Ionizing Radiation Resistance of Random Hole Optical Fiber for Nuclear Instrumentation and Control Applications

Bassam Alfeeli

Thesis submitted to the faculty of the Virginia Polytechnic Institute and State University in partial fulfillment of the requirements for the degree of

Master of Science
In
Materials Science and Engineering

APPROVED

Gary Pickrell, Chair
David Clark
Anbo Wang

May 4, 2009
Blacksburg, VA

Keywords: Nuclear energy, nuclear power generation, microstructured optical fibers, photonic crystals, optical fiber sensors, optical fiber fabrication

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Abstract

Random hole optical fibers (RHOF) offer advantages over other types of microstructured optical fibers (MOFs). They are inexpensive and easy-to-make when compared to the high cost of ordered hole MOFs. They also have unique characteristics since they contain open and closed holes. The open holes contain ambient air under normal conditions and the closed holes contain residual gases from the fabrication process at certain pressure. The objective of this research work was to investigate the radiation resistance of Random Hole Optical Fibers (RHOF) for possible use as both sensing element and data transmission medium in nuclear reactor instrumentation and control applications. This work is motivated by the demand for efficient, cost effective, and safe operation of nuclear power plants, which accounts for more than 14% of the world’s electricity production.

This work has studied the effect of gamma irradiation on RHOF fibers by comparing their performance to that of standard solid telecommunication fibers and commercially available specialty solid fiber designed to be radiations hardened fiber. The fibers were evaluated at different absorbed dose levels: 12 mGy(Si), 350 mGy(Si), and 7200 Gy(Si) by measuring their radiation induced absorption (RIA) on-line. In the low dose test, the maximum RIA measured in untreated RHOF was approximately 8 dB while the RIA in the untreated MMF fibers reached a maximum at about 28 dB. In the high dose test, the maximum RIA measured in untreated RHOF was 36 dB while RIA in the methanol washed RHOF was only 9 dB. RHOF also demonstrated superior radiation damage recovery time over all of the other fibers tested. Based on the experimental evaluations, it was deduced that RHOFs used in this work are resistant to gamma radiation and recover from radiation damage at a faster rate compared to other fibers tested. The radiation induced absorption (RIA) at the 1550 nm window in the RHOF fibers could be attributed to the OH absorption band tail. However, the existence of other mechanisms responsible for RIA is also postulated. Some of these mechanisms include bulk and surface defects which are related to the fabrication process and the influence of the gases confined within the RHOF microstructure.

Gamma radiation resistance of RHOFs can be attributed to the lack of dopants and also possibly the inherent OH and nitrogen content. The behavior of thermally annealed RHOF and their fast recovery is in favor of this hypothesis.
Acknowledgments.

I’m indebted to my faculty advisor and master’s degree committee chair Professor Gary Pickrell for his support, encouragement, patience, and feedback throughout my research work and thesis writing. I thank him for many valuable discussions on photonic materials and scientific experimentation in general. I’m grateful to Professor David Clark, head of the department of Material Sciences and Engineering for the many stimulating discussions on ceramics and ceramics manufacturing. I also extend my appreciation to Professor Anbo Wang of the department of Electrical and Computer Engineering for giving me the privilege to use the facilities and equipment available at Virginia Tech Center for Photonics Technology (CPT) which made this work possible.

My sincere thanks to Professor Mark Pierson of the department of Mechanical Engineering who introduced and continued to make my Nuclear Science and Engineering learning experience very exciting and Dr. Marc A. Garland of the Nuclear Science and Technology Division, Oak Ridge National Laboratory for all of his valuable assistance in making the high dose gamma irradiation test possible. I would also like to thank Professor Robert Hendricks for his insightful discussions on nuclear materials used in nuclear power plants. Mr. Doug Smiley from VT Health and Safety Division was invaluable in offering his time and expertise to make the low dose gamma irradiation test possible.

Special thanks to all my colleagues who help me through my experimental work especially, Chase Hammond, Matthew Hiser, and Cary Hill of the department of Material Sciences and Engineering and all members of CPT group. Finally, I would like to thank Dr. Abdel Soufiane from Verrillon, Inc. for providing a sample of their radiation hard optical fiber.
Preface

This thesis was written not only to satisfy requirements for a master’s degree but also to serve as a starting point for future students who will continue this endeavor and take this research work to the next level. The thesis provides elementary background on nuclear power generation for non nuclear science and engineering students with emphasis on instrumentation and control systems typically found in nuclear power plants. It also provides some background information to bring engineering students up-to-speed with optical fiber technology.

Bassam Alfeeli,
Blacksburg, VA
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1. Introduction

1.1 Nuclear Energy

Nuclear energy is the conversion of thermal energy originated from nuclear fission, fusion, or radioisotopic radiation sources into useful heat, mechanical work, and electric power. Energy is liberated from nuclear fission by splitting of heavy elements nuclei via neutron chain reactions as shown in Fig. 1(a). Energy is liberated from nuclear fusion by combining light elements nuclei by subjecting them to high temperature, pressure and magnetic field as shown in Fig. 1(b). Radioisotopic energy is released by radioactive decay of unstable isotopes. Radioactive decay occurs through the emission of fundamental particles from the nucleus. These fundamental particles are known as alpha, beta, and gamma [1]. The three particles will be explained in detail in a later section.

![Diagram of nuclear fission and fusion processes.](image)

Fig. 1 Process of (a) nuclear fission, (b) nuclear fusion [2], Artwork have been released into the public domain by their authors.

Soon after the discovery of neutrons in 1932 by Chadwick [3], Fermi came up with idea of bombarding elements with neutrons to produce new radioactive elements [4]. Hahn jointly with Meitner and Strassmann furthered this research in 1938. Unexpectedly, they burst the uranium nucleus into large fragments which were, essentially, isotopes of lighter elements [5]. The results of this work were interpreted as being nuclear fission [6] and marked the beginning of the nuclear age. Some of the early contributors to the field of nuclear fission are shown in Fig. 2. Three years later, the first man-
made reactor, known as Chicago Pile-1, went critical on December 2, 1942 [7]. A decade later, the Obninsk nuclear power plant was built to be the world’s first nuclear power plant (NPP) to generate electricity. The plant was connected to the power grid on June 26, 1954 and was part of the science city Obninsk, southwest of Moscow [8].

![Image of early contributors to nuclear fission: James Chadwick, Enrico Fermi, Otto Hahn, Lise Meitner, Fritz Strassman]

Fig. 2 Some of the early contributors to the field of nuclear fission [2], images have been released into the public domain by their authors.

Today, nuclear energy contributes significantly in meeting the world’s energy demands [9]. As of 2007, there were 438 NPPs operating in 31 countries accounting for 14% of the world’s electricity production [10]. Locations of NPPs around the world are shown in Fig. 3. New NPPs construction programs have already started, particularly, in East Asia, Russia, and India. The United States resumed construction of new NPPS after nearly 30 years of hold on nuclear energy expansion [10].

The foundation of nuclear energy renaissance stems from the growing demand for energy, the increasing awareness of the environmental benefits of clean nuclear power, and the strong economic and safety performance of nuclear power. However, this renaissance is faced with challenges such as high capital costs of new plants, nuclear waste management, and proliferation risks of weapons-grade nuclear material. Thus, nuclear power needs to meet four principal challenges to be sustainable [11]:

- Nuclear power must remain economically competitive.
- Current NPPS must continue to operate safely and future plants must continuously improve safety.
- Nuclear materials must be protected from proliferation for non-peaceful purposes.
• Nuclear fuel must be abundant and nuclear waste must be managed in cost effective and safe manner for an extended period of time.

![Map of nuclear power plants around the world](image)

**Fig. 3** Map of nuclear power plants around the world, Source: International Nuclear Safety Center, Argonne National Laboratory (February 2009)

The known uranium deposits recoverable with today's technology will last an estimated 50 to 65 years [8]. Uranium resources with less geological assurance are at least twice as much. A sample of uranium ore is shown in Fig. 4. Substantial amounts of uranium can be also found in phosphate deposits and seawater which can be considered as unconventional resources of uranium if advanced extraction technologies are developed. Moreover, only a small percentage of the world's spent fuel is currently reprocessed and recycled. Spent reactor fuel contains more than 98% of its original energy. Breeder reactors are capable of extracting most of the useful energy, which would extend the usable fuel from known uranium resources by a factor of sixty [8].

A great deal of reliable, economical, active and passive control, instrumentation, continuous monitoring and surveillance, and near-failure early warning systems is required for the operation of NPP. This is necessary to achieve lower operational costs and increase the safe operation of NPPS in addition to safeguard nuclear material and manage nuclear wastes. However, most of the current instrumentation and control systems are expensive, bulky, require highly trained operators, and require shielding against the harsh plant environments [12].
1.2 Instrumentation & Control Technologies in Nuclear Power Plants

Nuclear power plants rely heavily on instrumentation and control (I&C) systems for control, monitoring, tasks execution, protection, and display applications. In general, I&C systems include the following [10]:

- Sensors that continuously measure the plant variables such as neutron flux, temperature, pressure and flow
- Control, regulation, and safety systems that manage plant’s operation, optimize plant’s performance and keep the plant within a safe operating range
- Communication systems that transfer data and information
- Human–system interfaces that display information and allow interaction with plant operators
- Surveillance and diagnostic systems that monitor the integrity of the sensor signals
- Actuators such as valves and motors that adjust the plant’s physical processes
- Status indicators of actuators that provide signals to whether valves are open or closed, and whether motors are on or off

These systems provide accurate and appropriate information and permit judicious action during both normal and abnormal operation. They are therefore vital for the safe and efficient operation of the plant. I&C systems are installed throughout the plant with approximately 10,000 sensors and detectors, 5000 km of I&C cables, and 1000 ton of I&C related components in a typical NPP. This makes the I&C system one of most extensive and the heaviest non-structural segment in any NPP [10].

I&C systems are grouped into two categories: non-safety (control) and safety (protection) systems. The non-safety systems regulate plant conditions during startup, power operation, and shutdown. They are responsible for maintaining plant systems and components within their operating ranges, and they normally operate in a regulating mode. These systems are backed up by a set of independent and
redundant safety systems that are designed to take automatic action to prevent and alleviate accident conditions if the operators and the non-safety systems fail to maintain the plant within normal operating conditions. Safety systems protect the plant investment and the public health. The safety systems require substantial effort during their design, qualify, install, test, and maintenance stages [13]. Commercial off-the-shelf equipment usually does not meet these requirements and the costs of nuclear plant "safety-grade" systems and equipment can be 10 times that of the equivalent commercial quality equipment. Additionally, these control systems have redundant data buses to transport the large amounts of information handled in a NPP. Data buses are used to reduce and simplify the plant’s wiring and consequently reduce wiring configuration management and maintenance requirements [14].

I&C systems, except for the sensors, are located in protected area so that the environmental conditions they are exposed to are generally similar to office environment. This area is well-shielded and is known as the NPP control room. The control room is the nerve centre of an NPP and contains the information necessary for monitoring and controlling the plant together with the facilities needed for initiating most manual control actions. In the control room, I&C systems and the plant operators interact through human system interfaces as shown in Fig. 5 and Fig. 6 to carry out operations to produce power efficiently and safely.

Fig. 5 Training control room at North Anna Nuclear Power Plant, Louisa County, Virginia [15], Courtesy of J. Golden, Used with permission
1.3 Current Sensing Technologies Used in Reactor’s Instrumentation and Control

In an NPP, it is necessary to deal with a wide variety of signals, both nuclear and conventional, before reliable plant status information can be derived. These data are used as information inputs for the control and status reporting systems as well as for the actuation of systems important to safety. A large number of sensors and transducers are employed. They can be classified into [17]:

- **Nuclear instrumentation**: for neutron flux density and spatial distribution measurements used in reactor power determination.

- **Process instrumentation**: for measurements of reactor pressure, coolant or pressurizer level, steam flow, coolant temperature and flow, recirculation pump speed and containment building pressure, as well as for indicating component status such as valve and control rod position.

- **Radiation monitoring instrumentation**: for steam line monitoring, checking for gas effluents and site radiation monitoring.

- **Special instrumentation**: for meteorology, seismic monitoring, failed fuel detection and measurement of vibration, hydrogen concentration, water conductivity and boric acid concentration.
The following discussion has been adopted from [18]. The most important parameters that need to be measured using sensors in NPP are: neutron flux, temperature, pressure, liquid level, and flow as shown in Fig. 7.

