



Optical Imaging and Sensing in Harsh Environments

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Acknowledgments

The work was encouraged and supported mainly by the NASA Science Mission Directorate with additional support from the NASA Aeronautics Research Mission Directorate. The authors wish to express their gratitude to Mr. Mark Woike (NASA) for his recommendations regarding applications of the temperature-sensitive paint technology, and to Messrs. Bertram Floyd and Frank Lam from HX5 Sierra for their technical support in construction of the experimental setups and manufacturing of individual components.

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Summary

This paper discusses extraction of images and sensing information from targets located in harsh planetary environments. Various configurations of sensing systems with imaging fiber optic conduits are presented and discussed, including some experimental data. Prototypes are designed and their performance is demonstrated with a focus on potential applications in the Venusian atmosphere.

Introduction

Sensing is a process of collecting, processing, storing, and communicating information about the physical status of an object, such as location or chemical composition. It is also understood that the processing of the information is done by an observer, which could be a person or a mechanism designed specifically for that purpose. The observer is usually equipped with a device or sensor that acts as a detector and interpreter of the physical status of the object of interest. Because the object and the detector or observer are often located in different environments, and sometimes in extremely different environments, communication between the two may require physical separation by a wall. Special care should be taken in the collection of sensing information from the target and delivery of that information through the wall. Sensing consists of several elements that permit facilitation of this process. This paper discusses configurations of sensing systems based on imaging fiber optic (FO) conduits for potential applications in harsh planetary environments, and specifically in the Venusian atmosphere and on the planet's surface.

Optical Sensing in Harsh Environments

It is important to recognize the difference between variations of sensing. Such variations may include, for instance, imaging and non-imaging sensing, passive and active sensing, and means to communicate between the media.

Imaging and Non-Imaging Sensing

Sensing concepts can be divided into different types of implementations, such as imaging sensing, sensing based on the amplitude or phase of optical signal, spectral sensing, and various combinations of these concepts. In imaging sensing, the observer obtains an image of the object and processes that image

to extract the necessary information about the object. In spectral sensing, the necessary information is extracted from a spectrum emitted or absorbed by the object. In amplitude and phase sensing, the information about an object is extracted from either the amplitude of the optical signal, its phase, or both.

Other configurations could be done based on the way the information is propagated between the object and the observer, through waveguides or unbounded media. In the first case, the sensing and propagation of the information can be done with the assistance of optical fibers. The propagation of the information through an unbounded medium is characteristic of remote sensing. Sometimes a combination of the techniques gives particular advantages.

The list is not complete, and in this paper we will limit our discussion to imaging and spectral sensing in unbounded media.

Passive and Active Sensing

To facilitate the sensing process, the object should communicate particular information to the observer. That communication is either done spontaneously by the object or through the excitation of the object by an external factor. Based on that distinction, the sensing process is called either active or passive. A passive sensing system may, for instance, naturally emit a certain spectrum of electromagnetic radiation under given environmental conditions. Detection and processing of such radiation would permit extraction of said environmental conditions.

In an active sensing system, however, the information would have to be extracted through a response of the object to an external excitation. Such external excitation could be thermal, acoustical, electromagnetic, and so forth. Because visualization is a form of sensing and human eyes are sensors, the use of human eyes during daylight is an example of a passive form of sensing. However, a spectral image of a forest that is generated by light emitted by trees in response to artificial excitation is an example of active sensing.

Communications Between Two Media

Very often the object subjected to sensing and the observer (or detector) are located in media with different environments. Transmission of information in this case could be done either via some sort of optical waveguides, open air, or a combination of both.

The most commonly used optical waveguides for transmission of information between media with different environments are optical fibers. Various FO sensors and subsystems are currently available on the market, and numerous attempts have been made to introduce them into practical applications (Refs. 1 to 5).

Open-air communications or communications in an unbounded medium may require a wall separating the two media, especially when the sensor is in a harsh environment. An example could be an aerodynamic wind tunnel with windows to monitor the airflow. The object in this case could be a subsystem of an aircraft placed in a near-real flight situation for the purpose of performance evaluation (Refs. 6 to 9). The greater the differences between the media environments, the more complicated the mechanisms to transfer the information. The greatest challenge is presented when the object is in an extreme environment and the observer is in moderate or benign surroundings.

