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Measurement of emissivity with a new grey body and novel IR thermal sensor dubbed TMOS

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Abstract: The concept of emissivity has been with the scientific and engineering world since Planck formulated his blackbody radiation law more than a century ago. Nevertheless, emissivity is an elusive concept even for experts. It is a vague and fuzzy concept for the wider community of engineers. The importance of remote sensing of temperature by measuring IR radiation has been recognized in a wide range of industrial, medical, and environmental uses. One of the major sources of errors in IR radiometry is the emissivity of the surface being measured. In real experiments, emissivity may be influenced by many factors: surface texture, spectral properties, oxidation, and aging of surfaces. While commercial blackbodies are prevalent, the much-needed grey bodies with a known emissivity, are unavailable. This study describes how to achieve a calibrated and stable emissivity with a blackbody, a perforated screen, and a reliable and linear novel IR thermal sensor, 18 dubbed TMOS. The Digital TMOS is now a low-cost commercial product, it requires low power, and it has a small form factor. The methodology is based on two-color measurements, with two different optical filters, with selected wavelengths conforming to the grey body definition of the use case under study. With a photochemically etched perforated screen, the effective emissivity of the screen is simply the hole density area of the surface area that emits according to the blackbody temperature radiation. The concept is illustrated with ray tracing simulations, which demonstrate the approach. Measured results are reported.

Key words: blackbody, grey body, graybody, cavity blackbody, extended area blackbody, emissivity, IR thermometry, remote temperature measurement

Introduction

What is emissivity and who needs measurements of emissivity[1-2].

As a fundamental principle of physics, all materials emit electromagnetic radiation. The intensity of this radiation, measured in terms of power, is directly influenced by the material's temperature and its emissivity. Emissivity is a property that quantifies a material's ability to emit thermal radiation relative to a perfect black body.

More than a century ago, Planck formulated his radiation law, expressing the power emitted by a model body named "blackbody", as a function of temperature and wavelength.

Planck's radiation law is a mathematical model describing the amount of radiation from a closed metallic furnace held at a well-controlled temperature. The model body has become known as a blackbody.

Every material radiates power, but real materials are not perfect blackbodies. Emissivity is a material's ability to radiate a fraction of the power that a perfect blackbody would radiate at a given temperature. Thus, the amount of radiated power is dependent on the material's temperature and the material's emissivity.

IR thermometers take advantage of this. They measure the amount of power exiting an object in an infrared band. They calculate the temperature based on this measured power and the material's emissivity.

Accordingly, accurate temperature measurements cannot be obtained without measuring simultaneously the emissivity. The errors introduced by non-accurate emissivity value are significant and increase with object temperature.

Figure 1 illustrates the concept of the ideal blackbody and the ideal grey body.

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Ideal Blackbody	Ideal Grey Body
Idealized object that absorbs all the incident electromagnetic radiation Absorbed radiation = emitted radiation $\alpha_B = \varepsilon = 1$ ➢ Emissivity is a property between 0 to 1 ➢ Ideal radiator: 1 ➢ Ideal mirror: 0	Object that emits radiation at each wavelength in a **constant ratio** less than unity to that emitted by a black body at the same temperature $0 \leq \varepsilon < 1$ ε – the emissivity: **independant** of Wavelength and Temperature within a region of the electromagnetic spectrum

Fig. 1 Planck's radiation law is a theoretical physical concept. Left side: the parameters de-scribing the ideal blackbody. Right side: the parameters describing the ideal grey body.

1 Why is emissivity so difficult to measure [3]

Every material radiates energy. As discussed above, emissivity is a factor between 0 and 1, which multiplies Plank's radiation law. It is the ratio of the radiation emitted from the surface of a body to the theoretical emission of an ideal blackbody of the same size and shape according to Planck's Law.

The amount of radiated power is dependent on the material's temperature and the material's emissivity. The emissivity may vary with wavelength and temperature. A grey body has constant emissivity within the measurement IR optical bandpass filter. While the ideal blackbody has an emissivity = 1, the grey body emits a constant fraction of the radiation, which is termed emissivity. Thus, a grey body is a surface whose emissivity is constant regardless of wavelength.