![Diagram of nuclear power plant](image)

*Fig. 7 Main sensors used in PWR [18], Used under the Fair-Use Provision of Copyright Law*

Table 1 illustrates different process instrumentation, the parameters measured, and their location. Thermocouples and resistance temperature detectors (RTDs) are used for temperature measurement. Depending on the plant, there are normally between 16-32 RTD elements and 50-60 thermocouples in a plant. Like their commercial-grade counterparts, nuclear-grade RTDs can suffer from problems. Some of the problems typically encountered in NPPs are [18]:

<table>
<thead>
<tr>
<th>RTDs</th>
<th>Thermocouples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dynamic response problems</td>
<td>Large calibration shift, erratic and noisy</td>
</tr>
<tr>
<td>Failure of extension leads</td>
<td>output, or saturated output</td>
</tr>
<tr>
<td>Premature failure</td>
<td>Failure of extension cables, connectors, or</td>
</tr>
<tr>
<td>Wrong calibration table</td>
<td>circuit</td>
</tr>
<tr>
<td>Loose or bad connections</td>
<td>Reverse connection</td>
</tr>
<tr>
<td>Large EMF effect</td>
<td>Divergence from true temperature at high</td>
</tr>
<tr>
<td>Open element</td>
<td>temperatures</td>
</tr>
<tr>
<td>Thinning of platinum wire</td>
<td>Response time degradation</td>
</tr>
<tr>
<td>Cracking of the of the protective jacket</td>
<td>Not as accurate as RTDs</td>
</tr>
</tbody>
</table>
Pressure sensors used in NPP are electromechanical systems. In general a NPP uses about 200-800 pressure, flow, and level sensors to measure the process pressure, level, and flow in its primary and secondary systems. However, in NPP, pressure and differential pressure sensors are located away from the process to be measured in order to reduce the effect of temperature on the sensor’s operation. Other reasons for locating a sensor away from the process are to reduce the adverse effects of radiation and vibration and to make it easier for personnel to access the sensor for replacement and maintenance. To transport a pneumatic or hydraulic signal from the process to the sensors, sensing lines are used to connect the sensor to the process pipe, reactor vessel, or flow elements. Depending on the application, there will be one or two sensing lines for each sensor with line lengths ranging from 10-200 meters. Both liquid filled and gas filled sensing lines can be found in NPPs. Liquid-sensing lines are typically filled with either the process liquid or oil. Gas-sensing lines are filled with steam, air, nitrogen, or other gases. Sensing lines can encounter a number of problems that can affect the pressure sensing system’s accuracy and response time. These problems include:

- Blockages due to sludge, boron, or deposits
- Air or gas entrapped in low-pressure sensing lines
- Frozen sensing lines
- Improper line-up or seating of isolation and equalizing valves
- Leakage in sensing lines

Monitoring signals from sensors in NPP is not only to diagnose process anomalies but also it is necessary to verify the performance of the sensors and the associated instrumentations. Tests such as calibration verification, response time measurement, cable integrity checking, and noise diagnostics are required in NPP. In-situ test methods that use externally applied active test signals are also used to measure equipment performance or for providing diagnostics and anomaly detection capabilities. Cables including connectors, splices, and other components are tested by evaluating the impedance relationship along the cable.
Table 1 Different process instrumentation in NPP, the parameters measured, and their location, source [17]

<table>
<thead>
<tr>
<th>Instrumentation</th>
<th>Parameters Measured</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>Core power, also calculations of relative power distribution, coolant enthalpy, fuel burnup distribution, and coolant flow distribution</td>
<td>Neutron flux, temperature</td>
<td>In-core, out-of-core</td>
</tr>
<tr>
<td>Reactor cooling system</td>
<td>Average coolant temperature, coolant temperature at fuel element outlet, temperature of reactor vessel lid, coolant (collapsed) level inside reactor vessel, flow, pressure, level, pump speed</td>
<td>In-core, out-of-core, feedwater lines, pumps</td>
</tr>
<tr>
<td>Pressurizing system</td>
<td>Pressure, level, flow</td>
<td>Pressurizer</td>
</tr>
<tr>
<td>Steam system</td>
<td>Flow and pressure of the main steam lines, pressure in the first stage of the turbine</td>
<td>Steam lines, turbine</td>
</tr>
<tr>
<td>Control rod drive system</td>
<td>Location of rods, also flow, pressure and temperature in the hydraulic driving system</td>
<td>Out-of-core</td>
</tr>
<tr>
<td>Emergency core cooling system</td>
<td>Flow, pressure and temperature of the coolant, pump status</td>
<td>Auxiliary systems</td>
</tr>
<tr>
<td>Reactor water purification system</td>
<td>Flow, pressure, temperature, conductivity of the reactor water</td>
<td>Auxiliary systems</td>
</tr>
<tr>
<td>Boric acid solution injection system</td>
<td>Temperature, tank level, injection pressure</td>
<td>Auxiliary systems</td>
</tr>
<tr>
<td>Reactor vessel</td>
<td>Pressure inside the storage vessel and temperature and level of water detected inside the pressure suppression vessel</td>
<td>In-core, out-of-core</td>
</tr>
<tr>
<td>Containment structure</td>
<td>Flow and pressure</td>
<td>Containment building</td>
</tr>
<tr>
<td>Area radiation monitoring</td>
<td>Radiation level in all active areas, gas and aerosol monitors observe particles, iodine and noble gas concentrations in room air and also in ventilation ducts</td>
<td>Containment building</td>
</tr>
<tr>
<td>Process radiation monitoring</td>
<td>Activity of gaseous and liquid media in the process loops and the system activity released by the plant into the local environment</td>
<td>Containment building</td>
</tr>
</tbody>
</table>

1.4 Advantages of Optical Fiber Technology

Optical fiber technology has proven to be useful and beneficial in a wide range of applications including local and transoceanic communications, medical diagnostics, aerospace, and sensing including harsh environments sensing. Optical signals are immune to electromagnetic interference, temperature variations, generally do not disturb the process measured, and interact with matter on the atomic and molecular levels. Thus, they can provide information with high sensitivity and selectivity. Further, the ready availability and continuous development of optical components and instrumentations from the
optical communication industry give an economic advantage to optical sensors. The use of waveguides adds more advantages to optical sensing. Optical waveguides can be produced from different materials such as glass, plastic and single crystals. They can be inexpensive, robust, flexible, chemically inert, and biocompatible. They also have small physical dimensions, and can be sterilized. Waveguides, such as optical fibers, capillary tubes and planer waveguides, can deliver light to and from the active sensing element over large distances at different locations via multiplexing. This enables real-time, on-line, and multipoint monitoring of large structures and sensing in remote areas that are hazardous, hostile, or difficult to access [19].

The interaction of light with matter results in altering its properties. Optical sensors use this interaction to provide information about the parameter being measured [20]. Optical sensing devices can be classified into five categories based on the way they modulate light. The detection technique and the source requirements are prescribed by the modulation scheme. Table 2 summarizes the different schemes, their detection methods and limitations.

<table>
<thead>
<tr>
<th>Type of Information</th>
<th>Physical Mechanism</th>
<th>Detection Circuitry</th>
<th>Main Limitations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intensity ($I$)</td>
<td>Modulation of number of photons transmitted after absorption, or emitted by luminescence, scattering, or refractive index change</td>
<td>Analog detection</td>
<td>Normalization for source intensity variations and variable line and connector losses</td>
</tr>
<tr>
<td>Wavelength ($\lambda$)</td>
<td>Spectral-dependent variations of absorption and fluorescence</td>
<td>Amplitude comparison at two (or several) fixed wavelengths, or continuous wavelength scan</td>
<td>Wavelength-dependant line losses; suitable scanned-wavelength sources or spectrometers</td>
</tr>
<tr>
<td>Phase ($\phi$)</td>
<td>Interference between separate paths in Mach-Zehnder, Michelson, Fabry-Perot interferometers</td>
<td>Fringe counting, or fractional phase-shift detection</td>
<td>Stability and measurement of small phase shifts; coherent source and detection methods</td>
</tr>
<tr>
<td>Polarization ($p$)</td>
<td>Change in rotation of polarization</td>
<td>Polarization analyzer and amplitude comparison</td>
<td>Random polarization changes in line (induced birefringence in fibers and components)</td>
</tr>
<tr>
<td>Time resolved (t, time domain, $\omega$, frequency domain)</td>
<td>Transient behavior (lifetime) of luminescence or absorption</td>
<td>Analysis of time-decay amplitude signal</td>
<td>Model time dispersion in fibers; low intensity signal</td>
</tr>
</tbody>
</table>
Furthermore, different sensors have different measurement techniques and use different physical parameters that cause light modulation. The measurement techniques, the light modulation type, and the physical modulation parameters are tabulated in Table 3 [21].

<table>
<thead>
<tr>
<th>Measurement Technique</th>
<th>Light Modulation</th>
<th>Parameter Modulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Absorption, scattering, reflectance</td>
<td>$I$</td>
<td></td>
</tr>
<tr>
<td>Colorimetry, spectrometry (absorption, Raman, SERS),</td>
<td>$I$, $\lambda$</td>
<td></td>
</tr>
<tr>
<td>fluorimetry, luminescence</td>
<td>$I$, $\lambda$</td>
<td></td>
</tr>
<tr>
<td>Refractometry</td>
<td>$I$</td>
<td>$n$</td>
</tr>
<tr>
<td>Interferometry</td>
<td>$I$, $\phi$</td>
<td>$n$, $L$</td>
</tr>
<tr>
<td>Special Interferometry</td>
<td>$I$, $\phi$, $\lambda$</td>
<td>$n$, $L$</td>
</tr>
<tr>
<td>Polarimetry</td>
<td>$I$, $p$</td>
<td></td>
</tr>
<tr>
<td>Ellipsometry</td>
<td>$I$, $p$</td>
<td>$L$</td>
</tr>
<tr>
<td>Photokinetimc</td>
<td>$I$, $t$</td>
<td></td>
</tr>
<tr>
<td>Reflectometry</td>
<td>$I$, $t$</td>
<td>$L$</td>
</tr>
<tr>
<td>Combined refractometry and reflectometry</td>
<td>$I$, $t$</td>
<td>$n$</td>
</tr>
<tr>
<td>Evanescent spectroscopy, SPR</td>
<td>$I$, $\lambda$</td>
<td>$n$</td>
</tr>
<tr>
<td>Lifetime-based fluorimetry</td>
<td>$I$, $\lambda$, $t$</td>
<td></td>
</tr>
<tr>
<td>Flight-time fluorimetry</td>
<td>$I$, $\lambda$, $t$</td>
<td>$n$</td>
</tr>
<tr>
<td>Polarized lifetime-based fluorescence</td>
<td>$I$, $\lambda$, $p$, $t$</td>
<td></td>
</tr>
<tr>
<td>Photoacoustic</td>
<td>$I$, $\nu$</td>
<td>$P$</td>
</tr>
</tbody>
</table>

Notes: Abbreviations are as follows: SERS = surface-enhanced Raman spectroscopy. SPR = surface plasmon resonance. Light modulation: $I =$ intensity, $\lambda =$ wavelength, $\phi =$ phase, $p =$ polarization, $\nu =$ optical frequency, and $t =$ time. (The main type of modulation is indicated in bold type.) Physical parameter modulation: $L =$ path length, $n =$ refractive index, $P =$ pressure.

By utilizing different optical sensing schemes, optical fiber sensors have been developed to measure and quantify parameters such as temperature [22], pressure [23], strain [24], flow [25], liquid level [26], electric and magnetic fields [27, 28], electromagnetic radiations [29], neutron radiation [30], chemical species [25], and corrosion [31]. Optical fiber sensors can also be used in distributed sensing with configurations such as spatial, time, and frequency division multiplexing [32].
Typical NPPs used hard wired point-to-point connections from field instrumentation to control systems and panels in the control room. Essentially there is one wire per function or about 30-50,000 wires coming from the field to the cable spreading room and then control room. The use of optical fiber networks, which carry substantially more information, instead of copper cabling, can eliminate 400,000 meters of cabling and 12500 cubic meter of cable trays [9].

1.5 Thesis Objectives, Scope and Overview

The ultimate goal of this research work would be to mimic the human nervous system in the nuclear power plant by developing a network of sensors that communicate information about the surroundings, process the information, and respond with reactions (warnings and alarms) by using optical fiber technology. This technology would enable integrating the sensing element into the communication link directly, thus reducing the number of connectors or concerns about bad connections between the sensor and the lead wire. This is possible since the sensing signal originates from within fiber and travels through the same fiber to the signal processing electronics.

The objective of the presented work in this thesis is to investigate the radiation resistance of Random Hole Optical Fibers (RHOF) for possible use as both sensing element and data transmission medium in nuclear reactor instrumentation and control applications. This research focuses on the effect of gamma irradiation on RHOF by comparing their performance with other fiber types under various conditions. The thesis is organized by the following sections:

**Section 1:** Nuclear Energy: this section introduces nuclear energy, overviews instrumentation & control technologies used in nuclear power plants, presents some of the current sensing technologies used in nuclear reactors, and illustrates some of the advantages of optical fiber technologies for nuclear instrumentation and control.

