Remedies to Thermal Radiation in Fused Silica Optical Fibers

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https://doi.org/10.26636/jtit.2022.166222

Abstract — During a fire incident, optical fiber in a fire-resistant cable is usually exposed to temperatures 800 to 1000°C. The hot fiber generates thermal (incandescent) radiation within narrowband spectrum, and is affected by broadband thermal radiation from glowing surroundings. The power of the second component, initially negligible, increases with time due to rising number of fiber cracks and other defects serving as couplers for external radiation. Thermal radiation may interfere with measurements of fiber attenuation during fire test, but is rather unlikely to prevent data transmission with typical GbE and 10GbE transceivers during fire. Remedies to this problem, which can be combined, include use of single mode fibers instead of multimode fibers, filters for blocking thermal radiation with bandpass, and proper selection of emiter 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 fire, at temperatures up to 1000°C and for 15–120 minutes [1]–[3], providing connectivity for fire safety systems, video monitoring, and emergency communications. Such cables incorporate standard telecom fibers made of fused silica. Hot optical fibers either glow themselves and are exposed to radiation from surroundings usually from carbonized remains of polymer tubes and coatings. We have investigated both effects experimentally in [4], together with a short review of fire test standards and conditions. In this paper we present sources, spectral power distribution and power of thermal radiation (Section 2) based on results of conducted experiments, some methods of eliminating such phenomena (Section 3), and the possibility of interferences with operation of Ethernet data link (Section 4), as well as monitoring of fiber attenuation in a cable subjected to fire test (Section 5). Next, we report on experiment with using bandpass filters to reject thermal radiation (Section 6) and give the recommend action of fiber and wavelength to minimize such interferences (Section 7). Section 8 contains a summary.

2. Thermal Radiation in Fibers Under Fire

The detailed characteristics of radiation emerging from fused silica fibers held at temperatures up to 1000°C such as power, linebreak spectral power distribution (CSD), variation with time, and physical mechanisms are is included in paper [4]. Therefore, we include here only summaries and present representative examples.

2.1. Incandescence of Fiber

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

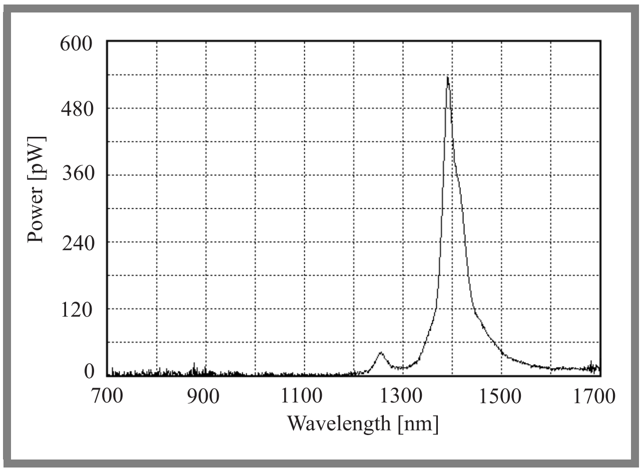

Fig. 1. Spectral power distribution of thermal emission of OM2 multimode fiber at 900°C. The total power is 49.39 dBm.

Incandescence of a single mode fiber, even exhibiting water peaks (ITU-T G.652.A) is substantially lower than for 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 an approx. 72-fold (18.6 dB) lower power can be expected, but real values measured in our experiments considerably varied.

Fiber incandescence decreases with time due to "drying" of fiber's core and diffusion of hydrogen through the cladding [5].

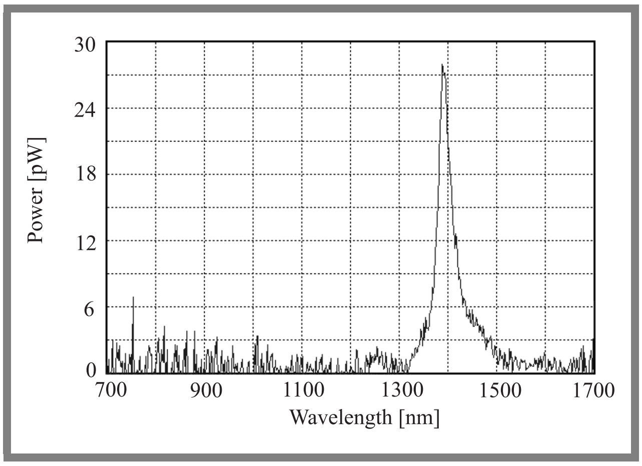

Fig. 2. SPDs of thermal emission of G.652.A single-mode fiber at 900°C. The total power is –66.71 dBm.

