Measurement of near-field radiation intensity above a tungsten emitter using a fibrous optical microscope

Katsunori HANAMURA*, Daisuke HIRASHIMA** and Kota FUJII**

*Department of Mechanical Engineering, Tokyo Institute of Technology
2-12-1 Ookayama, Meguro-ku, Tokyo 152-8550, Japan
E-mail: hanamura@mech.titech.ac.jp

**Department of Mechanical and Control Engineering, Tokyo Institute of Technology
2-12-1 Ookayama, Meguro-ku, Tokyo 152-8550, Japan

Received 23 June 2016

Abstract
Near-field radiation intensity above a tungsten emitter surface was measured using a silica-glass fibrous optical microscope with chromium coating and emitter temperature of 950 K. The aperture size of the glass fibrous probe was 550 nm. The signal was detected using a photo-multiplier with an active wavelength range of 950 to 1700 nm and was amplified using a lock-in amplification system corresponding to the sinusoidal movement of the emitter surface with an average amplitude of 2.6 μm from the outside to the inside of near-field effect regions. Consequently, it was clearly seen that the detected intensity increased monotonically as the gap between the probe tip and the emitter surface decreased. The tendency for the intensity to increase was in agreement with that of the near-field radiation flux between two semi-infinite planes obtained through calculations using a framework of fluctuation electrodynamics.

Key words: Near-field radiation, Measurement, Fibrous optical microscope, Tungsten emitter

1. Introduction

Near-field radiation transfer is very attractive for a high density energy conversion system because the energy flux is much higher than that of far-field radiation, i.e., the propagating wave component. The radiation transfer enhancement by near-field effect was detected using some configuration systems as follows. The impact of temperature on the near-field radiation transfer was demonstrated using two quartz glass plates with a gap of 1.0 μm (Hu et al., 2008). The near-field radiation transfer increased with decreasing gap between two parallel sapphire plates (Ottens et al., 2011) at approximately room temperature. The measured heat fluxes were close to those obtained from theory (Francoeur et al., 2011) though there were some discrepancies. In the case of the parallel configuration, it is not easy to align two plates with a uniform small gap. In contrast, a configuration using a spherical probe tip and a plate is useful in keeping a nano-scaled gap (Kittel et al., 2005). In this case, the gap between the plate and tip was measured using a tunneling current, where the electromagnetic local density of states from the tip to the plate was measured using a thermoelectric potential consisting of platinum and iridium. The results agreed well with those obtained by theory with a gap of greater than several tens of nanometers. Furthermore, a rigorous measurement of near-field radiation transfer was performed using a probe of an atomic force microscope (AFM) for the case of the quartz glass plate heated by an electric current (Shen et al., 2009, Kittel, 2009, Rousseau et al., 2009, Hoorn et al., 2014). In this case, using a probe supported by a bimetal-cantilever, the radiation transfer was measured through deflection of the probe when its temperature increased, while the gap was measured as the distance from the location of contact between the probe tip and plate. In addition, the evanescent wave field was detected using a tungsten AFM probe with a Cassegrain optical system and heated silicon carbide plate having a thin gold stripe (DeWilde et al., 2006). Through this experiment, it was found that the surface plasmon polaritons developed along the width of the gold stripe produced a Fabry-Perot resonance.

In addition, for energy conversion from thermal energy to electricity through the near-field radiation transfer, the
The evanescent component was measured using an indium antimonide semiconductor and a silicon emitter (DiMatteo et al., 2002) as a TPV electricity generator. The authors also developed an energy conversion system from thermal radiation to electricity through near-field radiation transfer using a parallel nanometer-sized gap between the surfaces of a high temperature tungsten emitter and TPV cell made of gallium antimonide (Hanamura et al., 2011 and Ashida et al., 2013). The output power was successfully increased with decreasing gap and the maximum power was four times higher than that of the propagating wave component. In this case, the large amount of heat loss was a concern because radiation with a wavelength longer than 1.8 μm could not be converted into electricity since the active wavelength range for conversion by the gallium antimonide cell was limited within 0.6-1.8 μm. As a result, spectral control was required even in the case of near-field radiation transfer to increase the radiation flux for the active range or to decrease the longer wavelength component. Recently, the authors proposed pillar array structured surfaces setup with parallel alignment as a new spectral control method for the near-field radiation transfer (Hanamura et al., 2013). In addition, the spectral control for far-field radiation, i.e., propagating wave component, was also achieved by the surface plasmon on the periodical surface structure (Hirashima et al., 2011). In order to clarify the mechanism of spectral control, the distribution of electromagnetic field intensity should be confirmed through experiment using a scanning near-field optical microscope. In the current study, a near-field optical microscope was developed for the purpose of measuring the intensity distribution above a structured surface at approximately 1000 K. Here, we have attempted to measure the intensity of the near-field radiation above the smooth surface made of tungsten using a silica-glass fibrous optical probe.

