Spectroscopic Sensing Via Dual-Clad Optical Fiber

Christopher L. Hagen, *Student Member, IEEE*, Jason R. Schmidt, and Scott T. Sanders

***Abstract*—Many optical sensors can be simplified and improved through the use of dual-clad fiber (DCF). Here, the authors highlight two applications related to combustion: H2O vapor temperature measurements in a gas-turbine combustor (by direct absorption spectroscopy) and piston temperature measurements in a reciprocating engine (by fiber-Bragg-grating thermometry). For both applications, the DCF conveniently provides a single-mode light "pitch" and a multimode light "catch" coaxially and within a single fiber. Both applications benefit from the ease of alignment and the access to "tight spaces," which comes from sensing through a single fiber port. In addition, both applications are improved in "bi-directional" mode: the former with an increased absorption in a double pass through the engine, and the latter by monitoring a reflection feature instead of a relatively weak-transmission feature. The authors discuss potential designs for DCF-based sensors in detail, including options for connecting both a light source and detector to one end of the DCF.**

***Index Terms*—Combustion diagnostics, double clad, fiber Bragg grating (FBG), gas turbine.**

I. INTRODUCTION

NONINVASIVE optical sensors are attractive because they do not disturb or require physical connection to the material under test, they have fast response times, and they are capable of measuring over a broad range of conditions. They are well suited to applications involving high-speed fluid dynamics, chemistry and mechanical motion. For increased convenience, many noninvasive sensors employing fiber optics to distribute light are now being deployed. In this paper, we focus on a novel fiber-optic design for optical sensing. In particular, we introduce a dual-clad fiber (DCF) as a convenient conduit for spectroscopic sensing.

DCF was originally developed for optical pumping (e.g., in fiber lasers and fiber amplifiers [1]). More recently, the DCF has been demonstrated as a bidirectional conduit in two sensing applications. First, as an *in vitro* florescence sensor [2] and, second, as an endoscopy (imaging) probe [3]. The purpose of our work is to expand on the range of DCF sensing applications. In this paper, we present novel sensing applications, in which the DCF provides unique advantages over traditional approaches. These applications are absorption spectroscopy (Application 1) and fiber-Bragg-grating (FBG) thermometry (Application 2).

Both applications offer the potential for quantitative results in harsh measurement environments such as engines. Mechanical motion and refractive index gradients often present challenges in such environments; however, as we have shown below, the coaxial DCF conduit can provide convenient solutions for such challenges.

II. APPLICATION 1: ABSORPTION SPECTROSCOPY

In absorption spectroscopy, material properties are generally inferred from its absorption spectrum. Typically, a wavelength-tunable source light is transmitted through the material and collected by a detector (Fig. 1). The ratio of the source light and collected light intensities can be reduced to the requisite spectrum using the Beer-Lambert law [4]. Absorption spectroscopy allows for an accurate, nonintrusive, and real-time sensing [5]. As an example, work has been done utilizing the absorption spectroscopy to monitor combustion gas temperatures in reciprocating engines with optical cylinders [6]. These cylinders allow for a straightforward arrangement of light sending (pitch) and collection (catch) optics. However, a line-of-sight access is not always available. An example is a gas-turbine engine. The source light can be "pitched" from a hole in the turbine outer casing, but to measure the gases, one may want to "catch" the light at or near the turbine shaft. Unfortunately, the limited space and high-speed shaft rotations can make a collection at this location difficult. The purpose of this paper is to introduce a sensing approach, utilizing DCF, capable of efficiently "pitching" and "catching" from the same fiber port, helping to meet such optical access challenges. Additionally, the DCF provides a convenient alignment and an increased absorption path length. However, in designing such a system, a careful attention must be given to the modal structure in the fiber.

A. Fiber Modes

Waves propagating in a confined space cannot propagate in an arbitrary fashion; the behavior of the propagation is affected by the confinement. In the case of fiber optics, the coupled light must arrange itself among the available fiber modes. If we imagine a cross section of the fiber, each mode will have a different intensity distribution. The number of modes present in the fiber is dependent on the optical wavelength, fiber numerical aperture (NA), and fiber core diameter [7]. In general, small-core fibers support a single-mode light profile that emerges with a smooth (Gaussian) appearance; large-core fibers support

