Thermal Emissivity Measurement with Two-temperature Method

Yunbin Ying1, Qiang Li1, Sandeep Kaur1 and Pintu Ghosh1*

1 State Key Laboratory of Modern Optical Instrumentation, College of Optical Science and Engineering, Zhejiang University, Hangzhou 310027, China
Email: ghosh@zju.edu.cn

Abstract. Thermal emissivity is one of the most important indices used to evaluate thermal emission capability of an object and is essential for characterization of thermal emitters, especially in the field of infrared thermal emission engineering for various applications, including personal thermal management, radiative cooling and heat preservation, infrared stealth, and infrared encryption. However, due to the natural background thermal emissions from the ambient environment and experimental setup, conventional methods generally ignore the background emissions while keeping the temperature of the radiating sample significantly higher than the ambient temperature. Here, we introduce a simple method that enables accurate measurement of emissivity of a given sample without necessitating high temperature through elimination of background emission noise by the difference of the measured emission signals of the sample at two different temperatures.

1. Introduction
Thermal emission is the electromagnetic field radiation emitted from all objects with temperature higher than absolute zero. Planck’s law states that the thermal emission from a standard blackbody depends mainly on its temperature [1]. In this regard, thermal emissivity measurement becomes important to evaluate the thermal emission capability of an object. The emissivity of a body is expressed as the ratio of the energy radiated by the body and the ideal blackbody at the same temperature. The emissivity of an ideal blackbody is equal to 1, and the emissivity of other objects lies between 0 and 1. Thermal emissivity measurement helps to accurately characterizing thermal emitters in the field of engineering infrared thermal emission for different applications, including personal thermal management [2], radiative cooling and heat preservation [3], infrared stealth [4], and infrared encryption [5].

In thermal equilibrium, the emissivity of sample is exactly equal to its absorptivity as described by the Kirchhoff’s law [6]. Therefore, we can obtain the emissivity indirectly by measuring the reflectivity and transmittance of the object. However, this method is not suitable for high scattering and absorptive samples [7]. On the other hand, direct thermal emission measurement can take care of these kinds of samples. Both these methods have their advantages and disadvantages, therefore often it requires to perform both indirect and direct measurements to maximize confidence in the measured results.

At present, the direct measurement of infrared radiation spectrum is mainly performed utilizing Fourier transform infrared spectrometer (FTIR). However, in the laboratory environment, it is challenging to measure the thermal emission of emitter accurately and precisely by direct measurement method mainly because the ambient environment and every component of measuring
instrument itself emit thermal radiation [8]. Therefore, when the temperature of the emitter is close to the ambient temperature, the environmental noises in the experiment process lead to a low signal-to-noise ratio [9].

In this work, we introduce a simple and accurate method to eliminate the background emission noise in thermal emission measurements and call it improvised two-temperature method. Compared with the conventional high-temperature method, we don't need high temperature equipment and also measure the emissivity of a sample that is not resistant to high temperature.

2. Methods

Figure 1 depicts the diagram of simplified experimental apparatus for measurement of thermal emission. The position of a thermal emitter placed on a heating stage is adjusted by a three dimensional mobile station. The thermal emission (red dotted arrows) of sample is collected and measured using FTIR (Bruker VERTEX 70), in which the thermal emission from the ambient environment (blue arrows) and components of the FTIR (green arrows) also enter the detector in FTIR. The thermal emissions from the three different sources mentioned above (red dotted arrows, blue arrows, and green arrows) can be recorded by a pyroelectric deuterated triglycine sulfate (DTGS) detector or a photoconductive mercury-cadmium-telluride (MCT) detector with higher sensitivity. Finally, the collected signals are fourier-transformed by the computer in order to obtain the total emission signals in the frequency domain. Therefore, the total measured emission signals, \( S_s(\lambda, T) \) from a sample can be expressed as [8]

\[
S_s(\lambda, T) = m(\lambda)\left[\varepsilon_s(\lambda, T)I_{\text{BB}}(\lambda, T) + B(\lambda, T)\right]
\]

(1)

where \( m(\lambda) \) is the system response function, \( \varepsilon_s(\lambda, T)I_{\text{BB}}(\lambda, T) \) is the emission signal of sample, \( \varepsilon_s(\lambda, T) \) is the spectral emissivity of the sample, \( B(\lambda, T) \) is the emission signal of the background caused by the environmental noise and instrument noise, and \( I_{\text{BB}}(\lambda, T) \) is the blackbody radiation distribution described by Planck’s law.

Figure 1. Diagram of simplified experimental apparatus for measurement of thermal emission.

