Infrared-Transmitting Fibers

August 1998

I. D. Aggarwal, L. E. Busse and J. S. Sanghera
Naval Research Laboratory, Code 5606
Washington, DC 20375

ABSTRACT

Chalcogenide glass fibers have been fabricated with minimum optical loss of 0.23 dB/m in the 1 - 6 μm region. We report on results of applications of these fibers including IRCM and chemical sensing. For IRCM we have demonstrated high power transmission through selected fibers using an Optical Parametric Oscillator with output in the 3 - 5 μm wavelength region. The maximum peak power used was 26.9 kW and the peak power density at the focus into the fiber was 1.07 GW/cm^2, which to our knowledge is the highest reported for these types of fibers. Analysis of the near field profile exiting the fibers showed that there was no speckle observed, which is highly desirable for this application. For chemical sensing, results of infrared reflectance spectroscopy and evanescent spectroscopy will be described wherein the application is the detection of toxic chemicals in soil or ground water.

1.0 INTRODUCTION

NRL is developing low loss IR-transmitting chalcogenide glass fibers (e.g. sulfide-selenide- and telluride-based compositions[1, 2]) for a variety of applications, including Infrared Countermeasures (IRCM). Recently, using advanced purification and fiber fabrication techniques developed at NRL, the optical loss in multimode sulfide fiber has been reduced to a minimum of 0.23 dB/m, as shown in Figure 1. The loss curve shows a residual absorption band near 4 μm which is due to hydrogen sulfide; it is expected that this absorption loss can be reduced by newly implemented purification methods.

The fibers are of step index design, with numerical aperture (N.A.) of 0.2 to 0.4, depending on choice of compositions for the core and clad. Typical core/clad fiber diameters for multimode fibers range from 100 μm/ 250 μm to 300 μm/ 400 μm. Bending strength[3] of the fibers is about 100 kpsi, which corresponds to a minimum bend diameter of 1 to 2 cm. In addition, as the results show in Figure 2, there was no measureable loss due to bending during transmission of mid-IR laser irradiation at wavelength λ, where 4 μm < λ < 5 μm.

REPORT DOCUMENTATION PAGE	Form Approved OMB No. 0704-0188

1. REPORT DATE (DD-MM-YYYY) 01-08-1998	2. REPORT TYPE Conference Proceedings	3. DATES COVERED (FROM - TO) xx-xx-1998 to xx-xx-1998

4. TITLE AND SUBTITLE Infrared-Transmitting Fibers Unclassified	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) Aggarwal, I. D. ; Busse, L. E. ; Sanghera, J. S. ;	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME AND ADDRESS Naval Research Laboratory Code 5606 Washington, DC20375	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME AND ADDRESS Director, CECOM RDEC Night Vision and electronic Sensors Directorate, Security Team 10221 Burbeck Road Ft. Belvoir, VA22060-5806	10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
APUBLIC RELEASE
,

13. SUPPLEMENTARY NOTES
See Also ADM201041, 1998 IRIS Proceedings on CD-ROM.

14. ABSTRACT
Chalcogenide glass fibers have been fabricated with minimum optical loss of 0.23 dB/m in the 1 - 6 mm region. We report on results of applications of these fibers including IRCM and chemical sensing. For IRCM we have demonstrated high power transmission through selected fibers using an Optical Parametric Oscillator with output in the 3 - 5 mm wavelength region. The maximum peak power used was 26.9 kW and the peak power density at the focus into the fiber was 1.07 GW/cm2, which to our knowledge is the highest reported for these types of fibers. Analysis of the near field profile exiting the fibers showed that there was no speckle observed, which is highly desirable for this application. For chemical sensing, results of infrared reflectance spectroscopy and evanescent spectroscopy will be described wherein the application is the detection of toxic chemicals in soil or ground water.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT Public Release	18. NUMBER OF PAGES 9	19. NAME OF RESPONSIBLE PERSON Fenster, Lynn lfenster@dtic.mil
a. REPORT Unclassified	b. ABSTRACT Unclassified	c. THIS PAGE Unclassified			19b. TELEPHONE NUMBER International Area Code Area Code Telephone Number 703767-9007 DSN 427-9007