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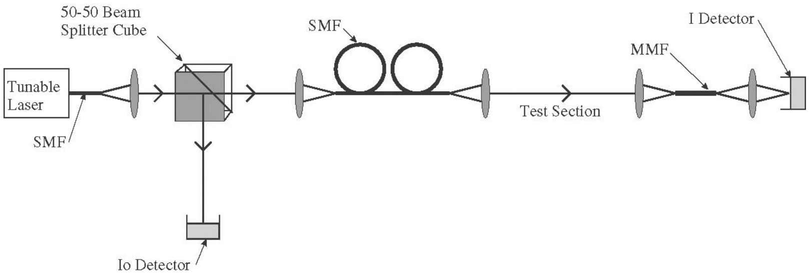

Fig. 1. Traditional approach to absorption spectroscopy by use of an SMF "pitch" and an MMF "catch."

multiple light mode profiles that result in recognizable patterns for the lower number of modes (e.g., cloverlike patterns for four modes), but become an indecipherable collection of "speckles" for higher mode numbers.

B. Single-Mode Absorption Spectroscopy

Small-core single-mode fiber (SMF) is a simple option for single-port fiber access. With precision stages, light may be "pitched" from an SMF, transmitted to a mirror at a normal incidence, and returned efficiently to the same fiber. Unfortunately, in typical applications, mechanical motions of optical components prevent efficient coupling in this manner. Furthermore, a phenomenon known as beam steering [8] also acts to reduce the coupling efficiency. Beam steering is an alteration of the light path from its intended path due to refractive index gradients. In gas flows for example, these gradients are commonly caused by density and/or concentration gradients in the probe path resulting in a diverging or wandering light beam. The larger multimode fiber (MMF) is best for efficiently collecting such a beam.

C. Multimode Absorption Spectroscopy

The increased size of MMFs increases collection efficiency and ease of alignment. However, MMFs generate a noise we term "mode noise," which does not affect the SMF. Mode noise is associated with the multimode "speckles." The speckle pattern changes in a seemingly random fashion whenever there is motion of the fiber or whenever the coupled light changes wavelength. If there are any imperfections in the system (e.g., scratches, dust, etc.), the "speckles" move on and off of the imperfections, creating an intensity noise in the final detected signal. The amplitude of this noise can easily exceed that of the absorption signal, resulting in an indecipherable measurement. Mode noise is particularly problematic in scan-wavelength spectroscopy. Whereas most other forms of noise can be shifted to relatively low frequencies simply by scanning the wavelength rapidly, mode noise is inherent to the wavelength tuning and, therefore, "keeps up" with it. In most practical measurement environments (e.g., in engines), it is not practical to keep access ports free of imperfections. Thus, sensors based entirely on MMF generally suffer from the mode noise. Although it seems that neither multimode nor SMFs alone are good selections for combustion single-port fiber sensing, a combination of an SMF to eliminate mode noise on the "pitch" side and an MMF "catch" to enable efficient light collection is a feasible solution.

TABLE I
NOMINAL SPECIFICATIONS FOR NUFERN PART NUMBER MM-GDF-20/400 DCF USED FOR TESTING

	Diameter (um)	NA
Core (glass)	20	0.06
Inner Cladding (glass)	400	0.46
Outer Cladding (acrylate)	550	na

D. Adjacent Fibers

One solution for a single-port measurement is a fiber with adjacent multimode and single-mode cores. This design eliminates mode noise and, also is nearly single-point optical sensing. However, because of the offset between the fibers, the alignment can be cumbersome. For example, if a light from the single-mode core is returned to the multimode core by a mirror, the angle of the mirror will need to be adjusted with its distance from the fiber. Alternatively, the mirror can be positioned at exactly normal incidence, but then, only a portion of the return light will be collected by the multimode core.

E. DCF

DCFs offer a single-mode core surrounded by a multimode first cladding. With this approach, the source light can be "pitched" from the single-mode core and recollected in the larger-area first cladding along a common coaxial light path. The large cladding-to-core area ratios available, four hundred-to-one for the fiber specified in Table I, make collection convenient and efficient. The coaxial path may even reduce sensitivity to beam-steering effects [8] (e.g., light might be made to retrace its path, "un-steering" in the process).

