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# Thermal emission from a single glass fiber

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## Abstract

In this article, we study the thermal light emission from individual fibers of an industrial glass material, which are elementary building blocks of glass wool boards used for thermal insulation. Thermal emission spectra of single fibers of various diameters partially suspended on air are measured in the far field by means of infrared spatial modulation spectroscopy. These experimental spectra are compared with the theoretical absorption efficiency spectra of cylindrical shaped fibers calculated analytically in the framework of Mie theory taking as an input the measured permittivity of the industrial glass material. An excellent qualitative agreement is found between the measured thermal radiation spectra and the theoretical absorption efficiency spectra.

*Keywords:* Far-field thermal radiation, Single object, Glass fiber, Spatial modulation spectroscopy, Mie theory

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## 1. Introduction

Glass wool is a random assembly of glass fibers which has been used for decades in the thermal insulation of buildings. In conventional thermal insulation, the voids between glass fibers are filled with air. Since low fiber volume fraction is used (less than 10%), the heat transfer is dominated by heat conduction through the air-filled regions, while heat convection is minimized. Typical apparent (effective) thermal conductivity of glass wool in air is about 40 mW/(m.K) [1] which is close to the thermal conductivity of air (26 mW/(m.K)) [2]. Thick glass wool board of about 30 cm must be used to efficiently reduce the heat transfer [1]. This conventional insulation is space and material consuming which does not fulfill the constraints imposed on the construction of future buildings. Substantially better thermal insulation is achieved when the air is evacuated from the solid fibrous assembly by lowering the air pressure to less than 0.1 mbar (10 Pa). The apparent thermal conductivity of a Vacuum Insulation Panel (VIP) with glass fibers as core material is expected to reach a value of few mW/(m.K) [3]. In such a highly evacuated fibrous glass assembly, the gaseous thermal conductivity is suppressed and the heat transfer occurs exclusively by radiation and solid conduction. Heat conduction through a solid fibrous skeleton has been evaluated by Kwon et al. using simplified theoretical model [4] and recently studied by Kallel et al. [5] by solving numerically the Laplace equation for three-dimensional complex geometries complementing earlier numerical works [6–8]. Heat transfer by radiation is often estimated by considering a conduction model [9] (also referred to as the Rosseland approximation). It is worth noting that the Rosseland analytical expression of the radiative conductivity of a gray optically thick

26 medium [10] is used by default for a fibrous galss assembly[1, 3]. In most  
27 of the works reported to date, the radiative heat transfer through a fibrous  
28 assembly or its radiative properties are investigated by solving the radiative  
29 transfer equation (RTE)[11–16]. In this work, we will focus on the thermal  
30 radiation from a single glass fiber. We compare theoretical findings with the  
31 measurement of the infrared (IR) thermal radiation from single micro-sized  
32 wires of various diameters from 4 to 9.5  $\mu\text{m}$  which are compatible for use in  
33 VIPs [17]. With respect to earlier reported optical measurements [18], ours  
34 are performed with significantly lower temperature heating and done over an  
35 area where the object is totally surrounded by air. The lower temperature  
36 heating leads to higher quality Q factor of the emission while the suspended  
37 structure would avoid not only the emission signal from the substrate but  
38 also the influence of the substrate on the emission of the fiber. Recently, a  
39 novel thermometry platform based on thin model has been developed by Shin  
40 et al. [19] which enables the measurement of the emissivity of an individual  
41 suspended SiO<sub>2</sub> nanoribbon at low temperature (down to 150 K).

42 The spectral thermal radiance (or intensity) of an object [20] is equal to  
43 that of a blackbody  $I_b(\lambda, T)$  at wavelength  $\lambda$  and temperature  $T$  (known as  
44 the Planck distribution function) multiplied by the emissivity of the object.  
45 When the object is opaque and its characteristic length is much larger than  
46 the thermal wavelength  $\lambda_{\text{th}}$  (i.e. in the geometrical-optics approximation),  
47 thermal radiation is easily quantifiable by means of radiometry theory. The  
48 emissivity of such an object is function only of the Fresnel reflection coef-  
49 ficients [21]. For an object with a characteristic length comparable to the  
50 thermal wavelength  $\lambda_{\text{th}}$ , thermal radiation can be determined using fluctu-