**Section 2:** Background: this section provides some background on nuclear power generation, the sensors used in nuclear power plants, nuclear radiations, optical fiber technology, and the different methods of fabricating optical fibers.

**Section 3:** Experimental: this section addresses the problem of interfacing microstructered optical fibers with standard solid fibers, gives a detailed description of the optical fiber samples used in the study, and discusses the low dose and high dose irradiation testing setups.

**Section 4:** Results and Discussion: this section presents the experimental results of both low and high dose irradiation tests and discusses them in detail.
Section 5: **Conclusions**: this section summarizes the most significant findings presented in this thesis.

Section 6: **Future Work**: this section suggests areas of further research and development.
2. Background

2.1 Nuclear Power Generation

Electric power is produced by NPP in the same way as other non-nuclear electric power plants. Steam is generated by heating water which turns the blades of a turbine that runs the shaft of an electric generator. The difference in NPPs is how the water is heated. The nuclear power generation process is demonstrated graphically in Fig. 8.

![Diagram of nuclear power generation process](image)

**Fig. 8** Nuclear power generation process in simplified terms [33], Courtesy of J. Gonyeau, Used with permission

All current commercial NPPs utilize nuclear fission reactors. Therefore and hereafter, we will only be concerned with nuclear fission reactors and these will be referred to as reactors. The classification of reactors [1] can be based on the neutron energy range (fast, intermediate, or thermal), what the reactor is used for (power, research, teaching), and type of coolant or fuel used in the reactor. Based on latter classification, there are:

- Gas cooled reactor (GCR), moderated with graphite and uses natural or slightly enriched uranium
- Light water reactor (LWR), moderated with water, (pressurized water reactor (PWR) or boiling water reactor (BWR)), uses slightly enriched uranium and water coolant
- Heavy water reactor (HWR), moderated with heavy water, uses natural uranium and light or heavy water coolant
- Liquid metal fast breeder reactor (LMFBR), no moderation, uses plutonium and uranium and liquid metal (sodium) coolant

To limit the scope of discussion, only PWR (most widely used design) will be discussed here. A typical nuclear power plant is shown in Fig. 9. The discussion on PWR power generation has been adopted from [34].

![North Anna Nuclear Power Plant, Louisa County, Virginia, NRC File Photo](image)

Fig. 9 North Anna Nuclear Power Plant, Louisa County, Virginia, NRC File Photo [35], Image has been released into the public domain by NRC

A typical PWR plant has various components. They are grouped into non-nuclear and nuclear components. The non-nuclear components are:

- Turbine building (label 1 in Fig. 10), houses the turbine, generator, condenser, condensate and feed water systems.
- Control room (label 3 in Fig. 10), the main control center in the plant
- Auxiliary building (label 4 in Fig. 10), houses support equipment (such as pumps, heat exchangers, filters) and emergency core cooling systems.
- Emergency diesel generator building (label 6 in Fig. 10), houses diesel generators that provide backup electrical power to safety and non-safety systems.

The nuclear components are:

- Containment building (label 2 in Fig. 10), is designed to sustain high pressures and houses the reactor and the related cooling system that contains highly radioactive fluids.
• Fuel building (label 5 in Fig. 10), houses a 40 foot deep storage pool used to store spent fuel in, it is also the place where spent fuel will be loaded in casks for shipping or onsite dry storage. The building also has an area for new fuel storage.

Fig. 10 Cross sectional view of AREVA EPR, NEI File Photo [36], Artwork has been released into the public domain by NEI

The design of a nuclear reactor is complex, but basically, each reactor has six main elements: fuel, control rods, coolant, moderator, and reactor vessel. Fuel is at the heart of the reactor. It consists of pellets of enriched uranium dioxide. The pellets are held inside 12-foot-long metal tubes called “fuel rods.” These fuel rods are bundled to form the fuel assembly. Control rods are used to control the rate of fission chain reaction by absorbing some of the neutrons released by the fission process. Most control rods use boron to absorb neutrons. To speed up the chain reaction, the rods are pulled up away from the fuel assembly. To slow the reaction down, the rods are lowered next to the fuel assembly. Water is used as a coolant in PWRs. It is pumped through the reactor to carry the generated heat away from the nuclear reaction. The hot water that leaves the condenser is sent to either cooling towers or discharged into large bodies of water such as cooling ponds, lakes, rivers, or an ocean. Water is used as a coolant since it is non-absorbant for neutrons, non-corrosive, resistant to high levels of radiation, can be easily
circulated by a pump and when pressurized, its chemical and physical properties do not change at high temperatures. Neutron moderation is required to sustain the chain reaction. It slows down the speed of fast neutrons after being emitted from a fissioning nucleus. Fast moving neutrons strike the moderator material, which is not efficient at absorbing them, and slows them down. Water is an excellent moderator because water can also serve as a coolant. The housing that contains all the components in the core is called the reactor pressure vessel as shown in Fig. 11. The material used to construct the vessel must be very strong and resilient to withstand great pressures.

![Diagram of Reactor Pressure Vessel](image)

**Fig. 11 Typical Reactor Pressure Vessel, NRC File Diagram [35], Diagram has been released into the public domain by NRC**

### 2.2 Nuclear Radiation

As discussed in section 1.1, nuclear energy originates from processes such as nuclear fission, fusion, or radioisotopic radiation. In these processes nuclei undergo a variety of changes resulting in radiation
emission. In the radioisotopic radiation process, radiation emission results from spontaneous disintegration of a nucleus to a different nuclei species or to a lower energy state of the same nucleus. In nuclear fission and fusion, one of the final products of the interaction of a nucleus with another particle or nucleus is the emission of radiation. The emitted radiations in both cases comprise of one or several different kinds of fundamental particles emitted at the same time. These particles include among others photons (x-rays and γ-rays), α-particles, β-electrons and positrons, Auger electrons, internal conversion electrons, neutrons, protons, and fission fragments [37]. While most of these particles radiate from the nucleus, some radiations arise from the electron cloud surrounding the nucleus. Table 4 summarizes the common types of radiations. Each type of radiation is characterized by an energy spectrum which indicates the nuclear process underlying it [37].

<table>
<thead>
<tr>
<th>Type</th>
<th>Origin</th>
<th>Process</th>
<th>Charge</th>
<th>Mass [MeV]</th>
<th>Spectrum (energy)</th>
</tr>
</thead>
<tbody>
<tr>
<td>γ-rays</td>
<td>Nucleus</td>
<td>Nuclear deexcitation</td>
<td>0</td>
<td>0</td>
<td>Discrete [keV-MeV]</td>
</tr>
<tr>
<td>x-rays</td>
<td>Electron cloud</td>
<td>Atomic deexcitation</td>
<td>0</td>
<td>0</td>
<td>Discrete [keV-MeV]</td>
</tr>
<tr>
<td>α-particles</td>
<td>Nucleus</td>
<td>Nuclear decay or reaction</td>
<td>+2</td>
<td>3727.33</td>
<td>Discrete [MeV]</td>
</tr>
<tr>
<td>β⁻-particles</td>
<td>Nucleus</td>
<td>Nuclear decay</td>
<td>-1</td>
<td>0.511</td>
<td>Continuous [keV-MeV]</td>
</tr>
<tr>
<td>β⁺-particles</td>
<td>Nucleus</td>
<td>Nuclear decay</td>
<td>+1</td>
<td>0.511</td>
<td>Continuous [keV-MeV]</td>
</tr>
<tr>
<td>Auger electrons</td>
<td>Electron cloud</td>
<td>Atomic deexcitation</td>
<td>-1</td>
<td>0.511</td>
<td>Discrete [keV-MeV]</td>
</tr>
<tr>
<td>Internal conversion electron</td>
<td>Electron cloud</td>
<td>Nuclear deexcitation</td>
<td>-1</td>
<td>0.511</td>
<td>Discrete [keV-MeV]</td>
</tr>
<tr>
<td>Neutrons</td>
<td>Nucleus</td>
<td>Nuclear reaction</td>
<td>0</td>
<td>939.57</td>
<td>Continuous or discrete</td>
</tr>
<tr>
<td>Fission fragments</td>
<td>Nucleus</td>
<td>Fission</td>
<td>20*</td>
<td>80-160</td>
<td>Continuous 30-150 MeV</td>
</tr>
</tbody>
</table>

*Average effective ionic charge

To limit the scope of the discussion, only gamma rays will be discussed here. Gamma rays travel at the speed of light and penetrate most objects with a gradual reduction in intensity but not wavelength. They pass through air almost unaffected but can be shielded using several feet of water, a few feet of concrete, several inches of steel, or few inches of lead [38]. Fig. 12 illustrates the penetrating ability of different nuclear radiations.
Based on the energy of the incident photon, gamma rays interact with matter in one of three ways: photoelectric absorption, Compton scattering, or pair production as shown in Fig. 13. Photoelectric absorption is the predominant effect at low energies whereas Compton scattering is the predominant effect at intermediate energies and pair production is the predominant effect at high energies.

In photoelectric absorption, the gamma photon loses all of its energy as it interacts with an entire atom which results in the ejection of one atomic electron, shown in Fig. 14(a). A small amount of the incident energy is used to overcome the binding energy of the electron, and an even smaller amount remains with the atom as recoil energy to conserve momentum. Most of the incident energy is transferred to the
freed electron as kinetic energy. In Compton scattering, the gamma photon loses part of its energy as it interacts with a free or weakly bound electron. Only a partial energy transfer is allowed, by the conservation of energy and momentum law, when the electron is not bound tightly enough for the atom to absorb recoil energy. This energy transfer frees an electron with kinetic energy equal to the difference of the energy lost by the gamma photon and the electron’s binding energy. Therefore, both the freed electron and the scattered gamma photon leave the interaction site as shown in Fig. 14(b). The amount of energy transferred to the electron during the interaction governs the directions of the electron and the scattered gamma photon. In pair production, the gamma photon loses all of its energy to create an electron-positron pair, shown in Fig. 14(c). This occurs when the photon is under the influence of the strong electromagnetic field in the vicinity of a nucleus. This interaction has a threshold of 1.022 MeV because that is the minimum energy required to create the electron and positron. In this interaction the gamma ray disappears and the nucleus receives a very small amount of recoil energy to conserve momentum. If the energy of the gamma photon exceeds 1.022 MeV, the excess energy is shared between the electron and positron as kinetic energy [40].

![Fig. 14 A schematic representation of (a) photoelectric absorption, (b) Compton scattering, (c) pair production [41], Artwork has been released into the public domain by its author](image)

2.4 Optical Fibers Technology

2.4.1 Solid Optical Fibers

Although optical fibers are produced from different materials such as glass, plastic and single crystals, silica glass has been and still is the dominate material used to produce fibers. Simple unclad
glass fibers have been known for a long time, as early as 1836 [42]. A little more than a century later, Hopkins and Kapany [43] reported the idea of coating a glass fiber with a second layer of glass, of lower refractive index to protect the surface of the light-guiding core from impurities and abrasion. In 1966, Kao and Hockham [44] were the first to propose telecommunication by optical fibers and suggested that attenuation of fibers was caused by impurities, which could be removed, rather than scattering. They speculated that optical fiber could be a practical medium for communication, if the attenuation could be reduced below 20 dB/km. This attenuation level was achieved four years later, by researchers at Corning Glass Works [45]. A few years later they produced a fiber with very low attenuation which led to optical fiber telecommunications and enabled the Internet. Nowadays, attenuations in optical cables are far less than those in electrical copper cables.

The field of optical fiber technology deals with emission, transmission, and detection of electromagnetic waves that span wavelengths from the ultraviolet (UV) to the infrared (IR). This range of wavelengths is commonly referred to as light. The optical fiber acting as the transmission medium is the most important component in any optical fiber system since its transmission characteristics affect the performance of the entire system. Optical fibers are essentially dielectric waveguides. The fiber waveguide is usually cylindrical, confines the light within its structure, and guides it in a direction parallel to its axis. The fiber structure establishes the waveguide bandwidth and also determines its response to perturbations in the surrounding environment. The light propagation in the waveguide can be described in terms of a set of guided waves called the modes of the waveguide. Only a certain number of modes are allowed to propagate along the fiber’s core. Each mode represents a pattern of electric and magnetic field distribution that is repeated along the waveguide at constant intervals [46]. The phenomenon governing the guidance of light through transparent fiber is the total internal reflection (TIR). This phenomenon describes the behavior of light incident upon the interface between two optical materials of different refractive indices. When a light ray propagates from the more dense material to the less dense material at an angle greater than the critical angle, it will be totally internally reflected. The critical angle depends solely on the refractive indices of the two media. An off-axis ray traversing in a 50 µm diameter fiber may be reflected 10,000 times per meter of fiber length [47]. The number of reflections is inversely proportional to the fiber diameter. Ideally, TIR results in lossless reflection thus, making light transmission possible. However, in reality, there is some loss at the interface. It should be noted that this loss does not include loss due to beam spreading and light scattering. Some of the factors that can cause light scattering from the geometric path include: interface irregularities, surface scattering, and bulk scattering. In addition to losses due to structural variation there are several other
sources of losses in optical fibers such as Rayleigh scattering, absorption, and microbending [47]. For reasons which will become apparent in later sections, absorption loss will be explained in detail in section 2.6.

