PD IEC/TR 61292-4:2014

BSI Standards Publication

Optical amplifiers

Part 4: Maximum permissible optical power for the damage-free and safe use of optical amplifiers, including Raman amplifiers

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National foreword

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The UK participation in its preparation was entrusted by Technical Committee GEL/86, Fibre optics, to Subcommittee GEL/86/3, Fibre optic systems and active devices.

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TECHNICAL REPORT

Optical amplifiers –
Part 4: Maximum permissible optical power for the damage-free and safe use of optical amplifiers, including Raman amplifiers

INTERNATIONAL
ELECTROTECHNICAL
COMMISSION

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

OPTICAL AMPLIFIERS –

Part 4: Maximum permissible optical power for the damage-free and safe use of optical amplifiers, including Raman amplifiers

FOREWORD

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IEC TR 61292-4, which is a technical report, has been prepared by subcommittee 86C: Fibre optic systems and active devices, of IEC technical committee 86: Fibre optics.

This third edition cancels and replaces the second edition, published in 2010, and constitutes a technical revision with updates reflecting new research in the subject area.

The text of this technical report is based on the following documents:

Enquiry draft	Report on voting
86C/1158/DTR	86C/1200/RVC

Full information on the voting for the approval of this technical report can be found in the report on voting indicated in the above table.

This publication has been drafted in accordance with the ISO/IEC Directives, Part 2.

A list of all parts in the IEC 61292 series, published under the general title, *Optical amplifiers*, can be found on the IEC website.

The committee has decided that the contents of this publication will remain unchanged until the stability date indicated on the IEC web site under "http://webstore.iec.ch" in the data related to the specific publication. At this date, the publication will be

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

A bilingual version of this publication may be issued at a later date.

IMPORTANT – The 'colour inside' logo on the cover page of this publication indicates that it contains colours which are considered to be useful for the correct understanding of its contents. Users should therefore print this document using a colour printer.

INTRODUCTION

This technical report is dedicated to the subject of maximum permissible optical power for damage-free and safe use of optical amplifiers, including Raman amplifiers. Since the technology is quite new and still evolving, amendments and new editions to this report can be expected.

Many new types of optical amplifiers are entering the marketplace and research is also stimulating many new types of fibre and non-fibre based optical amplifier research. With the introduction of such technologies as long-haul, over 40 Gb/s, WDM transmission and Raman amplification, some optical amplifiers may involve optical pump sources with extremely high optical power – up to, possibly, several watts.

Excessively high optical power may cause physical damage to the fibres/optical components/equipment as well as present medical danger to the human eye and skin.

The possibility of fibre damage caused by high optical intensity has recently been discussed at some technical conferences. The use of high intensity optical amplifiers may cause problems in the fibre such as a fibre fuse, a heating in the splice point (connection point), and the fibre end-face damage due to dust and the fibre coat burning due to tight fibre bending. IEC SC 86A (Fibres and cables) has published IEC TR 62547, and SC 86B (Fibre optic interconnecting devices and passive components) has published IEC TR 62627-01. IEC TC 31 (Equipment for explosive atmospheres) is also discussing the risk of ignition of hazardous environments by radiation from optical equipment.

Medical aspects have long been discussed at standards groups. IEC TC 76 (Optical radiation safety and laser equipment) precisely describes in IEC 60825-2 the concept of hazard level and labelling and addresses the safety aspects of lasers specifically in relation to tissue damage.

ITU-T Study Group 15 (Optical and other transport networks) has published Recommendation G.664, which primarily discusses the automatic laser power reduction functionality for safety.

With the recent growth of interest in fibre Raman amplifiers, however, some difficulties have been identified among optical amplifier users and manufacturers in fully understanding the technical details and requirements across all such standards and agreements.

This technical report provides a simple informative guideline on the maximum optical power permissible for optical amplifiers for optical amplifier users and manufacturers.

OPTICAL AMPLIFIERS

Part 4: Maximum permissible optical power for the damage-free and safe use of optical amplifiers, including Raman amplifiers

1 Scope and object

This part of IEC 61292, which is a technical report, applies to all commercially available optical amplifiers (OAs), including optical fibre amplifiers (OFAs) using active fibres, as well as Raman amplifiers. Semiconductor optical amplifiers (SOAs) using semiconductor gain media are also included.

This technical report provides a simple informative guideline on the threshold of high optical power that causes high-temperature damage of fibre. Also discussed is optical safety for manufacturers and users of optical amplifiers by reiterating substantial parts of existing standards and agreements on eye and skin safety.

To identify the maximum permissible optical power in the optical amplifier from damage-free and safety viewpoints, this technical report identifies the following values:

a) the optical power limit that causes thermal damage to the fibre, such as fibre fuse and fibre-coat burning;
b) the maximum permissible exposure (MPE) to which the eyes/skin can be exposed without consequential injury;
c) the optical power limit in the fibre that causes MPE on the eyes/skin after free-space propagation from the fibre;
d) the absolute allowable damage-free and safe level of optical power of the optical amplifier by comparing (a) and (c).

The objective of this technical report is to minimize potential confusion and misunderstanding in the industry that might cause unnecessary alarm and hinder the progress and acceptance of advancing optical amplifier technologies and markets.

It is important to point out that the reader should always refer to the latest international standards and agreements because the technologies concerned are rapidly evolving.

The present technical report will be frequently reviewed and will be updated by incorporating the results of various studies related to OAs and OA-supported optical systems in a timely manner.

2 Normative references

The following documents, in whole or in part, are normatively referenced in this document and are indispensable for its application. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60825-1:2007, *Safety of laser products – Part 1: Equipment classification and requirements*

IEC 60825-2:2004, *Safety of laser products – Part 2: Safety of optical fibre communication systems (OFCS)*
Amendment 1 (2006)
Amendment 2 (2010)

IEC TR 60825-14:2004, *Safety of laser products – Part 14: A user's guide*

IEC TR 62547, *Guidelines for the measurement of high-power damage sensitivity of single-mode fibres to bends – Guidance for the interpretation of results*

IEC TR 62627-01, *Fibre optic interconnecting devices and passive components – Part 01: Fibre optic connector cleaning methods*

ITU-T Recommendation G.664:2012, *Optical safety procedures and requirements for optical transport systems*

3 Abbreviated terms

For the purposes of this document, the following abbreviated terms apply.

ALS	automatic laser shutdown
APR	automatic power reduction
DSF	dispersion shifted fibre
LOS	loss of signal
MFD	mode field diameter
MPE	maximum permissible exposure
MPI-R	single channel receive main path Interface reference point
MPI-S	single channel source main path interface reference point
NOHD	nominal ocular hazard distance
NZ-DSF	non-zero dispersion shifted single-mode optical fibre
OA	optical amplifier
OFA	optical fibre amplifier
SMF	single mode fibre
SOA	semiconductor optical amplifier

4 Maximum transmissible optical power to keep fibres damage-free

4.1 General

The use and reasonably foreseeable misuse of high intensity optical amplifiers may cause problems in the fibre such as

a) fibre fuse and its propagation,
b) heating in the splice point/connection point,
c) fibre end-face damage due to dust and other contamination,
d) fibre coat burning and ignition of hazardous environments due to tight fibre bending or breakage.

This clause introduces their results concerning the above issues to give guidelines for the damage-free use of optical amplifiers. However, it should be noted that the following results are only valid under the conditions tested and that a higher power might be allowed under different conditions.

4.2 Fibre fuse and its propagation

The safety of optical amplifiers should be discussed from the viewpoint of laser hazard to the eyes and skin as well as fibre damage such as fibre-coat burning and fibre fusing. This clause experimentally analyses the fibre fuse and its propagation caused by high optical power and discusses the threshold power of fibre fuse propagation [1][1]. It is defined that the fibre fuse is the phenomenon in which an intense blue-white flash occurred and ran along the fibre toward the high power light source while forming periodic and/or non-periodic voids.

Figure 1 shows a typical measurement set-up for the threshold power of fibre fuse propagation. The fibre fuse is initiated by heating the optical fibre from outside of the fibre by using an independent heat source, while a high optical power is continuously launched into the fibre. Once the fibre fuse began propagating, the optical source power is continuously reduced until the fuse propagation stopped for measuring the threshold power. Table 1 shows the threshold powers which were measured at various wavelengths of the high-power optical source for various fibres. Although the threshold power depends on the wavelength of the high-power optical source, the power for the fuse propagation is less than 1,4 W and 1,2 W for a standard single mode fibre (SMF) and a dispersion shifted fibre (DSF) respectively, which are used as the optical fibre for typical optical fibre communication systems.

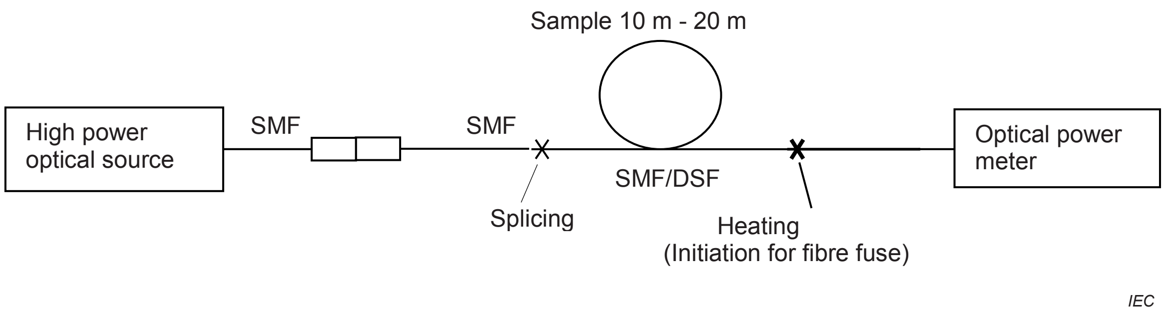


Figure 1 – Experimental set-up for fibre fuse propagation

Table 1 – Threshold power of fibre fuse propagation for various fibres

Fibre type	Measurement wavelength µm	Threshold power of fibre fuse propagation W
Standard single mode fibre	1,064	1 [2]
	1,467	1,4 [2]
	1,48	~1,2 [3]
	1,55	1,39 [4]
Dispersion shifted fibre	1,064	1,2 [2]
	1,467	0,65 [2]
	1,55	~1,1 [5]
Dispersion compensation fibre	1,55	~0,7 [5]

The difference in the fibre mode-field diameter has been the major reason for the difference in the threshold powers because the fibre fuse depends on the power density [1].