51 ationnal electrodynamics [21–23] which is based both on Maxwell equations  
52 and the fluctuation-dissipation theorem. Based on the theory of fluctuation-  
53 nal electrodynamics, Golyk et al. [24] have derived the heat radiation of an  
54 infinitely long cylindrical object. An easier way to evaluate the thermal radi-  
55 ation is to rely on the Kirchhoff’s law [25]. This law, which arises principally  
56 from reciprocity [26], states that the emissivity of any object is equal to its  
57 absorptivity for every direction, wavelength and polarization. Originally, the  
58 Kirchhoff’s law was derived in the geometrical optics approximation but it  
59 is valid even for small objects [27]. The local form of this law, which was  
60 established for any finite-size object, equates the absorption cross-section  
61 density with the emissivity density [22, 28]. Bohren and Huffman demon-  
62 strated that a sufficient condition is required to satisfy the energy balance  
63 for any arbitrary isolated spherical particle [29]. This condition imposes that  
64 the absorption efficiency, defined as the ratio of the absorption cross section  
65 to the geometric cross section, is equal to the emissivity.

66 The outline of the paper is as follows. In Sec. 2, we present the experimen-  
67 tal set-up employed for the spectral measurement of the thermal radiation  
68 from a single fiber and we give also details on the acquisition procedure and  
69 the experiment conditions. In Sec. 3, we first show theoretically how the  
70 measured thermal radiation spectrum is directly proportional to the absorp-  
71 tion efficiency spectrum, and then analyse the dependence of the absorption  
72 efficiency spectrum on the fiber diameter and compare the measured spectra  
73 with computed theoretical spectra. Finally, in Sec. 4, we briefly summarize  
74 and draw some conclusions, and suggest some possible directions for future  
75 research.

## 76 2. Description of the experimental apparatus and measurements

77 The measurements have been realized with a new technique of IR spa-  
78 tial modulation spectroscopy (SMS), inspired from SMS technique previ-  
79 ously developed for measuring the optical extinction cross-section of single  
80 nano-objects using a laser [30] or a white lamp [31]. Details of the IR-SMS  
81 technique and of our experimental setup can be found in Ref. [32]. It has  
82 recently proven its ability to detect the far-field thermal emission of a single  
83 subwavelength object [32] and to spectrally analyze it with a Fourier trans-  
84 form IR (FTIR) spectrometer. The goal of the experiment is to extract the  
85 weak signal of the thermal emission from an individual object that coex-  
86 ists with a strong broadband background thermal emission. To achieve this  
87 goal, we spatially modulate the position of the studied object and use a syn-  
88 chronous detection processed by a lock-in amplifier. This allows us to record,  
89 at the modulation frequency, the thermal emission of the studied object with  
90 strongly reduced background contribution [32]. Without using spatial mod-  
91 ulation, the studied object must be kept at relatively high temperature as  
92 in the case of 1- $\mu$ m-diameter single silicon carbide (SiC) rod ( $T= 718$  K)  
93 [18], this despite the fact that the SiC is highly efficient IR thermal emitter  
94 material.

95 The experimental set-up is shown schematically in Fig. 1. A single glass  
96 fiber is deposited on a gold plated silicon substrate and is kept in the object  
97 focal plane of a Cassegrain objective with numerical aperture (NA) of 0.5.  
98 The substrate is located on a heating plate. The edge of the heating plate  
99 is maintained at a constant temperature of 433 K. The blackbody used in  
100 our experiment is a black soot deposit whose emissivity is about 0.96 in the