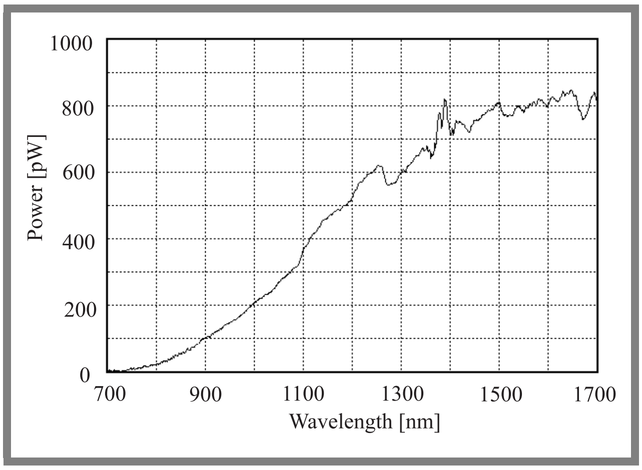

Fig. 3. Spectral power distribution of coupled thermal emission of OM2 multimode fiber at 1000°C. The fiber exhibited localized escape of light due to cracks, but retained optical continuity. Total power is 39.79 dBm.

Aa 50% intensity reduction was observed in our experiments after 1–2 at 1000°C [4], which corresponds to a typical duration of a fire incident or fire test. The fading phenomena is slower when fiber cladding is doped with fluorine.

2.2. Thermal Radiation Coupled Into Fiber

Coupling of external radiation into fiber comes from reflections of this radiation by cracks penetrating fiber's cladding and core, created when microscopic inclusions of cristobalite (crystalline form of silica) appear on the fiber surface [4]–[10]. Cracks in heat-degraded fibers have complex shapes and various depth.

A crack reflects a small part, about 4% of incoming radiation at angle dependent on crack direction. A small part of external radiation is directed into the fiber's acceptance angle, while similar part 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 fiber due to higher numerical aperture, i.e. 0.20 in 50/125 μm OM2/OM3/OM4 graded index multimode fiber versus 0.14 in ITU-T G.652 single-mode fiber.

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

2.3. Changes of Thermal Radiation Spectrum With Time

When fused silica fiber is exposed to high temperature (over 800°C) for a duration typical for fire incident defined in standards [1], [2] as 30–120 minutes, two concurrent changes occur with time:

- fading of thermal emission due to destruction of OH^- ions [5],
- progressive degradation of fiber by cristobalite inclusions and cracking [4], [6].

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

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

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

2.4. Power of Incandescent and Coupled Radiation

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

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

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

Thermal radiation coupled into fiber features self-limiting mechanism. Increasing density of cracks and inclusions in deteriorated fiber raises the coupled power (per unit length), but also attenuation grows due to escape of guided radiation from fiber. The measurements made during a fire test in accordance with DIN4102–12 standard suggest that saturation length of OM2 multimode fiber at 1000°C is 2–3 m (test duration: 90 minutes). Power of coupled radiation measured in these conditions was –38 to –35 dBm for a 32 m section of OM2 fiber placed in the fire zone, which constituted power saturation conditions. For a 3 m effective saturation section, the power of coupled radiation accumulated in long fiber sample is approx. 5 dB higher in comparison to 1 m sections we have tested in the laboratory.

We estimate the maximum expected power of thermal radiation in fire conditions according to DIN4102-12 [2] standard as approx. 37 dBm, –51 dBm and –55 dBm, respectively, for undamaged fibers indicated above, using InGaAs photodiode (800–1700 nm) as detector sensor. For 850 nm sensor based on silicon photodiode, with real sensitivity up to 1100 nm and multimode fiber, this power is reduced to approx. –45 dBm.

3. The Limitation of External Thermal Radiation

In this section we present two possible methods of modifying the design of fire resistant cable to prevent coupling of undesirable thermal radiation into the optical fibers.

