Restoring transmission of irradiated image fiber bundles[a]

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Image fiber bundles are employed in fusion experiments and other high radiation environments where they are used to transmit an image from an unprotected objective lens to a radiation shielded camera. Due to their exposure to neutron and gamma radiation the transmission of these expensive image fiber bundles can rapidly degrade, especially at the shorter visible wavelengths, and require costly replacement. A cost-effective, non-destructive heat treatment process in which entire fiber bundles are heated gradually in air to 150°–200°C and held for tens of hours has been shown to recover much of the transmission lost due to the radiation induced absorption. The restoration process can be repeated multiple times without a loss in effectiveness, although some physical degradation of inter-fiber alignment has been observed. The results and the apparatus used for the successful restoration of the transmission of multiple image fiber bundles across their entire wavelength band will be presented.
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I. INTRODUCTION

Coherent image fiber bundles allow the fiber optic guiding of an image over a distance in places where a set of imaging relay optics would be too expensive or complicated to implement. In fusion research environments, they provide flexibility in installing camera views while allowing the radiation-sensitive camera to be placed in a remote, shielded enclosure. However, the glass fibers themselves are not immune to radiation and have been shown to darken or discolor by a process commonly known as radiation induced absorption (RIA). The details of the RIA mechanism depend on the type of glass used, the type of radiation to which it is exposed, and the temperature at which the material was exposed. In general, energetic photons, electrons, and/or neutrons interact with the glass matrix to form point defects and electron/ion trap sites, leading to changes in valence electron structure and the formation of light absorption centers in the material. At elevated temperatures, many of these defects can be annealed out, restoring the glass to its original transmission.[1–4]

Both constant and cyclic heating of single strand silica and glass fiber optics as well as bulk silicate glass up to 400°C has been previously demonstrated to reduce RIA after exposure to gamma and neutron radiation produced in fission and fusion devices.[5–8] This work describes the RIA observed in Schott IG-163 silicate glass image fiber *bundles* exposed to neutron, gamma and hard x-ray (HXR) radiation on the DIII-D tokamak, as well as the effects and consequences of annealing out the RIA by heating the fiber bundle assemblies up to 200°C in a specially designed oven.

II. FIBER BAKING OVEN DESIGN AND EXPERIMENTAL SETUP

Initial proof-of-principle tests were conducted in a small convection oven with poor temperature control. An irradiated fiber bundle was heated to between 120°C and 250°C for 200 h while coiled into a 14-in. diameter loop, restoring transmission close to that of a new fiber bundle, but a significant number of individual multi-fiber strands had broken. A post-mortem dissection of the fiber bundle found a majority of the broken strands near one end of the bundle, and that the remaining intact strands were very fragile. It is presumed that the overheating had weakened the multi-fibers and that the bending stresses from coiling had caused the breakage.

Thus, an oven was designed to heat fiber bundles uniformly and gently, without bending or twisting them. The oven is composed of a segmented, horizontal heated stainless steel tube, able to accept fibers of up to16 ft in length and up to 1.5 in. in diameter. The segments are connected with KF-40 type silicone o-ring sealed flanges, and form a hermetic chamber that can be evacuated or purged during bakes. The ends of the oven can be left open, allowing access to the fiber ends for *in situ* measurements. Heat is applied externally using a set of five insulated 255 W electric heater jackets, connected in parallel and powered by a solid-state zero-cross power switching module. Oven temperature is controlled using a single-zone proportional integral derivative and ramp-rate capable programmable temperature controller with a thermocouple sensor attached to the center heater segment. As a safety feature, all five heating segments are wired to a multi-zone temperature limit sensor that turns off the heaters if any one of them exceeds a preset temperature limit of 252°C.

The fiber bundle transmission spectrum is measured before, during, and after baking, giving good indications of a relative change in transmissivity. The absolute fiber transmission is calculated based on a constant source spectrum intensity, measured before and after each bake. An Ocean

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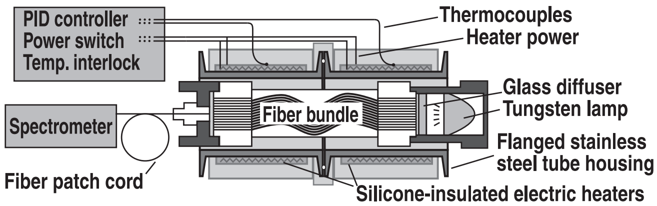

FIG. 1. Schematic representation of a fiber bundle in the baking oven with transmission instrumentation connected.