As indicated above, light is reflected at the boundary between the core and cladding. At this point, the standing wave of light, while being reflected, penetrates about a quarter wavelength into the cladding. This penetrating wave is known as the evanescent wave. It has a characteristic penetration depth of 50-100 nm and decays exponentially with distance from the boundary [47].

The structure of conventional optical fibers consists of single solid dielectric cylinder of higher refractive index material known as the core. The core is surrounded by a solid dielectric cladding of lesser refractive index material. The cladding reduces scattering loss, adds mechanical strength, and protects the core from absorbing surface contaminates. In addition, the cladding is used to enclose the evanescent field tails of the bounded core modes. Evanescent field tails travel along with the fields in the core. The cladding of optical fibers is usually coated with an elastic and abrasion-resistant polymer. The polymer has refractive index that is slightly higher than that of the cladding. This material adds further strength and acts as cladding modes suppressant [48]. Variation in the core’s dimension gives rise to two standard fiber types: single mode and multimode. Single mode fiber (SMF) allows only one mode of propagation, whereas multimode fiber (MMF) may allow a large number of modes. Typical sizes for single mode fibers range from 8-12 µm and multimode fibers from 50-200 µm. The large core of the multimode offer advantages such as the ease of core alignment during fiber splicing, the capability of launching large optical power into the fiber, and the ability to use light emitting diode sources, whereas single mode fiber requires laser diodes. However, multimode fiber suffers from intermodal dispersion [46].

2.4.2 Microstructured Optical Fibers

Microstructured optical fibers (MOF) or “holey fibers” are another class of optical fibers. This type of fibers employs a microstructured arrangement of low index material that surrounds the fiber’s core. The low index region is typically provided by air voids running along the length of the fiber. MOF’s may be divided into high index guiding fibers and low index guiding fibers. High index guiding fibers guide light in a solid core by the phenomenon of modified total internal reflection (MTIR). This phenomenon is termed modified TIR because the air holes effectively lower (or modifies) the refractive index of the cladding as compared to the solid core [49]. Low index guiding fibers guide light by the photonic band gap (PBG) effect [50] which will be explained subsequently.
The majority of the reported high index MOFs have uniformly ordered holes but differ in the size, spacing and number of air holes present in the cladding region. However, it was demonstrated theoretically that holes in high index MOFs do not need to be arranged in a periodic lattice to guide light [51] and within few years RHOFs were developed [52]. In this type of fiber, thousands of longitudinal air holes which are random in size, lengths, and spatial location surround the pure silica core [53]. The size, number and location of the holes occurring in these fibers can be controlled to produce a variety of different properties in the fiber.

Photonic band gap structures or photonic crystals (PCs) have recently attracted much interest among researchers because of their special properties and potential applications in light guiding and manipulation. Photonic crystals are man-made materials with periodic structure on the order of the wavelength of light. The optical properties of one-dimensional (1-D) PCs in the form of periodic multilayers were first analyzed by Lord Rayleigh in 1887 [50]. The concept of two and three-dimensional PCs was first discussed by Purcell in 1946 [54], and further generalized by Yablonovitch and John independently in 1987 [55, 56]. After a large theoretical effort [57, 58], it was finally shown conclusively that such photonic band gap materials were possible [59, 60]. The first experimental demonstration appeared in 1991 [61].

The photonic band gap effect can be found in nature, where the beautiful and bright colors that are seen in butterfly wings and sparkling gem opal, are the result of naturally occurring periodic microstructures as shown in Fig. 15.

![Fig. 15 Natural photonic band gaps occur in some butterfly wings (left) and in opals (right). A micrograph of a fractured butterfly scale (center) shows the submicron size face-centered cubic structure inside, Courtesy of H. Ghiradella [62], Used with permission](image)

The periodic microstructure in the butterfly wing results in a photonic band gap, where light in certain wavelength regions cannot propagate. In the butterfly wing, this light is reflected back, and is seen as the bright colors. Opals consist of submicron-size silica spheres arranged in a face-centered...
cubic (close-packed) structure. In both cases, the band gap is incomplete. It is not effective in every direction, but it produces iridescent colors.

For simplicity let us consider 1-D PCs. The general idea is PCs do to photons what semiconductor crystals do to electrons, i.e. they create a situation whereby photons in a certain energy range cannot travel through the crystal and are reflected when impinging onto the crystal or are not allowed to propagate at all when generated inside it. A photonic crystal consists of an ordered structure in which two media with different dielectric constant or refractive indices are arranged in a periodic form [63].

Light entering the crystal will refract through and partially reflect off the multiple internal interfaces between the two media. The complex pattern of overlapping beams will reinforce or cancel one another out according to the light’s wavelength, and its direction of travel through the crystal. Perfect cancellation in all directions for a narrow band of wavelengths means that this band of light cannot propagate through the crystal. For a wavelength in the band gap, a wave incident on a band gap material Fig. 16(1) partially reflects off each layer of the structure Fig. 16(2). The reflected waves are in phase and reinforce one another. They combine with the incident wave to produce a standing wave Fig. 16(3) that does not travel through the material. Otherwise, at a wavelength outside the band gap Fig. 17(1), the reflected waves are out of phase and cancel out one another Fig. 17(2). The light propagates through the material only slightly attenuated Fig. 17(3).

![Fig. 16 Wavelength in the band gap [62], Used under the Fair-Use Provision of Copyright Law](image-url)
The PBG discussion has been adopted from [50]. The PBG structures for three different multilayer films are shown in Fig. 18. The left plot shows the band gap structure for single layer with dielectric constant $\varepsilon = 13$. The center plot shows the structure for alternating layers between $\varepsilon = 13$ and $\varepsilon = 12$. This plot has a gap in frequency between the upper and lower branches of the lines. There is no allowed mode in the crystal that has a frequency within this gap. The right plot shows the structure for alternating layers between $\varepsilon = 13$ and $\varepsilon = 1$. In this plot the gap widens considerably as the dielectric contrast is increased.
It is observed that in 1-D PCs, a gap occurs between every set of bands at either the edge or the center of the Brillouin zone. This is illustrated in Fig. 19. Moreover, band gaps always appear in 1-D PCs for any dielectric contrast, the smaller the contrast, the smaller the gaps.

![Photonic Band Structure](image)

Fig. 19 The photonic band structure of a multilayer film with lattice constant $a$ and alternating layers of different widths, [50], Courtesy of Princeton University Press, Used with permission

The main factors that determine the properties of photonic crystals are the refractive index contrast, the fraction of high and low index materials in the lattice and the arrangement of the lattice elements. The most frequently used design is that of a quarter-wave PC, where each layer thickness corresponding to one quarter of the wavelength for which the PC is designed for. An additional factor is that the structure must be large compared to the beam size (i.e. many wavelengths deep) to experience the full interaction with the periodic lattice.

A 2-D PC is periodic along two of its axes and homogeneous along the third axis. Unlike 1-D PC, it can prevent light from propagating in any direction within the plane. The band structures for transverse electric (TE)\(^a\) and transverse magnetic (TM)\(^b\) modes can be completely different. It is possible that there are PBGs for one polarization but not for the other. Let’s consider the propagation of light in the $xy$ plane of dielectric pillars arranged in a square array as shown in Fig. 20. The band structures of both the

\(^a\) In TE mode, the electric field is perpendicular to the direction of propagation
\(^b\) In TM modes, the magnetic field is perpendicular to the direction of propagation
TE and TM modes are shown in Fig. 21. The y-axis represents the frequency expressed as a dimensionless ration and the x-axis represents the in-plane wave vector from $\Gamma$ to $X$ to $M$ along the triangular edge of the irreducible Berillouin zone [50].

The TM modes have a complete gap between the first (dielectric) and second (air) bands. However, there is no complete band gap for the TE modes. This can be explained by examining the field patterns. In order to lower its frequency, a mode concentrates most of its electric field energy in the high
dielectric region. This means that the first band, which has low frequency, has most of its energy in the dielectric region. However, the next band above the first one should have a higher frequency, and thus must expel some of its energy in the low dielectric region which allows higher frequency. The size of the band gap depends on the difference in energy distribution of consecutive modes. That is, large energy distribution contrast results in large band gap. The electric field in the lowest TM mode is concentrated within the pillars. The field in the next TM mode must expel some of its energy in the air region which in turn results in large energy distribution contrast between the first and second mode. The displacement field of the TE modes has no choice but to penetrate the air region to be continuous. Thus, the field of both lowest and second TE modes has a significant concentration in the air region. This in turn, results in small energy distribution contrast between the first and second mode [50].

Another possible 2-D PC is the square grid of dielectric belts shown as an inset in Fig. 22. This structure is considered complementary to the square lattice of pillars because it is a connected structure. The complementary nature is reflected in the band structure of Fig. 25. Here, there is a gap in the TE band structure but not in the TM band. The electric field, in the lowest TM mode is concentrated within the dielectric crosses and vertical veins, whereas the field of the second mode is concentrated in the horizontal dielectric veins. Both consecutive modes manage to concentrate their energy in dielectric regions, thus there is no large energy distribution contrast. To be continuous, the displacement field of the first TE mode can extend through the vertical veins without leaving the dielectric regions. However, the second TE mode is forced into the air regions to increase its frequency. This in turn, results in large energy distribution contrast between the first and second mode [50].

Fig. 22 The photonic band structure for a square grid of belts [50], Courtesy of Princeton University Press, Used with permission
To arrange both isolated and connected regions of dielectric material in air seems to be difficult to realize. Nevertheless, this situation can be resembled by semi-isolated regions linked by narrow belts as shown in Fig. 23. If the air pillars are large enough, the spots between the pillars look like localized regions which are connected through a narrow squeeze between the air pillars. The band structure for this configuration has PBGs for both the TE and TM polarizations as shown in Fig. 24.

Fig. 23 The spots and veins of a triangular lattice [50], Courtesy of Princeton University Press, Used with permission

Fig. 24 The photonic band structure for the modes of a triangular array of air pillars [50], Courtesy of Princeton University Press, Used with permission

Since reflectivity is essential for many optical devices, the design of a PC mirror is discussed here which is essentially the building block in a waveguide. This design example was adopted from [50]. Let
us consider the design of a 2-D PC that reflects all in-plane TM waves within some specified frequency band. We choose a particular wavelength, say $\lambda = 1.5 \, \mu m$, the wavelength that is most commonly used in telecommunication. For the sake of clarity, we choose a material that will give a very large dielectric contrast. Our choice of material will be gallium arsenide which has $\varepsilon = 11.4$ at $\lambda = 1.5 \, \mu m$. To achieve maximum reflectivity, we should choose a crystal structure that has TM band gap. The locations and sizes of PBGs in several different 2-D and 3-D PCs structures have been mapped to serve as a convenient atlas for PC design. See Appendix A for some examples of 2-D gap maps. Therefore, we consult with such an atlas to find a suitable structure based on the design requirements. A particularly simple structure that meets the design requirements is the square lattice of dielectric pillars, which has a large TM band gap. The gap map is shown in Fig. 25, and exhibits a large TM gap for a pillar radius of $r = 0.2a$, where $r$ is the pillar radius and $a$ is the lattice constant. This radius corresponds to $\omega a/2\pi c = 0.287$ to $\omega a/2\pi c = 0.422$ and a midgap at $\omega a/2\pi c = 0.355$. These dimensionless quantities need to be converted into physical units. This can be easily done as shown below:

$$\frac{\omega a}{2\pi c} = \frac{a}{\lambda} = \frac{a}{1.5 \, \mu m} = 0.355 \Rightarrow a = 0.533 \, \mu m$$

Given $a$, we can calculate the pillar radius $r = 0.2a = 0.107 \, \mu m$. The TM gap ranges from a wavelength of $a/0.422 = 1.26 \, \mu m$ to $a/0.287 = 1.86 \, \mu m$ with $1.5 \, \mu m$ at the center of the gap.