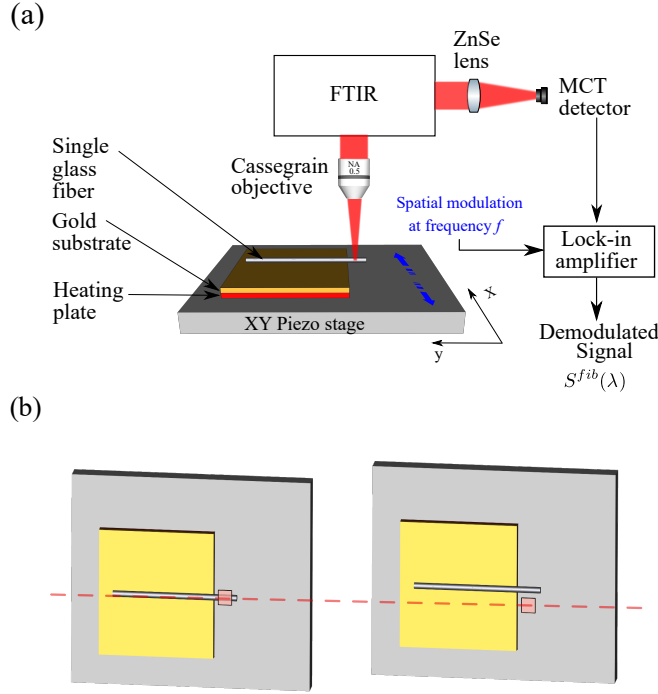


Figure 1: (a) Schematic illustration of the spatial modulation spectroscopy setup for measuring the infrared thermal emission of an individual glass fiber. (b) Top view images showing the fiber at two different positions during the spatial modulation: inside (left) and outside (right) the  $30 \mu\text{m} \times 30 \mu\text{m}$  area probed by the setup.

101 mid-infrared range [20]. A piezoelectric XY stage holds the heating plate  
 102 and allows to modulate the lateral position of the ensemble (heating plate,  
 103 gold coated substrate and fiber) with a sinusoidal waveform. The spatial  
 104 modulation is applied along the  $x$  direction at frequency  $f=21$  Hz with a  
 105 peak-to-peak amplitude of  $80 \mu\text{m}$ . The light collected by the Cassegrain ob-  
 106 jective passes first through a Fourier Transform IR (FTIR) spectrometer and  
 107 is then focused by means of a zinc selenide (ZnSe) lens on a liquid nitrogen-  
 108 cooled mercury-cadmium-telluride (MCT) IR detector. The magnification of

109 the system is such that the IR detector captures light from a  $30\ \mu\text{m}\times 30\ \mu\text{m}$   
110 area within the object focal plane of the Cassegrain objective. Initially, the  
111 XY stage is moved in a manner such that this detection area includes the  
112 fiber but is not lying on the substrate. However, care has been taken to cover  
113 the latter with gold (Au), i.e. a low emissivity material, as its radiation on  
114 the fiber could potentially produce a background scattering contribution to  
115 the detected signal. A lock-in amplifier is used to extract the amplitude of  
116 the first Fourier component (at the frequency  $f$ ) from the output signal of  
117 the IR detector, by taking the sinusoidal drive signal as the lock-in reference  
118 signal. The extracted amplitude values are not only proportional to the ther-  
119 mal radiation emitted by the fiber but also to the response of the different  
120 components of the experimental setup. In order to eliminate the influence of  
121 the experimental setup, the spectrum recorded with a fiber sample  $S^{fib}(\lambda)$   
122 has been divided by the spectrum obtained for a blackbody reference heated  
123 at the same temperature of 433 K. We note that the measurements have  
124 been carried out in a specific spectral range, between 6 and 13  $\mu\text{m}$ , which is  
125 directly related to the spectral response of the IR detector. Before perform-  
126 ing the measurement, a glass fiber is locally heated by using an IR laser and  
127 pulled in order to decrease its diameter. The local diameter of the fiber is  
128 measured from bright-field optical images using a visible light illuminator. It  
129 is essentially constant in the whole spatial region that can be probed by the  
130 apparatus, which is  $30\ \mu\text{m}$  wide.



131 **3. Comparison experiment-theory**

132 Let us recall first how the thermal emission from a single isolated fiber  
 133 can be determined theoretically. The power radiated per unit wavelength  
 134 interval by a fiber in an elementary solid angle  $d\Omega = \sin\theta d\theta d\varphi$  around the  
 135 direction  $\mathbf{u}_r$  at a given wavelength  $\lambda$  can be expressed by [28]

$$dP_e(\lambda) = \sigma_{\text{abs}}(-\mathbf{u}_r, \lambda) I_b(\lambda, T) d\Omega \quad (1)$$

136 where  $I_b(\lambda, T)$  is the spectral intensity of a blackbody radiation and  $\sigma_{\text{abs}}(-\mathbf{u}_r, \lambda)$   
 137 is the absorption cross section for non-polarized incident light in the direc-  
 138 tion  $-\mathbf{u}_r$  with a wavelength  $\lambda$  (see Fig. 2). As mentionned in the introduction,  
 139 the absorption cross-section  $Q_{\text{abs}}$  normalized with respect to the geometrical  
 140 cross section of the fiber ( $\sigma_{\text{geo}} = D L$ ,  $D$  and  $L$  are the diameter and the  
 141 length of the fiber respectively), also known as the absorption efficiency, is  
 142 equal to the emissivity of the fiber [29]. This equality is nothing other than  
 143 the Kirchhoff's law [25] for a finite-size object for every direction, wavelength  
 144 and polarization.

