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## **Hardware Authentication Using Transmission Spectra Modified Optical Fiber**

Prepared by Juan A. Romero and Robert K. Grubbs

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# Hardware Authentication Using Transmission Spectra Modified Optical Fiber

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## Abstract

The ability to authenticate the source and integrity of data is critical to the monitoring and inspection of special nuclear materials, including hardware related to weapons production. Current methods rely on electronic encryption/authentication codes housed in monitoring devices. This always invites the question of implementation and protection of authentication information in an electronic component necessitating EMI shielding, possibly an on board power source to maintain the information in memory. By using atomic layer deposition techniques (ALD) on photonic band gap (PBG) optical fibers we will explore the potential to randomly manipulate the output spectrum and intensity of an input light source. This randomization could produce unique signatures authenticating devices with the potential to authenticate data. An external light source projected through the fiber with a spectrometer at the exit would “read” the unique signature. No internal power or computational resources would be required.

## **ACKNOWLEDGMENTS**

The authors would like to thank William Sweatt of the Sensing and Imaging Technologies group for the conversation which started the thought process leading to the use of PBG fiber. Dennis De Smet of the Advanced Prototyping S&T group for his work fabricating test samples. Dante Berry of the Advanced and Exploratory Systems group for his expertise in fiber optic connection techniques. Pin Yang of the Advanced Prototyping S&T group for the generous use of his optical equipment and help.

# CONTENTS

1. Introduction.....	7
1.1 Background.....	7-8
2. Experimental Approach.....	9-10
3. Results.....	11-12
4. Conclusion.....	14
5. References.....	14
Distribution.....	15

# FIGURES

Figure 1. Photonic band-gap type structures that guide light.....	7
Figure 2. The current state of the art in photonic crystal manufacture.....	8
Figure 3. Test assembly.....	10
Figure 4. Light source baseline. No fiber.....	11
Figure 5. Uncoated fiber spectra.....	11
Figure 6. Fiber coated with approximately 1000 angstroms aluminum oxide.....	12
Figure 7. Fiber coated with approximately 1000 angstroms zinc oxide.....	12
Figure 8. SEM photo of PBG fiber channel.....	13
Figure 9. EDS map of Zn present on fiber .....	13

## NOMENCLATURE

ALD	Atomic Layer Deposition
PBG	Photonic Band Gap
$\mu\text{m}$	Micron
mm	Millimeter
nm	Nanometer
mTorr	Millitorr
SEM	Scanning Electron Microscope
EDS	Energy Dispersive X-ray Spectroscopy

# 1. INTRODUCTION

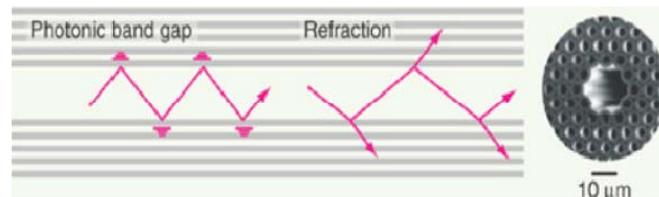
Current methods of authentication rely on electronically stored encryption/authentication codes housed in a device. Due to the nature of electronic media requiring stored charge, this stored charge can be manipulated or erased by external electromagnetic fields or loss of power. By producing a non-electrical passive method to authenticate a device these issues are avoided resulting in a secure monitoring system. A passive method such as fiber optics now becomes attractive. Due to the non-charged nature of light, external magnetic and electrical fields have little effect on a beam of light. This property also makes it difficult to “read” information impressed on it using non-contact remote methods. This research attempts to demonstrate the feasibility of producing a unique spectral output signature from light transmitted through a hollow core photonic band gap (PBG) fiber coated internally with materials of differing refractive index. These materials are deposited using atomic layer deposition (ALD) techniques.

## 1.1 Background

Photonic band gap (PBG) fibers are a class of optical fibers first studied by Knight et al<sup>1</sup>, which consisted of a solid silica inner core surrounded by an array of hollow air core channels. Work with hollow core fibers surrounded by hollow core channels followed through work done by Cregan et al<sup>2</sup>, and West et al<sup>3</sup>.

As shown in figure 1 the operation of the hollow core PBG fiber is based on the formation of a band gap which reflects light of a specific wavelength along the length of the fiber. Core diameters are in the range of 9  $\mu\text{m}$  to 3  $\mu\text{m}$  in diameter This is contrast to conventional solid core optical fiber which relies on reflection within a solid core.