	Standard Form 298 (Rev. 8-98) Prescribed by ANSI Std Z39.18

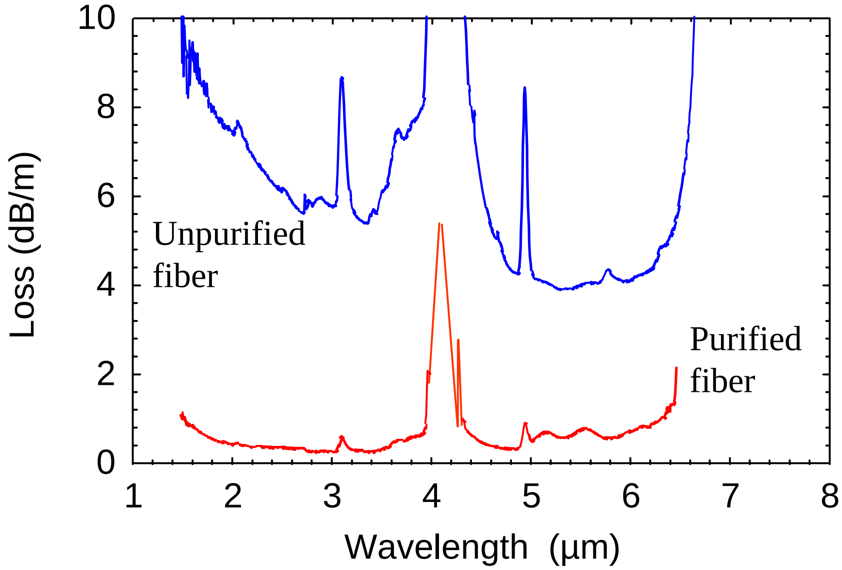

Figure 1. Optical loss of arsenic sulfide fiber, showing improved minimum loss of 0.23 dB/m with improved purification methods.

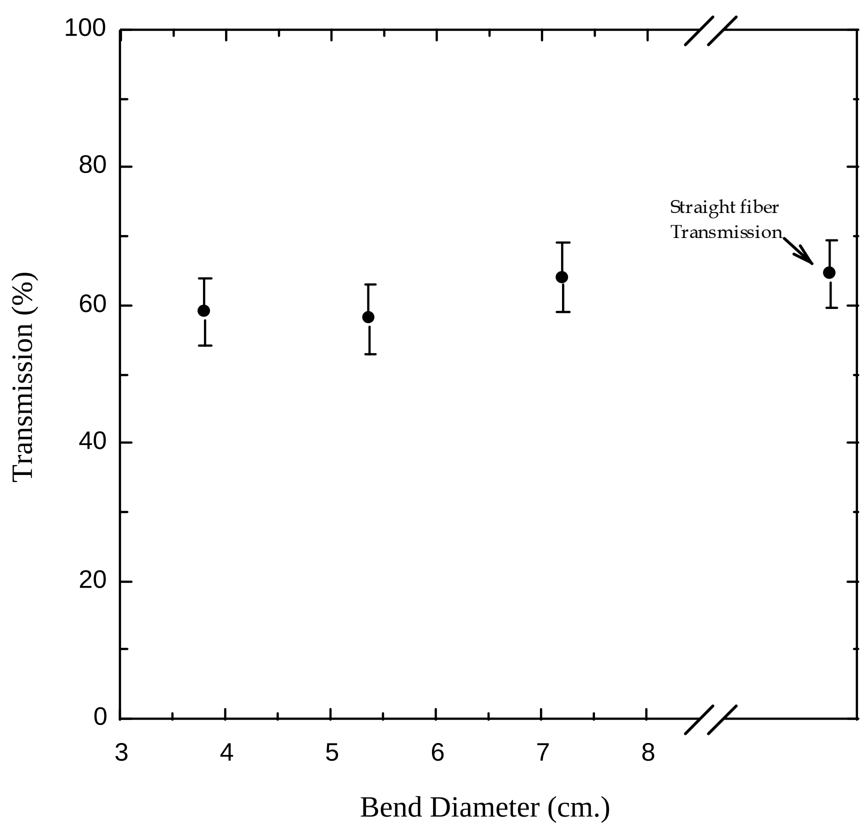

Figure 2. Transmission with circular bends in fiber of various diameters, as tested with a laser in the 4 - 5 µm region. *No measureable change was observed.*