If the change from harsh to benign environments occurred in space gradually, one might be able to identify a zone with moderate environments. Such zones may partially eliminate the stress put on individual components by large gradients in parameters, such as temperature, pressure, species concentration, and so forth. A sensing system to measure the engine gas exhaust temperature as described in Reference 10 shows a gradual change of environments. In this system, the temperature-sensing element, an optical fiber Bragg grating, is placed in the plume of the exhaust gases, and the signal propagates through an optical fiber away from harsh environments toward a detector that is located in benign environments.

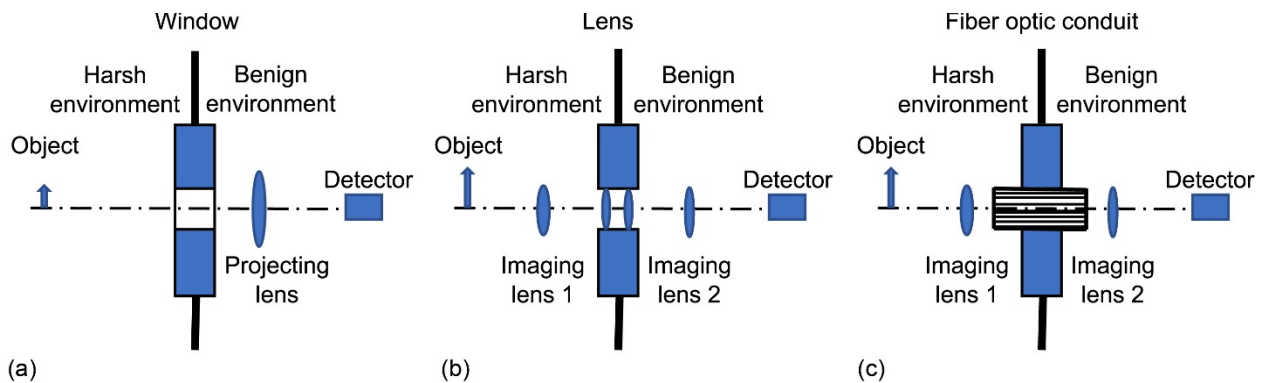


Figure 1.—Examples of separators between media with capabilities to transfer information. (a) Transparent window. (b) Transparent window with imaging lenses. (c) Fiber optic conduit with imaging lenses.

In another case, the two media are separated by a wall with practically no region with a moderate environment. An example could be an aerodynamic wind tunnel with windows to monitor the airflow. The object in this case could be a subsystem of an aircraft placed in a near-real flight situation for the purpose of performance evaluation. A transparent window in the tunnel serves as both separator between two media and the means to transmit sensing information between them.

Differences in the environments between the media require a separator that facilitates the transfer of information between them. Examples of such separators are shown in Figure 1.

Figure 1(a) shows a separator with a transparent window. In Figure 1(b), a transparent window is enhanced with included lenses. As the difference in physical properties and composition of gases between the media increases, neither of these configurations may form an appropriate barrier between the two media. However, the third configuration, which employs a FO conduit (Figure 1(c)), has advantages. It may provide a better barrier, a better seal, and a mechanical structure to support optical attachments.

Visualization in Harsh Environments

While transparent windows (Figure 1(a)) have been used in aerodynamic wind tunnels, and windows with lenses (Figure 1(b)) may be beneficial in some applications, these configurations may not be appropriate in extreme environments with high temperatures, high pressures, and noxious gases. The configuration shown in Figure 1(c) employs an imaging rod that is simply an imaging FO conduit consisting of many optical fibers with small core diameters fused together into a multicore element with a common cladding. Figure 2 shows a photograph of a face of this type of FO conduit with an inset depicting a magnified section. The granular structure seen in the inset is due to the presence of multiple fibers.

The concept described in Figure 1(c) is explained in more detail in Figure 3. Figure 3 shows schematically a FO conduit with two imaging lens attachments (Figure 3(a)), an equivalent representation for the FO conduit using geometric optic principles (Figure 3(b)), and some possible configurations of object projection lenses (Figure 3(c)).

The FO conduit itself transmits an image from one of its faces to another with unity magnification. Imaging lens 1, attached to the object side of the conduit, serves to change the field and depth of view in the object environment (Figure 3(a)). Imaging lens 2, attached to the other end of the conduit, permits changing the magnification of the image formed on the face of the conduit and projecting it on the sensitive area of a camera or photodetector. Various configurations of the object projection lenses permit flexibility in the design of the lens attachments to fit particular applications (Refs. 11 and 12).