On the other hand, it is difficult to identify the threshold powers for the fibre fuse self-initiation (without any external cause) because it varied significantly, although they well exceeded

1 Figures in square brackets refer to the Bibliography.

1,4 W and 1,2 W for standard single mode fibre (SMF) and dispersion shifted fibre (DSF) respectively.

Further information such as the generating mechanism, the characteristics of fibre fuse and the prevention and the termination for the fibre fuse is described in Annex A.

4.3 Loss-induced heating at connectors or splices

In extremely high power optical amplifiers, the loss-induced heating at fibres and connectors or splices could lead to damage, including fibre-coat burning, fibre fuse, etc. This subclause provides experimental data and considerations for the information of the thermal effects induced by connector and splice losses in high-power amplifiers [6].

Figure 2 shows temperature increase versus connection loss, which are measured by the conditions that shown in Table 2. MU type optical connectors for standard single mode fibre (SMF) and dispersion shifted fibre (DSF) were used for this measurement. The connector loss was increased by optical fibre misalignment. The optical source used was a 2-W Raman pump at 1 480 nm. The connector temperature was measured by a thermocouple placed on the sleeve. Since the MU ferrule diameter was only 1,25 mm, the sleeve temperature was almost the same as that of the ferrule; ferrule temperature is the most important factor determining the long-term reliability of optical connectors [7].

Larger increase in temperature is observed in DSF than in SMF due to higher power density. The result suggests that the temperature increase could be within 10 °C under practical conditions of loss and power. A commercial dry-type connector cleaner was used in every test for cleaning the endface of the connectors.

During repeated connection-disconnection of the connectors, neither damage nor fibre fuse was observed. The experiments with the use of the cleaner identified no problems in terms of fibre/connector damage and reliability. Without the cleaner, however, the experiment with the DSF connector indicated that fibre fuse could occur after repeated connection-disconnection of more than 200 times.

Such temperature increase, and accordingly the danger of fibre fuse, for non-zero dispersion shifted single-mode optical fibre (NZ-DSF) connectors will be worse than SMF connectors but better than DSF connectors; the effective areas are SMF>NZDSF>DSF. Further quantitative studies are needed. Other types of physical contact (PC) connectors such as SC connectors will show similar temperature responses because only their ferrule radii differ.

In conclusion, it is shown that the thermal effects induced by connector and splice losses in high-power amplifiers could be acceptable under any practical conditions foreseeable at this moment. However, special care should be taken to eliminate dust and contamination from the connector end faces and splice points that could locally induce high-temperature increases according to the power density absorbed.

Table 2 – Measurement conditions

Parameter	Conditions
Fibre	SMF, DSF
Connectors	MU type
Ferrule	Zirconia
Connector/splice loss	Imperfect alignment
Wavelength	Raman pump – 1 480 nm
Power	2 W
Temperature measurement	Thermocouple on the sleeve

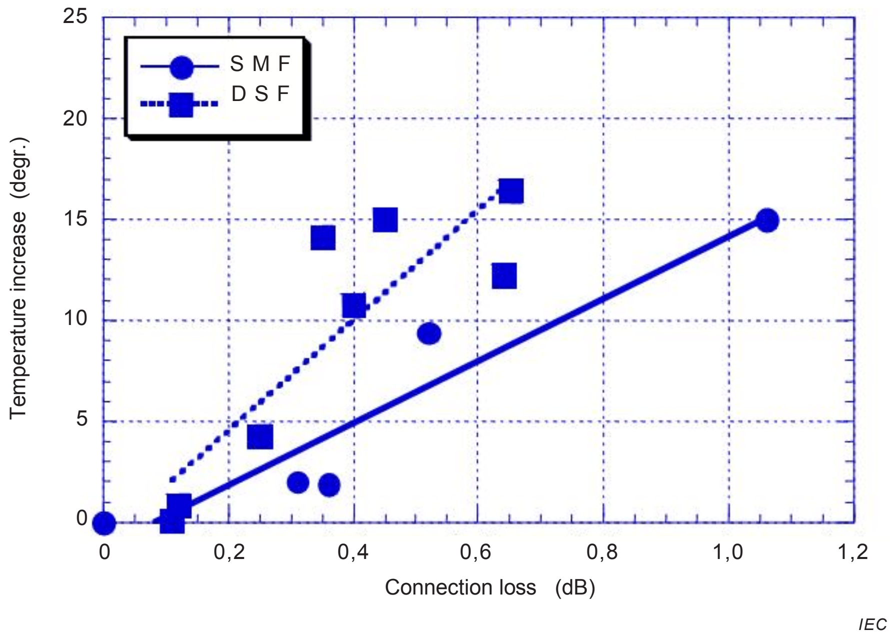


Figure 2 – Connection loss versus temperature increase

4.4 Connector end-face damage induced by dust/contamination

The purpose of this clause is to show the increase in attenuation of the connector under test when the light power into the fibre is extremely high [8].

Figure 3 shows the scheme of the measurement set-up used in the test. The laser pump of a Raman amplifier is used with a maximum nominal power of 2 W, at a wavelength of 1 455 nm.

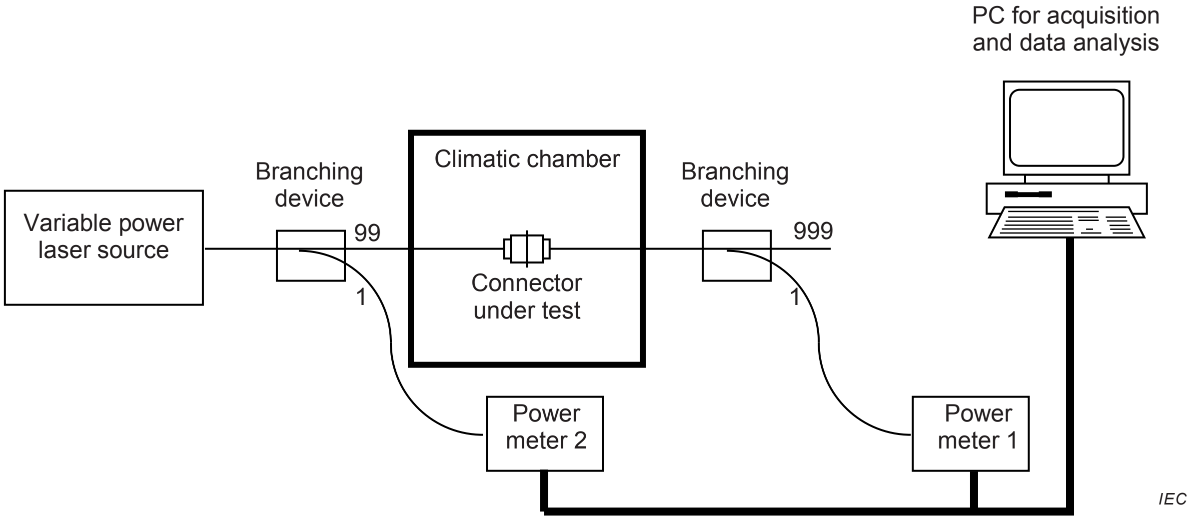


Figure 3 – Test set-up

The optical connectors used is SC-PC type with a perfectly clean surface, with skin grease (from operators), with dust (from the floor of the lab) and with metal filings (from a metallic sleeve).

a) Test result on clean connectors

Two plugs without defects on the polished fibre surface are used. The laser power is increased in steps to 1,2 W after a thorough cleaning. The test was conducted at ambient temperature and in a chamber at 70 °C. During the entire test, the variation of the attenuation was less than 0,02 dB and the visual examination of the fibre surface at the microscope did not show any damage.

b) Test result on connectors contaminated with skin grease

A layer of grease was put down on two plugs without any defect, by simply touching the polishing surface with the hands. When increasing the power from 100 mW to 1 200 mW at ambient temperature, the attenuation varied within a few hundredths of a dB. The visual inspection with a microscope after the test showed a cleaning effect, probably due to high temperature near the fibre. After the surface cleaning, no damage was observed.

c) Test result on connectors contaminated with dust

In this case, dust from the laboratory floor was put on the polishing surface of the plugs. After the initial increase of the attenuation from zero (= normalized value) to 0,06 dB with 200 mW input power, the attenuation started to decrease with the increase in the power until –0,15 dB with 1,2 W input power. This effect of improvement in power transmission could be due to a cleaning action of the high temperature on the finest particles. Also in this case, after the cleaning at the end of the test, the surfaces did not show any damage.

d) Test result on connectors contaminated with metal dust

In this test, we put down on the plug surfaces metal dust obtained by filing a metallic sleeve of an adapter. This condition simulates the presence of metallic particles produced by the friction of the ferule during the insertion into a metallic sleeve.

The first test was performed by heavily contaminating the surfaces, as Figure 4 shows. This is clear from the initial attenuation value that was 3 dB to 4 dB higher than the ones for the other conditions.

