Evaluation of High-power Endurance in Optical Fiber Links

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ABSTRACT The capacity of optical communications networks has increased rapidly in the past several years with the introduction of wavelength division multiplexing (WDM) technology, and optical power in the optical fiber link has risen accordingly. However, when optical power rises, system reliability suffers, with problems like damage to the fiber or optical components, safety of the human body, etc. This paper reports experimental data gathered on three problems generated by high optical power in optical communications, i.e., damage to the connector endface, the phenomenon known as fiber fuse, and damage to the fiber coating.

1. INTRODUCTION

The capacity of optical communications networks has increased rapidly in the past several years with the introduction of wavelength division multiplexing (WDM) technology, and optical power in the optical fiber link has risen accordingly. For example, the optical power of 1400 nm band laser diodes (LD) has reached as high as 400 mW, and in distributed Raman amplification, which has attracted attention in recent years, a flat gain characteristic has been achieved over a broad band while pumping light power even reaches 1 W or more [1). However, when optical power rises, system reliability suffers, with problems like damage to the fiber or optical components, safety of the human body, etc. We consider these problems associated with higher power in four categories.

The first is damage to the connector endface. It has been reported that the endface will be damaged by high optical power if there is contamination of the endface [2). Specifically, it has been reported that phosphor bronze, which is currently used in conventional FC connectors, caused damage to the connector endface [3), and FC connectors without phosphor bronze have now come into use.

The second problem is so-called fiber fuse, a phenomenon in which only the core of the optical fiber melts locally due to high optical power in the fiber and the damage is propagated toward the light source, emitting visible light. After propagation, the fiber typically shows a string of voids in the core region. It keeps propagating until the light source is shut down or the optical power drops below a certain threshold. Experimentally, fiber fuse propagation lengths of more than 1.5 km have been reported [4). Fiber fuse was observed in optical fibers in the 1980s [5), but none of the proposed theories could explain all the observations [6).

The third problem is damage to the fiber coating. This may be caused by light leaking from the fiber when it is broken or bent accidentally in a high power environment with the introduction of a Raman amplifier. The leaked light is absorbed by the fiber coating generating heat, and in the worst case, it may ignite.

The fourth problem is the safety of the human body under laser light radiation when there is a fracture in an optical fiber link or a separation of connectors. With present technology, we can consider such methods as using connectors with shutters, or detecting the reflected light and shutting down the light source.

These problems are crucial to operating optical fiber communications systems safely, and progress is being made in creating guidelines aimed at international standards [7). Accordingly, we report in this paper the results of experiments carried out to investigate damage to connector endfaces, fiber fuse, and damage to fiber coatings.

2. DAMAGE TO CONNECTOR ENDFACE

2.1 Experimental Method

Figure 1 shows an example of damage to the endface of an FC connector due to high optical power with phosphor bronze contaminating the endface. This is a result of the fact that phosphor bronze is sometimes used in the adapter sleeve or the connector key in FC connectors,

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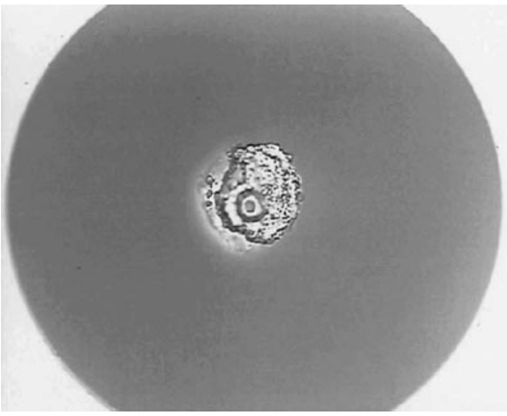

Figure 1 Damage to connector endface.

and may be ground into a powder that gets on the endface during connector connection. Even with other connectors that do not use phosphor bronze, however, the same phenomenon may occur.

Accordingly, we made detailed investigations of cases in which the connector endface had scratches (by polishing etc.) or various kinds of contamination that would tend to damage the connector. We used a 2-W light source with a peak wavelength of 1480 nm, the same band as the pumping light for EDFAs and Raman amplifiers. Test samples were prepared FC connectors for single mode fibers (SMF). We input 2-W laser light into the system, and investigated the changes in the samples.

