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INTERFERENCE DUE TO THERMAL RADIATION IN LOSS MEASUREMENTS DURING FIRE TESTS OF OPTICAL FIBER CABLES

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Abstract

Certain applications of fused silica optical fibers, in particular fire-resistant cables and sensors working in hot environments (*e.g.*, nuclear reactors) require short- or long-term operation at temperatures exceeding 800 °C. Peak temperatures during fire tests of fire-resistant cables vary between 830 °C and 1040 °C depending on applicable standards. If the fiber contains OH– ions and hydrogen, it exhibits both increased loss and incandescence in the corresponding absorption bands. Additionally, deteriorated fiber with multiple cracks and other microscopic defects collects radiation from glowing surroundings. During loss measurements with a standard setup including light source and power meter, thermal radiation from both sources adds to radiation from the light source, causing false decrease of indicated fiber loss. Several methods to eliminate this interference are presented.

Keywords: fused silica optical fiber, fire-resistant cable, loss measurement, fire test, incandescence.

1. Introduction

Fire-resistant fiber optic cables provide connectivity for safety systems, video monitoring, and emergency communications, and are required to retain optical continuity during fire for 15-–120 minutes [1-3]. Such cables incorporate standard telecom fibers made of fused silica. Resistance to fire is tested in simulated fire conditions using gas burners. *International Electrotechnical Commission* (IEC) tests involve temperatures around 840 °C [1], while maximum temperature stipulated in German standard DIN 4102-12 [2] exceeds 1000 °C after 90 minutes, in accordance with data for "cellulosic" fire given in the ISO 834-1 standard [3]. Loss of fibers is monitored [4], and its rise during fire test limited to [5]:

- 1 dB/m at 1550 ± 10 nm for single mode fibers [6],
- 2 dB/m at 1300 ± 20 nm for multimode mode fibers [7].

Fused silica fibers heated to temperatures above 800 °C both glow themselves (incandesce) and collect thermal radiation emitted by the surrounding matter – usually soot left from thermal decomposition of polymeric tubes and fiber coatings. Incandescence is made of few spectral peaks associated with OH^- (hydroxyl) ions present in fused silica. It fades with time during heating, as the hydroxyl ions are broken down:

$$2(\equiv\text{Si}-\text{OH}) \leftrightarrow (\equiv\text{Si}-\text{O}-\text{Si}\equiv) + \text{H}_2\text{O}, \tag{1}$$

$$2(\equiv\text{Si}-\text{OH}) + (\equiv\text{SiH}) \leftrightarrow (\equiv\text{Si}-\text{O}-\text{Si}\equiv) + \text{H}_2 \tag{2}$$

and resultant hydrogen and water vapor diffuse out of the fiber [8, 9]; this process is sometimes referred to as "fiber drying". Collected radiation is broadband, with spectral distribution close to perfect blackbody radiator, and its intensity rises with time due to growing number of microscopic cracks and cristobalite (crystalline form of SiO_2) inclusions serving as optical couplers [9] and crack initiators.

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Thermal radiation distorts results of loss measurements performed with a *Light Source and Power Meter* (LSPM) setup. It adds to the test signal from a light source; the power meter indicates higher power and lower fiber loss than without it. The can lead to acceptance of fire test result being in fact negative, with excessive of fiber loss or even a fiber break.

This situation is an exception in optical fiber cable testing, where absence of interference from internally generated or collected radiation is normally assumed. The only other case of meaningful interference is in multi-wavelength loss measurements, where wavelength division multiplexers with high level of crosstalk (–30 …–20 dB) are often used.

In the following sections we present sources, spectra and powers of thermal radiation emerging from hot optical fibers (section 2), resulting errors in measurements of fiber loss in such conditions (section 3), and some methods of eliminating them (section 4), recommended by the author after experience with monitoring of fiber loss in a cable during fire test. Conclusions are presented in section 5.

2. Thermal radiation in fibers under fire conditions

2.1. Fibers under tests and test procedures

All optical characteristics presented in this paper, except for section 2.2, have been measured in the course of high temperature experiments at National Institute of Telecommunications on telecom fibers belonging to three classes:

a) modern single mode fibers with low content of hydroxyl ions, conforming to current ITU-T standards G.652.D and G.657.A2 (2 types of fibers);
b) old (1990-1993) single mode fibers with high content of hydroxyl ions, conforming to old ITU-T standard G.652.A (3 types of fibers);
c) modern 50/125 μm multimode fibers of OM2 and OM3 types (3 types of fibers).

During most tests, a single fiber was placed straight in electric oven having 1 m long hot zone with ceramic tube, and protected by a fused silica tube. This tube was not sealed, so during test, polymeric fiber coatings first carbonized at 350 – 450 °C and later burned out at 500 – 600 °C. To investigate effects of carbon char surrounding optical fibers during fire test, the fiber was placed in a stainless steel tube having 1 mm inner diameter with ends sealed and carbon char produced by pyrolysis of coating did not burn.

For optical measurements, fiber sample 3 – 4 m long was fusion spliced to pigtail with FC/PC connector at one end (for measurements of radiation power and spectra). The other end was protected against entry of light. Variations in loss at high temperatures were tested separately on selected samples spliced to pigtails at both ends, using laser sources (850, 1310 and 1550 nm) and optical power meter, as described in section 3.1.

Fibers under test were normally subjected to temperatures rising from room temperature up to 1000 °C. Beginning from 400 °C, the temperature was raised in fixed 50 °C steps. Measurements of power of thermal radiation from single-mode fibers were possible starting from 400 – 450 °C, and required darkroom conditions. Optical spectra of radiation from fibers (b) and (c) were normally measured at 800, 900 and 1000 °C. Radiation emitted from fibers belonging to class (a) was too weak for spectral measurements.

Experiments of several samples were repeated 2 – 3 times to observe fiber "drying" and deterioration, and/or to measure fiber loss. Progressive drying and deterioration of fiber caused differences between results of repeated tests mentioned in sections 1 and 2.3 – 2.6. In particular, additional time required for spectral measurements resulted in detectable skips on recorded power vs. temperature graph. Those phenomena are of limited importance for fire tests, which are short and cable samples are tested only once. Situation is different during operation of fiber sensors, not covered here.