For calibration and simulation of remote temperature systems, a "grey body" with a variable emissivity down to low emissivity in the range of 0-0.98, is required.

Blackbody manufacturers strive to provide a near-ideal blackbody with an emissivity as close to 1 as possible, which is theoretically not achievable because such an ideal blackbody does not emit. State-of-the-art blackbody manufacturers provide blackbodies with an emissivity of 0.98 ± 0.02. A commercial grey body with well-calibrated emissivity is not available, since in real experiments, emissivity may be influenced by many factors: surface texture, spectral properties, oxidation, and aging of surfaces. This is why emissivity measurements are challenging, as further explained below.

2 Commercial blackbodies

There are two types of blackbodies: cavity and extended area, as illustrated in Fig. 2. An extended area blackbody is preferred for calibration since the measured signal from cavity type blackbody depends on the geometry of the cavity as well as the observation angle.

Extended area blackbodies are made of a heated, high-conductivity metallic plate, which is covered by black paint. A calibrated Resistance Temperature Detector (RTD) made of platinum controls the temperature of the metallic plate.

In theory, an extended area blackbody may provide a good calibration. In practice, there are several issues. The emissivity of the metal layer is anywhere from 0.02 to 0.50 depending on the metal. Furthermore, most metals oxidize. This does increase the emissivity, up to 0.80, but it also results in a very large uncertainty due to the time-dependent variance in the emissivity of oxides. To get around these problems with metals, the surface is painted with black paint. In the 8 – 14 μm bandwidth special paints are available that have an average emissivity of 0.96 to 0.98. However, the black paint also oxidizes during operation, and its emissivity changes.

Industrial factories monitor the manufacturing process with remote temperature sensing using black tape on the monitored surface. The black tape is calibrated, and its emissivity is measured to be ~0.95. However, tapes with well-calibrated emissivity in a wide range of values are not available. Military equipment suppliers provide low-emissivity tape, lower than 0.3, to camouflage mili-

Fig. 2 There are 2 types of commercial black bodies. On the left: image of extended area blackbody for calibration. On the right: an image of cavity blackbody. Images from Ref. [4].

tary systems and equipment in the dark. Such tapes are not available for everyone.

To summarize, in real experiments, emissivity may be influenced by many factors: surface texture, spectral properties, oxidation, and aging of surfaces. Hence, it is essential to measure simultaneously both temperature as well as emissivity.

There are no blackbody manufacturers that provide a "grey body" with known lower surface emissivity. This raises the question of how to test, calibrate, and measure remote temperature device performance with a target that has unknown emissivity.

3 The new grey body. – with the screen approach

Below, in Fig. 3, we demonstrate how to achieve a calibrated and stable emissivity source with a blackbody, a perforated metallic screen, and a reliable and linear novel IR thermal sensor, dubbed TMOS.

We prepare a set of perforated screens with varying fractions of holes relative to the overall area. With a perforated screen, the effective emissivity of the surface is simply the hole density area of the surface area that emits according to the blackbody temperature radiation. The remaining density area of the screen, which is metallic and highly reflective, reflects radiation according to the ambient temperature. If the screen temperature is equal to the ambient temperature, the emissivity of the screen is not relevant since what is emitted by the screen is compensated by what is reflected from the screen.

As illustrated in figure 4, the sensor's field of view is directed towards the blackbody emitting area, which is partially obscured by a perforated screen. The blue shaded area represents the solid portion of the screen. If the screen were an ideal mirror (a perfect reflector), its temperature would be inconsequential as it would only reflect ambient radiation. However, real-world materials are not perfect reflectors, and some radiation is emitted based on the screen's temperature. To mitigate this effect, it is beneficial to maintain the screen's temperature in thermal equilibrium with the ambient environment.