To meet optimum transmission requirements, the fibers need to have AR coatings, due to the high refractive index (n=2.4) of the glass. AR coatings have been deposited by an outside vendor which have increased transmission from 58% in an uncoated fiber to 83% for a fiber with AR coated endfaces, as measured in the 4 - 5 μm region.

Because to their low loss, high mechanical strength and flexibility, the chalcogenide fibers are favorable as replacements for all-mirror systems currently being fabricated to connect IR lasers to the Jam Head in IRCM systems. When compared to an open beam path (such as a mirror-based mechanical arm), a cable link has distinct advantages, such as simple and robust alignment from the laser to the Jam Head, flexibility of placement of laser and Jam Head in the aircraft, resistance to platform vibration and flexure and crush resistance. As a demonstration of fiber feasibility for this application, we have recently shown successful jamming of missile seekers using mid-IR laser output from these fibers.

To meet the requirements for the IRCM application, the fibers must be capable of handling high optical power in the 2 - 5 μm region. In this paper we report on recent tests done to determine the optical power handling capability of the fibers using a state-of-the-art, high power optical parametric oscillator (OPO) in the 2 - 5 μm region. These results will be presented below in Section 2.0.

In addition to the IRCM applications, the fibers have been used in chemical sensing applications. Two types of applications will be described, where both have goal of sensing toxic chemicals (e.g. toluene, benzene) in the soil or groundwater, using methods of IR reflectance spectroscopy and evanescent wave spectroscopy. NRL successfully conducted a field test using twenty meter length cables of chalcogenide fibers inside a cone penetrometer, whereby evidence of toxic effluents in the ground were detected. These results will be presented in Section 3.0.

2.0 RESULTS AND DISCUSSION: IRCM APPLICATIONS

The benchtop laser used in these experiments consisted of a $ZnGeP_2$ OPO crystal pumped by a diode-pumped Ho:YLF laser whose radiation was passed through dual Ho:YLF amplifiers. The beamline consisted of collinear radiation at two bands in the 3 - 5 μm wavelength region. The maximum available average power at the fiber input was 2.69 W. The repetition rate was 10 kHz and pulsewidth was 10 ns, yielding a maximum available peak power (per pulse) of 26.9 kW. The focused beam diameter (at the $1/e^2$ intensity points of the Gaussian beam profile) was measured to be about 80 microns. The laser input to fiber alignment was first obtained by maximizing transmission through the fiber. A split-off portion of the input power, previously calibrated to the total input power at the fiber focus, was measured after reflection from a beam splitter while the fiber output power was recorded. Each fiber was approximately 1 m. in length, and had its endfaces polished in SMA connectors.

A total of three different sections of fiber without AR coatings were tested for transmission with the OPO laser source. Figure 3 shows transmission results obtained for the fiber with 160 µm core diameter. The transmission was about 69% per meter, which agreed with previous measurements of the loss in this fiber. A summary of these results is given in Table I.

