



**GAMMA VERSUS NEUTRON RADIATION
EFFECTS ON YTTERBIUM-DOPED
OPTICAL FIBERS**

THESIS

Olivia M. Borman, Captain, USAF
AFIT-ENP-MS-16-M-057

**DEPARTMENT OF THE AIR FORCE
AIR UNIVERSITY**

AIR FORCE INSTITUTE OF TECHNOLOGY

Wright-Patterson Air Force Base, Ohio

DISTRIBUTION STATEMENT A
APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED

The views expressed in this document are those of the author and do not reflect the official policy or position of the United States Air Force, the United States Department of Defense or the United States Government. This material is declared a work of the U.S. Government and is not subject to copyright protection in the United States.

AFIT-ENP-MS-16-M-057

GAMMA VERSUS NEUTRON RADIATION EFFECTS ON
YTTERBIUM-DOPED OPTICAL FIBERS

THESIS

Presented to the Faculty
Department of Engineering Physics
Graduate School of Engineering and Management
Air Force Institute of Technology
Air University
Air Education and Training Command
in Partial Fulfillment of the Requirements for the
Degree of Master of Science in Nuclear Engineering

Olivia M. Borman, BSEE, BA
Captain, USAF

March 2016

DISTRIBUTION STATEMENT A
APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED

AFIT-ENP-MS-16-M-057

GAMMA VERSUS NEUTRON RADIATION EFFECTS ON
YTTERBIUM-DOPED OPTICAL FIBERS

THESIS

Olivia M. Borman, BSEE, BA
Captain, USAF

Committee Membership:

Lt Col Briana J. Singleton, Ph.D.
Chair

Dr. John W. McClory
Member

Abstract

Multimode ytterbium-doped optical fibers (YDFs) are increasingly utilized in military applications involving fiber lasers and amplifiers. YDFs were irradiated with three different radiation sources (neutron, gamma, and mixed gamma/neutron) in order to determine the independent effects that gamma and neutron radiation have on the fibers. The transmission spectra of the fibers were measured during each irradiation and the spectral shapes and attenuation were compared at similar doses. Comparisons of the spectra showed that gamma radiation results in increased attenuation over the 550-975 nm wavelengths. Fast neutrons were found to contribute to increased attenuation near 500 nm. Neutron radiation also caused up to twice the amount of radiation induced absorption that gamma radiation did over all wavelengths in the spectrum measured from 500-1100 nm at the same dose. The spectrum from 980-1100 nm was the same shape between the fast neutron and gamma-only irradiations. This indicates that a ^{60}Co source could potentially be used to approximate the effects on the operating range of YDFs resulting from fast neutrons.

A recovery prediction model was also applied and evaluated against actual recovery data. It was found to be unreliable as an accurate predictor of the initial (~ 15 minutes) recovery of YDFs exposed to a dose rate of 65 krad(Si)/hr neutron and 9 Mrad(Si)/hr gamma. By adjusting one parameter in the model to account for the initial faster rate of recovery, the model was able to closely approximate the recovery of the fibers after longer irradiations out to longer recovery periods.

AFIT-ENP-MS-16-M-057

To my parents, for the encouragement and support they've always given me.

Acknowledgements

I would like to thank my advisor, Lt Col Briana Singleton, for setting me up for success on this project and for her guidance and support throughout. Thanks to Dr. John McClory for his valuable input and support. I would also like to thank the scientists and staff at the Fast Burst Reactor Facility and Ohio State University Nuclear Reactor Lab for their assistance, accommodation, and expertise. Eric Taylor is owed thanks for his assistance with last-minute logistics. Finally, thank you to my classmates for their companionship during the long hours spent “thesising” in building 470. And, most of all, thank you to my husband, for his love and support throughout the entire degree program.

Olivia M. Borman

Table of Contents

	Page
Abstract	iv
Acknowledgements	vi
List of Figures	ix
List of Tables	xi
1. Introduction	1
1.1 Motivation	1
1.2 Background	2
1.3 Research Objectives	3
1.4 Previous Studies	3
2. Theory	5
2.1 Optical Fiber Overview	5
Composition and Defects	6
Fiber Types	7
2.2 Ytterbium-Doped Fiber Amplifiers	9
2.3 Radiation Effects in Silica Optical Fibers	11
Atomic Level Effects	12
Device Level Effects	15
Neutron vs. Gamma Effects	15
2.4 Radiation Sensitivity of RE-doped Fibers	16
Summary	17
3. Methodology	18
3.1 Experiments	18
Fast Burst Reactor	20
Ohio State University Research Reactor	21
Ohio State University ⁶⁰ Co Source	21
3.2 Research Approach	22
Fiber Preparation	22
Fiber Characterization and Measurements	24
Determining Defect Contributions	25
Neutron Dose Calculations	29
Growth and Recovery Data Modeling	31

	Page
4. Results and Analysis	34
Chapter Overview	34
OSURR Irradiation	36
FBR Irradiation	44
^{60}Co Irradiation	47
Neutron versus Gamma Comparisons	52
Recovery Analysis	58
Recovery Prediction Model	62
5. Conclusions	69
Neutron versus Gamma Effects	69
Recovery Prediction Model	71
Future Work and Recommendations	71
Bibliography	72

List of Figures

Figure	Page
1	Amorphous silica. 7
2	Various point defects of amorphous silica. 7
3	Cross sections of fibers. 9
4	Energy level structure for Yb^{3+} 11
5	Absorption and emission cross-sections for Yb in SiO_2 12
6	Photon interactions with matter. 13
7	Diagram of relevant radiation damage processes for SiO_2 14
8	Setup for white light source. 19
9	OSURR Rigs. 22
10	^{60}Co elevator. 23
11	Defect deconstruction methodology. 27
12	Watt fission spectrum. 30
13	Power-law fit example. 33
14	OSURR spectra comparison. 37
15	Plot of OSURR energy shift of NBOHC. 38
16	Comparison of 10 μm fiber spectra irradiated with and without the cadmium shield in the OSURR. 39
17	OSURR defect deconvolution. 40
18	OSURR RIA and defect growth comparison. 41
19	RIA at defect centers for each OSURR experiment. 43
20	RIAs as a function of wavelength over select doses. 45
21	Defect contribution for FBR irradiation. 46
22	FBR RIA and defect growth comparisons. 46

Figure		Page
23	RIA at 1064 nm of fibers irradiated multiple times.	48
24	^{60}Co RIA and defect growth comparisons.	49
25	^{60}Co spectra deconvolution.	50
26	Deconvolution of ^{60}Co 1.56 Mrad(Si) spectrum with 5 NBOHCs.	51
27	^{60}Co versus FBR spectra comparison.	53
28	OSURR versus FBR spectra comparison.	55
29	^{60}Co versus OSURR spectra comparison.	57
30	Plot of artificial gamma spectrum.	58
31	Recovery of YDFs.	59
32	Relationship between degradation and recovery.	62
33	Prediction model versus actual recovery data for ^{60}Co irradiation.	65
34	Prediction model versus actual recovery data for FBR irradiation.	66
35	Prediction model versus actual recovery data for OSURR irradiation with the cadmium box.	67
36	Prediction model versus actual recovery data for OSURR irradiation without the cadmium box.	68

List of Tables

Table		Page
1	Equipment List for Experiments	19
2	List of experiments	35
3	Fluence and dose totals for three OSURR experiments.	36
4	Characteristics of absorption bands used for the decomposition of the RIA curves from the OSURR irradiations.....	39
5	Fluences and dose totals for 5 hour FBR irradiation.	44
6	Characteristics of absorption bands used for the decomposition of the RIA curves from the FBR irradiations.....	46
7	Characteristics of absorption bands used for the decomposition of the RIA curves from the ^{60}Co irradiations.....	50
8	Five NBOHCs contributing to absorption in Yb-doped fibers.	51
9	Percentage of YDF recovery from initial losses at select times post irradiation in the OSURR.	60
10	FBR Rates of degradation and recovery.	60
11	Rates of degradation and recovery for 20 μm YDF irradiated with ^{60}Co	61

GAMMA VERSUS NEUTRON RADIATION EFFECTS ON YTTERBIUM-DOPED OPTICAL FIBERS

1. Introduction

1.1 Motivation

Fiber optic cables are highly desirable for use in military applications due to their immunity to electromagnetic interference, relative security from eavesdropping, ability to span long distances without repeaters, low cable weight, ruggedness, and ability to transmit multiple signal types [1]. These qualities make optical fibers preferable for use over electrical cables, however, their increased sensitivity to radiation mandates testing and characterization be performed prior to their use in a nuclear environment.

Ytterbium (Yb)-doped optical fibers (YDFs) are of special interest to the military for use in fiber lasers and amplifiers. Due to the potential for exposure to a low or high flux of neutron and gamma radiation in military operations, it is important to characterize changes in the operation of Yb-doped fibers during and following gamma and neutron irradiation. Discerning any differences between neutron and gamma radiation effects provides valuable information on the feasibility of using optical fibers, and their expected performance, in nuclear operations. Demonstrating a correlation between gamma and neutron effects at similar total doses or dose rates may also allow future testing to be done using only a gamma source, which is cheaper and simpler than operating a reactor. Establishing a correlation between gamma and fast neutron radiation specifically has special implications as fast burst reactors capable of simulating the radiation output of nuclear weapons are decommissioned.

1.2 Background

Low loss optical fibers have been around since the 1970s, but it wasn't until the 1980s that RE-doping of optical fibers was demonstrated, and in 1987 the first fiber amplifiers were demonstrated [2] [3]. Fibers used in amplifiers are manufactured with cores that contain small amounts of rare-earth (RE) elements, called dopants, which can be stimulated to emit light. Amplifiers work in specific spectral bands, which are determined by the type of dopant in the fiber [2]. Erbium-doped fiber amplifiers have been the most extensively studied, however, the use of ytterbium as the RE dopant has gained in popularity due to benefits of its energy structure over erbium. The focus of this thesis will be Yb-doped fibers, which operate as fiber amplifiers/lasers at wavelengths from 1030 to 1120 nm. As a result there is special interest in the effect that radiation has on the fiber's transmission in that wavelength range.

Yb-doped fibers, as well as other RE-doped fibers, have demonstrated greater sensitivity to gamma and mixed gamma/neutron radiation than un-doped fibers. This is due to impurities in the rare-earth elements, as well as smaller amounts of other dopants included (e.g. Al, Ge, P) to optimize the fibers for amplifier or laser applications [4]. When radiation interacts with the materials in the fiber, defects such as color centers can be created. Color centers are point defects that result in absorption of light, and therefore degrade the power of the signal that is being transmitted. This overall effect is also known as radiation-induced attenuation (RIA). Color centers can be temporary or permanent. Studies have shown that the color centers may anneal within minutes after irradiation, or can incur permanent damage to fiber operation. The overall damage is dependent on total dose rather than dose rate [5] [6].

Past research has been done to characterize the degradation of various types of optical fibers as a result of gamma, mixed gamma/neutron, proton, and neutron

only irradiation over a wide range of doses and dose rates. Radiation effects on optical fibers have been studied for many nuclear power plant applications, as well as space and fission reactor and fusion environments, at combined total dose and dose rates non-representative of nuclear weapon effects [7]. Recent research has been done by Singleton to characterize the effects of radiation on YDFs and ytterbium doped fiber amplifiers (YDFAs) at doses and dose rates representative of nuclear weapon output [6].

1.3 Research Objectives

The research had the goal of evaluating the effects of gamma only, neutron only, and mixed gamma/neutron radiation on passive YDFs. The data was collected by irradiating fibers with a ^{60}Co source and in reactor environments with differing fluxes and spectrums of neutrons. The data from the experiments was then used to discern whether there is a significant difference in damage to YDFs due to gamma versus neutron radiation. The other objective was to collect recovery data and determine the factors that contribute to the recovery speed of the fiber. A prediction model was also run and compared to the actual recovery data.

1.4 Previous Studies

Recent studies have shown that fibers irradiated with high energy (20 MeV and 180 MeV) neutrons only degraded weakly [5]. The flux density of the neutrons during this experiment only ranged from 0.3 to 5×10^5 n/cm²/s. There have also been at least three studies done to directly compare the effects of gamma and neutron irradiation on phosphorous (P), germanium (Ge), and fluorine (F) doped fibers. Two studies used 14 MeV neutrons and gammas from a ^{60}Co source. In the first study the comparison revealed that before a certain total fluence of neutrons is received, the same dose of

gamma irradiation causes 2.5 to 4 times higher loss, however, after a certain fluence is reached the loss is roughly the same, and at very high fluences, neutrons will cause more damage than gammas of the same dose. Fibers measured included one RE-doped fiber and multiple silica based fibers. Only two wavelengths of light, however, were used for this study at 830 and 1303 nm [8]. The second study showed that gamma and neutron irradiations lead to the same defect generation in Ge and F-doped silica based optical fibers. It also determined that losses from neutron irradiation could be either higher or lower than losses from gamma radiation at the same dose. This result was deemed to be due to measurement uncertainties [9]. The third study examined loss spectra of radiation-hard fluorine (F)-doped optical fiber irradiated at neutron fluences of 10^{17} n/cm², 10^{16} n/cm², and 10^{15} n/cm², and gamma-ray doses of 1 MGy, 5.5 MGy, and 3 MGy. The results indicated that neutrons mixed with gammas contributed to an increase in loss over gamma-only irradiation at some wavelengths in the visible spectrum [10].

2. Theory

The chapter includes information about the composition of Yb-doped optical fiber, the operation and performance of Yb-doped fiber amplifiers (YDFAs), and defects intrinsic in silica optical fiber and those introduced by irradiation. Previous results of gamma and neutron irradiations on various types of optical fiber are also included as part of the theory on radiation effects.

2.1 Optical Fiber Overview

Fiber optic cables operate by transmitting information signals in the form of light. The individual optical fibers are typically made of silica glass (SiO_2), and at the basic level consist of a glass core and cladding. The core is the inner portion of the fiber that guides the light, while the cladding surrounds the core. The cladding has a lower refractive index than the core and a higher refractive index than air, which is what enables the phenomenon of total internal reflection to occur [2]. As a result of total internal reflection, optical fibers are able to transmit light over long distances without significant signal loss. The relationship is given by

$$\begin{aligned} n_{clad} &< n_{core} \\ \theta_c &= \sin^{-1} \frac{n_{clad}}{n_{core}} \end{aligned} \tag{1}$$

where θ_c is the critical angle, n_{clad} is the refractive index of the cladding, and n_{core} is the refractive index of the fiber core. Light entering the fiber at an angle greater than or equal to θ_c will experience total internal reflection.

Fiber optic technology as a means of long distance communication was thought to be non-viable for a time until it was discovered that low loss could be achieved by reducing the number of impurities and defects in the glass fiber material. Ordinary

glass absorbs too much light for effective use in optical fibers due to the many impurities it contains. The critical impurities that absorb light are iron, copper, cobalt, nickel, manganese, and chromium. These absorb light from about 600 to 1600 nm and must be reduced to one part per billion. Modern fibers use fused silica, or an extremely pure form of SiO_2 , in order to make extremely clear glass. Pure SiO_2 has virtually no absorption wavelengths from the visible to about 1600 nm in the near infrared portion of the spectrum. Even with pure SiO_2 , however, some defects can be introduced into the fiber during the manufacturing procedure and the treatments to the fiber that occur later [2].

Composition and Defects.

Optical fiber cores are typically made from pure amorphous silica (a-SiO_2), shown in Figure 1, which can be doped with RE elements such as Yb. The amorphous nature of SiO_2 means that it lacks periodicity, extended symmetry, or any long range order. The ideal and most generally accepted structural model for a-SiO_2 is the continuous random network (CRN). In this model there is short range order, with each Si atom at the center of a regular tetrahedron and four O atoms at the vertexes. Each O atom binds to two Si atoms and bridges the tetrahedra. The angle, α , may vary, resulting in a distribution of SiO_4 tetrahedra at random orientations [11].

Pre-existing defects in the fiber inherent to the material and resulting from the manufacturing and treatment process are called precursors. These defects can be classified as intrinsic and extrinsic. Intrinsic defects are those that are due to irregular arrangements of the Si and O atoms in SiO_2 . Specific intrinsic defects in silica include the neutral oxygen vacancy ($\text{O}\equiv\text{Si-Si}\equiv\text{O}$), the peroxy bridge ($\text{O}\equiv\text{Si-O-O-Si}\equiv\text{O}$), the non-bridging oxygen hole center (NBOHC, $\text{O}\equiv\text{Si-O}^*$), the tricoordinated silicon (E' center, $\text{O}\equiv\text{Si}^*$), and the twofold coordinated silicon ($\text{O}=\text{Si}^{**}$) depicted in Figure 2.

Extrinsic defects are impurities, or atoms differing from Si or O, that exist in the SiO_2 . These impurities are usually introduced as a result of the manufacturing process [11].

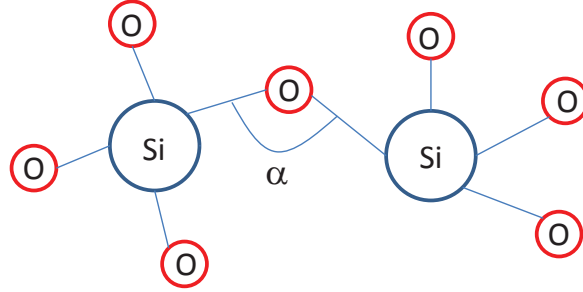


Figure 1. Representation of the basic constituent of the CRN structure of amorphous silica.

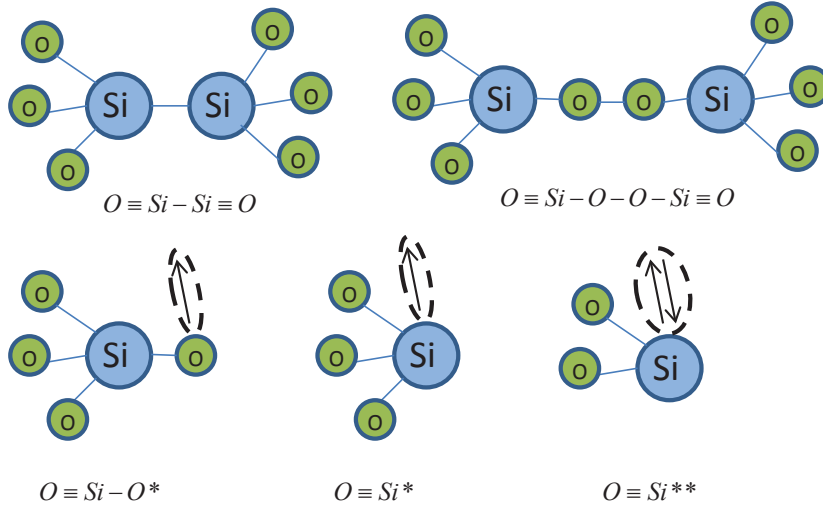


Figure 2. Various point defects of amorphous silica. Arrows indicate electron spins in the orbitals. Recreated from [11].

Fiber Types.

Fibers can be manufactured with various elements incorporated into the core or cladding depending on the fiber's intended use. Uses for optical fiber include communications, replacing copper wiring in various systems, and specialty applications such

as fiber amplifiers and lasers, to name two. Typical cross sections for two different types of optical fibers are shown in Figure 3. Communications fibers have round core and cladding cross sections and a single cladding, while most RE-doped fibers have a non-round cladding cross section, as well as a second outer cladding. There are also different modes of fiber that can be used: single mode and multimode. Modes describe the distribution of light energy across the fiber [2].

A single mode fiber requires that the core be small enough to restrict signal transmission to a single mode, and is typically used in telecommunications. The single mode of transmission avoids dispersion, noise, and other effects caused by multimode transmission. Single mode fiber can carry signals at the highest speed, and so are ideal for long-distance applications [2].

Multimode fibers have a larger core that can carry multiple signal modes and are used for communication over short distances, such as within a building or an electronic system to replace electrical wiring or cabling. For the purposes of this study, only multimode fibers will be irradiated.

RE-doped fibers are a kind of specialty fiber used in fiber amplifiers and fiber lasers. Light is pumped into the RE-doped fiber at a wavelength adequate to excite the RE atom to a higher energy level. The RE atom will stay at the higher energy level unless the energy level is short lived (about 10^{-8} or 10^{-9} s lifetime [12]), in which case the atom will relax to a lower, longer lived (metastable) energy level. The atom will sit at the metastable energy level with the extra energy for a long time, relative to a 10 ns atomic standard, waiting to be stimulated. A second light source (i.e. signal light) can then stimulate the atom to de-excite and release the energy in the form of a photon at the exact same wavelength and in the same direction as the photon that stimulated the emission, resulting in amplification of the light. If the atom is not stimulated it will eventually undergo spontaneous emission and release a photon

that is not necessarily at the same wavelength or going in the same direction as the signal photons. The most common RE dopant up until recently has been erbium due to its popular amplification wavelengths (1530-1620 nm). Ytterbium has gained in popularity due to the benefits of its energy structure (described in greater detail in section 2.2). It amplifies light from around 1060-1120 nm. Some other popular RE elements and their amplification wavelengths are praseodymium (1310 nm), thulium (1450-1500 nm), and neodymium (1047-1062 nm) [2].