Once the advantages of DCF were realized, the next step was to select a DCF cladding design. The two options familiar to the authors were bundle cladding and concentric cladding. Bundle clad fiber consists of a continuous core and adjacent cladding fibers placed around the periphery of the core. Again, like the single adjacent fiber, the weakness of the bundle clad fiber is collection efficiency. Since the cladding material is not continuous around the core, a percentage of the return light will miss both the cladding and the core, resulting in a "wasted"

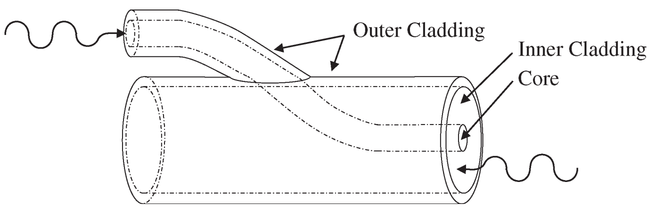

Fig. 2. Hypothetical direct access DCF.

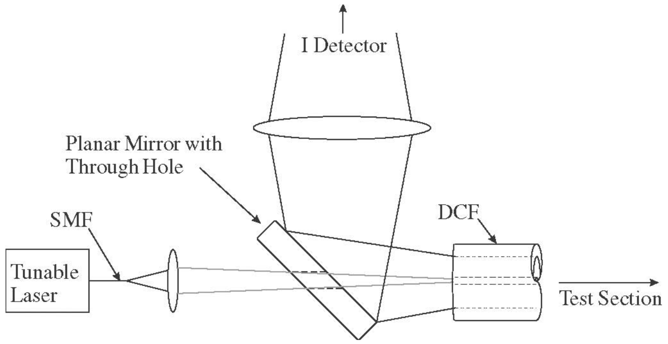

Fig. 3. NA-based access for DCF sensing.

light. Concentric clad fiber is similar to traditional fiber designs, the exception being the addition of a second (outer) cladding. This fiber, with a continuous first (inner) cladding, has higher collection efficiency than the bundled cladding (no wasted light).

Concentric DCF was chosen to send and receive light, and thereby making the single port sensing feasible. However, this convenience comes at a cost. Accessing the core and cladding separately at the nonmeasurement end is challenging. Three access options were explored to meet this challenge (direct, NA-based, and direction-based).

F. Direct Access

A DCF with separated access to the core and cladding at one end would be especially convenient in this application. We imagine a fiber fabricated as shown in Fig. 2. The challenge is in the three-dimensional (3-D) microfabrication. To our knowledge, this structure cannot be easily fabricated using commercial processes.

G. NA-Based Access

An alternative approach to separating the core and cladding light is to utilize the difference in the maximum light acceptance angle, or NA between the two. The core acceptance angle is generally much shallower than that of the cladding (Table I). This difference will allow the source light to be sent through a hole in a mirror to the core. Upon returning, most of the cladding light is reflected by the mirror and collected (Fig. 3). The advantage of NA-based access is the potential for collecting nearly all of the light that is initially coupled into the core. A well-designed system is capable of collection efficiencies on the order of the ratio of the square of the NAs ($\sim$98%).

The disadvantage of this approach is that, it can be challenging to implement in a limited space. Further, the approach is susceptible to minor amounts of mode noise, since the return light is not uniformly collected.

H. Direction-Based Access

The approach chosen for the experiments reported in this paper is direction-based fiber access (Fig. 4). The source light is sent through a 50%–50% beam splitter. Half of the light transmits through the splitter and is coupled into the core of the fiber. The second half of the light reflects at a 90° angle to the source light and could be collected by a source-light photodetector (I_o).

Once the light has traveled through the single-mode core and the measurement path, it is collected in the cladding. After returning through the cladding to the beam splitter, half of the light is transmitted through the splitter and does not participate in the measurement (“wasted” light). The remaining light, which includes any return light coupled into the core, is reflected at a 90° angle and focused onto a second photodetector (I). The “retroreflector” shown in Fig. 4 could be any of several optics in practice; for example, we have successfully used a plane mirror, a corner-cube retroreflector (as shown), an array of corner cubes, and a diffuse scattering surface. A spherical mirror with a radius of curvature approximately equal to the length of the test section is expected to reduce sensitivity to beam steering; however, it may be more cumbersome to implement in practice.

Direction-based access allows a close grouping of components, which will be desirable when the sensor is packaged. Also, this approach is easier to align than NA-based access (source light does not have to be aligned through a small diameter hole). Ease of alignment, however comes at a cost. As mentioned, some of the light is wasted, and therefore, the maximum collection efficiency for the “I” signal that can be achieved with direction-based access is 25% of the source.