During the test, already at 200 mW, the attenuation increased by about 0,3 dB. At the 400 mW step, the damage was evident with attenuation increased to 1,1 dB (Figure 5). As failure occurred, the test was stopped to visually inspect the surfaces.

Obvious signs of burning were observed on the core of both fibres that could not be eliminated by cleaning the surface. The visual inspection of polished surface through a microscope (Figure 6) shows fused metal glued on the fibre cores. These clots are not removable by cleaning the surfaces.

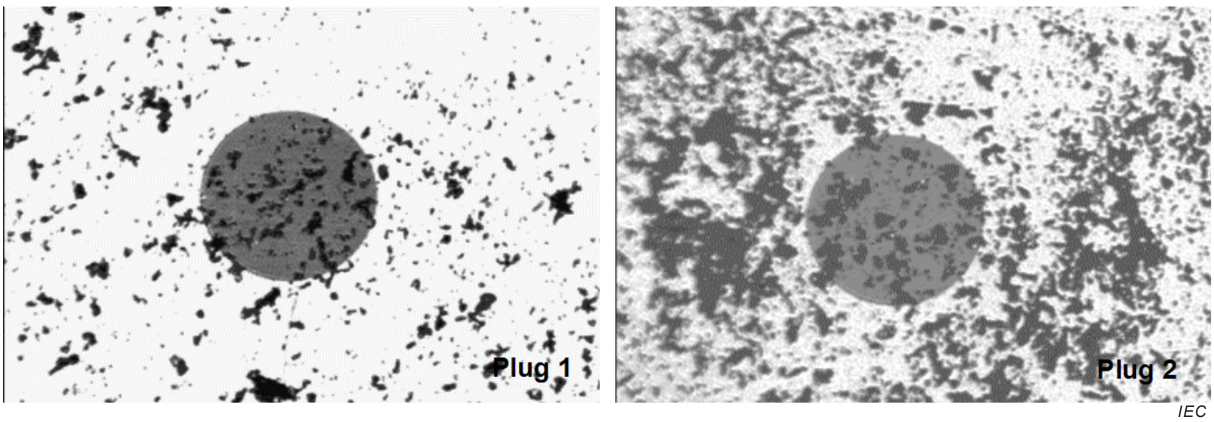


Figure 4 – Surface condition contaminated with metal filings, before the test

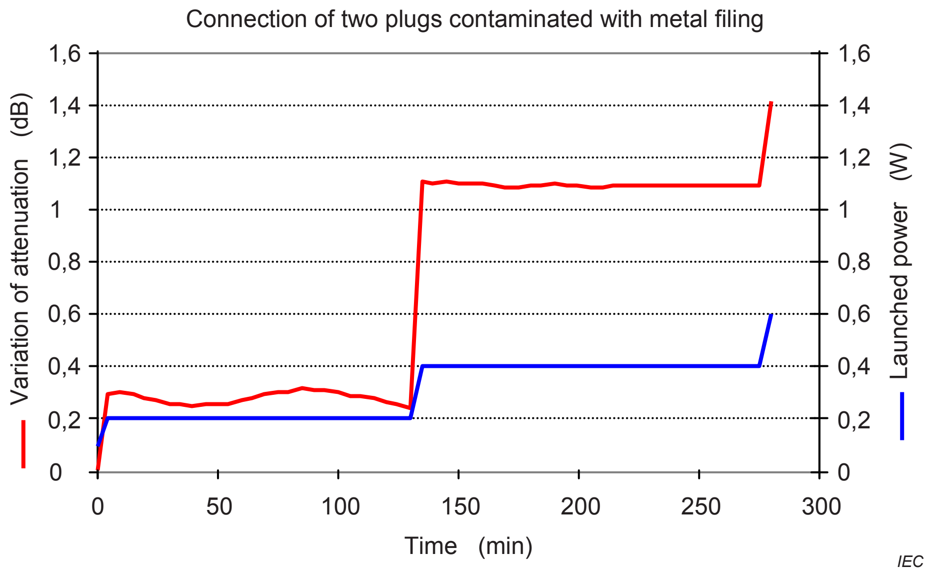


Figure 5 – Variation of the power attenuation during the test at several power input values for plugs contaminated with metal filings

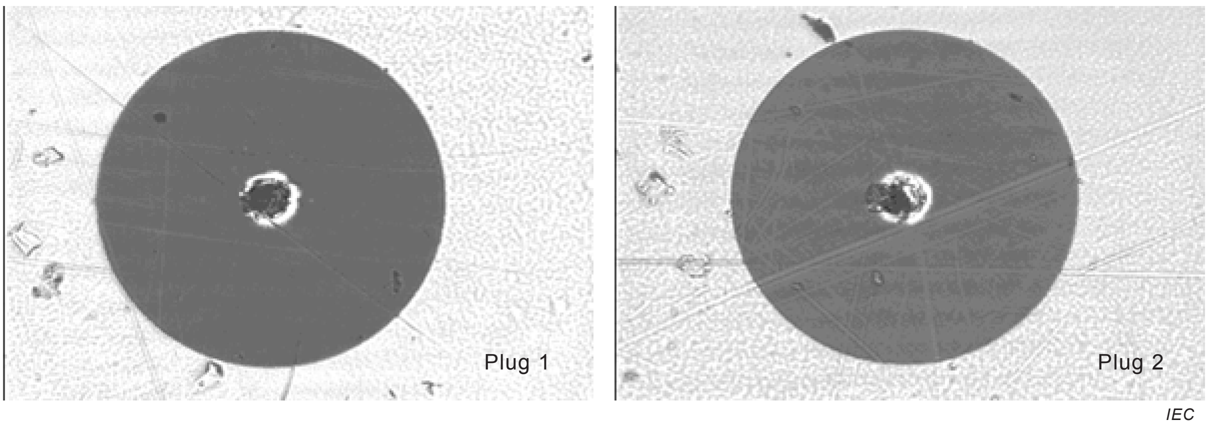


Figure 6 – Polishing surface condition contaminated with metal filing, after the test

In conclusion, it is confirmed that there is no risk of damage on the connectors due to high optical power under the conditions tested, if the connectors are correctly used and handled. In particular, it is recommended never to open connectors while high optical power is passing through them. However, a correct cleaning procedure and visual analysis of the polished connector surface is fundamental for a good and reliable network, particularly when metallic sleeves are used.

4.5 Fibre-coat burn/melt induced by tight fibre bending

This subclause provides some examples of the fibre coat burn/melt induced by tight fibre bending where the fibre coatings used were

a) UV curable resin: white, blue, green and uncoloured, and

b) nylon white [2].

The fibre used was single mode (SMF).

By using a thermo-viewer image of the bent fibre, the highest temperature at the surface of each fibre coating was measured. Figure 7 shows an image of the tightly bent fibre with an optical power of 3 W at 1 480 nm. Shown in Figure 8 is the temperature at the coating surface versus bending diameter for 3 W at 1 480 nm. The temperature of the nylon-coat surface reached 150 °C or higher; the nylon coating melted or even burned. The nylon coat burned in the test after the fibre break at the point where the fibre coat melted.

By considering the test results together with the long-term reliability degradation of coated SMF, it is suggested that the coated fibre bend diameter should be kept at >20 mm and >30 mm for the optical powers of 1 W and 3 W, respectively, under the conditions tested. Another test revealed that transparent UV-resin was more durable than coloured UV-resin against tight bending.

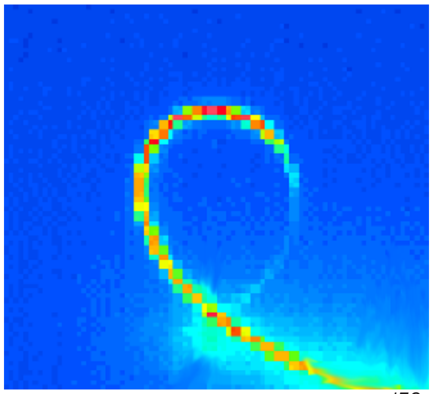


Figure 7 – Thermo-viewer image of tightly bent SMF with optical power of 3 W at 1 480 nm

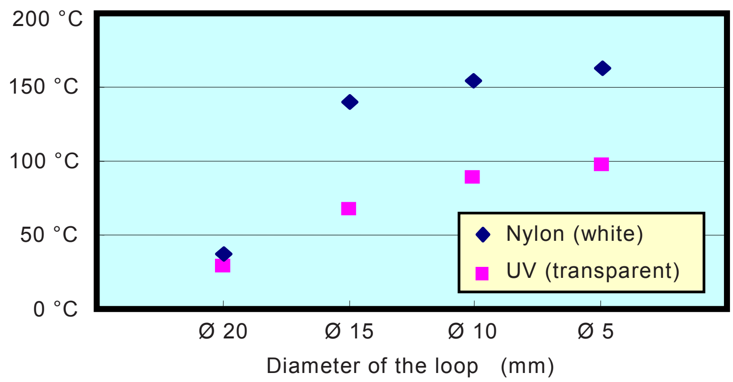


Figure 8 – Temperature of the coating surface of SMFs against bending with optical power of 3 W at 1 480 nm

4.6 Summary of the fibre damage

In 4.2, it was found that fibre fuse, once it was initiated for any reason, propagated if the input signal power was higher than 1,4 W and 1,2 W for SMF and DSF, respectively, under the conditions tested. However, care should be taken not to momentarily push the fibre across a sharp edge that may induce a tight bend and trigger fibre fuse even at a lower power than the above.

In 4.3, it was shown that the thermal effects induced by the connector and splice losses in high-power amplifiers could be acceptable under any practical conditions.