Detailed characteristics of radiation emerging from fused silica fibers held at temperatures up to 1000 °C: power, spectral distribution, variation with time, and physical mechanisms responsible are presented in paper [10]. This chapter includes a summary and examples needed to understand the characteristics of optical interference encountered during fire tests of optical fiber cables and in high temperature fiber sensors.

2.2. Absorption bands of hydroxyl ions in fused silica ("water peaks")

Table 1 shows central wavelengths, relative intensity of absorption, and spectral width at half-maximum (FWHM) for water peaks in the 700 – 1700 nm range of interest for fiber optic measurements, based on data from [11]. Wavelengths corresponding to four components of the 1390 nm absorption peak increase reversibly by 7 nm when temperature rises from 20 °C to 800 °C [12]. Hydroxyl absorption is little affected by details of preform making and fiber drawing operations, and spectral data are quite accurate. However, optical attenuation coefficients per ppm of OH^- in the glass reported in literature differ considerably [11].

Table 1. The strongest hydroxyl absorption bands of fused silica between 700 and 1700 nm.

Central wavelength [nm]	**Relative intensity [dB]**	**σ parameter [nm]**	**FWHM (2.355 σ) [nm]**
724	-29.1	----	----
825	-42.2	----	----
878	-28.9	----	----
943	-16.1	----	----
1139	-29.5	----	----
1246	-13.7	≈ 10.7	≈ 25.3
1353	-10.6	20.2	47.5
1382	0.0	6.7	15.8
1393	-2.4	10.6	25.0
1407	-7.0	29.2	68.8

Intensity of the strongest, combined peak at 1390 nm (actually four combined peaks at 1353/1382/1393/1407 nm, see Fig. 1) rises with temperature in accordance with Arrhenius formula, with reported activation energy of 1.13 eV [13] or 0.82 eV [9]. Attenuation at 1390 nm increases at the same rate and reaches 5 – 8 dB/m at temperatures in the 900 – 1000 °C range [8, 10] – see Fig. 6. In such conditions, the power of accumulated incandescent radiation is self-limiting, or "saturating" in a fiber longer than some 0.5 m; this length is shortened with increase of temperature. Fiber attenuation at wavelengths away from "water peaks", *e.g.*, 1300 nm is little affected.

The strongest absorption (and incandescence) bands are shown in Fig. 1. Measured spectra of fiber's incandescence (Figs 2 and 3) show only the combined peak at approx. 1390 nm and much weaker one at 1246 nm. Interestingly, the next strongest peak at 943 nm, well known as loss peak in multimode fibers, was almost undetectable during our measurements due to internal noise of optical spectrum analyzer.

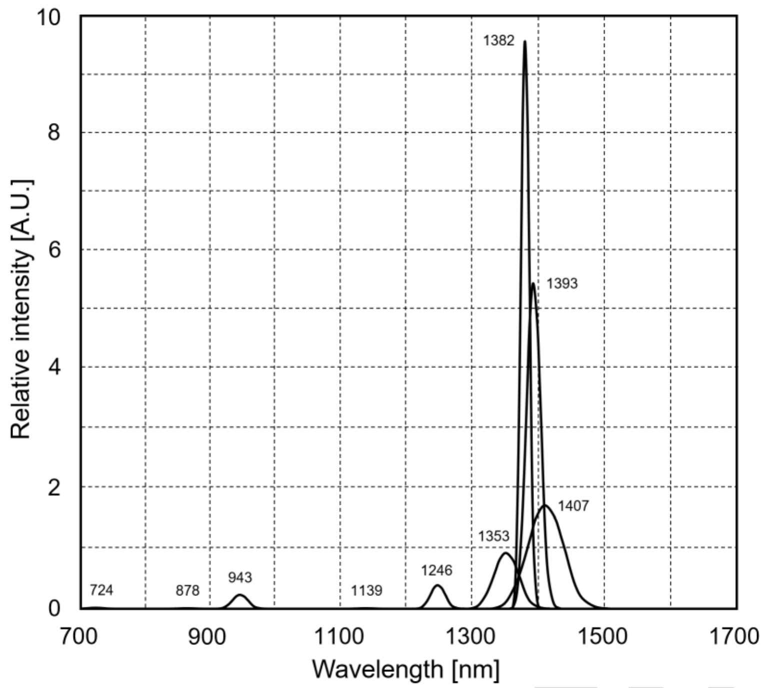

Fig. 1. Main absorption bands of fused silica contaminated with hydroxyl ions. This graph is based on data from paper [11]. Spectral range corresponds to measured spectra presented in Figs 2, 3, 5 and 6.

2.3. Incandescence of hot optical fiber

Figures 2 and 3 show spectra of radiation emitted by a:
- 50/125 µm graded index multimode fiber, and
- single mode fiber conforming to old ITU-T G.652.A Recommendation [14],

respectively, measured in our lab. The samples were 1 m long and heated to 900 °C shortly before measurements. Fibers were tested in the air inside a ceramic tube. Their coatings have fully burned out before, and power of coupled radiation (2.3) was low, but still detectable.