145 Integration of Eq.(1) over the entire far-field sphere and over all wave-  
 146 lengths results in total thermal radiation emitted by the isolated fiber [29]

$$P_{\text{tot}} = 4\pi \int_0^\infty I_b(\lambda, T) Q_{\text{abs}}(\lambda) \sigma_{\text{geo}} d\lambda. \quad (2)$$

147 We assumed that the normalized absorption cross section  $Q_{\text{abs}}(\lambda)$  is the same  
 148 whatever the direction of the incident light.

149 As shown in Fig.2, the amount of thermal radiation emitted by the fiber  
 150 and collected by the apparatus, depends on the collection angle of the ob-  
 151 jective  $\theta_{\text{coll}}$  ( $=\arcsin(\text{NA})$ ), and on the geometrical cross-section probed by

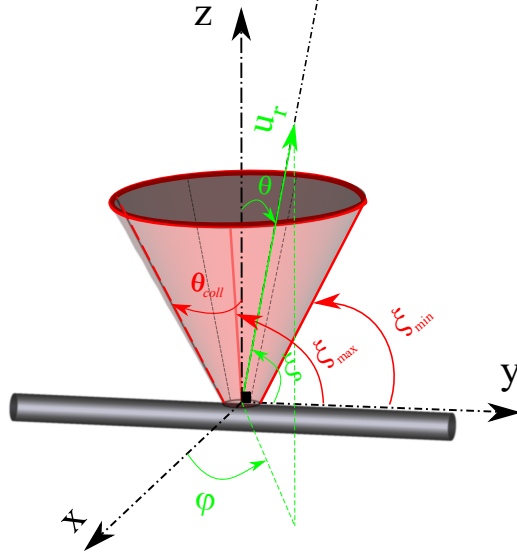


Figure 2: Scheme showing the cone of half angle  $\theta_{coll}$  through which a portion of the light emitted by the fiber is collected by the objective.  $\xi_{min}$  ( $= 90^\circ - \theta_{coll}$ ) and  $\xi_{max}$  ( $= 90^\circ$ ) are respectively the minimum and maximum possible values of the angle of incidence  $\xi$ .

152 the apparatus  $\sigma_{probed} = D l$ , where  $l=30 \mu\text{m}$  is the size of the detection area  
 153 optically conjugated with the IR detector,

$$P_{coll} \propto \int_{6\mu\text{m}}^{13\mu\text{m}} d\lambda \int_0^{2\pi} d\varphi \int_0^{\theta_{coll}} d\theta \sin\theta Q_{\text{abs}}(\theta, \varphi, \lambda) I_b(\lambda, T) D l. \quad (3)$$

154 The thermal radiation spectrum of the fiber  $S^{fib}(\lambda)$  can be roughly expressed  
 155 as follows

$$S^{fib}(\lambda) \propto \int_{90^\circ - \theta_{coll}}^{90^\circ} d\xi Q_{\text{abs}}(\xi, \lambda) I_b(\lambda, T) D l \quad (4)$$

156 where  $\xi$  is the angle of incidence. One can normalize the spectrum  $S^{fib}(\lambda)$   
 157 by dividing it with the thermal radiation spectrum of a blackbody and thus  
 158 obtain

$$S_N^{fib}(\lambda) \propto \int_{90^\circ - \theta_{coll}}^{90^\circ} d\xi Q_{abs}(\xi, \lambda) D. \quad (5)$$

159 Since the numerical aperture of the objective used in the experimental  
 160 setup is equal to 0.5 (see Fig. 2), the angle of collection  $\theta_{coll}$  is  $30^\circ$  and the  
 161 angle of incidence  $\xi$  varies from  $60$  to  $90^\circ$ . Over this incidence angle range,  
 162 the absorption efficiency spectrum is approximately the same and does not  
 163 differ significantly from that obtained for  $\xi = 90^\circ$  (data not shown). This  
 164 latter result, reported already for other wires [33], allows us to write the  
 165 following estimation

