Planck Spectroscopy
Yuzhe Xiao¹, Chenghao Wan¹,², Jad Salman¹, Ian J. Maywar¹, Jonathan L. King¹, Alireza Shahsafi¹, and Mikhail A. Kats¹,²,³,*
¹Department of Electrical and Computer Engineering, University of Wisconsin-Madison, Madison, Wisconsin 53706, USA
²Materials Science and Engineering, University of Wisconsin-Madison, Madison, Wisconsin 53706, USA
³Department of Physics, University of Wisconsin-Madison, Madison, Wisconsin, USA 53706
*Email address: mkat@wisc.edu

We developed and experimentally demonstrated a minimalistic spectroscopic technique that does not require wavelength-selective components such as prisms, gratings, or interferometers—instead using the temperature and wavelength dependence of Planck’s law of thermal emission. © 2021 The Author(s)

All existing spectrometers use wavelength-selective optical components to enable spectral measurements. Depending on the operating mechanisms, typical spectrometers can be classified into the following types: (i) spectrometers that use a dispersive component, such as diffraction grating [1], or a prism [2] to spatially segregate light at different wavelengths; (ii) spectrometers that obtain the spectrum by measuring the temporal coherence of light via reconfigurable interferometers, such as Fourier-transform spectrometers (FTS) [3]; and (iii) spectrometers that reconstruct the spectrum through the use of multiple filters [4]–[6], or multiple detectors [7].

In this work, we developed a new infrared spectroscopy technique—Planck spectroscopy—which can be configured to measure spectral emissivity, reflectance, or transmittance. To our knowledge, Planck spectroscopy requires fewer optical components than any other spectrometer: it uses only a temperature stage and a detector, without any wavelength-selective optical components. We experimentally demonstrated Planck spectroscopy for the wavelength region from 3 to 13 μm, with a resolution of approximately 1 μm.

Planck spectroscopy is illustrated in Fig. 1 (a). When a sample is at a temperature T, the total emission power is

\[ P(T) = \int \epsilon(\lambda) I_{BB}(\lambda, T) d\lambda , \]  \hspace{1cm} (1)

where \( \epsilon(\lambda) \) is the sample emissivity and \( I_{BB}(\lambda, T) \) is given by Planck’s law. Due to the temperature and wavelength dependence of \( I_{BB}(\lambda, T) \) (Fig. 1c), the emissivity spectrum, \( \epsilon(\lambda) \), is encoded in the temperature-dependent total emission power, \( P(T) \). For example, an object with a constant emissivity (\( \epsilon_2 \), Fig. 1b) has \( P(T) \) proportional to \( T^4 \) (\( P_2 \), Fig. 1d), which is Stefan-Boltzmann law. Meanwhile, for objects with wavelength-dependent emissivity (\( \epsilon_1 \) and \( \epsilon_3 \), Fig. 1b), \( P(T) \) deviates from the Stefan-Boltzmann law, with a shape determined by \( \epsilon(\lambda) \) (\( P_1 \) and \( P_3 \), Fig. 1d).

Considering a set of sample temperatures \([T_1, T_2, \ldots, T_N]\) and discretized wavelengths, Eq. 1 can be rewritten as:

\[ \left[ \begin{array}{c} P(T_1) \\ \vdots \\ P(T_N) \end{array} \right] = \left[ \begin{array}{cccc} I_{BB}(\lambda_1, T_1) & \ldots & I_{BB}(\lambda_N, T_1) \\ \vdots & \ddots & \vdots \\ I_{BB}(\lambda_1, T_N) & \ldots & I_{BB}(\lambda_N, T_N) \end{array} \right] \left[ \begin{array}{c} \epsilon(\lambda_1) \\ \vdots \\ \epsilon(\lambda_N) \end{array} \right] \Delta \lambda \]  \hspace{1cm} (2)

Therefore, the \( N \) unknown spectral emissivity values, \( \epsilon(\lambda_i) \), can be extracted from the measured power, \( P(T_i) \), at \( N \) temperatures by solving a constrained linear least-squares problem.