In 4.4, the connectors were tested with the input powers up to 1,2 W. It was found that only case discovered that the only case that caused permanent damage to the fibre core was when surfaces were contaminated by metal particles.

In 4.5, fibre coat burning induced by fibre tight bending was addressed. It is suggested that the bend diameter of coated fibre should be kept over 20 mm and 30 mm for optical powers of 1 W and 3 W, respectively, under the conditions tested.

Based on 4.2 to 4.5, it is concluded that power levels up to at least 1,2 W can be used without damaging OAs; the actual upper limit of the power is under study by considering, for example, the types of fibre and cleanliness of the fibre end faces.

In addition, IEC TR 62627-01 has been published in order to prevent damage to the connector and IEC 62547 in order to measure the damage of fibre tight bending.

5 Maximum transmissible optical power to keep eyes and skin safe

5.1 Maximum transmissible exposure (MPE) on the surface of eye and skin

Definition 3.59 of IEC 60825-1:2014 defines MPE as follows:

" level of laser radiation to which, under normal circumstances, persons may be exposed without suffering adverse effects"

Here, the MPE values IEC uses have been specified in ANSI-Z136 [10] based on animal experiments. Clause 4 of IEC TR 60825-14:2004 gives more details of MPE.

Subclause 4.8.2 of IEC 60825-2:2004 includes the following normative text in which it is requested that optical fibre communication systems be designed not to exceed the maximum permissible exposure (MPE), including the time period before an automatic power reduction (APR) system completes its function:

“Where the OFCS uses an automatic power reduction feature to meet the limits of a hazard level that is lower than that which would have to be assigned if no automatic power reduction feature would be present, the irradiance or radiation exposure during the maximum time to reach the lower hazard level shall not exceed the irradiance or radiant exposure limits (MPE). For controlled locations the measurement distance is 250 mm for this subclause only”.

Here, the hazard levels of the laser products including OAs are determined based on the classification rule of IEC 60825-1. In the existing standards, automatic laser shutdown (ALS) could have the same meaning as automatic power reduction (APR).

5.2 Maximum permissible optical power in the fibre for the safety of eye and skin

5.2.1 General

Informative Annex D of IEC 60825-2:2004 and IEC 60825-2:2004/AM2:2010 gives the following formula that calculates the maximum permissible optical power P in the fibre by using the maximum permissible exposure (MPE) to the eyes/skin after free-space propagation.

$$P = \frac{\pi d^2 MPE}{4t} \frac{1}{1 - \exp\left[-0{,}125\left(\frac{\pi\omega_0 d}{\lambda NOHD}\right)^2\right]} \tag{1}$$

where

P is the total power in fibre, in W;

MPE is the maximum permissible exposure, Jm^{-2};

ω_0 is the mode field diameter ($1/e^2$ power density), in m;

d is the limiting aperture diameter, in m;

t is the shut down time, in s;

$NOHD$ is the nominal ocular hazard distance, in m;

λ is the wavelength, in m.

Based on Formula (1), Table D.14 of IEC 60825-2:2004 and IEC 60285-2:2004/AMD2:2010 shows examples of power limits for optical fibre communication systems that have the APR to reduce the power to a lower hazard level. MPEs used in the calculation are shown in Tables 5, 6 and 7 of IEC 60825-14:2004.

Table 3 reiterates Table D.14 of IEC 60825-2:2004 and IEC 60285-2:2004/AMD2:2010. It shall be noted that the maximum permissible optical power in such OAs can be increased by reducing the power reduction time of the APR (the shut down time).

Table 3 – Examples of power limits for optical fibre communication systems having automatic power reduction to reduce emissions to a lower hazard level

Wavelength nm	Fibre mode field diameter µm	Maximum power output unrestricted mW	Maximum power output restricted mW	Maximum power output controlled mW	Shutdown times s	Measurement distance m
980	7	9,4	9,4	–	1	0,1
980	7	N/A	7,2	–	3	0,1
980	7	N/A	–	39	3	0,25
1 310	11	78	78	–	1	0,1
1 310	11	N/A	59	–	3	0,1
1 310	11	N/A	–	314	3	0,25
1 400 … 1 500	11	1 598	1 598	–	0,3	0,1
1 400 … 1 500	11	650	650	–	1	0,1
1 400 … 1 500	11	N/A	389	–	2	0,1
1 400 … 1 500	11	N/A	288	–	3	0,1
1 400 … 1 500	11	N/A	–	2 403	2	0,25
1 400 … 1 500	11	N/A	–	1 774	3	0,25
1 550	11	2 539	2 539	–	0,5	0,1
1 550	11	1 273	1 273	–	1	0,1
1 550	11	N/A	639	–	2	0,1
1 550	11	N/A	428	–	3	0,1
1 550	11	N/A	–	2 640	3	0,25

NOTE 1 The fibre parameters used are the most conservative case. Listed figures for λ = 1 310 nm … 1 550 nm are calculated for a fibre of 11 microns mode field diameter (MFD) and those for λ = 980 nm are for 7 microns MFD.

Many systems operating at 1 550 nm with the use of erbium doped fibre amplifiers (EDFAs) pumped by 1 480 nm or 980 nm lasers use transmission fibres with smaller MFDs. For example, 1 550 nm dispersion shifted fibre cables have upper limit values of MFD of 9,1 microns. In this case, the maximum power outputs for unrestricted and restricted areas at 1 480 nm and 1 550 nm are 1,44 times the values in Table D.14, and those for controlled areas at 1 480 nm and 1 550 nm are 1,46 times the values in same table.

NOTE 2 Times given in the table are examples; shutdown at any shorter time than the maximum is permissible, and may permit the use of higher powers (the maximum times are 1 s for unrestricted locations and 3 s for restricted and controlled locations, respectively).

Here, it is assumed that the user does not employ any optical instrument or viewing optics within the beam. When optical instruments or viewing optics are not used, devices classified as 1M are considered safe under the conditions indicated in Clause 8 of IEC 60825-1:2007. However, they may be hazardous if the user employs optical instruments or viewing optics within the beam.

5.2.2 Need for APR

Appendix II of ITU-T Recommendation G.664:2012 states the following, suggesting that the APR is needed not only on the main optical signal sources but also on all pump-lasers employed:

“In particular Distributed Raman amplification systems will need specific care to ensure optically safe working conditions, because high pump powers (power levels above + 30 dBm are not uncommon) may be injected in optical fibre cables.

“Therefore APR procedures are required in order to avoid hazards from laser radiation to human eye or skin and potential additional hazards such as temperature increase (or even fire) caused by local increased absorption due to connector pollution/damages or very tight fibre bends.

“In order to ensure that the power levels emitting from broken or open fibres connections are at safe levels, it is necessary to reduce the power not only on the main optical signal sources but also on all pump-lasers employed, in particular the backward pumping lasers.”

5.2.3 Wavelengths

The safe limit of the optical amplifier power set by the MPE limit should include main optical signals, pump-laser powers and optical supervisory channel power, if used.

5.2.4 Locations

Table 4 shows location types within an optical fibre communication system and their typical installations. See IEC 60825-2.

Table 4 – Location types within an optical fibre communication system and their typical installations

Location type	Typical installation (informative)
Unrestricted access	Accessible by the public (e.g. domestic premises, premises open to the public
Restricted access	Secured areas within business/commercial premises not open to the public (e.g. telephone PABX rooms, computer systems, etc.)
Controlled access	Cable duct, street cabinets, dedicated and delimited areas of distribution centres

5.2.5 Nominal ocular hazard distance (NOHD)

In controlled locations, NOHD at which the level of exposure should drop to the MPE for the eye is 25 cm, because personnel should be trained to keep the 25 cm distance. Otherwise the NOHD is 10 cm, because the minimum focal distance for the human eye is generally known as 10 cm.

5.2.6 Power reduction times

Power reduction time is the maximum time span after the incident before the APR completes its task. ITU-T Recommendation G.664 suggests as information the power reduction times for OAs in multi-vender systems. For systems without line amplifiers, the APR time suggested is less than 800 ms, and that for OAs in systems with line amplifiers is less than 3 s, as follows.

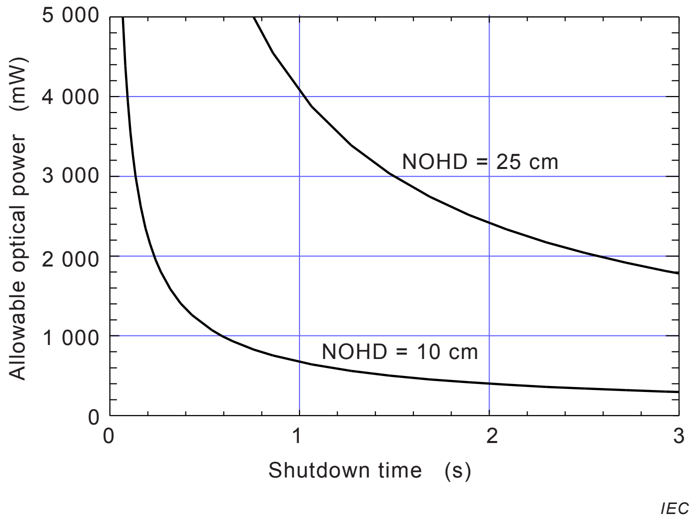
Appendix III of ITU-T Recommendation G.664:2012, states the following:

"After at least 500 ms of continuous presence of the LOS (loss of signal) defect, the actual shutdown command will be activated, which shall result in reduction of the optical output power at MPI-S (single channel source main path interface reference point) within 800 ms from the moment loss of optical signal occurs at MPI-R (single channel receive main path Interface reference point).

"In order to avoid exposure to hazardous optical power levels, all amplifiers (boosters and line amplifiers) shall have sufficiently short deactivation times to accommodate shutdown of all amplifiers between MPI-S and MPI-R within 3 s from the moment the actual connection interruption occurs.