$$S_N^{fib}(\lambda) \propto Q_{abs}(\xi = 90^\circ, \lambda) D \quad (6)$$

166 The absorption efficiency  $Q_{abs}$  for non-polarized light illumination (as  
 167 well as the scattering efficiency  $Q_{sca}$ ) can be calculated using the Mie theory  
 168 [34] which solves the problem of scattering of a plane wave by an infinitely  
 169 long cylinder at oblique incidence. The non-polarized light illumination is  
 170 the average of two orthogonal polarized incident lights: Transverse electric  
 171 (TE) and transverse magnetic (TM), which implies that the dimensionless  
 172 far-field quantity  $Q_{abs,sca}(\xi, \lambda) = \frac{Q_{abs,sca}^{TE}(\xi, \lambda) + Q_{abs,sca}^{TM}(\xi, \lambda)}{2}$ . For details, the reader  
 173 can refer to [34, chapter 8, section 8.4] and [33, Appendix, section 1]. The  
 174 analytical Mie theory has the advantage to allow an exhaustive study. The  
 175 absorption/elastic scattering spectra of individual wires, which are calculated  
 176 using this theory, are often compared with those measured qualitatively and  
 177 not quantitatively [33, 35, 36]. The quantitative comparison requires, in ad-  
 178 dition to the accurate measurement through a rigorous calibration, the use  
 179 of a numerical approach such as the finite element method (FEM) or the

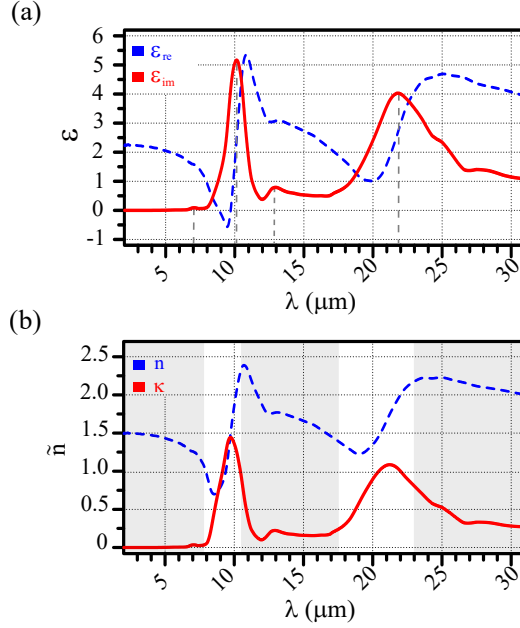


Figure 3: (a) Complex permittivity  $\varepsilon = \varepsilon_{re} + i \varepsilon_{im}$  and (b) complex refractive index  $\tilde{n} = n + i \kappa$  of the bulk industrial glass material. The vertical dashed lines indicates in (a) the characteristic peaks of the spectrum  $\varepsilon_{im}(\lambda)$ . The grey coloured regions shown in (b) correspond to wavelength regions in which the refractive index  $n$  is relatively higher than the extinction coefficient (or extinction index)  $\kappa$ .

180 boundary element method (BEM).

181 The material constituting the fiber is an industrial glass. Its complex  
 182 permittivity and refractive index, determined at Saint-Gobain Recherche [13],  
 183 are plotted as a function of the incident light wavelength in Figs. 3(a) and  
 184 3(b), respectively. These bulk values are considered to be the same for the  
 185 glass fiber. Note that the temperature and strain effects on the complex  
 186 permittivity are assumed to be negligible. In addition, the glass fiber is  
 187 assumed to be surrounded by vacuum.