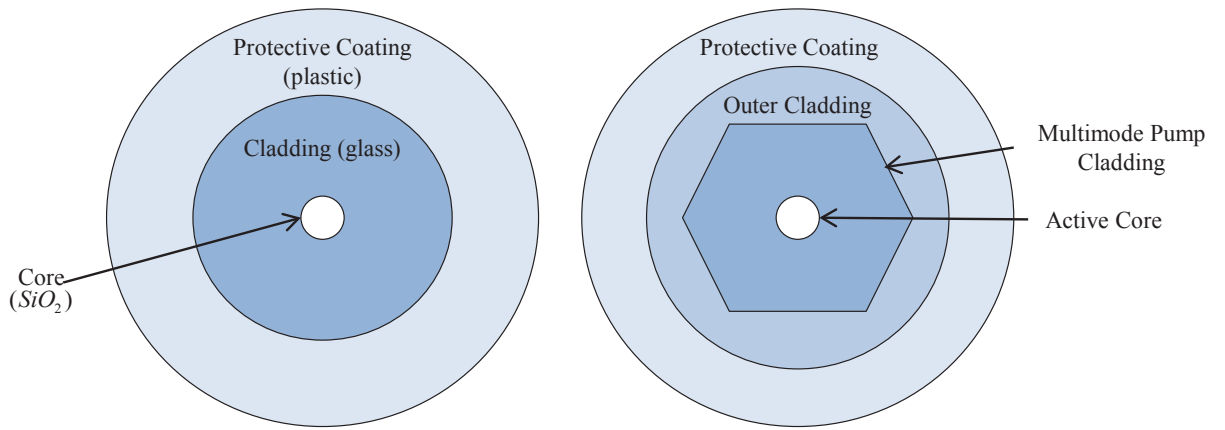


Figure 3. Cross section for a single clad fiber on the left. Cross section for a double clad doped fiber on right.

2.2 Ytterbium-Doped Fiber Amplifiers

In order to create a fiber amplifier, the optical fiber must be doped with a RE element that can be stimulated to emit light. An optical fiber doped with Yb or another RE element will amplify a signal if the pump light is at a wavelength that corresponds to strong absorption and the signal corresponds to emission in the element. Therefore, an important parameter for selecting the RE element to be used in the amplifier is the strength and energy of its absorption and fluorescence spectrum [3]. The absorption spectrum holds information about the location of possible pump wavelengths that will excite the RE ions to higher energy levels.

Yb has become a popular optical fiber dopant for use in fiber amplifiers due to its ability to provide amplification over a broad range of wavelengths from about 975 to 1200 nm. In Yb-doped amplifiers trivalent Yb ions (Yb^{3+}) are utilized. The energy structure of the ions gives it benefits over the widely used erbium-doped fiber due to the absence of excited state absorption and concentration quenching by interionic energy transfer. The use of Yb also allows for higher doping levels in the fiber, which leads to high gain in a short length of fiber [13].

In a YDF, the relevant pump wavelengths range from about 860-1064 nm, and the two relevant states for the Yb^{3+} atoms are the $^2F_{7/2}$ ground state and the $^2F_{5/2}$ excited state [13]. The Stark level manifolds each consist of multiple sublevels having slightly different energies. The ground state consists of four sublevels, and the excited state consists of three sublevels, as shown in Figure 4. Due to the absence of other energy levels, excited state absorption of pump or signal light, or concentration quenching by ion-ion energy transfer processes, does not occur as it does in other RE-doped fibers [13].

Pump light is injected into the fiber cladding and absorbed by the Yb^{3+} ions. Yb^{3+} only has a ground state and a metastable excited state, so ions are excited into the metastable state and hold their energy there from 700-1400 μs [14]. The signal light then deexcites the ions to a lower energy level and stimulates the emission of a photon. The stimulated emission always goes into the same mode as the light which causes it, amplifying that light [2].

The absorption maxima at 975 and 909 nm are shown in Figure 5. The pump wavelength that is commonly used is 975 nm, which pumps ions from the ground state to level 2. The intense absorption peak at 975 nm is a result of the transition between the lowest Stark levels of the two manifolds. The upper state population is limited to 50% due to the equal absorption and emission cross sections at that wavelength, at

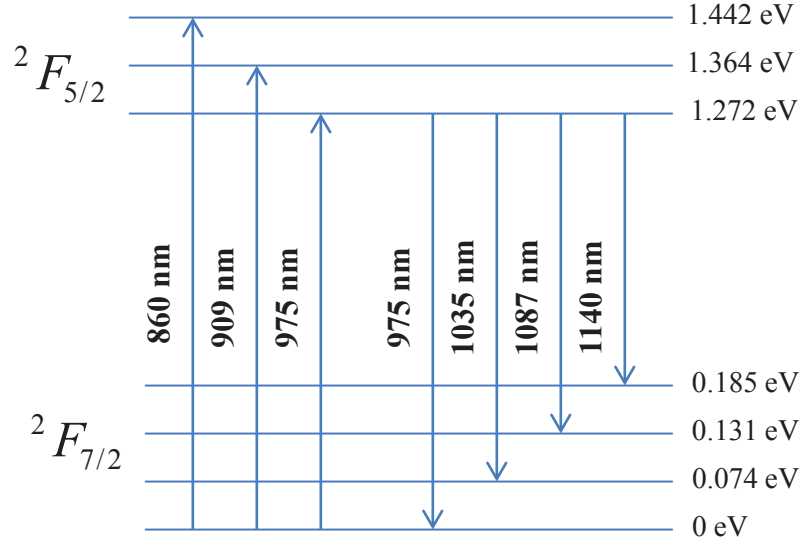


Figure 4. Energy level structure for Yb^{3+} [15].

which point gain saturation occurs. At this wavelength the absorption and emission compensate each other. At 909 nm, however, there is little emission, so the pump light can be absorbed even above 90% excitation [13].

In addition to stimulated emission, there is also spontaneous emission, which can be amplified, resulting in higher noise in the fiber amplifier. If the ion relaxes to the ground state before the signal light stimulates it, the photon emitted will not be in phase with signal photons. The spontaneous photon can also interact with excited ions and stimulate their emission, resulting in amplification of the spontaneous emission. This is known as amplified spontaneous emission (ASE).

2.3 Radiation Effects in Silica Optical Fibers

Effects of radiation on optical fibers can be analyzed at the atomic and device levels. Atomic level defects are generally created from atomic displacements (knock-on damage) or ionization processes. Knock-on damage creates vacancies and intersti-

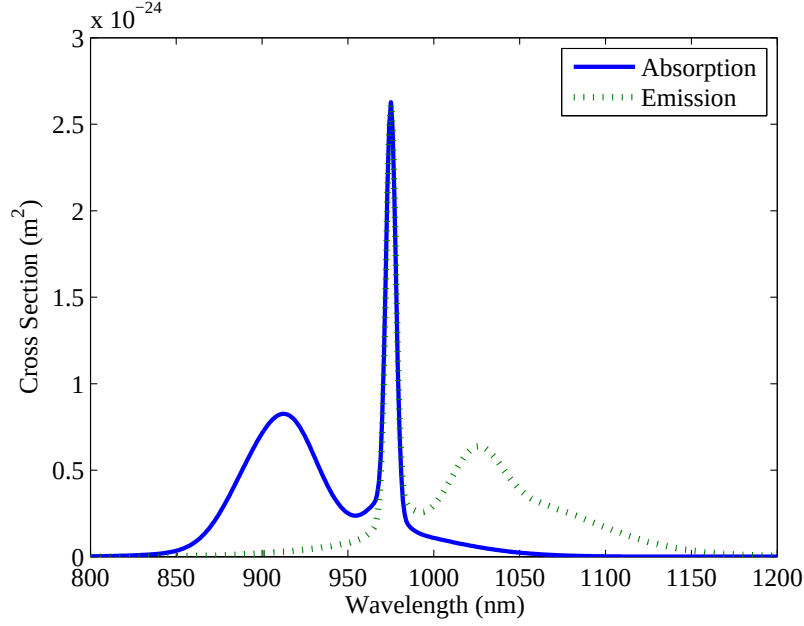


Figure 5. Absorption and emission cross-sections for Yb in SiO₂ [16].

tials in the silica matrix, while ionization results in valence defects. Particle radiation such as neutrons, protons, and heavy ions are mainly responsible for knock-on damage, while gamma-rays and X-rays are mainly responsible for ionization damage. Both radiation types, however, can be responsible for each type of damage. Device level radiation effects include radiation-induced attenuation (RIA), radiation-induced emission (RIE), and refractive index (RI) change [7]. The atomic level radiation induced defects result in the effects seen at the device level.

Atomic Level Effects.

Gamma-rays interact with matter through the photoelectric effect, Compton effect, and pair production. These interactions give rise to primary electrons and scattered energetic electrons and photons as shown in Figure 6. In order for knock-on damage to occur, an incoming particle must transfer a sufficient amount of energy to the material. This occurs through a collision between the incoming photon and an electron. A fast electron ejected from an atom then undergoes an elastic collision

with an oxygen atom to break two Si-O bonds, or with a silica atom to break four Si-O bonds. The displacement energies in SiO₂ are 10 eV for oxygen and 18 eV for silica, while the corresponding threshold energies for displacement by electrons are 64 keV for oxygen and 197 keV for silica [17]. For a ⁶⁰Co gamma radiation source, the gamma energies emitted are 1.17 and 1.33 MeV, where the Compton effect dominates in generating the primary electrons in SiO₂. The maximum energy of the scattered electron is given by $T_{max} = \frac{2h\nu}{2+mc^2/h\nu}$, which is equal to 0.96 and 1.12 MeV for the photon energies, respectively. The gammas are therefore of sufficient energy to induce knock-on processes. However, the Compton electrons are more likely to cause ionizing damage as they travel through the fiber material and lose energy.

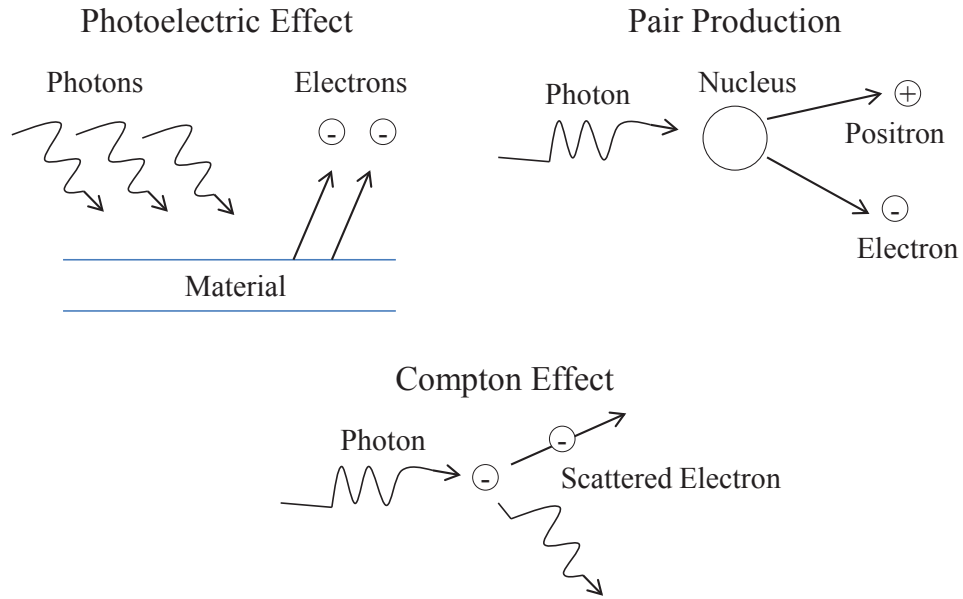


Figure 6. Principle mechanisms of energy deposition by photons in matter.

In amorphous silica, the predominant effects produced by a ⁶⁰Co source are due to radiolytic processes. In radiolytic processes, ionization or electron excitation creates damage by causing bond ruptures to occur or by initiating atomic motion such as elastic collisions [11]. Ionization processes occur when electrons from the valence band are transferred to the conduction band by energetic particles. A hole is then generated

in the valence band and created electron hole pairs recombine either radiatively or non-radiatively. In non-radiative recombination, energy is dissipated through the creation of phonons or by secondary radiolytic processes which could lead to the generation of point defects. Radiative recombination occurs when an electron in the conduction band recombines with a hole in the valence band and the excess energy is emitted in the form of a photon. The photon can then cause further ionization in the material, leading to additional generation of point defects. The cascade of defects is diagrammed in Figure 7. These point defects, also known as color centers, are accepted to be the main cause of increased attenuation in optical fibers [7].

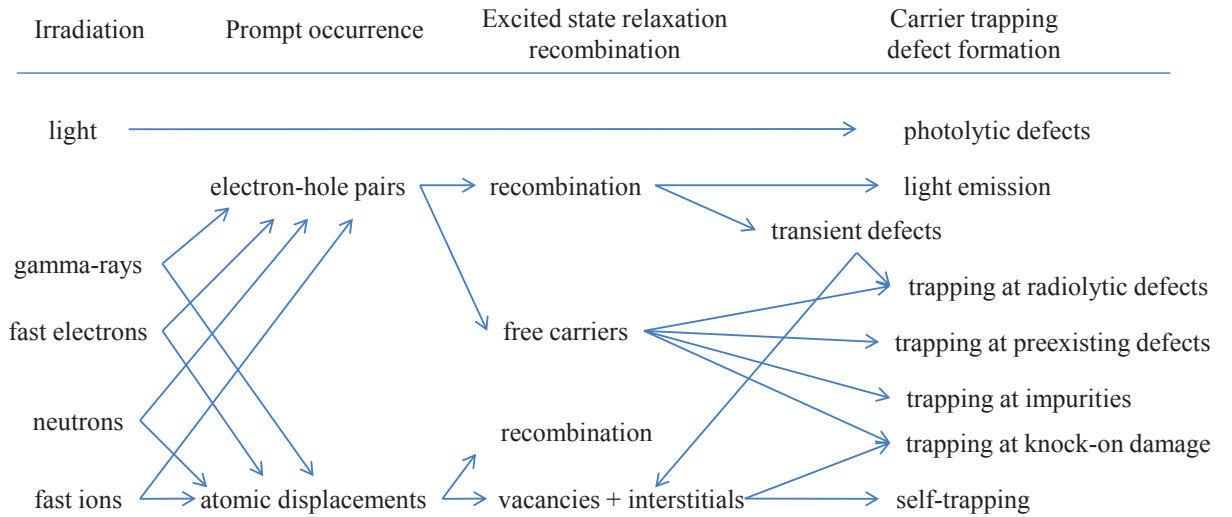


Figure 7. Diagram of relevant radiation damage processes for SiO_2 . Reproduced from [11].

Neutrons can cause displacement damage or indirect ionization. Since point defects include vacancy, interstitial, and valence defects caused by particle and ionizing radiation, neutrons may also be responsible for color center formation. In addition, neutron irradiation can transform the structure of silicon dioxide (both amorphous and crystalline) into a new phase called the metamict phase. The metamict phase is characterized by a narrower Si-O-Si angle, around 135° . The density and refractive index of a- SiO_2 increase by approximately 3% [18].

Device Level Effects.

The dominant effect due to neutron and gamma radiation at the device level is radiation-induced attenuation (RIA) [7]. Radiation induced color centers absorb light being transmitted through the fiber, which corresponds to an increased linear attenuation of the glass. The magnitude of RIA seen is dependent on irradiation time and will vary for different wavelengths due to the differences in energy that the various defects absorb. The equation for RIA is given by

$$RIA(\lambda, t) = \frac{-10}{L} \times \log_{10} \frac{P(\lambda, t)}{P(\lambda, t_0)} \text{ dB/m}, \quad (2)$$

where L is the length of the fiber being irradiated, $P(\lambda, t)$ is the power through the fiber at a specific wavelength at a specific time during irradiation, and $P(\lambda, t_0)$ is the power through the fiber at a specific wavelength at the time just prior to the start of irradiation.

Other device level effects are radiation-induced emission (RIE) and changes in refractive index (RI). RIE can be due to luminescence from precursors or radiation induced defects that are excited by incoming particles. RI change can occur from changes in the density of the fiber or from very high doses of radiation.

Neutron vs. Gamma Effects.

There have been some studies conducted to directly compare the effects of neutron versus gamma radiation on optical fibers. Girard et al. produced results that show that gamma rays, 14 MeV neutrons, and X-rays globally lead to the same defect generation in Ge and F-doped silica-based multimode optical fibers, with small differences in the concentration of the defects. The kinetics of RIA growth with dose between the fibers were shown to be the same [9].

Henschel et al. showed that the loss ratio in Ge-doped fibers from gamma versus neutron irradiation was dependent on the total neutron fluence received by the fibers. For a neutron fluence up to about $10^{13}/\text{cm}^2$ of 14 MeV neutrons, the loss was almost three times as much for gammas as for neutrons at the equivalent dose calculated from kerma values. At $10^{13}/\text{cm}^2$ the loss ratio decreased to ≤ 2.0 and by extrapolation it was determined that the loss ratio would probably reach about 1 for $10^{14}/\text{cm}^2$ [8].

2.4 Radiation Sensitivity of RE-doped Fibers

The amplitude and kinetics of RIA induced from the same irradiation can differ greatly from one RE-doped fiber to another due to the differences in spectroscopic properties of the ions. The signal wavelength, power level, etc. used can also affect the RIA in the fiber from irradiation. Measurements performed by Girard et al. provide evidence for a significant decrease in the transmission of selected RE-doped fibers that is a factor of 1000 greater than the losses measured in communications fibers. He further states that the excess of losses seems related to the host matrix that is necessary to incorporate the RE ions [19].

RE-doped fibers have been found to be less radiation resistant than common undoped optical fiber. Among RE-doped fibers, however, Yb-doped fibers have been found to be the most radiation resistant. The underlying reason for the increased sensitivity to radiation is not necessarily due to the RE dopant, but due to the co-dopants such as Al, P, and Ge, which are included in order to optimize the fibers [4].

A large percentage of aluminum compared with the RE and other co-dopants has been shown to produce larger absorption features in the visible region, along with a tail near the IR region. The intensity of the absorption increases with the excess of aluminum. Phosphorous has also been shown to counter some of the effects of the aluminum. Fibers with concentrations of $P > Al$ showed no absorption band in the

visible and near the IR range, while fibers with concentrations of Al>P did [20].

Summary.

The majority of research comparing the effects of gammas versus neutrons has been conducted on optical fibers that aren't doped with RE metals. There has been increasing research conducted on Yb-doped fibers in passive and amplifier and laser configurations in order to determine the effects that exposure to radiation has on their operation. There is still a need to directly compare the effects that various forms of radiation have on Yb-doped fibers, however, in order to determine what testing should be done in the future on fibers that may potentially be exposed to radiation environments.

3. Methodology

The purpose of the experiments was to irradiate YDFs with gamma only, and mixed gamma/neutron radiation at total doses that could be used to compare damage induced in the fibers from each radiation source. The experiments were conducted at the Fast Burst Reactor (FBR) at White Sands Missile Range, New Mexico, the Ohio State University (OSU) Research Reactor (OSURR), and the ^{60}Co gamma irradiator at OSU. The FBR and OSURR are both sources of mixed gamma/neutron radiation, and the ^{60}Co gamma irradiator was used to test the sensitivity of the fibers to gamma-only radiation.

3.1 Experiments

All fiber measurements were conducted using a white light source and CCS175 and CCS200 CCD spectrometers that utilize Thorlabs, Inc. Optical Spectrum Analyzer software (OSA). The spectrometers have the capability of measuring signal intensity through the fiber from 500 to 1100 nm and 200 to 1000 nm respectively. The spectra were recorded continuously throughout irradiation and the change in the spectra recorded during irradiation from the initial spectrum were used to determine the amount of RIA induced in the fiber. The power of the light source was not high enough to induce excitation of the Yb ions.

The bare YDF measured on-line was coupled to matched passive fiber by universal bare fiber terminators. The passive fiber was routed from the irradiation facility to the signal monitoring area as shown in Figure 8. Spectra were recorded prior to irradiation, during irradiation, and following the end of irradiation. The length of time the fiber transmission was measured post irradiation ranged from 28 minutes to 40 hours. The equipment used in the experiments is listed in Table 1.

Table 1. Equipment List for Experiments

Item	Specification
Yb-doped fiber	LMA-YDF-20/400-VIII Nufern YB1200-10/125DC LMA Thorlabs YB1200-6/125DC SM Thorlabs
Passive double-clad (DC) fiber	P-10/125DC Thorlabs P-20/390DC Thorlabs
CCD spectrometer	CS175 (500-1100 nm) Thorlabs CS200 (200-1000 nm) Thorlabs
White light source (Tungsten-Halogen)	Fiber coupled 300-2600 nm Thorlabs
Patch cable	50 μm , SMA-SMA, 25 meters
Universal bare fiber terminators w/ connectors	SMA905 Multimode Connectors: 410 μm and 128 μm bore
Fiber connector adapters	SMA-SMA and PC-SMA

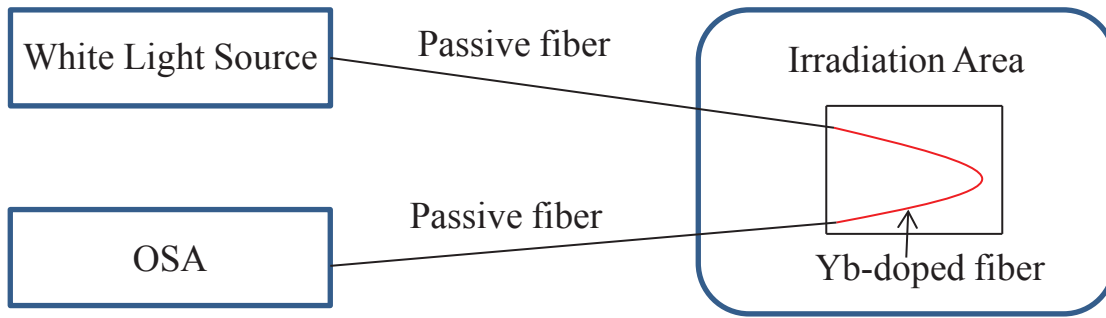


Figure 8. Setup for MM YDF operation with white light source.

Fast Burst Reactor.

The Fast Burst Reactor (FBR) is a molybdenum-alloy Godiva II type reactor located at White Sands Missile Range, NM. The core is mounted to a small stand fastened to a hydraulic lift, which is used to lower the assembly into a pit beneath a shield. The U-235 core is 6-8 inches in diameter and $7\frac{5}{8}$ inches high with a total mass of 81 kg [21]. The reactor is unmoderated to produce a spectrum of neutron energies similar to that of a nuclear weapon. The average gamma dose in relation to neutron fluence is approximately 2×10^{-10} rad/neutron/cm² [22].