The band gap is designed by utilizing a high refractive index solid material and a low index core material which is normally a gas or vacuum (Fig 1). Light is thus propagated in a gas or vacuum as opposed to a solid material. Both types of fibers are currently based on silica as the solid portion of the fiber. Figure 2 illustrates the manufacture of the PBG fiber.



**Figure 1.** Photonic band-gap type structures that guide light.  
(PJ Brown, National Textile Center Annual Report: November 2005)

Due to the unique structure of the PBG fiber it is possible to tune the fiber to transmit specific wavelengths of light. By varying the diameters of the hollow channels and the spacing between

channels a Bragg filter type mirror is produced accomplishing the tuning function. It has also been demonstrated that introducing liquids of higher refractive index in the channels enables modification of the tuned wavelengths<sup>4,5</sup>. The use of liquids is not a practical solution which led to the idea of placing discrete thicknesses of high and low refractive index materials on the channel walls of the fiber in order to modify the optical characteristics of the fiber. This approach appears to be a novel method with great potential for application of PBG fibers in areas such as sensors, bio active surfaces, and catalysis.



**Figure 2: The current state of the art in photonic crystal manufacture is via preform stacking methods in glass.**

( Russell, P., *Photonic Crystal Fibers*. Science, 2003. 299(5605): p. 358-362)

## 2. Experimental Approach

NTK HC-800 PBG fiber was used with an 830 nm center wavelength. Central core diameter was 9.3  $\mu\text{m}$  with secondary holes surrounding the core which are approximately 3  $\mu\text{m}$  diameter on a 2.3  $\mu\text{m}$  pitch extending to a diameter of 40  $\mu\text{m}$ . The fiber is fabricated from pure silica with a 135  $\mu\text{m}$  cladding diameter and 220  $\mu\text{m}$  acrylate coating diameter.

The fiber was cleaved into approximately 100 mm test sections and ends stripped for future attachment of connectors. Prior to ALD coating fibers were cleaned in a plasma asher to remove the acrylate coating and other organic contaminants using a 100% oxygen plasma.

Two different coating materials were identified based on ease and reliability of the coating process. Index of refraction was also considered. Final coating choices were aluminum oxide with a refractive index of 1.66 at 587 nm and zinc oxide with a refractive index of approximately 2.0 at 500 nm. Silica exhibits a refractive index of 1.45 at 587 nm while air has a refractive index of 1. Deposition thickness was targeted at 1000 angstroms due to time constraints on equipment usage and lack of time to produce an accurate model of the optical effects of the coatings on the photonic band gap.

The atomic layer deposition (ALD) process was chosen for the deposition of coating materials due to its ability to conformally coat high aspect ratio structures (aspect ratio =  $l/d$  = length of pore/diameter of pore). ALD is a reactive deposition technique similar to chemical vapor deposition (CVD). The ALD process is different and relies on self-limiting surface chemistry.

In CVD the reactants are brought to the surface simultaneously. In ALD the chemical reactants are exposed to the surface sequentially with a purge step between reactant pulses. This sequential addition of reactants and the self-limiting nature of the surface reactions give ALD the ability to provide acute thickness control and the ability to conformally coat high aspect ratio structures.

These photonic optical fibers have center aperture running the length of the fiber on the order of 9  $\mu\text{m}$  in diameter. This center aperture is surrounded by smaller channels on the order of 3  $\mu\text{m}$ . With an experimental optical fiber length of 10 cm, the aspect ratio for the larger center hole is  $l/d = 10,000$ . This is a very large aspect ratio to conformally coat. In order for ALD chemistry to conformally coat high very aspect ratios the reactor has to be run in a quasi-static configuration and not a flow configuration.

The quasi-static condition allows the sample to soak in chemical reactant in a static condition to allow time for the diffusion of reactant to diffuse down the length of the center aperture. An equal amount of time is required on purge step the reactant and possible reaction products out of the center aperture.

The first deposition was ALD alumina which was performed at 200°C. This deposition was performed in a flow condition and not in a quasi-static configuration. 1040 ALD cycles were performed to deposit an alumina thickness of 1010 angstroms of alumina. It was not expected that this deposition of alumina would conformally coat the inside of the photonic lattice.