188 The computed absorption efficiency spectra are shown in a color map as

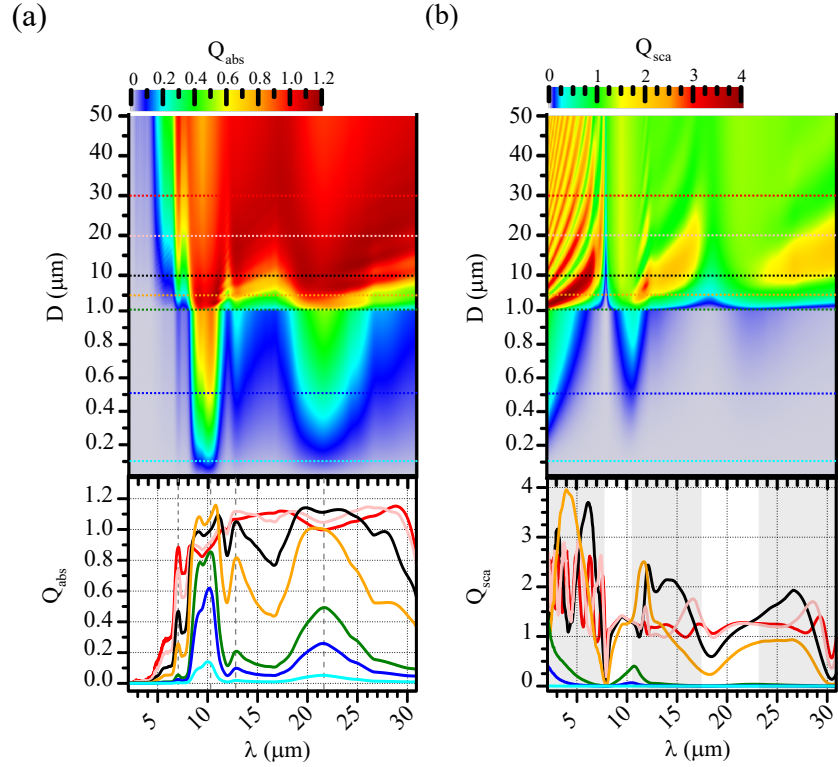


Figure 4: (a) Absorption efficiency  $Q_{\text{abs}}$  and (b) scattering efficiency  $Q_{\text{sca}}$  of a glass fiber in vacuum as a function of its diameter  $D$  and the incident light wavelength  $\lambda$  under normal incidence illumination ( $\xi = 90^\circ$ ) and for non-polarized incident light. The  $Q_{\text{abs}}$  spectra and  $Q_{\text{sca}}$  spectra are taken for a glass fiber with selected diameters :  $D = 0.1, 0.5, 1, 5, 10, 20$  and  $30 \mu\text{m}$ . Dashed horizontal lines on the map with various colors correspond to the spectra shown.

189 a function of the fiber diameter in the upper part of Fig. 4(a). Note that  
 190 the efficiency values are coded with different colors. The spectra of fibers  
 191 with selected diameters ( $D = 0.1, 0.5, 1, 5, 10, 20$  and  $30 \mu\text{m}$ ) are plotted  
 192 in the bottom part of Fig. 4(a). Results are presented for an incident light  
 193 with wavevector normal to fiber axis (normal incidence), corresponding to

194 an angle of incidence  $\xi = 90^\circ$ .

195 We initially focus on the absorption of small glass fibers with diameter be-  
196 low than or equal to  $1 \mu\text{m}$ . In the color map in Fig 4(a), we can distinguish  
197 two relatively broad absorption bands: the first one, extending approximately  
198 from  $8$  to  $12 \mu\text{m}$ , the other one, from  $18$  to  $26 \mu\text{m}$ . They are centered ar-  
199 round  $10 \mu\text{m}$  and  $22 \mu\text{m}$ , respectively. An additional weaker absorption band  
200 appears near  $13 \mu\text{m}$  and a very low intensity and tiny peak at  $7 \mu\text{m}$ . We can  
201 observe that the absorption increases over the entire spectrum when the fiber  
202 diameter increases. We remark that the spectrum of the absorption efficiency  
203 of small glass fibers is similar in shape to the spectrum of the imaginary part  
204 of the permittivity  $\varepsilon_{\text{im}}(\lambda)$  (see the solid red curve in Fig. 3(a)). The peaks  
205 observed in the absorption spectra (see the solid cyan, blue and green curves  
206 in Fig. 4(a)) are indicated by vertical dashed lines. Their spectral positions  
207 coincide with the positions of the peaks in the spectrum of the imaginary part  
208 of the permittivity (indicated also by vertical dashed lines). The absorption  
209 bands are absolutely identifiable in the extinction coefficient spectrum  $\kappa(\lambda)$   
210 (see the solid red curve in Fig. 3(b)). The three main absorption bands are  
211 attributed to the resonance of Si-O-Si vibrations [37]. It is worth pointing  
212 out that the industrial glass is composed mainly of silica,  $\text{SiO}_2$ . This ex-  
213 plains why the complex dielectric function and complex refractive index of  
214 the industrial glass, as shown in Fig. 3, are so similar to those of silica glass  
215 [37]. The weak peak at  $7 \mu\text{m}$  is owing to the presence of boron oxide ( $\text{B}_2\text{O}_3$ )  
216 in the composition of the industrial glass [13]. Thus, we can deduce that the  
217 absorption of the glass fiber is strongly dependent on the absorption proper-  
218 ties of the industrial glass material. Moreover, the absorption band, located

219 between 8 to 12  $\mu\text{m}$ , contains a peak around 9  $\mu\text{m}$ . This peak appears in the  
 220 spectral region where the real part of the permittivity  $\varepsilon_{\text{re}}$  becomes negative.  
 221 Ideally, the surface phonon-polariton resonance (SPhPR) takes place at the  
 222 wavelength when the complex permittivity  $\varepsilon$  is purely real and equals to -1.