The irradiation facility is an open room surrounding the reactor that is lifted out of the pit in the floor. The room designated for taking measurements is located above and adjacent to the reactor room. A hole leading from the measurement room to the reactor room allows cabling to be routed for *in-situ* measurements. During this experiment, two 25 meter passive cables were routed into the reactor room in order to take *in-situ* measurements of the YDF being irradiated.

The purpose of the experiment was to expose the fiber to an environment of mixed neutron and gamma irradiation. Dosimetry setup and analysis was performed by FBR scientists. Sulfur pellets and thermoluminescent dosimeters (TLDs) were used to measure the neutron fluence and gamma dose, respectively. The fiber being measured was positioned a radial distance of 28 inches from the center of the reactor. The reactor was operated in steady-state mode at 8kW for five hours. At this distance and exposure the fiber received a fluence of approximately 9.3×10^{13} neutrons/cm² and a gamma dose of 21 krad(Si). This gamma dose is achievable in less than one hour in the OSU ⁶⁰Co irradiator, and less than 30 seconds in the OSURR.

Ohio State University Research Reactor.

The OSURR is a pool type reactor with beam ports and dry tubes as irradiation facilities. The fuel is 19% enriched U_3Si_2 . The moderator and primary coolant are both light water with a secondary coolant of ethylene glycol. The irradiation facility used in all experiments was the 7-inch dry tube. The maximum flux achievable from this irradiation facility is 1.5×10^{12} n/cm²/s when the reactor is run at 450 kW [23].

The OSURR experiments exposed the fibers to mixed gamma/neutron radiation. Two different rigs were used in the experimental setup in order to expose the fibers to different neutron spectra. Rig 1 did not include a cadmium (Cd) box, while Rig 2 did as shown in Figure 9. Approximately 25 feet of passive fiber was required to route the YDF from the measuring station to the bottom of the 7-inch dry tube in the 20 foot reactor pool. Fibers placed in Rig 1 were irradiated with the full spectrum of neutrons. Rig 2 was used to attenuate the thermal neutrons below 0.5 eV, decreasing the flux from 1.5×10^{12} n/cm²/s to 4.1×10^{11} n/cm²/s, and creating a faster overall neutron spectrum. The rigs with fibers attached were placed in the 7-inch dry tube adjacent to the center of the reactor. The reactor was operated at 450kW in steady state during both runs, producing the maximum achievable flux.

Ohio State University ⁶⁰Co Source.

The OSU Gamma Irradiator is a ⁶⁰Co source surrounded by a 10 foot deep pool of water. The experiments are placed in an elevator that is inserted into a 6-inch dry tube. The depth of the pool required that approximately 15 feet of passive fiber be used to route the YDF from the equipment platform to the bottom of the irradiator. The height of one of the elevator platforms can be adjusted to achieve the desired dose rate as shown in Figure 10. The elevator is then lowered to the bottom of the dry tube. The start of measurements was taken to be when the elevator was

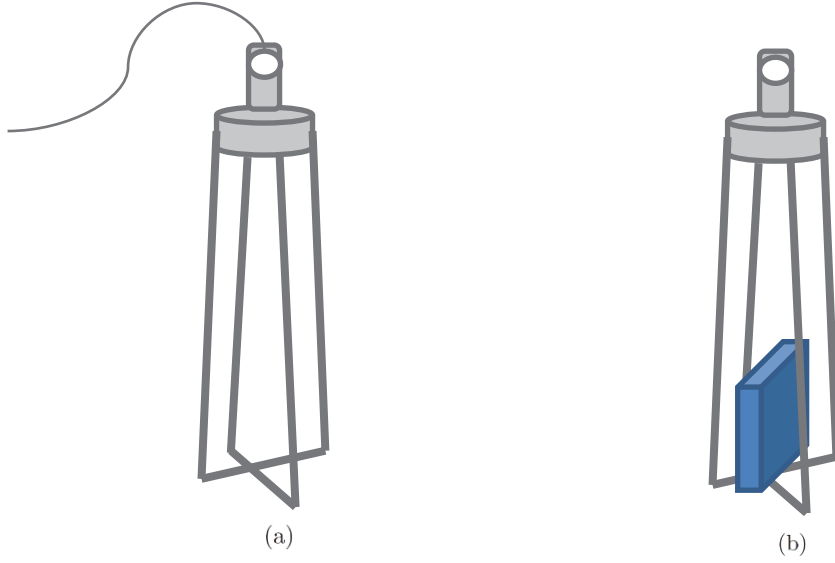


Figure 9. OSURR rigs are made of aluminum. Devices are attached to the interior of the rig and lowered into the 7-inch tube. (a) Rig 1 with no Cd box. (b) Rig 2 showing Cd box attachment that attenuates neutrons below 0.5 eV.

fully lowered and in place. The end of irradiation measurements were also started when the fibers were fully removed from the 6-inch dry tube. In all experiments the fibers were positioned to receive the maximum dose rate of approximately 32 krad/hr. Irradiation times ranged from 3 hours to 48 hours in order to achieve total doses of gamma radiation that were comparable to the FBR and OSURR experiments.

3.2 Research Approach

Fiber Preparation.

Multimode double clad YDFs for all experiments were cut to 28 centimeters and then stripped and cleaved, leaving between 24-26 centimeters of length per fiber. Universal bare fiber terminators were attached to either end of the fiber for coupling to matched passive fiber. Due to the increased radiation sensitivity of RE-doped fibers, this length is all that is needed for radiation-induced loss measurements [8].

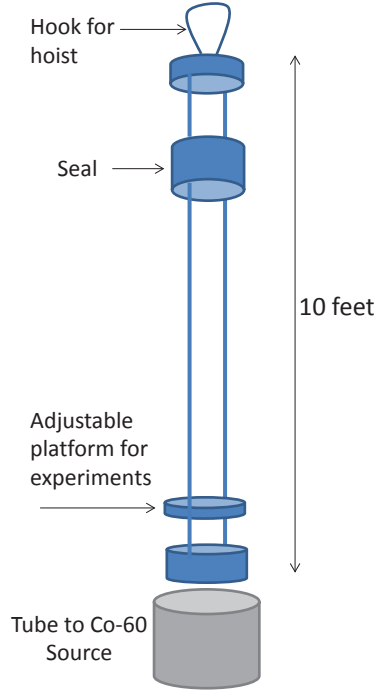


Figure 10. Elevator used to lower experiments into the ^{60}Co irradiator. The adjustable platform can be raised or lowered to adjust dose rate received by the test object based on the pre-determined dose rate profile [24].

The white light source and CCD spectrometer attachments use sub-miniature version A (SMA) type connections. SMA connectors are suited for use with multimode fiber. In the FBR and ^{60}Co experiments, 20 μm MM YDFs were coupled by bare fiber terminators configured with SMA connectors and SMA-SMA couplers to 25 meter patch cables. The 10 μm MM YDFs were custom prepared by the manufacturer to be 30 cm in length with SMA connectors permanently attached to each end. These fibers were coupled to bare matched fiber. The 6 μm single mode YDF used in one of the OSURR experiments was also manufactured to a specification of 30 cm in length with ferrule connector/physical contact (FC/PC) connectors permanently attached to each end. The 6 μm fiber was coupled to the matched passive fiber using PC-SMA adapters and bare fiber terminators configured with SMA connectors. Universal bare fiber terminators configured with SMA connectors were also attached to the source and receiving ends of the passive fibers in order to connect to the white light source

and CCD spectrometer.

Fibers were secured with painter’s tape to the rigs and elevator in the OSURR and ^{60}Co experiments in order to minimize movement during insertion into and extraction from the irradiation facility. In both experimental setups the Yb-doped fiber was taped flat to the bottom of the rigs and the passive fiber was routed up the sides and securely taped.

The YDF irradiated in the FBR did not have to be moved once it was put into position in the reactor room. It was secured to a six foot wooden platform with painter’s tape, however, to prevent it from experiencing movement due to a fan blowing during reactor operation.

Fiber Characterization and Measurements.

The pre-irradiation operation of the fibers was characterized by measuring with the white light source and CCD spectrometer prior to irradiation. Prior to each experiment, the white light source was also measured using a one meter optical patch cable for one hour. Light intensity through the fiber was recorded by the OSA software and then evaluated for stability.

The measurements taken during irradiation were analyzed by looking at the RIA of the signal through the fiber. The RIA is determined using Equation 2. Spectra were taken at least once every second during irradiation and once every minute post irradiation for recovery measurements collected over more than a few hours. Spectra were collected once every few seconds for recovery measurements taken for less than three hours.

Measurements taken post irradiation were used to analyze the recovery of the fiber. In the case of the FBR experiment, recovery measurements were only taken for 28 minutes due to time constraints at the facility. Recovery measurements of fibers

irradiated in the OSURR and OSU gamma irradiator were collected for longer times of hours to days. Ending irradiation of the fibers by the ^{60}Co source required fibers to be removed from the irradiator via a hydraulic lift. This movement sometimes resulted in the fibers or connectors getting shifted. These shifts changed the transmission spectrum before recovery measurements could be taken. The spectra that were shifted are not used in the recovery analysis presented. The OSURR provided the best recovery measurements as the fibers were not moved from the 7-inch tube following irradiation.

Determining Defect Contributions.

One method of determining the specific defects that contribute to the device level degradation is to fit the wavelength dependent RIA curve to a Gaussian curve and then deconvolve the curve into several other Gaussians centered at known absorption wavelengths. The amplitude of the deconvolved Gaussians are adjusted until the sum fits the RIA curve. The relative height of the deconvolved Gaussians corresponds to the magnitude of the defect's contribution to the RIA. Equations 3 and 4 are used to deconvolve the RIA spectra obtained from experiments at the OSURR, FBR, and OSU ^{60}Co irradiator. These equations are taken from Girard and Marcandella who use this method to decompose spectra into silica related defects in the UV-Visible part of the spectrum such as SiE' , SiODC(I) , SiODC(II) , Peroxy, NBOHC, and STHs. They create the Gaussian bands using the function

$$G(n) = A_n(t) \times H(E), \quad (3)$$

where n is the number of Gaussian bands and $A_n(t)$ is the time dependent amplitude. $H(E)$ is given by

$$H(E) = \exp\left(-2 \times \left(\frac{E - E_n}{w_n}\right)^2\right), \quad (4)$$

where E_n is the energy that the defect is centered on and w_n is the width of the defect. E_n and w_n are fixed parameters, whereas the amplitude of the band A_n is the free parameter [25].

The bands are chosen by inspecting the absorption spectrum and determining where increased absorption is present. A strongly asymmetric band generally indicates one or more hidden bands and a band with a flat maximum indicates two strongly overlapped bands. The width of the bands is estimated by using one or more bands not overlapped by other bands. As a first approximation, this is used for all bands in the spectrum [26]. After a general fit is produced the amplitude is adjusted until a best fit is acquired.

The spectrum resulting from one irradiation in the OSURR using the spectrometer capable of measuring from 200-1020 nm is deconvolved in Figure 11. This spectrum is chosen as the baseline due the ability to identify the absorption peak centered at 475 nm. The peak is hidden in other spectra measured with the 500-1100 nm spectrometer. The same absorption bands and their widths determined from the first deconvolution are then used to deconvolve absorption spectra from subsequent experiments. This method was taken from Brichard et al. who identifies defects in KU1 glass fibers irradiated with a ^{60}Co source and research reactor by the same method. The RIA spectra from his experiments were obtained by measuring the fibers *in situ* using a tungsten-halogen white light source [27].

The types of defects contributing to absorption were determined by looking at previous studies of optical fiber irradiations and the defects that were associated with the absorption spectra from these studies. Optical absorption (OA) and electron spin resonance (ESR) spectroscopy have been used to experimentally identify many

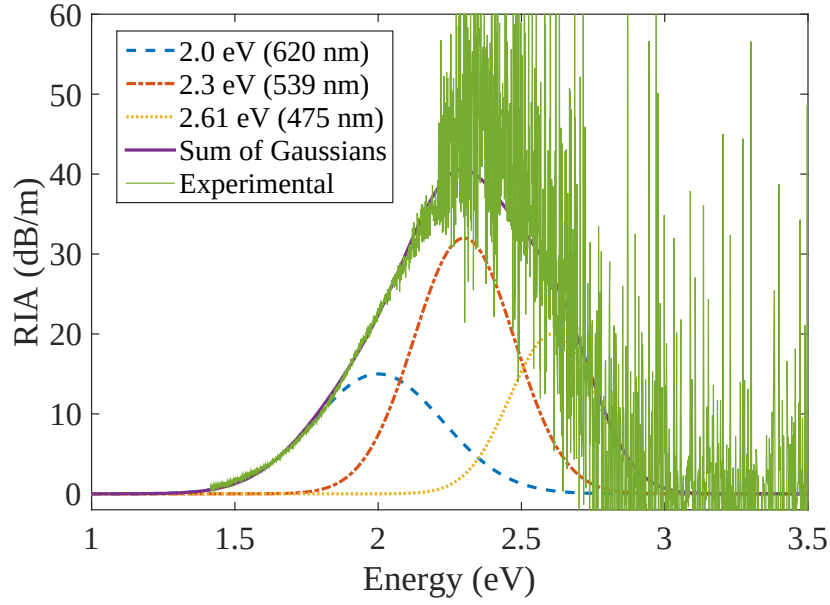


Figure 11. Deconvolved RIA spectrum of a YDF irradiated in the OSURR. The spectrum is chosen as the baseline due to the additional spectral data available below 500 nm (2.5 eV).

defects in silica-based optical fibers [20].

The first absorption center was identified using the work of Arai et al. who determined defects that contribute to photodarkening in YDFs specifically. The YDFs in his study were co-doped with aluminum, and the defects found to contribute the most to absorption were the Al-OHCs centered at 388 and 539 nm the Al-E' centered at 302 nm [28]. Aluminum is commonly used as a co-dopant in YDFs to reduce the clustering of the RE metal. For this reason, the Al-OHC centered at 539 nm was identified in this research as the first contributor to absorption in the irradiated YDFs.

A prominent absorption peak between 620 and 650 nm was identified in several RIA spectra. This peak was attributed to the NBOHC, which has been extensively studied in silica fibers, as well as Yb-doped fibers [29]. The defects arise from the presence of dopants or contaminants that are network modifiers. This type of defect might be expected from a large concentration of a RE dopant and other co-dopants.

Certain properties of this defect are well known, including its OA band at 2.0 eV (620 nm) and its photoluminescence (PL) at 1.9 eV (653 nm). There is evidence that the introduction of Yb increases the concentration of NBOHC defect centers, leading to the conclusion that the centers are in the vicinity of, or coordinated to, the RE dopant. Dragic et al. irradiated two passive fibers and Yb-doped fibers with green light (532 nm), and observed that the Yb fibers showed increased absorption at the 620 nm wavelength. In his study the introduction of the RE dopant appeared to increase the NBOHC relative to passive fibers. He states that this could lead to the conclusion that the centers are in the vicinity of, or coordinated to, the RE dopant. Therefore, the characterization of certain defects in the UV-visible range can provide insight into the local bonding structure of Yb doped silica fibers [29] [30].

The absorption peak near 475 nm is more difficult to firmly attribute to a specific defect. There are multiple defects that can be attributed to absorption near this wavelength, including defects that can result from P or Ge doping, which are located at wavelengths near 400 and 500 nm [9]. There are also two types of self-trapped holes (STHs) that exist in SiO_2 , one of which has been determined to be centered at 475 nm. The STHs are denoted as STH_1 and STH_2 . STH_1 corresponds to a hole localized at the oxygen site of a regular Si-O-Si bond, whereas STH_2 corresponds to a hole shared by two neighboring oxygen atoms. The defects are known to be unstable at room temperature, but there have been many studies where their generation in silica-based optical fibers have been observed. The two bands that have been experimentally shown are located at 2.16 eV and 2.61 eV, which correspond to STH_2 and STH_1 respectively [25] [31].

The STH located at 2.61 eV has been shown to have a broad band with a width, of approximately 1.2 eV. The NBOHC located at approximately 2.0 eV has a much narrower band with the width reported to be approximately 0.2 eV. The widths of

these defects determined from experimental studies on various silica and non-RE-doped fibers do not correspond to the widths of the defects established from the initial deconstruction (0.45 eV for the 2.0 eV band and 0.3 eV for the 2.61 eV band). The increased width of the NBOHC can possibly be attributed to the presence of multiple types of NBOHCs, however, for the analysis it is represented as one band. The defect characteristics of the three identified bands remain consistent across the multiple radiation sources in this research and provide a good fit to the RIA spectra.

Neutron Dose Calculations.

Neutron doses were calculated so that spectra resulting from the three sources of radiation could be normalized against one another. Gamma and neutron doses in silicon are published for the OSURR and OSU ^{60}Co irradiator, so all doses were calculated in terms of silicon (as opposed to SiO_2) for ease of comparison.

Neutron doses received by the fibers were determined using the Watt distribution of neutron energies, given by Equation 5, and the kerma coefficients of the neutron energies for ^{28}Si . The probability, $P(E)$, of a neutron from fission having an energy between E and $E+dE$ is given by the empirical formula,

$$P(E) = 0.4865 \sinh(\sqrt{2E}) e^{-E} \text{MeV}^{-1}. \quad (5)$$

The distribution is for neutrons from fission of ^{235}U with a slow neutron, but varies little for other types of fission. The spectrum is plotted using Equation 5 and shown in Figure 12.

The kerma coefficients for neutrons with energies from 0.0253 MeV to 150 MeV are taken from Chadwick et al. for ^{28}Si . Kerma (Kinetic Energy Released per unit Mass) is a quantity that is related to dose for indirectly ionizing radiation. It is the initial kinetic energy of all charged particles liberated by the radiation per unit mass,

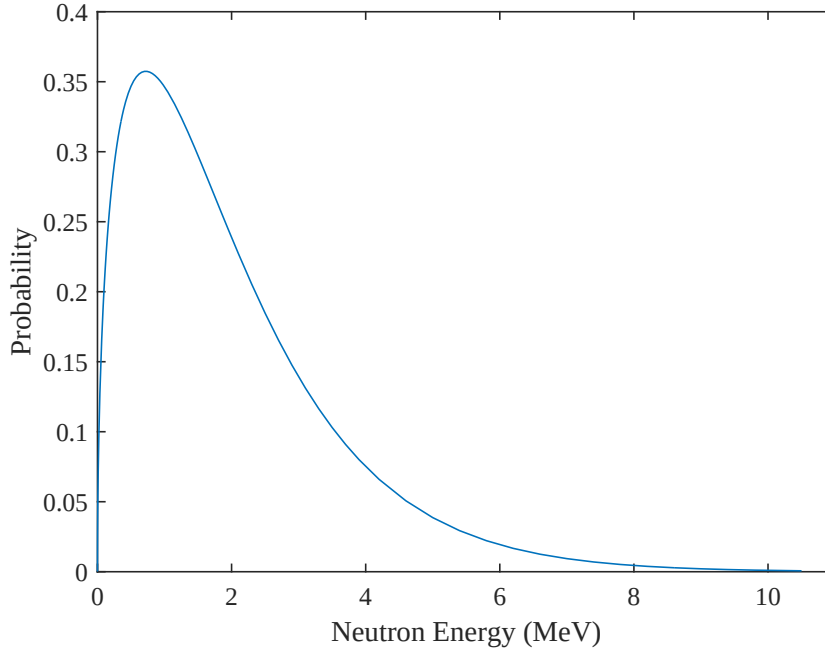


Figure 12. Watt Distribution of neutron energies for ^{235}U fission with a slow neutron.

and is quantified as the absorbed dose in a material. It can also be thought of as the first collision dose [32]. The kerma coefficients calculated Chadwick et al. were based on neutron cross sections for nonelastic and elastic reactions. The cross section data came from the Evaluated Nuclear Data File (ENDF) evaluations for energies below 15 MeV and directly from calculated cross sections in the laboratory for energies above 20 MeV. Between 15-20 MeV there is a lack of experimental data, so values in this range were found by linearly interpolating between data from ENDF/B-VI and laboratory calculated results at 20 MeV [33].

The kerma coefficients are given in units of fGy/m², so a factor of 10⁻⁹ is used to convert to rad/cm². To perform these dose calculations, probabilities per neutron energy were separately normalized over energy ranges where neutron fluences were specifically known. The probabilities were then multiplied by the neutron fluences given for the energy ranges. This estimated neutron fluence for each neutron energy is then multiplied by the kerma value for the corresponding energy and summed to

get the absorbed dose in rad(Si).

The dose rate from neutrons for the irradiation at the OSURR without the Cd box was determined to be 65.815 krad(Si)/hr. With the Cd box, the dose rate was determined to be 65.734 krad(Si)/hr. The total neutron dose achieved at the FBR was calculated to be 5.2 krad(Si).

Growth and Recovery Data Modeling.

The phenomenon of defect growth kinetics in optical fibers takes the form

$$q(D) = CD^f. \quad (6)$$

This equation is well known as the power law equation, where D is the radiation dose and C and $f(<1)$ are empirical constants. The RIA at a specific dose is calculated as $q(D)$ based on the empirical constants. C represents the magnitude of the curve while f is representative of the linearity of the degradation curve. Griscom shows that RIA growth and decay behaviors are simultaneously interpretable in terms of the power-law growth and standard bimolecular kinetics (recombination of electrons and holes or vacancies and interstitials) [34]. The data that he used to test the model were gamma-ray induced losses at 1300 nm in Ge-doped-silica core fiber. Griscom states that the model has also been used successfully to analyze radiation damage data of other multimode and single mode fibers.