2.2 Effect of Scratches

In terms of scratches on connector endfaces, we evaluated three kinds of samples, (1) without scratches in the core area, the level of products on the market, (2) with scratches in the core area due to inadequate polishing condition, which did not adversely affect connection loss, and (3) with scratches caused by a 5-μm file, which adversely affect connection loss. Five samples of each were evaluated, with the results shown in Table 1. No changes in the endface state was observed for any of the samples, and in those samples with large scratches made by the 5-μm file, a temperature increase of more than 50°C was observed. This temperature increase was probably due to connection loss. Concerning the relation between connection loss and heat generation, it is reported that to control the generation of heat within 10 degrees in MU connectors, the connection loss should be 0.25 dB or less [8]. and of the scratches are within the range in which they have no effect on connection loss, heat generation will be so little that it unlikely to cause endface damage.

2.3 Effect of Contaminants

We evaluated samples of seven kinds of contamination, which are in practice likely to contaminate the endfaces. The results are shown in Table 2. With the contaminants of high transparency, such as (4) ethanol, (5) oil from the hand, and (6) index-matching oil, no damage to the endface was observed. Only in the case of index-matching oil did a temperature increase sometimes occur, probably due to a larger connection loss, caused by air bubbles in the oil, which is not usually used in FC connectors. With light absorbing contaminants like metals or black compounds, such as (7) epoxy resin with carbon, (8) Ni plating, (9) oil-based black ink, or (10) phosphor bronze, when the connection loss was small, endfaces were damaged and in some cases fiber fuse occurred. Specifically with phosphor bronze, the endfaces were damaged only at 50 mW. On the other hand, some samples of epoxy resin or phosphor bronze caused no damage to the endfaces, but when the samples were observed after the experiment, it was found that the contaminants were not present in the core area.

Table 1 Effect of scratches.

	Condition	Typical connection loss	Results (n=5)
①	No scratches on core	0.12 dB	No change: n=5
②	Polishing scratches	0.18 dB	No change: n=5
③	5-μm file scratches	0.78 dB	Temp. increase: n=5

Table 2 Effects of contaminants.

	Condition	Typical connection loss	Results (n=5)
④	Ethanol	0.14 dB	No change: n=5
⑤	Oil from hand	0.21 dB	No change: n=5
⑥	Index matching oil	0.64 dB	No change: n=2 Temp. increase: n=3
⑦	Epoxy resin with carbon	0.67 dB	No change: n=1 Temp. increase: n=2 Endface damaged: n=2
⑧	Ni plating	1.39 dB	Temp. increase: n=2 Endface damaged: n=3
⑨	Oil-based black ink	0.24 dB	Endface damaged: n=4 Fiber fuse: n=1
⑩	Phosphor bronze	1.12 dB	No change: n=1 Endface damaged: n=3 Fiber fuse: n=1

2.4 Consideration of Endface Damage and Countermeasures Adopted

The experiments showed that only those contaminants that absorb optical power easily produce damage to fiber endfaces. However, even when scratches in the core area do not directly result in endface damage, they are better avoided because they may trap such contaminants. The use of index-matching oil should also be avoided in a high-power environment, because it easily traps air bubbles and contaminants.

It has also been found that endface damage may occur even with so little contamination that it has no effect on connection loss. Thus the most effective method of preventing endface damage is to clean it carefully every time a connection operation is performed. Cleaning during the emission of high power light should be avoided, however, because experiments have shown that it might damage the endface whether alcohol is present or not, and it may also be dangerous to the human body.

Therefore, connectors exposed to high-power light need careful handling, and cleaning and checking of the endface should only be carried out with the light source turned off.

3. FIBER FUSE

3.1 Experimental Method

Fiber fuse is a phenomenon in which voids are formed typically having the shape of bullets in the core area, and propagate as shown in Figure 2. Propagation continues as long as optical power is provided until the light source is shut down or the power drops below a certain threshold, and may eventually reach the light source and damage it. In this work, we measured the threshold power at which fiber fuse stops propagating.

