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Transmission of Free-Running Laser Pulses of High Energy and Power Densities Through Previously Gamma-Radiated Fiber Waveguides

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Abstract

The surface threshold damage levels (STDL's), ξ_1 and ρ_1 , (input energy and power densities) and coupling efficiencies, ϵ , (ratio of output-to-input energy) have been determined for single and multiple optical fiber waveguides of three manufacturers before and after they were exposed to a ^{60}Co source. For 400 μs duration Nd^{+} free-running laser pulses the largest STDL of $\xi_1 = 4.66 \text{ J/cm}^2$ and $\rho_1 = 46.6 \text{ MW/cm}^2$ was observed for multiple laser shots in a Fiberoptic Cable Corp. fiber followed by a single laser shot in a Corning Glass Works fibers with an STDL of $\xi_1 = 4.50 \text{ J/cm}^2$ and $\rho_1 = 45.0 \text{ MW/cm}^2$. The 10^4 rad(Si) of gamma irradiation to 1 cm of fiber did not reduce the low or high ξ_1 , ρ_1 or ϵ values in any of the three types of fibers tested. At lower than STDL, many free-running laser pulses were transmitted through the Corning Glass Works, Fiberoptic Cable Corp. and Valtac Corp. fibers without decreasing $\epsilon > 20\%$. For all fibers in which STDL's were reached there was no evidence that the observed decrease in ϵ was caused by other than optical damage at the input face of the fibers.

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I. INTRODUCTION

A fiber optic waveguide application under consideration includes transmitting multi-mode free-running laser pulses^{1,2} (~400 μ s-duration) containing high energy and power. It is a concern whether sufficient energy density ($>100 \text{ J/cm}^2$) can be transmitted through fiber waveguides to perform the required function after the fibers are subjected to a high gamma radiation dose of 10^6 rad at a dose rate of 10^5 rad/h. Many investigators have measured radiation-induced permanent and transient effects³⁻⁹ in fiber optic waveguides at varying gamma, X-ray, electron, and neutron radiation levels, but no one has transmitted high laser energy and power through the fiber after irradiation.

The output energy and power handling capacity of optical fiber are limited both by optical damage to the fiber²⁰⁻²⁵ and by losses in the fiber resulting from residual and radiation-induced³⁻¹⁹ absorption in the core materials, scattering at the core-cladding interface, Rayleigh scattering, and backward-stimulated Raman and Brillouin scattering²⁶⁻³¹.

It is the purpose of this report to describe measurements of the coupling efficiency (output energy/input energy), input and output energy and power densities, the surface threshold damage levels (STDL's) and the optical damage in three types of fiber optic waveguides. These properties of fibers from Valtac Corp. (VC), Fiberoptic Cable Corp. (FOC), and Corning Glass Works (CGW) were measured using 400 μ s-duration Nd:glass laser pulses before and after irradiation with a ^{60}Co gamma ray source.

II. SCOPE

In addition to the Introduction and Scope Sections, this report describes the experimental set-up used in testing the optical fibers (Section III); the theory of light coupled and transmitted through optical fibers (Section IV); experimental results (Section V); and discussions and conclusions (Section VI).

III. EXPERIMENTAL SET-UP

This section describes the mechanical and optical experimental set-up used to generate and amplify the free-running laser pulses, hold the optical fibers, detect the temporal power profile and energy contained in the laser pulses, align the entire laser and optical fiber systems, and photograph the ends of the fibers. It also describes

the electrical timing of the entire system.

Mechanical and Optical

The mechanical and optical set-up used in studying the threshold damage level of optical fibers is shown in Figure 1. The oscillator³² (OSC) consists of two 90 deg., chip-free, knife-edge, right-angle prisms (PR_1 and PR_2), with their knife edges oriented 90 deg., used as end reflectors; a 50 percent reflective beamsplitter (BS_5) output coupler; Nd^{3+} glass laser rod (LR) pumped by a doubled elliptical cavity, containing two EG&G FX47C Xenon flashlamps (FL); and a 3.87-mm-diameter aperture (A_1). The laser rod, of ED-2 glass, is 0.96 cm in diameter by 17.0 cm long. The laser rod, flashlamp, and cavity walls are water cooled for more stable operation.

