Remedies to Thermal Radiation in Fused Silica Optical Fibers

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Abstract — During fire incidents, optical fibers located within a fire-resistant cable are usually exposed to temperatures of 800°C to 1000°C. Hot fibers generate narrowband thermal (incandescent) radiation and collect broadband thermal radiation originating from the heated surroundings. The power of the second component, initially negligible, increases with time due to the rising number of fiber cracks and other defects acting as couplers for external radiation. Thermal radiation may interfere with fiber attenuation measurements performed during a fire test, but is rather unlikely to prevent data transmission with typical GbE and 10GbE transceivers during a fire. This problem may be remedied by combining the following methods: using single mode fibers instead of multimode fibers, using bandpass filters to block thermal radiation, and selecting proper transmitter power, wavelength and photodetector.

Keywords — attenuation testing, fire resistant fiber optic cable, fire test, fused silica optical fiber, incandescent emission, interference filtering

1. Introduction

Fire-resistant fiber optic cables temporarily retain optical continuity during a fire, at temperatures of up to 1000°C and over periods of 15–120 minutes [1]–[3], providing connectivity for fire safety and video surveillance systems, as well as for emergency communications. Such cables comprise standard telecom fibers made of fused silica.

Hot optical fibers either glow themselves or are exposed to radiation from their surroundings – usually from carbonized remains of polymer tubes and coatings. We have investigated both effects experimentally in [4], presenting a short review of fire test standards and conditions.

In this paper, we present the sources, spectral power distribution (SPD) and the power of thermal radiation (Section 2), based on results of the experiments conducted, specific methods relied upon for eliminating such phenomena (Section 3), the potential interference with Ethernet data links (Section 4), as well as methods for monitoring fiber attenuation in a cable in the course of a fire test (Section 5). Then, we present the results of an experiment in which bandpass filters have been used to reject thermal radiation (Section 6) and specify the activities recommended in connection with the fiber itself and with the wavelength in order to minimize such interference (Section 7). Section 8 contains a summary.

2. Thermal Radiation in Fibers Under Fire

Detailed characteristics of radiation generated by silica fibers at temperatures of up to 1000°C (such as power, spectral power distribution, variation with time, and physical mechanisms) are presented in paper [4]. Therefore, we only provide the summaries and representative examples thereof.

2.1. Incandescence of Fiber

Figures 1 and 2 show the measured SPDs of radiation emitted by a 50/125 μm multimode fiber OFS OM2 [7] and a single mode fiber conforming to the ITU-T G.652.A Recommendation [8], respectively. The 1 m samples were heated to 900°C before conducting the measurements. Due to the fact that the measurement resolution was limited (5 nm or 10 nm), the three strongest emission peaks at 1383 nm, 1393 nm and 1407 nm [9] are visible as a single peak. SPDs for all multimode and single-mode telecom fibers we have tested were similar, except for varying power levels. The power of radiation exiting each fiber was measured with an InGaAs sensor in the 800–1700 nm spectral range.

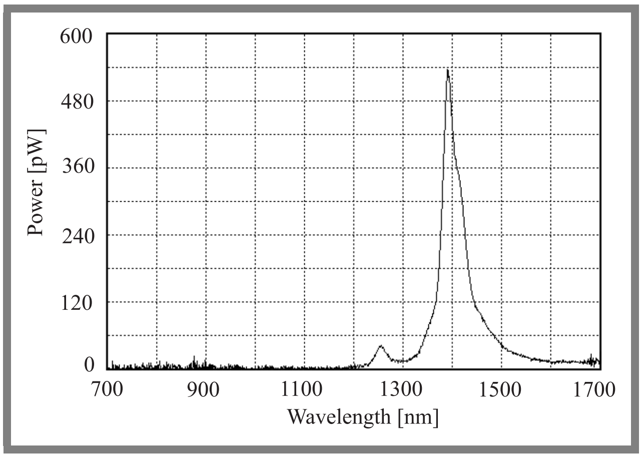

Fig. 1. Spectral power distribution of thermal emissions from an OM2 multimode fiber at 900°C. The total power is −49.39 dBm.

Incandescence of a single mode fiber, even exhibiting water peaks (ITU-T G.652.A), is substantially lower than of a 50/125 μm OM2/OM3/OM4 multimode fiber, due to differences in core diameter (8.3 vs. 50 μm) and numerical aperture (0.14 vs. 0.20). For the same OH^- content and temperature, power that is approx. 72 times lower (18.6 dB) may be expected, but real values measured in our experiments varied considerably.