We demonstrated Planck spectroscopy using the experimental setup in Fig. 2a. Sample temperature was controlled using a temperature stage and the thermal-emission power was focused into a broadband electrically cooled infrared
A laboratory blackbody reference was used to calibrate the response function of our setup, which includes the detector responsivity and the collection efficiency of the optical path. The calibrated response (Fig. 2c) shows very good agreement with the expected value, which is the product of the detector response from the vendor and the transmittance of the lens and the heater window. Using the calibrated response, we extracted the spectral emissivity of our samples from the measured voltages (circles in Fig. 2d-g). To confirm these results, we also measured the sample emissivity separately using an FTS (solid curves in Fig. 2d-g) [9], demonstrating excellent agreement.

The accuracy of Planck spectroscopy depends on the accuracy and precision of the power measurements. In our experiment, we achieved an average mean-squared error (MSE) in the extracted emissivity of about 0.007 from power measurements precision close to 0.1 % in Fig. 2b. We estimate that the expected MSE can be reduced to 0.004 with an improved power measurement precision of 0.01 %. The accuracy also depends on the range of temperatures where these measurements are performed. For a given power measurement precision, a larger range of measurement temperatures will lead to a bigger contrast in the shape of $I_{\text{p}}(\lambda, T)$, which will improve the accuracy. We experimentally achieved an approximate resolution of 1 $\mu$m in Fig. 2d-g. Through numerical simulations with realistic experimental conditions, we found that Planck spectroscopy can capture an isolated peak or dip of about 0.4 $\mu$m in spectral width and resolve a two-peak feature if the peaks are more than 2 $\mu$m apart. Both the accuracy and the spectral resolution depends on the extraction algorithm, and better performance can be expected using more sophisticated algorithms and additional constraints to the solution.

In summary, we demonstrated a new infrared spectroscopic technique, Planck spectroscopy, based on Planck’s law of thermal emission. Planck spectroscopy does not need any optical wavelength selective components and requires fewer optical components than any existing spectrometer. We envision implementations of Planck spectroscopy using infrared cameras to enable low-cost infrared hyperspectral imaging and imaging ellipsometry. We acknowledge support from the Office of Naval Research (N00014-20-1-2297).

Reference

[1] R. Cheng, et al., “Broadband on-chip single-photon spectrometer,” Nat. Commun., vol. 10, no. 1, pp. 1–7 (2019)
[2] J. R. Nielsen, et al., “An infra-red prism spectrometer of high resolving power,” J. Opt. Soc. Am., vol. 37, no. 4, pp. 296–301 (1947)
[3] P. R. Griffiths and J. A. De Haseth, Fourier Transform Infrared Spectrometry: Second Edition. Wiley (2006)
[4] E. D. Nelson and M. L. Fredman, “Hadamard Spectroscopy,” J. Opt. Soc. Am., vol. 60, no. 12, p. 1664 (1970)
[5] J. Bao and M. G. Bawendi, “A colloidal quantum dot spectrometer,” Nature, vol. 523, no. 7558, pp. 67–70 (2015)
[6] Z. Wang et al., “Single-shot on-chip spectral sensors based on photonic crystal slabs,” Nat. Commun., vol. 10, no. 1, pp. 1–6 (2019)
[7] Z. Yang et al., “Single-nanowire spectrometers,” Science, vol. 365, no. 6457, pp. 1017–1020 (2019)
[8] K. Mizuno et al., “A black body absorber from vertically aligned single-walled carbon nanotubes,” Proc. Natl. Acad. Sci. U. S. A., vol. 106, no. 15, pp. 6044–7 (2009)
[9] Y. Xiao, et al., “Precision Measurements of Temperature-Dependent and Nonequilibrium Thermal Emitters”. Laser Photon. Rev. 14, 1900443 (2020).