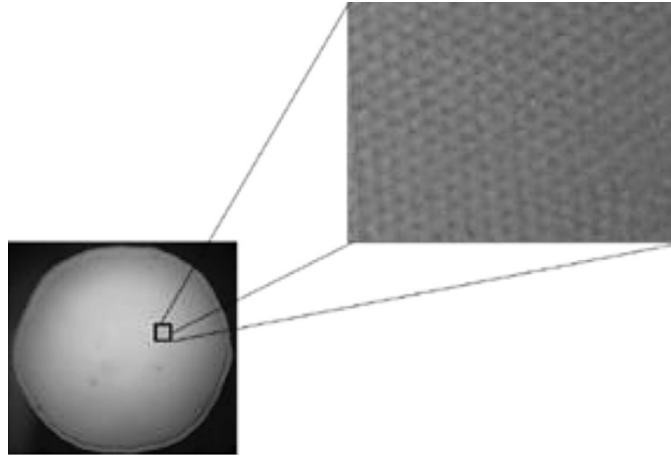


Figure 2.—Fiber optic conduit face and magnified section (inset).

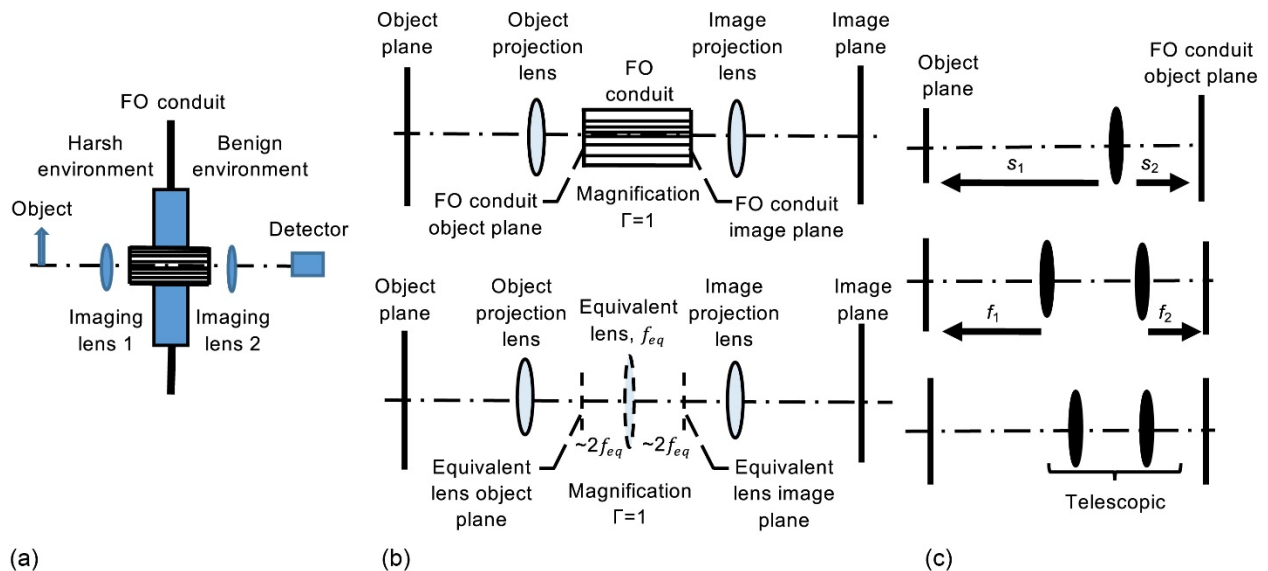


Figure 3.—Imaging through fiber optic (FO) conduit. (a) Two media separated by wall with FO conduit with imaging lens attachments. (b) Equivalent representation of FO conduit using geometric optical principles. (c) Some possible configurations of object projection lenses.

Imaging lens 1, which forms an image of the object on the face of the FO conduit, depends on the mission requirements, such as magnification and resolution or field of view. Figure 3(c) shows examples of potential designs of the corresponding lens attachment. It is obvious from the geometric optics approximation for thin lenses that, in the uppermost case shown in Figure 3(c), the relationship between distances s_1 and s_2 is such that as the distance from the observed object s_1 to the lens decreases from infinity to $2f$, where f is the focal length of the lens, the distance s_2 increases accordingly from f to $2f$. Moreover, in the case for which the distances of both object plane s_1 and FO conduit object plane s_2 are equal to $2f$, the magnification of the optical system is equal to 1.