Another ALD alumina deposition was performed on two 10 cm pieces of the naked photonic optical fiber under quasi-static conditions. Here, the reactor conditions were set to coat an aspect ratio of 5000 which would be  $\frac{1}{2}$  of the calculated 10,000 since reactants can enter and exit either end of the fiber. The exposures of both trimethyl aluminum (TMA) and water were 500 mTorr for 60 seconds each. There was a subsequent step of purging after the addition of each of these reactants which was also 60 seconds. This resulted in an exposure of 30 Torr\*seconds or 30,000,000 Langmuir of exposure (1 Langmuir =  $1 \times 10^{-6}$  Torr\*seconds). This is a reasonable exposure to coat aspect ratios of  $\sim 5000$ <sup>6</sup>. The cycle time for one ALD cycle was 242 seconds or  $\sim 4$  minutes. Initially, 500 ALD cycles were performed. This resulted in a film 704 angstroms thick as measured by ellipsometry on a witness wafer. An additional 500 cycles, performed under identical conditions, were run to increase the thickness of the alumina. The resulting final thickness after the 1000 cycles total was 1360 angstroms. Since this deposition was performed in a quasi-static reactor configuration, the large aperture should be conformally coated with this alumina layer but the smaller 3  $\mu\text{m}$  apertures probably only partially coat down the 10 cm length of the fiber. This is a result of the x3 greater aspect ratio for the smaller apertures.

In another ALD deposition zinc oxide, ZnO was deposited on two similar fibers in the quasi-static reactor condition. Here, similar exposure conditions were employed. Namely, exposures of 30,000,000 L were used for both the diethyl zinc and water precursors similar to the exposures used for the alumina ALD. The growth rate of ZnO ALD is 2.0 angstroms per ALD cycle at 200 °C (compared to the  $\sim 1$  angstrom per ALD cycle for alumina). It was therefore only necessary to run 500 ALD ZnO cycles for a deposition thickness of  $\sim 1000$  angstroms. A witness wafer was deposited along side these fibers. Unfortunately, ellipsometric data could not be used to determine the resulting thickness of this deposition. The deposition showed signs of carbonization on both the witness and the on the fibers. This was observed as a very thin film of dark brown suet on top of the film. Interestingly, the film under the dark brown film appeared blue indicating that a substantial  $> 500$  angstroms was deposited. It is not clear why this deposit formed on top of the growing film. After the ALD deposition these ALD coated fibers were subsequently spectroscopically analyzed for transmission.

The coated fibers were built into test pieces as shown in Figure 3. Due to the fragile nature of the fiber and the short length, a rigid tube sleeve was chosen to prevent any bending of the fiber.

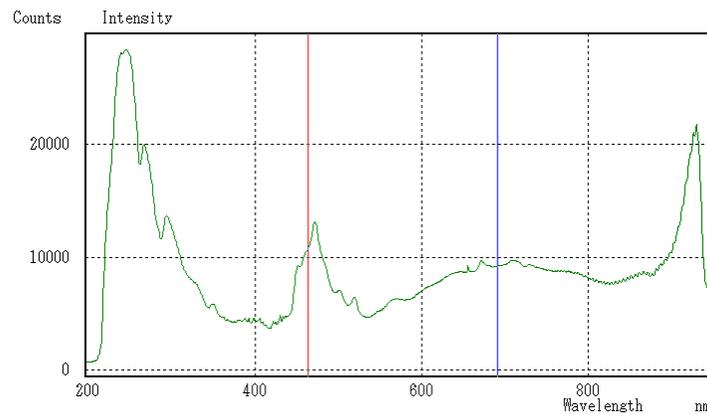


**Figure 3.** Test assembly

### 3. Results

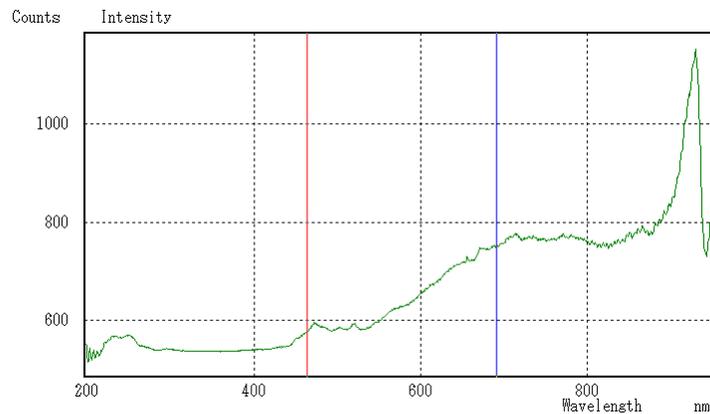
Spectra were collected using an Ocean Optics DH-2000-BAL UV-VIS-NIR light source comprising a halogen lamp and deuterium lamp to provide a light source spectrum extending from 200 nm to 1.1  $\mu\text{m}$  wavelength. A Hamamatsu model C10027-1 photonic multichannel analyzer was interfaced with a lap top to collect the resulting transmission spectra of the test fibers.