223 We now turn our attention to the absorption of glass fibers with diam-  
 224 eter above 1  $\mu\text{m}$ . As the diameter increases, the absorption band at longer  
 225 wavelengths becomes wider and wider. Furthermore, in the spectral range  
 226 between this band and the neighbouring band around 13  $\mu\text{m}$ , the glass fiber  
 227 absorbs more and more efficiently with increasing the diameter. Since the  
 228 fiber is constituted by a low refractive index material (see blue curve in Fig.  
 229 3 (b)), the increased absorption cannot be attributed to whispering Gallery  
 230 modes (called also Mie resonances or leaky modes) due to the inefficient  
 231 light trapping caused by the small index contrast between the fiber and the  
 232 surrounding medium (i.e. vacuum). Thus, it is not related to an optical res-  
 233 onance effect but rather to the fact that the light attenuation becomes more  
 234 and more important as the thickness of the object increases. This behaviour  
 235 may be described by the the Beer-Lambert law. It is, in fact, very similar to  
 236 that of a glass slab of thickness  $D$ . The absorption efficiency of a fiber is ap-  
 237 proximately equal to the absorbance of a slab, i.e.  $Q_{\text{abs}} \approx A = 1 - e^{-\alpha D}$  where  
 238  $\alpha = \frac{4\pi\kappa}{\lambda}$  is the absorption coefficient. Thick fibers exhibit a nearly flat spec-  
 239 tral absorption for wavelengths longer than 12.5  $\mu\text{m}$ . For instance, the pink  
 240 curve in the bottom panel of Fig. 4(a) is the spectrum for a 20  $\mu\text{m}$  diameter  
 241 fiber that shows particularly absorption efficiency values close to 1.1 in the  
 242 12.5-29  $\mu\text{m}$  wavelength range. It is interesting to note that, for diameters  
 243 ranging from 15 to 50  $\mu\text{m}$ , the absorption efficiency is higher than 0.9 and

244 exceeds unity over a broad spectral range (see Fig. 4(a)), top). This finding  
 245 is consistent with the results reported by Golyk et al. [24] showing that for  
 246 large diameters (i.e.  $D \geq 20 \mu\text{m}$ ) the total heat radiation of  $\text{SiO}_2$  cylinder  
 247 exceeds that of the plate. It should be mentioned that the short-wavelength  
 248 absorption band intensity decreases slightly while the absorption peak at 7  
 249  $\mu\text{m}$  increases in strength as the diameter of the fiber diameter increases. The  
 250 discussion above remains valid for glass sphere. In fact, the absorption effi-  
 251 ciency spectrum of  $\text{SiO}_2$  sphere, as plotted in Fig. 1(b) of Ref. [38], exhibits a  
 252 diameter-dependence similar to that of glass fiber, despite the discrepancies  
 253 in shape and complex permittivity.

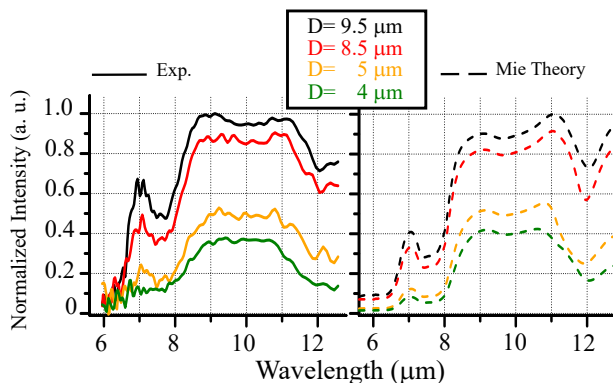


Figure 5: Normalized measured thermal radiation spectra (left) and normalized absorption efficiency spectra multiplied by the fiber diameter, ie,  $Q_{\text{abs}}(\xi = 90^\circ, \lambda) \times D$  (right) for different fiber diameters. The normalization is done with respect to the maximum of the spectrum obtained for a diameter of  $9.5 \mu\text{m}$ .

254 From Eq.6, one expects the measured thermal radiation to be propor-  
 255 tional to the product of the absorption efficiency and the fiber diameter. We  
 256 now compare in Fig.5 the measured spectra with the absorption efficiency  
 257 spectra calculated with the Mie theory, multiplied by the fiber diameter.