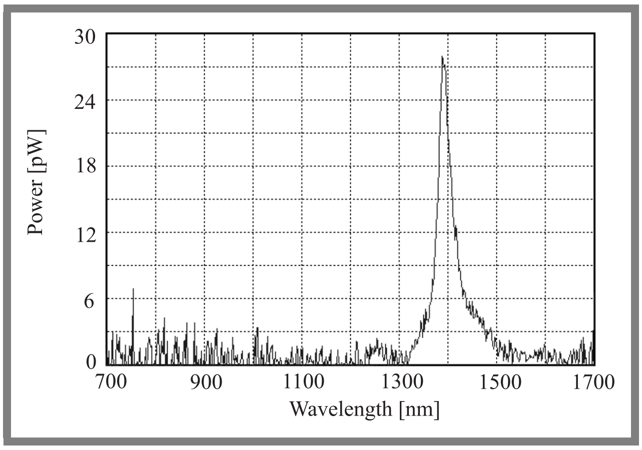

Fig. 2. Spectral power distribution of thermal emission from a G.652.A single-mode fiber at 900°C. Total power was −66.71 dBm.

Fiber incandescence decreases with time due to the ‘drying’ of the fiber’s core and diffusion of hydrogen through the cladding [5]. A 50% intensity reduction was observed in our experiments after 1–2 hours at 1000°C [4], which corresponds to a typical duration of a fire incident or a fire test. The fading phenomenon is slower when fiber cladding is doped with fluorine.

2.2. Thermal Radiation Coupled into the Fiber

The coupling of external radiation into the fiber is caused by radiation being reflected through cracks penetrating the fiber’s cladding and core, created when microscopic inclusions of cristobalite (crystalline form of silica) appear on the fiber’s surface [4], [6], [10]. Cracks in heat-degraded fibers have complex shapes and various depths.

A crack reflects a small portion, i.e. approx. 4% of incoming radiation at an angle dependent on the crack’s direction. A small portion of external radiation is directed into the fiber’s acceptance angle, while a similar portion of radiation transmitted through the fiber is lost. Other defects in fiber core or at the core/cladding interface, like inclusions of cristobalite, tiny gas bubbles or defects introduced by gamma radiation [11], also facilitate unwanted coupling of external radiation.

This coupling phenomenon occurs more efficiently in multimode fibers due to their higher numerical aperture, i.e. 0.20 in a 50/125 μm OM2/OM3/OM4 graded index multimode fiber, versus 0.14 in a ITU-T G.652 single-mode fiber.

We have observed that the power of coupled radiation and the number of defects in the fiber section affected by high temperature grow as the heating duration increases. Light may be seen escaping from the fiber at locations with cracks or inclusions in the core. The strongest interference is experienced when the fiber is surrounded by black char, as its emissivity coefficient is close to 1. For temperature and wavelength ranges of interest, thermal radiation is characterized by continuous SPD and its intensity is rising along with wavelength. An example of such an SPD we have measured is shown in Fig. 3.

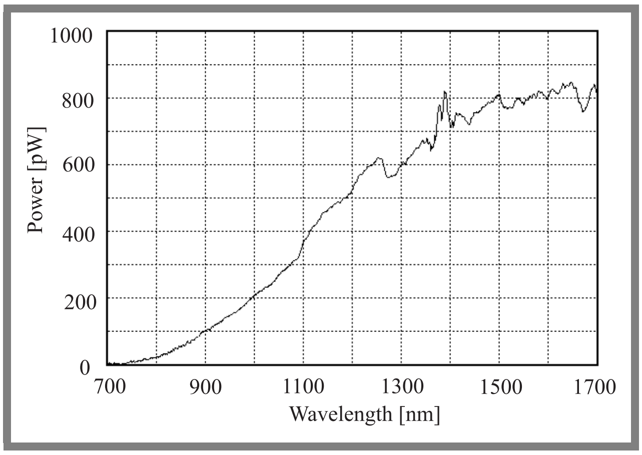

Fig. 3. Spectral power distribution of coupled thermal emissions of an OM2 multimode fiber at 1000°C. Localized light escapes were noticed due to cracks, but optical continuity of the fiber was retained. Total power equaled −39.79 dBm.

2.3. Changes of Thermal Radiation Spectrum over Time

When fused silica fiber is exposed to high temperatures (over 800°C) for a duration typical for a fire incident, defined in standards [1], [2] as 30–120 minutes, two concurrent changes take place over time:
- fading of thermal emissions due to the destruction of OH^- ions [5],
- progressive degradation of the fiber by cristobalite inclusions and cracking [4], [6].

We have observed a gradual decrease of (narrowband) fiber incandescence and an increase in (broadband) radiation coupled into the fiber.

Initially, the SPD is composed of narrow peaks (see Figs. 1 and 2), but a continuous long-wavelength component rises steadily with time and becomes dominant in a degraded fiber (Fig. 3). Lowered effectiveness of the bandpass filter in blocking related interference is one of the consequences of such a phenomenon.