When the temperature of sample is much higher than the ambient temperature (\( T \gg 300K \)), the background emission is negligible. Therefore, equation 1 can be well approximated by [8]
\[ S_\gamma(\lambda, T) = m(\lambda)\varepsilon(\lambda, T)I_{bb}(\lambda, T) \quad (2) \]

When the sample is in thermal equilibrium with a constant temperature, \( S_\gamma(\lambda, T) \) is proportional to the \( \varepsilon(\lambda, T) \). Therefore, \( \varepsilon(\lambda, T) \) can be obtained simply by measuring the emission signals from the sample and a known reference blackbody \( (\varepsilon_r \approx 1) \), and it can be expressed as \[ \varepsilon(\lambda, T) = \varepsilon_B \frac{S_\gamma(\lambda, T)}{S_b(\lambda, T)} \quad (3) \]

We denote equation 3 as method 1: conventional high-temperature method. Now we introduce a simple method 2 to eliminate the background emission noise in thermal emission measurements, and call it improvised two-temperature method. In this technique, we can measure thermal emissivity simply and accurately without the requirement of high temperature \( (T \geq 300K) \). Most thermal emitters have temperature-independent emissivity, therefore the background emission noise \( B(\lambda, T) \) can be eliminated by the difference of the measured emission signals of the sample at temperature \( T_1 \) and temperature \( T_2 \) and is given by \[ S_\gamma(\lambda, T_1)-S_\gamma(\lambda, T_2) = m(\lambda)\varepsilon(\lambda)\{I_{bb}(\lambda, T_1)-I_{bb}(\lambda, T_2)\} \quad (4) \]

Similar to the derivation of Equation 3, \( \varepsilon(\lambda, T) \) can be expressed as
\[ \varepsilon(\lambda) = \varepsilon_B \frac{S_\gamma(\lambda, T_1)-S_\gamma(\lambda, T_2)}{S_b(\lambda, T_1)-S_b(\lambda, T_2)} \quad (5) \]

3. Results and Discussion
In the experiment, we used single polished silica wafers \((15 \times 15 \times 0.5 \text{ mm}^3)\) as sample A and single polished sapphire wafers \((15 \times 15 \times 0.43 \text{ mm}^3)\) as sample B. A commercial vertically aligned carbon nanotube (CNT) with a constant emissivity \((\approx 0.97)\) was used as the reference blackbody \([10]\). The liquid-nitrogen-cooled photoconductive MCT detector was used for measuring the emission signals from the sample at various temperatures.

Firstly, according to the Fresnel formula and Kirchhoff’s law, we can get the theoretically calculated emissivity of the silica (blue dashed line shown in figure 2). Thereafter, according to the method 1, we get the measured emissivity of the silica at different temperatures (solid lines in figure 2). With the increase of temperature, we can find that the measured emissivity is closer to the theoretically calculated emissivity. It is because of the effect of background emission which becomes negligible when the temperature of sample is significantly higher than the ambient temperature. The slight error of experiment and theory is due to the change of dielectric constant of the sample at the ultrahigh temperature.

In order to validate the improvised two-temperature method (method 2), we used the measured emission signals at 50°C and 75°C to get the measured emissivity of the silica (red dashed line in figure 2). We can find that the measured emissivity of the silica is consistent with the theoretically calculated emissivity. Therefore, we can use method 2 to measure thermal emissivity simply and accurately without requiring high temperature, and the result is more accurate compared to the result obtained following the conventional method 1.
Figure 2. Experimental thermal emissivity of a silica sample using the Method 1 at different temperatures (solid lines), calculated emissivity corresponding to the silica using Fresnel formula and Kirchhoff’s law (blue dashed line), and measured emissivity of the silica using the Method 2 at 50°C and 75°C (red dashed line).

The Comparison of the improvised two-temperature method of thermal emissivity measurement using different thermal radiation detectors are shown in figure 3. Figure 3(a) shows the experimental thermal emissivity of the silica (red line) and sapphire (pink line) using MCT detector. We can find that the experimental thermal emissivity of the silica and sapphire is consistent with the theoretically calculated emissivity. Figure 3(b) shows the experimental thermal emissivity of the silica (red line) and sapphire (pink line) using DTGS detector. Through comparison of the experimental thermal emissivity with Method 2 using different thermal radiation detectors, we can find that MCT detector is more suitable for using Method 2 to measure thermal emissivity simply and accurately without requiring high temperature. Compared with the pyroelectric DTGS detector, the photoconductive MCT detector has better accuracy, sensitivity and response speed.

Figure 3. Comparison of the improvised two-temperature method of thermal emissivity measurement using different thermal radiation detectors. (a) Experimental thermal emissivity of the silica (red line) and sapphire (pink line) using MCT detector. (b) Experimental emissivity of the silica (red line) and sapphire (pink line) using DTGS detector. Calculated thermal emissivity of the silica and sapphire using Fresnel formula and Kirchhoff’s law (blue and black dashed lines).

4. Conclusion
In summary, we have demonstrated an improvised two-temperature method for thermal emissivity
measurement without necessitating high temperature. In this method, the background emission noises are eliminated by the difference of the measured emission signals of the same sample at two different temperatures. In the experiments, we used the single polished silica wafers and single polished sapphire wafers as the experimental test samples. Compared with the conventional high-temperature method, we find that the results obtained from the improvised two-temperature method is more accurate, and the latter doesn't need high temperature. Through comparison of the improvised two-temperature method using different thermal radiation detectors, we find that MCT detector is more suitable compared to the DTGS detector for using this method to measure thermal emissivity in a simpler manner but accurately without requiring high temperature.

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