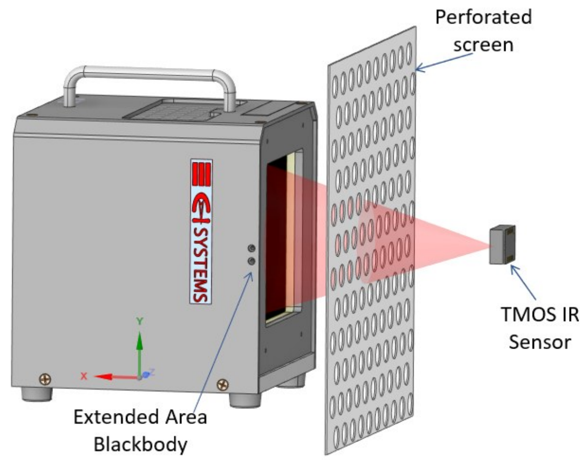

Fig. 3 The new grey body is based on a high-quality extended area blackbody, a perforated screen, and a high-performance IR uncooled thermal sensor. The metallic screen transmits only a fraction of the blackbody radiation, depending on the density of the holes. Accordingly, a set of perforated screens transform the blackbody into a grey body, as explained in the text below.

This ensures that the emitted radiation from the screen closely matches the reflected ambient radiation, minimizing any potential impact on the measurement results.

To mitigate this effect, it is beneficial to maintain the screen's temperature in thermal equilibrium with the ambient environment. This ensures that the emitted radiation from the screen closely matches the reflected ambient radiation, minimizing any potential impact on the measurement results.

Thus, a perforated screen with a controlled hole density, held at the ambient temperature, allows us to control the emissivity of a commercial blackbody.

The perforated holes are designed with the following rules: to be uniformly distributed, and the hole diameter is designed to be small and with an adequate number of holes within the field of view of the sensor. By applying Far Field Approximation to the measurements, we aim to

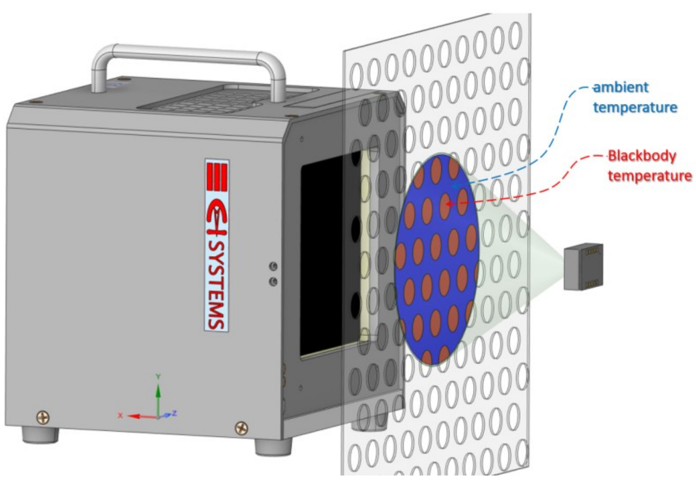

Fig. 4 Illustration of the sensor field of view facing an extended area black body with a perforated screen

neglect diffraction effects [5]. The angular diameter of the Airy disk is commonly used to estimate the diffraction limited spot size and is defined as 2.44×**λ**/D where D is the aperture diameter and **λ** is the wavelength. The linear diameter of the airy disk on the sensor is estimated by 2.44×**λ** ×$f_{\#}$. The area of the airy disc is $\boldsymbol{A} = \boldsymbol{\pi} \times \left(1.22 \times \frac{\boldsymbol{\lambda}}{\boldsymbol{D}} f\right)^2$. As the aperture increases the image area decreases, and the effect of diffraction is decreased. A rule of thumb recommends that the aperture will be greater than 100×**λ**. For 10 μm radiation, that means apertures (holes) of $1.22 \times 10 \times 10^{-6} \times 100$ is equal to approximately 1.2 mm. If the diameter is less than this threshold the far field approximation is violated. To be on the safe side, we increased the holes' diameter to 2mm. The bandpass filters are of the same order of magnitude (around 10μm) and therefore the holes diameter of the perforated screen is adequate.