A fast and total fiber failure is possible at temperatures above 950°C. The fiber loses its optical continuity, the power of coupled thermal radiation increases to approx. −33 dBm and −50 dBm for a 1 m section of an OM2 multimode and single-mode fiber at 1000°C, respectively. The SPD is similar to that illustrated in Fig. 3. In our experiments, almost 30% of multimode samples and only one sample of a single mode fiber failed under such conditions.

2.4. Power of Incandescent and Coupled Radiation

During the experiments, the power of incandescent radiation measured in the 800–1700 nm band was relatively low, i.e. amounted to −60 to −49 dBm over a 1 m section an OM2 or OM3 multimode fiber at 900°C and −85 to −66 dBm in a single-mode fiber under the same conditions, including old G.652.A fibers with high OH^- content.

The radiation exiting at the end of the fiber may exhibit a dip at "water peak" wavelengths of approx. 1390 nm, indicating high attenuation in hot fiber at this range i.e. 5–8 dB/m at 900–1000°C. Consequently, the accumulated power of incandescent radiation is self-limiting (saturating) in fiber samples longer than 0.5–1 m.

The power of coupled radiation measured during laboratory tests on 1 m fiber sections heated to 900°C and covered by carbon char equaled approx. −42 dBm for OM2 and OM3 multimode fibers, −56 dBm for a G.652.A single mode fiber, and −60 dBm for a G.657.A2 single mode fiber.

Thermal radiation coupled into the fiber is also self-limiting. Increasing density of cracks and inclusions in deteriorated fibers raises the coupled power (per unit of length). However, attenuation grows as well, due to the escape of guided radiation from the fiber. Measurements performed during a fire test in accordance with the DIN 4102-12 standard suggest that saturation length of an OM2 multimode fiber at 1000°C is 2–3 m (test duration: 90 minutes). The power of coupled radiation measured under such conditions was −38 to −35 dBm for a 32 m section of an OM2 fiber placed in the fire zone, meaning that power saturation conditions were met. For a 3 m effective saturation length, the power of coupled radiation accumulated in a long fiber sample is approx. 5 dB higher compared to 1 m sections tested in the laboratory.

We estimate the maximum expected power of thermal radiation in a fire according to the DIN 4102-12 [2] standard as approx. −37 dBm, −51 dBm and −55 dBm, respectively, for undamaged fibers indicated above, using an InGaAs photodiode (800–1700 nm) as sensor. For a 850 nm sensor based on a silicon photodiode, with sensitivity up to 1100 nm and a multimode fiber, this power is reduced to approx. −45 dBm.

3. Limitation of External Thermal Radiation

In this section, we present two potential methods for modifying the design of fire resistant cables in order to prevent coupling of undesirable thermal radiation into optical fibers.

3.1. Elimination of Black Soot

If the material surrounding the glass fiber is characterized by low emissivity and high opacity at the wavelength of interest, e.g. 1300 nm, coupled radiation will be eliminated. Titanium dioxide (TiO_2) with the grain size of 2 μm is an example of such material. The black carbon soot left after pyrolysis of fiber coatings, the loose tube and the gel must be fully burned. However, since typical fire resistant cables include a fire barrier made of mica tape and often also a steel armor [4] layer, no oxygen source is available to ensure such a full burn inside the cable. Although oxygen may be provided by incorporation of a solid oxidizer, a rapid burn process would produce undesirable heat and flue gases, such as CO_2, CO, and H_2O vapor, making this idea impractical.

3.2. Fibers with Photonic Barrier

Another concept is to use fibers with a photonic barrier surrounding the core, made of microscopic gas-filled holes – like hole-assisted fibers (HAF) [12], [13] or 'needles' existing in Corning NanoStructures fibers [14]. Such fibers were originally developed for bending-insensitive cables in FTTH networks. The photonic barrier prevents both radiation escape from bent fibers (this was the original purpose) and entry of external radiation. Unfortunately, fibers with a photonic barrier are inconvenient to splice and expensive. After 2010, such fibers were replaced by other designs. Their reintroduction in fire resistant cables would be valuable.

4. Interference in Operation of Digital Fiber Optic Links

Transmission of data over fibers in a cable affected by fire may subject to:

a) increase in fiber attenuation due to physical deterioration and light escape,

b) addition of unmodulated thermal radiation to the data carrying signal at the receiver.