3.1. Elimination of Black Soot

If the material surrounding glass fiber features low emissivity and high opacity at wavelength of interest, e.g. 1300 nm, the coupled radiation will be eliminated. An example of suitable material is titanium dioxide (TiO_2) with grain size of 2 μm. The black carbon soot left after pyrolysis of fiber coatings, loose tube and gel must be fully burned. However, since typical fire resistant-cable includes a fire barrier made of mica tape and often also a steel armor [4], there is no oxygen source available to do so inside cable. Although there may by oxygen provided by incorporation of solid oxidizer, the rapid burn would produce undesirable heat and flue gases like 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 fiber (this was the original purpose) and outside radiation entry. Unfortunately, fibers with photonic barrier are inconvenient to splice and are expensive. After 2010 such cables were replaced by other designs. Their re-introduction for use in fire resistant cables would be valuable.

4. Interference in Operation of Digital Fiber Optic Link

The data transmission over fibers in cable affected by fire my by subject to:

a) increase of fiber attenuation at ”water peak” wavelengths [4],
b) increase of fiber attenuation due to physical deterioration and light escape,
c) addition of unmodulated thermal radiation to data carrying signal at the receiver.

Phenomenon (a) is not important, as the used for transmission wavelengths are away from OH^- absorption bands, but extra loss due in case (b) is wavelength-independent and cannot be avoided.

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

$$EXT_{TX} = 10\ \log \frac{P_1}{P_2}. \tag{1}$$

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

$$EXT_{RX} = 10\ \log \frac{P_1 + P_I}{P_0 + P_I}. \tag{2}$$

The signal levels difference between 1 and 0 at the receiver decision circuit is maintained by automatic gain control sensing signal power for 0 and 1 in optical modulation amplitude (OMA) [15], but due to dark photodiode current the noise level increases while transmitting P_1.

How much interferences may 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 varies between 3 and 9 dB — see Table 1. This corresponds to power emitted in the 0 state of 50.0% and of 12.6% in the 1 state, respectively. Therefore, a rough limit of tolerant power of thermal radiation may be set at 12.5% of signal power at 1 level –6 dB without degrading the receiver sensitivity.

Parameters including thermal radiation power, receiver sensitivity and interferences limit for Ethernet transceivers are presented in Table 1. IEEE 802.3 includes different requirements

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 WDM bandpass filter.

for receiver sensitivity measured when the input signal has the lowest extinction ratio permitted for transmitter (stressed receiver sensitivity) – shown in parentheses. However, the limit of interfering thermal radiation in Tab. 1 is calculated for receiver sensitivity measured at optimal conditions, including high EXT.

The use of G.652.A fiber is assumed for single mode links up to 10 km long, as this transmission medium is still permitted in the ISO/IEC11801 standard for structural cabling systems [16].

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

If the estimated power of optical interferences may by an issue one solution is to use a high power transmitter in order to keep the signal to noise ratio high enough for error-free transmittion. The receiver must be fitted with attenuator to reduce input power to upper level of specified range, for best tolerance to increase of fiber loss.

The other method is bandpass filtering described in Section 6. Duplex transceiver designed for access networks have built-in bandpass filters for separation of signals transmitted in opposite directions at different wavelengths, which also reduce interferences coming from thermal radiation.

5. Interference During Measurements of Fiber Attenuation

5.1. Comparison of LSPM and OTDR Methods

Changes in fiber attenuation during cable fire testing are normally measured using a light source and power meter (LSPM) setup as shown in Fig. 4. It is ”Method B” in the EN60793-1-40 standard [17] and, has several advantages:

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

The disadvantage of LSPM method is sensitivity to interferences from thermal radiation. They add to radiation from the light source, hence measured fiber attenuation (or its change vs. initial conditions) is lower than real.

Measurements with optical time domain reflectometer (OTDR), called ”Method C” in EN60793-1-40, are better idea for to testing of long fibers, connectors and splices, and fault location. Both methods are approved in EN60793-1-46 standard [18] for testing of fibers and cables, when effects of external factors (mechanical actions on the cable or fiber, temperature, aging, etc.) on fiber attenuation are to be established. In OTDR measurements, interferences from thermal radiation increases noise floor at the receiver and reduces dynamic range. OTDR does not indicates the hot zone as upwards shift of fiber trace, but can show the loss resulting from fiber deterioration or bending there. Distance measurements are not affected.