Thus, a change in the distance s_1 leads to a longitudinal adjustment of the lens in order to have a projection of the object on the face of the conduit. That adjustment will lead to a change in the magnification. Figure 4 shows images of 1/64-in. scale on a FO conduit about 6 mm in diameter using a 15-mm focal length lens and different distances to the scale, s_1 . Figure 4(a) has a field of view of about 1/2 in. (12.7 mm), while Figure 4(b) covers about 1/4 in. (6.35 mm). The case shown in Figure 4 has an example of so-called telescoping magnification, which fits an image of a larger size object into a smaller image space. For both cases, $f = 15$ mm. The image in Figure 4(c) is obtained using a lens with $f = 25$ mm. If we continued moving the object plane closer to the lens, between distances $s_1 = 2f$ and $s_1 = f$, the lens would act as a magnifying lens.

Another challenge is to provide illumination of the object when the natural illumination is either weak or nonexistent. We provide the illumination externally through the same FO conduit. We have found that among various configurations of imaging systems with external illumination, the most efficient is the one with illumination through the face of the FO conduit so that all fiber cores deliver and collect light. Figure 5(a) shows schematics of such a system, and Figure 5(b) depicts the image of a scale with 1/64-in. gradation through a 1-m-long FO conduit.

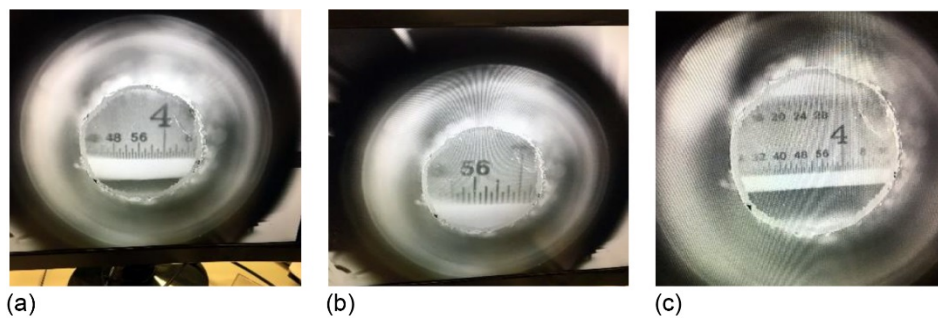


Figure 4.—Images of 1/64-in. scale positioned at different distances from lens and projected on face of fiber optic conduit using lenses with different focal lengths. (a) $f = 15$ mm. (b) $f = 15$ mm. (c) $f = 25$ mm.

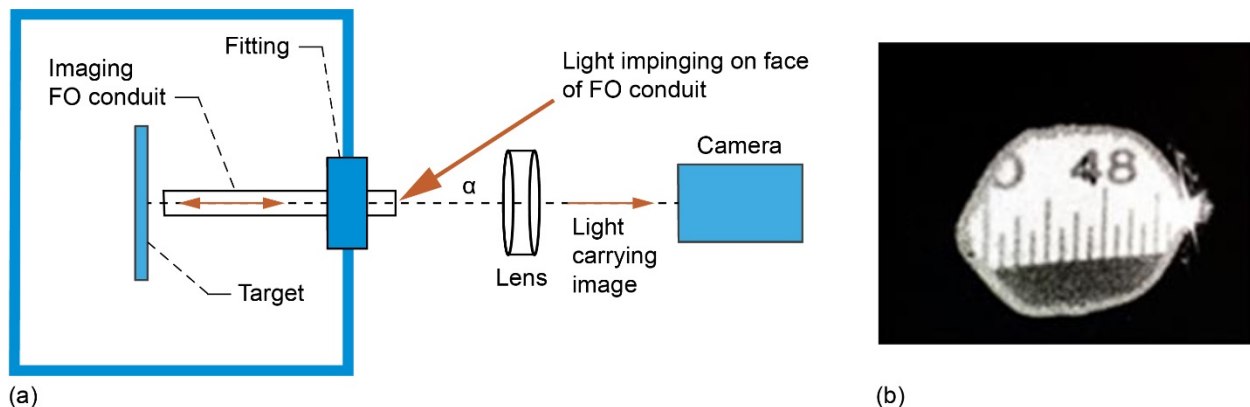


Figure 5.—Imaging of 1/64-in. scale using external illumination through face of 1-m-long fiber optic (FO) conduit. (a) System schematics. (b) Image.