The light source spectra is shown in Figure 4 with no test fiber present.



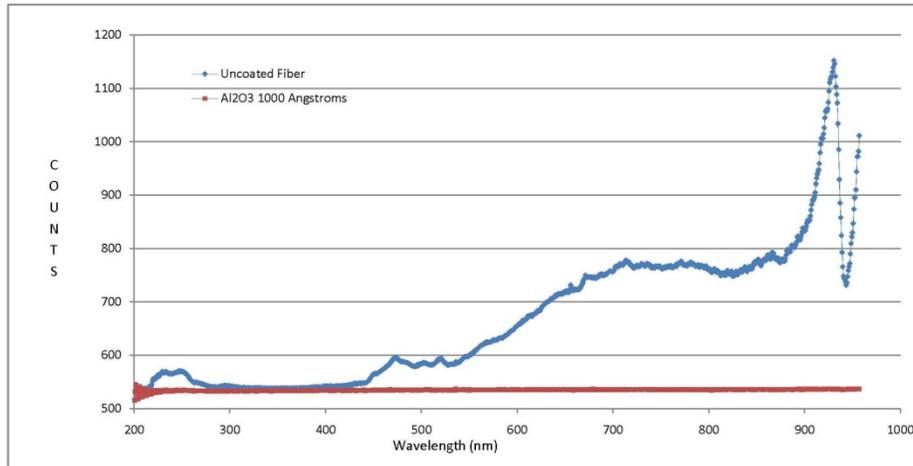
**Figure 4.** Light source baseline. No fiber.

An uncoated fiber was then placed inline resulting in the spectra shown in Figure 5.

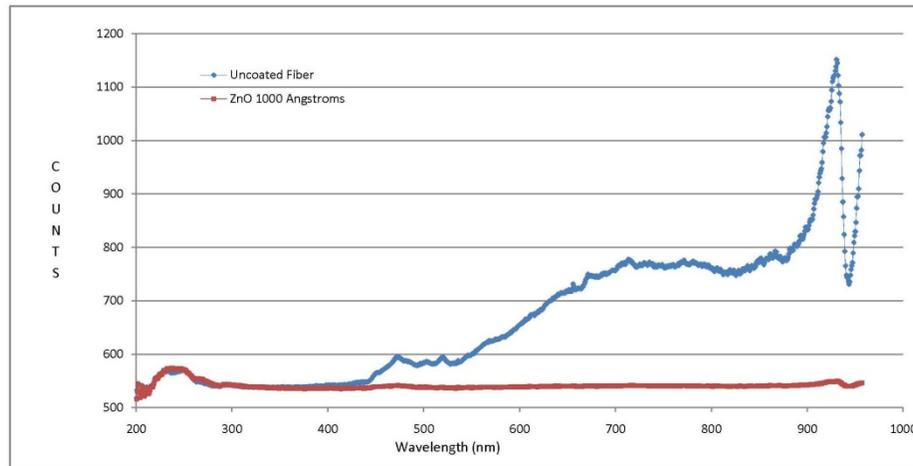


**Figure 5.** Uncoated fiber spectra.

Following these measurements, spectra was taken of the coated test samples. Figures 6 and 7 illustrate the coated fiber spectra overlaid on the uncoated fiber spectra. The coatings produced a notable change in the spectra from that of the uncoated fiber shown in Figure 5.