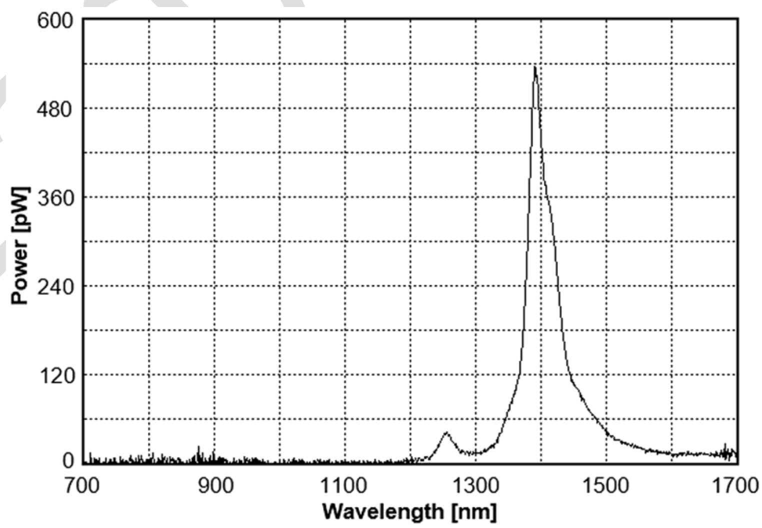

Fig. 2. Spectrum of thermal emission of OM2 multimode fiber at 900 °C, total power: -49.39 dBm.

Spectra were measured with Yokogawa AQ-6315B optical spectrum analyzer. Due to low power exiting test fibers and relatively large spectral widths of "water peaks" (Table 1), a resolution of 5 nm or 10 nm was selected. This, together with large spectral widths of four strongest emission peaks at 1353 nm, 1382 nm, 1393 nm and 1407 nm [8], made them appear as single peak of irregular shape – see Fig. 2. Total power of radiation exiting fiber under test was measured with HP 8152A optical multimeter and HP 81532A InGaAs power sensor sensitive in the 800 – 1700 nm spectral range.

Incandescence of a single mode fiber, even one exhibiting water peaks (ITU-T G.652.A) is substantially weaker than of 50/125 µm OM2/OM3/OM4 multimode fiber; actual values measured in our experiments varied considerably. Factors influencing intensity of thermal radiation exiting hot fiber are listed and explained in section 2.6.

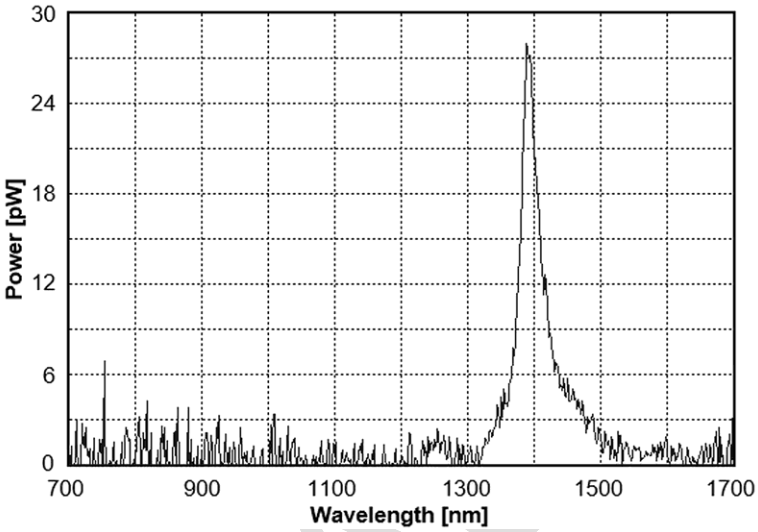

Fig. 3. Spectrum of thermal emission of G.652.A single-mode fiber at 900 °C, total power: -66.71 dBm.

Incandescence spectra were very similar for single-mode and multi-mode fibers, except for power levels, and in agreement with data in Table 1.

2.4. Thermal radiation coupled into fiber

The strongest mechanism of coupling of external radiation into the fiber involves reflections of this radiation by cracks penetrating fiber's cladding and core at varying angles, created when microscopic inclusions of cristobalite (crystalline, denser form of silica) appear on the surface of fiber [15,16,17]. Because specific gravity of cristobalite (2.35) is higher than one of fused silica (2.20), local loss of ca. 6% material volume produces extreme strain and initiates glass breaks. Microscope photograph of fiber damage is shown in Fig. 4. Two cracks of uneven width and directions extend from this location. Identified pieces of dust were retouched to improve image clarity. More data can be found in [10].

Due to different refractive indices of fused silica (1.46) and air (1.00), a crack reflects ca. 4% of impinging radiation at angle dependent on crack direction. A part of external radiation is directed into fiber acceptance angle, while part of radiation propagating in the fiber is lost. Other defects in fiber core or at the core/cladding interface, like inclusions, gas bubbles, or defects produced by γ-radiation [18] also facilitate coupling of external radiation. A weak coupling, increasing with duration of heating, was observed also in fibers exhibiting no visible cracks – see [10], in particular Figs. 8 and 15 there.

Infrared radiation collected by deteriorated fiber is considerably stronger than produced inside fiber by incandescence, even with high content of hydroxyl ions.

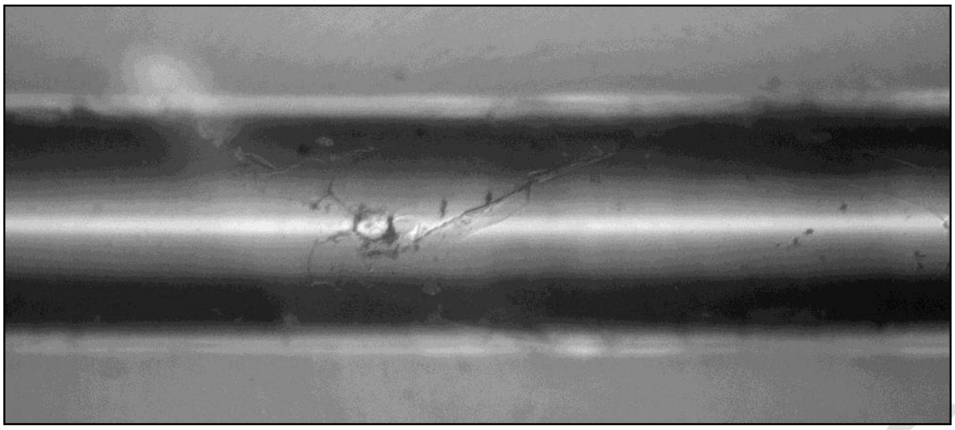

Fig. 4. Surface defect in optical fiber (circular feature) after 4.5 h of heating to 900 – 1000 °C, area shown: 200 x 500 µm.