In IR thermography, we focus the main wavelength of IR radiation are around 10 μm, and therefore holes around 1 mm in diameter are adequate. We refer to the above setup (Figure 1) as a grey body and define the effective emissivity of the measured blackbody with a perforated screen as follows:

$$\varepsilon_{eff} = \frac{\varepsilon_{\rm screen}(T_{\rm BB},T_{\rm amb}) - S_{\rm mirror}(T_{\rm amb})}{\varepsilon_{\rm BB}(T_{\rm BB},T_{\rm amb}) - S_{\rm mirror}(T_{\rm amb})} \quad , \quad (1)$$

Where $\boldsymbol{S}_{\rm screen}(\boldsymbol{T}_{\rm BB}, \boldsymbol{T}_{\rm amb})$ is the detector signal measured facing the screen between the blackbody, as shown in Figure 1, $\boldsymbol{S}_{\rm BB}(\boldsymbol{T}_{\rm BB}, \boldsymbol{T}_{\rm amb})$ is the detector signal measured facing the blackbody at the same temperature without the screen, and $\boldsymbol{S}_{\rm mirror}(\boldsymbol{T}_{\rm amb})$ is the measured signal of the detector facing a highly reflective metallic plate made of the same material of the screen.

The signal from the screen is equal to the ratio of the holes of the perforated screen to the total area if the screen and ambient air are at the same temperature. To achieve that, the screen is "soaked" in the ambient temperature (~20 °C), and the measurement is applied rapidly (10 s or less). Thus, the screen with a known percentage of holes can "transform" a near ideal extended area blackbody to a practical grey body with a known emissivity.

Photochemically etched perforated screens provide a precise, robust, and repeatable solution[6]. As there is no mechanical tooling, the shape and integrity of the metal is maintained to provide a fast, economical, and high-quality result for a wide range of materials. These include typically hard to machine metals such as stainless steel, titanium, and aluminum, which have highly desirable anti-corrosion properties.

With photochemical etching, perforated screens are manufactured from a single piece of metal, including thicknesses down to 100-micron foil. Finally, the screens are packaged in a frame. This gives them greater strength and integrity as well as a more vertical etching profile.

We have designed a screen made of 0.1 mm stainless steel with holes with a radius of 1 mm and a pitch between the center of the holes of 2.15 mm. The spec for the product is +/−0.05 mm. The perforated screen provides a ratio of $A_{\rm holes}/A_{\rm plate} \approx 0.8$ between the holes area to the whole plate.

The measurement setup is described in Figure 3. According to expression (1), three measurements are sufficient to determine the effective emissivity of the perforated screen. The measured signals are obtained by the signal from the blackbody $\boldsymbol{S}_{\rm BB}(\boldsymbol{T}_{\rm BB}, \boldsymbol{T}_{\rm amb})$, the signal of the perforated screen $\boldsymbol{S}_{\rm screen}(\boldsymbol{T}_{\rm BB}, \boldsymbol{T}_{\rm amb})$ and the signal of the mirror $\boldsymbol{S}_{\rm mirror}(\boldsymbol{T}_{\rm amb})$. The mirror is made of the same sheet of stainless steel from which the screen is made.

The "screen approach" is based on the following assumptions: thermal equilibrium; conservation of energy; Kirchhoff Law; an opaque blackbody; a reflecting plate; and a perforated screen. It is discussed in detail at Ref. [8].

4 How the error in emissivity affects the error in temperature

In specific optical band pass regions, the error in temperature may be related to the emissivity by simulations. For the sake of simplicity, we discuss this issue for monochromatic radiation.