The output of the oscillator is directed through the laser amplifier (AMP) to the input end of the optical fiber by four mirrors (M_2 , M_3 , M_4 , and M_5). The amplifier, built at Sandia Laboratories, consists of a 61-cm-long by 1.27-cm-diameter, 5 percent Nd^{3+} ED-2 glass rod, four 50.8-cm by 1.3-cm-diameter linear Xenon flashlamps in a close couple pumping geometry, and a power supply. The ends of the rod are cut parallel to each other, with their normals 6 deg. relative to the geometric axis of the laser rod, to eliminate reflection feedback into the oscillator. The power supply charges four 275 μF capacitors to 1.7 kJ.

The oscillator laser beam is sampled at Station (STA) #1 by a beamsplitter (BS_1). The amplified beam also is sampled at STA #2 by a beamsplitter (BS_2). STA #2 samples the amplified beam between the fiber aperture (A_2) and the entrance into the fibers. Each station contains two uncoated quartz beamsplitters (BS_1 or BS_2 and BS_3); a 50-50 coated BK-7 beamsplitter (BS_4); a KD1 photodiode (D_1 or D_2) manufactured by Korad; and two linear semiconductor diode arrays (RA) manufactured by Reticon. BS_1 and BS_2 each sample 4 percent of the incident laser beam of which 3.7 percent is directed to a pressed magnesium oxide diffuser (DF). Photodiodes D_1 and D_2 sample the energy and temporal shape of the laser pulses scattered by the magnesium oxide diffuser. The responses of D_1 and D_2 are calibrated against the energy in the laser beam by energy meters EM_1 (manufactured by Quantronic) and EM_2 , respectively. EM_3 measures the energy transmitted through the fibers.

Approximately 0.1% of the incident beam is directed toward the Reticon Model EC-256 and EC-512 diode array, which are 1.27 and 254-cm-long and contain 256 and 512 diodes in STA #1 and STA #2, respectively. The diodes, each 0.00254 cm on edge, are fixed 0.065 cm on line center. At each station, one array displays energy contained in a 0.00254-cm-slit height across the laser beam in a horizontal direction (H) and another

Figure 1. The mechanical and optical set-up used in studying surface threshold damage levels of optical fibers is illustrated. The components are the Nd³⁺ laser oscillator (OSC) and amplifier (AMP), alignment gas laser (He-Ne), beam sampling stations (STA #1 and STA #2), energy meters (EM₁, EM₂, and EM₃), lens system (L), microscope (M), auto-collimator (AC), optical fiber, directing mirrors (M₁, M₂, M₃, M₄, and M₅), beam splitters (BS₀, BS₁, BS₂, BS₃, and BS₄), and restricting apertures (A₁, A₂, and A₃). Each beam sampling station has two beam splitters (BS₀ and BS₁), a diffuser (DF), a photodiode (D₁ or D₂), and two linear diode arrays (RA).

displays energy in a vertical direction (V). Neutral density filters keep the arrays and photodiodes operating in their linear regimes.

Aperture A_2 , beamsplitter BS_2 , trinocular system L, and microscope M are mounted on adapter plates which are kinematically mounted onto plate #1. The microscope is also kinematically mounted onto plate #2. This mounting technique allows both the microscope, which is used to photograph the ends of the fibers at a magnification of 35.6 X, and the other components to be removed and repositioned without refocusing or realigning.

The lens system (L) provides options of either a single lens pointing system or a Hadron trinocular viewing and focusing system. In the first method a laser burn is made on Hadron "fingerprint" paper placed at the input end of the fiber approximately at the focal point of an 8.09 cm focal length lens (L_1). A pointer is placed at the center of the laser burn. The paper is removed. The input end of the fiber is centered onto the pointer. A 10X eyepiece is used in positioning all the above.

The Hadron trinocular viewing and focusing system contains a flip-flop mirror to view the input end of the fiber and the burn. With the flip-flop mirror up, a burn is made on "fingerprint" paper placed at the input end of the fiber approximately at the focal point of the 9.01-cm focal length lens (L_2) of the Hadron trinocular viewing and focusing system. With the flip-flop mirror down, the crosshair of the viewing eyepiece is centered over the image of the burn by moving the mirror. The image of the input end of the fiber is centered on the crosshair by moving the input end of the fiber.

The microscope (M) is a Zeiss-Model PS-45 trinocular polarizing tube with a Nikon photomicrographic attachment (Model EFM) containing a relay lens, an eyepiece, and a polaroid adapter.