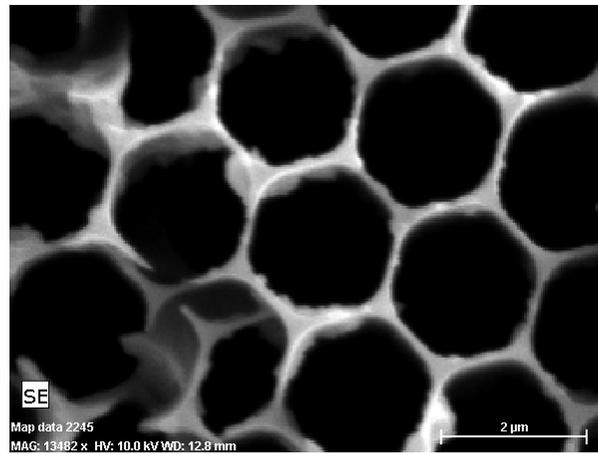


**Figure 6.** Fiber coated with approximately 1000 angstroms aluminum oxide.

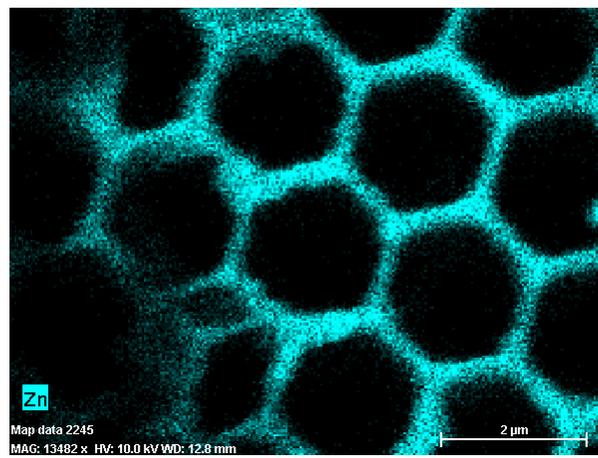


**Figure 7.** Fiber coated with approximately 1000 angstroms zinc oxide.

SEM photos and EDS analysis (Fig. 8 and 9) of the zinc oxide coated fibers confirm the ALD coating was conformal and evenly distributed within the  $3\mu\text{m}$  channels of the fiber.



**Figure 8. SEM photo of PBG fiber channel**



**Figure 9. EDS map of Zn present on fiber channels**

## 4. Conclusion

The presented work represents approximately two months effort. However, based on the data, potential exists to produce a passive hardware authentication method based on optical fiber transmission spectra manipulation using PBG fibers and ALD. Use of ALD to deposit films within the channels of PBG fibers is an enabling technology to produce coatings which could impact optical transmission in a significant manner.

Most apparent is the degree to which very thin coatings drastically affect the optical spectra. The interaction of the coating with the band gap characteristics of the fiber has potential to use very thin coatings to tailor optical properties which is in direct contrast to conventional multilayer dielectric mirrors.

Due to the short duration of the project, optical modeling was not possible but would be useful in the future. Other materials of high and low refractive index should be explored as well as multilayer coatings of high and low index materials. Effects of varied coating thickness is another area requiring exploration. ALD processes also provide potential to use PBG fibers in areas other than optics such as sensors, bio active coatings, and catalysis.

## 5. REFERENCES

1. J.C. Knight, J. Broeng, T.A. Birks, and P.S.J. Russell, "Photonic band gap guidance in optical fibers," *Science* **282** (5393), 1476-8, 1998.
2. R.F. Cregan, B.J. Mangan, J.C. Knight, T.A. Birks, P.S.J. Russell, P.J. Roberts, and D.C. Allan, "Single-mode photonic band gap guidance of light in air," *Science* **285** (5433), 1537-9, 1999.
3. J.A. West, J.C. Fajardo, M.T. Gallagher, K.W. Koch, N.F. Borelli, and D.C. Allan, "Demonstration of an IR-Optimized Air-Core Photonic Band-Gap Fiber," presented at the Proc. Europ. Conf. Opt. Comm., Munich, Germany, 2000.
4. J. Sun, C. C. Chan, X. Y. Donga, P. Shuma, "Tunable photonic band gaps in a photonic crystal fiber filled with low index material", *Journal Of Optoelectronics and Advanced Materials* Vol. 8, No. 4, 1593 – 1596, August 2006.
5. R.T. Bise, R.S Windeler, K.S. Kranz, C. Kerbage, B. J. Eggleton, and D. J. Trevor, "Tunable photonic band gap fiber", 2002 Optical Society of America.
6. J.D. Elam, D. Routkevitch, P.P. Mardilovich, S.M. George, *Chemistry of Materials*, **15**, 3507 (2003).

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