Monochromatic Planck's radiation law:

$$W_\lambda(T) = \varepsilon\frac{2\pi hc^2}{\lambda^5}\cdot\frac{1}{e^{\frac{h\nu}{\lambda kT}} - 1}\left[\frac{W}{\mathrm{cm}^2\mu\mathrm{m}}\right] \quad , \quad (2)$$

The relation between emissivity differentiation to temperature differentiation for monochromatic radiation:

$$\frac{dT}{d\varepsilon} = \frac{\frac{dW_\lambda(T)}{d\varepsilon}}{\frac{dW_\lambda(T)}{dT}} = \frac{\lambda kT^2}{\varepsilon hc} = \frac{T}{\varepsilon}\cdot\frac{kT}{\frac{hc}{\lambda}} \quad , \quad (3)$$

To show the impact of uncertainty in emissivity evaluation on the calculated temperature from the radiation it can be inferred for example with expression (3) for monochromatic radiation λ=10 μm, object emissivity of 0.98 and object temperature of 310K, an in-accuracy of Δε =0.01, introduces temperature in-accuracy of 0.6862°° C. The uncertainty caused by emissivity increases with the wavelength (**λ**) as well as temperature (T^2).

5 The novel thermal sensor dubbed TMOS

The TMOS is a novel micromachined n-MOS CMOS transistor operating at subthreshold and performing as a thermal IR uncooled sensor. The TMOS stands for thermal MOS. It was originally invented at Technion, and a patent was filed and granted in 2003.

The development was funded by TODOS Technologies [9]. The TMOS is currently manufactured at STMicroelectronics[8] and the data sheet of the generic TMOS is reported in ST catalog. The performance metrics and the noise mechanisms of the digital TMOS are reported in Ref. [10]. Reference [10], describe in greater detail the analog TMOS, which was invented at Technion and transferred to STMicroelectronics to make it a commercial, qualified product.

The TMOS Uncooled thermal sensor has the following advantages: small form factor, lightweight, low-power, low-cost and high performance tailored for the specific use case of the grey body discussed in this work. An important feature of the Digital TMOS is the linearity with emissivity. A circuit implemented on the Digital TMOS, known as PTAT- Proportional to Absolute Temperature, measures the sensor physical temperature, which is determined by the ambient temperature and the measurement conditions.

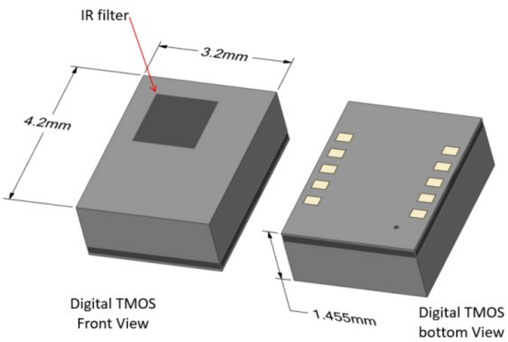

Fig. 5 Image of commercial Digital-TMOS

Sensing specifications:
· IR sensitivity: 2000 LSB/℃
· RMS noise: 25 LSB_{rms}
· Operating wavelength: 5 μm to 20 μm
· Local temperature sensor accuracy: ±0. 3℃

$$Noise = \frac{d(signal)}{d(\Delta T_{BB})}(\Delta T_{BB})_{min} \rightarrow (\Delta T_{BB})_{min} = \frac{Noise}{\frac{d(signal)}{d(\Delta T_{BB})}} = \frac{25[LSB]}{2000\left[\frac{LSB}{K}\right]} = 12.5[mK] \quad , \quad (4)$$

Based on the upgraded RMS noise of 25 LSB (RMS), the resolution is therefore NETD ~12 mK. The TMOS has emerged in the last decade as a preferred uncooled IR thermal sensor, since it features low fabrication cost, typical of CMOS thermopiles, and high performance, typical of bolometers [11]. In contrast to the high-power operation of Bolometers and the relatively high power of the CMOS thermopiles, the TMOS uses very low power for operation. The TMOS is fully compatible with wafer level CMOS processes and packaging, features 1. 25 × 107 V/W responsivity in contrast to ~1*103 V/watt of the thermopiles. The thermal resolution of the TMOS is ~12. 5 mK. This is obtained by estimating the minimal detectable temperate, according to (4) and noting that the RMS noise is 25 LSB.