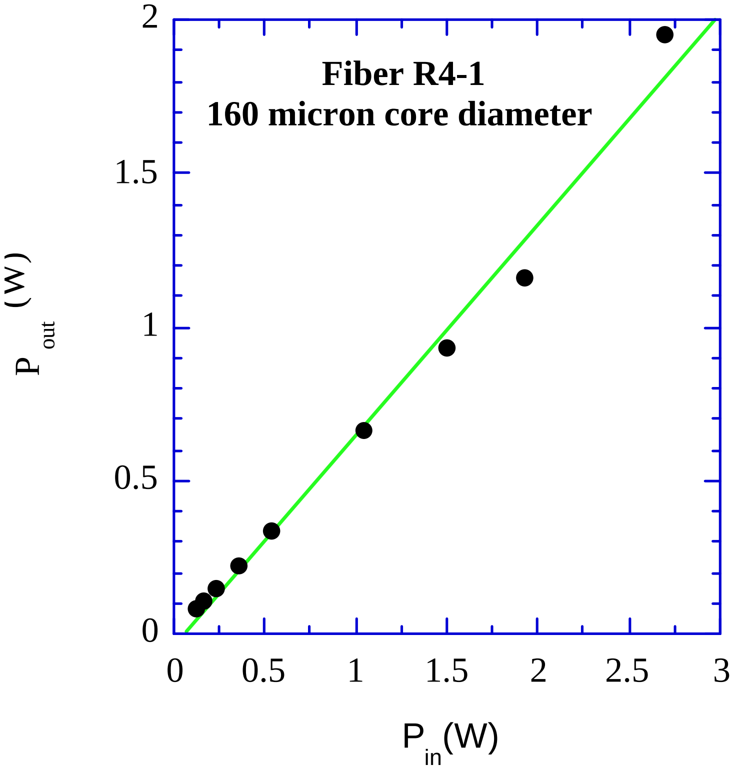

Figure 3. Transmission through 1 m length of fiber in 3 - 5 µm region.

Table I: Results for IR power transmission through chalcogenide fiber *with no optical damage.*

Wavelength (µm)	**Pulsewidth (nsec)**	**Max. Peak Power per Pulse (kW)**	**Max. Peak Power Density (GW/cm^2)**	**Max. No. Pulses**
3 - 5	10	26.9	1.07 GW/cm^2	1.7 x 10^7

Similar results were obtained for the other two fibers tested, which had core diameters of 130 µm and 300 µm, respectively.

The fiber was then irradiated at the maximum peak power input of 26.9 kW for 25 min. total irradiation time. This corresponds to 1.5 x 10^7 pulses total irradiation at the highest power. As shown in Figure 4, there was no change in transmission during this irradiation, and upon removal of the fiber after the test, no observable change to the fiber endfaces was observed with a 200X handheld microscope.

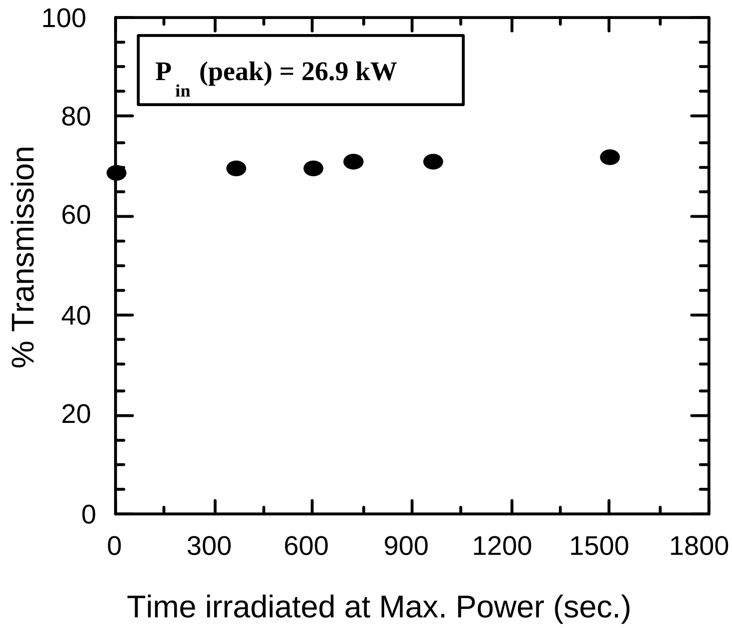

Figure 4. Long time irradiation of Fiber R4-1 at highest input power.
No damage was observed.

Tests with an AR coated fiber were also conducted, in which it was observed that a decrease in transmission (from 76% to 68%) occurred after about 18 min. irradiation at 1.78 W. Upon subsequent examination a small damage spot was observed in the fiber AR coating on the input end. The peak power density at which the damage first occurred was estimated to be 477 MW/cm^2. Similar effects were observed when the fiber was re-tested with input and output ends reversed. The cause of the damage is unknown; however, with improvements in the AR coating process higher damage thresholds are anticipated.