The observed RIA curves can be decomposed into the contributions from defect production and recombination. Each curve is characterized by a different production rate constant K and a recombination rate constant R related to K by a semi-empirical formula. Griscom shows that R is related to K by

$$R = K^{\frac{|f(1-n)-1|}{f-1}} C^{\frac{n}{f-1}} (1-f)\dot{D}, \quad (7)$$

where n describes the order on which kinetic formulations occur ($n=2$ for bimolecular kinetics) and $\dot{D}$ is the dose rate. He then shows that this reduces to a dose dependent formula

$$R = C^{1-n} D_{(cum)}^{[f(1-n)-1]} (1 - f) \dot{D}. \quad (8)$$

The model is then said to make a “no-adjustable-parameters” prediction of the recovery curves to be expected once irradiation has ceased. The only knowledge required consists of the empirical growth parameters C and f determined from fitting the growth data to the power law, the dose rate $\dot{D}$, and the final accumulated dose $D_{(cum)}$. The standard n^{th} order kinetic solution for $n > 1$ is then

$$q(t) = q_o \left\{ 1 + (n - 1) q_o^{n-1} R t \right\}^{1/(1-n)}, \quad (9)$$

where $q_o = C(D_{cum})^f$ and R is given by Equation 8.

Equations 6, 8, and 9 are the only equations needed to predict the recovery of the fiber. Figure 13 shows a power law fit and the corresponding prediction for the recovery of the fiber. The prediction is based solely on the empirical values determined from the fit and the order of kinetics chosen for the prediction. The data used to create the example was taken from the FBR experiment, which involved a 20 μm YDF irradiated up to a dose of approximately 25 krad(Si) including the gamma and neutron dose. The f value is approximated based on the linearity of the RIA curve and the C value is adjusted to match the magnitude of the degradation. The empirical values along with the total dose and dose rate are then used to predict the recovery of the fiber over the desired length of time.

The methodology is applied to data from experiments performed with the three radiation sources. The empirical constants are determined for select wavelengths in

various experiments and the prediction is developed and compared to actual recovery data collected post-irradiation.

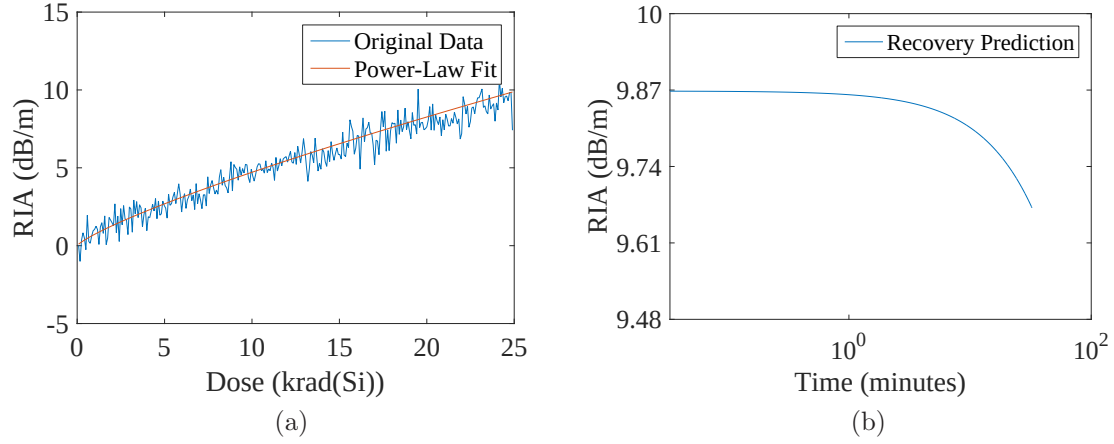


Figure 13. (a) An example of a power law fit to arbitrary RIA data. From Equation 6, the empirical C value is 0.73 and the f value is 0.81 for a dose rate of 5 krad(Si)/hr. (b) Recovery prediction based on empirical values derived from power-law fit.

4. Results and Analysis

Chapter Overview.

The FBR, OSU ^{60}Co source, and OSURR facilities were used to gather data on neutron, gamma, and mixed gamma/neutron radiation effects on Yb-doped optical fibers, respectively. The experiment conducted at the FBR was the first completed, and the OSURR and ^{60}Co experiments that followed were designed to provide data in order to differentiate between gamma and neutron radiation effects at similar doses.

The experiments performed are listed in Table 2 along with the different fiber types used for each experiment. The performance of all fibers was evaluated *in-situ* using white light as the source and a CCD spectrometer as the receiver. OSA software was used for data collection and analysis. Exposure times varied for each experiment but dose rates were the same for experiments performed with each radiation source. Across radiation sources, however, the dose rates varied. All data taken during and after experiments was done at room temperature.

The main source of degradation is from absorbing species that are produced in the fiber during irradiation, so the analysis is accomplished using the absorption spectra of the YDFs. Fits of the absorption spectra are obtained by deconvolving the spectra into a series of Gaussians and using the sum of the Gaussians as a fit to the experimental data. The defect growth rates are compared across different fibers sizes and experiments to the wavelength dependent degradation curves. The fits are used as a means to directly compare the spectra and identify how each radiation source contributes to attenuation in the YDFs. It is shown that the gamma and neutron irradiations globally lead to the same defects. Individual analysis is also performed on data from each irradiation experiment and comparisons between absorption spectra are also made in order to discern the differences in damage production for each

radiation source. Analyses of recovery data are also performed and actual recovery data is compared to the recovery prediction model. An evaluation is made of the reliability of the prediction model.

Table 2. List of experiments

Exp. No.	Fiber Core/Clad Size (μm)	Fiber No.	Facility	Dose Rate	Irradiation Time	Wavelengths Measured
1	20/400	1	FBR	1 krad(Si)/hr (neutron) 5 krad(Si)/hr (gamma)	5 hrs	500-1100 nm
3	10/125	2	OSURR (No Cd)	65.8 krad(Si)/hr (neutron) 9 Mrad(Si)/hr (gamma)	2.5 hrs	500-1100 nm
2	10/125	3	OSURR (With Cd)	65.7 krad(Si)/hr (neutron) 9 Mrad(Si)/hr (gamma)	3 hrs	500-1100 nm
4	20/400	4	OSURR (No Cd)	65.8 krad(Si)/hr (neutron) 9 Mrad(Si)/hr (gamma)	0.75 hrs	500-1100 nm
	6/125	5				200-1020 nm
5	20/400	6	Co-60 (OSU)	32.3 krad(Si)/hr	4.5 hrs	500-1100 nm
6	20/400	6	Co-60 (OSU)	32.3 krad(Si)/hr	4.5 hrs	500-1100 nm
7	20/400	6	Co-60 (OSU)	32.3 krad(Si)/hr	3 hrs	500-1100 nm
8	10/125	7	Co-60 (OSU)	32 krad(Si)/hr	5 hrs	500-1100 nm
	20/400	8				200-1020 nm
9	10/125	7	Co-60 (OSU)	32 krad(Si)/hr	48 hrs	500-1100 nm
	20/400	9				200-1020 nm

OSURR Irradiation.

Three experiments were performed in the OSURR with three MM and one SM YDF. Experiment 1 irradiated a 10 μm YDF for 2.5 hours. Experiment 2 irradiated a pristine fiber of the same manufacture with a Cd shield for 3 hours. Experiment 3 simultaneously irradiated a 20 μm and a 6 μm fiber. The transmission spectra for the 10 μm and 20 μm fibers were recorded from 500-1100 nm and the 6 μm fiber transmission spectra were recorded from 200-1020 nm.

All experiments were performed in the 7-inch dry tube positioned next to the reactor core at a reactor power of 450 kW. The fluences achieved for the three experiments are listed in Table 3. The total flux achieved for Experiment 1 was 1.5×10^{12} neutrons/cm²/s and the flux for Experiment 2 with the attenuation of thermal neutrons was 0.4×10^{12} neutrons/cm²/s. The spectra are compared in Figure 14 up to a time of 48 minutes, or fluences of 4.32×10^{15} neutrons/cm² in Figure 14(a) and 1.15×10^{15} neutrons/cm² in Figure 14(b). The total calculated neutron dose at each of these fluences is 52 krad(Si), since the thermal neutrons have small kerma values and contribute little to the total ionizing dose. The gamma dose rate for this reactor operating at 450 kW is approximately 9 Mrad(Si)/hr, so the gamma dose contributing to the spectrum shown for 52 krad(Si) in both cases is approximately 7.2 Mrad(Si).

Table 3. Fluence and dose totals for three OSURR experiments.

	Fluence/Dose		
	Experiment 1	Experiment 2	Experiment 3
Total Fluence (ϕ) (n/cm ²)	1.35×10^{16}	4.43×10^{15}	4.05×10^{15}
$\phi > 0.5$ eV (n/cm ²)	3.69×10^{15}	4.43×10^{15}	1.11×10^{15}
1 MeV(Si) Equivalent (n/cm ²)	1.8×10^{15}		1.54×10^{14}
Total Dose (γ) (Mrad(Si))	22.5	27	6.75

Both spectra in Figure 14 exhibit a shift in the peak of the absorption band initially centered at 650 nm at higher doses that makes it appear that absorption has decreased between 650-900 nm. The change in energy with respect to dose is shown

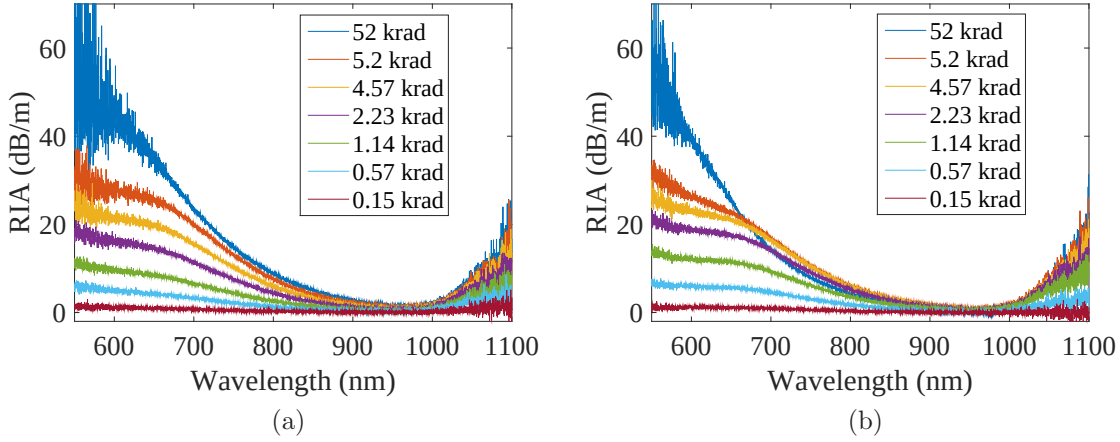


Figure 14. OSURR spectra comparison. (a) YDF spectra with no Cd present. (b) Spectra of YDF inside the Cd box while being irradiated. The curves are plotted for corresponding neutron doses.

in Figure 15. It can be seen that the shift in the absorption band occurs at a higher dose in the no-Cd spectrum. The absorption band appears to maintain the same width and move from being centered at 650 nm to 620 nm. The initial position of the NBOHC at 650 instead of 620 nm can be explained by the composition of the fiber, but the potential cause of the shift in energy during irradiation could not be found in the literature.

Dragic et al. characterized the NBOHCs in a Yb-doped fiber co-doped with aluminum. The absorption peaks were induced by cladding-injecting white light from a tungsten-halogen white light source and measuring the absorption spectrum using a fiber-coupled spectrometer. The NBOHC emission spectrum was excited with a 532 nm doubled Nd:YAG laser providing 200 mW of power. Five NBOHC PL peaks were observed from 632-750 nm with corresponding absorption peaks ranging from 596-723 nm. The spectral widths of the absorption peaks were all equal to approximately 0.16 eV. In a previous study there was also consistently an increasing red shift in the emission peak of the spectra with increasing Al/Yb ratio for the Yb-doped fibers studied [29] [30].

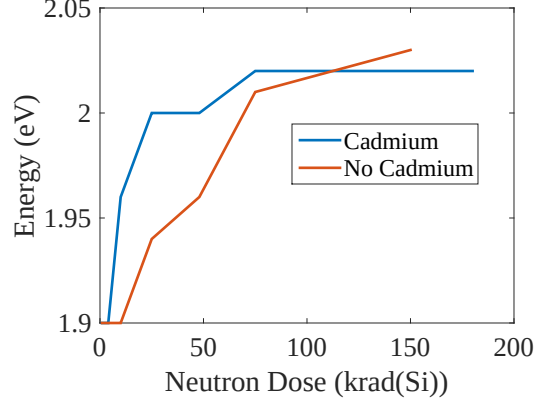


Figure 15. Energy shift of NBOHCs as a function of dose for Cd and no-Cd spectra.

Fits of the Figure 14 spectra are compared in Figure 16(a) at a neutron dose of 5 krad(Si). Since the dose from the thermal neutrons is negligible, it is expected that the spectra should be the same. However, additional attenuation is seen between 600 and 900 nm in the no-Cd spectrum. The increased attenuation in that range is attributed to the dose from gamma-rays, as described in the comparison of spectra in Section 4.

Thermal neutrons have a much higher probability for capture in silicon than fast neutrons, so it is possible that gammas emitted from these interactions contribute to the additional attenuation through their contribution to ionizing radiation damage. It has been shown that a neutron fluence of 2×10^{12} n/cm² is equivalent to a dose of 100 rad (SiO₂) [10]. The gamma dose associated with the neutron fluence in the OSURR at any given time is approximately one quarter of the actual gamma dose, meaning that at higher neutron doses, the secondary ionization effects from the neutrons can be considered negligible with respect to the gamma induced ones. At low doses (relative to megarads) the secondary ionization effects from the neutrons may still be considered comparable to those from the gammas. Figure 16(b) shows a comparison of the spectra at a higher dose of neutron radiation, and seems to confirm that at higher doses the effects of the thermal neutrons are negligible.

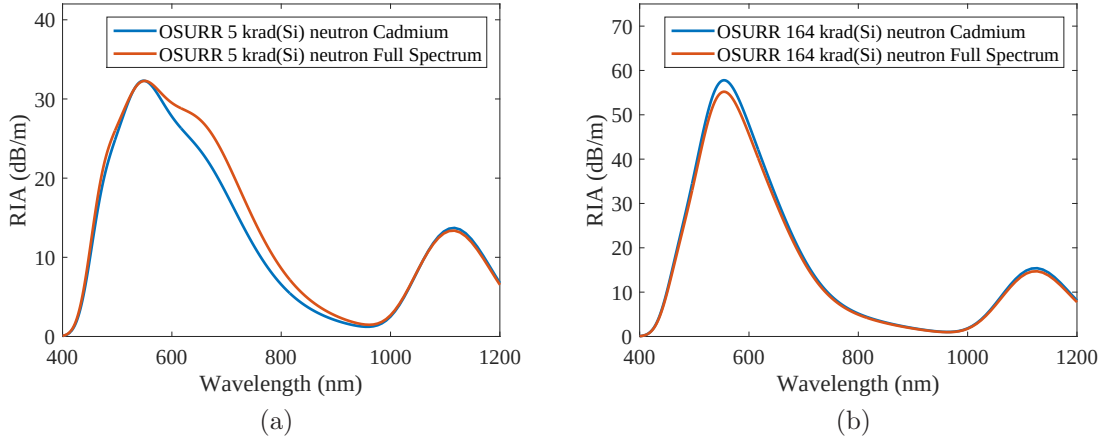


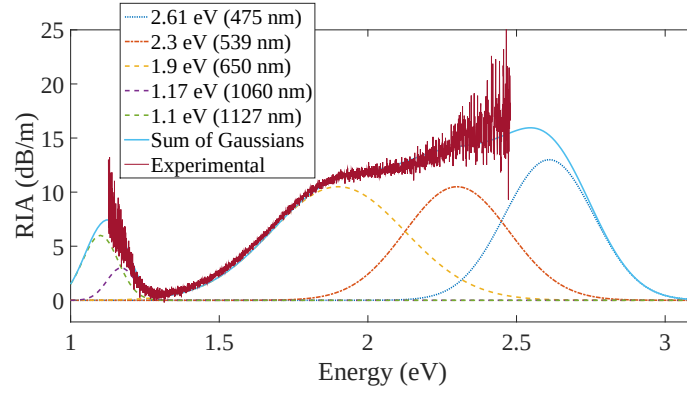
Figure 16. Comparison of $10\ \mu\text{m}$ fiber spectra irradiated with and without the cadmium shield in the OSURR. At a lower doses the contribution of thermal neutrons to ionizing radiation damage is apparent, while at higher doses it is negligible.

The deconvolved absorption spectra show that absorption is dominant at 539 nm, except in the no-Cd spectra, where the amplitude of the NBOHC becomes approximately equal to the amplitude of the AlOHC. The relative contributions of the defects are shown in Figure 17, while the growth of the defects is shown in Figure 18. The characteristics of the defects are given in Table 4. The same band widths of the defects are maintained throughout irradiation.

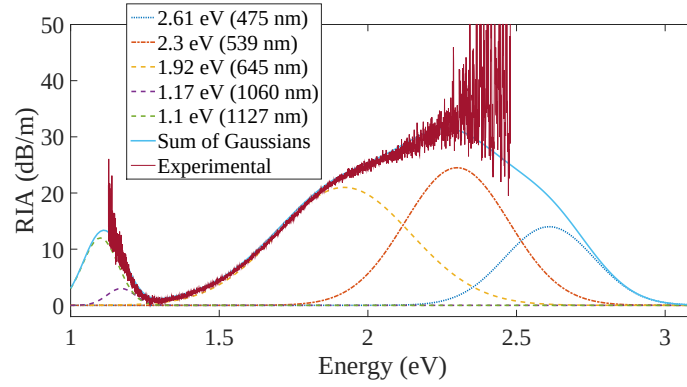
Table 4. Characteristics of absorption bands used for the decomposition of the RIA curves from the OSURR irradiations.

	NBOHC	Al-OHC	Unknown	Interstitial O ₂
Spectral position, E_n (eV)	1.9-2.0 eV (620 - 650 nm)	2.3 eV (539 nm)	2.61 eV (475 nm)	1.17, 1.1 eV (1060, 1127 nm)
Width, w_n (eV)	0.45 eV	0.35 eV	0.3 eV	0.1 eV

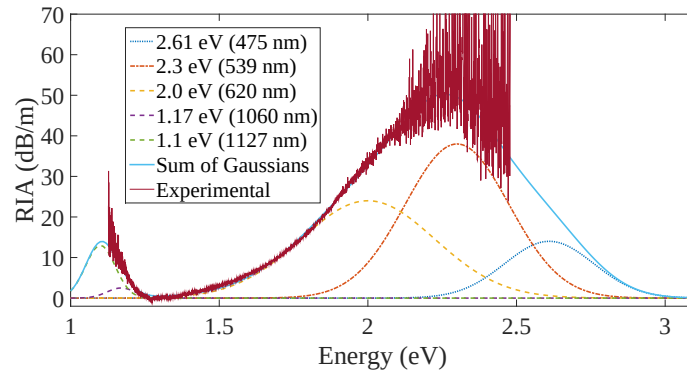
The wavelength dependent degradation of the YDF irradiated with Cd, shown in Figure 18(c), does not experience saturation as rapidly as the no-Cd spectrum irradiated to the same dose, further indicating that thermal neutrons may play a role in contributing to the ionizing radiation dose. The $20\ \mu\text{m}$ spectrum has the largest defect amplitude at 475 nm, likely due to the lesser concentration of NBOHCs.



(a)



(b)



(c)

Figure 17. Deconvolution of Cd absorption spectra from Figure 14(b) into primary defects known to be present in Yb-doped and passive silica fibers. (a) RIA at 1 krad(Si) deconstructed to concentrations of defects at 475, 539, and 620 nm. (b) RIA at 5 krad(Si) showing distribution of defects centered at 475, 539, and 620 nm. (c) RIA at 52 krad(Si) showing increased magnitude of 539 nm defect.

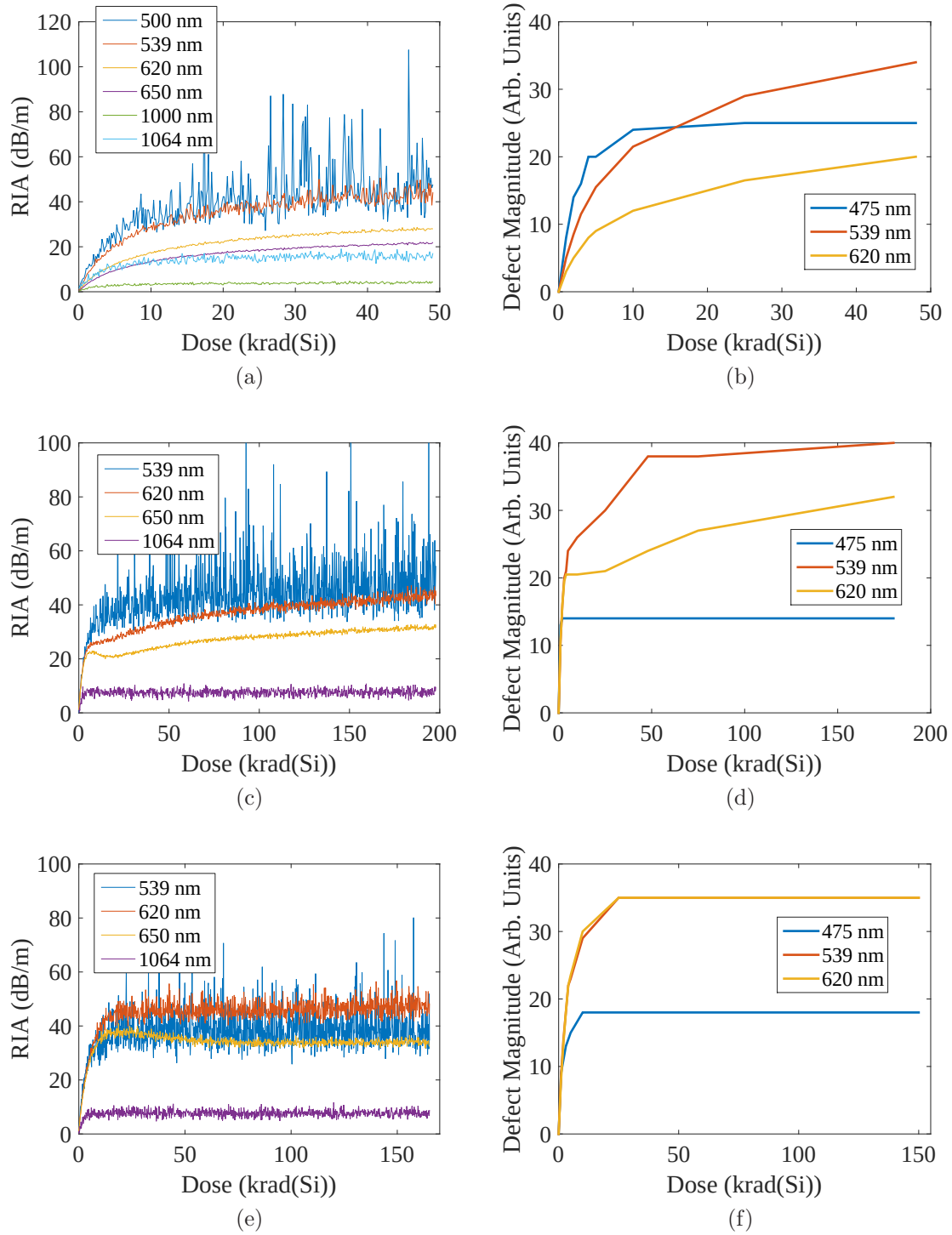


Figure 18. OSURR RIA and defect growth comparisons. (a) Wavelength dependent degradation as a function of dose for 20 μm fiber with no Cd present. (b) Defect growth rates for 20 μm fiber with Cd present. (c-d) 10 μm fiber with Cd present. (e-f) 10 μm fiber with no Cd present.