6 TODOS Two-channel Radiometer based on the Digital-TMOS

The unique feature of this device is that it simultaneously employs two sensors with different optical bandpass filters. Accordingly, the measurement yields two power equations with two unknowns: the temperature and the emissivity. By solving these two equations, the effective emissivity is derived. This approach enabled us to measure remotely and accurately the forehead temperature and emissivity [12]. We are currently developing a watch that measures the wrist temperature and emissivity. The developed prototype is shown in Figure 6. Excellent results are achieved. The mean errors for temperature and emissivity are, respectively, 0. 003℃ and 6. 07e^{-5}. The prototype of Figures 6-7 may be adapted to commercially available smartwatches.

Fig. 6 The front side of the watch-like prototype for measuring wrist temperature

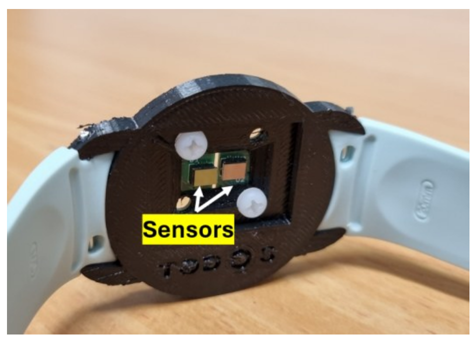

Fig. 7 The backside of the watch-like prototype for measuring wrist temperature. Two TMOS sensors with modified filters sense the skin temperature and emissivity with great accuracy.

7 The Emissivity of the Human Body Skin

Figure 8 depicts the emissivity of the skin of human beings [13]. Skin emissivity strongly depends on wavelength. It is obvious that grey body approximation for the skin is relevant only in the optical IR window 8-14 um. In that optical region, it may vary approximately between 0. 95-1. Skin emissivity is determined mainly by water and melanin. It is not affected by skin color (black or white people). It is affected by sweat, sun lotions and cosmetics as well as additional bio-parameters like blood pressure. When we measure human skin temperature there are 2 unknowns: temperature and emissivity. Therefore, 2 TMOS sensors with 2 different bandpass optical filters are required, corresponding to the optical window where the grey body approximation holds. Unless we know the emissivity, the measurement in-accuracy is significant as discussed in section 5. It is well above the medical grade requirements, as specified in the ASTM document[14].

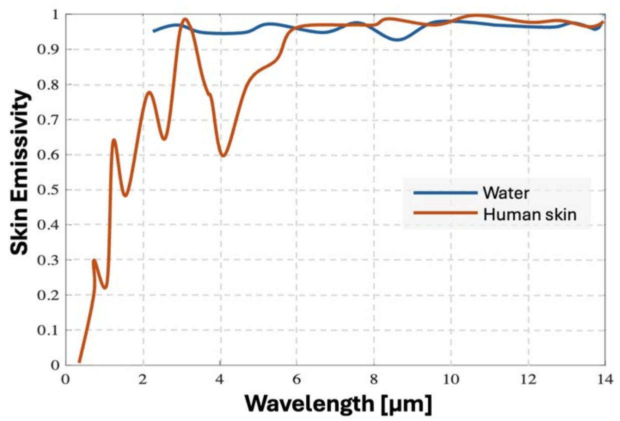

Fig. 8 The emissivity of the human skin as a function of wavelength, in comparison to water. Based on Ref. [13]

8 Simulations

In an earlier paper[7], we reported considerable experimental data to support the new grey body. In the current work, we supplement the evidence by simulations.

Ray tracing simulations[5] were carried out using a commercial ray tracing software [15]. A 3D model of the blackbody surface, the hole mask and the detector were created. The hole mask was designed as a triangular lattice of holes with given radius and spacing. All surfaces were taken as solid walls without secondary reflections. In order to reduce the complexity of the calculations, an opposite ray tracing simulation was performed, using the detector as the ray source and the blackbody surface as the ray detector. This maximizes the effectiveness of the simulation as the blackbody surface is much bigger and hence most of the emitted rays will never actively participate in the simulation (as they will never reach the vicinity of the detector).