The output of narrowband laser radiation from a multimode fiber usually exhibits an intensity distribution or speckle pattern of high and low intensity regions. Such a speckle pattern is undesirable for IR countermeasures since it effectively results in a beam with “holes” in the radiation distribution. This speckle can effectively be smoothed by randomizing the output speckle distribution as a function of time. NRL has developed a method,[4] which involves dynamically varying the input angle to the fiber using piezo-driven mirrors, effectively producing a time-averaged superposition of speckle patterns at the output. Alternatively, we can take advantage of the fact that speckle is a function of spectral linewidth of the laser source by employing lasers with wide spectral bandwidths, thus reducing the laser coherence length and resulting in a smooth output beam from the multimode fibers.

The wide spectral bandwidth (≈100 nm) at each of the output wavelength bands from the OPO was expected to result in a spatially smooth beam, appropriate for IRCM. The calculated RMS noise was predicted[5] to be 1% or less for a fiber with N.A. = 0.2. A lens was used at the fiber output to image the near field distribution of the fiber onto a Spiricon infrared camera, from which beam smoothness could be ascertained. Results for the fiber with 130 μm core diameter and N.A. = 0.29 are shown in Figure 5. As expected, the output distribution was smooth with no discernible minima.

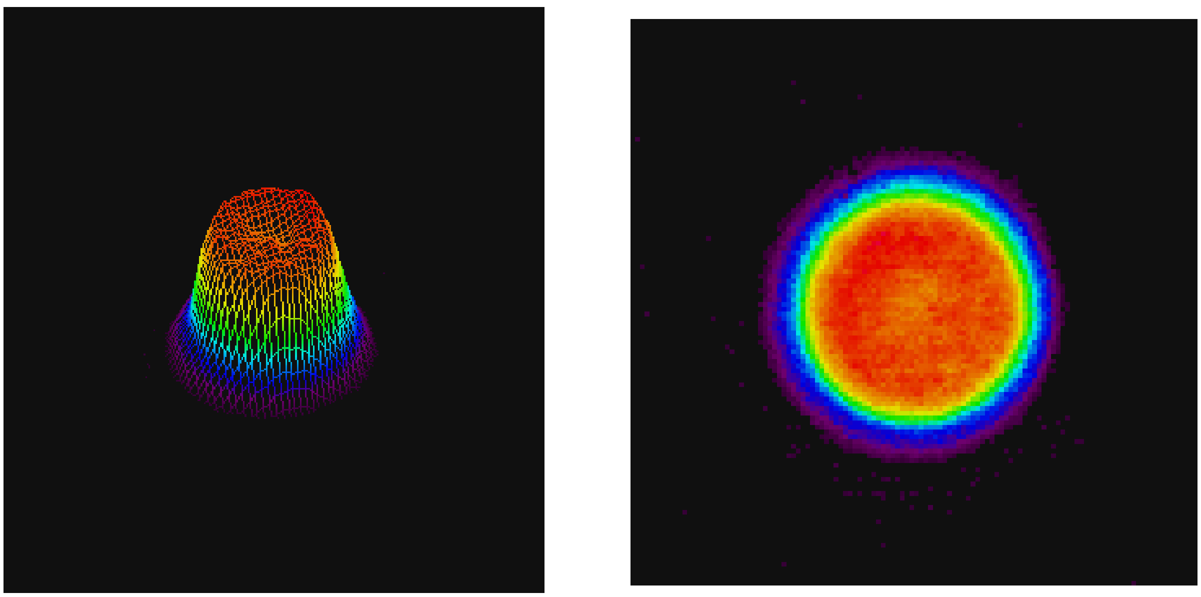

Figure 5. Output spatial distribution (3D and 2D views) from 1 m fiber (130 μm core diameter and N.A. = 0.29) showing smooth intensity profile for broadband 3 - 5 μm laser input.