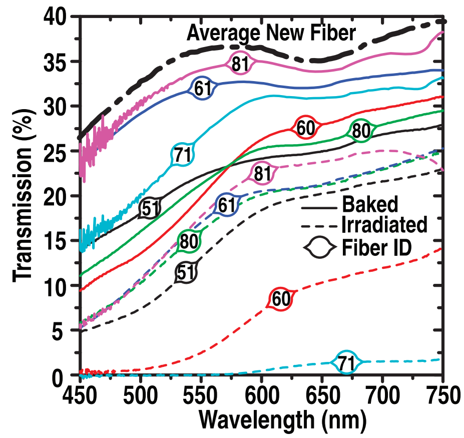

FIG. 2. Transmission spectra of a typical fiber bundle before irradiation (dashed-dotted), and several fiber bundles after a period of irradiation (dashed), and subsequent baking (solid).

Optics USB-4000 spectrometer, sensitive from 200 to 1100 nm, directly couples to either the fiber bundle or the light source through a 400 μm core diameter fiber optic patch cable, as shown in Fig. 1. The transmission measurements assume uniform spatial transmission across the fiber bundle face, since only a small subset of fiber bundle fibers couple to the patch cord. The light source used is a tungsten halogen light bulb diffused by a ground glass disc and driven with a constant current power supply.

III. TRANSMISSION RECOVERY OF IRRADIATED FIBER BUNDLES

The transmission spectra of several fiber bundles exposed to varying amounts and types of radiation around the DIII-D tokamak were measured before and after various heat treatment cycles. While the precise composition of the glass in the Schott IG-163 fibers is proprietary, it is known that the fibers have a lead silicate core with a borosilicate cladding. The primary source of radiation around the tokamak is high energy D-D fusion neutrons and decay gammas from neutron activation of surrounding materials.[9] In addition, certain plasma disruptions can trigger a runaway avalanche of relativistic electrons that persist for hundreds of milliseconds and that produce large amounts of HXR photons with a broad distribution of energies up to 60 MeV when the electrons strike a material surface. These relativistic electrons travel toroidally in a relatively narrow beam and thus the outward directed radiation is usually localized to the equatorial midplane.[10]

Figure 2 shows the transmission spectra of several fiber bundles after various radiation exposures and their transmission after baking, compared with the spatially averaged transmission spectrum of an un-irradiated fiber bundle. All the fiber bundles in this study were exposed to radiation at room temperature. Fibers 60, 71, and 80 were installed at or near the midplane during HXR generating discharges. The induced absorptions appear to match those observed in previous studies of x-ray and gamma ray irradiation of silicate glasses creating non-bridging oxygen-hole centers.[11] Table I summarizes the irradiation conditions, bake conditions, and transmission loss and recovery at 550 nm for each fiber bundle restoration cycle shown in Fig. 2. Table I also summarizes the prior accumulated bake and irradiation history for each fiber bundle, where data were available. Since the absorbed dose to each fiber bundle was not recorded directly, it is assumed to be proportional to the dose recorded by various detectors installed in fixed locations around the machine and thus is listed in arbitrary units. The observed RIA correlates with higher levels of neutron, gamma, and HXR radiation exposure. Notably, the fiber bundles showing the strongest RIA were those with the highest HXR exposure, and these fiber bundles also show a greater amount of induced absorption below 500 nm.

The fiber bundles showing the greatest recovery over the shortest bake time also had the lowest amount of accumulated radiation dose before each bake, indicating that shorter, more frequent bakes may be more effective at maintaining optimum transmission. Fiber bundles baked multiple times do not show any clear difference in the restorability of the transmission nor any change in sensitivity to radiation, but they do show lower levels of transmission over time due to an accumulation of unrestored losses. Most fibers were heated to a maximum temperature of 200°C, with gradual heat and cool down rates ranging from 11° to 48°/h, and were held at temperature for a period of 24–300 h. The slow but nearly complete recovery results from a single fiber bundle baked for 196 h at 165 °C hint that that lower temperatures may be used to recover transmission over longer periods of time.

TABLE I. Details of the irradiation and bake conditions for the fiber bundle restoration cycles shown in Fig. 2, as well as the accumulated history of irradiation and bake time for each bundle. The transmission values listed are taken at 550 nm.

Fiber ID	51	60	61	71	80	81
Final irradiation and bake cycle						
Max temp (°C)	200	200	200	200	165	200
Duration (h)	64	113	59	61	196	22
Neutron (au)	1.0	9.0	16	6.8	1.5	5.4
Gamma (au)	0.15	1.1	2.3	0.88	0.24	0.71
HXR (au)	0	60	0.24	960	60	0
Tx before irradiation	25%	22%	35%	NA	22%	36%
Tx after irradiation	13%	2%	17%	<1%	17%	18%
Tx after baking	22%	19%	32%	27%	21%	34%
Prior accumulated totals						
Duration at 200°C (h)	182	718+	0	268	218	0
Total neutron (au)	3.1	7.5+	0	NA	NA	0
Total gamma (au)	0.48	0.93+	0	NA	NA	0
Total HXR (au)	740	740	0	NA	NA	0