A telescope (T), aperture (A_3), mirrors (M_6 and M_7), and beamsplitter (BS_5) are used with the Spectra Physics Model 124B laser (He-Ne) to align the OSC, AMP, optical fiber, and other components. Components BS_5 and M_7 are positioned on kinematic mounts for ease of removing and precise repositioning during alignment. All the mirrors which reflect both the He-Ne and the Nd^{3+} laser beams are coated for maximum reflectivity at both 632.8 and 1060 nm.

Electrical

Figure 2 shows the block diagram of the electrical connections of the laser OSC and AMP, oscilloscopes (SCOPE), photodiodes (KDI), Reticon arrays (H and V), and associated equipment (generators and power supplies). A switch closure in the operator's hand initiates the triggers of the Rutherford Generator at $T_0 = 0$.

Figure 2. This block diagram illustrates the electrical connections of the laser OSC and AMP, oscilloscopes (SCOPE), photodiodes (KDI), Reticon arrays (H and V), and associated equipment (HP 214 GEN. #1, #2, and #3, Rutherford generator, DC power supply, and Reticon power supply). The relative time sequence is also illustrated.

The trigger T_3 to section B of SCOPES 1 and 2 is adjusted to the free-lasing pulse emission time. The oscilloscope sweep speeds are adjusted so that each array is read out in ten divisions, making each scale division 0.127 and 0.254 cm for Model EC-256 and EC-512 arrays, respectively. The timing sequence is illustrated in the lower part of Figure 2.

IV. Theory

For a highly collimated laser light source with no area mismatch to the fiber, the entire energy is coupled into the fiber except for Fresnel reflection and fiber-packing fraction losses (neglecting scattering from the input face), since the acceptance angle of the fibers is larger than the laser divergence. The coupling efficiency which accounts for losses due to transmission (T), scattering (σ), absorption (α), and fiber packing fraction (f_1) is given as

$$\epsilon = T f_1 \alpha = E_2/E_1, \quad (1)$$

where E_2 and E_1 are the output and input energy of the fiber, respectively. The transmission is given as

$$\begin{aligned} T &= (1-R)^2 = (1-\rho^2)^2 \\ &= \left(1 - (\eta_0 - \eta_2)^2 / (\eta_0 + \eta_2)^2\right)^2, \end{aligned} \quad (2)$$

where η_0 and η_2 are the refractive indices of the air and core material, respectively. For long fibers (> several metres) the packing fraction, which consists of the packing density (γ) and the core fraction (f_2) is given by

$$f_1 = \gamma f_2. \quad (3)$$

The maximum packing density is 0.79 or 0.91 for square or hexagonal packed fiber array³³ respectively. If the fibers are loosely packed, these values will be smaller. The core fraction is

$$f_2 = (a/b)^2, \quad (4)$$

where a and b are the core and core plus clad diameters. The lengths of the fibers were $0.3 \pm .001$ m. Cladding modes were not removed for these short fibers. For these short, low-loss fibers (<40 db/Km) scattering and absorption losses are negligible within $\pm 1.2\%$.

V. Experimental Results

In this study we tested optical fibers manufactured by Valtac Corp (VC), Fiber-optic Cable Corp. (FOC), and Corning Glass Works (CGW)³⁴. The physical and optical characteristics of these fibers are listed in Table I. The fiber bundles were in single and multiple fiber forms. An epoxy binder was used to hold the fibers in the CGW bundles. A Silicon type binder was used to hold the fibers in the FOC and VC bundles. "Ref loss %" in Table I refers to Fresnel reflection losses.

TABLE I
PHYSICAL AND OPTICAL CHARACTERISTICS OF FIBERS

Fiber No.	Mfg	Core Mat	No. of Fibers	Core dia (μ m)	Core η	Ref Loss %	T	NA
FN10-FN17, FN22	VC	Silica	1,7 1	100-140 250	1.449	3.36	0.934	0.30
FN18-FN21	FOC	Silica*	7	210-240	1.449	3.36	0.934	0.30
FN23-FN27	CGW	Silica ⁺	7	87-96	1.467	3.62	0.929	0.15 [†]

NA is numerical aperture

* Cladding plastic

⁺ Ge-doped core and boron doped silica cladding

[†] Calculated at $\lambda = 1.060$ nm, $\eta = 1.467$ (core) and 1.459 (cladding)

Free-running laser pulses were transmitted through optical fibers before and after they were exposed to $\geq 10^6$ rad(Si) of gamma radiation. The optical fibers were irradiated at the Sandia Laboratories Gamma Irradiation Facility using a ^{60}Co source. Test durations ranged from 9.7 to 11.6 hr, yielding 8.5×10^4 to 10^5 rad/h dose rate.