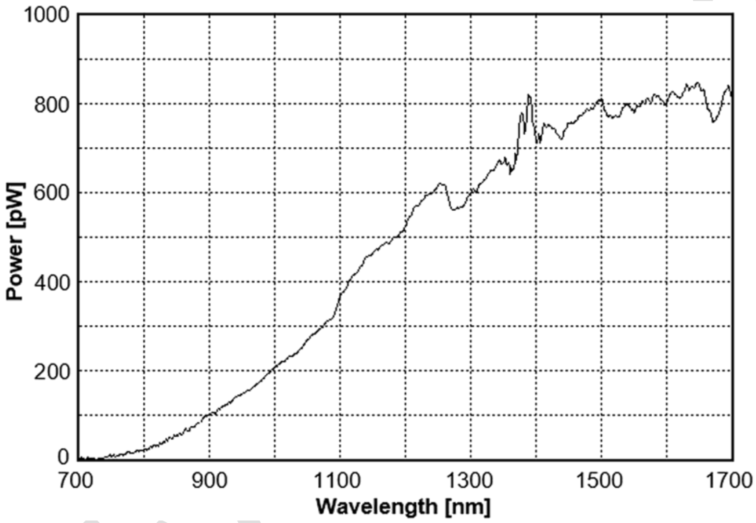

Fig. 5. Spectrum of coupled thermal emission of OM2 multimode fiber at 1000 °C. The fiber exhibited localized escape of light due to cracks, but retained optical continuity. Total power: -39.79 dBm.

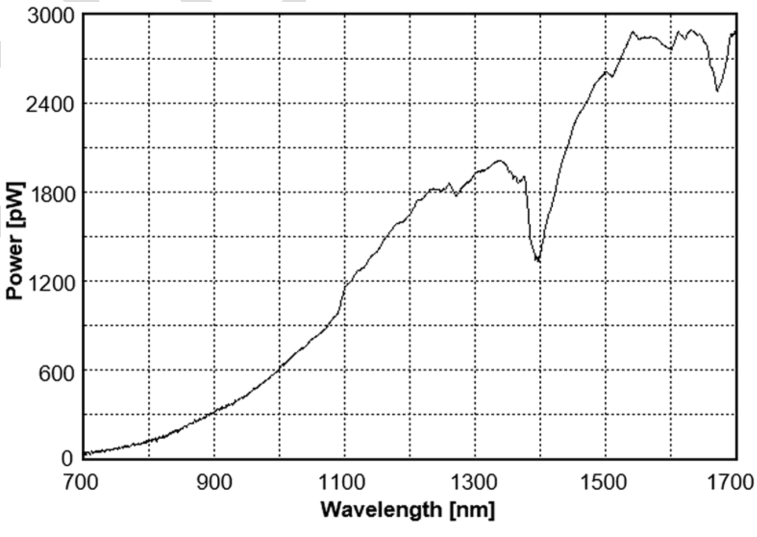

Fig. 6. Spectrum of thermal emission of carbon soot collected by cleaved end of OM2 multimode fiber at 1000 °C. Fiber placed in the hot zone was 0.3 m long and exhibited attenuation of approx. 2 dB at 1390 nm. Total power: -33.38 dBm.

2.5. Evolution of radiation spectrum with time

When optical fiber is subjected to high temperature (≥800 °C) for a duration typical of fire, defined in EN 50575 [19] as 15 – 120 minutes, two concurrent changes with time occur:

- decrease of (narrowband) fiber incandescence due to fiber "drying" (chapter 1), and
- increase of (broadband) radiation coupled into the fiber with its deterioration (section 2.4).

Initially, the spectrum is composed of few peaks (Fig. 1, 2 and 3), but a continuous, long-wavelength component steadily rises and eventually dominates in strongly deteriorated fiber (Fig. 5). Changing spectrum and power make it impossible to establish power vs. temperature characteristics for a given fiber, as results of repeated tests differ [10].

2.6. Power of thermal radiation exiting hot fiber

Table 2 shows ranges of power of incandescent and coupled radiation emerging from 1 m long fiber sample held at 900 °C, measured in 800 – 1700 nm spectral range for each fiber class defined in section 2.1. Incandescent radiation was measured in fibers heated in the air, with all coatings burned out. Absence of coupled radiation was confirmed by spectral measurements. All measurements were made approx. 5 minutes after temperature of 900 ºC was reached, before significant change of incandescence with time (section 2.3) took place. Coupled radiation was measured in fibers surrounded by carbon soot and protected against access of oxygen by stainless steel tube. Results for different fibers from each class varied by up to 7 dB for reasons listed below.

Table 2. Typical powers of incandescent and coupled radiation at 900 °C.

Fiber type and standard	**Incandescent radiation [dBm]**	**Coupled radiation [dBm]**
Single mode without water peak [G.652.D, G.657.A2]	-85 ... -81	-60
Single mode with water peak [G.652.A]	-71 ... -66	-56
50/125 µm multimode (OM2 and OM3)	-57 ... -50	-42

In general, intensity of thermal radiation exiting the fiber depends primarily on five factors:

1) Core cross-section, because total power of incandescent radiation is proportional to volume of hot glass. Comparing single-mode and multimode fibers, power of radiation generated in a multimode fiber with 50 µm core is ca. 30 times (15 dB) higher than in single-mode fiber having ≈ 8.3 µm core diameter and ≈ 9.5 µm *mode field diameter* (MFD) [6, 7, 14]. Multimode fiber has also higher GeO_2 (germania) content in the core – this doping increases emissivity of fused silica. For the same OH^- content and temperature, at least 72-fold (18.6 dB) higher incandescent power can be expected in multimode fiber. Additionally, 50/125 µm multimode fiber has higher numerical aperture: 0.14 vs. 0.20, and the proportion of omnidirectionally emitted thermal radiation accepted by multimode fiber is twice as large.
2) Glass emissivity is proportional to its absorption. Of primary importance is the component of fiber attenuation associated with hydroxyl (OH^-) content in the glass the fiber's core is made of. The difference between intensity of incandescence in a typical pre-1999 single mode fiber (ITU-T G.652.A) with ≈ 1 dB/km added loss at water peak wavelength (≈ 1390 nm, Table 1) and current low-OH fiber (ITU-T G.652.D) with the same loss below 0.05 dB/km is by a factor of 20 – 100 (13 – 20 dB). Multimode fibers have higher OH^- content

than single mode ones and their incandescence observed in our experiments was ca. 20x (10 dB) stronger than in old G.652.A single mode fiber [10], as seen in Figures 2 and 3.