3.0 RESULTS AND DISCUSSION: CHEMICAL SENSING APPLICATIONS

Due to the wide spectral transmission range (1 - 12 μm, depending on choice of compositions[1, 2]) of the chalcogenide fibers, they are excellent candidates for remote chemical sensing applications for a number of toxic chemicals with infrared absorption signatures. For example, we have reported[6] results of evanescent wave spectroscopy using chalcogenide fibers to sense chemicals including benzene, toluene and xylene. In these experiments, unclad telluride-based fiber was coupled to a FTIR (Fourier Transform Infrared) spectrometer and a 18 cm section of the 1 m length fiber was immersed in chemical solutions. It was estimated that a detection limit of 5% toluene in benzene mixture was reached, which could be substantially increased by a longer length of fiber in contact with the solution or by tapering the fiber.

A successful chemical sensing field test[7] was carried out using 10-meter lengths of a cabled fiber bundle, with the setup schematically shown in Figure 6. The cable was threaded into a hardened steel hollow shaft (the cone penetrometer) which was forced into the ground below a truck, containing an FTIR spectrometer. Inside the end of the penetrometer was an IR light source which was directed onto the soil, from which the IR reflectance was collected by optics and injected into the fiber connected on the other end to the FTIR. The fiber tolerated the unusually rough handling conditions of the test without failure, thus proving its feasibility for such applications. An example of diffuse reflectance spectra collected is shown in Figure 7 for diesel fuel marine (DFM) on sand.