Most low- and medium-speed data links [15] use non-return to zero (NRZ) modulation, with the signal transmitted either at full power (logical '1') or low power (logical '0'). There is a minimum value of the EXT power ratio in '1' and '0' states (in dB) of the signal at the receiver input that is required for error-free transmission. Without optical interference, the extinction signal ratio at the receiver port is the same as at the transmitter port:

$$\mathrm{EXT_{TX}} = 10 \log \left(\frac{P_1}{P_0} \right).$$

Additional optical interference power P_I is defined as a sum of incandescent and coupled radiation accumulated in the hot section of a fiber and attenuated in the section of between the fire zone and the receiver. The extinction ratio, as seen by the receiver, is then:

$$\mathrm{EXT_{RX}} = 10 \log \left(\frac{P_1 + P_I}{P_0 + P_I} \right).$$

In the receiver, a fixed difference between "1" and "0" levels at the decision circuit is maintained by automatic gain control responding to the difference between power received in "0" and "1" states, designated as OMA (Optical Modulation Amplitude) [15], but noise level increases, as PI produces an equivalent of dark current in photodiode.

How much interference may an Ethernet optical link tolerate? The EXT values required in IEEE 802.3 [15] for 100 Mb/s, 1 Gb/s and 10 Gb/s transmitters vary between 3 and 9 dB – see Table 1. This corresponds to power emitted in the "0" state being equal to 50.0% and 12.6% of power emitted in the "1" state, respectively. Therefore, a rough limit for tolerable thermal radiation power may be set at 12.5% of signal power at "1" level, or 6 dB below receiver sensitivity.

Tab. 1. Parameters of Ethernet interfaces defined in IEEE 802.3 [15], calculated tolerated interference limit and estimated power of thermal radiation at 1000°C.

Interface designation by IEEE	Max. link length [m]	Fiber type	Nominal wavelength [nm]	Transmitter EXT min. [dB]	Receiver sensitivity [dBm]	Interference limit [dBm]	Thermal radiation max. [dBm]
100BASE-BX10*	10 000	SMF	1310/1550	6.6	−28.2 (−23.3)	−34.2	−51.0
1000BASE-SX	550	MMF	850	9.0	−17.0 (−13.0)	−23.0	−45.0
1000BASE-LX	550	MMF	1300	9.0	−19.0 (−14.4)	−25.0	−37.0
1000BASE-LX	5 000	SMF	1310	9.0	−19.0 (−14.4)	−25.0	−55.0
10GBASE-SR	400	MMF	850	3.0	−11.1 (−7.5)	−16.1	−45.0
10GBASE-LR	10 000	SMF	1310	3.5	−14.4 (−10.3)	−20.4	−51.0
10GBASE-ER	30 000	SMF	1550	3.0	−14.1 (−11.3)	−20.1	−55.0
10GBASE-LRM	220	MMF	1300	3.5	−6.5 (−6.0)	−12.5	−37.0
10GBASE-PR-D4*	40 000	SMF	1270/1578	6.0	−29.0 (−27.0)	−35.0	−55.0

Abbreviations: MMF – 50/125 μm multimode fiber (OM2 – OM5), SMF – single mode fiber.
* Duplex transceiver for access networks incorporating a WDM bandpass filter.

Such parameters as thermal radiation power, receiver sensitivity and interference limit for Ethernet transceivers, are presented in Table 1. IEEE 802.3 includes different requirements for receiver sensitivity, measured when the input signal has the lowest extinction ratio permitted for the transmitter (stressed receiver sensitivity) – as shown in parentheses. However, the limit of interfering thermal radiation presented in Tab. 1 is calculated for the receiver sensitivity measured under optimal conditions, including high EXT.

The use of a G.652.A fiber is assumed for single mode links that are up to 10 km long, as such a transmission medium is still permitted in the ISO/IEC 11801 standard for structural cabling systems [16].

Data from Tab. 1 prove that thermal radiation will not disturb a 100 Mb/s, 1 Gb/s or 10 Gb/s Ethernet data link, but compliance must be verified in the case of very sensitive receivers or analog transmission equipment.

If the estimated power of optical interference may be an issue, the use of a high-power transmitter can keep the signal-to-noise ratio high enough for an error-free transmission. The receiver must be fitted with an attenuator to reduce input power to the upper level of the specified range, to ensure best tolerance to an increased fiber loss.

The other method is to use a bandpass filter, as described in Section 6. Duplex transceivers designed for access networks have built-in bandpass filters separating signals transmitted in opposite directions at different wavelengths, which also reduces interference originating from thermal radiation.

5. Interference During Fiber Attenuation Measurements

5.1. Comparison of LSPM and OTDR Methods

Changes in fiber attenuation during cable fire testing are normally measured using a light source and a power meter (LSPM) setup as shown in Fig. 4. There is the "Method B" from the EN 60793-1-40 standard [17] and it offers several advantages:

– wide dynamic range, up to 80 dB with commercially available instruments,
– high resolution: 0.01 dB or 0.001 dB with typical measurement equipment,
– no need for launch and tail fibers to test a short fiber,
– short measurement time of up to 1 ms.

The disadvantage of the LSPM method is its sensitivity to thermal radiation. It adds to light source radiation, meaning that indicated fiber attenuation (or its change vs. initial conditions) is lower than real one.