Active Sensing

Configurations with an imaging FO conduit can also be used to conduct active sensing in harsh environments. An optical beam coupled into the conduit reaches the target and triggers a spectral response based on the chemical composition of the target and the wavelength and power of the beam. Fluorescence, phosphorescence, laser-induced breakdown spectroscopy (LIBS), and other phenomena can be observed using this technique. For instance, illumination of targets coated with temperature- or pressure-sensitive paints by optical beams of appropriate wavelengths would trigger spectral responses dependent on the temperature or pressure of the target. The technique could also be useful in spectral analysis involving LIBS. Pulsed laser beam propagation through FO conduits with generation of plasma discharges is possible under conditions in which the surface energy density at the entrance face of the conduits is below the damage threshold.

Figure 6 shows a schematic of the experimental setup (6(a)) and its implementation (6(b)). The schematic in Figure 6(a) is similar to the one shown in Figure 5. However, there are a few differences. In Figure 6, a target is placed inside a furnace and coated with a temperature-sensitive paint (TSP). The light used to excite the TSP has a spectrum within the excitation wavelength range for the paint. The FO conduit is about 305 mm long and about 6.4 mm in diameter and consists of a uniform cladding and about 50,000 individual optical fiber cores, each about 24 μm in diameter. Light at a certain wavelength enters the FO conduit, reaches the target, and excites the temperature-sensitive paint. The paint, in response to the excitation, luminesces. The spectrum analyzer, a miniature spectrometer capable of measuring wavelengths from 330 to 1,050 nm, detects and processes the spectrum.

In the non-imaging implementation of the experimental setup (Figure 6(b)), the light to excite the temperature-sensitive paint was introduced through the face of the FO conduit. The TSP responds by emitting luminescing light at a different wavelength that travels back through the same conduit and reaches a spectrum analyzer. Neither the target disk with TSP coating inside the furnace nor the spectrum analyzer is shown in the figure.

The tests were done in two phases. The first phase involved using a commercially available TSP usable at temperatures up to slightly over 70 °C. When the paint was illuminated by a light source in the 380- to 520-nm range, the luminescent molecules in the paint-emitted light peaked around 610 nm. During the test, the light-emitting diode (LED) light source intensity was increased until the spectrometer almost saturated at the peak at 452 nm. As the temperature in the oven increased from 23 to 72 °C, the intensity of the light spectrum luminescing back from the TSP at the 610-nm wavelength decreased.

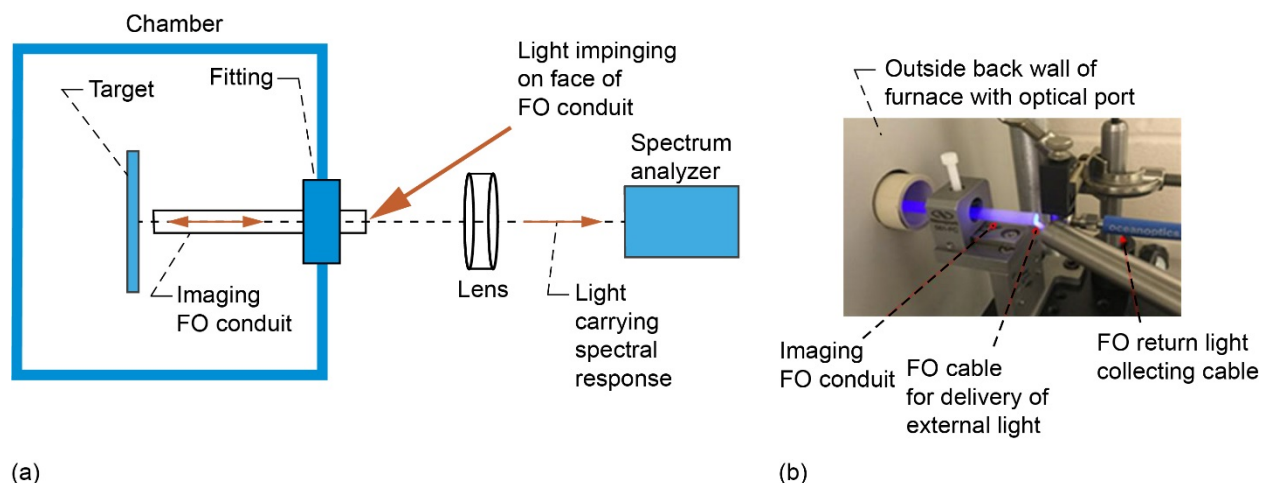


Figure 6.—Experimental setup. Fiber optic, FO. (a) Schematic. (b) Implementation.