Table II lists results for the 18 fibers tested. The maximum calculated output energy density $\xi_2(M) = E_2(M)/A(f)$, where $E_2(M)$ is the maximum output energy and $A(f)$ is the total area of the fiber core or cores and the maximum calculated input energy density $\xi_1(M) = \xi_2(M)/T$ where T is given by Eq. 2. The total number of laser shots transmitted through the fiber at both low-and high-energy density and before or after gamma irradiation (irr) is recorded under "No. Laser Shots." Fibers FN10-FN16 were aligned relative to the free-running laser pulse using the pointing system, while fibers FN17-FN27 were aligned using the Hadron trinocular viewing system. Bot. systems were described earlier.

TABLE II

ENERGY DENSITIES AND COUPLING EFFICIENCIES IN FIBERS

Fiber No.	Mfg	No. Fibers	Maximum		ϵ (Max.)	No. Laser Shots	Irr. Mrad*
			E_2 kJ/cm ²	E_1 kJ/cm ²			
FN10	VC	7	0.061	0.065	0.160	3	-
FN11	VC	7	0.093	0.100	0.107	4	-
FN12	VC	1 ⁺	0.014	0.015	0.017	5	-
FN13	VC	1 ⁺	0.739	0.791	0.896	3	-
FN14	VC	7	2.766	0.962	0.881	7	10 ⁶
FN15	VC	1 ⁺	2.450	2.623	0.708	3	-
FN16	VC	1 ⁺	3.554	3.806	0.887	3	-
FN17	VC	1 ⁺	0.286	0.306	0.800	3	-
FN18	FOC	7	1.022	1.094	0.788	12	-
FN19	FOC	7	0.135	0.145	0.814	7	10 ⁶
FN20	FOC	7	0.907	0.971	0.852	11	10 ⁶
FN21	FOC	7	0.269	0.288	0.858	1	10 ⁶
FN22	VC	1 ⁺	0.079	0.085	0.908	5	-
FN23	CGW	7	2.680	2.895	0.792	11	10 ⁶
FN24	CGW	7	0.278	0.300	0.744	4	10 ⁶
FN25	CGW	7	3.978	4.282	0.688	5	10 ⁶
FN26	CGW	7	1.950	4.500	0.295	2	10 ⁶
FN27	CGW	7	0.281	0.303	0.905	6	10 ⁶

* Background $< 3.8 \times 10^3$ rad(Si)

+ PC10

† PC5

VC Fibers

Initially the input ends of VC fibers FN10 and FN11 were placed 0.87 cm ahead of the focal point of L_1 . The laser pulse was incident on all 7 fibers of these fiber bundles. The total area $A(f)$ of the 7 fiber cores of FN10 was 6.4×10^{-4} cm². An E_2 of 0.038 J resulted in $\epsilon_2 = 0.059$ kJ/cm², $\epsilon_1 = 0.063$ kJ/cm², and a low $\epsilon = 0.16$. From the $E_1 = 0.242$ J for the same shot and ϵ_1 value above, the calculated area of the laser beam A was $E_1/\epsilon_1 = 0.242/0.063 = 3.75 \times 10^{-3}$ cm². The area of the ferrule containing all the fibers was slightly larger, 2.89×10^{-3} cm². No visual damage occurred at these low input power levels. A similar calculation for FN11 resulted in an $A(f)$ of 5.58×10^{-4} cm² and a slightly smaller A of 4.86×10^{-3} cm².

For both VC fibers, photographs after each laser shot (LS) show that the binding and cladding materials vaporized and recollected onto the ends of the fiber. This accounts for the observed decrease in ϵ with increasing number of laser shots (LS's), as well as the physical change to the input face of the fibers.