Figure 3 shows the test setup. We used two light sources with peak wavelengths of 1064 and 1467 nm. The point to be noted here is that fiber fuse does not necessarily occur, even under high light power. It has been reported that the silicon fiber itself can withstand over 10 GW/cm^2 and generally SMF is sufficiently durable to withstand light intensities in the order of several Watts. If, however, there is some trigger to initiate fiber core fusion at some point, from which it will propagate toward the light source. In actual light transmission paths, light absorption by contaminants adhering to a connector endface, or the concentration of light energy by multi-refection at fiber breaks can constitute such a trigger. The probability of fiber fuse initiation thus tends to increase as optical intensity rises, but the probability and threshold power for the initiation of fiber fuse differ dramatically according to what the trigger is.

During this investigation, in order to increase the probability of fiber fuse easily, fibers carrying 5 W of laser light power were heated locally by arc discharge to over 1000°C. Once fiber fuse occurred, we decreased the light intensity level gradually by adjusting the bias level of the laser source until fiber fuse stopped, and measured that power level which is the threshold value. This threshold power for fuse propagation is determined solely by fiber type and laser light wavelength, and is independent of the method of fuse initiation. And since this threshold power is the level below which fiber fuse cannot propagate, we also believe it to be the point below which it cannot be initiated.

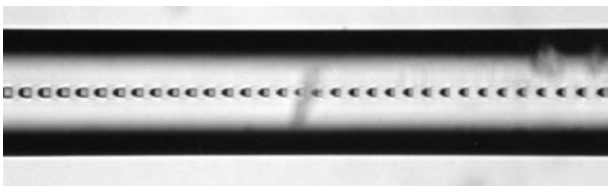

Figure 2 Optical fiber after fuse propagation.

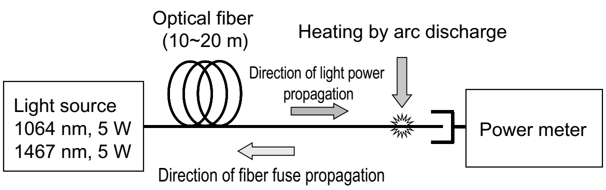

Figure 3 Setup for testing fiber fuse.

3.2 Threshold Power of Fiber Fuse Propagation

Figure 4 shows the power threshold for fuse propagation measured at two wavelengths for SMF and ITU-T G.653 dispersion shifted fiber (DSF). The fact that the power threshold is lower for DSF than for SMF is thought to be due to the higher power density because of the smaller mode field diameter (MFD). Figure 5 shows the threshold power for several fibers with different MFD, measured at a peak wavelength of 1467 nm. The fibers used were dispersion compensating fiber (DCF) for SMF, DSF, and locally core expanded SMF (diameters of 20 µm and 30 µm). For SMF, DSF, and DCF, the actual measured values are plotted and for the core-expanded fibers is shown as a range, the value at which the fuse passed the expanded part plotted as maximum and the value at which it stopped as the minimum.

Against our expectations, the result showed that the power threshold is in proportion not to effective area (A_{eff}), but to MFD. If the power were in proportion to A_{eff}, the

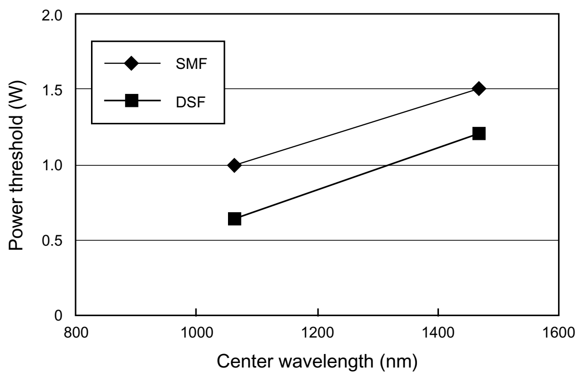

Figure 4 Wavelength dependence of power threshold for fiber fuse propagation.