Measurements performed with an optical time domain reflectometer (OTDR), called the "Method C" in EN 60793-1-40, are a better idea for testing long fibers, connectors and splices, and for locating faults. Both methods are approved in the EN 60793-1-46 standard [18] for testing fibers and cables when the impact of external factors (mechanical force applied to the cable or fiber, temperature, aging, etc.) on fiber attenuation are to be established. In OTDR measurements, interference from thermal radiation increases the noise floor at the receiver and reduces dynamic range. OTDR does not indicate a hot zone as an upward shift of fiber trace, but can show the loss resulting from fiber deterioration or bending. Distance measurements are not affected.

5.2. Interference During Measurements with LSPM

The optical path between the light source and the optical power meter includes a relatively short (1–30 m) fiber encased in a cable subjected to fire (Fig. 4). Its initial loss IL_F may change during the test. The combined loss of all other components along the optical path, i.e. fibers outside the fire zone, splices, connectors and in multi-channel, multi-wavelength or filter-equipped setups, including switches, splitters or filters (IL_C), is significantly higher than IL_F and equals up to

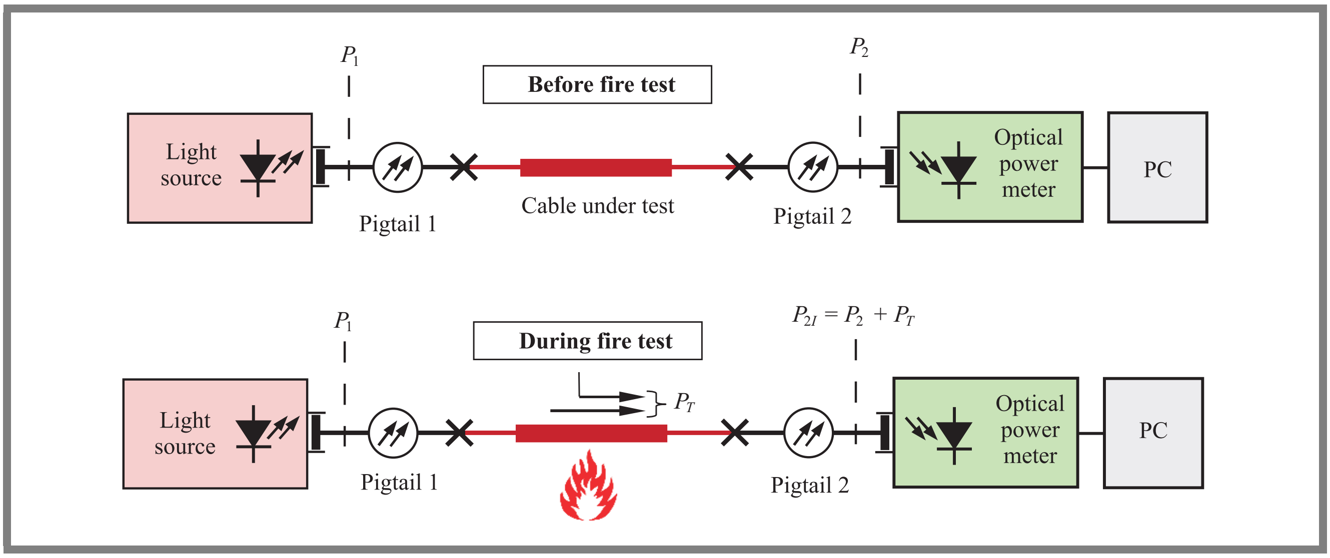

Fig. 4. LSPM setup for measuring and recording variations in attenuation (loss) of a single optical fiber in a cable during a fire test. The fiber tested is fusion spliced to pigtails to provide connections to test instruments.

20 dB in some cases. It is assumed that IL_C is constant during the test and that variations of the measured power are caused by changes in IL_F only. As all pieces of measurement equipment are affected by specific level of uncertainty, IEC standards for fiber cables [19] define an indicated loss change of up to 0.05 dB for a single-mode fiber and 0.20 dB for a multimode fiber, as a 'no loss change' condition.

Unfortunately, the standards relate only to testing fibers that are free of any optical interference. It is assumed that all radiation present in the fiber being tested originates from the light source which generates radiation characterized by a stable power (P_1) and SPD. Therefore, variations in output optical power (P_2) measured with an optical power meter can be directly converted to fiber attenuation (IL_F) changes.

Using logarithmic scale of power (in dBm) and loss (in dB), the following formulas for power reaching the input of the optical power meter (P_2) and the fiber loss variations measured are used:

$$P_2 = P_1 - (IL_F + IL_C),$$
$$\Delta IL_C = -\Delta P_2,$$

where ΔIL_C and ΔP_2 are variations of parameters from values before the start of the fire test.