I. Results

The direction-based DCF approach to absorption spectroscopy (Fig. 4) was used to measure H_2O vapor in a laboratory setting, for which the “test section” was a mock-up of a gas-turbine main burner. A tunable diode laser (New Focus 6327) with a scan range of 1380–1460 nm was coupled into a short length ($\sim$5 m) of DCF. Light was collected with a Thorlabs PDA 400 InGaAs detector, and data was recorded by a 12-bit, 10-MS/s, PC-based data-acquisition system. The data was reduced to the absorption spectrum shown in Fig. 5 using the Beer-Lambert law [4]. We estimated the minimum detectable absorbance (MDA) for the data shown in Fig. 5 to be 1%. This MDA value is approximately ten times larger than we routinely achieve in a similar setup but without the DCF. The relatively large MDA is due to an insufficient polish angle on the end faces of the DCF (11°, insufficient because of the high NA of the cladding), allowing unwanted back reflections to be guided by the fiber. These back reflections for the fiber specified in Table I would be eliminated by increasing the polish angle to 18.8° or greater. We are currently working to reduce the residual noise with a lower NA DCF customized for our

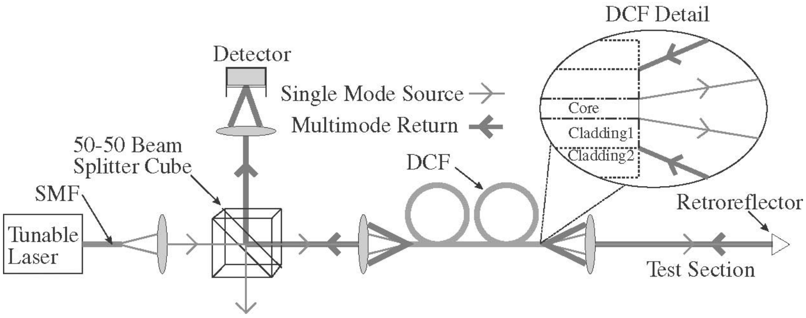

Fig. 4. DCF approach to absorption spectroscopy.

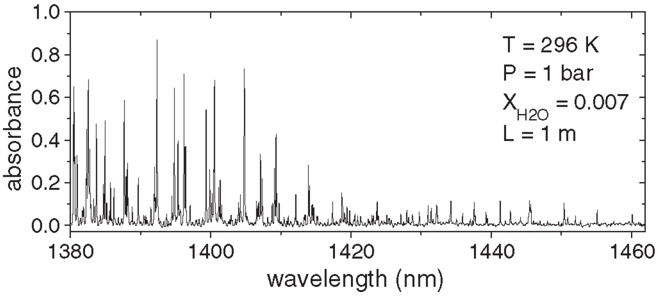

Fig. 5. Absorption spectrum for room humidity collected using DCF in a laboratory setup simulating a gas-turbine engine.

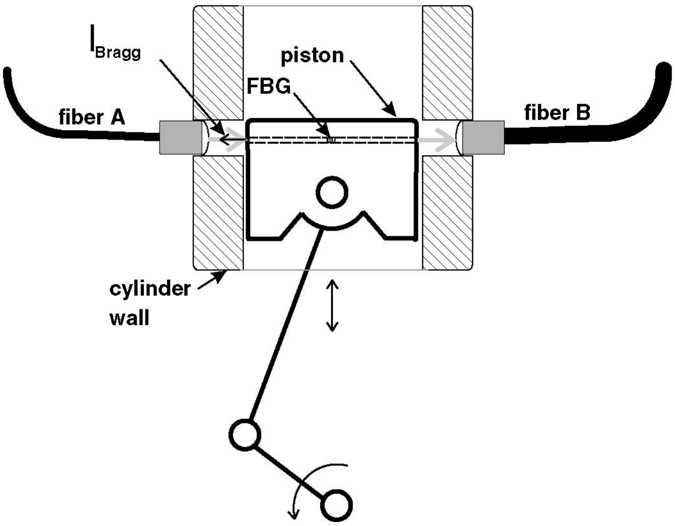

Fig. 6. Experimental arrangement for FBG piston temperature measurement.

applications. However, even with an MDA of 1%, we expect to be able to measure gas temperatures accurate to within 1% in many applications.