3) Fiber temperature – intensity of incandescence of fiber rises with temperature [9, 13], while spectrum does not change (section 2.2). Intensity of radiation from carbon soot rises also, but with shift of peak to shorter wavelengths. Example is shown in Fig. 7.
4) Thermal history of fiber: heating causes gradual destruction of hydroxyl ions and out-diffusion of resulting hydrogen through the cladding (chapter 1). Incandescence fades with time due to ongoing destruction of OH^- ions and escape of resultant H_2 and H_2O through the cladding [8]. A 50% (3 dB) reduction of radiation intensity was observed after 1 – 2 hours at 1000 °C; it was slower in fiber with fluorine outer core [10].
5) Density of surface defects and cracks in the fiber (section 2.4), which rises with duration and temperature of heating. More cracks and defects means more efficient coupling of external radiation into fiber's core, when some defects reflect radiation into acceptance cone of fiber core. While at the beginning of high temperature test the broadband (blackbody-like) radiation observed at the end of fiber is almost absent (Fig. 2), it gradually gets more intense and dominates in strongly degraded fiber (Fig. 5).
6) Carbonization of fiber coating and tube, and later burning of this carbon (only in the air). The result is marked increase of coupled radiation at temperatures starting from 450 °C, permanent in oxygen-free environment [10].

Measured spectra and powers of thermal radiation are relatively consistent for fibers belonging to a given class defined in section 2.1, and when test conditions: temperature, heating duration, surrounding material, access of air are identical. The exception was rapid, often in less than 1 minute, deterioration of some multimode fibers at temperatures between 900 and 1000 °C, resulting in total complete loss of optical continuity and strong coupled radiation: -36 … -33 dBm with broadband spectrum.

For a 3 m long cable and fiber in the fire zone, which is the minimum length required in DIN 4102-12, the values listed in Table 2 still apply because of self-limiting effect (section 2.2). Power of thermal radiation emerging from a 3 m long 50/125 µm multimode fiber heated to 1000 ºC measured during actual fire test on cable was approx. -36 dBm.

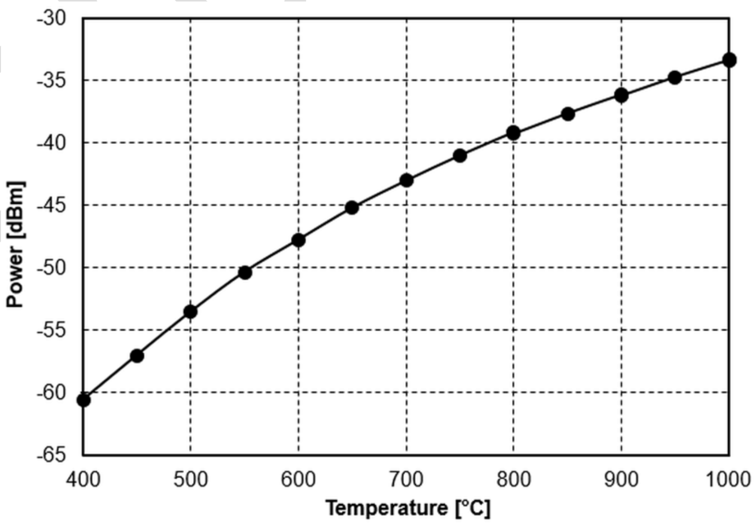

Fig. 7. Power of thermal radiation from OM2 multimode fiber surrounded by carbon soot vs. temperature.

Figure 7 shows power of thermal radiation emerging from a 1 m long straight sample of 50/125 µm OM2 multimode fiber surrounded by carbon char (soot) left from pyrolysis of fiber coating and 0.9 mm tight buffer in absence of oxygen as a function of temperature, measured in the lab. This can be assumed the maximum level of interference expected during fire tests on fire-resistant cables. Fiber under test was placed in a thin stainless steel tube sealed at both ends to imitate conditions inside fire-resistant cable, where the polymer tube with fibers is surrounded by mica tapes blocking access of air and burn-out of carbon.

3. Interference during measurements of fiber loss

3.1. LSPM method for fiber loss testing

Variations in fiber loss (attenuation) during fire testing of cable are normally measured using a *Light Source and Power Meter* (LSPM) setup shown in Fig. 8. More elaborate setups may include fiber switches for monitoring of multiple fibers, or multiple light sources and *Wavelength Division Multiplexing* (WDM) multiplexers for simultaneous measurements at several wavelengths.

This method *is designated "Method B" in E*N-60793-1-40 standard for measurements of absolute fiber loss [20]. Monitoring of loss changes with a similar setup is covered by EN60793-1-46 [21] and named "Method A". It is widely accepted for cable tests. However, during fire test, thermal radiation adds to radiation launched into fiber under test from the light source. Indicated power is higher and loss is lower than true one.