As presented in Section 2 and in paper [4], a hot fiber both generates and collects radiation from its surroundings, which adds to radiation emitted by the light source, as shown in Fig. 4. With classical LSPM setup, the optical power meter (OPM) displays a sum of:

– real test power P_2 originating from the source and attenuated of rariation to the power meter,

– power of interfering thermal radiation P_T.

Let us identify a value of P_2 affected by optical interference as P_{2I}:

$$P_{2I} = P_2 + P_T \quad \text{for power values in [W]}$$

or

$$P_{2I} = 10 \log \left[10^{\frac{P_2}{10}} + 10^{\frac{P_1}{10}} \right] \quad \text{for power values in [dBm].}$$

The error in loss indication $Err\,IL$ (in the logarithmic scale) depends on P_T and P_2 ratio:

$$Err\,IL = 10 \log \left(\frac{P_2 + P_T}{P_2} \right) = 10 \log \left(\frac{P_1}{P_2} + 1 \right) \quad \text{in linear scale}$$

or:

$$Err\,IL = 10 \log \left(10^{\frac{P_T - P_2}{10}} + 1 \right) \quad \text{in log scale.}$$

P_T measured by OPM when the light source is off is not accurate, because:

– sensitivity of the photodetector in the power meter is wavelength-dependent,

– the power meter is calibrated for the central wavelength of the light source used, and not for thermal radiation,

– a portion of thermal emissions lies outside of photodetector's sensitivity range.

However, this effective value of interference power is useful for error calculations.

The power and loss evaluation error resulting from P_T is shown in Table 2.

Tab. 2. Fiber loss indication error ($Err\,IL$) as a test signal P_2 to interference P_T ratio.

$Err\,IL$ [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

To be compliant with 'no loss change' limits, the thermal radiation error shall be below 0.05 dB for single-mode fiber cables or 0.20 dB for multimode fibers. This condition is ensured when interference power P_T at the input to the power meter is 13.5 dB or 19.5 dB lower, respectively, than the power indicated with an active light source. This condition shall be met at the maximum increase of loss of the cable under test.

During fire testing, intense thermal radiation can mask even a large increase in fiber attenuation or a fiber failure, producing erroneous decrease in fiber loss. Such a phenomenon is explained in Fig. 5, showing the measurement data from a DIN 4102-12 [2] fire test [4].

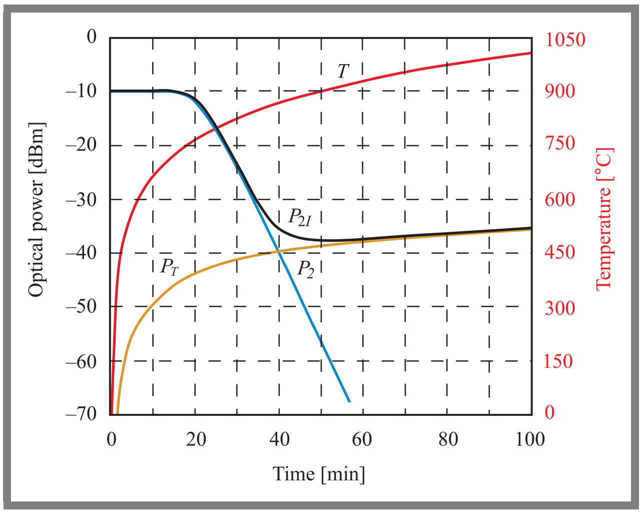

Fig. 5. Temperature T, power P_2, P_T and P_{2I} versus time in a 33 m section of an OM2 multimode fiber fire resistant cable during a DIN 4102-12 fire test. Interference caused by thermal radiation may result in a false test pass status, remaining unnoticed.

A similar problem exists when the LSPM test setup measures loss variations at several wavelengths, e.g. 1310 nm, 1550 nm, and 1625 nm for single mode fibers, i.e. with multiple light sources and a WDM demultiplexer with limited selectivity (typically 25 dB). To minimize errors in multi-wavelength measurements, the power of all light sources shall be adjusted, e.g. by using attenuators, to obtain similar readouts on the power meter with each source used solo. This compensates for the loss differences in WDM multiplexers or fibers at all wavelengths.

5.3. Limitations Imposed by Optical Interference

The simplest way of overcoming interference from thermal radiation is to employ a light source with minimum output power, dependent on:

– maximum measurable loss (IL_{MAX}),

– maximum expected power of thermal radiation (P_T).

Table 3 shows a data for fire test performed in accordance with DIN 4102-12 [2], and with the peak temperature of 1000°C. The setup allows to measure the increase in attenuation up to 120% of the limit defined in EN 50582 [20] i.e. 1 dB/m for a single mode fiber at 1550 nm and 2 dB/m for a multimode fiber at 1300 nm, with $Err\,IL$ limited to 0.05 dB and 0.20 dB, respectively. In both cases, the power meter incorporates an InGaAs photodetector, with a sensitivity window of 800–1700 nm.