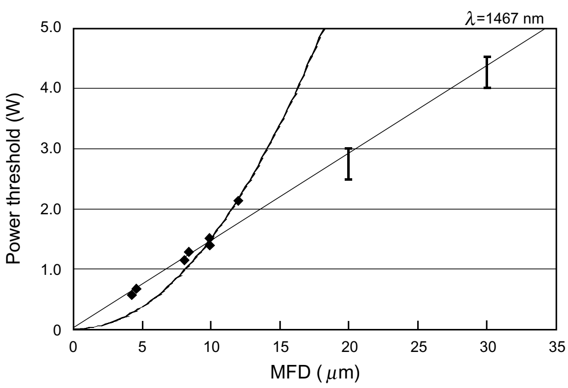

Figure 5 MFD dependence of power threshold for fiber fuse propagation.

plotted data would not be on a straight line, but on the locus of a quadratic equation. However, we were able to confirm that expanding the MFD is an effective way to raise the power threshold for fiber fuse propagation.

3.3 Consideration of Fiber Fuse and Countermeasures Adopted

All that is necessary to assure that fiber fuse is not initiated is to keep the optical power of the light source below the propagation threshold. For example, we have found experimentally that at 1467 nm, the pumping light wavelength, the power threshold of SMF is approximately 1.5 W, so that it is certainly safe with respect to fiber fuse when operated below this level. However, since the power levels in fiber optic communication networks may rise to more than 1.5 W, technology for stopping fuse propagation is also needed.

Detecting optical output power and turning off the laser light source is the most effective method to stop fiber fuse propagation. When fiber fuse is initiated, output power decreases precipitously, as shown in Figure 6, so, if the drop is detected and the laser source turned off immediately, the propagation will stop, because the propagation speed is several meters per second at most. Especially, an automatic power reduction (APR) system, which is described in ITU-T as a method for shutting down the light source in case of fiber breakage, is effective not only in terms of safety to the human body, but also of fiber fuse.

There is also another technique that is effective in providing an area of expanded MFD in the optical path. For example, we made SC connectors using fibers with partially expanded MFD, as shown in Figure 7. The length of the expanded part is about 4 mm, the expanded MFD is 30 μm, and the MFD at the endface is 10 μm, so these connectors are compatible with standard SC connectors. It was confirmed experimentally that they can stop fuse propagation at 4-W transmission at a peak wavelength of 1467 nm.

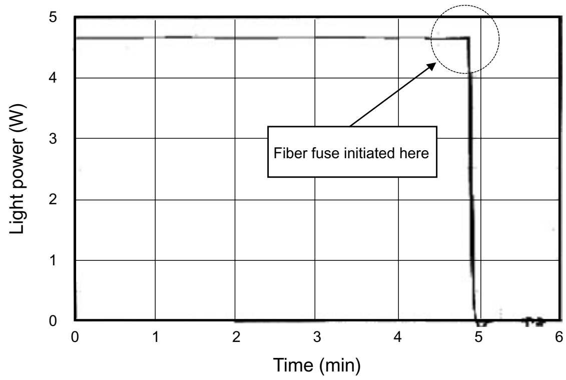

Figure 6 Power meter readings on changes in output power for tests according to Figure 3.

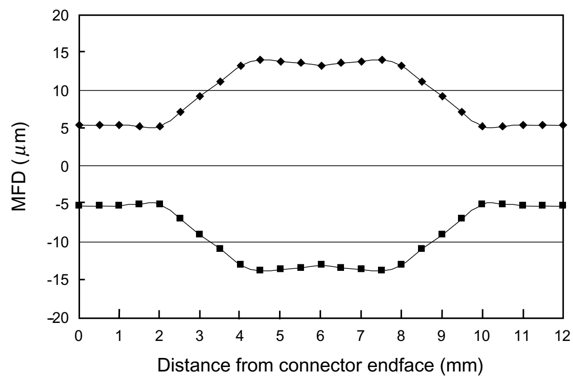

Figure 7 Profile of MFD.