A single PC10 VC fiber (FN12) was placed 0.38 cm beyond the focal point of L_1 . The area of the fiber core ($A(f)$) was $5.27 \times 10^{-4} \text{ cm}^2$ whereas the calculated area of the laser beam A was $E_1/\xi_1 = 0.415/14.5 = 2.86 \times 10^{-2} \text{ cm}^2$. Photographs of FN12 in Figures 3A-3E, taken after each LS, show that the left side of the core is increasingly overlayed with what appear to be recondensed vapors of the vaporized plastic cladding. This vapor accounts for the observed decrease in ϵ from 0.017 to 0.0108 with increasing number of LS's. Only the left side of the cladding shows deterioration because the other portion was broken at a slant range away from the plane of the paper so that the laser beam was not incident on it with as high an ξ_1 . The low ϵ values indicate a large mismatch between the laser beam diameter and the core diameter.

Figure 3. Photographs of the input end of VC fiber FN12 illustrate its surface damage and decrease in ϵ (lower no.) for low ξ_2 values (upper no. in kJ/cm^2) with increasing laser shot (LS) no. Photographs A-E were taken after the 1st-5th LS, respectively.

Another single PC10 VC fiber (FN13) was used in an attempt to decrease the laser beam to fiber core mismatch. The L_1 -to-fiber dimension was increased by another 0.15 cm, thus positioning FN13 0.53 cm beyond the focal point of L_1 , as was determined by burn dimensions on "fingerprint" paper as a function of distance from L_1 . The 0.53 cm dimension resulted in the smallest burn diameter. The maximum ϵ value for this fiber position was 0.896. The area of the fiber core, $A(f)$, was $5.03 \times 10^{-4} \text{ cm}^2$ whereas A was $E_1/\xi_1 = 0.415/791 = 5.25 \times 10^{-4} \text{ cm}^2$ (slightly larger than $A(f)$). The photographs after the LS's do not show any apparent damage to the fiber core, yet ϵ decreased from 0.896, 0.876, to 0.723 for approximately constant ξ_1 values.

The central fiber of VC FN14 was tested with the same laser beam diameter as used for testing FN13. The ξ_2 and ϵ values are listed in the upper (kJ/cm^2) and lower number in each photograph in Figure 4. Photograph A was taken after

the first LS. Photographs B-I were taken after 1 cm of the fiber had been exposed to the 10^6 rad(Si) of gamma radiation. The appearance of the input end of the fibers changed gradually until the 4th LS, where an abrupt change occurred. More LS's continued to change the physical characteristics of the input face of the fibers.

Figure 4. Photographs of the input end of VC fiber FN14 illustrate the increase in its surface damage and corresponding decrease in ϵ (lower no.) for high ϵ values (upper no. in kJ/cm^2) with increasing laser shot (LS) no. Photograph A was taken after the 1st LS. Photographs B-F and H were taken after the 1st-6th LS after irr. Photographs F and G were taken after the 5th LS after irr and H and I after the 6th LS after irr. Photograph J was taken before the 1st LS.

The high values of ϵ calculated for FN14 in Figure 4 indicate that the laser energy was transmitted through only the central fiber. The central core area $A(f)$, was $1.37 \times 10^{-4} \text{ cm}^2$, while the calculated laser beam area, A , was $1.43 \times 10^{-4} \text{ cm}^2$ (slightly larger than $A(f)$). For the lower value of $\epsilon = 0.426$, the calculated laser beam area of $3.00 \times 10^{-4} \text{ cm}^2$ is slightly larger; although the laser beam area was not changed for this shot. The larger calculated laser area indicates that the ξ_1 value was smaller because the transmission decreased at the face of the fiber due to vapors recondensing over the entrance or core of the central fiber of FN14. The ratio of the laser beam areas $1.45 \times 10^{-4} / 3.00 \times 10^{-4}$ is approximately equal to the ratio of ϵ 's. The conclusion, therefore, is that all the energy went through the central fiber core.

We placed VC fiber FN15-FN17 into the test system to determine whether we could couple the laser energy into single fibers of 1.21 to $1.26 \times 10^{-2} \text{ cm}$ core diameter (d). The variations in the observed ϵ values for these fibers (Table II) are attributed to the uneven breaks in the ends of the fibers. The ξ_2 of 3.554 kJ/cm^2 for FN16 was the highest recorded for VC fibers.