---

**Fig. 25** Gap map showing TM gap locations versus pillar radius for square lattice of pillars and a fixed $\varepsilon$ ratio of 11.4:1 [50], Courtesy of Princeton University Press, Used with permission.
One might ask, what is the optimal radius that maximizes the gap size as a function of the $\varepsilon$ contrast. Also, what is the minimum contrast required to obtain a gap for a giving geometry. This can be answered with a plot called a gap recipe (See Fig. 26). This is a plot of the optimal radius and the corresponding gap size as a function of refractive index contrast. The gap size increases monotonically with index contrast. The optimal radius, on the other hand, decreases with index contrast. This is because the diameter of the pillar should be on the order of half wavelength in the dielectric material, and the relative wavelength in the material decreases proportional to the index contrast.

Since atoms are the basic building blocks of matter, PC material thickness cannot be less than 2.5 Å limiting the PC operation to wavelengths larger than 1 nm. Thus, PC can only be designed for wavelengths longer than X-rays. A common misconception is that PC structures can be made to control electromagnetic waves at all wavelengths from radio waves to gamma rays.

![Fig. 26 Gap recipe for the lowest TM gap of the square lattice of dielectric pillars [50], Courtesy of Princeton University Press, Used with permission](image)

### 2.5 Optical Fiber Fabrication

#### 2.5.1 Conventional Optical Fibers

There are various techniques to fabricate solid silica fibers. The main two techniques to fabricate commercial silica fibers are [46]: direct-melt method and vapor-phase oxidation process. In both techniques there are two main steps in the process of converting raw materials into optical fiber. First, the fabrication of pure glass preform and second, the drawing of the preform. A preform is a solid rod
that provides the source material from which the glass fiber will be drawn in a single, continuous strand. The direct-melt method follows traditional glass-making procedures in which preforms are made by melting mixtures of purified powders of silicate glasses and the optical fibers are drawn directly from the molten state [64]. In the vapor-phase oxidation process, highly pure vapors of silicon tetrachloride (SiCl\(_4\)) and germanium tetrachloride (GeCl\(_4\)) or phosphorus trichloride (POCl\(_3\)) react with oxygen to form germanium or phosphorus doped SiO\(_2\) particles. Doping glass with these elements increases its refractive index. The particles are collected on a surface and sintered by either:

- Outside Vapor-Phase Oxidation (OVPO) [65]
- Vapor-Phase Axial Deposition (VAD) [66]
- Modified Chemical Vapor Deposition (MCVD) [67]
- Plasma-Activated Chemical Vapor Deposition (PCVD) [68]

In OVPO and VAD processes the glass particles are deposited radially outward on a target rod. In MCVD and PCVD processes glass particles are deposited radially inward on a target tube.

OVPO process consists of two steps: soot deposition and sintering as shown in Fig. 27. In the deposition step, the soot (SiO\(_2\) particles) is deposited from a burner onto a rotating and traversing ceramic target rod. The glass soot adheres to this rod in, a partially sintered state and layer by layer, a cylindrical porous glass preform is built up. When deposition is complete, the ceramic rod is removed, and the porous preform is then sintered at 1500 °C under helium atmosphere to a solid, bubble-free, and transparent glass blank [65] as shown in Fig. 28.
Glass particle formation in VAD is similar to OVPO. However, the porous preform is grown in the axial direction. The porous perform transforms into solid rod as it moves upward by zone melting as shown in Fig. 29. VAD offers three advantages over OVPO. First, there is no center hole in the preform. Second, the perform can be made in continuous lengths, thus increasing product yields. Third, preforms are made in a clean environment since the deposition chamber and zone heating are tightly connected to each other in one enclosure.

MCVD process also consists of two steps: soot deposition and sintering. The reactants gases are fed at the end of a rotating silica tube. The tube is heated by a traversing oxygen-hydrogen burner which also sinters the glass particles as they deposit as shown in Fig. 30. The soot is deposited on the internal wall of the tube from the gas phase. When the desired thickness has been achieved, the gas flow is stopped and the tube is heated to cause it to collapse into a solid rod [67]. The PCVD process is similar to MCVD. However, a microwave plasma initiates the chemical reaction which results in the deposition of a clear glass material directly as shown in Fig. 31. Thus, sintering is not required. By properly controlling the constituents of the vapor stream during the deposition process, the desired glass compositions and dimensions for the core and cladding can be incorporated into the preform [68].
Fig. 29 Vapor-Phase Axial Deposition (VAD) process [71], Courtesy of D. Stadnik, Used with permission

Fig. 30 Modified Chemical Vapor Deposition (MCVD) process [69], Used under the Fair-Use Provision of Copyright Law
The finished glass preform is subsequently mounted on a fiber-drawing tower. The glass blank is then lowered into the top of the draw furnace at 1800-2200 °C. The tip of the blank is heated until a piece of molten glass, begins to fall from the blank at a viscosity of $10^5$-$10^6$ poise depending on glass composition [65]. As the molten glass falls, it pulls behind it a thin strand of glass, the beginning of an optical fiber. The molten glass is cut off, and the fine fiber strand is threaded into a computer-controlled tractor assembly and drawn as shown in Fig. 32. Then, as the diameter is monitored, the assembly speeds up or slows down to precisely control the size of the fiber’s diameter. In the case of OVPO performs, the central hole in the perform collapses during the drawing process.

![Fig. 31 Plasma-Activated Chemical Vapor Deposition (PCVD) process [72], Used under the Fair-Use Provision of Copyright Law](image1)

![Fig. 32 Optical Fiber Drawing tower [47], Courtesy of Polymicro Technologies, LLC, Used with permission](image2)
2.5.2 Microstructured Optical Fibers

Similar to conventional fiber fabrication, the MOF fabrication starts with a fiber preform. Microstructures can be achieved by drilling tens of periodic holes into the preform. Alternatively, silica capillary tubes and solid rods can be hand stacked to form the desired air/silica structure allowing low cost, fast and flexible preform fabrication [73]. Using an ultrasonic drill, a central hole is drilled into the solid silica rods. The outside of the fabricated tubes are then milled to form six flats. The large tubes are drawn into smaller dimensions and stacked in a close-packed manner in a supporting tube to provide a fiber perform as shown in Fig. 33 [74].

![Fig. 33 MOF fabrication process by stacking tubes in close-packed arrangement](image1)

A simpler method of fabricating performs is by direct stacking of tubes and rods without any modifications as shown in Fig. 34.

![Fig. 34 Photonic band gap fiber fabrication process](image2)

This method, however, can introduce additional air gaps at the interstitials sites between three adjacent tubes or rods as shown in Fig. 35.
It should be noted that accurate control of hole dimensions and location is essential for achieving photonic band gap fibers with specific properties. The precision control requirement increases the fiber fabrication cost significantly which makes photonic band gap fibers relatively more expensive compared to the solid fibers. Once the perform construction is complete (shown in Fig. 36), it is drawn into a fiber similar to conventional fiber drawing procedures [77].

2.5.3 Random Hole Optical Fiber

The RHOF, a new type of optical fiber, was developed at Virginia Polytechnic Institute and State University, U.S Patent 7,444,838. A preform is made by placing a 2.5 mm diameter solid rod of fused quartz in the middle of a thick walled tube (9 mm ID, 15 mm OD) made of the same material as shown in
Fig. 37. The tube serves as a container to hold the cladding material and provide structural strength to the fiber. The cladding material can be prepared by mixing with 100-mesh size, 99.7% purity silica powder with a gas producing material such as silicon nitride ($\text{Si}_3\text{N}_4$). The mixture is then placed into the empty space surrounding the solid core. When the preform is heated in the graphite element furnace in the draw tower, the silica powder fuses into a single mass thus, preventing any gas from escaping. Then, as the temperature increases, the silicon nitride oxidizes. The by-product of the oxidation reaction is more silica glass and nitrogen and/or $\text{NO}_x$ gases which forms bubbles in the preform [78]. The formation of bubbles in the molten glass is referred to as “in-situ” bubble formation. The choice of the gas producing material and its particle size determines the size of the gas bubbles produced in the preform, and ultimately, the size of the holes in the fiber. Finally, when the silica softens, the spherical bubbles are drawn out into long thin tubules as the fiber is drawn from the preform as shown in Fig 38. The fiber can be coated with Desolite™ polyurethane acrylate which is an ultraviolet cured polymer [76].
An optical micrograph taken in transmission mode (a) and an SEM micrograph (b) of one of the fabricated fibers are shown in Fig. 39. Analysis of the SEM micrographs of some of these fibers showed that they contained over a thousand holes with sizes ranging from less than 100 nm to more than 1 μm [53].

Fig. 39 (a) Optical image of RHOF, (b) SEM image of RHOF [29], Image is available under the terms of the Creative Commons Attribution license

RHOF fibers are inexpensive and easy-to-make when compared to the high cost of MOFs. The random nature of the in-situ bubble formation gives RHOFs unique characteristics. Unlike ordered hole fibers, the holes in a RHOF are not continuous over indefinite lengths of the fiber. Instead, the fiber contains open and closed holes. Some holes become opened since they are part of the cleaved edge of the fiber. These holes can contain ambient air under normal conditions. Other holes remain closed and therefore, contain residual gases from the fabrication process at certain pressure.

2.6 Absorption in Optical Fibers

There are three different mechanisms that can cause absorption of the optical signal in optical fibers: intrinsic absorption, extrinsic absorption, and absorption by defects in the glass matrix composition. The following discussion has been adopted from [46]. Intrinsic absorption defines the fundamental lower limit on absorption for any particular material. It results from electronic absorption bands in the ultraviolet region and from atomic vibration bands in the near-infrared region. Absorption can occur when a photon interacts with an electron in the valence band and excites it to a higher energy level. The inherent infrared absorption is associated with the characteristic vibration frequency of the particular chemical bond between the atoms of the material. An interaction between the vibrating bond and the electromagnetic field of the optical signal results in a transfer of energy from the field to the bond, thus
giving rise to absorption. Extrinsic absorption results predominantly from transition metal ions such as iron, chromium, cobalt, and copper and from OH (water) ions. The transition metal impurities which are present in the starting materials used for direct melt fibers range between 1-10 parts per billion (ppb), causing losses from 1-10 dB/km. The impurity levels in vapor-phase deposition process are one or two orders of magnitude lower. Impurity absorption occur either due to electronic transitions between the energy levels associated with the incompletely filled inner subshell of these ions or because of charge transition from one ion to another. The presence of OH ion impurities in the fiber results in large absorption peaks at 725, 950, and 1400 nm. These are the third, second, and first overtones, respectively, of the fundamental absorption peak of water near 2700 nm. Between these absorption peaks there are regions of low absorption. By reducing OH content of fibers to around 1 ppb, standard commercial single mode fibers have losses of 0.5 dB/km in the 1300 nm window and 0.3 dB/km in the 1550 nm window. Defects are imperfections in the atomic structure of the fiber material such as missing molecules, high density clusters of atom groups, or oxygen defects. Usually, absorption losses arising from these defects are negligible compared with intrinsic and extrinsic absorptions. However, they can become significant if the fiber is exposed to ionizing radiations. The basic response of a fiber to ionizing radiation is an increase in absorption owing to the creation of atomic defects or absorption centers that absorb optical energy.

2.7 Radiation Effects on Optical Fibers

The magnitude of the gamma radiation effects on optical fibers depends on a variety of factors. These factors include the structure of the fibers, the clad structure, and the dopant concentration both in the core and in the cladding. The effects of gamma irradiation on doped and pure silica core optical fibers have been studied previously [30, 80-83]. The influence of cladding co-dopants on the optical fiber behavior under radiation environments has also been investigated [84]. However, reports of radiation effects on MOF are only preliminary and limited [29, 85-87]. Microstructured optical fibers, being dopant-free fibers, could provide excellent light transmission in harsh environments such as at high temperatures and/or high levels of radioactivity.

A material encounters a variety of different interactions when placed in a radiation field. In the midst of a nuclear radiation field, the material is bombarded with electrons, photons (gamma rays), helium ions (alpha particles), protons, and neutrons. These different radiations induce two distinct changes within the material, ionization and atomic displacement. High energy neutrons are the primary cause of atomic displacements in materials because of their large mass and relatively high energy. Other
radiations, such as gamma rays, primarily induce ionization within the material. This effect is less severe than atomic displacement and can be temporary in nature. The effect of gamma rays in this study (≈1MeV) is assumed to be completely due to the ionization effects [88].

When the energy of an incident photon is large enough to displace an electron there are a number of reactions that can occur. These include the creation of non-bridging oxygen holes (NBO), oxygen vacancies or \((E')\) centers, and peroxy radicals. A non-bridging oxygen is an oxygen with a missing electron. An \(E'\) center is a silicon atom with a missing electron due to the fact that it is only bonded to three oxygens. A peroxy radical is another compound with an oxygen that is missing an electron. All of these reactions create an electron/hole pair. These electrons and holes can become trapped in the lattice and create defects [89]. Fig. 40 shows the various defects that could be created by the ionization affects of gamma rays.