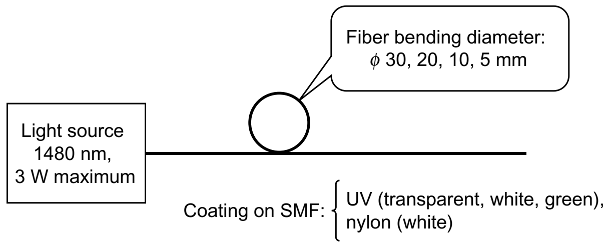

Figure 8 Setup for testing damage to fiber coating.

4. DAMAGE TO FIBER COATING

4.1 Experimental Method

Tight bending of optical fibers is not conducive to long time reliability, but in actual systems fibers may be tightly bent. When tightly bent the light is radiated to the fiber coating, which is heated particularly under high power conditions. We have investigated damage to the fiber coating induced by tight bending under high power conditions in the short term.

Figure 8 shows the test setup for the investigation. We used a 1480 nm high-power light source having a maximum output power of 3 W. The fibers tested were G.652 fiber, with coating of 0.25 mm UV curable resin (transparent, white, and green) and 0.9 mm tight buffer (white nylon). The bending diameters of the fibers were 30 mm, 20 mm, 10 mm, and less than 5 mm. The ambient temperature was approximately 25°C.

First, the temperature changes at a point on fibers bent to a 3-mm diameter were measured at 3 W input power, as shown in Figure 9. This shows that heat equilibrium is reached within 5 minutes, so in our experiments the tested fibers were exposed to high input power for 5 minutes.

4.2 Evaluation of Damage to Fiber Coatings

The experimental results after 5 minutes exposure are shown in Table 3. We distinguished the conditions of coating damage qualitatively into four stages: “deformed” means that the coating resin is hardened by the heat; “discolored” means that, in addition, the color of coating becomes dull; “melted” means that a part of the coating melted; “ignited” means that the coating burst into flame and burned.

In the case of bending diameters of less than 5 mm, the nylon coatings were melted at 1 W and ignited at 3 W, and

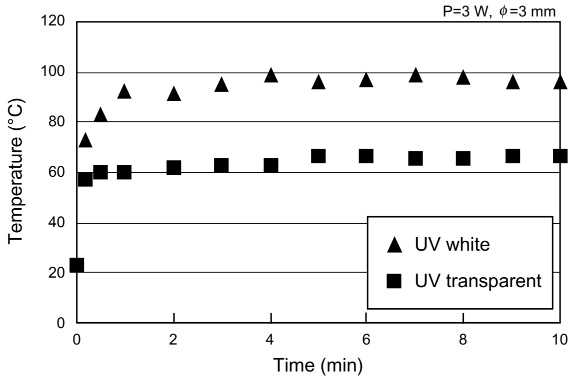

Figure 9 Temperature change in fiber coating at bending diameter of 3 mm and input power of 3 W.

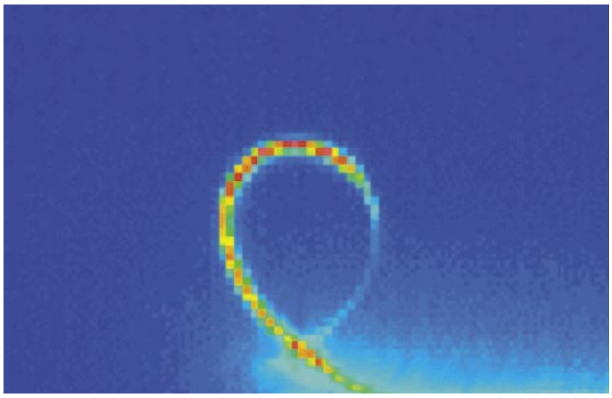

Figure 10 Observation by thermo-viewer.

Table 3 Result of tests for fiber coating damage.