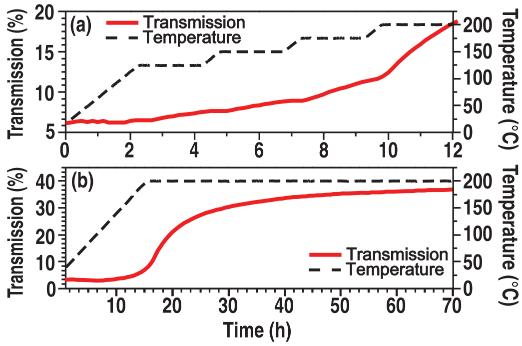

FIG. 3. Temperature and transmission at 550 nm vs time for two different fiber bundles: (a) Short temperature steps at 125°, 150°, 175°, and 200°C, showing the dependence of transmission recovery with temperature; (b) long bake at 200°C showing the slow recovery following a fast initial rise.

To illustrate the temperature dependence of transmission recovery, the transmission at 550 nm vs time is shown for two typical fibers in Fig. 3. Figure 3(a) illustrates how the transmission recovery rate increases with temperature, revealing that the rate of recovery starts to increase dramatically above 175°C. Figure 3(b) shows how the rate of recovery tapers off with time at constant temperature. At 200°C, it was found that 60 h was sufficient for recovering the majority of transmission losses in several fiber bundles.

IV. THERMALLY INDUCED DAMAGE

The manufacturer's operating temperature limit for the fiber bundles is 120°C, above which the strength of the binding epoxies and the integrity of the teflon sheath material start to degrade. Epoxies are used in the construction of the fiber bundle to bind individual 10 μm diameter fibers into flexible 6×6 arrays called multi-fibers, and also to rigidly bind the multi-fibers into 8×10 mm, spatially coherent rectangular arrays over the last 2–3 cm at each end of the fiber bundle. Thermal damage caused by overheating the various binders can lead to reduced multi-fiber flexural strength and reduced shear strength of the inter-multi-fiber binder epoxy.

Evidence of damage induced by the baking process has been observed on certain fiber bundles. This was seen by imaging through the fiber bundles a pattern of lines aligned to the long (horizontal) and short (vertical) dimensions of the rectangular fiber bundle face. Magnified images of the output ends of three example fiber bundles are shown in Fig. 4. An original, unbaked fiber (Figs. 4(a) and 4(b)) is compared to one that experienced excessive thermal transients and gradients leading to damage (Figs. 4(c) and 4(d)), and one that was baked uniformly and showed no damage (Figs. 4(e) and 4(f)). The distortion observed results from the randomly distributed, non-uniform shifting of rows of multi-fibers along horizontal slip directions due to the weakened inter-multi-fiber epoxy yielding at temperature to the internal stresses built up during assembly or induced due to thermal gradients. A small number of broken multi-fibers, seen as dark squares, have been observed after a number of bake cycles, but it is unclear whether these are due to baking or general use of the fiber bundle. No correlation has been found between the induced distortion and the bake temperature or duration. However, the fiber bundles

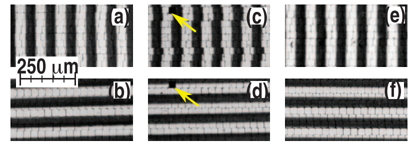

FIG. 4. Images of the same vertical and horizontal line patterns viewed through three different fiber bundles. (a) and (b) are through a new, unbaked fiber bundle. (c) and (d) are through a fiber bundle that was cycled twice to 200°C (once at 12°/h and once at 50°/h with 100°/h cooling), held for a total of 218 h, with forced air cooling of the fiber ends. (e) and (f) are taken through a fiber bundle that was cycled four times to 200°C (twice at 8.3°/h and twice at 50°/h) and held for a total of 421 h, with uniform heating through the fiber ends. The yellow arrows in images (c) and (d) points to a broken multi-fiber.

showing the greatest amount of distortion were also exposed to either the highest thermal transients or thermal gradients.

V. SUMMARY

Fiber bundles exposed to the tokamak radiation environment exhibit a loss in transmission across the visible spectrum. Neutron exposure and gamma radiation account for a moderate degradation, but an exposure to short bursts of hard x-rays accounts for the greatest amount of degradation observed. The transmission loss was shown to be recoverable to varying degrees by heating the fiber bundles to temperatures ranging from 120° to 200°C, with greater and more rapid recovery observed at higher temperatures. The amount of restored transmission depends on many factors, including bake duration, total accumulated radiation dose, and the type of radiation. Thermal damage effects, such as the minor loss of spatial coherence of the transmitted image, can be reduced by improving temperature uniformity of the fiber bundle during heating, reducing thermal transients, and minimizing any fiber bending during heating.

ACKNOWLEDGMENTS

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