![Diagram of ionization defects created by gamma rays in silica glass](image)

Fig. 40 Ionization Defects created by Gamma Rays in Silica Glass [90], Courtesy of Elsevier Science, Used with permission

In a good conductor, ionization effects are very temporary and will disappear rapidly. However, in poor conductors, such as glass, ionization can cause more detrimental and less temporary imperfections. These new configurations within the atomic structure of the glass can cause light absorption within the material. As a result of this, these atomic configurations have been deemed “color centers” [91]. The different configurations have different light absorption wavelengths. For example a NBO has optical absorption bands centered around 620 and 440nm, and an \(E'\) center with a band at
215 nm [83] This means that the different centers will produce different colors and can be identified within the glass matrix. The optical absorption bands within the materials are what cause light attenuation (i.e. transmission loss) within the glass when introduced to a gamma field [89].

An increase in the intrinsic absorption of optical fibers has been shown to correspond with gamma irradiation. This phenomenon can be related to the defects discussed above. It has been shown that the formation of NBO bind free electrons less tightly than oxygens in normal lattice spots. The tendency of these defects to less tightly bond free electrons results in an increase in the valance band of the material. The increase in the valance band results in the reduction of the material’s band gap energy within the material which in turn causes more light absorption. Increasing gamma irradiation increases the formation of these ionization defects and further decreases the material’s band gap resulting in an increase in the intrinsic absorption of the optical fiber [89]. Moreover, the addition of dopants to the silica matrix increases the number of defects (stress or strain related defects), thus giving rise to absorption by defects in addition to the already existing intrinsic and extrinsic absorptions. It is believed that these defects interact with the already existing defects such as NBOs to create different “color centers” that would not be present if the dopant was not there. For example, the introduction of phosphorus can cause the formation of phosphorus oxygen hole centers (POHCs) which have optical absorption peaks at different wavelengths than radiation induced defects seen in pure silica fibers [92]. Light attenuation in the near-IR region is typically small compared to that experienced in the UV region [93]. The absorption peaks responsible for transmission loss in UV-visible regions are associated with the formation of color centers such as non-bridging oxygen hole center (NBOHC) with a band at 630 nm [94], point defects related to impurities in silica like chlorine, for example, with a band around 330 nm [95], germanium related defects with a band at 475 nm [96], and many others. The origin of the incremental growth of the near-IR transmission loss, in low-OH fibers, is mainly attributed to the UV-visible absorption band tails [97]. However, the presence of color center absorption peaks in the higher end of the near-IR region (>1800 nm) [97], and self trapped holes with a band at 1800 nm [98] have also been reported to contribute to the near-IR transmission. In high-OH fibers, the near-IR RIA has been reported to be due to excitation of the OH vibrational band [30].

Under gamma irradiation, optical signals propagating in optical fibers are affected by radiation induced absorption (RIA) and radiation induced luminescence (RIL) which is usually accompanied by Cerenkov emission [94]. RIA can be described simply as the difference in dB between the transmitted optical power in the fiber before and after radiation exposure divided by the fiber length [96]. Or it is usually expressed by:
\[ RIA(\lambda, t) = \frac{-10 \log \left( \frac{P(\lambda, t)}{P(\lambda, t_o)} \right)}{L} \]  \hspace{1cm} (1)

where \( \lambda \) is the wavelength, \( t \) is the irradiation time, \( L \) is the length of the fiber, \( P \) is the optical power in Watts and \( t_o \) is the irradiation start time.
3. Experimental

3.1 Interfacing MOFs with Standard Solid Fibers

To date, handling and interfacing MOFs to standard solid fibers continues to be a challenge to overcome. The difficulty of cleaving MOFs and splicing them without damaging the microstructures has limited their use in real world applications [99]. Conventional fiber handling tools such as cleavers, strippers, and splicers are designed for standard solid fibers and thus don’t produce the expected results when used to handle MOFs. For example Fig. 41 shows the irregular cleaved surface produced by standard fiber cleaver. An irregular cleaved surface affects the quality of the splice junction. It’s also clear that the cleaving process can damage the microstructures of the fiber. Additionally, the small debris from the damaged microstructures can find their way into the holes and get trapped there. Such hole contamination may affects the optical signal propagation in the fiber.

![Irregular cleaved surface produced by standard fiber cleaver](image.png)

Fig. 41 Irregular cleaved surface produced by standard fiber cleaver [99], Used with permission (© 2008 IEEE)

Recently, micromachining MOFs has been proposed as an alternative to mechanical cleaving. Focused ion beam (FIB) was used to produce a smooth and clean cross sectional surface of the MOF [99]. By sputtering action, FIB can locally remove and mill away material. In this method, the milling process was carried out at two stages to reduce the milling time. First, rough milling is performed by a high beam current of 6.4 nA at 25 kV. This milling step machines the MOF and produces the surface shown in Fig. 42. Second, fine milling by thin beam (128 nm in diameter) at 0.25 nA beam current is used. This step produces a smooth and clean surface as shown in Fig. 43. It takes about 9 hours for the milling process (rough and fine milling) to be complete.
Another difficulty in splicing MOFs is fiber alignment. Conventional arc fusion splicers rely on a profile alignment system (PAS) technology for fiber alignment [100]. The system detects the core position via an image processing system and aligns the cores of the two fibers to be spliced accordingly. PAS utilizes the forward scattering light detection method [101] shown in Fig. 44. Collimated light is transmitted through the fiber and converges by the lens effect of the cladding and the difference in refractive index between the core and cladding. The transmitted light is then detected by a camera.
On the splicer’s monitor screen, as shown in Fig. 45, the cladding/core boundaries of the fiber can be distinguished as two faint dark lines in the center bright area (dashed red lines are used to guide the reader’s eyes). The area between the dark lines represents the core axis. The core axis must be aligned in both x and y directions.

However, it is difficult to distinguish the core/cladding boundaries of MOF’s fibers by the forward scattering light detection method as shown in Fig. 46. This is because the core and cladding in MOFs have similar refractive index. Therefore splicing MOFs using a conventional fusion splicer is prone to core misalignment.
Even with perfect cleave and alignment, splice loss is inevitable. Other parameters that splice losses depend on include geometrical and wave guide characteristics of the two fiber ends, power distribution to the splice junction, and the fiber length between the optical source and the splice point [46]. The fiber-to-fiber coupling efficiency is defined as

$$\eta_F = \frac{M_{\text{comm}}}{M_E}$$

where $M_{\text{comm}}$ is the common mode volume and $M_E$ is the number of modes in the emitting fiber. Splice loss in multimode fibers is difficult to estimate as the loss depends on the power distribution among the propagating modes [103]. Since core size of the RHOF available for this study fell in between the core sizes of standard SMF and MMF, it was necessary to determine the best splice combination of the RHOF, SMF, and MMF that would result in the minimum loss. The two possible configurations are shown in Fig. 47. In configuration (a), the light signal travels from SMF through RHOF to MMF. In configuration (b), the signal propagation direction was reversed. That is, light travels from MMF through RHOF to SMF.
The optical power losses in the two configurations are shown in Fig. 48. The red spectrum represents configuration (a) and the blue spectrum configuration (b). As mentioned above core misalignment, mode mismatch, and Fresnel reflection at the glass-air interface contribute to the splice loss. The results are in agreement with Equation 2. In configuration (a) the emitting fiber has smaller core than the receiving fiber (emitting fiber supports less modes than the receiving fiber). Therefore this configuration resulted in less loss. Fig. 48 also shows the dependence of splice loss on the wavelength. It is approximately 1.0 dB in the wavelength range of 1520-1570 nm, which is believed to be mainly caused by mode field mismatch and light reflection from the silica air interface.

![Graph showing optical power losses in two splice configurations](image)

**Fig. 48 Power losses in the two splice configurations**

### 3.2 Optical Fiber Samples

To study the radiation resistance of the RHOF fibers, a collection of standard telecommunication SMF and MMF (Corning SMF-28e and InfiniCor 600 respectively), harsh environment pure silica core (PSCF), fluorine down-doped inner cladding, and pure silica outer cladding fiber (SMF-2-A-125, Verrillon, Inc.), and RHOF fibers were used in this study. All samples were spliced to 3 m long labeled standard pigtails using a standard high quality fusion splicer (Type-36 Fusion Splicer, Sumitomo). Fiber optic connection cables, SMF (8.3/125) and MMF (50/125), simplex with standard FC/FC connectors (Stonewall Cable, Inc.) were used for SMF and MMF pigtails.

For the low dose test, the fiber samples illustrated in Table 5 were used. The inclusion of the MMF fibers was based on the fact that RHOF fibers have been experimentally shown to be highly multimoded.
The annealing temperature was chosen to be 300 °C since this corresponds to the primary loop temperature in a typical light-water reactor. Thus, a group of RHOF fibers was irradiated offline for extended period of time before irradiating them again. This group of fibers was termed high dose RHOF. The PSCF fiber was also exposed to serve as a reference.

<table>
<thead>
<tr>
<th>Treatment Combination</th>
<th>Fiber Type</th>
<th>Treatment</th>
<th>Number of Samples</th>
</tr>
</thead>
<tbody>
<tr>
<td>RHOF</td>
<td>RHOF</td>
<td>None</td>
<td>3</td>
</tr>
<tr>
<td>MMF</td>
<td>Multimode</td>
<td>None</td>
<td>3</td>
</tr>
<tr>
<td>Thermally annealed</td>
<td>RHOF</td>
<td>Heat - 4 hours at 300°C</td>
<td>3</td>
</tr>
<tr>
<td>RHOF</td>
<td>Heat - 4 hours at 300°C</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Thermally annealed</td>
<td>MMF</td>
<td>Multimode</td>
<td>3</td>
</tr>
<tr>
<td>RHOF exposed to higher Dose</td>
<td>Gamma Irradiation - 87 hours at 400 mR/hr</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>PSCF</td>
<td>Single mode</td>
<td>None</td>
<td>1</td>
</tr>
<tr>
<td><strong>Total Number of Samples</strong></td>
<td></td>
<td></td>
<td>16</td>
</tr>
</tbody>
</table>

For the high dose test, the fiber samples illustrated in Table 6 were used. RHOF washing was done by flowing methanol through the holes using a pressurized solvent reservoir. The samples were wound and fixed on 10 cm diameter rigid “flat spools.” Fixing the fiber samples on a rigid surface allowed easy handling and eliminated significant bending loss variations.

<table>
<thead>
<tr>
<th>Fiber Type</th>
<th>Treatment</th>
<th>Number of Samples</th>
</tr>
</thead>
<tbody>
<tr>
<td>SMF</td>
<td>None</td>
<td>2</td>
</tr>
<tr>
<td>MMF</td>
<td>None</td>
<td>2</td>
</tr>
<tr>
<td>RHOF</td>
<td>None</td>
<td>2</td>
</tr>
<tr>
<td>ROHF</td>
<td>Methanol washed</td>
<td>2</td>
</tr>
<tr>
<td>PSCF</td>
<td>None</td>
<td>2</td>
</tr>
<tr>
<td><strong>Total Number of Samples</strong></td>
<td></td>
<td>10</td>
</tr>
</tbody>
</table>
3.3 Low Dose Irradiation

The fibers outlined in Table 5 were placed on a Styrofoam platform as shown in Fig. 49, 28 cm away from the source. The source of radiation was a 96 mCi cesium-137 isotope. Cesium-137 decays with a half-life of 30 years by beta emission to barium-137. Barium-137 then decays with a half-life of 2.55 minutes, releasing 0.662 MeV gamma rays. As discussed in section 2.2, gamma rays ionize matter, thus, its presence can be measured in terms of the number of ions or electrons produced in the material. Consequently, ionizing radiation exposure is conventionally measured in units of Roentgen (R).