2. Experimental setup and procedure

Figure 1 shows a schematic diagram of an experimental setup of the near-field radiation measurement. A thin (1 mm) tungsten disk was prepared for this experiment. The surface was smoothed by an electrolytic polishing process; as a result, the roughness is less than a few nanometers. In the current study, only the smooth surface was used. In the case of a periodic nanometer sized-structured surface, a pillar array structure was made on the smooth surface using electron beam lithography to produce a grid pattern on the resist and reactive ion etching was used to create the pillars. The disk was put on a heat reservoir block made of stainless steel. The reservoir block played an important role in suppressing temperature fluctuations. The heat reservoir block was heated by a ceramic heater from the bottom surface. The heat reservoir block was covered by a water-cooled jacket. Their surfaces were mirror polished to reduce heat loss by radiation transfer. Those heat reservoir block and water-cooled jacket were mounted on the piezo-actuator system to make a nanometer sized gap. In the case of the pillar array structured surface, its topological image can be made by shear force control. A silica-glass fibrous probe was set up on a holder that was mounted on another piezo-actuator system. The probe was vibrated laterally to create a shear force between the emitter surface and probe tip in the case of the pillar array structured surface. In order to avoid a temperature increase of the holder, a radiation shield with a
A mirrored surface was inserted between the holder and the heated surface as shown in Fig. 1(b). The whole system was installed in a vacuum chamber, whose pressure was fixed at about 0.1 Pa. As a result, the energy transfer was caused mainly by radiation even in the case of propagating radiation dominant, while the contribution of conduction heat transfer was only 1% of the total energy transfer from the tungsten disk emitter to the probe tip.

Figure 2(a) shows a scanning electron microscope (SEM) image of the fibrous probe and a schematic of detection of intensity of near-field radiation in the vicinity of tungsten emitter surface. The silica-glass fibrous probe was coated with a thin layer of chromium. The diameter of the aperture at the probe tip was about 550 nm. Due to the diffraction limit, only the near-field component can pass through the aperture, and be converted to a scattering ray, i.e., a propagating wave traveling through the core glass. The propagating wave intensity was measured using a photo-multiplier with an active wavelength of 950 to 1700 nm. The temperature of the tungsten emitter was 950 K and was measured using a thermocouple welded on its surface.

Figure 2(b) shows the principle of near-field radiation intensity detection using a lock-in amplification method. The probe was fixed while the tungsten emitter moved upward and downward with a sinusoidal oscillation. The amplitude, $d$, was 2.6 μm and the frequency, $\omega_e$, was 2.7 Hz. When the average gap between the probe tip and the emitter surface was much greater than the distance of the near-field effect, there is no signal detected by the photo-multiplier as shown in Fig. 1(b)(left). When the probe tip periodically enters the region in which the near-field effect is dominant, a periodic signal is detected with frequency, $\omega_r$, that is the same as emitter oscillation frequency, as shown in Fig. 1(b)(right). If an optical signal, $A \sin \omega_e t$, is obtained, the product with $2 \sin \omega_r t$ is described as follows.

$$A \sin \omega_e t \times 2 \sin \omega_r t = A \left[ \cos (\omega_e - \omega_r) t + \cos (\omega_e + \omega_r) t \right]$$

(1)

By using a low band pass filter, the alternative component, i.e., the second term on the right hand side is eliminated. As a result, since $\omega_e = \omega_r$, the periodic signal has the maximum value, $A$, which is the signal detected at the location of the smallest gap during a one cycle of periodic movement.

The tungsten emitter was moved using a piezo-actuator with a stroke of 15 μm, a spatial resolution of 2 nm and a precise repeatability within ±2 nm. The frequency and amplitude of the sinusoidal oscillation of the tungsten emitter were controlled by a function generator. The displacement of the center of oscillation was controlled manually by changing the off-set voltage of the function generator; as a result, the minimum displacement was several hundred nanometers. In order to obtain a high-resolution displacement, an adder circuit was installed between the function generator and a piezo-actuator driver; as a result, the minimum displacement was reduced by 20 nm. In the current study, only the smooth tungsten surface was used for measurement.