The photographic sequence for FN16 ($d = 1.21 \times 10^{-2} \text{ cm}$) in Figure 5 shows that after the 1st LS containing large input energy density, ($\xi_1 = 3.806 \text{ kJ/cm}^2$) Figure 5A, slight

damage appeared at the input face. This was the 2nd LS into the fiber, the 1st was at ($\xi_1 = 0.307 \text{ kJ/cm}^2$). The next LS, $\xi_1 = 3.768 \text{ kJ/cm}^2$ (Figure 5B) increased the damage. At lower ξ_1 values in FN17 ($d = 1.21 \times 10^{-2} \text{ cm}$) more severe damage occurred after the 3rd LS into the fiber (compare photographs in Figure 5C taken after the 1st LS $\xi_1 = 0.131 \text{ kJ/cm}^2$, to Figure 5D taken after the 3rd LS, $\xi_1 = 0.306 \text{ kJ/cm}^2$). The calculated laser areas for FN15, FN16, and FN17 was 1.65 , 1.21 , and $1.35 \times 10^{-4} \text{ cm}^2$, respectively. These areas for FN15 and FN16 compare favorably to that calculated for FN14, when the same test configuration was used. The Hadron viewing system was used for FN17 with the fiber at the focus of L_2 ($f = 9.01 \text{ cm}$).

Figure 5. Photographs A and B of the input end of VC fiber FN16 illustrate the increase in its surface damage after two high ξ_1 value (upper no. in kJ/cm^2) laser shots (LS's). Photographs C and D of the input end of FN17 illustrate the increase in its surface damage after the 1st and 3rd LS for low ξ_2 values.

The 10^6 rad(Si) of gamma irradiation did not reduce the ξ_2 or ϵ values observed for VC fibers (compare FN13 to FN14 in Table II).

FOC Fibers

Both low and high ξ_2 values were calculated for the FOC fibers FN18-FN21. The cross-sectional areas of the central fiber cores tested varied from 3.49, 3.49, 4.17, to $4.49 \times 10^{-4} \text{ cm}^2$, respectively. The calculated ξ_2 values in Table II are low since the area used was that of the core of the fiber tested. The laser beam cross-sectional area calculated from FN17 data was $1.34 \times 10^{-4} \text{ cm}^2$ or 2.60, 2.60, 3.11, and 3.35 times smaller than the core area of fibers FN18-FN21, respectively. The variations in ϵ from fiber-to-fiber are attributed to variations in surface finish of the ends of the fiber.

As a means of determining the area of the laser beam for FN18-FN21 more accurately, we tested a VC fiber FN22 with a $1.13 \times 10^{-2} \text{ cm}$ core diameter giving an area of $9.94 \times 10^{-5} \text{ cm}^2$. As shown in Table II, the maximum ϵ value observed was 0.908, but the variation in its value was from 0.881, 0.908, 0.895, to 0.885, for an average of 0.892. If the fiber losses consisted of only Fresnel reflection losses at the ends, $\epsilon = T = 0.929$ (Table I), then it can be concluded that the cross-sectional area of the laser beam at the input end of FN22 was equal to the the cross-sectional area of FN22 core to within $\pm 2\%$. The calculated value of the laser beam areas varied from 1.02, 1.02, 1.04, to $1.08 \times 10^{-4} \text{ cm}^2$ for an average value of $1.03 \times 10^{-4} \text{ cm}^2$. Using this calculated average as the laser beam area for FN18-FN21, the calculated ξ_2 and ξ_1 values changed as shown in Table III. These values are the

TABLE III
CALCULATIONS OF ξ_2 AND ξ_1 USING
THE AVERAGE A FROM FN22

Fiber No.	A(F)/A	Maximum	
		ξ_{out} kJ/cm ²	ξ_{in} kJ/cm ²
FN18	3.4	3.490	3.675
FN19	3.4	0.453	0.487
FN20	4.1	3.640	3.897
FN21	4.4	1.162	1.245

ratio of the fiber core area to the calculated laser beam area ($A(f)/A = 3.4, 3.4, 4.1$ and 4.4) times larger than those listed in Table II for FN18-FN21, respectively.