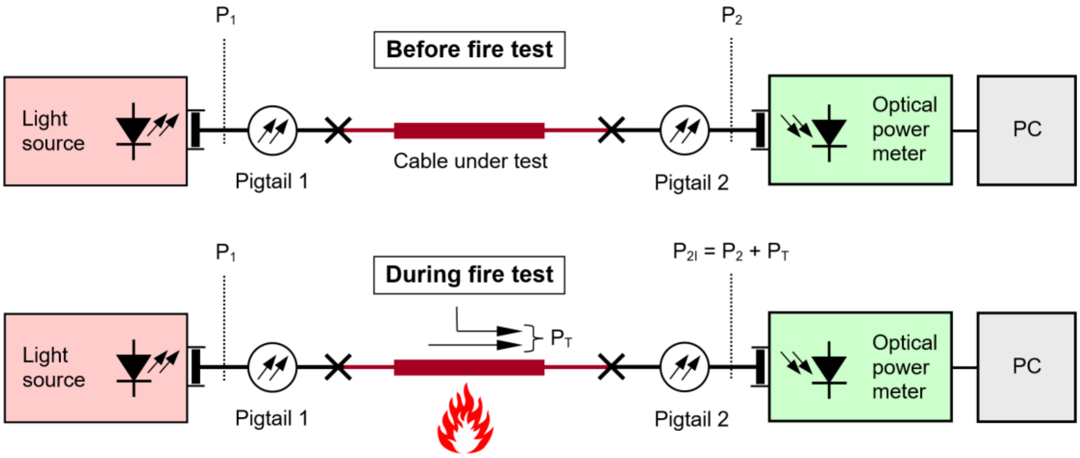

Fig. 8. The LSPM setup for measuring and recording variations in attenuation (loss) of optical fiber in a cable during fire test. Fiber under test is fusion spliced to pigtails for connections to test instruments.

3.2. Interference during measurements with LSPM setup

The optical path between light source and optical power meter (Fig. 8) includes a relatively short fiber under test encased in the cable subjected to fire; its *initial loss* (IL_F) can change during the test. The combined loss of all other passive components of optical path: lengths of fibers outside the fire zone, splices, connectors, switches, splitters or filters (IL_C) is substantially higher than IL_F – up to 20 dB in some cases.

First, it is assumed that IL_C has a fixed value during test, and variations of measured power are caused by changes in IL_F only. Second, it is assumed that all radiation present in the fiber under test originates from the light source, which launches radiation characterized by a stable power (P_1) and wavelength, so variations of optical power exiting the fiber (P_2) and measured with optical power meter can be directly converted to change of fiber attenuation (IL_F).

When logarithmic scale of power (dBm) and loss (dB) is used, we have the following formulae for power reaching the input port of optical power meter (P_2):

$$P_2 = P_1 - (IL_F + IL_C) \tag{3}$$

and measured variations in fiber loss (ΔIL_C):

$$\Delta IL_C = -\Delta P_2, \tag{4}$$

where ΔIL_C and ΔP_2 are variations of respective parameters from initial values.
As presented in section 2, hot fibers generate and collect radiation, which adds to radiation launched from the light source, as shown in Fig. 8. If no special modifications to LSPM setup are made, optical power meter shows a sum of:

- true test power (P_2), launched from source and attenuated on the way to power meter,
- power of interfering thermal radiation (P_T),

indicating a value of P_2 distorted by optical interference (P_{2I}):

$$P_{2I} = P_2 + P_T \tag{5}$$

(for power values in W), or

$$P_{2I} = 10\log\left[10^{\left(\frac{P_2}{10}\right)} + 10^{\left(\frac{P_T}{10}\right)}\right] \tag{6}$$

(for power values in dBm).

As a result, indicated power increases, and indicated fiber loss decreases. The *error in loss indication* (*ErrIL*) (value in logarithmic scale, dB) depends on the ratio of powers P_T and P_2 (values in linear scale):

$$ErrIL = 10\log[(P_2 + P_T)/P_2] = 10\log[(P_T/P_2) + 1] \tag{7}$$

or, when logarithmic scale is used exclusively:

$$\mathrm{ErrIL} = 10\log\left[10^{\left(\frac{P_T - P_2}{10}\right)} + 1\right]. \tag{8}$$

Examples of errors in power/loss measurements are shown in Table 3. For example, for a 0.01 dB permitted error, -36 dBm thermal radiation power in 50/125 µm multimode fiber, and 16 dB loss rise to be measured during test (2x the limit for a 4 m fiber in a fire zone), the power launched into fiber under test must exceed +6.4 dBm. This "brute force" solution is effective, but requires expensive, high-power light source for multimode cables.

Table 3. Error in fiber loss indication (*ErrIL*) as a function of test signal (P_2) to interference (P_T) ratio.

***ErrIL* [dB]**	**P_T/P_2**	**P_2/P_T**	**P_2/P_T [dB]**
1.00	0.2589	3.86	5.87
0.50	0.1220	8.20	9.14
0.20	0.0471	21.23	13.27
0.10	0.0233	42.92	16.33
0.05	0.0116	86.21	19.36
0.02	0.0046	216.65	23.36
0.01	0.0023	433.79	26.37

During fire test executed in accordance with DIN 4102-12 [2], the author observed that intense thermal radiation at temperatures around 1000 ºC completely masked increase of fiber loss, and even total loss of fiber continuity in the cable under test, producing an erroneous

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impression of stable or even decreasing loss. Examples of such power and loss measurements for one fiber in a cable under test are shown in Figs 9 and 10. In order to measure 8 fibers, the light from a single source was divided by means of 1:8 optical splitter, which reduced launched power by approx. 10 dB with respect to direct connection.

During this test, loss measurements started 20 minutes before ignition of burners in the fire chamber. The gaps between measurement data result from sequential switching of power meter input to 8 fibers in cables under test; full switching cycle was 160 s long.