At the beginning of the experiment, after the emitter temperature reached 950 K, the emitter was moved using a
stepping motor. Using a CCD camera, the probe rod and heated emitter surface were monitored as shown in Fig.3. Through observation of both the probe rod and its reflected image, the probe tip could approach the emitter to within 10 μm. The gap of 10 μm is a resolution limit of the CCD camera. Subsequently, the emitter was moved using the piezo-actuator. When the phase shift which is related to the difference between \( \omega_L \) and \( \omega_r \) reached 15 degrees, the measured voltage was regarded as an intensity signal with a lock-in condition.

3. Results and discussion

Figure 4 shows the intensity of the signal detected by the near-infrared photo-multiplier and the periodic movement of the heated smooth surface with \( d \) and \( \omega_L \). The horizontal axis shows the elapsed time from the beginning of measurement. The vertical axis on the left hand side shows the voltage of the photo-multiplier in proportion to the detected intensity. The vertical axis on the right hand side shows the distance between the oscillation center and an arbitrary origin. The gap between the probe tip and emitter surface could not be directly measured in the experiment, therefore the dash-dotted horizontal lines in each interval of the time show the distance from the arbitrary origin. During an elapsed time of about 7 s from the beginning of the measurement, the voltage for the signal intensity did not change even when the emitter surface (the center of oscillation) moved 1 μm toward the probe tip from the arbitrary origin. When the emitter surface moved an additional 500 nm, the first increase in signal intensity was detected. Subsequently, the signal intensity increased monotonically as the emitter surface moved toward the probe tip step by step. As a result, the signal intensity was observed to increase by a factor of four as the location of oscillation center moved 2.5 μm toward the probe tip.

Fig.4 Signal intensity corresponding to the periodic movement of the emitter surface with an amplitude, \( d \), of 2.6 μm and frequency of 2.7 Hz and displacement of center of oscillation from an arbitrary origin toward the probe tip.
Figure 5 shows change in signal intensity with respect to the displacement of emitter surface from an arbitrary origin with respect to the probe tip. The blue circles show the increase in signal intensity for the case of approaching the probe tip, while the red triangles show the decrease in signal intensity for the case of receding from the probe tip.

Figure 5 shows change in signal intensity with respect to the displacement of emitter surface from an arbitrary origin. The blue circles show the case when the emitter surface approaches the probe tip, while the red triangles show the case when the emitter surface is receding. It is clearly seen that the signal intensity increases monotonically as the emitter surface approaches the probe tip. Moreover, the results obtained from both cases of approaching and receding of the emitter surface were approximately on the same line (dotted line with an exponential function). This shows that there is a high reproducibility between the increase in signal intensity and displacement of the emitter surface with a high spatial resolution and a high precision repeatability of the piezo-actuator.

Figure 6 shows the tendency of the radiation flux to increase with decreasing distance between the probe tip and emitter surface for a wavelength band of 950 to 1700 nm corresponding to the active range of the infrared photo-multiplier with an emitter temperature of 950 K. The solid lines show the result calculated using fluctuation electro-dynamics theory (Francoeur et al., 2008), where the blue, red and green lines show the propagating component, near-field component and total radiation flux, respectively. In addition, the purple diamond and blue square symbols show the experimental results obtained using low- and high-resolution controls for the piezo-actuator, respectively. In the analytical calculation, it was assumed that two semi-infinite smooth plates made of chromium (probe coating material) and tungsten (emitter material) were fixed facing toward each other, as described in Appendix A. In the case of a long distance between two surfaces, the radiation flux was kept at constant since the radiation was transferred by a

![Figure 5](image1.jpg)  
**Figure 5** Signal intensity of signal with respect to displacement of emitter surface (center of oscillation) from an arbitrary origin with respect to the probe tip. The blue circles show the increase in signal intensity for the case of approaching the probe tip, while the red triangles show the decrease in signal intensity for the case of receding from the probe tip.