III. APPLICATION 2: FBG THERMOMETRY

FBG sensors are established means for determining the temperature and strain [9]. These sensors typically utilize a multiwavelength source to monitor the spectrum of the FBG, just as the above example monitors the spectrum of a gas. The FBG generally has a single reflection feature with a spectral width of 1 nm or less. The center wavelength of this reflection feature depends on the FBG temperature and strain, as thoroughly discussed elsewhere [10]. In brief, an FBG is typically formed by exposing a portion of an SMF to ultraviolet light in such a way that the refractive index of the core varies along the fiber. Most light propagating in the fiber is unaffected by the FBG; however, wavelengths that are resonant with the periodicity of the index variations are partially reflected. The periodicity changes with strain and temperature, because the index of the fiber core and the physical size of the FBG depend on these parameters.

Traditional FBG sensors record either the reflected or the transmitted light. Both of these approaches are straightforward if the source light is coupled into a stationary FBG. Recent work has been done to explore the use of FBGs for noncontact measurements of moving metal parts [11], [12]. To enable temperature measurements in a moving piston, an FBG (O/E Land FBG 14-033-3-8514) with a Bragg wavelength (λ_{Bragg}) of 1426.4 nm at 26 °C is embedded in the piston [12] (Fig. 6). Light is then periodically coupled into the FBG as the piston reciprocates. Initially, FBG piston temperature measurements were performed in a transmission mode (analogous to replacing the "test section" in Fig. 1 with the piston). The three fiber components (fiber A "pitch," FBG, and fiber B "catch") are briefly aligned as the piston passes by the optical ports. The fiber A "pitch" and FBG are both sized for single-mode transmission for the predetermined source wavelengths to eliminate mode noise. The fiber B "catch" fiber is a large MMF intended to compensate for misalignment.

To assess the suitability of DCF in this application, we configured the experiment in Fig. 6 by replacing the SMF A with DCF (analogous to replacing the "test section" in Fig. 4 with the piston), and monitored the FBG in reflection mode. We also monitored the transmission simultaneously for comparison. DCF is a natural fit for the reflection-mode measurements. As in absorption spectroscopy, DCF allows this measurement to be made using a single fiber port, thus simplifying the sensor. Alignment challenges associated this time with irregular piston motion (rather than beam steering) are managed effectively by the DCF.

A. Results

As shown in Fig. 7, the reflected DCF signal appears "cleaner" than the transmitted signal. This is because, the former monitors an obvious signal riding on a small background of residual reflection, whereas the latter, monitors a feature

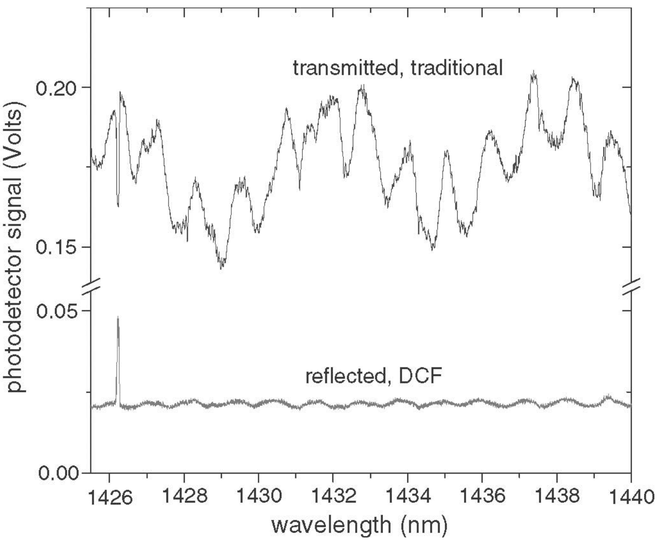

Fig. 7. FBG piston temperature measurement results.

within a relatively large and noisy signal (the noise is due to unwanted etalons in the setup).

IV. DISCUSSION

We have introduced the DCF as a convenient conduit for signals in a variety of optical sensors. The DCF can potentially improve the signal quality, ease of alignment, immunity to beam steering, and access into challenging locations. We have presented example data from the absorption spectroscopy and FBG thermometry applications utilizing source wavelengths (1380–1460 nm), which are well within the transmission range of the glass core/cladding fiber used here (200–2700 nm, for short lengths on the order of 1 m). In addition, a DCF made of fluoride glasses is now commercially available, extending the upper limit of transparency to ~3700 nm.

Our research group intends to continue investigating and refining DCF-based sensors. We believe that the DCF can open the door to new opportunities in the field of optical measurement as well as increase the commercial feasibility of existing methods.

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