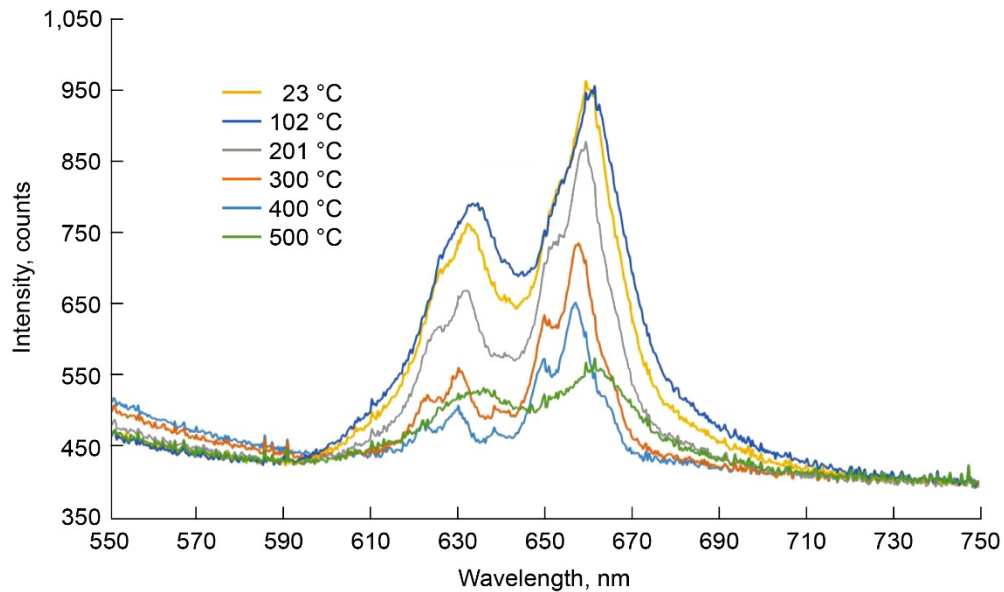


Figure 7.—Phosphorescent peaks of $\text{Mg}_4\text{FGeO}_6\text{:Mn}$ painted on target inside an oven.

During the second phase, the operational temperature was increased to 500 °C and a higher temperature thermographic phosphor paint, $\text{Mg}_4\text{FGeO}_6\text{:Mn}$, was used. Often a phosphor is used as a thermometer by measuring its fluorescent decay time. However, decay time measurements would have required different equipment than the current experiment. Therefore, a different property of the $\text{Mg}_4\text{FGeO}_6\text{:Mn}$ phosphor, the ratio between two phosphorescent peak heights, was used to measure temperature. Because different wavelengths have different temperature sensitivities, one can calibrate the ratio of the peak intensities of two different lines (Refs. 13 to 15). For this experiment, a 0.5-m-long FO conduit was used. Approximately 0.24 m of its length was completely within the furnace. Another 0.15 m of the conduit traversed the wall of the furnace. The same LED light source with a peak wavelength of 452 nm illuminated the paint through the optical conduit. A long-pass filter with a cutoff of 550 nm was used to reduce the excitation peak by 99 percent. Five hundred spectra, each with an integration time of 100 ms, were averaged. Figure 7 shows the two phosphorescent peaks of $\text{Mg}_4\text{FGeO}_6\text{:Mn}$ at 631 and 657 nm taken at six different temperatures from 23 to 500 °C.

The drop in intensity of both peaks at 500 °C is expected because at higher temperatures, nonradiative de-excitation becomes the dominant relaxation pathway. The energy is then dissipated to the ground state via thermal lattice vibrations (Ref. 16). Figure 8 shows the natural logarithm of the ratio of phosphorescent peak intensities at two wavelengths, 631 and 657 nm, emitted by $\text{Mg}_4\text{FGeO}_6\text{:Mn}$ at various temperatures. The ratio of the peak intensities is presented after a subtraction of the background with the LED off.