This unit is defined as the amount of radiation required to liberate positive and negative charges of one electrostatic unit of charge in 1 cm³ of dry air at standard temperature and pressure (1 R = 2.58x10⁻⁴ coulombs per kilogram). Based on the source’s activity, the exposure rate constant of Cs-137 (3.28 R·cm²/mCi·hr), and the distance between the source and sample, the exposure rate was calculated to be about 400 mR/hr from the following equation

\[ \text{Exposure rate} = \frac{\Gamma A}{d^2} \]  

(3)

where \( \Gamma \) is the exposure rate constant, \( A \) is the activity of the nuclide, and \( d \) is the distance between the source and the target. Exposure rate can be easily determined but the usefulness is limited because it is only a measure of the ionizations of the molecules in a mass of air. However, since we are concerned with radiation damage in materials, then, the exposure rate should be converted to an absorbed dose rate which relates to the amount of energy actually absorbed in the material. The Gray (Gy) is the SI unit
used to measure the total dose a material receives. One gray is equal to one joule of energy deposited in one kg of a material. The absorbed dose of radiation in any kind of material depends on the typical ionization energy of the particular material. The conversion of exposure rate to absorbed dose rate requires the use of weighted mass energy absorption coefficients for the material of interest which is given by

\[
D = \left( \frac{\mu_{\text{en}}/\rho}{\mu_{\text{en}}/\rho_{\text{air}}} \right)_{\text{material}} D_{\text{air}} \left( \frac{\psi_{\text{material}}}{\psi_{\text{air}}} \right)
\]

where \((\mu_{\text{en}}/\rho)\) is the mass energy absorption coefficient, \(D\) is the absorbed dose in air form 1 R exposure, and \((\psi_{\text{material}}/\psi_{\text{air}})\) is the transmission factor. Optical fibers are predominantly SiO₂ and a comparison of the density weighted dE/dx for Si and SiO₂ shows that the absorbed doses will be equivalent to within 2% [104]. For silicon irradiated with 0.6 MeV gamma rays, \((\mu_{\text{en}}/\rho) = 0.0296 \text{ cm}^2/\text{g} \) [105] and for air irradiated with the same gamma energy \((\mu_{\text{en}}/\rho) = 0.0293 \text{ cm}^2/\text{g} \) [106]. Assuming a unity transmission factor, the absorbed dose in SiO₂ is equivalent to that of air which is about 0.01 Gy for every 1 R exposure and thus the absorbed dose rate in this test was 4 mGy(Si)/hr. The total dose received by the fibers during measurement was 12 mGy(Si). Using the same source the high dose RHOFs accumulated a absorbed dose of 350 mGy(Si). Ionization of the fibers was verified visually through the observation of excessive collection of dust particles on the fibers at the end of the irradiation test.

Measurements were taken using a high-resolution component testing system (CTS) (Si720, Micron Optics Inc.), which is essentially a spectrometer with a built-in tunable 5 mW fiber ring laser that is continuously swept from 1520 to 1570 nm with wavelength accuracy of 1 pm and has dynamic range detection capability of more than 60 dB. A MATLAB code was developed (See Appendix B) to acquire the spectral data, label it, and then save it in ASCII format for later processing. Fig. 50 shows the setup with the computer, CTS and fibers. It should be noted that in order to measure RIA, a probe signal needs to be transmitted through the fibers. However, due to limited resources, only one RIA measurement per fiber was recorded every time a measurement was taken. The switching among the fibers was done manually in fixed order. This resulted in discontinuous measurements throughout the duration of the experiment. Reference measurements were taken before irradiation to determine the measurements’ natural variation.
3.4 High Dose Irradiation

To study the behavior of RHOFs at high dose irradiation, another set of fibers were irradiated at a dose rate 5 orders of magnitude higher (400 Gy(Si)/hr) than the low dose irradiation test and received a total dose of 7200 Gy(Si). The fiber irradiation test was performed at an Oak Ridge National Laboratory gamma ray irradiation facility using the J.L. Shepherd irradiator which contains $^{60}$Co (1.173 MeV and 1.332 MeV gamma rays) cylindrical sealed sources. The irradiator had a sample chamber with a 15 cm diameter and 20 cm high cavity as shown in Fig. 51.
With the sample chamber in the withdrawn position, the fiber samples were stacked in the middle of the sample chamber and connected to the optical signal detection electronics. Two instruments were used for optical signal detection, one was used to measure the RIA centered at 1550 nm and the other was used to measure the broadband spectrum in order to capture the RIL and Cerenkov radiation if present. The CTS was used for the RIA measurements. The same discontinuous measurement procedure carried out in the low dose irradiation test was followed. An Ando optical spectrum analyzer (OSA) (AQ-6315E, Yokogawa Corp.) was used for the RIL measurements (also discontinuous measurements). This system spectrally resolves intensity measurements in the range 350-1750 nm with wavelength accuracy better than 0.05 nm. The system is sensitive enough to measure light intensities as low as a few picowatts. Reference measurements were taken before the sample chamber was inserted into the irradiation position. When the irradiation test was completed, the fiber samples were kept in the dark for a period of time and then exposed to ambient light to assess post irradiation recovery behavior.
4. Results and Discussion

4.1 Low Dose Test Results

4.1.1 General Observations

The radiation induced absorption data was plotted over time where time before the “0” time represents preirradiation readings and time beyond 180 minutes is post-irradiation readings. Based on the definition of RIA (Equation 1), positive values indicate optical power loss compared to the reference (loss before irradiation) and negative values indicate reduction in optical power loss compared to the reference (loss before irradiation). The data was normalized to preirradiation, by subtracting out the loss at the final reading before irradiation. Measurements for each fiber were taken every twenty minutes, the time required to complete one switching cycle. To show the general trend in all fibers tested, RIA for all six treatment combinations was plotted in Fig. 52.

![Fig. 52 Radiation induced absorption for all 6 treatment combinations](image)

The overall trend is cyclical in nature with increases and decreases in RIA throughout irradiation. The RIA in the PSCF was negligible. The initial RIA appears to reach a maximum at about an hour into irradiation. After that, RIA in the fibers begins to trend back towards the initial values. Then after another hour the RIA begins to increase again and reached a different maximum. Finally, after
irradiation was stopped, all the fibers again trend toward their initial values. A negative value of RIA indicates improvement in the fibers transmission due to radiation exposure. This is consistent with observations reported elsewhere [96, 107].

The cyclical trend in the data has been also reported by other groups [107, 108]. However, this phenomenon has not been explained previously. One possible explanation for this observation could come from the relatively slow electron recombination rate which results in carrier build-up. It is believed that once a critical concentration of carriers is reached, the carriers’ lifetime rapidly decreases resulting in sudden recombination. This could explain the rapid but temporary recovery of the fibers during irradiation. Another possible explanation is related to the uncertainty in measurement. The transmission loss measurement required launching an optical signal through the fibers during irradiation (probe signal). It should be noted that the damaging process, or bond breaking, of the radiation and the healing process (photobleaching), or bond repairing, of the probe signal are competing with each other. Therefore, it is possible that the irradiation damage was being gradually healed every time a measurement was taken. Yet, the irradiation was continuous and the dose was accumulating. Therefore, the fluctuation in RIA could be a result of continuous damaging with pulsed healing. This could also explain the accelerated healing rate of all fibers after irradiation was ceased. Photobleaching can have significant effects on RIA within 10 seconds of 0.5 mW probe signal illumination [109]. This behavior can be modeled by considering the net number of bonds, number of bonds damaged (lost), and number of damaged bonds repaired. It should be noted that this is a qualitative model and only aimed to give some insight of the phenomenon. This can be expressed as

\[
N_{net} = N_{total} - N_D \left(1 - N_R \right)
\]  

(5)

where \(N_{net}\) is net number of bonds, \(N_{total}\) is total number of bond in the irradiated volume, \(N_D\) is number of damaged bonds, and \(N_R\) is number of repaired bonds that was damaged.

\[
N_D \propto ADt
\]  

(6)

The number of damaged bonds is directly proportional to dose rate (D) and irradiation time (t) where A is constant of proportionality.

\[
N_R \propto BP
\]  

(7)

the number of repaired bonds due to photobleaching is directly proportional to optical power (P) where B is constant of proportionality. The parameter \(N_R\) is relative to \(N_D\) and thus assumes values between 0 and 1. The zero value represents no damaged bonds were repaired and the value of one represents that all damaged bonds were repaired. This model also assumes that \(D\) and \(P\) have the same order of
magnitude. To demonstrate the similarity of the model prediction with the experimental results, equation 5 is plotted (as shown in Fig. 53) over arbitrary number of bonds and time lengths. The photobleaching effect was represented here by a triangle wave.

![Graph](image)

**Fig. 53 Behavior of continuous damaging with pulsed healing**

### 4.1.2 MMF with Different Treatments

Fig. 54 shows the comparison between untreated and thermally annealed MMFs. The excessive optical loss is attributed to splice losses. In this work, the splices were made between different fiber types. Results reported elsewhere are based on same type fiber splices which usually result in minimal loss. Results showed that the thermally annealed MMF fibers used in this test are more resistant to gamma radiations than the untreated one. These results were surprising as change in MMF resistance was not anticipated. Change in germanium doping profile within the fibers was regarded as a possible reason. However, germanium diffusion was determined to be insignificant by calculation of the diffusion rate of germanium in amorphous silica at 300°C. The degradation of the protective polymer coating by the thermal treatment could explain this behavior. As discussed in section 2.4.1 the protective polymer coating acts as a cladding modes suppressant. The change in the coating properties due to high temperatures can change the optical properties of optical fibers [110]. It is believed that the change in the polymer properties caused cladding modes to appear. Subsequently, mode coupling might have occurred as the core and cladding modes propagated through the fiber. Mode coupling causes exchange
of power back and forth between the core and cladding modes. The portion of the optical signal, propagating in the cladding, which is made from pure silica, does not experience extrinsic absorption and thus, under gamma irradiation, experience less RIA.

The measured RIA values for MMFs were high compared to the published data on commercially available optical fiber [111]. The source of this discrepancy comes from the difference in sample lengths. The published data is based on fibers with lengths that ranged from 50 m to 100 m. The samples used in this work were less than 0.3 m. It is accepted that there exist nonpropagating modes within the first tens of meters of the optical fiber [46]. Moreover, the short lengths of the sample are not enough for the establishment of steady state modal equilibrium. A distance of about 50 m is required for the launched modes to reach equilibrium [46]. The nonpropagating modes and the transit state modes could be attributed to the difference in RIA values in MMFs.
4.1.3 RHOF with Different Treatments

Fig. 55 shows the comparison between the three treatments of RHOF fibers: untreated, thermally annealed, and treated with high dose of radiation. It can be seen that the thermal annealing has a negative effect on the gamma radiation resistance of the RHOF fibers. The untreated and hi dose fibers behave very similarly with a maximum RIA of about 8 dB as compared to about 18 dB for the thermally annealed fibers. The degradation of the thermally anneal RHOF gamma radiation resistance suggests the depletion of species responsible for the radiation resistance. It can also be related to partial crystallization of the silica matrix in some regions of the core [112].

![Graph showing RIA (dB/m) vs. Time (min) for different RHOF treatments](image)

Fig. 55 Comparison of RIA due to irradiation among different RHOF treatments normalized to preirradiation

4.1.4 RHOF vs. MMF

Fig. 56 shows the comparison between the untreated MMF and untreated RHOF fibers. It is clear that under irradiation, untreated RHOF performed better than the untreated MMF fibers. The maximum RIA measured in untreated RHOF was approximately 8 dB while the RIA in the untreated MMF fibers reached a maximum at about 28 dB. As discussed previously, dopants in the standard fibers were responsible for the large RIA in the untreated MMF fibers. The RHOF fibers are technically dopant-free,
and therefore performed better under gamma irradiation. Furthermore, the open voids in the RHOF, which account for 32% of the fiber volume, resulted in the large surface area, which in turn, is exposed to the ambient atmosphere. This made the RHOF hydroxyl (OH) rich fibers [52]. It has been shown that OH rich fibers are more resistant to irradiation [113]. It should be noted that nitrogen is inherently present in the RHOF fiber as a result of the fabrication process. Moreover, some of the closed voids in the fiber could act as a nitrogen reservoir. It has been reported that the presence of nitrogen in optical fibers improves their irradiation resistance [114]. Therefore, residual nitrogen present within the fiber matrix or the continuous provision of nitrogen to the fiber matrix from the nitrogen reservoirs could be responsible for RHOF’s radiation resistance.

Fig. 56 Comparison between RHOF and MMF fibers normalized to preirradiation

Fig. 57 shows the comparison between the thermally annealed MMF and RHOF fibers. The improvement of radiation resistance in the annealed MMFs and the degradation of radiation resistance in the annealed RHOFs brought the performance of the two fiber types to a similar level. Both fibers showed recovery behavior during irradiation. This gives some insight on the recovery during irradiation mechanism. It is independent of the fiber type and composition.
Fig. 57 Comparison between thermally annealed MMF and RHOF fibers normalized to preirradiation

4.1.5 RHOF vs. PSCF

The commercial radiation resistant, pure silica core fiber (PSCF) was exposed along with the other fiber samples to serve as a reference. The results in Fig. 58 showed that RHOFs are not completely radiation resistant. However, we believe that there is room for improvement of the RHOFs radiation resistance. The material’s type and purity used in the preform as well as drawing conditions which include speed, temperature and tension can influence the RIA in optical fibers as reported in the literature [115]. The use of relatively impure powder mixtures in the making of RHOF fibers introduces high levels of impurities. Moreover, the RHOF drawing conditions have not been optimized yet. Thus, future improvement of the RHOF performance is anticipated.
4.1.6 RHOF Recovery Behavior

Due to the low irradiation dose and the relatively high power of the measurement signal, it was not possible to accurately determine the recovery behavior of the fibers under investigation. However, RHOF fiber recovery behavior was investigated during the high irradiation dose test.