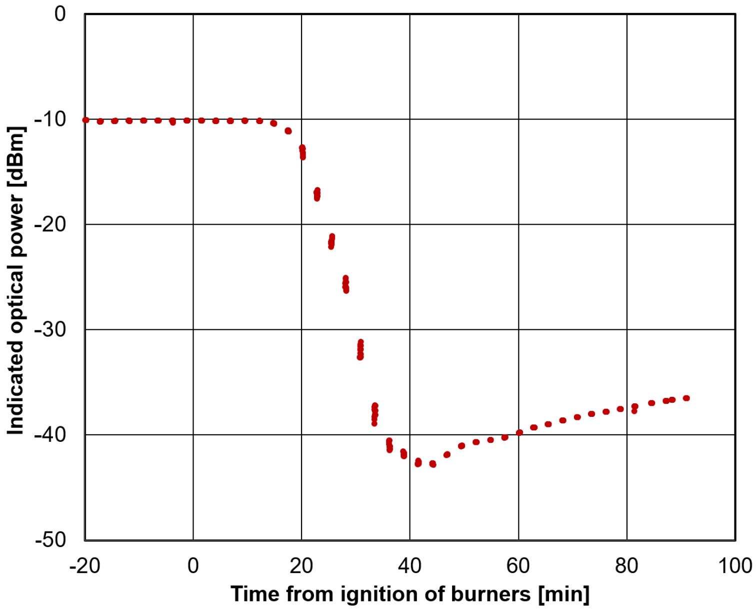

Fig. 9. Indications of optical power during fire test of cable in accordance with DIN 4102-12. Measurements of single multimode OM2 fiber with 33 m length passing through the fire zone.

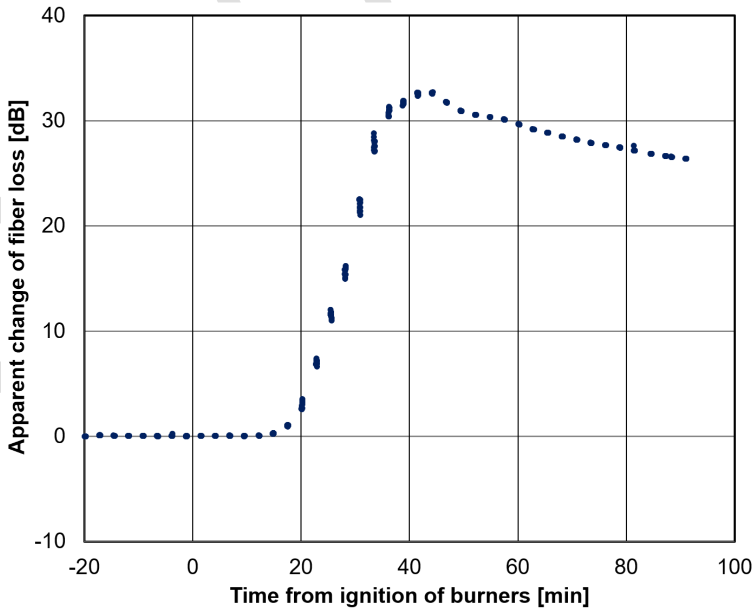

Fig. 10. Evolution of fiber loss with time calculated from power measurements shown in Fig. 9.

At the end of this test, the power indicated by optical power meter with 0.01 dB resolution did not change after deactivation of light source, because thermal radiation (P_T) was much stronger than attenuated test signal (P_2), as shown in Fig. 11. Due to confidentiality agreement, more details of this test cannot be published.

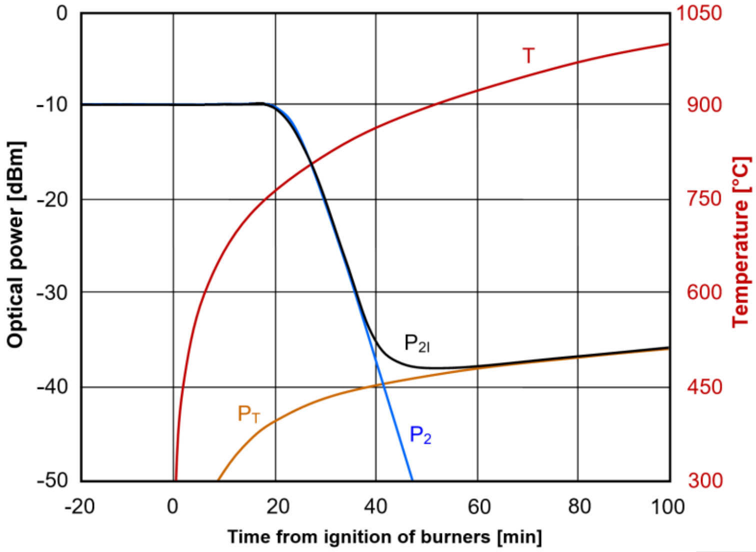

Fig. 11. Evolution of temperature (*T*), and optical powers P_2, P_T and P_{2I} with time during fire test, explaining the results shown in Figs. 9 and 10.

On the other hand, interference from thermal radiation encountered during fire tests performed in accordance with EN 50200 [1] and EN 50282 [4] was negligible due to:

- lower maximum temperature: 840 ºC instead of 1040 ºC, and 6 – 8 dB weaker thermal radiation [10]), as shown in Fig. 7,
- 10 dB higher optical power launched into fiber under test, because no 1:8 splitter was used on the light source side of the test setup.

4. Elimination of interference from thermal radiation in LSPM loss measurements

The following methods can be recommended:

a) Use of high power light source to increase signal-to-interference ratio to value listed in the right-hand column of Table 3 for a required value of *ErrIL*;
b) Suppression of thermal radiation with bandpass filters: 1300 nm for multimode fibers, and 1550 nm for single mode fibers, placed at the input of the power meter (4.1);
c) Periodic ON/OFF switching of light source to measure power of interference from thermal radiation (in OFF state) and subtract it from the power measured in ON state (4.2). Alternatively, light source with amplitude modulation at fixed frequency and optical receiver responsive only to AC component of optical power can be used (4.3);
d) Shortening of fiber under test placed in the fire zone, *e.g.*, by inclusion of only one fiber from cable under test in the test circuit; this reduces maximum loss increase to be measured and increases minimum expected value of P_2, while power of thermal radiation is similar due to its self-limitation in the hot fiber;
e) Adoption of 850 nm or 940 nm for OM5 fibers as test wavelength for multimode cables instead of 1300 nm, and use of power meter with silicon photodetector, sensitive only to wavelengths below ≈ 1150 nm, and blind to incandescence at 1353/1382/1393/1407 nm (Figs. 1, 2), instead of InGaAs detector sensitive to wavelengths up to ≈ 1750 nm.