The strength of absorption in Yb-doped fibers near 975 nm is an indicator of the doping concentration in the fiber. In the set of fibers irradiated at the OSURR the 10 μm fibers had the highest doping concentration, at 2.5 times the absorption of the 6 μm fiber and 5.5 times the absorption of the 20 μm fiber at 975 nm. This correlates with the idea that the concentration of NBOHCs increases with the Yb doping concentration, as the 10 μm fibers demonstrated the largest growth of this defect. The doping concentration can then potentially explain the differing behavior of the fibers.

The 20 μm fiber that is also irradiated without Cd does not experience a shift in energy of the NBOHC defect as do the 10 μm fibers. It remains centered at 620 nm throughout irradiation. Additional differences are observed in Experiment 3 at wavelengths from 1000-1100 nm. At 1064 nm at a neutron dose of 52 krad(Si) the attenuation in the 20 μm fiber is 16 dB/m, while the attenuation in the 10 μm fibers is approximately 8 dB/m. The spectral shape and attenuation differences are likely a function of the concentration of Yb-doping and co-dopants used, as the fibers are from different manufacturers. Figure 19 shows a direct comparison of RIA at the central wavelengths of primary defects (539 and 620 nm), as well as the 1064 nm wavelength. The attenuation reached at 1100 nm is 23 dB/m for both fiber types.

The IR absorption has not been firmly attributed to a defect with known structure. It is suspected that the culprit is interstitial O_2 molecules that may be created radiolytically in the silica. These have been identified by measuring their infrared luminescence at 1272.2 nm after being excited with a Nd-YAG laser at 1064.1 nm. Activation energy is 1.17 eV (1060 nm) for diffusion of O_2 molecules in silica glass, which is much higher than any of the other known defect species in silica [34]. SiO_2 samples irradiated with gamma and neutron radiation have revealed the interstitial O_2 molecules in concentrations between 10^{14} and 10^{16} molecules/ cm^3 [35].

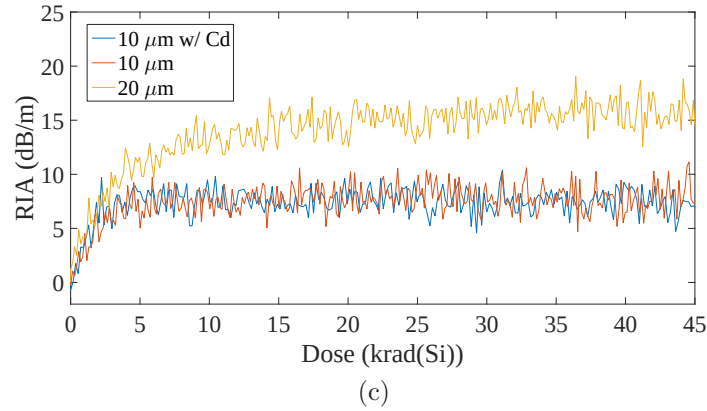
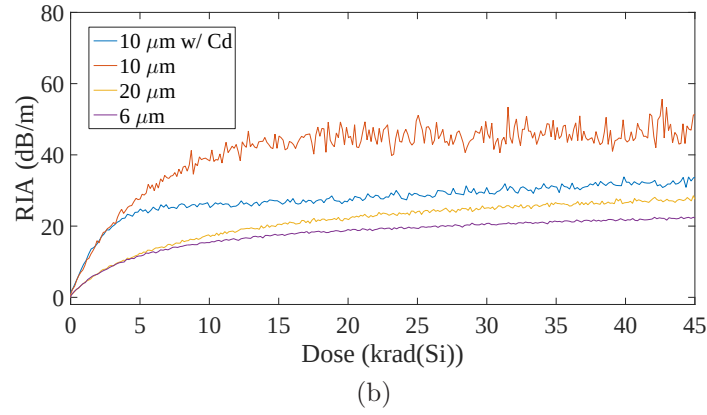
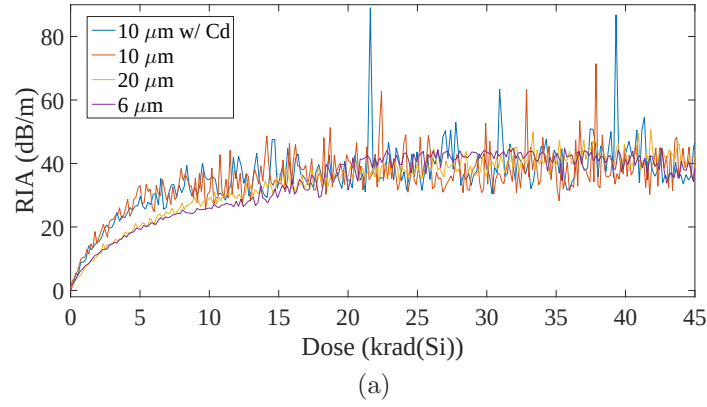


Figure 19. RIA at defect centers for each OSURR experiment. Doses are neutron doses. Gamma doses are approximately 150 krad(Si) per 1 krad(Si) neutron dose. (a) RIA at 539 nm. (b) RIA at 620 nm. (c) RIA at 1064 nm.

FBR Irradiation.

A 20 μm MM YDF was exposed to mixed gamma/neutron radiation from a highly enriched U-235 reactor operated at 8 kW for 5 hours. The degradation was measured over the course of 5 hours of irradiation. The total neutron fluences and gamma dose received by the fibers were determined by taking the average of values obtained from analysis of the sulfur pellets and TLDs. The values are shown in Table 5. The uncertainty was determined by calculating the standard deviation of measurements for the four sulfur pellets and four TLDs.

Table 5. Fluences and dose totals for 5 hour FBR irradiation.

	Fluence/Dose	Uncertainty
Total Fluence (ϕ) (n/cm^2)	9.35×10^{13}	+/- 5.4×10^{11}
$\phi > 3$ MeV (n/cm^2)	1.15×10^{13}	+/- 6.5×10^{10}
1 MeV(Si) Equivalent (n/cm^2)	8.01×10^{13}	+/- 4.6×10^{11}
Total Dose (γ) (krad(Si))	21.35	+/- 0.45

The FBR produces radiation that is also different from the OSURR in that the neutron moderation is greatly reduced, resulting in a faster overall neutron spectrum. The conversion from fluence to dose is then necessary to draw a reasonable comparison to the OSURR irradiation. The total dose from the neutron fluence was determined to be approximately 5 krad(Si). A fluence comparison can also be drawn between the 1 MeV(Si) equivalent fluences for the OSURR and FBR. The 1 MeV(Si) equivalent fluence at 5 minutes in the OSURR irradiation, where the neutron dose was calculated to be approximately 5 krad(Si), is 6.0×10^{13} n/cm^2 , which is on the same order of magnitude as the equivalent fluence determined for the FBR irradiation. It is slightly lower due to the difference in the neutron spectra. The neutron to gamma ratio is also much higher for the FBR radiation than the OSURR. The FBR ratio is 1 krad(Si) neutron per 4 krad(Si) gamma, while the OSURR ratio is 1 krad(Si) neutron per 14 krad(Si) gamma.

The attenuation in the fiber is similar to that in the OSURR irradiated fibers at the 500 and 1064 nm wavelengths at the same dose. The RIA spectrum shape is different, as shown in Figure 20 with a sharper decrease in the absorption curve at wavelengths between 500 and 700 nm. There is also a lack of attenuation between 750 and 970 nm.

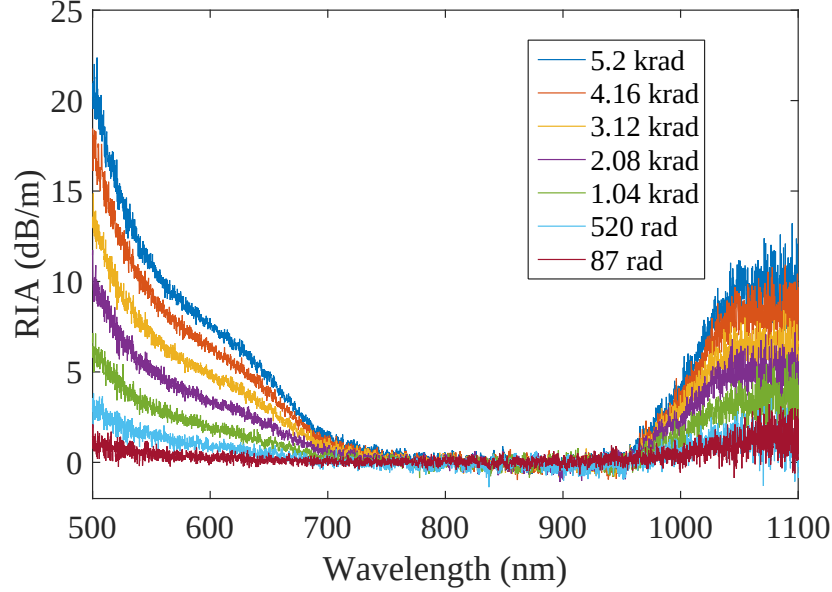


Figure 20. RIA as a function of wavelength over select doses.

The deconvolution of the spectrum at a neutron dose of 5 krad(Si) is shown in Figure 21. The width of the 620 nm defect, given in Table 6, is notably narrower than the width of the defect produced by the OSURR irradiation. The defect is also initially centered at 620 nm and does not experience a shift during irradiation. All defects increase linearly with one another, which is characteristic of fast neutron irradiation and is shown in Figure 22 [8]. Displacement damage is the primary effect of fast neutrons. When they interact with a material most of their energy is deposited in a single collision. This results in a clustering of defects, whereas gamma-rays are more likely to deposit their energy throughout the material. The apparent sharp drop off in absorption is due to the large concentration of defects near 500 nm.

Table 6. Characteristics of absorption bands used for the decomposition of the RIA curves from the FBR irradiations.

	Si-NBOHC	Al-OHC	Unknown	Interstitial O ₂
Spectral position, E_n (eV)	2.0 eV (620 nm)	2.3 eV (539 nm)	2.61 eV (475 nm)	1.17, 1.1 eV (1060, 1127 nm)
Width, w_n (eV)	0.28 eV	0.35 eV	0.3 eV	0.1 eV

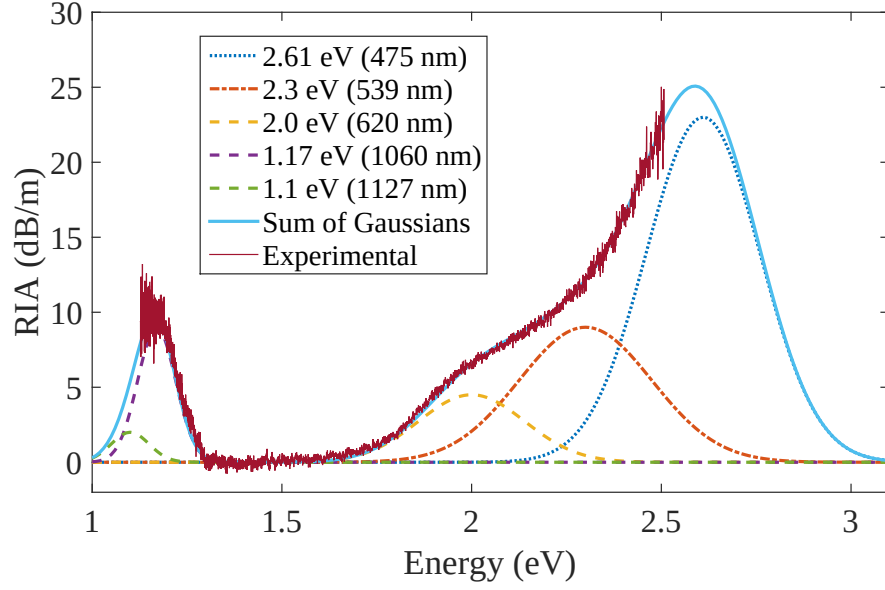


Figure 21. Defects that contribute to attenuation in the 20 μm YDF irradiated with the FBR.

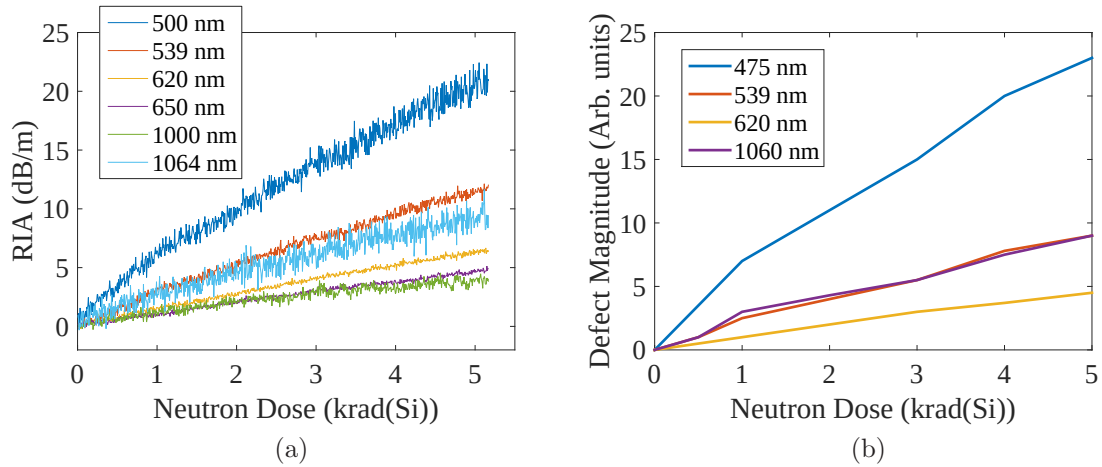


Figure 22. FBR RIA and defect growth comparisons. (a) Wavelength dependent degradation as a function of dose for 20 μm fiber. (b) Defect growth rate for 20 μm fiber.

⁶⁰Co Irradiation.

Multimode fibers of 20 μm and 10 μm core size were irradiated in two series of experiments. The first series of experiments irradiated one 20 μm YDF and took place over three days. The fiber was irradiated up to a total dose of 145 krad(Si) each of the first two days at a dose rate of 32.3 krad(Si)/hr. On the third day the fiber was irradiated for three hours up to a dose of approximately 100 krad(Si), resulting in a total dose of 390 krad(Si). The second series of experiments irradiated one 10 μm YDF and two 20 μm YDFs and also took place over three days. The first day a YDF of each size was irradiated for 5 hours up to a dose of 160 krad(Si). On the second and third days a second 20 μm YDF and the same 10 μm YDF were continuously irradiated for 48 hours to achieve a dose of approximately 1.6 Mrad(Si). The dose rate for the second series of experiments was 32 krad(Si)/hr.

A decrease in radiation sensitivity after multiple irradiations is shown in Figure 23. After the first irradiation the damage growth rate slows. After two consecutive irradiation sessions the damage growth rate of the 20 μm YDF does not decrease again, but stays the same. The recovery periods between irradiations were the same, so this behavior could indicate that the recovery rate of the defects remains the same after multiple irradiations, but the rate of defect formation may slow after one irradiation where the fiber does not have time or ability to fully recover. It is also possible that after the first irradiation, permanent defects are formed, that decrease the rate at which defects can form during subsequent irradiations. The 1064 nm wavelength did not show the same decrease in degradation rate after multiple irradiations, indicating that the defect kinetics are much different in the 975-1100 nm wavelength range.

The curvature of the RIA growth in the ⁶⁰Co irradiated fiber is logarithmic in shape rather than linear as with the FBR irradiated fiber. This is shown in Figure 24. This is likely because the gamma-rays can ionize atoms and create defects very

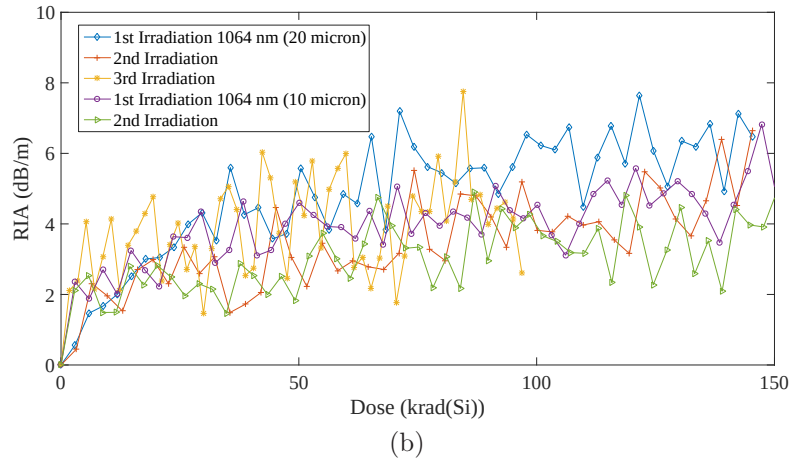
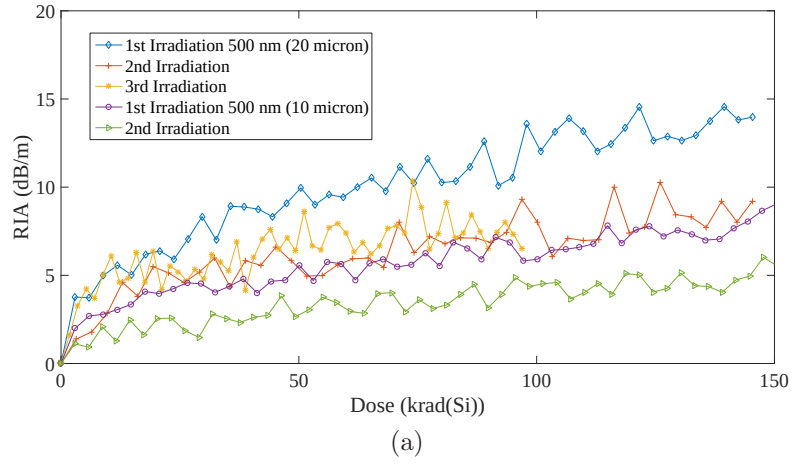


Figure 23. RIA at 1064 nm of a 20 μm fiber irradiated three times and a 10 μm fiber irradiated twice. The RIA for the second irradiation is determined based on the spectrum measured just prior to the start of irradiation.

rapidly, but as the concentrations become saturated, the rate of defect creation slows.

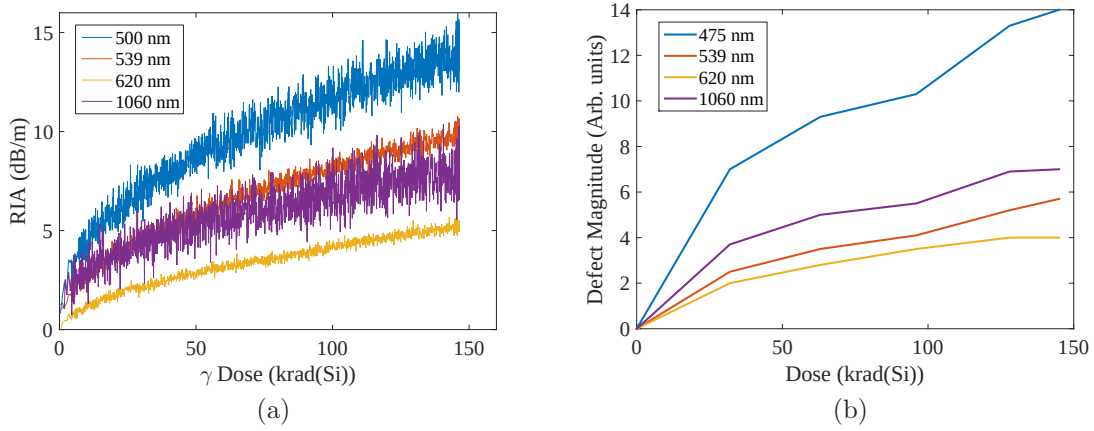


Figure 24. ^{60}Co RIA and defect growth comparisons. (a) Wavelength dependent degradation as a function of dose for $20\ \mu\text{m}$ fiber. (b) Defect growth rate for $20\ \mu\text{m}$ fiber.

Figure 24(a) shows that the attenuation has the greatest rate of increase at 500 nm. The 539 nm and 1060 nm wavelengths increase at similar rates indicating the defect formation may be correlated. The same similarity in degradation was observed in the FBR irradiation. The OSURR irradiations, however, did not show a correlation between degradation of the 539 and 1064 nm wavelengths.