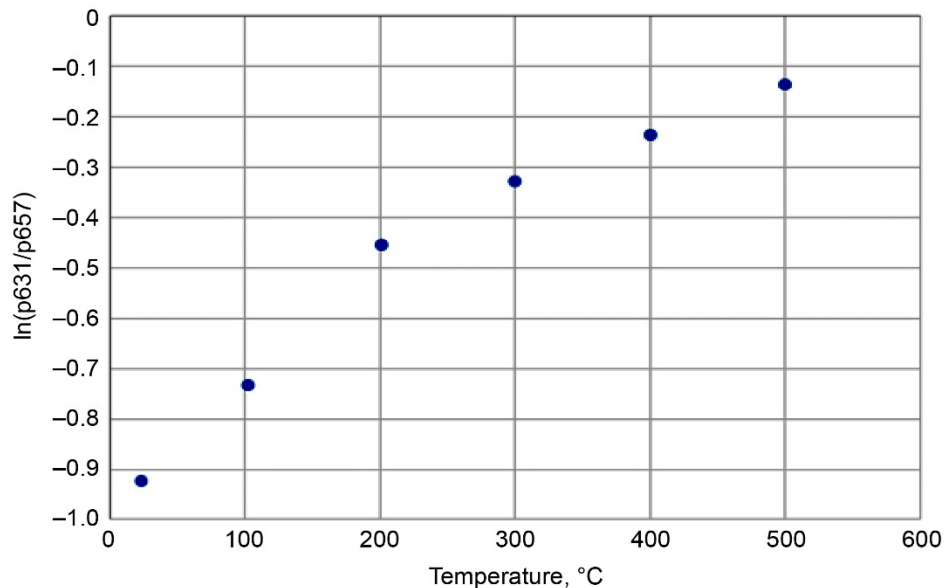


Figure 8.—Natural logarithm of ratio of peak intensities at two wavelengths, 631 nm (p631) and 657 nm (p657), emitted by Mg4FGeO6:Mn at various temperatures.

Adaptation to Venusian Environments

Optical sensing configurations with FO imaging conduits are the most beneficial in harsh environments where the sensing targets have to be insulated from detectors located in more benign surroundings. An example of such an environment is the Venusian atmosphere, where the temperature on the surface of the planet reaches 480 °C, the pressure is up to 92 atm, and the atmosphere is a mixture of extremely corrosive gases (Ref. 17). On Earth, similar environments are produced artificially in special chambers, with the best known among these being the NASA Glenn Extreme Environments Rig (GEER) (Refs. 18 and 19).

To accommodate the sensing concepts described above, a number of steps were taken, including selection of materials, development of feedthroughs, packaging of the optical system, and evaluation of the effects of temperature on the optical properties of the FO conduits.

The selection of materials was done based on previous work of NASA researchers that identified effects of the Venusian atmosphere, especially noxious gases, on the chemical stability of metals, metallic compounds, and glasses (Refs. 20 and 21). Moreover, a practical implementation of a FO conduit to transmit imaging and sensing information between two media with different environments requires packaging of the FO conduit such that mechanical robustness of the structure is assured and the separation of the environments is secured.

A preliminary design of a structure to hold the FO conduit is shown in Figure 9. The structure is made out of a stainless steel modular tube with an adjustable lens attachment. The imaging FO conduit is inserted inside the tube toward the lens attachment. The depth of the insertion permits the projection of a target on the face of the rod by the lens installed in the lens attachment. The attachment also permits manual changes in the lens position with a change in the distance to the target. This design permits using the same structure for multiple applications and adjusting the position of the lens in advance, depending on the application.

Figure 10 depicts fields of view at 1/64-in. scale observed by the lens at various distances. The focusing was accomplished by a corresponding adjustment of the lens attachment.

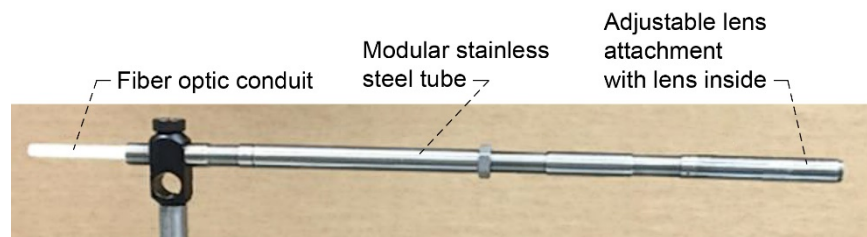
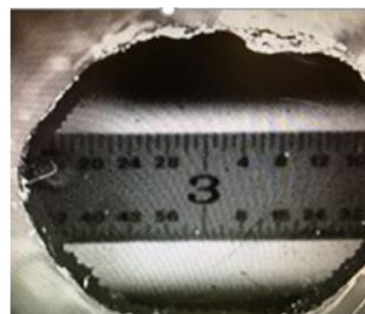


Figure 9.—Preliminary design of structure to hold fiber optic imaging rod with lens attachment.



(a)

(b)

Figure 10.—Imaging setup. (a) Position of 1/64-in. scale at various distances. (b) Corresponding images.