Thermal radiation is a bigger problem during fire testing of multimode cables, because:

- power of thermal radiation is 15 – 20 dB higher in multimode fibers (section 2.6),
- permitted increase of attenuation of multimode fiber during fire test is twice the value for single-mode fiber (2 dB/m vs. 1 dB/m) [4].

Two or more of methods (a) – (d) can be combined for better rejection of interference [17].

P_T indicated when light source is disconnected (*e.g.*, with fiber switch) or deactivated is not a true power of thermal radiation generated in and collected by the fiber under test [17], but is suitable for correction of test results (section 4.2).

Testing of multimode fibers at 850 nm wavelength is desirable also because their current applications, including CWDM networks with OM5 fibers, are restricted to center wavelengths ≤ 940 nm [22]. Unfortunately, the current IEC standard for testing of fiber cables [23] requires loss testing of multimode cables at 1300 ± 20 nm, unless the longest specified operating wavelength is shorter. This standard, however, includes 850 ± 20 nm as an alternative test wavelength.

4.1. Bandpass filtering

An optical bandpass filter with central wavelength corresponding to one of source is placed at the input of optical power meter. Effectiveness of this method is limited for several reasons:

- Wavelength tolerances of sources (typ. ± 10 nm or ± 20 nm) and filters (typ. ± 10 nm), plus the spectral width of radiation emitted by Fabry-Perot lasers (typ. 5 – 10 nm) dictate a selection of bandpass 30 – 50 nm wide, unless the source and filter are spectrally characterized and matched.
- Fiber test wavelengths are set in standards, although alternative arrangements between cable supplier and user are often permitted. In particular, most standards for testing of multimode cables still stipulate loss measurements at 1300 nm wavelength, near "water peaks" (Table 1), and requiring wideband InGaAs detector, while all current applications of OM2/3/4/5 fibers are at wavelengths between 850 and 940 nm (nominal values).
- Low-cost bandpass filter often has too narrow blocking band to filter out thermal radiation across whole sensitivity range of InGaAs photodetectors, which extends from less than 800 nm to over 1750 nm. Filter specifications must be read carefully.

Experiments in our laboratory [17] involved commercial Thorlabs and Edmund Optics filters having 30 nm, 25 nm and 12 nm wide passbands and 1300 nm central wavelengths. Improvement in signal to interference ratio (P_T/P_2) was better for incandescent than for coupled radiation: 21 – 25 dB and 16 – 21 dB, respectively. The best results were obtained with a 12 nm filter, but in this case the wavelength of light source and filter's passband had to be individually measured and matched because of their manufacturing tolerances.

4.2. Periodic ON/OFF switching of light source

This technique involves:

- periodic disconnection, *e.g.*, with optical switch, or deactivation of light source,
- two measurements in each cycle: one with source on (P_{2I}) and one with source off (P_T),
- subtraction of P_T from P_{2I} to obtain true power of test signal (P_2):

$$P_2 = P_{2\mathrm{I}} - P_{\mathrm{T}} \tag{9}$$

(power values in W).

The last operation is performed by software running on a data acquisition computer (Fig. 8). Improvement in signal-to-interference ratio is limited by quantization errors dependent on resolution of the power meter used, normally 0.01 dB or 0.001 dB, and combined noise of light source and power meter for the time interval between measurements of P_T and P_{2I}. Because properties of cable under test during fire tests tend to change slowly, as can be seen in Figs. 9 – 11, duration of ON/OFF cycle is usually measured in seconds. This allows to perform measurements with a standard optical power meter indicating *Continuous Wave* (CW) power.

For a 0.002 dB combined resolution and noise, equal to minimum detectable power difference, interference from thermal radiation can be reduced by 33.36 dB with respect to its original value, but with high noise level in corrected signal, approx. –3 dB. The improvement corresponding to 0.05 – 0.20 dB uncertainty in the same conditions is 20 – 25 dB.

4.3. Amplitude modulation (AM) of light source

This method is similar in principle to method presented in section 4.2, but implemented differently:

- modulation frequency is higher, typically 270, 1000 or 2000 Hz (fixed). Portable light sources with such ON/OFF keying are commercially available;
- optical receiver or power meter capable of separating and bandpass-filtering the AC component of input power, then measuring its equivalent power is used. This functionality is available in some versatile benchtop power meters [24]. Portable power meters (some) only indicate presence of light modulation for identification of fiber or test wavelength.

With no such instrument available, one can assemble a setup which usually includes photodetector, AC amplifier, narrowband filter, and some instrument to measure amplitude of AC signal: digital oscilloscope, lock-in amplifier, audio level meter, *etc.* At the source side, a direct modulation of radiation from LED or laser is usually employed; chirp and chromatic dispersion effects can be ignored because of low modulation frequency and short optical path.

This method ensures high rejection of un-modulated interference encountered during fire tests. With proper choice of modulation frequency, low frequency noise of photodetector and amplifier, and mains interference (50 or 60 Hz and harmonics) can be also eliminated.

Polarization modulation at source is not a good choice: the state of polarization of light propagated in a single mode fiber is affected by mechanical influences on this fiber, like twisting or bending, encountered when cable burns, sags and otherwise moves during fire test. Additionally, majority of fire resistant cables include multimode fibers, which support large number of modes and corresponding polarization states.

5. Conclusions

Data gathered during high temperature experiments with telecom fused silica fibers and fire tests of fiber optic cables indicate that optical fiber, especially a multimode one, heated to temperatures above approx. 900 °C becomes a source of thermal radiation of non-negligible power. The resulting interference cannot be ignored in some situations, in particular during measurements of small attenuation changes, when totally misleading results are possible.

There are several relatively effective ways to eliminate or at least considerably reduce this interference. Unfortunately, current standards for testing of fiber optic cables do not include a warning of this problem and recommendations how to reduce measurement errors caused by thermal radiation in the fiber under test.

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