Power 1480 nm	Diameter (mm)	Fiber coating			
		UV transparent	UV white	UV green	Nylon white
1 W	ϕ 30	No change	No change	No change	No change
	ϕ 20	No change	No change	No change	No change
	ϕ 10	No change	Deformed	Deformed	Deformed
	$\leq\phi$ 5	No change	Deformed	Discolored	Melted
3 W	ϕ 30	No change	No change	No change	No change
	ϕ 20	No change	No change	Deformed	No change
	ϕ 10	No change	Deformed	Deformed	Deformed
	$\leq\phi$ 5	Discolored	Discolored	Discolored	Ignited

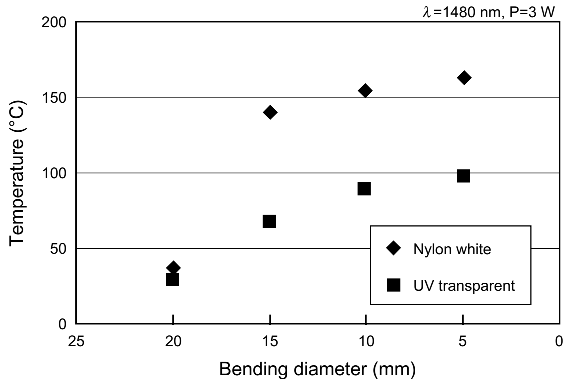

Figure 11 Dependence of maximum coating temperature on bending diameter.

the UV coatings also had became discolored at all levels. Thus it is considered that diameters of less than 5 mm constitute a very dangerous region. In the case of bending diameters of 10 mm for up to 3 W, the nylon and colored UV coatings were deformed. In the case of 20 mm at 3 W, one of the green coatings was deformed. Diameters of less than 10 mm for up to 1 W and less than 20 mm up to 3 W should therefore also be avoided.

From these experimental data, ignition is not likely to occur up to 3 W as long as the fiber is not bent to less than a diameter of 5 mm. However, in order not to lower transmission path reliability, the diameter of fiber bends must be more than 20 mm up to 1 W, and 30 mm up to 3 W. Lastly, it was determined that transparent UV was more durable than colored UV.

4.3 Consideration of Coating Damage and a Model for Heat Generation

We also measured the surface temperature of bent fibers by means of a thermo-viewer, as shown in Figure 10. The maximum temperatures were measured and plotted on the graph in Figure 11. The temperature of nylon reached 160°C, which is almost the melting point but less than the ignition point. It is therefore considered highly probable that fiber coating ignition in Table 3 occurred because the nylon melted leading to reduced coating strength and fiber breakage and to radiation of light from broken fiber.

We also attempt to provide theoretical support for the temperature changes obtained experimentally. We assume that bending loss occurs due solely to light leak and that all the light leakage is absorbed by the fiber coating and converted into heat. In addition, if it is assumed that the heat generated does not escape from the inside the fiber coating, the average temperature increase may be represented as follows.

$$\Delta T=\frac{P\alpha\eta}{C_p\phi\pi^2(r_2{}^2-r_1{}^2)\rho} \quad (1)$$

where: P is light intensity, α is bending loss, η is absorption index of the coating resin, and ρ is the specific heat of the coating resin, ϕ is bend diameter, and r_1 is the inner radius and r_2 the outer radius of the fiber coating. Since a state of thermal equilibrium is reached, the approximation described above is valid for only a few tens of seconds. Taking, for example, the transparent UV, with P of 3 W, α of 95 %, and ϕ of 5 mm, the temperature is calculated to reach about 105°C after 10 seconds, from an ambient temperature of about 25°C. The value measured in the experiment was 95°C, which was substantially in agreement with the calculated result.

5. CONCLUSION

The capacity of optical communications networks has increased rapidly in the past several years with the introduction of wavelength division multiplexing (WDM) technology, and optical power in the optical fiber link has risen accordingly. However, when optical power rises, system reliability suffers, with problems like damage to the fiber or optical components, safety of the human body, etc. This paper reports experimental data gathered on three problems generated by high optical power in optical communications, i.e., damage to the connector endface, the phenomenon known as fiber fuse, and damage to the fiber coating.

This time, the qualitative tendency and a certain quantitative prospect were obtained about three high power problems. More data must be accumulated in order to reach a conclusion as to reliability or guaranteed values. We plan to continue these evaluations and want to contribute to the development of an optical fiber communications system with products of higher power durability and safety.

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