258 Measurements have been performed using our experimental apparatus, as  
 259 described in Section 2, on single glass fibers of various diameters 4.0, 5.0, 8.5  
 260 and 9.5  $\mu\text{m}$ . The wavelength range covered by the experimental spectrum  
 261 extends from 6 to 13  $\mu\text{m}$ . As indicated above, in this spectral region  $Q_{\text{abs}}(\lambda)$   
 262 is expected to show only a small peak at 7  $\mu\text{m}$  followed by a broad band  
 263 between 8 and 12  $\mu\text{m}$ . We can distinguish these two main spectral features  
 264 in the experimental curves, as shown in the left panel of Fig. 5. We also note  
 265 a drop in intensity of the 7  $\mu\text{m}$  absorption peak as the diameter shrinks, in  
 266 agreement with theoretical expectations. In Fig. 4(b) we plot the calculated  
 267 scattering efficiencies, in the same manner as the absorption efficiencies in  
 268 Fig. 4(a). The  $Q_{\text{sca}}$  spectra are different from those of  $Q_{\text{abs}}$  whatever the  
 269 fiber diameter. The light scattering is more efficient for thick fibers (ie,  $D >$   
 270 1  $\mu\text{m}$ ). For thick fibers, efficient light scattering occurs when the refractive  
 271 index  $n$  is much higher than the extinction coefficient  $\kappa$  (see grey coloured  
 272 regions in Fig. 3(b) and lower panel of Fig.4(b)). In the corresponding wave-  
 273 length regions, we observe branches showing high efficiency values on the  
 274 upper panel of Fig.4(b). These branches are not associated with specific Mie  
 275 resonances but are due to the overlap of different resonance modes (noting  
 276 that the industrial glass is low-refractive-index material). The above discus-  
 277 sion raises the question of whether the scattering of the background thermal  
 278 radiation by the fiber contributes considerably to the signal measured. In  
 279 the lower panel of Fig. 4(b), the orange curve shows the spectrum  $Q_{\text{sca}}(\lambda)$  for  
 280 a diameter of 5  $\mu\text{m}$  while the black curve for a diameter of 10  $\mu\text{m}$ . Enhanced  
 281 scattering is observed in both spectra in the range of 6-6.5  $\mu\text{m}$ . However, the  
 282 measured signal in this spectral region is very weak for all of the diameters

283 studied, as shown in Fig.5. Furthermore, for a fiber of 5  $\mu\text{m}$  diameter the  
284 scattering spectrum contains a narrow peak around 11.6  $\mu\text{m}$  and for a 10  $\mu\text{m}$   
285 diameter fiber a peak around 12.2  $\mu\text{m}$ . These spectral features are totally  
286 absent in the experimental spectra. The distinct differences between scatter-  
287 ing efficiency and experimental thermal radiation spectra indicate that the  
288 contribution of scattering of the background thermal radiation is unsignifi-  
289 cant in the measured signal using the spatial modulation technique. Finally,  
290 it is interesting to mention that Fig. 5 shows that the intensity of the whole  
291 thermal radiation spectrum increases much more than twofold while increas-  
292 ing the fiber diameter from 4 to 9.5  $\mu\text{m}$ . Consequently, the total radiating  
293 power is expected at least to double and so the larger diameter would lead  
294 to higher radiation. To minimize the heat transfer by radiation, it would be  
295 necessary to use fibers with smaller diameters-this assuming of course a weak  
296 optical interaction between the fibers.

#### 297 4. Conclusions

298 We have measured the thermal radiation spectra of individual glass fibers  
299 using a method based on the modulation of the sample position. We find  
300 that there is an obvious similarity between the measured spectra and the  
301 absorption efficiency spectra calculated by means of Mie theory. The scat-  
302 tering of the background thermal radiation did not appear to contribute  
303 significantly to the measurement. The thermal radiation spectral features of  
304 a single glass fiber or equivalently the absorption, are strongly linked to the  
305 optical properties of the glass material. Since the glass wool used for thermal  
306 insulation is composed by an assembly of fibers, future research should focus

307 on the radiative properties of glass fibrous assembly. We intend to calculate  
308 it using a boundary element method [39, 40] which requires only the mesh  
309 of the surface that we have succeeded in creating [5].The fluctuating-surface-  
310 current formulation developed by Rodriguez et al. [41–43] has proven to be  
311 a promising approach for analysing the radiative heat transfer by arbitrary  
312 geometries.

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