Figure 6 illustrates two phenomena; first the variations in the surface finish of the ends of FOC fibers represented by the speckle appearance or white spots on the ends of the fibers and second the optical damage to the central fiber of FN20 (Figure 6A-6L) after $\xi_1 = 0, 0.068, 4.090, 3.974, 4.090, 4.283, 4.100, 4.042, 4.023, 4.071, 4.139$, and 4.234 kJ/cm^2 , incident on the fiber for the 1st LS before

Figure 6. Photographs of the input end of FOC fiber FN20 illustrate the gradual increase in the surface damage to the central fiber and decrease in ϵ (lower no.) for large ξ_2 values (upper no. in kJ/cm^2). Photograph A is before any laser shot (LS); B is for after the 1st LS; and C-L are for after the 1st-10th LS after irr, respectively.

irr and 1st-10th LS after irr, respectively. There is no drastic change from one photograph to another, but rather, a gradual change takes place in the immediate surroundings of the central fiber between the 12 o'clock and 4 o'clock position, a blistering on the periphery of its core between the 11 o'clock and 1 o'clock position, and an overlayer of recondensed binding or fusing material located over the central core radially inward from the 12 o'clock position. This small change in appearance from start to finish is in agreement with the observed change in ϵ of about 5.7%.

Again the 10^6 rad(Si) of gamma irradiation did not reduce the ξ_2 or ϵ values for the FOC fibers (compare FN18 to FN20). Comparable or higher ϵ values were obtained both before and after irradiation.

CGW Fibers

The CGW fibers (FN23-FN27) were the last group of fibers tested. Both low-and high-energy densities were propagated through these fibers. The cross-sectional area of the fiber core of FN23-FN27 varied from 5.97, 5.97, 6.36, 5.59, to $6.76 \times 10^{-5} \text{ cm}^2$, respectively. These fibers had the smallest core diameter of all the fibers tested, resulting in the largest ξ_2 values (FN25) shown in Table II.

Figures 7A-7C are photographs of the input end of FN25 before the 1st LS, after the 1st LS ($\xi_1 = 4.282 \text{ kJ/cm}^2$) after irr, and after the 2nd LS ($\xi_1 = 4.477$

Figure 7. Photographs A-C of the input end of CGW fiber FN25 illustrate the damage to the central fiber during the 2nd LS after irr (C). Photograph B is after the 1st LS after irr. Photographs D-F, are of the input of FN26 before the 1st LS, after the 1st LS, and after the 1st LS after irr, respectively. The ξ_2 values are the upper no. in kJ/cm^2 and the ϵ values are the lower no.

kJ/cm^2) after irr, respectively. A total of five LS's were incident onto FN25; three had an ξ_2 of 0.107, 0.107, and 0.121 kJ/cm^2 before irr and the remaining two LS's had an ξ_2 of 3.978 and 0.173 kJ/cm^2 after irr. The corresponding ξ_1 values were 0.132, 0.135, 0.135, 4.282, and 4.477 kJ/cm^2 . The low ξ_1 value was calculated using a laser beam area of $8.22 \times 10^{-5} \text{ cm}^2$, which was obtained from the E_1 and the ξ_1 values of the previous LS. The low ξ_2 value of 0.173 kJ/cm^2 for the last LS indicates that the fiber was either not aligned or broke during the shot. Figure 7C shows that after the last LS the central fiber core was broken.

Figures 7D-7F are photographs of the input end of FN26 before the 1st LS, after the 1st LS ($\xi_1 = 0.089 \text{ kJ/cm}^2$), and after the 1st LS ($\xi_1 = 4.500 \text{ kJ/cm}^2$) after irr, respectively. The area of the laser beam was the same as for FN25. There is evidence in the last photograph (Figure 7F) that the beam could have been larger than the central core since not only did it change in appearance but also the cross-sectional area of the damaged area was $5.84 \times 10^{-4} \text{ cm}^2$. If this latter is taken as the area of the laser beam instead of the cross-sectional area of the central fiber core, then, $\xi_2 = 0.187 \text{ kJ/cm}^2$. An earlier test of FN22 established an upper limit on the laser beam area of $1.03 \times 10^{-5} \text{ cm}^2$, setting a lower limit of $\xi_2 = 1.05 \text{ kJ/cm}^2$ for FN26. What looks like burned areas around the central fiber could be recollected blow off of binding material.

At lower ξ_1 and ξ_2 values, the input ends of CGW fibers were damaged less severely, as is illustrated in Figures 8A-8G for the top fiber of FN23. A total of 11 LS's were incident onto this fiber. Figure 8A is a photograph before any LS's, and Figures 8B-8G are for 1st-5th, and 7th LS's after irr, with ξ_1 values of 2.750, 2.262, 2.406, 2.895, 0.887, and 2.804 kJ/cm^2 , respectively. The low ϵ calculated for Figure 8F indicates that the laser beam was misaligned, causing damage to the surroundings of the top fiber. The inhomogenous material around the top fiber in Figures 8F and 8G appears to be recondensed vaporized binding material.