4.2 High Dose Test Results

To further understand the behavior of RHOFs under gamma irradiation, a high dose irradiation test was performed. Hereafter, the results are labeled according to the following color scheme: SMF (blue), MMF (red), PSCF (green), RHOF “as made” (yellow), RHOF “methanol washed” (magenta), to aid the reader in interpretation and comparison. Although the exact reason is not known for sure, the reason that the “as made” and “methanol washed” RHOFs have different transmitted optical power could be related to the splice induced loss as discussed above and the residual liquid methanol inside the fiber’s holes. Furthermore, RIL and/or Cerenkov emission were not detected by the OSA in any of the fibers. This could be due to the short length of the fibers being irradiated.
Fig. 59 demonstrates the RIA during the entire duration of the experiment. It also shows the recovery behavior of the fiber after the irradiation ceased. The recovery time of RHOFs was less than the other fibers by approximately 10 hours. Similar to the low dose test, “0” time represents the fiber attenuation state before irradiation. Linear behavior, at dose values < 10 kGy(Si), was observed in all fiber samples.

![Graph showing RIA over time for different fiber types](image)

Fig. 59 RIA at 1520-1570 nm range of the sample fibers subjected to high dose irradiation

Since MMFs carry larger optical power than SMFs, the RIA in MMF was less than in SMF due to photobleaching. In general, the RHOF samples have a lower RIA compared to the standard fibers. The RIA in the 1550 nm window in the RHOF could be linked to the OH absorption band tail. However, for a reason as yet unknown, the methanol washed RHOF sample showed superior resistance to radiation compared to the “as made” RHOF fiber. Therefore, it is possible that some other mechanisms that contribute to the observed RIA in the RHOF fibers. Some of the possible mechanisms that could exist, which were proposed for RIA in photonic band gap fibers [87], are fabrication related defects, and the influence of the confined gases within the RHOF microstructure. The material type and purity used in the preform as well as drawing conditions which include speed, temperature and tension can influence the RIA in optical fibers as reported in the literature [115]. Due to the nature of the RHOF structure, not all the optical signal propagating through the fiber is confined in the core region. This has been clearly shown in the use of RHOF fibers as gas sensors [116]. The evanescent field of the optical signal interacts
with gases inside the holes in the RHOF fiber and can clearly be seen as absorption peaks in the transmitted optical signal. Therefore, defects in the bulk portion of the cladding could significantly influence the radiation sensitivity of the fiber. The use of relatively impure powder mixtures in the fabrication process of the RHOF introduces high levels of impurities which could be associated with extrinsic absorption. Moreover, the large number of holes within the fiber structure provides large surface area which in turn introduces large numbers of surface defects to the structure. There is little known about the nature of these surface defects at this point, but we assume that they originate during bubble formation and/or fiber drawing. The gases confined within the holes could also play a role in the RIA in RHOFs. The ionized gases could interact with the surface generating light absorbing species. The “methanol washed” results support the existence of other mechanisms contributing significantly to the RIA as discussed above and also implies the possibility of employing post-fabrication treatment processes to improve the radiation resistance of the RHOF fibers. Post-fabrication treatment of the photonic band gap fiber with hydrogen gas has been reported to improve the fiber’s resistance to radiation [117]. Determining the exact mechanisms responsible for the RIA in RHOF fibers and improving the radiation resistance further will be the subject of future investigation.

5. Conclusions

The newly developed RHOFs offer advantages over other types of MOFs as they are inexpensive and easy-to-make when compared to the high cost of MOFs. They also have unique characteristics since they contain open and closed holes. The open holes contain ambient air under normal conditions and the closed holes contain residual gases from the fabrication process at certain pressure.

This work has studied the effect of gamma irradiation on RHOF fibers by comparing their performance to that of standard SMF, MMF and commercial radiation resistant fibers (PSCF). The effect of thermal treatment (300°C for 4 hours) was also investigated for both RHOF and MMF fiber types. The following can be deduced from the obtained results:

- Generally, RHOFs used in this work are resistant to gamma radiation
- Optimization of RHOF fabrication can increase the gamma radiation resistance of RHOF and possibly exceeds that of the PSCFs.
- Using different treatments, the gamma radiation resistance of RHOF can be increased or decreased
• Post irradiation recovery time of RHOF is relatively shorter compared to the other fibers used in this work.

There seems to be competing mechanisms at work during the irradiation of these fibers, which affect their performance. The cyclic nature of the performance during irradiation confirms these competing mechanisms and is consistent with results reported elsewhere. However, this phenomenon has not been discussed before and remains to be understood completely. The RIA at the 1550 nm window in the RHOF fibers could be attributed to the OH absorption band tail. However, the results indicate the existence of other mechanisms responsible for RIA such as bulk and surface defects which are related to the fabrication process and the influence of the gases confined within the RHOF microstructure. The material’s type and purity used in the preform as well as drawing conditions which include speed, temperature and tension can influence the RIA in optical fibers as reported in the literature [115]. The use of relatively impure powder mixtures in the making of RHOF fibers introduces high levels of impurities. The RHOF drawing conditions have not been optimized yet. Thus, future improvement of the RHOF performance is anticipated.

Gamma radiation resistance of RHOFs can be attributed to the lack of dopants and also possibly the inherent OH and nitrogen content. The behavior of thermally annealed RHOF is in favor of this hypothesis.

6. Future Work

The future work of this endeavor has four main areas. First and foremost is MOF’s handling and interfacing. The difficulty of cleaving MOFs and splicing them has limited their use and will continue to do so until practical and effective cleaving methods and splicing techniques are developed. One possible alternative to mechanical cleaving which goes along the lines of the focused ion beam micromachining discussed above is to utilize highly anisotropic etch process such as deep reactive ion etching technique. This etching process alternates repeatedly between plasma etching and the deposition of a chemically inert passivation layer. Each step lasts for several seconds. The plasma contains some ions, which attack the surface from a nearly vertical direction creating a small trench. The passivation layer protects the sidewalls of the trench from further chemical attack and prevents further etching. However, during the etching step, the directional ions that bombard the material attack the passivation layer at the bottom of the trench (but not along the sides). They collide with it and sputter it off, exposing the material to the chemical etchant. These etch/deposit steps are repeated many times over resulting in deep trench
with vertical walls. The passivation layer would protect the fiber’s microstructures from damage during the micromachining process. The passivation layer can be easily and effectively removed by exposing the micromachined surface to oxygen plasma. As for fiber alignment before splicing a new image processing system that would be capable of aligning MOF cores should be developed. Furthermore, one possible solution to prevent the holes in MOFs from collapsing during fusion splicing is to fill them with degradable material that would act as a support (for very short period of time) before the fusion process degrade it.

The second area of the future work is related to the optimization of the RHOF fabrication process. The impurity levels and the sources of defects should be reduced in order to minimize absorption within the fiber’s material. More specifically, parameters such as the material type and its purity to be used in the preform as well as drawing conditions which include speed, temperature and tension can influence should be considered. Moreover, different post fabrication treatments (chemical and physical) should be investigated for possible improvement of the fiber after fabrication.

The third area is related to studying the behavior of RHOF’s under neutron irradiation. Contrary to ionization (by electron, photon, proton, or α-particles) where the effects are typically temporary, atomic displacement by neutrons is a permanent damage. Because the neutron has a high penetrating power, no charge, and heavy mass, it produces damage only by energetic interaction with nuclei which results in a significant change in the materials properties. Neutrons can cause defects in the atomic arrangement within the material. Moreover, neutron interaction with nuclei can also result in nuclear transmutations which can have severe impact on the fiber’s performance.

The fourth area and most exciting aspect is relating to integrating sensing elements within RHOFs. Based on the current understanding of the RHOF behavior in ionizing radiation environments, it is possible to develop a fiber optic radiation sensing system based on scintillation light from scintillator phosphor embedded within the RHOF microstructure. The holes in the RHOF can be coated with a thin film of scintillation phosphors used in the detection of UV, X-ray and gamma radiation enabling multiradiation detection capability in a single sensing element. Different scintillators with different scintillation light wavelengths could be deposited at different locations in the fiber to add directional capability to the proposed sensor. The scintillation light, generated as a result of the interaction of the ionizing radiation with the phosphors material, will collect inside the fiber core and will be guided to the photo detector. The sensor’s signal demodulation system electronics and computer algorithms convert the optical signal to a radioactive dose or dose rate. The efficiency of the sensor can be adjusted by varying the RHOF length and the amount of the scintillation phosphor embedded within the holes as
well as the structure of the original RHOF fiber. Some possible scintillation materials could include Yttrium Aluminate: Cerium (Y₃Al₅O₁₂:Ce) or Silver activated Zinc Sulfide (ZnS(Ag)) phosphors; both emit in the visible range when irradiated with ionizing radiation. Quantum dots such as Cadmium Selenide Zinc Sulfide Core Shell (CdSe/ZnS) which emit in the visible range or Lead-Sulfide (PbS) core quantum dots which emit in the infrared range can also be utilized. Potential applications of this sensing system could be for on-line flexible dose rate distribution monitoring in (1) radiation facilities like nuclear power plants, accelerator facilities, and radioactive waste storage sites, (2) environmental protection such as monitoring radioactive fallout from atomic weapons testing, nuclear accidents, and other intrusions of radioactive materials, as well as (3) clinical nuclear medicine dosimetry.
References


Appendixes

Appendix A: Atlas of Band Gaps

Gap map of square lattice of air holes in dielectric ($\varepsilon = 11.4$) [50], Courtesy of Princeton University Press, Used with permission

Gap map of triangular lattice of dielectric pillars ($\varepsilon = 11.4$) [50], Courtesy of Princeton University Press, Used with permission
Gap map of triangular lattice of air holes in dielectric ($\varepsilon = 11.4$) [50], Courtesy of Princeton University Press, Used with permission.

Gap map of honeycomb lattice of dielectric pillars ($\varepsilon = 11.4$) [50], Courtesy of Princeton University Press, Used with permission.
Appendix B: MATLAB Code for Spectral Data Acquisition

Main function

```matlab
function DataAq(NumberOfSamples)

i = 1;
DirName = fullfile(pwd, 'Data', num2str(i));
OverwtFlag = 0;
while(exist(DirName, 'file') == 7)
    disp(' ');
    disp([DirName ' exist!']);
    Decision = input(['Do you want to overwrite it? (Y/N) ', 's']);
    if strcmp(Decision, 'y') || strcmp(Decision, 'Y')
        OverwtFlag = 1;
        break;
    end
    i = i + 1;
    DirName = fullfile(pwd, 'Data', num2str(i));
end

FileName = fullfile(DirName, 'Nuk_Spec'.mat);

for (j = 1:NumberOfSamples)
    FileName = fullfile(DirName, num2str(j).mat');
    DataLabel = input(['Enter Fiber label: ', 's']);
    Disc = DataLabel;
    if isempty(DataLabel)
        break;
    end
```

```matlab
end
end
```
end
spec = getFullSpectrum(1);
Div = 0.0025;
wavelength = [0:length(spec)-1]*Div +1520;
MEAN = mean(spec);
figure(1);
subplot(2,1,1, 'replace');
plot(wavelength,spec); title(['fiber #' num2str(j)]);
xlabel('Wavelength(nm)','FontSize',14,'FontWeight','bold');
ylabel('Power Intensity(dB)','FontSize',14,'FontWeight','bold');
grid on
subplot(2,1,2); hold on
plot(j,MEAN,'go--','MarkerFaceColor','g','MarkerSize',5);
xlabel('Sample Sequence','FontSize',14,'FontWeight','bold');
ylabel('Mean Power Intensity(dB)','FontSize',14,'FontWeight','bold');
grid on
save(FileName,'spec','MEAN','Disc');
disp(['Sample No.',num2str(j),' of ' num2str(NumberOfSamples)]);
clear spec;
end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
Communication function
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% set the IP address: 10.0.0.10
% and Subnet mask: 255.0.0.0 (this should be filled automatically when the IP address is set)

function spec = getFullSpectrum(Channel)

t = tcpip('10.0.0.127', 3000, ...
    'InputBufferSize', 40100, ...
    'ByteOrder', 'littleEndian');
fopen(t);

fprintf(t, ['ACQ; DUT' num2str(Channel) ':XPO?']);

fread(t, 10, 'uchar');
Header = fread(t, 7, 'int32');
spec = fread(t, 20000, 'int16')/100;
fclose(t);
delete(t);
clear t;