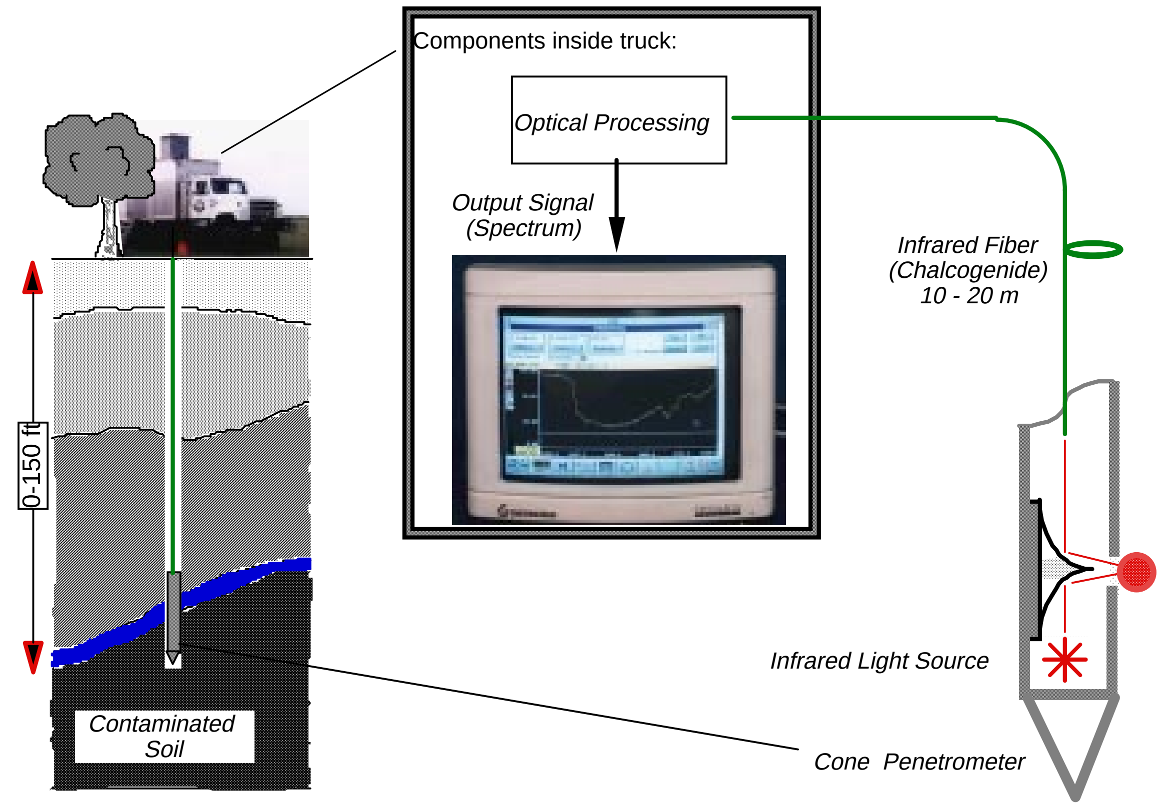

Figure 6. Schematic of Cone Penetrometer chemical sensing field test utilizing chalcogenide fiber.

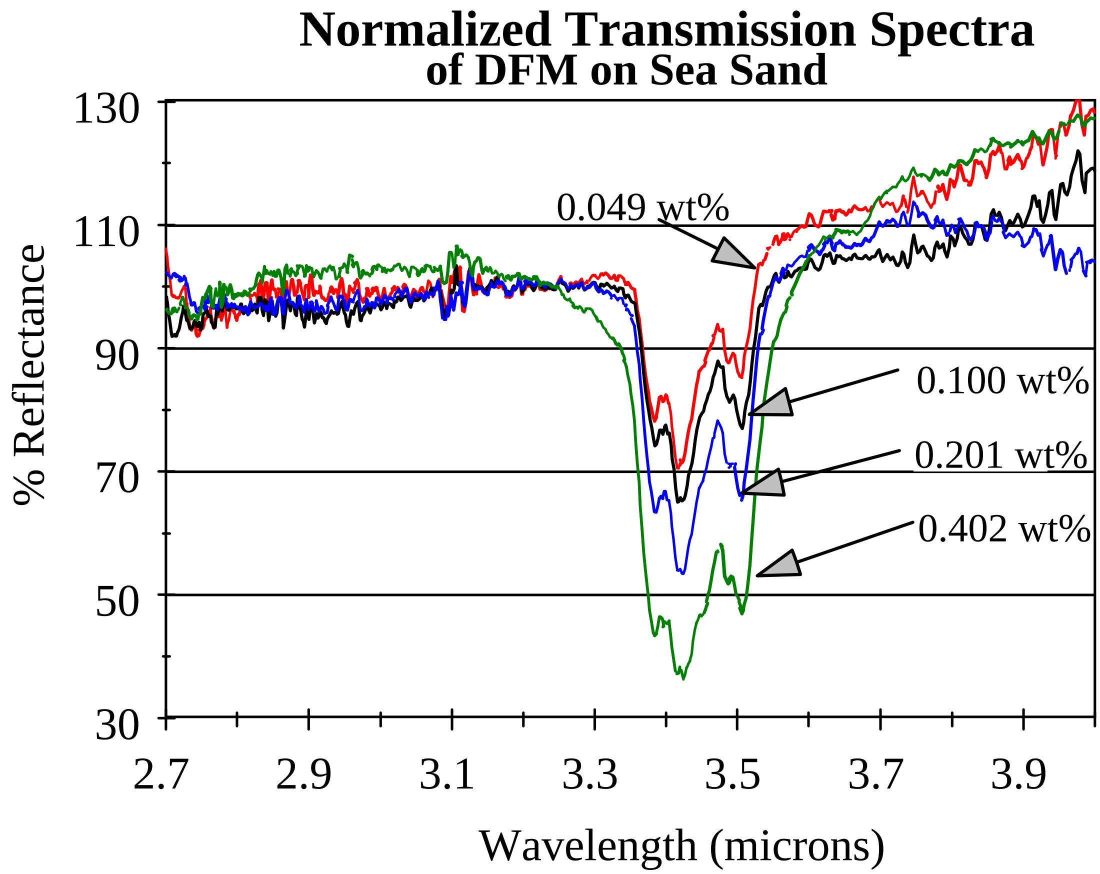

Figure 7. IR Reflectance results for Diesel Fuel Marine (DFM), using chalcogenide fibers and FTIR spectroscopy.