"NOTE Depending on the actual operational power the 3 s shutdown time (defined in the past) might not be fast enough. A check against IEC 60825-1 is recommended."

Within the above limit, the maximum permissible optical power shown in Table 3 can be increased if the power reduction time for the APR can be shortened. Figure 9 shows the maximum permissible power in the fibre against APR power reduction times that were derived by using Formula (1) in 5.2.1.



NOTE 1 In the restricted/controlled area, the OA classification is determined based on the optical power measured 3 s after the incident.

NOTE 2 Fibre mode field diameter = 11 μm, wavelength = 1 480 nm.

Figure 9 – Maximum permissible power in the fibre against APR power reduction time

5.2.7 Medical aspects of the safety of eyes and skin in existing standards

Concerning the medical aspects of the safety of eyes and skin, the following information is found in IEC 60825-14:

a) "The retinal hazard region is typically understood as 400 nm to 1 400 nm (see 4.3.3 of IEC 60825-14:2004).
b) The pupil diameter used here is 7 mm assuming a dark room, although it is 4 mm to 5 mm in a regular room (see 4.3.2 of IEC 60825-14:2004).
c) From 1 400 nm to 1 500 nm for exposure time t = 1 ms to 10 s, the MPE values are the same for cornea and skin, being given as 5 600 t 0,25 Jm–2 (Table 5 of IEC 60825-14:2004). However, the consequences of injury to the eyes are usually much more serious than equivalent injuries to the skin (see 7.3.3.1 of IEC 60825-14:2004).
d) There is no "eye-safe" waveband (see 7.3.3.2 b) of IEC 60825-14:2004)."

Infrared light with a wavelength >1 400 nm (or sometimes >1 300 nm) normally does not penetrate into the eye but causes damage to the cornea. It is also understood that visible light (400 nm to 700 nm) and light ≤1 400 nm penetrate and cause damage to the retina. It is also known that retina damage is normally incurable: retinal cells do not re-grow.

6 Maximum optical power permissible for optical amplifiers from the viewpoint of fibre damage as well as eye and skin safety

Based on 4.2 to 4.5 of this technical report, it was concluded in 4.6 that power levels up to at least 1,2 W can be used without damaging fibres under the conditions tested if the following conditions apply:

- the fibre bend diameter is more than 20 mm;
- the connectors are kept “clean”.

Next, from the viewpoint of eyes and skin safety, it was understood from 5.2 that pump power at the 1 480 nm range for distributed Raman amplifiers can go up to 1,77 W or 2,59 W depending on the fibre mode field diameter (see Table 3) for the pump APR time of 3 s, if the high intensity light could leak only within controlled locations. With APR time shorter than 3 s, higher power is allowed.

It can then be concluded that the maximum optical power permissible for the damage-free and safe use of optical amplifiers can go up to at least 1,2 W, within controlled locations under the conditions shown in the present technical report and with the APR time shorter than 3 s. The actual upper limit of the power is under study by considering, for example, the types of fibre and cleanliness of the fibre end faces.

However, where there is potential light leakage due to, for example, a fibre break, any system operating with an optical power of 1,2 W shall not exceed permitted hazard levels (see IEC 60825-2). APR can be used to limit optical power to a suitable level. Moreover, it shall be noted that, although signal power at the 1 550 nm range is generally much less than Raman pump power, signal power cannot always be neglected for OA safety and damage.

7 Conclusion

It is concluded under the conditions tested and considered that the optical power permissible for the damage-free and safe use of optical amplifiers can go up to at least 1,2 W for controlled locations when APR times are shorter than 3 s.

Since the technologies are constantly evolving, it is requested that readers refer to the latest versions of this technical report as well as the relevant documents referred to in this report.

Annex A
(informative)

General information for optical fibre fuse

A.1 Introductory remark

Optical power in optical fibre is being increased to achieve an efficient transmission network by increasing the optical signal channel number and by maintaining a suitable SNR at a high transmission speed by using a high power optical fibre amplifier and Raman amplification. This has led to increased concern about the damage caused by the fibre fuse phenomenon. Once the phenomenon is initiated, a bubble train forms in the fibre core after the fibre fuse, and it propagates towards the high optical power source and continues until the optical power in the core falls below the threshold fibre fuse power. Optical signals cannot be transmitted through fibre damaged in this way. There have been several studies regarding the generation mechanisms, the bubble formation mechanism and the emission properties from the plasma discharge that occurs when bubbles are formed. Recently, several prevention and termination methods for the fibre fuse have been proposed.

This annex gives a general description of the generating mechanism and characteristics of fibre fuse and prevention and termination for the fibre fuse for a greater understanding about optical fibre fuses.

This annex is based on Technical paper TP08/AM-2010 [11].

A.2 Generating mechanism

The fibre fuse phenomenon was first observed in 1987 by Kashyap and Blow [1]. If this phenomenon was initiated in the fibre, an intense blue-white flash occurred and ran along the fibre core toward the light source at a relatively low velocity of the order of 1 m/s. Periodic and/or non-periodic voids were left after the blue-white flash passed through the core (see Figure A.1). This phenomenon results in catastrophic destruction of the optical fibre waveguide.

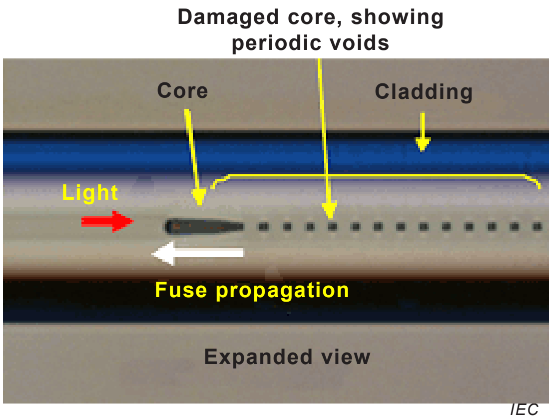


Figure A.1 – Front part of the fibre fuse damage generated in the optical fibre

In the experiments, the fibre fuse can be initiated by contacting the fibre output end with absorbing materials, heating the fibre by arc discharge, formation of bends and knots, and heating the fibre end with a flame or the heating furnace. The local heating of the fibre core due to large high-temperature light absorption is closely related to the generation of the fibre fuse phenomenon.

Several hypotheses have been put forward to explain the fibre fuse phenomenon. Typical hypotheses are shown as follows.

a) Self-propelled self-focusing model [1]: It is considered that thermally generated third-order nonlinearity is produced by avalanche ionization in this model. The heating process increases the number of free electrons in the core through collisions, and increases the local third-order nonlinearity. The increase in the nonlinearity causes self-focusing and collapse of the laser beam, resulting in the fibre fuse.
b) Solitary thermal shock wave model [9]: In this model, a solitary thermal shock wave is responsible for the fibre fuse. The periodic damage track left after the passage of the shock wave arises through mode focusing in the thermal lens created by the wave.
c) Exothermic chemical reaction model [12]: It is proposed in this model that the high temperature in the fibre fuse occurs by an exothermal chemical reaction of Ge-related defect formation with no light absorption.
d) Radiative-collision reactions model [13]: In this model, the fibre fuse occurs by the radiative-collision reactions between SiO molecules and neighbouring non-bridge O atoms in the fibre core with large light absorption coefficients.
e) SiO absorption model [14]: In this model, the fibre fuse occurs by the thermal production of SiO molecules with large light absorption coefficients at high temperatures.

Among these models, the avalanche ionization of the silica glass described in a) cannot be realized by using the conventional CW laser (0,1~10W output power) for the fibre fuse experiments. The thermal lens formation described in b) needs the large light absorption coefficient of 540 cm-1 to obtain a large temperature gradient in the core. However, the origin of the large absorption coefficient is not at all clear in v). Point c) cannot explain the generation of the fibre fuse observed in non-Ge-doped optical fibbers. The radiative-collision reaction described in d) is not popular for US and European researchers.

On the other hand, e) is based on the well-known thermochemical reaction of SiO_2, and it can be applicable to many types of optical fibres. The fibre fuse parameters estimated by using e) are in fair agreement with the experimentally determined values.

The SiO absorption model is shown in Figure A.2. The α (unit: 1/m) exhibits the absorption coefficient of SiO (at the wavelength of 1 064 nm) per unit length of 1 m. The fibre fuse generation processes due to this model are as follows:

1) When the optical fibre is heated up to high temperatures of >2 000 K, a lot of SiO molecules are produced by the thermal decomposition of SiO_2 glass, which is the main component of the optical fibre.
2) SiO exhibits a large light absorption coefficient at high temperatures of >2 000 K. So, heating of the optical fibre is enhanced by increasing the optical absorption of the SiO.
3) The heat in the core, produced by the optical absorption of the SiO, diffuses into the low-temperature parts placed outside the core.
4) When the heat produced in the core overcomes the heat consumed by diffusion, the core temperature is reached at 10 000 K or higher, where the SiO is thermally decomposed into the neutral atoms or charged ions, and is in the plasma state.
5) The plasma state occurred in the core is continuously maintained by absorbing the laser power supplied by the light source, and is propagated along the fibre toward the source.