5.2. Interferences During Measurements with LSPM

The optical path between light source and optical power meter includes a relatively short (1–30 m) fiber under test encased in a cable subjected to fire (Fig. 4). Its initial loss IL_F may change during the test. The combined loss on all other components of optical path: fibers outside the fire zone, splices, connectors and in multi-channel, multi-wavelength or filter-equipped setups also switches, splitters or filters (IL_C) is significantly higher than IL_F – up to 20 dB in some cases. It is assumed that IL_C is constant during test, and variations of measured power are caused only by changes in IL_F. As all measurement equipment have their uncertainties, the IEC standards for fiber cables [19] define an indicated loss change

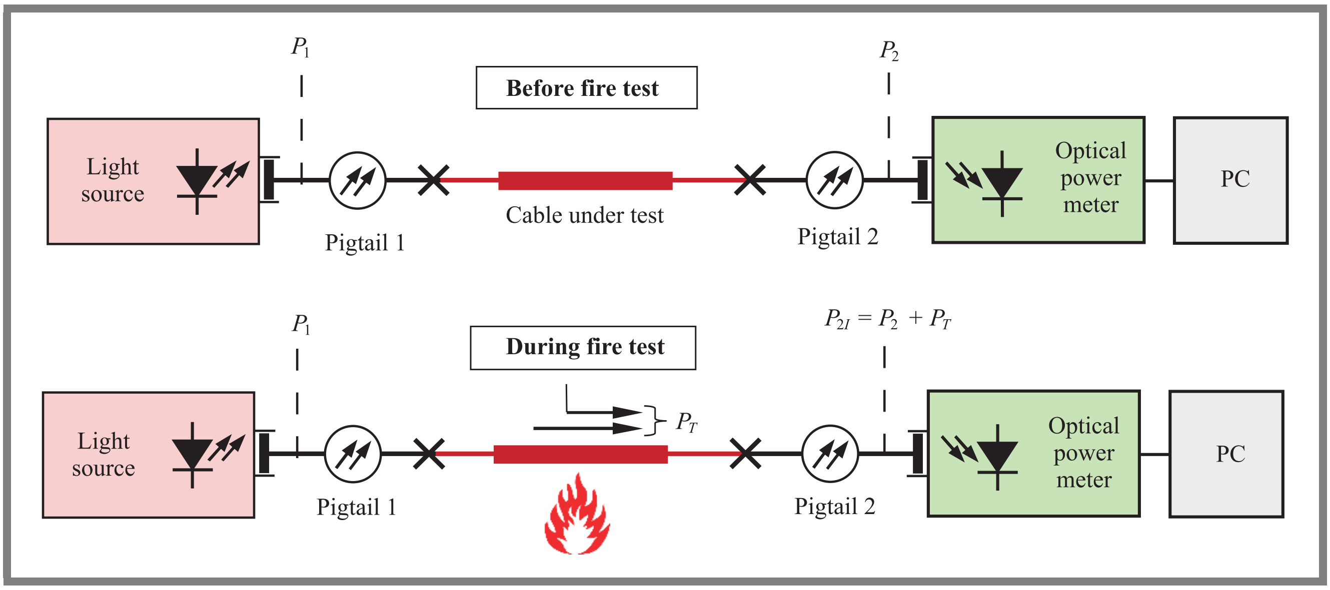

Fig. 4. The LSPM setup for measuring and recording variations in attenuation (loss) of a single optical fiber in a cable during fire test. Fiber under test is fusion spliced to pigtails for connections to test instruments.

up to 0.05 dB for single-mode fiber and 0.20 dB for multimode fiber as a "no loss change" condition.

Unfortunately, the standards defines only testing of fibers free of optical interferences. 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 SPD. Therefore, variations of output optical power (P_2) measured with optical power meter can be directly converted to fiber attenuation (IL_F) change.

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

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

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

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

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

– real test power P_2, coming from source and attenuated by the distance to power meter,

– power of interfering thermal radiation P_T.

– no need for launch and tail fibers to test a short fiber,

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

$$P_2I = P_2 + P_T \tag{5}$$

for power values in [W] or

$$P_2I = 10\ \log[10^{(\frac{P_2}{10})} + 10^{(\frac{P_T}{10})}] \tag{6}$$

for power values in [dBm],

The error in loss indication $ErrIL$ (in logarithmic scale) depends on P_T and P_2 ratio:

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

in linear scale or in log scale:

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

The P_T measured by OPM when light source is off is not valid, because:

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

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

– part of thermal emission lies outside of photodetector sensitivity range.