In order to avoid a full 3D ray tracing simulation, which is both time and resource-consuming, the semi-azimuthal symmetry of the problem was used, with ray tracing performed on 2D cross-sections rather than the entire 3D problem. For each such cross-section, the ratio between the number of rays emitted from the source and rays reaching the detector was calculated, as well as the length ratio between the holes' total length and the mask's diameter. The effective emissivity of each 2D cross-section is taken as the ratio between detected and emitted rays, and is expected to equal the hole-mask length ratio.

As the hole mask does not have complete azimuthal symmetry, several 2D cross-sections were used. The overall mask's emissivity is taken as the average of all 2D emissivity and the overall mask's hole area to mask area ratio is taken as the average of all 2D length ratios. The two sizes are expected to be equal, proving the validity of a blackbody source with a hole mask acting as an effective grey body.

Infrared The radius of the holes in the mask was taken as 1mm. Two-hole spacings were simulated: 2.15 mm and 2.5 mm. The simulation demonstrated a good match between the length ratios and ray ratios, showing that for each cross-section, the effective emissivity matches the mask's hole to diameter ratio. The averaged emissivity and averaged hole to mask area ratio also demonstrated a good match, indicating that the hole mask, combined with the blackbody source, form an effective grey body.

For the 2.15 mm-spaced mask, the emissivity obtained from the ray tracing simulation was 0.7793 ± 0.0278 and the emissivity obtained from the geometric hole to mask area ratio was 0.7838 ± 0.0141. For the 2.5 mm-spaced mask, the emissivity obtained from the ray tracing simulation was 0.5851 ± 0.0313 and the emissivity obtained from the geometric hole to mask area ratio was 0.5811 ± 0.0278. For both spacings, we can see that the obtained geometric and ray-tracing emissivity closely match. The difference can be attributed to the accuracy

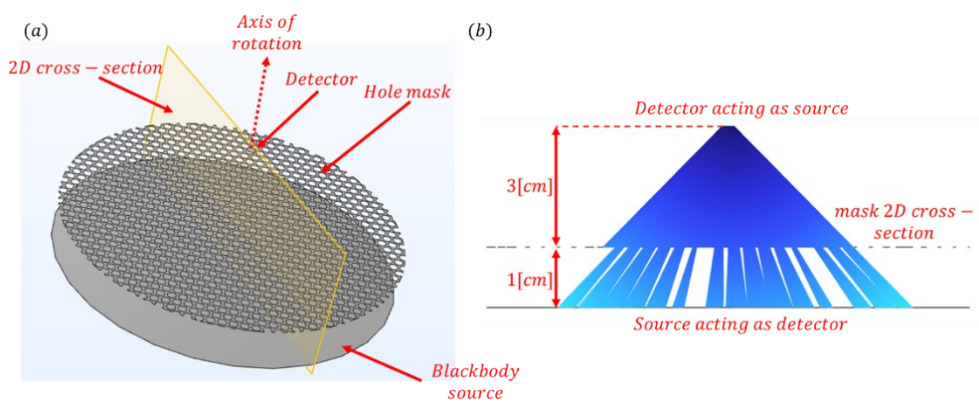

Fig. 9 (a) The complete 3D model of the simulation. a 2D cross-section is marked as a yellow place intersecting the detector, mask and source. (b) Example of a ray tracing simulation done on a single 2D cross-section.