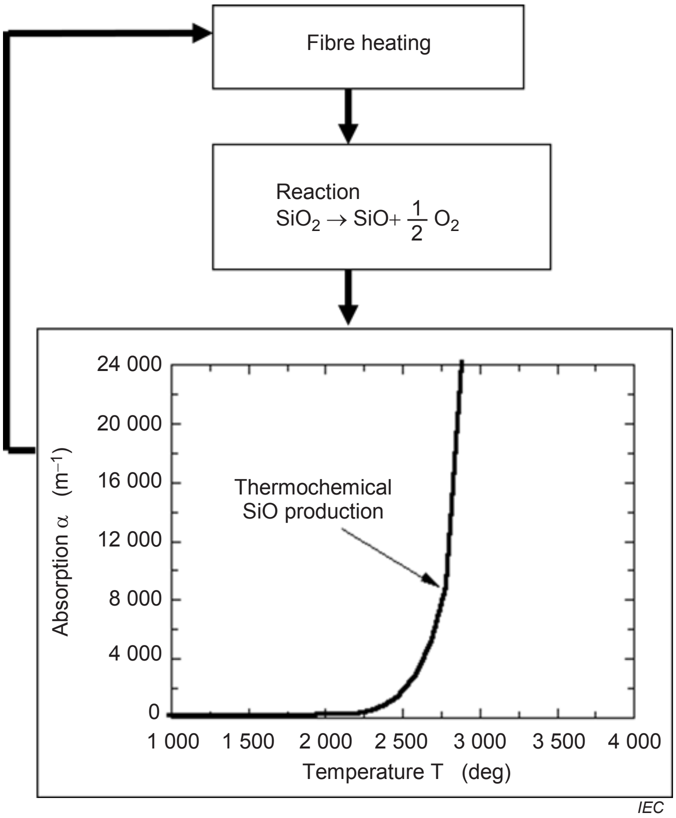


Figure A.2 – SiO absorption model

Figure A.3 exhibits the calculated fibre fuse propagation behaviour simulated with the SiO absorption model. Value z is the axis along the fibre length and of the laser-light propagation. Laser light propagates toward + direction of the z axis. r/r_f is the normalized radial distance r divided by the outer radius r_f (= 62,5 μm) of the optical fibre, and r/r_f = 0 is the location of the core centre. As the initial condition of Figure 3 at the time t = 0 s, it was assumed that the small core region (length: 500 μm) at z = 0 was heated at 2 500 K. When the 2 W laser light (at the wavelength 1 064 nm) was incident into the fibre core, the temperature (T) distributions in the optical fibre after 1 ms (t = 1 ms), 22 ms (t = 22 ms), and 43 ms (t = 43 ms) are shown in Figure 3. As shown in Figure A.3, a sharp thermal peak with high temperature of >50 000 K occurs after 1 ms at the small core region at z = 0, which was pre-heated at 2 500 K and t = 0 s. This peak is propagated along the core centre toward – direction of the z axis with the velocity of about 0,4 m/s. This fibre fuse velocity estimated with the SiO absorption model agrees very closely with the experimentally determined one [15, 16]. In addition, the propagation behaviour of the thermal peak is also explained by the propagation of the heat dissipative soliton [17].

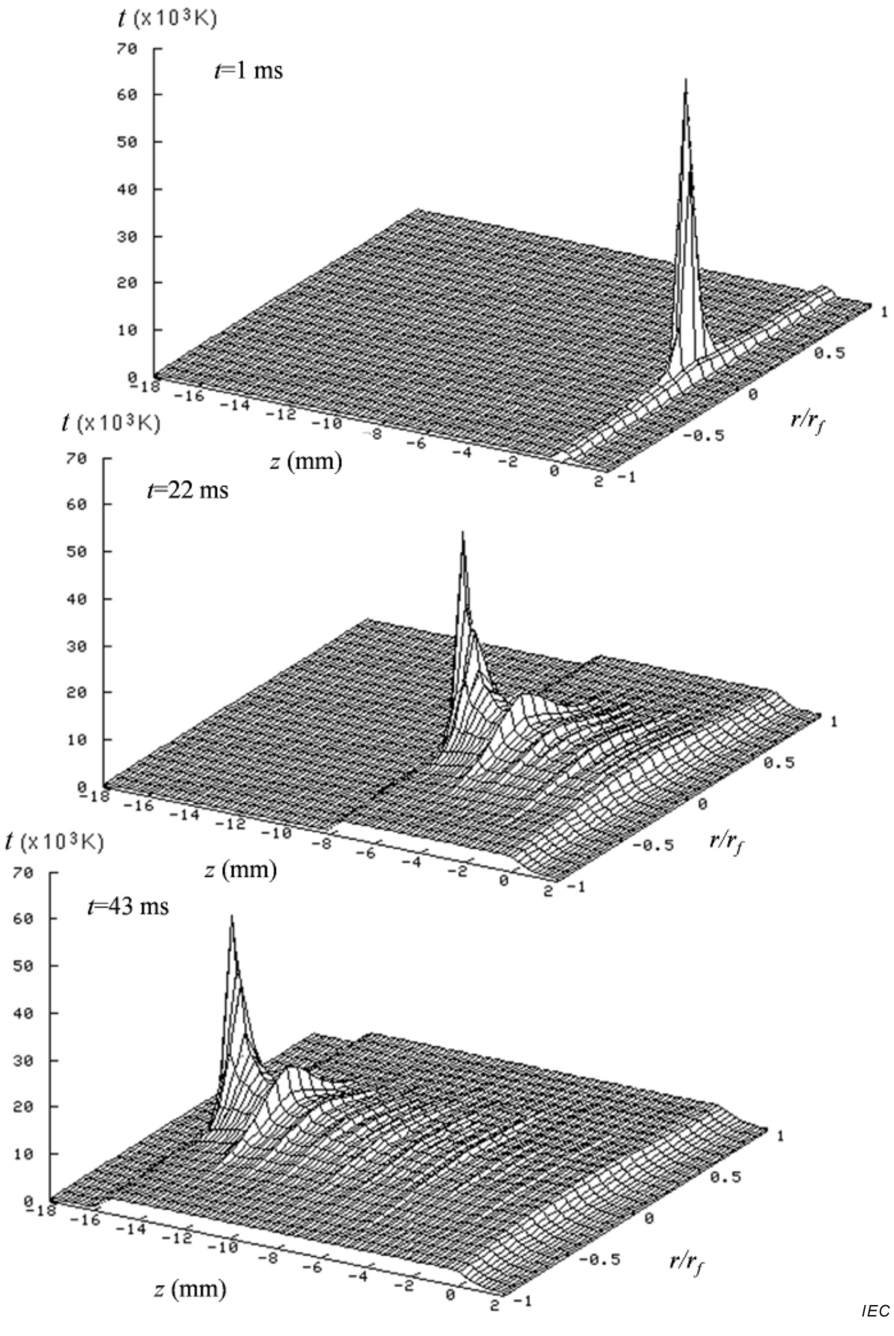


Figure A.3 – Calculated fibre fuse propagation behaviour simulated with the SiO absorption model

A.3 Void formation mechanism

In order to investigate the void formation mechanism, it is necessary to observe the molten glass surrounding a fibre fuse directly, but this is hardly possible due to its strong light emission, i.e. black-body radiation more than several thousand K [18]. Alternatively, a mechanism has been proposed on the basis of the observation of the voids left after quenching a fibre fuse. Figure A.4 shows a set of fused damage micrographs that suggests a mechanism of periodic void formation [19]. These are the front part of void trains obtained by switching off the 9,0 W pump laser (wavelength: 1 480 nm) after a fibre fuse was generated in a single mode optical fibre and was moving through a bare fibre segment. The reason of terminating the fuse at a jacket-free segment is to maximize the quenching rate of the molten glass by eliminating a re-absorption of backscattered visible radiation at the pigments in the jacket. They are sorted in order of increasing the distance between the top of the first large void in the left and the regular voids in the right. This sorted sequence seems to show frozen structures during a single void formation process for 18,7 µs as described below.

a) a bridge appears at the tail of the top long void (Figure A.4 (1), (2));
b) the pinched-off void is compressed by the pressure of the plasma (Figure A.4 (3) through (6));
c) to form a bullet-like shape (Figure A.4 (1),(2)).

The origin of this bridge formation is proposed to be Rayleigh instability [14] or electrostatic repulsion induced on the liquid-plasma interface [20].

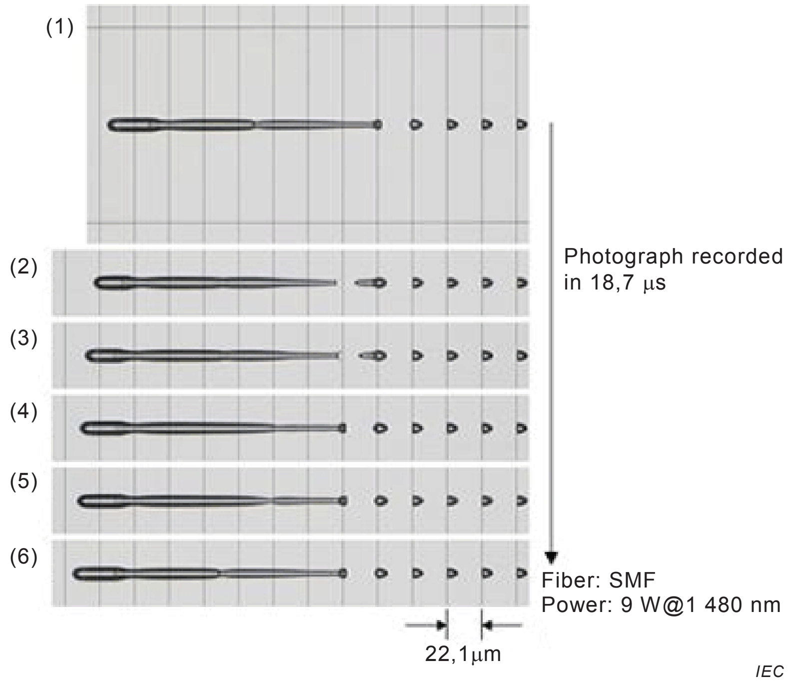


Figure A.4 – Series of optical micrographs showing damage generated by 9,0 W 1 480 nm laser light suggesting a mechanism of periodic void formation

A.4 Propagation characteristic of a fibre fuse

This clause describes two basic characteristics: plasma propagation and periodicity of the voids in optical fibbers.