However, this effective value of interference power is useful for errors calculation.

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

Tab. 2. Fiber loss indication error ($ErrIL$) as a test signal P_2 to interference P_T ratio

$ErrIL$ [dB]	P_T/P_2	P_2/P_T	$T_2 - P_T$ [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 error from thermal radiation shall be below 0.05 dB for single-mode fibers cables or 0.20 dB for multimode fibers. This condition is ensured when the interference power P_T at the input to power meter is 13.5 dB or 19.5 dB lower, respectively, than power indicated with active light source. This condition shall be met at maximum loss increase of loss of cable under test.

During fire testing, high thermal radiation can mask even a large increase of fiber attenuation or fiber failure, as well as indicates give an erroneous impression of decrease of fiber loss. Such a phenomen is explained in Fig. 5, showing measurement data observed during a DIN4102-12 [2] fire test [4].

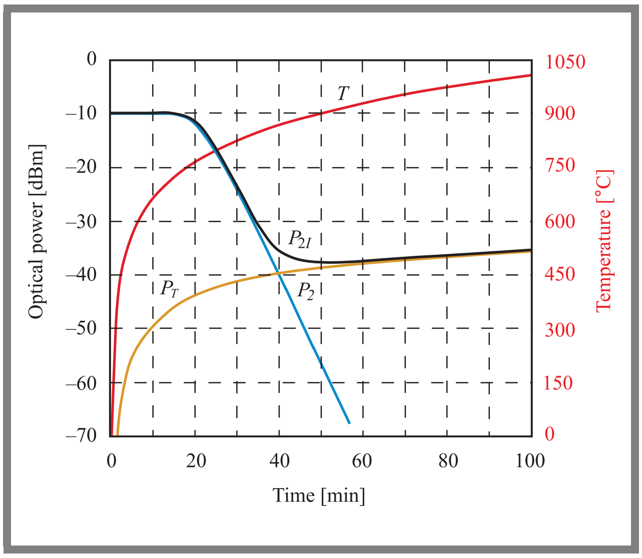

Fig. 5. Temperature T, power coefficient P_2, P_T and P_{2I} versus time in 33 m section of OM2 multimode fiber fire resistant cable during DIN4102-12 fire test. Interferences from thermal radiation could result in a false test pass status while being unnoticed.

Similar kind of 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 WDM demultiplexer with limited selectivity (25 dB typical). To minimize errors in multi-wavelength measurements, the power of all light sources shall be adjusted, e.g. by using of attenuators, to obtain similar read out on power meter with each source solo. This compensates 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, defined by:

– maximum measurable loss in the setup (IL_{MAX}),

– maximum expected power of thermal radiation (P_T).

Table 3 shows a result obtained in fire test performed in accordance with DIN4102-12 [2], and to peak temperature of 1000 °C. The setup allows to measure increase of attenuation up to 120% of limits defined in EN50582 [20] i.e. 1 dB/m for single mode fiber at 1550 nm and 2 dB/m for multimode fiber at 1300 nm, with $ErrIL$ limited to 0.05 dB and 0.20 dB, respectively. In both cases, the power meter usually incorporates an InGaAs photodetector, with sensitivity window 800–1700 nm.

The DIN4102-12 standard requires the cable in fire chamber to be min. 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 sake of simplicity, a uniform distribution of attenuation increase along the fire-affected zone is assumed.

Typical light sources with a FP laser have a offer power between –10 dBm and +3 dBm. For such a source, the maximum section in the fire chamber is limited to 15–25 m for single mode fibers and 7–10 m for multimode fibers. Because of contatenation possibility testing multiple fibers in not allowed. Fortunately, the increase of attenuation allowed for fire tests [19] is high enough to ensure good accuracy with samples section just 0.8–1 m.