4.0 SUMMARY AND CONCLUSIONS

The low optical loss, high mechanical strength and flexibility of IR-transmitting chalcogenide fibers make them an attractive solution to a number of applications, including the coupling of IR lasers to Jam Heads in IRCM systems and chemical sensing applications. For IRCM, the highly successful laser transmission tests reported in this paper show their capability to transmit high infrared optical power, as required by such systems. These results showed that the uncoated fibers were able to tolerate at least 1.07 GW/cm^2 peak input intensity for up to 1.5 x 10^7 pulses, with 26.9 kW peak power input in the 3 - 5 μm wavelength region, and that optical damage limits were not determined for the uncoated fiber at these wavelengths, since *no damage was observed for defect-free fibers*. AR coated fiber sustained damage to the coating at a lower input power density , but improvements are expected with optimized coating processes. The spatial distribution at the output from the multimode fiber showed no speckle for the output in the 3 - 5 μm region, due to the large laser spectral bandwidth. These results will enable the implementation of fiber cable in a variety of IRCM systems, including Multispectral Countermeasures, the Navy TADIRCM system, and the Air Force LIFE system.

The fibers have also shown feasibility in a number of chemical sensing applications, including IR evanescent spectroscopy and IR reflectance spectroscopy. The fibers were cabled in 20-meter lengths and successfully used without failure in a field test utilizing a Cone Penetrometer system, to detect toxic effluents in the soil.

Acknowledgements: This work was sponsored in part by the U.S. Army CECOM, AMSEL-RD-NV- S, Ft. Monmouth, NJ, the Office of Naval Research and the Air Force Office of Scientific Research. We gratefully acknowledge the technical support of M. Tarr, P. Budni, L. Pomeranz, C. Miller and E. Chicklis at Sanders (Lockheed-Martin) for their assistance in obtaining the laser transmission results.

5.0 REFERENCES

1. J. S. Sanghera, V. Q. Nguyen, P. C. Pureza, , F. H. Kung, R. E. Miklos and I. D. Aggarwal, "Fabrication of Low-Loss IR-Transmitting $Ge_{30}As_{10}Se_{30}Te_{30}$ Glass Fibers", *J. Lightwave Tech.* 12, 737 (1994).

2. J. S. Sanghera, V. Q. Nguyen, P. C. Pureza, R. E. Miklos, F. H. Kung and I. D. Aggarwal, "Fabrication of Long Lengths of Low-Loss IR Transmitting $As_{40}S_{(60-x)}Se_x$ Glass Fibers", *J. Lightwave Tech.* 14, 743 (1996).

3. J. Sanghera, I. Aggarwal, L. Busse, P. Pureza, V. Nguyen, R. Miklos, F. Kung and R. Mossadegh, "Development of Low Loss IR Transmitting Chalcogenide Glass Fibers", *Proc. SPIE* 2396, 71 (1995).

4. J. A. Moon, L. E. Busse and I. D. Aggarwal, "Angular Speckle Correlations and Speckle Removal in Multimode Fiber Laser Delivery", *Proc. CLEO '96*, Anaheim, CA (1996).

5. L. E. Busse, J. S. Sanghera, I. D. Aggarwal, B. Carbonaro, M. P. Tarr, L. A. Pomeranz, C. A. Miller, P. A. Budni and E. P. Chicklis, "Multi-kilowatt Peak Power Transmission through Infrared Fibers in the 3 - 5 μm Region", Proc. IRIS-IRCM Meeting, 5 - 7 May, 1998, to be published by ERIM.

6. J. S. Sanghera, F. H. Kung, L. E. Busse, P. C. Pureza and I. D. Aggarwal, "Infrared Evanescent Absorption Spectroscopy of Toxic Chemicals Using Chalcogenide Glass Fibers", *J. Am. Ceram. Soc.* 78, 2198 (1995).

7. G. Nau, F. Bucholtz, K. J. Ewing, S. T. Vohra, J. S. Sanghera and I. D. Aggarwal, "Fiber Optic Reflectance Sensor for the Cone Penetrometer", *SPIE* 2504, 291 (1995).