Figure A.5 shows some images of fibre fuse ignition taken with an ultra-high speed camera (Figure A.5a and A.5b) and an optical micrograph of the damaged fibre (Figure A.5c) [21]. The fuse was initiated by the heat from light absorptive powder pressed on the output end of a single-mode optical fibre delivering 9 W of light (1 480 nm). After a preliminary process, a stable running plasma appeared at the inside from the fibre end (approximately 300 µm in this case) leaving a periodic void train. Its speed was found to be constant at the resolution of microseconds.

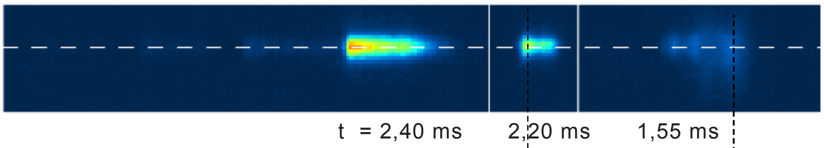


Figure A.5a – Photographs of visible light emission around the fibre fuse ignition in which original grayscale images are converted to colour- scale ones

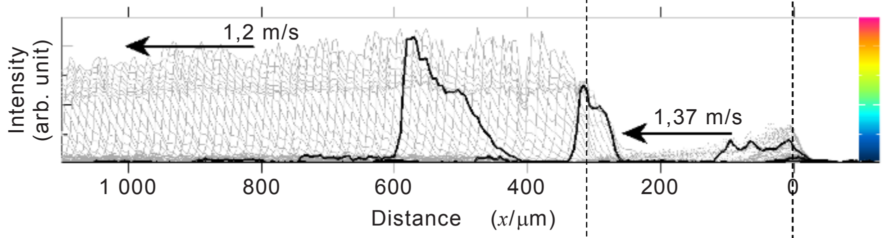


Figure A.5b – Intensity profiles along the dashed lines on the photographs taken every 10 ms

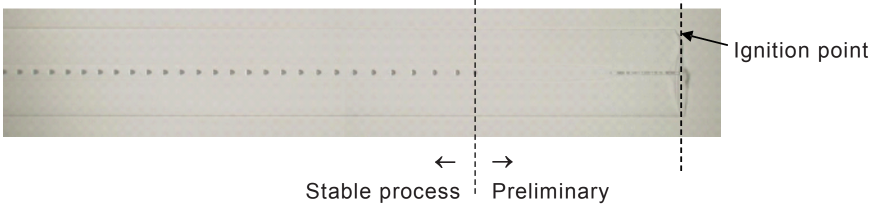


Figure A.5c – Optical micrograph of a damaged fibre

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Figure A.5 – Images of fibre fuse ignition taken with an ultra-high speed camera and an optical micrograph of the damaged fibre

Figure A.6 shows the relationship between the power density supplied to the fibre fuse and the propagation velocity at the wavelengths of 1 064 nm and 1 480 nm [14]. The open and closed circles are the experimental results [15,16,22]. The velocity of the fibre fuse increases with increasing the power density, and exhibits the values of 0,2~1,2 m/s. The solid lines are the calculation results estimated with the SiO absorption model. The step-index single-mode optical fibre was assumed in the calculation. This fibre-fuse velocity estimated with the SiO absorption model agrees very closely with the experimentally determined ones.

In addition, Figure 7 shows various void train patterns that were obtained by changing the pump laser power (1 480 nm) [19]. Under some conditions, the periodicity was lost. In other cases, the void interval increases with the laser intensity. When the laser power is reduced below 1,2 W, the fibre fuse cannot propagate stably and diminish spontaneously.

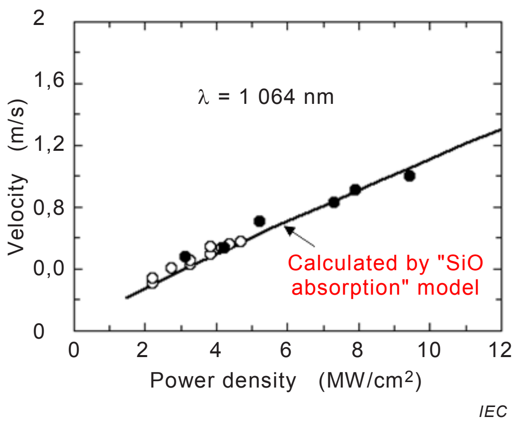

Figure A.6a – Propagation velocity at the wavelengths of 1 064 nm

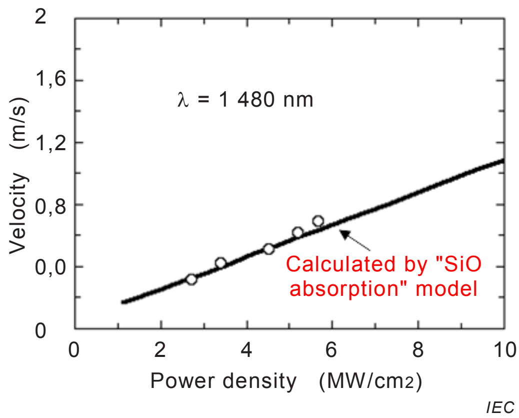

Figure A.6b – Propagation velocity at the wavelengths of 1 480 nm

Figure A.6– Power density dependence of the fibre-fuse propagation velocity

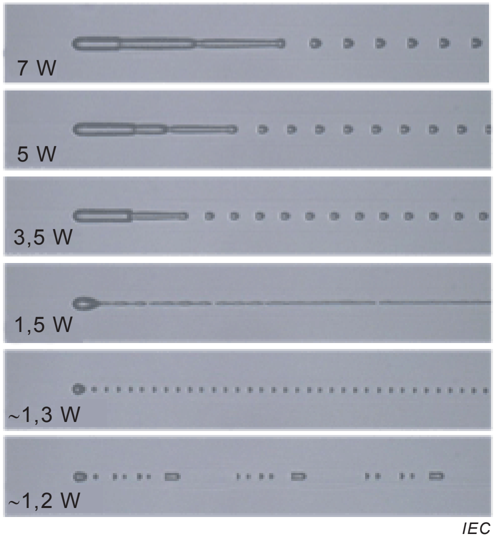

Figure A.7 – Optical micrographs showing front part of the fibre fuse damage generated in SMF-28 fibres with various laser intensities (1 480 nm)

A.5 Prevention and termination

A.5.1 General

If an optical fibre fuse is generated, optical signal transmission becomes impossible from the resulting damage. A prevention method that prevents the optical fibre fuse from being generated, and a termination method to prevent damage from propagating when it is generated, are both required for achieving practical optical fibre transmission systems. The prevention method and termination method which have been reported so far are introduced in the following subclauses.

A.5.2 Prevention methods

In order to prevent fibre fuse, the counter-measure against contamination of an optical fibre connector endface, which is one of the main generating factors of the fibre fuse, is important. IEC TR 62627-01 describes this countermeasure. Furthermore literature relating to an optical fuse and optical limiting devices for suppressing light intensity in an optical fibre within light intensity for an optical fibre fuse to generate or propagate exist [23].

A.5.3 Termination methods

A.5.3.1 General

In order to terminate the fibre fuse, two methods currently exist:

a) the passive method which prevents an optical fibre fuse by increasing the fibre fuse propagation threshold value above which a fibre fuse propagates by expanding the mode field diameter of the optical fibre;

b) the active method which halts or reduces the output of the light source by detecting a characteristic return light observed when the optical fibre fuse is generated.

A.5.3.2 Passive termination methods

The principle of the passive method is shown in Figure A.8a. The fuse propagation threshold power increases in proportion to the mode field diameter (MFD) of the optical fibre [24]. So it is possible to increase the fuse propagation threshold power by adopting the taper structure [25] and the TEC (Thermally-diffused expanded core) structure [26] as the core of the optical fibre, and a fibre fuse can be discontinued in the section to which MFD was expanded. Figure

A.8b) shows a photograph of the fibre fuse terminator which adopts a TEC structure [26]. Although the MFD of the section connected to the transmission fibre is the same as the usual optical fibre, the MFD of the fibre core of the middle section of a terminator is expanded. By expanding the MFD of a fibre core to 20~30 μm, it is realizable that the optical fibre fuse generated by a strong laser light (wavelength of 1 480 nm) of 2 W can be discontinued in the TEC section. In addition, it is reported that hole-assisted structure is also effective for increasing the fuse propagation threshold power [27-30]. Figure A.9 shows the photograph in which the fibre fuse propagated on the left from the right is discontinued in a hole-assisted fibre [27]. It is considered that the fibre fuse termination by hole-assisted structure is for not reaching a temperature required in order to propagate the fibre fuse, when the hole interval of a hole-assisted fibre is narrow and the high temperature area is limited by the heat insulation effect by the hole layer, and the quantity of SiO which is a source of heat absorption lacks [28]. However, the more detailed study about the termination mechanism by the hole-assisted structure, is required. In addition, it was proposed that inserting a short segment of a hollow optical fibre in a normal single-mode optical fibre line was effective.

