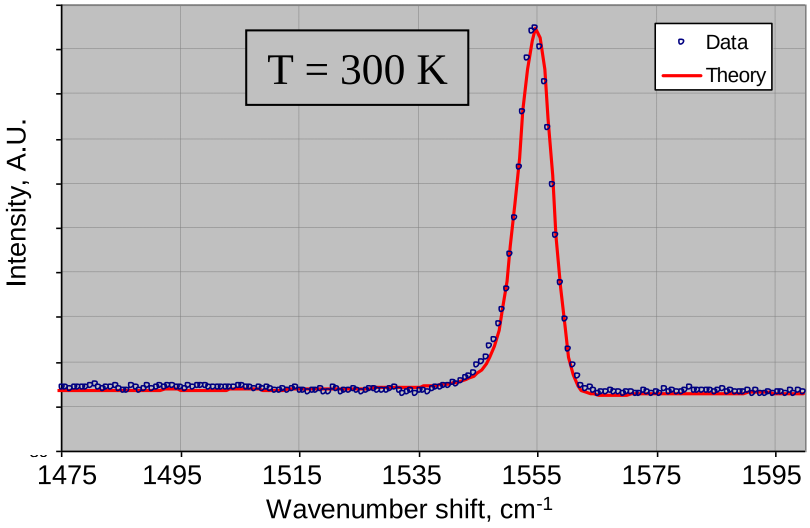


Figure 8. Sample measurement results of Fiber CARS test. *There is excellent agreement between the measurement and the theoretical room temperature spectra generated by CARSFT code. The tests demonstrate that hollow core fibers can deliver adequate laser intensity and beam quality for use in a CARS system.*

IV. Future Work

In continuing this work, a CARS system with fiber-delivered beams is currently being developed to map the exhaust products in a jet engine plume, specifically the J85 test engine at the University of Tennessee Space Institute (Fig. 9), which is adjacent to AEDC. For these tests, 5 m long hollow core waveguides will be used. Specific engineering details that are appropriate for the engine test stand are being developed for coupling into and out of the fibers. In addition, while the current fiber technology is sufficient for this specific application, improvements in the fiber coating technology are also being investigated to reduce the loss (both overall loss and bending loss) in the hollow core waveguides. Such improvements would enable longer fibers with tighter bends to be used for a wider range of applications.

Figure 9. Picture of the test engine to be used for further demonstration of fiber CARS. *J85 engine shown at the University of Tennessee Space Institute test facility.*

V. Discussion

The work described in this paper provides a specific example of the use of fibers for improving the ability to use spatially resolved diagnostics in propulsion test facilities. Relatively large-bore hollow core waveguides have been demonstrated in a CARS experiment by effectively delivering 10-mJ, 5-ns, pulsed laser beams with sufficient beam quality to generate a CARS signal. The authors of this paper are currently working on continuing to move the technology into "the field" by developing specific optomechanical details for utilizing 5 m long fibers on a full-scale engine test facility. This work should open up the use of such fibers for a variety of techniques beyond CARS, including Rayleigh scattering, Raman spectroscopy, absorption spectroscopy, tunable diode laser spectroscopy, laser-induced fluorescence, and Hydroxyl Tagging Velocimetry. Furthermore, while current glass waveguide fibers are sufficient for initial demonstrations, improved coating techniques are being pursued to reduce losses and enable longer, more efficient fibers.

As an aside we consider fiber delivery of picosecond pulse lasers specifically for CARS systems.[11] Although the beams in a picosecond system have less energy/pulse than the nanosecond pulse lasers considered throughout this paper, the pulse duration is by definition shorter, and it turns out that the peak power of the beams is of a similar magnitude (i.e., ~ 2 MW). Furthermore, there is recent evidence that it is this peak power (rather than the energy/pulse) that is the determining factor in regards to initiation of damage in silica via an avalanche breakdown process.[12] In other words, nanosecond and picosecond pulsed lasers should have similar characteristics in terms of damage threshold limitations for fiber CARS experiments, and thus neither is preferred for fiber-delivered systems. This statement may be controversial on both sides: those in favor of nanosecond pulses may argue that time dispersion is much more of a concern for picosecond lasers, and on the other side those in favor of picosecond pulses may argue that the higher energy/pulse with a nanosecond lasers is more of a concern in the event that breakdown does occur. Determining which type of laser is more appropriate for fiber-delivered experiments remains an open question, and the answer may ultimately come down to other considerations such as complexity and cost.

Acknowledgments

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