5.4. Bandpass filtering

The signal filtering improves the P_2/P_T ratio by 15–25 dB and also:

– reduces measurement error $ErrIL$ as shown in Tab. 2,

– increases maximum loss which can be measured with same $ErrIL$ by 15–25 dB,

– allows to use lower powerful light source or increase connection loss (I_{LC}) 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 to eliminate interferences from thermal radiation researched by the authors involves:

– periodic disconnection by fiber switching or deactivation of light source or by reduced power,

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

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

– subtraction of P_T from P_{2I} to obtain true power value of test signal (P_2): $P_2 = P_{2I} - P_T$ power values in [W].

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

Assuming 0.002 dB of combined instrument resolution and noise, the minimum detectable power difference of 0.002 dB enables to reduce the CW interferences from thermal radiation by 33.36 dB. Unfortunately, the noise level in corrected signal (with P_2 at lowest level) will be approx. 3 dB. The real improvement corresponding to 0.05–0.20 dB uncertainty plus

Tab. 3. Power of thermal radiation and required output power of light source for several types of fiber and its lengths in 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]	1.2x 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
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

coming from LSPM resolution and noise, is 20–25 dB. Such value is comparable to improvement made by including an optical bandpass filter in front of power meter. Combinational use of both techniques can reduce interference by approx. 40 dB.

6. Rejection of Thermal Radiation with Bandpass Filters

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

– Insertion of filter adds 2–4 dB of signal loss;
– Wavelength tolerance of transmitters and light sources (typ. $\pm$20 nm) and filters (typ. $\pm$10 nm), plus the spectral width of radiation emitted by FP lasers (typ. 5–10 nm) requires of 30–50 nm bandpass, unless the components are trimmed;
– Fiber test wavelengths are defined in standards, most of them for testing of multimode cables forces loss measurements at 1300 nm, near emission peaks (Tab. 1), and requires wideband InGaAs detector, while all applications of OM2/3/4/5 fibers works at wavelengths 850 and 940 nm;
– Low-cost bandpass filter often has too narrow stop band to effectively filter out thermal radiation across whole sensitivity range of InGaAs photodetectors. The designer of data link or test system must carefully select filter specifications. When silicon photodetector is used in 850 nm multimode system, the bandpass filter needs to block wavelengths only up to 1100–1150 nm.

6.1. Experiment Result

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

As expected, the bandpass filtering was more effective against fiber thermal emission (which is illustrated as few narrow peaks in Fig. fref1), than coupled wideband blackbody radiation (Fig. 3), such a part always falls in the filter's passband. The SPD shown in Fig. 3 suggest that bandpass filtering will be less effective at 1550 nm due to higher spectral density of encountered coupled, thermal radiation, with estimated S/I gain approx. 2.5 dB lower than at 1300/1310 nm. The evolution of thermal radiation spectrum with duration of heat exposure slowly reduces S/I improvement provided by filtering, because of growing wideband coupled radiation.

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

The recommendations below summarize how lower negative impact thermal radiation:

– single mode fiber gives low thermal emission,
– use wavelength band with low spectral density of thermal emission,
– Si photodetector is insensitive to most of thermal emission a bandpass filter,
– bandpass filter gives and improvement in signal-to-interference ratio.

Using cable with 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 using in the 850 nm band, where spectral density of thermal radiation of either type is low (Figs. 2, 3). Using of silicon photodetectors in 850 nm single wavelength or 850–940 nm CWDM links operating over OM5 fiber is a great idea due to in sensitivity to radiation with wavelengths longer than 1100 nm, where the bulk of thermal radiation is located (Fig. 3).

Tab. 4. Measured improvement in S/I ratio by insertion of bandpass filter [dB]. Transmission wavelength was 1304 nm and radiation source was carbon soot heated to 800°C and 1000°C. The emission spectrum is as 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 by insertion of bandpass filter [dB]. Transmission wavelength was 1304 nm, radiation source OM2 fiber heated to 800°C and 900°C. Emission SPD as in Figs. 1 and 2. Test at 1000°C was impossible due to fiber failure 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

8. Summary

The data gathered from experiments with telecom fused silica fibers and fire tests of fiber optic cables indicate that optical fiber heated to temperatures above 850°C becomes a source of thermal radiation of non-negligible power. The resulting interferences to transmission cannot be ignored in some application, in particular during attenuation measurements.

Fortunately, there are several effective methods of preventing or reducing this phenomenon, when the designer of fiber optic system is aware of the issue. Unfortunately, current standards for testing of fiber optic cables do not include a warning or commentary and how to reduce negative impact from thermal radiation in the fiber path.

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