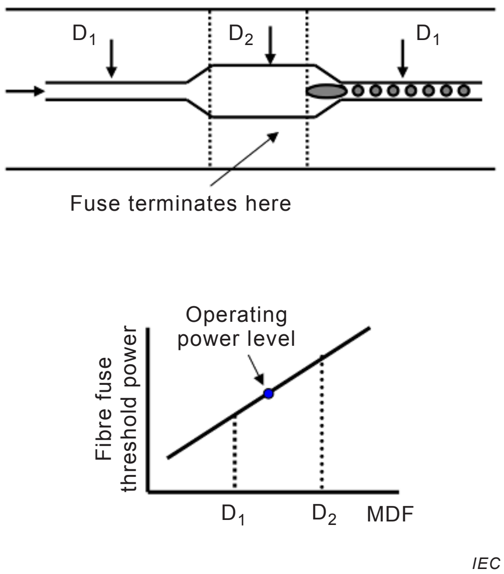

Figure A.8a – Principle of the optical fibre fuse passive termination method

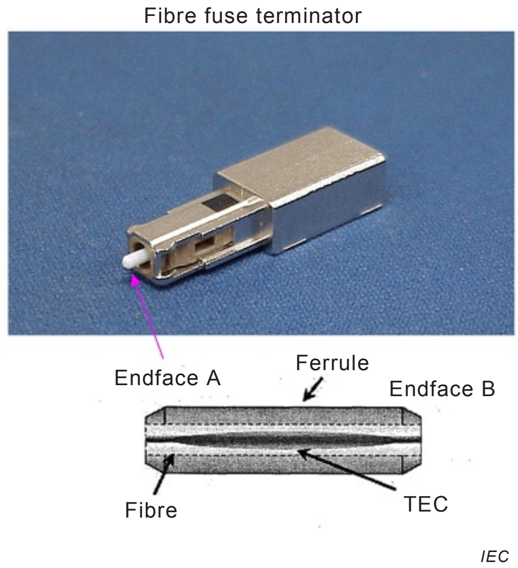

Figure A.8b – Photograph of the fibre fuse terminator which adopted TEC structure

Figure A.8 – Principle of the optical fibre fuse passive termination method and photograph of the fibre fuse terminator which adopted TEC structure

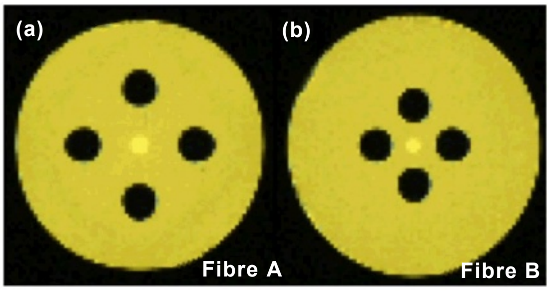

Figure A.9a – Cross-section photograph of hole assisted fibre

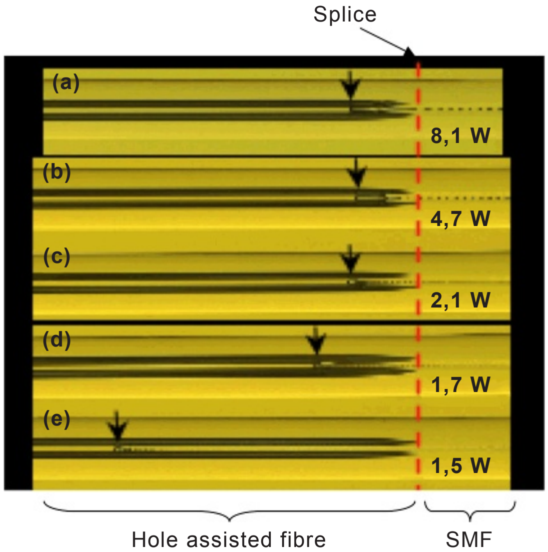

Figure A.9b – Photograph of the fibre fuse termination using a hole assistant fibre

Figure A.9 – Photograph of hole-assistant fibre and fibre fuse termination using a hole-assistant fibre

A.5.3.3 Active termination methods

By using the active method, fibre fuse generation is detected and the light of the high output light source which has caused the fibre fuse is halted [4]. Figure A.10 shows the scheme of this method. In this scheme, fibre fuse generation is apprehended, by detecting back reflected optical light from the void formation section using the photodiode, and the output signal from the photodiode is passing through a DC filter and an electric power sensor which can distinguish the generating of a fibre fuse. When such a generation has been perceived, a control signal is sent from an electric power sensor to a light source, and the fibre fuse is then interrupted by halting the output of light source which caused the fibre fuse. Figure A.11 shows the electric spectrum (Figure A.11a)) measured through the photodiode, and the electric output signal (Figure A.11b)) from the electric power sensor which assesses generation of an optical fibre fuse. The optical power of 2,75 W is launched into the conventional optical fibre. The propagation velocity of the fibre fuse is 0,45 m/s. When the fibre fuse is generated, the electric spectral intensity increases by about 40~50 dB over the wide spectral region. In addition, two signature spectrum components which correspond to the interval of the void formed with the fibre fuse (f_c interval, 31 kHz in this example) and Doppler shift frequency f_D (at 876,6 kHz in this example) are observed in the electric spectrum. The f_c and f_D are described as follows:

$$f_c = v/p$$

$$f_D = 2nv/\lambda \qquad (A.1)$$

where p is the void interval formed with the fibre fuse（14,5 μm in this example）, n, v and λ are the refractive index of fibre core, the void velocity and the wavelength of optical light which generate the fibre fuse, respectively. Figure A.11 shows the transformation of electric signal by optical fibre fuse. The response time of this active method is around a few milliseconds, as shown in Figure A.11b. It is possible to minimize the damage of the fibre fuse.

In addition, another method of fuse detection was proposed with a FBG temperature sensor thermally attached to the optical line.

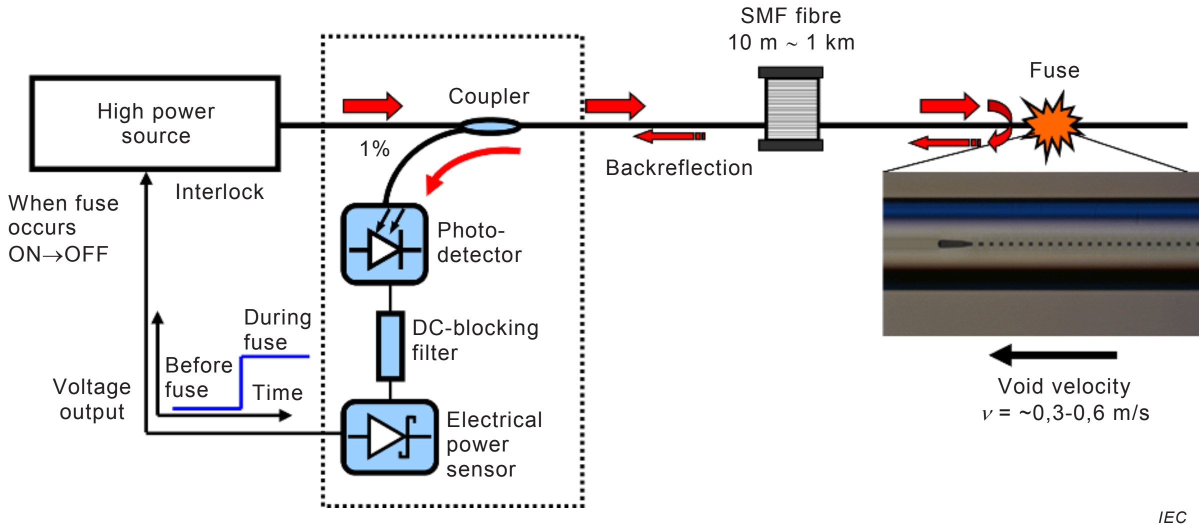

Figure A.10 – Example of fibre fuse active termination scheme

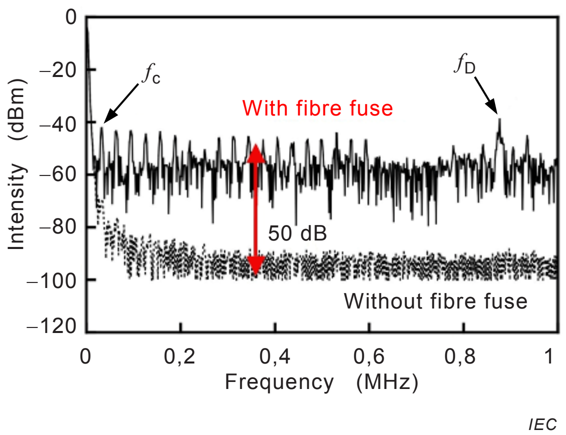

Figure A.11a – Generating electric spectrum outputted from the photodiode

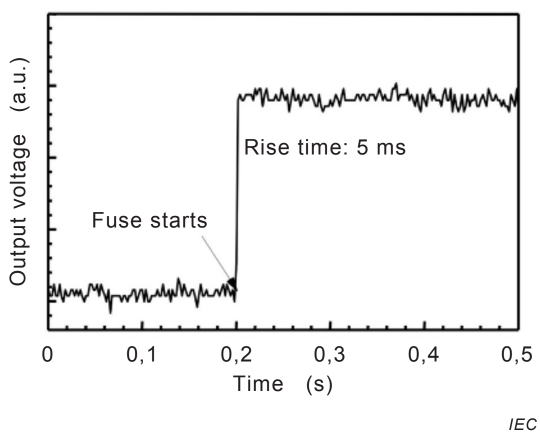

Figure A.11b – Generating electric output signal from the electric power sensor

Figure A.11– Transformation of electric signal by optical fibre fuse

A.6 Conclusion

General information concerning an optical fibre fuse, the generating mechanism, general characteristics and prevention methods as well as termination methods have been outlined. The optical fibre fuse is an important phenomenon from the viewpoint of the reliability of optical fibre communications systems and their safety operation.

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