The defects contributing to attenuation in the YDF from the ^{60}Co irradiation are the same as those present in the FBR and OSURR irradiations as shown in Figure 25. The NBOHC has a width larger than both the OSURR and FBR. The defect distribution is more similar to the FBR spectrum at a low gamma dose. At a higher gamma dose, the spectrum cannot be explained by only the three bands with set widths. An absorption center is added at 1.5 eV (830 nm) to account for the increased absorption from 800-1000 nm. This seems reasonable since self-trapped holes are well known to exist at 760 and 860 nm. Interstitial O_2 molecules have also been associated with the 765 nm wavelength, so these could also be contributing to the absorption in this range [25]. The characteristics of the primary bands are given in Table 7.

Table 7. Characteristics of absorption bands used for the decomposition of the RIA curves from the ^{60}Co irradiations.

	Si-NBOHC	Al-OHC	Unknown	Interstitial O_2
Spectral position, E_n (eV)	2.0 eV (620 nm)	2.3 eV (539 nm)	2.61 eV (475 nm)	1.17, 1.1 eV (1060, 1127 nm)
Width, w_n (eV)	0.55 eV	0.35 eV	0.3 eV	0.1 eV

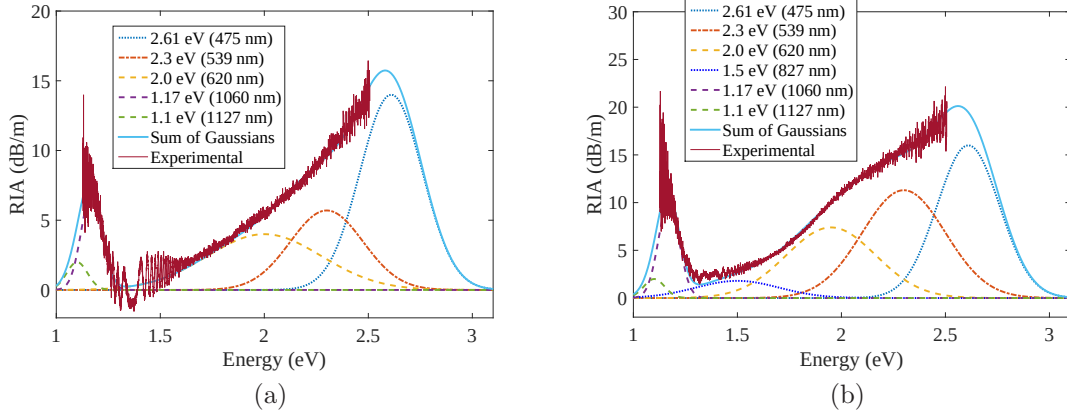


Figure 25. ^{60}Co spectra deconvolution. (a) ^{60}Co spectrum for 20 μm fiber irradiated to 145 krad(Si). (b) Spectrum of 10 μm fiber irradiated to 1.56 Mrad(Si).

The spectrum of the 10 μm fiber irradiated to 1.56 Mrad(Si) was also deconvolved using the five NBOHC defects specified by Dragic et al. in order to see if this would account for the increased absorption between 700 and 1000 nm. Table 8 lists the locations and widths of the NBOHCs. Figure 26 shows that the NBOHCs do not explain the additional attenuation, which must still be accounted for by a band at 827 nm.

One thing of note is that the total Gaussian resulting from the five NBOHCs is skewed, which changes the size distribution slightly between the defects at 539 and 475 nm.

Table 8. Five NBOHCs contributing to absorption in Yb-doped fibers [30].

#	Peak Abs. Wavelength (nm)	Peak Abs. Wavelength (eV)	Spectral Width (eV)
1	596	2.08	0.165
2	631	1.97	0.165
3	667	1.86	0.153
4	694	1.79	0.159
5	723	1.72	0.130

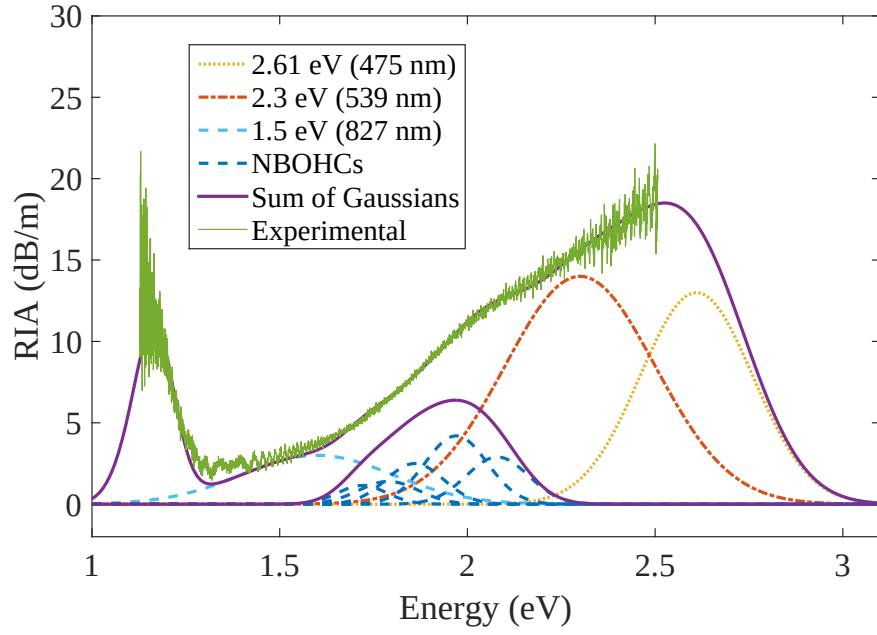


Figure 26. Deconvolution of ^{60}Co 1.56 Mrad(Si) spectrum with 5 NBOHCs given in Table 8.

Neutron versus Gamma Comparisons.

The spectra from the FBR, OSURR, and ^{60}Co irradiations are directly compared to each other using fits obtained from the Gaussian deconvolutions. Figure 27 shows a comparison of the ^{60}Co and FBR irradiations. The fits for each spectrum are compared at similar doses. In each set of comparisons, the top figure is a comparison made at similar gamma or neutron doses, while the bottom figure compares spectra at doses where attenuation at the 1060 nm wavelength is similar. This approach is taken since the shape of the spectrum in the 975-1100 nm wavelength range is similar between all radiation sources. Overlaying spectra at doses that are normalized to this wavelength then reveals a better differentiation of the attenuation in the spectral range of 500-975 nm.

Figure 27(a) shows the 5 krad(Si) neutron and 20 krad(Si) gamma dose FBR spectrum compared to the 20 krad(Si) ^{60}Co spectrum. The comparison at the same gamma dose shows that the fast neutron dose contributes much more significantly to attenuation at almost all wavelengths except between 700 and 975 nm. There is increased attenuation present from 700 to 975 nm in the gamma irradiated spectrum even though the gamma doses contributing to both spectra are equal. This indicates that the presence of fast neutrons in a radiation source may inhibit some damage that would normally be caused by the ionizing radiation.

Figure 27(b) shows the 5 krad(Si) neutron dose FBR spectrum compared to the 1.4 Mrad(Si) dose ^{60}Co spectrum. The attenuation at 1060 nm for these two irradiations is the same, as well as the shape of the Gaussian. The figure shows that the neutrons contribute to increased attenuation for wavelengths of 500 nm and below. The increased gamma dose contributes to attenuation from the 500 to 975 nm wavelengths.

Figure 28 provides a comparison of the OSURR and FBR spectra. Figure 28(a) is

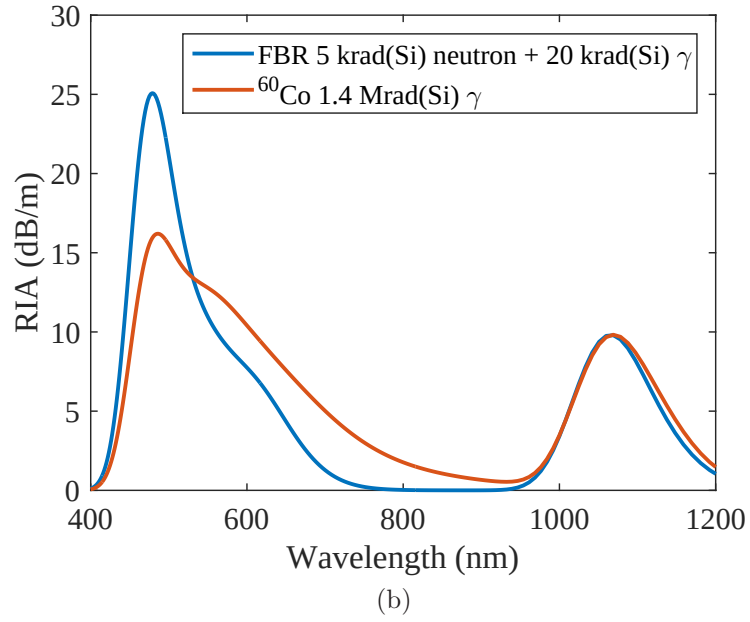
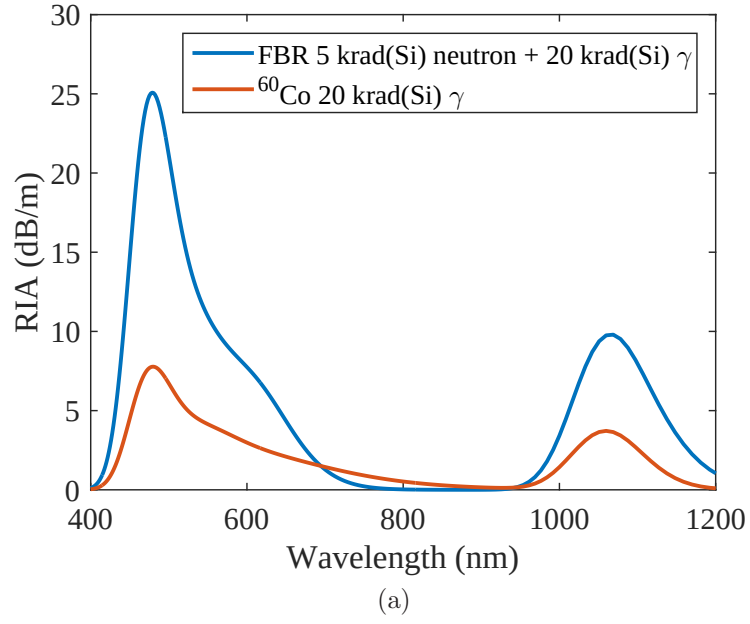


Figure 27. ^{60}Co versus FBR spectra comparison. (a) 20 krad(Si) ^{60}Co spectrum compared to the 5 krad(Si) (neutron) FBR spectrum. (b) 1.4 Mrad(Si) ^{60}Co spectrum versus 5 krad(Si) (neutron) plus 20 krad(Si) (γ) FBR spectrum.

un-normalized and directly compares the attenuation spectra at similar neutron doses. The OSURR spectra has a much higher gamma dose, which contributes to increased attenuation from 500 to 975 nm due to higher defect concentrations. The difference in defect shapes can be more clearly seen in the dose normalized spectra of Figure 28(b). The neutron only radiation causes increased attenuation at 500 nm. The gamma radiation causes increased attenuation from 500 to 975 nm, consistent with the comparison of the FBR and ^{60}Co spectra. The smaller difference in attenuation near 500 nm can be attributed to the contribution of the fast neutrons from the OSURR.

Figure 29 is a comparison of the OSURR versus ^{60}Co irradiation. Since the OSURR is highly contaminated with gamma radiation it is expected that the spectra will differ over the mainly neutron sensitive wavelengths (<500 nm) only. Figure 29(a) shows the spectra of the 20 μm fiber irradiated in the OSURR compared to the 10 μm fiber irradiated by the ^{60}Co source.

Figure 29(b) compares the 10 μm YDF ^{60}Co spectrum with the spectrum of the 20 μm YDF irradiated in the OSURR without the cadmium shield. The spectra are compared at doses that produce the same attenuation near 1060 nm. The only difference in the spectra is increased attenuation near 500 nm, where the dose from fast neutrons contribute to the RIA. Morana et al. also compare neutron and gamma radiation effects on an F-doped optical fiber. The radiation sources used are a research reactor and ^{60}Co source. They normalize their spectra to the peak attenuation that occurs at the 620 nm wavelength and show that the neutron radiation produced increased attenuation from approximately 400-600 nm [10], similar to what is shown in Figure 29(b).

Another significant difference between the OSURR spectra and both the FBR and ^{60}Co spectra is the shape of the Gaussian in the 975-1100 nm range. The shape

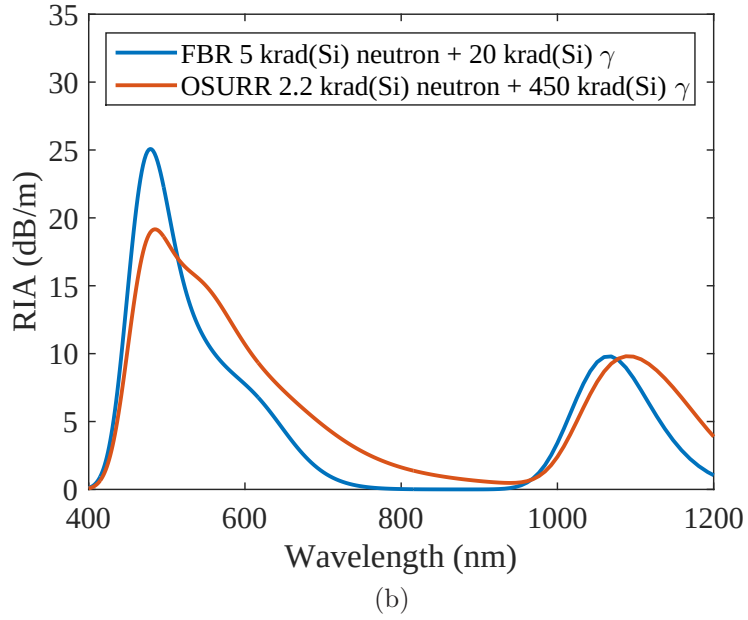
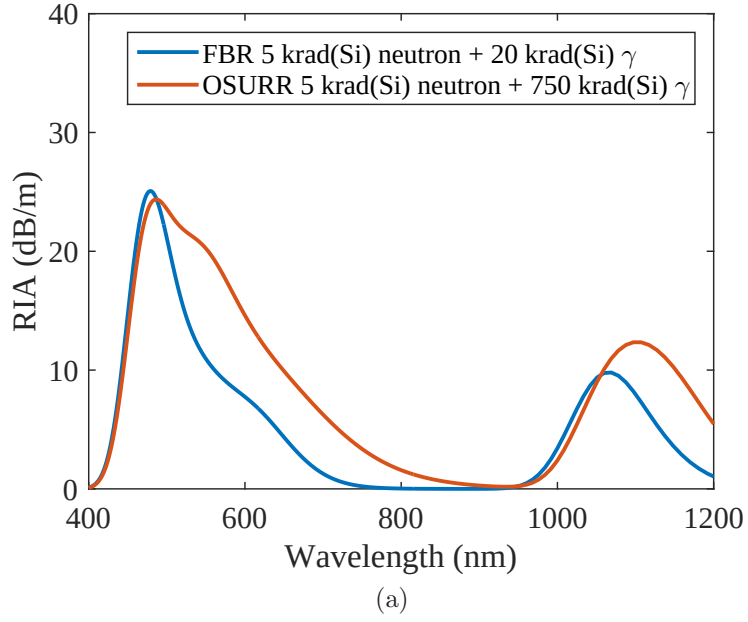


Figure 28. OSURR versus FBR spectra comparison. (a) 5 krad(Si) neutron plus 750 krad(Si) γ spectrum compared to the 5 krad(Si) (neutron) plus 20 krad(Si) γ FBR spectrum, un-normalized. (b) 5 krad(Si) neutron plus 20 krad(Si) γ FBR spectrum compared to the 2.2 krad(Si) (neutron) plus 450 krad(Si) γ OSURR spectrum.

is similar, but the Gaussian band resulting from the OSURR irradiation is slightly shifted, so that the peak is closer to 1100 nm. The spectrum in the 975-1100 nm range was decomposed in the previous sections using bands centered at 1060 and 1127 nm for all three radiation sources. The band at 1127 nm appears greater in magnitude for the OSURR irradiation, however, due to the continued rise in attenuation at 1100 nm. In the ^{60}Co and FBR spectra, the peak attenuation appears to be at 1060 nm.

Figure 30 shows the OSURR spectrum compared to the ^{60}Co spectrum at the same dose with the neutron dose subtracted out. This is shown by subtracting the attenuation seen at the FBR from the OSURR attenuation. The result is a spectral shape that is comparable to the original ^{60}Co spectrum and also has a similar degree of attenuation.

The degree and character of degradation in the YDFs differs for each radiation source. The neutron dose is far more damaging than an equal dose of gammas in krad(Si). A fast neutron dose of 5 krad(Si) by itself has approximately the same effect that a 1-2 Mrad(Si) dose of gammas has at the 1064 nm wavelength.

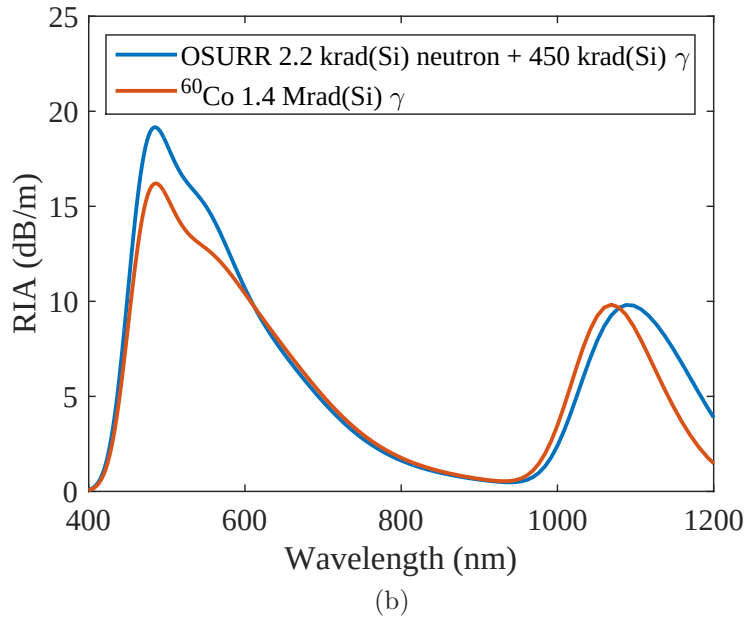
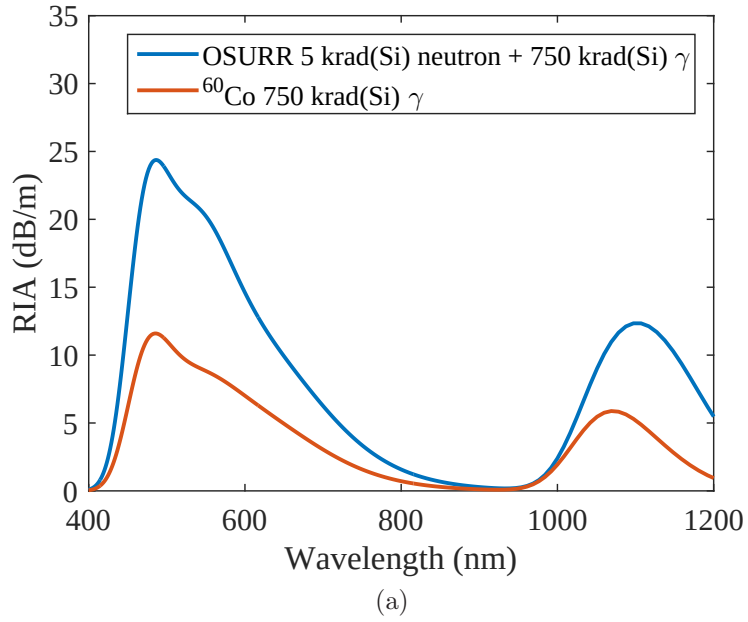


Figure 29. ^{60}Co versus OSURR spectra comparison. (a) 5 krad(Si) neutron plus 750 krad(Si) γ spectrum without cadmium compared to the 750 krad(Si) γ ^{60}Co spectrum. (b) 2.2 krad(Si) neutron plus 450 krad(Si) γ spectrum with cadmium compared to the 1.4 Mrad(Si) γ ^{60}Co spectrum.

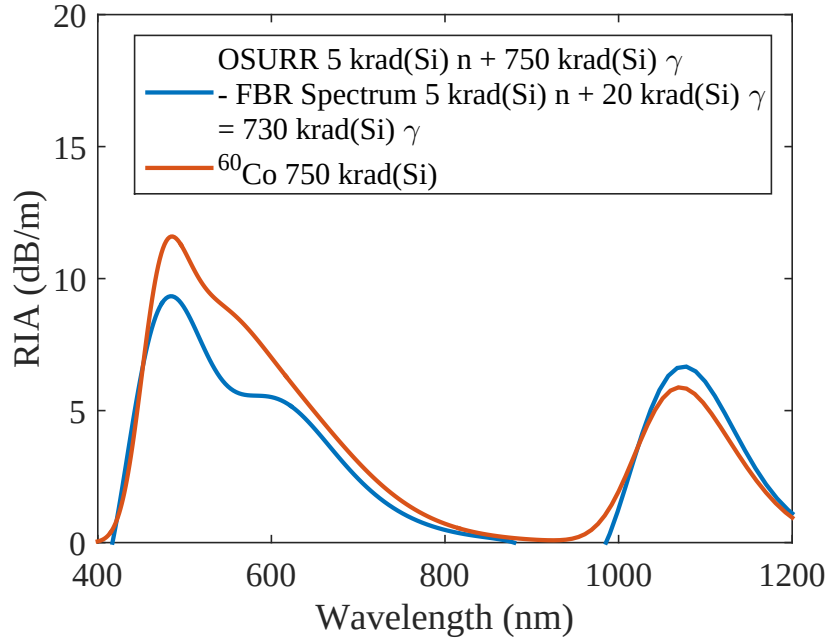


Figure 30. The FBR spectrum is subtracted from the OSURR spectrum to demonstrate the contribution of fast neutrons to attenuation in the fiber.

Recovery Analysis.