The ϵ values were observed to decrease with increasing number of LS's for all fibers whose input ends were damaged. Figure 9 illustrates the decrease in ϵ values for large ξ_1 (AVG) values for FN18, FN20, and FN23 as functions of laser shot number. The decreases in ϵ values from start to finish were 0.071, 0.059, and 0.173 for FN18, FN20, and FN23, respectively. The erratic behavior of the FN23 ϵ values is attributed to the laser beam diameter being approximately equal to the fiber core diameter and to some varying misalignment between the two.

Figure 8. Photographs A-G of the input end of CGW fiber FN23 show little changes to the top fiber for large ξ_2 values (upper no. in kJ/cm^2). Photograph A is before any LS and B-G after the 1st-5th and 7th LS after irr, respectively. The ϵ values are the lower no.

Figure 9. The decrease in ϵ values is illustrated for two FOC fibers (FN18 and FN20) and one CGW fiber (FN23) as functions of laser shot number.

VI. Discussions and Conclusions

Fibers tested with free-running laser pulses were damaged initially at the cladding or binding material used to hold nearest neighbors. Table IV lists the STD L for 7 of the 18 fibers tested. For multiple LS's, two FOC fibers FN18 and FN20, exhibited the largest STD L's followed by two VC fibers, FN16 and FN14,, then by a CGW fiber, FN23. For single LS's two CGW fibers, FN25 and FN26, exhibited the largest STD L's followed by a VC fiber, FN15. The STD L for a single LS was not determined for FOC fibers.

TABLE IV
STD L IN FIBERS

Fiber No.	Mfg	STD L		No. of Laser Shots
		ϵ_1 kJ/cm ²	ρ_1 MW/cm ²	
FN14	VC	2.962	29.62	3
FN15	VC	>2.623	26.23	1
FN16	VC	>3.806	38.06	2
FN18	FOC	3.675	36.75	2
		4.660*	46.60	2
		3.897	38.97	8
FN20	FOC	4.320*	43.20	8
		2.895	28.95	6
FN23	CGW	4.282	42.82	1
FN25	CGW	4.500 ⁺	45.00	1

* $A = 1.03 \times 10^{-4} \text{ cm}^2$ determined from FN22 test

+ Damaged during laser shot

At lower than STD L, many free-running laser pulses can be transmitted through VC, FOC, and CGW fibers with only slight decreases in ϵ , $\Delta\epsilon$, as shown in Table V.

The 10^6 rad(Si) of gamma irradiation to 1 cm of fiber did not reduce the ϵ_2 or ϵ in VC fibers (compare FN14 to FN16 in Table II), in FOC fibers (compare FN18 to FN20) or in CGW fibers. The ϵ values were approximate the same for both low or high ϵ_2 values after gamma irradiation of the fibers, as seen for FOC fibers (compare FN19 and FN21 to FN20) and for CGW fibers (compare FN24 and FN27 to FN23, FN25, and FN26).

TABLE V
DECREASE IN ϵ FOR MULTIPLE
LASER SHOTS IN FIBERS

Fiber No.	Mfg	$\Delta\epsilon$	No. of Laser Shots	Avg ϵ_{in} kJ/cm ²
FN14	VC	0.185	4	2.873
FN18	FOC	0.071	9	1.052
FN20	FOC	0.059	10	0.929
FN23	CGW	0.173*	7	2.605

* Variation, last shot ϵ largest

In general the damage caused by free-running laser pulses was much less severe than that caused by giant laser pulses as illustrated in previous tests^{1,2,35,36}.

For all fibers in which FTDL's were reached there was no evidence that the observed decrease in ϵ was caused by nonlinear optical behavior. It is believed that the decrease in ϵ was due to increases in observed optical damage at the input face of the fibers.

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34.
 - a) VC fibers were LH-PC05-07 with att. of <40 db/km, PC05 with att. of <40 db/km, PC0 with att. of <20 db/km all at $\lambda = 820$ nm.
 - b) FOC fibers were QLR-7-10 with att. of <40 db/km, QLR-1-10 with att. of <20 db/km both at $\lambda = 820$ nm.
 - c) CGW fibers were Code No. 1452-1300 and Code No. 49-1003 OVPO with att. of 3.7 db/km at $\lambda = 820$ nm.
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