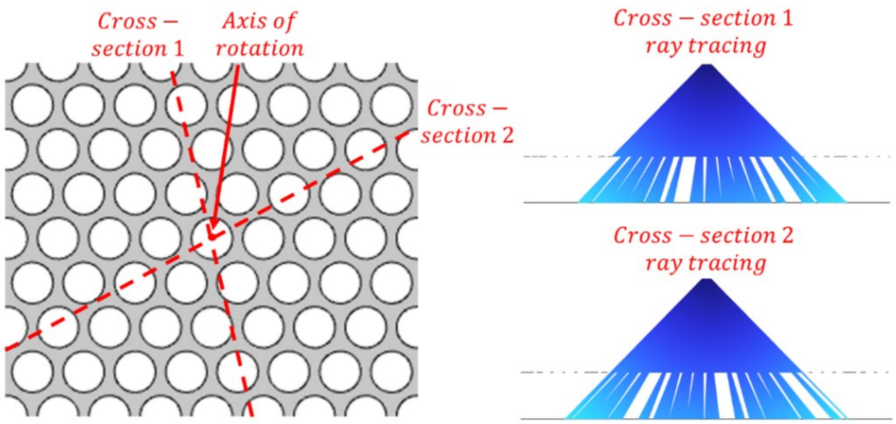

Fig. 10 Two cross-sections of the hole mask and their respective ray tracing simulations. The resulting ray tracing pattern is different due to the different mask cross-section for each axis.

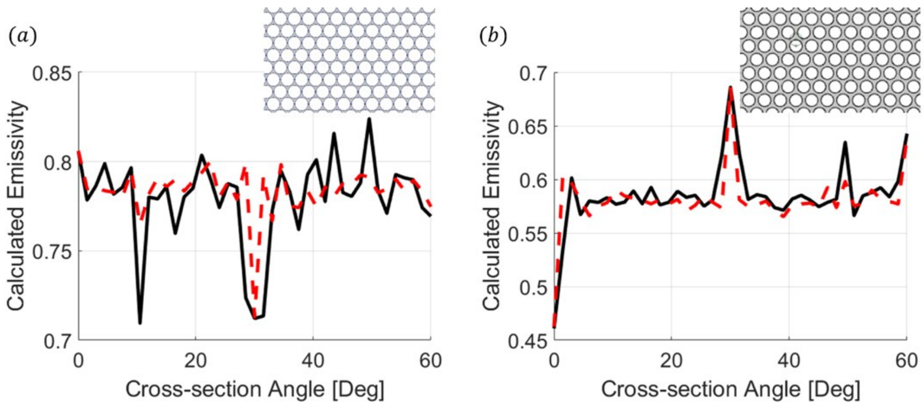

Fig. 11 Two cross-sections of the hole mask and their respective ray tracing simulations. The resulting ray tracing pattern is different due to the different mask cross-section for each axis

of the ray-tracing simulation. A more accurate simulation requires additional rays and is thus more time and resource consuming. The variance in emissivity is a result of the different mask 2D cross-sections at each angle. The variance is expected to decrease for a more refined mask with smaller holes and smaller spacings, resulting in a smoother intensity profile for the graybody source.

9 Summary and conclusions

Infrared (IR) radiometry is a very useful form of temperature measurement in industrial, scientific, and medical applications. The unique advantages of radiometry are quick response times and that is a remote sensing approach. Namely, it does not have to be in contact with the area being measured. The major drawback is that IR radiometer accuracy depends on calibration.

Calibration requires a well-calibrated blackbody as well as determination of the emissivity of the surface being measured. Emissivity is a physically well-defined parameter but in real experiments, it may be influenced by many factors: surface texture, spectral properties, oxidation, and aging of surfaces.

This work describes a methodology for how to calibrate radiometers in the lab or in the factory or FAB, using the "screen approach" and the novel thermal sensor dubbed Digital TMOS.

In summary, we cannot measure temperature correctly by remote sensing unless we take into consideration the emissivity.

The industry tends to ignore this fact since the emissivity of materials is unknown and hard to assess. We have invented and developed a grey body, which enables us to use it as a reference for emissivity to validate the TODOS remote temperature measurements.

The TODOS Digital TMOS with our algorithm measures the temperature of people's forehead temperature, regardless of the presence of varying layers of cosmetics or sun lotions. Commercial remote temperature systems cannot achieve that.

The interested markets should be manufacturers of mobile phones who want to integrate remote temperature applications; Health industry for Hospitals: not requiring patient collaboration, avoiding contamination, reducing nurses' workload, saving costs associated with biomedical thresh; Agriculture Industry for farm animals, pets, and more.

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