The recovery of the YDFs irradiated in the OSURR proceeds at a pace directly related to the initial degradation. The wavelengths that experienced a faster degradation experience a faster recovery. Figure 31 shows a third order polynomial fit of the recovery data with respect to elapsed time after the reactor was shut down. The times over which recovery measurements were collected in Figures 31(a) and 31(b) were 18 hours and 12 minutes, respectively. The initial recovery of the fiber irradiated in Experiment 1 occurs quickly in the first 5 hours. Table 9 shows that percentage of recovery to be over half of the final recovery at 18.3 hours. At 18.3 hours, the fiber recovers 34% of its original signal transmission at 650 nm and 7% of its original signal at 1064 nm. The recovery of the YDFs after irradiation with all three sources follows an exponential pattern and varies in rate at each wavelength.

The total dose of YDF irradiation also has a large impact on the recovery. The

higher the dose, the more time it takes to recover to its original signal intensity. The total combined neutron and gamma dose of the YDF in Experiment 1 was 22.7 Mrad(Si), Experiment 2 was 27.2 Mrad(Si), and Experiment 3 was 6.8 Mrad(Si). The 20 μm YDF in Experiment 3 was irradiated to approximately one third the dose of the YDF in Experiment 1, but between 60-80% of the recovery was achieved in 1% of the time. The 1064 nm wavelength experienced the largest percentage of recovery in the 20 μm YDF, however, the signal degradation was greater than for the 10 μm fibers.

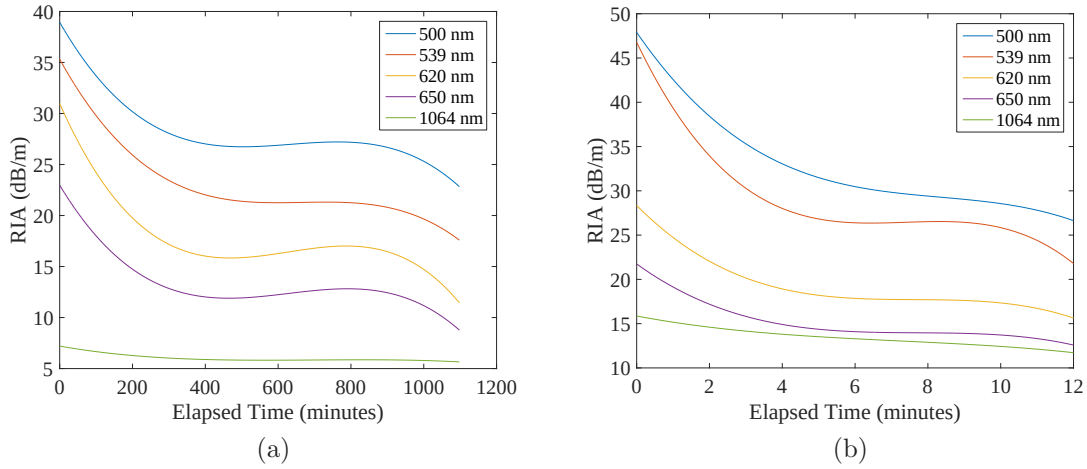


Figure 31. Recovery of YDFs irradiated in the OSURR. (a) Recovery of 10 μm YDF (Experiment 1) over 18 hours. The YDF was irradiated for 2.5 hrs to a total combined neutron and gamma dose of 22.7 Mrad(Si). (b) Recovery of 20 μm YDF (Experiment 3) over 12 minutes. The YDF was irradiated for 45 minutes to a total combined neutron and gamma dose of 6.8 Mrad(Si).

Table 10 shows the growth and recovery rates of RIA at select wavelengths. Recovery data was taken from the end of irradiation up to about 30 minutes after. The speed of the recovery follows the rate of RIA growth: the faster the RIA growth, the faster the recovery. Wavelengths whose RIA growth rates were closely matched also have recovery rates that are closely matched. The recovery percentages of Experiment 1 at 30 minutes are compared to the FBR recovery percentages. The comparison indicates that the recovery rate is directly dependent on the length of time the fiber

Table 9. Percentage of YDF recovery from initial losses at select times post irradiation. Experiment 1 recovery measurements were taken for 18.3 hours, Experiment 2 for 17.7 hours, and Experiment 3 for 12 minutes.

λ (nm)	Recovery (%) Experiment 1 at 5 hrs	Rec. (%) Exp. 1 at 18.3 hrs	Rec. (%) Exp. 2 at 5 hrs	Rec. (%) Exp. 2 at 17.7 hrs	Rec. (%) Exp. 3 at 12 min
500	7.66	13.87	1.96	13.8	12.23
539	11.18	20.95	7.81	18.44	18.25
620	18.9	33.57	11.55	21.43	19.86
650	20.83	34.12	14.46	25.02	19.66
1064	5.16	6.87	0	4.77	11.07

is irradiated as well as the degree of degradation it experiences. Wavelengths near 500 nm experienced greater degradation due to the higher ratio of fast neutrons to gammas, so the total recovery is higher. The 650 nm wavelength, which was highly affected in the OSURR irradiations experiences a greater overall percentage of recovery.

Table 10. Rates of degradation and recovery for YDF irradiated for 5 hours to a combined gamma and neutron dose of 25 krad(Si) in the FBR. Recovery measurements were taken for 32 minutes. The recovery measurements from OSURR Experiment 1 for 32 minutes are also shown as a comparison.

Wavelength (nm)	Degradation Rate (dB/m/krad(Si))	Degradation Rate (dB/m/s)	Recovery Rate (dB/m/s)	Recovery (%) FBR	Recovery (%) OSURR
500	4	0.00111	0.000833	2.94	0.94
539	2.4	0.00067	0.000437	2.49	1.27
620	1.4	0.00039	0.000113	2.9	2.17
650	1	0.00028	0.000158	0.88	2.71
1000	0.8	0.00022	0.0000982	1.78	
1064	2	0.00056	0.000416	1.34	0.82

Since the rate of degradation of the fiber irradiated with the ^{60}Co source is not as linear as the rate at the FBR over the course of 5 hours, the degradation rate is only an average taken from the data in Figure 24. Table 11 shows the degradation and recovery rates for select wavelengths. Its intention is to show the relationship between the average rate of degradation up to a finite time versus the rate of recovery

of the fiber.

Over a similar time period (4.5 versus 5 hours), the rate of degradation in the YDF irradiated by the ^{60}Co source at 32.3 krad(Si)/hr follows closely with the rate of degradation of the fiber irradiated at the FBR, as shown in Figure 32. The rate of degradation is larger at the 500 nm wavelength for the FBR irradiated YDF, but the rate of degradation is closely matched between the two radiation sources at other wavelengths. The rates of recovery appear to be less closely matched, with the FBR having a faster rate over all wavelengths. The recovery time periods covered are different, however, with the FBR recovery time period covering only 30 minutes, and the ^{60}Co recovery time period covering 77 minutes. It has been seen that the initial rate of recovery is very rapid and then slows, which results in the lower average recovery rate for the ^{60}Co irradiated fiber.

Table 11. Rates of degradation and recovery for 20 μm YDF irradiated for 4.5 hours to a dose of 145 krad(Si). Recovery data was collected for 77 minutes.

Wavelength (nm)	Degradation Rate (dB/m/s)	Recovery Rate (dB/m/s)	Recovery (%)
500	0.00087	0.000558	7.76
539	0.00061	0.000338	5.86
620	0.00031	0.000078	1.76
650	0.00029	0.000030	0.69
1000	0.00021	0.0000047	1.19
1064	0.00043	0.000255	5.33

Information about the initial and long term recovery rates associated with different total doses and dose rates can be used to estimate the time to when a device may be operational again after exposure to radiation. The recovery prediction model shown in Section 4 can also be useful if this initial recovery relationship is established.

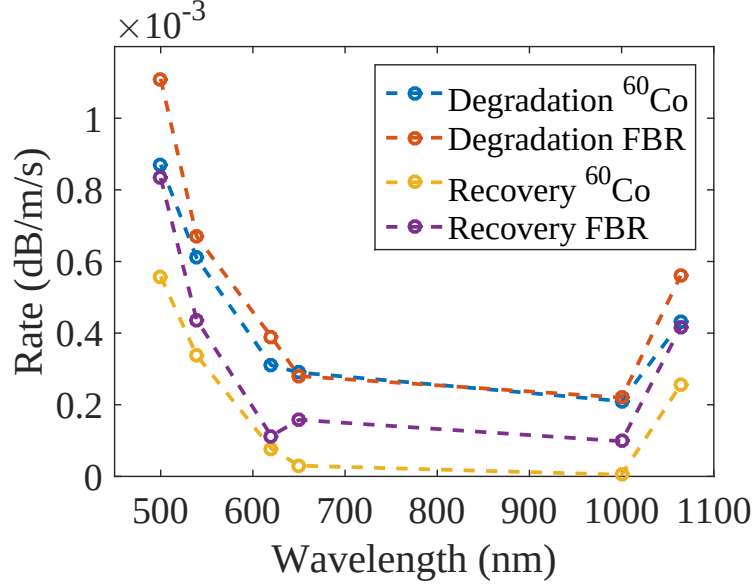


Figure 32. Plot of data from Tables 10 and 11 showing similar relationship between degradation and recovery rates at select wavelengths in the fiber. The similar relationship between the ^{60}Co and FBR degradation and recovery rates is also shown. Data points are connected to show the overall trend.

Recovery Prediction Model.

Losses are thought to occur as a result of defect centers created by electron and/or hole trapping during irradiation and by the creation of vacancy/interstitial pairs. Analysis suggests there is a set (or continuum) of defect subpopulations characterized by the rate-constant pairs (K, R) , where K is the growth rate and R is the recombination rate.

The model is developed under the premise that the underlying kinetic rate constants are truly constant (i.e., independent of dose and time). From analysis of recovery data, this does not seem to be the case for the fibers studied. The recovery of the YDF is dependent on the total dose and time as evidenced by the recovery of the fiber irradiated for 2.5 hours and the YDF irradiated for 45 minutes in the OSURR.

The prediction model was compared to actual recovery data taken from the FBR, OSURR, and ^{60}Co irradiator. Recovery data was collected over long and short lengths

of time for varying total doses of radiation. It was found that the initial rate of recovery of the fibers is faster than what is predicted. The recovery rate of the fibers is dependent on both the dose rate and total dose of radiation (length of irradiation) that the fiber receives.

The model was adjusted based on the initial recovery of the fiber in the first 10-15 minutes after irradiation and then compared to actual data to determine whether this would allow recovery prediction out to longer periods of time. Figure 33 shows a high order fit of the recovery data compared to the prediction model at various lengths of time. The empirical C value, or magnitude, of the RIA degradation is adjusted so that the recovery of the fiber at 10 minutes aligns with the endpoint of the recovery prediction model. Once this has been modified, no other parameters are adjusted, and the prediction model is run for longer periods of time against the actual recovery data. The comparisons show that the model does a reasonable job of predicting the recovery endpoint at subsequent times.

The same method is applied to the FBR and OSURR data, as shown in Figures 34 through 36. The recovery of the first three wavelengths (539, 620, and 650 nm) are predicted relatively well for all three radiation sources. The 1064 nm wavelength, however, does not experience as much recovery is predicted at longer lengths of time. The start of the recovery data appears to shift in some of the OSURR plots due to the way the data was fit. The endpoints of the recovery fit are valid, however.

The recovery over all wavelengths is exponential in that there is an initial recovery that occurs at a fast rate, but slows to a point where full recovery would not occur, or would take a large amount of time. This implies that some defects would be relatively permanent. The recovery prediction model doesn't account for the slowing or eventual end of recovery, but continues to predict recovery to the fibers' original transmission intensity. Due to this it is not a good predictor of the fiber's recovery

over very long periods of time.

The model predicts the recovery of the fiber based solely on the dose rate, the total dose of radiation the fiber receives, and the empirical values determined from the power law equation. The f value for all wavelengths transmitted through a fiber should be roughly the same, meaning the rate of recovery predicted by the model will be approximately equal for all wavelengths, even though the actual recovery rates may be different due to the differing kinetics of the various defects contributing to RIA. The f values averaged to 0.85 for the FBR irradiated YDF, 0.4 for the ^{60}Co YDFs, and 0.1 for the YDFs irradiated in the OSURR. The f values determined from the ^{60}Co data were used in the prediction of the FBR recovery, and the f values determined from the degradation of the fiber in the OSURR experiment with Cd were used to predict the recovery of the fiber from the no-Cd experiment. The order of kinetics used for the FBR and ^{60}Co recovery data was $n = 2$, while the order of kinetics used for the OSURR data was $n = 5$.

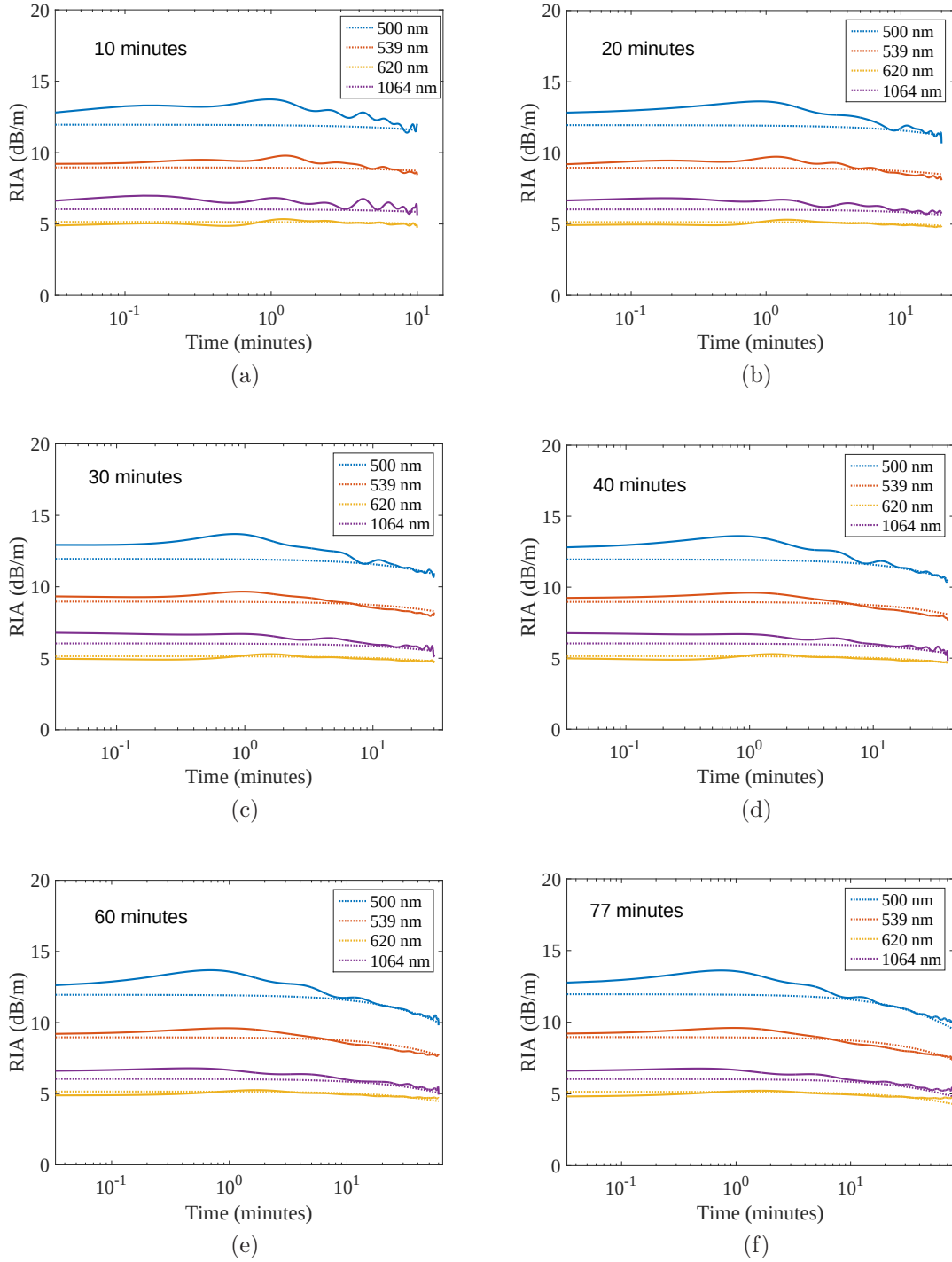


Figure 33. Prediction model versus actual recovery data for ^{60}Co irradiation. The dashed line is the prediction, and the solid line is the experimental data. (a) Recovery of YDF at 10 minutes. (b) 20 minutes. (c) 30 minutes. (d) 40 minutes. (e) 50 minutes. (f) 77 minutes.

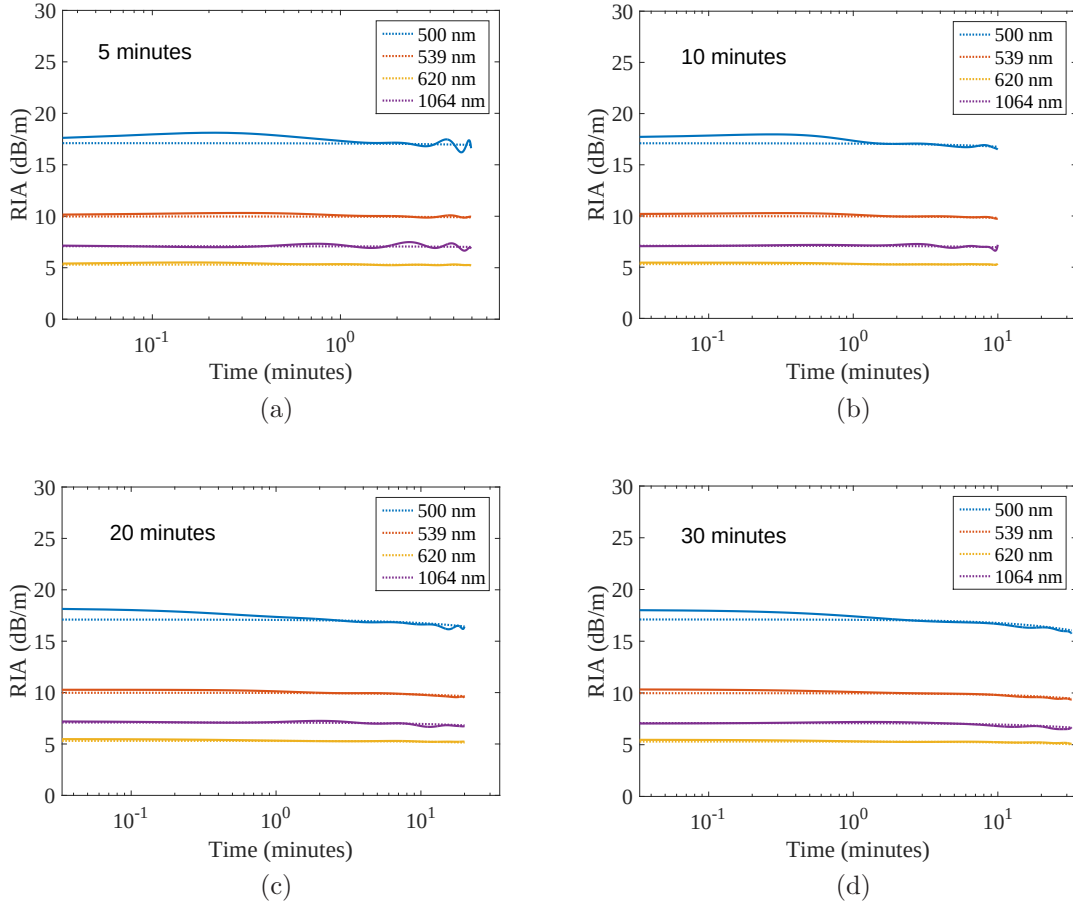


Figure 34. Prediction model versus actual recovery data for FBR irradiation. The dashed line is the prediction, and the solid line is the experimental data. (a) Recovery of YDF at 5 minutes. (b) 10 minutes. (c) 20 minutes. (d) 30 minutes.