The DIN 4102-12 standard requires the cable placed in the fire chamber to be at least 3 m long, hence the accumulated power of (predominantly coupled) thermal radiation is close to saturation and reaches values presented in Subsection 2.4.

For the sake of simplicity, a uniform distribution of attenuation increase along the fire-affected zone is assumed.

Typical light sources with an FP laser generate power between -10 dBm and $+3$ dBm. For such a source, the maximum length of fiber in the fire chamber is limited to 15–25 m for single mode fiber and 7–10 m for multimode fibers. Because of these limits, concatenation of multiple fibers in the cable under test shall be avoided. Fortunately, the increase of attenuation allowed for fire tests [19] is high enough to ensure good measurement accuracy with samples of just 0.8–1 m.

5.4. Bandpass Filtering

Signal filtering improves the P_2/P_T ratio by 15–25 dB, and also (alternatively):

– reduces measurement error $Err\,IL$, as shown in Tab. 2,

– increases maximum loss which can be measured with the same Err_{IL} by 15–25 dB,

– allows to use a less powerful light source or to increase the connection loss (IL_C) by 15–25 dB.

However, the improvement from filtering can be insufficient, e.g. while testing multimode fibers longer than 20 m (Tab. 3).

5.5. Correction of Thermal Radiation Background

Another method used for eliminating interference caused by thermal radiation, as researched by the authors, involves the following:

– periodic disconnection by switching fibers or deactivating of light source,

– two power measurements performed in each cycle: one with the source on (P_{2I}) and one with the source off (P_T),

– subtraction of P_T from P_{2I} to obtain a true power of the test signal (P_2):

$$P_2 = P_{2I} - P_T \quad \text{power values in [W]}.$$

Such a method may be automated. Assuming the power of the light source in its off state is zero, the improvement in signal-to-interference ratio is limited by the resolution of power meter used (typically 0.01 or 0.001 dB) and by the combined internal noise of the light source and power meter for the time interval between measurements of P_T and P_{2I}.

Assuming that combined instrument resolution and noise equals 0.002 dB, the interference caused by thermal radiation is reduced by 33.36 dB. Unfortunately, the noise level in the corrected signal (with P_2 at the lowest level) will be approx. 3 dB. The real improvement corresponding to uncertainty of 0.05–0.20 dB, limited by LSPM resolution and noise, is 20–25 dB. Such a value is comparable to the improvement achieved by including an optical bandpass filter in front of the power meter. Combined use of both techniques may reduce interference by approx. 40 dB.

Tab. 3. Power of thermal radiation and required output power of the light source for several types of fibers and their lengths in a cable subjected to fire. Connection loss IL_C is 1 dB in all cases. Signal-to-interference ratio is: 19.5 dB for single-mode fibers and 13.5 dB for multimode fibers.

Fiber type	Fiber length [m]	1.2× max. fiber loss [dB]	Max. total loss [dB]	P_T [dBm]	P_2 [dBm]	P_1 [dBm]
Single mode G.652.D, G.657.A1, G.657.A2	4	4.8	5.8	−55.5	−36.0	−30.2
	10	12.0	13.0	−55.0	−35.5	−22.5
	20	24.0	25.0	−55.0	−35.5	−10.5
	30	36.0	37.0	−55.0	−35.5	+1.5
Single mode G.652.A	4	4.8	5.8	−51.5	−32.0	−26.2
	10	12.0	13.0	−51.0	−31.5	−18.5
	20	24.0	25.0	−51.0	−31.5	−6.5
	30	36.0	37.0	−51.0	−31.5	+5.5
Multimode 50/125 μm OM2, OM3, OM4, OM5	4	9.6	10.6	−37.5	−24.5	−13.9
	8	19.2	20.2	−37.0	−24.0	−3.6
	10	24.0	25.0	−37.0	−24.0	+1.0
	12	28.8	29.8	−37.0	−24.0	+5.8

6. Elimination of Thermal Radiation with Bandpass Filters

In theory, passive bandpass filtering performed at the receiver's input in the case of a data link or optical power meter in the case of an attenuation test system eliminates unwanted radiation having wavelengths outside of the transmission/test band. However, effectiveness of such an approach is limited by the following factors:

– Insertion of filter adds 2–4 dB to signal loss;
– Wavelength tolerance of transmitters and light sources (typically ±20 nm) and filters (typ. ±10 nm), plus the spectral width of radiation emitted by FP lasers (typically 5–10 nm) requires a 30–50 nm bandpass, unless the components are individually matched;
– Fiber test wavelengths are defined in applicable standards, most of them require testing of multimode cables loss at 1300 nm, i.e. near emission peaks (Tab. 1), and require a wideband InGaAs detector, while all applications of OM2/3/4/5 fibers are at wavelengths from 820 to 940 nm.
– A low-cost bandpass filter often has too narrow a stop band to effectively filter out thermal radiation across the entire sensitivity range of InGaAs photodetectors. Designers of data links or test systems must carefully review filter specifications. When a silicon photodetector is used in 850 nm multimode system, the bandpass filter needs to block wavelengths of up to 1100–1150 nm only.