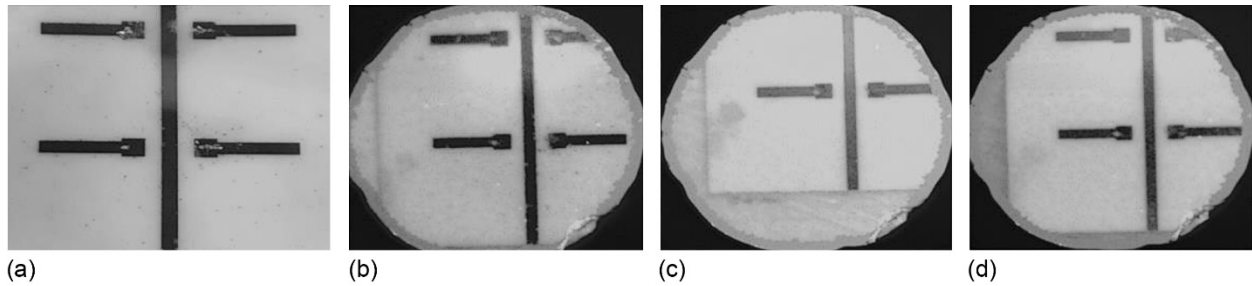


Figure 11.—Original target circuit and its images during tests. (a) Microscope image of gold on alumina target circuit. (b) Image through the fiber optic conduit at room temperature (light-emitting diode (LED) current 26 mA). (c) Image after holding for 2.5 h at 500 °C (LED current 26 mA). (d) Image after all three temperature cycles to 500 °C (LED current 18 mA).

To demonstrate the suitability of FO conduits for imaging at temperatures up to 500 °C, we tested a 0.50-m-long FO conduit in a furnace. Similar to the setup described in the Active Sensing section of this paper, a portion of the conduit approximately 0.24 m long was fully inside the furnace, while another 0.15 m traversed the wall of the furnace. The rest of the conduit was outside the furnace. The target used was a gold circuit deposited on an alumina substrate. Figure 11(a) shows the circuit as seen through a microscope. The thickness of the circuit traces in the images is 213 μm . The same LED light source with an intensity peak at 452 nm was used to provide illumination from outside the furnace. The light traveled through the conduit, illuminated the circuit, and returned through the same conduit to the camera. A small universal serial bus (USB) camera was used to capture the images. Figure 11(b) shows the image of the circuit through the conduit at room temperature.

The target was heated to 500 °C several times. On the first heating, the image became noticeably brighter after sitting at 500 °C for 2.5 h, as seen in Figure 11(c). The image is shifted upward because of thermal expansion of the sample holder. After cooling back down to 28 °C the next day, the image remained significantly brighter. A second heating to 500 °C for 3 h showed no additional brightness at high temperature. However, the image after cooling down was again brighter than before heating. A third heating to 500 °C for 26 h showed similar results.

To obtain the same apparent image brightness as measured by the eye (red, green, and blue (RGB) values confirmed constant brightness within a few percent), the LED current was lowered after each heating cycle. The first cycle used 26 mA, the second cycle used 20 mA, and the third cycle used 18 mA. Figure 11(d) shows the same image as in Figure 11(b) after all three temperature cycles between 22 and 500 °C with a total of 32 hours at 500 °C. This lowering of the necessary illumination may indicate that the conduit is being annealed by temperature cycling. Similar effects of high temperature on light transmission through optical fibers have been observed and recorded (Refs. 22 and 23).

Concluding Remarks

We have constructed and demonstrated a proof of concept of an active optical sensing system for applications in environments where there is no direct access to the target. We also demonstrated suitability of an imaging FO conduit consisting of multiple fiber optic (FO) cores confined to one uniform cladding to provide both external excitation of the target and extraction of image and spectral information for further processing. Furthermore, we constructed and demonstrated optical attachments capable of projecting an image of a remotely located object on the face of the optical image conduit for the followup processing.

In the process of thermal analysis, we also observed variations of the intensity of images transmitted through the FO conduits at elevated temperatures. These observations, confirmed by earlier research, reinforced the necessity of annealing FO components for stable operations at high temperatures.

Future work is planned to combine both the imaging and spectral measurements into one system capable of simultaneous measurements using the same conduit. Work is also planned to test other types of spectroscopic measurements through the optical conduit. One exciting possibility is to use a laser to excite a plasma in the chamber and measure the resulting spectra. Raman spectroscopy is another potential option to gain valuable optical data through an optical conduit.

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