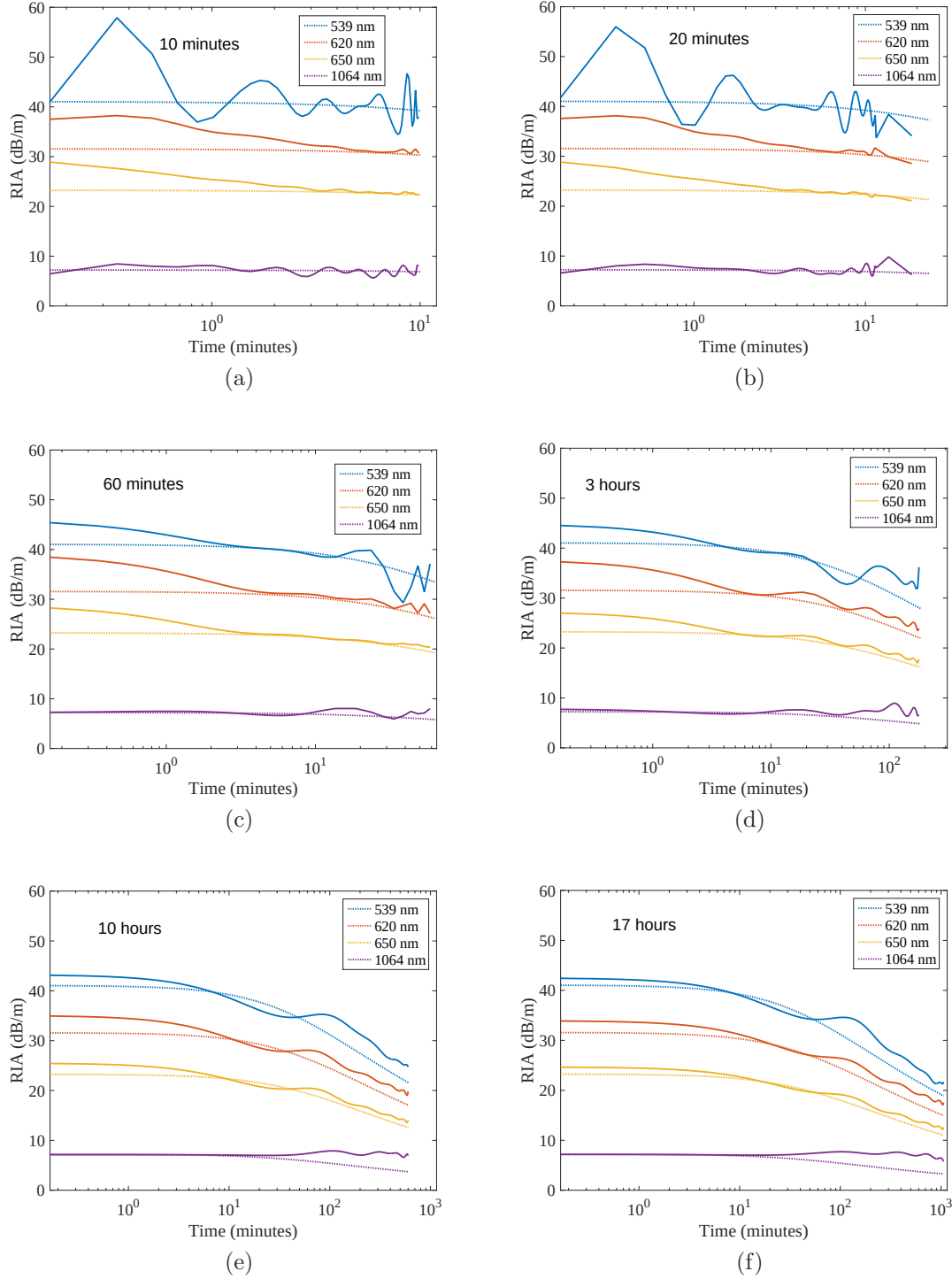


Figure 35. Prediction model versus actual recovery data for OSURR irradiation with the cadmium box. The dashed line is the prediction, and the solid line is the experimental data. (a) Recovery of YDF at 10 minutes. (b) 20 minutes (c) 60 minutes. (d) 3 hours. (e) 10 hours. (f) 18 hours.

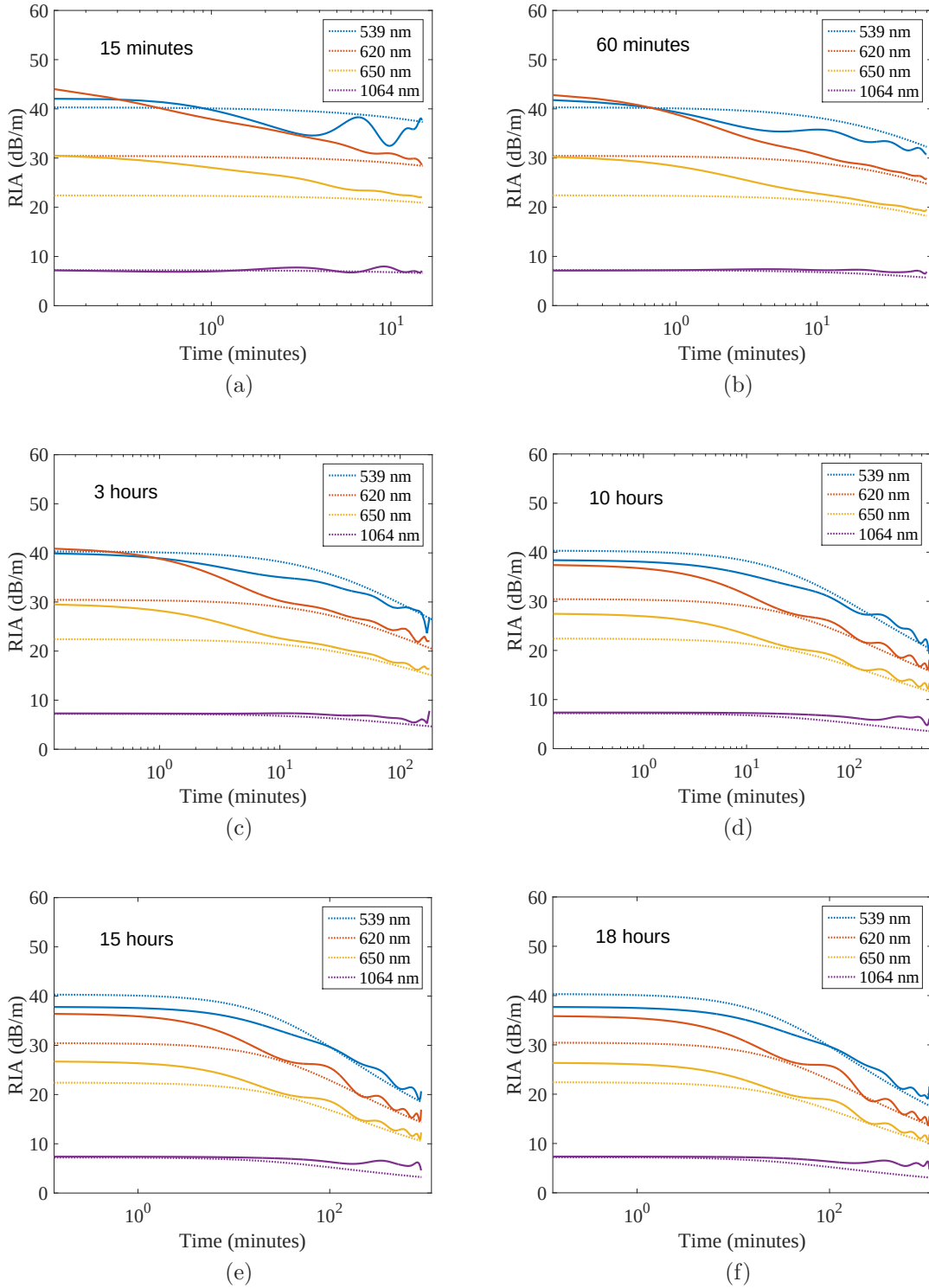


Figure 36. Prediction model versus actual recovery data for OSURR irradiation without the cadmium box. The dashed line is the prediction, and the solid line is the experimental data. (a) Recovery of YDF at 15 minutes. (b) 1 hour. (c) 3 hours. (d) 10 hours. (e) 15 hours. (f) 18 hours.

5. Conclusions

Neutron versus Gamma Effects.

The ALOHC and NBOHC are the two known primary defects that globally lead to attenuation in the fiber from all radiation sources used in the experiments. A defect that was not able to be identified near 500 nm contributes to most of the attenuation seen at this wavelength for fast neutrons. The defects in this region may cause attenuation in the wavelengths primarily of interest for the operation of amplifiers and lasers if they become coordinated to Yb ions or the Gaussian bands have long tails that extend in to the IR region. The results of the experiments, however, did not show defects in the visible region with tails extending into the IR range. There are also defects that contribute to increased attenuation from 975-1100 nm that are not well known. It has been speculated that the main defect responsible is the creation of interstitial O₂ molecules in SiO₂.

The NBOHC concentration seems to be strongly related to the ratio of ionizing radiation to fast neutrons. A comparison of the ⁶⁰Co and FBR data at the same dose of gamma-rays indicates that absorption induced in the wavelength range from 700-900 nm is influenced by a high concentration of only ionizing radiation. The YDF irradiated at the FBR experienced virtually no attenuation in this range, even with the same dose of gammas. The dependence on the formation of NBOHCs also seems to correspond to the doping concentration in the fiber. The 10 μm YDFs, which had specifications indicating they had the highest doping concentration, experienced high concentrations of NBOHCs at low doses in the OSURR irradiation, while the 20 μm YDF experienced a lesser formation of NBOHCs in comparison to other visible range defects. This would indicate that the types of defects formed have a strong correlation with fiber composition as well as the radiation type.

The wavelengths over which each radiation source increases attenuation is:

- ^{60}Co versus FBR: 550-975 nm (^{60}Co), <550 nm (FBR)
- OSURR versus FBR: 550-975 nm (OSURR), <550 nm (FBR)
- OSURR versus ^{60}Co : <600 nm (OSURR)

This indicates that the increased attenuation from 550-975 nm is distinct to ionizing radiation and the increased attenuation below approximately 600 nm is a primarily result of neutron irradiation (potentially fast neutron irradiation causing displacement damage in particular).

The degree of attenuation as a result of fast neutron radiation is much higher than that observed from gamma-only radiation at comparable doses. The main spectral differences as a result of neutron irradiation are seen near the 500 nm wavelength. The attenuation in the 975-1100 nm range is affected by both neutron and gamma radiation similarly with as a function of dose. The shape of the spectrum is the same for the gamma only and neutron only irradiations, indicating that the defect kinetics at those wavelengths is the same. The OSURR spectrum shape was slightly different in this region, however, indicating that a mix of gamma and neutron radiation causes higher order kinetics to take place. The recovery prediction model also indicated this, as the order of kinetics used to predict recovery of the OSURR irradiated fibers was $n = 5$, while the order of kinetics used for both the FBR and ^{60}Co was $n = 2$.

The similarity of the spectral shape and attenuation in the absorption and emission range of the Yb-doped fibers suggests that the attenuation from the fast neutrons can be approximated using gamma-only radiation as the test source. The shape of the spectrum is the same for the neutron-only and gamma-only irradiation regardless of the total dose and dose rate. The attenuation is larger at lower, neutron doses, though, so a dose to RIA equivalency between radiation sources would need to be

better established. The dose uncertainty in the ^{60}Co irradiation was large, so in the future it may be beneficial to use TLDs to gain more accurate dose measurements associated with RIA.

Recovery Prediction Model.

The rate of recovery of the Yb-doped fibers follows a highly exponential curve. As a result, the recovery prediction model is unable to accurately approximate the recovery of the fiber at short times following exposure to high dose rate irradiation. If the initial recovery is accounted for by adjusting the magnitude parameter of the model, however, it is able to approximate the recovery of the fiber out to longer periods of time. The model was only able to be compared to data out to 18 hours, however, so it is unknown to what extent the prediction model remains accurate. The model also will not accurately predict the recovery of the 1064 nm wavelength at longer recovery times, due to the increased rate at which the recovery slows compared to other wavelengths.

Future Work and Recommendations.

There is still knowledge lacking on the effects of fast neutrons on Yb-doped fibers. Additional neutron-only exposures should be performed on the fibers in order to gain a better understanding of the defect kinetics. Additional longer-time recovery data should also be collected for neutron-only irradiations to further that knowledge. The recovery prediction model should also be modified to incorporate the faster rate of initial recovery to gain an accurate prediction of the recovery of Yb-doped fibers within the first few minutes post irradiation. This could probably be accomplished through fitting the initial recovery data and adding a separate component to the equations used to predict the recovery.

Bibliography

1. J. F. Benzoni and D. T. Orletsky, "Military Applications of Fiber Optics Technology," RAND Corporation, Santa Monica, CA, Tech. Rep., May 1989.
2. J. Hecht, *Understanding Fiber Optics*, 5th ed. Auburndale, MA: Laser Light Press, 2015.
3. A. Bjarklev, *Optical fiber amplifiers: design and system applications*. Artech House, 1993.
4. H. Henschel, O. Köhn, H. Schmidt, J. Kirchhof, and S. Unger, "Radiation-induced loss of rare earth doped silica fibres," in *Radiation and Its Effects on Components and Systems, 1997. RADECS 97. Fourth European Conference on*. IEEE, 1997, pp. 439–444.
5. M. Lezius, K. Predehl, W. Stoewer, A. Tuerler, M. Greiter, C. Hoeschen, P. Thierolf, W. Assmann, D. Habs, A. Prokofiev, C. Ekstroem, T. Haensch, and R. Holzwarth, "Radiation Induced Absorption in Rare Earth Doped Optical Fibers," *IEEE Transactions on Nuclear Science*, vol. 59, no. 2, pp. 425–433, April 2012.
6. B. J. Singleton, "Radiation Effects on Ytterbium-Doped Optical Fibers," Ph.D. dissertation, Air Force Institute of Technology, June 2014.
7. S. Girard, J. Kuhnhehn, A. Gusarov, B. Brichard, M. Van Uffelen, Y. Ouerdane, A. Boukenter, and C. Marcandella, "Radiation effects on silica-based optical fibers: Recent advances and future challenges," *Nuclear Science, IEEE Transactions on*, vol. 60, no. 3, pp. 2015–2036, 2013.
8. H. Henschel, O. Köhn, W. Lennartz, S. Metzger, H. Schmidt, J. Rosenkranz, B. Glessner, and B. Siebert, "Comparison between fast neutron and gamma irradiation of optical fibres," in *Radiation and Its Effects on Components and Systems, 1997. RADECS 97. Fourth European Conference on*. IEEE, 1997, pp. 430–438.
9. S. Girard, J. Baggio, and J. Bisutti, "14-MeV neutron, γ -ray, and pulsed X-ray radiation-induced effects on multimode silica-based optical fibers," *Nuclear Science, IEEE Transactions on*, vol. 53, no. 6, pp. 3750–3757, 2006.
10. A. Morana, S. Girard, M. Cannas, E. Marin, C. Marcandella, P. Paillet, J. Périsse, J.-R. Macé, R. Boscaino, B. Nacir *et al.*, "Influence of neutron and gamma-ray irradiations on rad-hard optical fiber," *Optical Materials Express*, vol. 5, no. 4, pp. 898–911, 2015.
11. S. Agnello, "Gamma ray induced processes of point defect conversion in silica," *University of Palermo, Palermo*, 2000.

12. E. Hecht, *Optics*, 4th ed. Pearson Education, Inc., 2002.
13. R. Paschotta, J. Nilsson, A. C. Tropper, and D. C. Hanna, "Ytterbium-doped fibre amplifiers," *IEEE Journal of quantum electronics*, vol. 33, no. 7, pp. 1049–1056, 1997.
14. M. J. Digonnet, *Rare-earth-doped fiber lasers and amplifiers, revised and expanded*. CRC press, 2001.
15. H. Pask, R. J. Carman, D. C. Hanna, A. C. Tropper, C. J. Mackechnie, P. R. Barber, and J. M. Dawes, "Ytterbium-doped silica fiber lasers: versatile sources for the 1-1.2 μm region," *Selected Topics in Quantum Electronics, IEEE Journal of*, vol. 1, no. 1, pp. 2–13, 1995.
16. L. Rumbaugh, "Fiber Lasers and Amplifiers Design Toolbox - File Exchange," July 2013.
17. R. Pfeffer, "Damage center formation in SiO₂ thin films by fast electron irradiation," *Journal of applied physics*, vol. 57, no. 12, pp. 5176–5180, 1985.
18. W. Primak, "Fast-neutron-induced changes in quartz and vitreous silica," *Physical Review*, vol. 110, no. 6, p. 1240, 1958.
19. S. Girard, Y. Ouerdane, B. Torteche, C. Marcandella, T. Robin, B. Cadier, J. Baggio, P. Paillet, V. Ferlet-Cavrois, A. Boukenter *et al.*, "Radiation effects on Ytterbium-and Ytterbium/Erbium-doped double-clad optical fibers," *Nuclear Science, IEEE Transactions on*, vol. 56, no. 6, pp. 3293–3299, 2009.
20. T. Deschamps, H. Vezin, C. Gonnet, and N. Ollier, "Evidence of AlOH⁺ responsible for the radiation-induced darkening in Yb doped fiber," *Optics express*, vol. 21, no. 7, pp. 8382–8392, 2013.
21. T. Wimett, "Fast burst reactors in the United States of America," in *Pulsed Neutron Research. Vol. II. Proceedings of the Symposium on Pulsed Neutron Research*, 1965.
22. J. A. Wall and J. F. Bryant, "Radiation Effects on Fiber Optics," Air Force Cambridge Research Laboratories, Hanscom AFB, MA, Tech. Rep., April 1975.
23. "NRL Irradiation Facility Neutron Fluxes and Dose Rates," <https://reactor.osu.edu/sites/reactor.osu.edu/files/uploads/Facility%20Fluxes.pdf>, accessed: 2015-10-22.
24. "Co-60 Gamma Irradiator Dose-Rate Curve in 6" Tube," <https://reactor.osu.edu/gamma-irradiators>, accessed: 2015-12-30.

25. S. Girard and C. Marcandella, "Transient and steady state radiation responses of solarization-resistant optical fibers," in *Radiation and Its Effects on Components and Systems (RADECS), 2009 European Conference on*. IEEE, 2009, pp. 566–573.
26. E. J. Billo, *Excel for chemists: a comprehensive guide*. John Wiley & Sons, 2004.
27. B. Brichard, A. F. Fernandez, H. Ooms, P. Borgermans, and F. Berghmans, "Dependence of the POR and NBOHC defects as function of the dose in hydrogen-treated and untreated KU1 glass fibers," *IEEE Transactions on Nuclear Science*, vol. 50, no. 6, pp. 2024–2029, 2003.
28. T. Arai, K. Ichii, K. Okada, T. Kitabayashi, S. Tanigawa, and M. Fujimaki, "Photodarkening phenomenon in Yb-doped fibers," 2008.
29. P. D. Dragic, C. G. Carlson, and A. Croteau, "Characterization of defect luminescence in Yb doped silica fibers: part I NBOHC," *Optics express*, vol. 16, no. 7, pp. 4688–4697, 2008.
30. P. D. Dragic, "Observation of NBOHC excitation in pulsed Yb-doped fiber amplifiers," *Photonics Technology Letters, IEEE*, vol. 20, no. 21, pp. 1760–1762, 2008.
31. D. L. Griscom, "Self-trapped holes in pure-silica glass: A history of their discovery and characterization and an example of their critical significance to industry," *Journal of non-crystalline solids*, vol. 352, no. 23, pp. 2601–2617, 2006.
32. J. E. Turner and C. A. Kelsey, *Atoms, radiation, and radiation protection*. Wiley New York, 1995.
33. M. Chadwick, H. Barschall, R. Caswell, P. DeLuca, G. Hale, D. Jones, R. MacFarlane, J. Meulders, H. Schuhmacher, U. Schrewe *et al.*, "A consistent set of neutron kerma coefficients from thermal to 150 MeV for biologically important materials," *Medical physics*, vol. 26, no. 6, pp. 974–991, 1999.
34. D. Griscom, M. Gingerich, and E. Friebele, "Model for the dose, dose-rate and temperature dependence of radiation-induced loss in optical fibers," *Nuclear Science, IEEE Transactions on*, vol. 41, no. 3, pp. 523–527, 1994.
35. L. Skuja, B. Güttler, D. Schiel, and A. Silin, "Infrared photoluminescence of preexisting or irradiation-induced interstitial oxygen molecules in glassy SiO₂ and α -quartz," *Physical Review B*, vol. 58, no. 21, p. 14296, 1998.

REPORT DOCUMENTATION PAGE					<i>Form Approved OMB No. 0704-0188</i>	
The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number. PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.						
1. REPORT DATE (DD-MM-YYYY) 24-03-2016		2. REPORT TYPE Master's Thesis		3. DATES COVERED (From — To) October 2014 - March 2016		
4. TITLE AND SUBTITLE Neutron versus Gamma Radiation Effects on Ytterbium-doped Optical Fibers				5a. CONTRACT NUMBER		
				5b. GRANT NUMBER		
				5c. PROGRAM ELEMENT NUMBER		
				5d. PROJECT NUMBER		
6. AUTHOR(S) Borman, Olivia M., Capt, USAF				5e. TASK NUMBER		
				5f. WORK UNIT NUMBER		
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Air Force Institute of Technology Graduate School of Engineering and Management (AFIT/EN) 2950 Hobson Way WPAFB OH 45433-7765				8. PERFORMING ORGANIZATION REPORT NUMBER AFIT-ENP-MS-16-M-057		
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) Defense Threat Reduction Agency POC: Lt Col Michael Pochet (michael.c.pochet.mil@mail.mil) 8725 John J. Kingman Road Ft. Belvoir, VA 22060				10. SPONSOR/MONITOR'S ACRONYM(S) DTRA		
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)		
12. DISTRIBUTION / AVAILABILITY STATEMENT Distribution Statement A. Approved for public release; Distribution Unlimited.						
13. SUPPLEMENTARY NOTES This material is declared work of the U.S. Government and is not subject to copyright protection in the United States.						
14. ABSTRACT Multimode ytterbium-doped optical fibers (YDFs) are increasingly utilized in military applications involving fiber lasers and amplifiers. YDFs were irradiated with three different radiation sources (neutron, gamma, and mixed gamma/neutron) in order to determine the independent effects that gamma and neutron radiation have on the fibers. The transmission spectra of the fibers were measured during each irradiation and the spectral shapes and attenuation were compared at similar doses. Comparisons of the spectra showed that gamma radiation results in increased attenuation over the 550-975 nm wavelengths. Fast neutrons were found to contribute to increased attenuation near 500 nm. Neutron radiation also caused up to twice the amount of radiation induced absorption that gamma radiation did over all wavelengths in the spectrum measured from 500-1100 nm at the same dose. The spectrum from 980-1100 nm was the same shape between the fast neutron and gamma-only irradiations. This indicates that a ⁶⁰ Co source could potentially be used to approximate the effects on the operating range of YDFs resulting from fast neutrons. A recovery prediction model was also applied and evaluated against actual recovery data. It was found to be unreliable as an accurate predictor of the initial (~ 15 minutes) recovery of YDFs exposed to a dose rate of 65 krad(Si)/hr neutron and 9 Mrad(Si)/hr gamma. By adjusting one parameter in the model to account for the initial faster rate of recovery, the model was able to closely approximate the recovery of the fibers after longer irradiations out to longer recovery periods.						
15. SUBJECT TERMS Radiation effects, Ytterbium-doped, Optical fibers, Neutron, Gamma						
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT		18. NUMBER OF PAGES	
a. REPORT	b. ABSTRACT	c. THIS PAGE	UU		Lt Col Briana J. Singleton, AFIT/ENP	
U	U	U			19b. TELEPHONE NUMBER (include area code) (937)255-3636 x.4571; briana.singleton@afit.edu	