6.1. Experiment

We have measured attenuation of unwanted thermal radiation with commercially available bandpass filters for both blackbody radiation coupled into the fiber (Tab. 4) and thermals emission from a multimode fiber (Tab. 5). Filters were installed in a Thorlabs FOMF/M fiber-to-fiber coupler with FC interfaces. 50/125 μm multimode (OM2) type fibers were placed on both sides. The optical power meter (HP 81532A) was equipped with an InGaAs photodetector. The improvement in signal-to-interference (S/I) ratio was calculated as a reduction of power observed after insertion of the filter into the optical path, corrected by the insertion loss of the same coupler with a 1304 nm filter, measured separately. This parameter reflects an improvement in the S/I ratio of the data link or in attenuation of test setup operating at 1300 nm or 1310 nm wavelengths.

As expected, bandpass filtering was more effective against thermal emissions (illustrated as a few narrow peaks in Fig. 1) than against coupled wideband blackbody radiation (Fig. 3), as a portion of blackbody radiation always falls within the filter's passband.

SPD shown in Fig. 3 suggests that bandpass filtering will be less effective at 1550 nm due to higher spectral density of the coupled thermal radiation encountered, with an estimated S/I gain being approx. 2.5 dB lower than at 1300/1310 nm. The evolution of thermal radiation spectrum with the increasing duration of heat exposure slowly reduces S/I improvement provided by filtering, because of the growing wideband coupled radiation.

7. Selection of Fiber and Wavelength to Minimize Interference from Thermal Radiation

The recommendations below summarize how to mitigate the negative impact of thermal radiation:

– single mode fibers generate low thermal emissions,
– wavelength bands with low spectral density of thermal emissions should be used,

Tab. 4. Measured improvement in S/I ratio achieved by insertion of a bandpass filter [dB]. The transmission wavelength was 1304 nm and the radiation source was carbon soot heated to 800°C and 1000°C. The emissions spectrum was as presented in Fig. 3.

Manufacturer and type of filter	Central wavelength [nm]	Passband width [nm]	Blocking band [nm]	S/I improvement at 800°C [dB]	S/I improvement at 1000°C [dB]
Thorlabs FB1300-30	1300	30	200 – 2600	16.65	15.99
Edmund Optics FB1300-25	1300	25	200 – 1800	18.12	17.45
Thorlabs FB1300-12	1300	12	200 – 2600	20.94	20.34

Tab. 5. Improvement in S/I ratio achieved by insertion of a bandpass filter [dB]. The transmission wavelength was 1304 nm and the radiation source was an OM2 fiber heated to 800°C and 900°C. Emission SPD was as shown in Figs. 1 and 2. The test could not be performed at 1000°C due to the failure of the fiber at 950°C.

Manufacturer and type of filter	Central wavelength [nm]	Passband width [nm]	Blocking band [nm]	S/I improvement at 800°C [dB]	S/I improvement at 900°C [dB]
Thorlabs FB1300-30	1300	30	200 – 2600	22.28	20.86
Edmund Optics FB1300-25	1300	25	200 – 1800	24.70	23.20
Thorlabs FB1300-12	1300	12	200 – 2600	25.34	25.76

– Si photodetectors are less sensitive to thermal emission,
– bandpass filters improve the signal-to-interference ratio.

Using a cable with an OH-free single mode fiber compliant with ITU-T G.652.D or G.657.A1/A2 [21] is the best approach. With 50/125 μm multimode fibers [21], the best option is to use the 850 nm band, where spectral density of thermal radiation of either type is low (Figs. 2, 3). The use of silicon photodetectors at the 850 nm single wavelength or 850–940 nm CWDM links operating over an OM5 fiber is a great idea due to insensitivity to radiation with wavelengths longer than 1100 nm, where the bulk of thermal radiation is located (Fig. 3).

8. Summary

The data obtained in the course of the experiments with telecom-grade fused silica fibers and fire tests of fiber optic cables indicate that optical fibers heated to temperatures above 850°C become a source of thermal radiation of non-negligible power. The resulting interference cannot be ignored in some applications, in particular during attenuation measurements.

Fortunately, there are several effective methods of preventing or mitigating this phenomenon, provided that the designer of fiber optic system is aware of the issue. Unfortunately, current standards for testing fiber optic cables do not include a warning or any advice how to reduce the negative impact of thermal radiation.

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