![Figure 6](image2.jpg)  
**Figure 6** The tendency of increase in net near-field radiation flux with decreasing distance between the probe tip and emitter surfaces. The experimental results were well fitted with theoretical near-field radiation flux.
far-field radiation with a view factor of almost unity. The near-field component is negligibly small. As the distance
decreases, the radiation flux fluctuated due to the interference of radiation with the width of the gap. When the distance
is smaller than 600 nm, the near-field radiation becomes the main component of the total radiation flux. As mentioned
above, we were unable to measure the gap between the probe tip and emitter surfaces; as a result, only an increase in
signal intensity corresponding to probe displacement could be obtained in the present experiment. Consequently, the
signal intensity increased by a factor of four as the probe moved 2.5 \( \mu m \), while it increased by a factor of seven as the
probe moved 100 nm. The signal intensity increase corresponding to the displacement of the probe tip could be fitted
along the red line of the near-field radiation component. Since the aperture size of the probe was set to approximately
550 nm as shown in Fig.2(a), most of signal intensity came from the near-field radiation component introduced into the
fibrous optical microscope. Although there is no method to measure the near-field radiation flux directly, the measured
signal intensity may be proportional to the near-field radiation intensity, even if the electromagnetic field is changed by
the probe.

4. Conclusion

The near-field radiation intensity distribution was measured using a silica-glass fibrous optical probe for an emitter
temperature of 950 K. The increase ratio of signal intensity detected by an infrared photo-multiplier to the displacement
of the probe was in agreement with the increase ratio estimated using fluctuation electrodynamics theory. The
near-field radiation flux increased by a factor of about seven as the gap between the probe tip and emitter surface
decreased from 160 to 60 nm, while it increased by a factor of about four as from 2900 to 400 nm approximately as
estimated through fluctuation electrodynamics. The measured signal intensity may be linearly proportional to the
near-field radiation intensity.

Appendix A

Radiation fluxes for propagating, \( q^\eta_{\text{prop}}(\omega) \) and evanescent, \( q^\eta_{\text{evan}}(\omega) \) components are expressed as follows (Francoeur et al., 2008).

\[
q^\eta_{\text{prop}}(\omega) = \int_{\omega_1}^{\omega_2} \left[ I_B(\omega,T_1) - I_B(\omega,T_2) \right] d\omega \cdot \int_{\omega_1}^{\omega_2} \frac{(1 - |r^\eta_{\text{vac}}|^2)(1 - |r^\eta_{\text{air}}|^2)KdK}{(\omega c)^2 \left[ 1 - |r^\eta_{\text{vac}}|^2 \exp[i2\gamma_{\eta}z_o]|^2 \right]} \tag{A1}
\]

\[
q^\eta_{\text{evan}}(\omega) = \int_{\omega_1}^{\omega_2} \left[ I_B(\omega,T_1) - I_B(\omega,T_2) \right] d\omega \cdot \int_{\omega_1}^{\omega_2} \frac{\text{Im}[r^\eta_{\text{vac}}] \text{Im}[r^\eta_{\text{air}}] \exp[-2\gamma_{\eta}z_o]}{(\omega c)^2 \left[ 1 - |r^\eta_{\text{vac}}|^2 \exp[-2\gamma_{\eta}z_o]|^2 \right]} \tag{A2}
\]

In the integral domains in expressions (A1) and (A2), \( \omega_1 \) and \( \omega_2 \) are angular frequencies which were equivalent to
the limits of the wavelength for the detector, i.e., 950 and 1700 nm, respectively. Here, \( \omega , \ K , \ I_B , \ c_o \) and \( z_o \) are
the angular frequency, wave number in the horizontal direction, black body radiation intensity, speed of light in vacuum
and distance between two smooth surfaces. In addition, the superscript \( \eta \) denotes an \( s \) or \( p \) polarized wave. The
subscripts \( o, 1, \) and \( 2 \) denote the vacuum area between two surfaces, emitter with a high temperature \( T_1 \) and receiver
with a low temperature \( T_2 \). The wave number in the vertical direction is shown as a complex number including
evanescent wave component as follows.

\[
\gamma = \gamma' + i\gamma'' \tag{A3}
\]

Moreover, \( r^\eta_{ij} \) denotes the following expressions for surfaces between emitter and vacuum and between vacuum and
receiver for an \( s \) or \( p \) polarized wave.

\[
r^\eta_{ij} = \frac{\gamma_i - \gamma_j}{\gamma_i + \gamma_j} \tag{A4}
\]
\[ r^p = \frac{\varepsilon_j \gamma_i - \varepsilon_i \gamma_j}{\varepsilon_j \gamma_i + \varepsilon_i \gamma_j} \]  

(A5)

Acknowledgements

The authors would like to express our gratitude to the financial support by the Grant-in-Aid for Scientific Research (A) 24246037 of Ministry of Education, Culture, Sports, Science and Technology, Japan.

References

Ashida, Y., Yoshida, J. and Hanamura, K., “Thermophotovoltaic Generation of Electricity through Evanescent Wave Effect Using GaSb Cells”, Trans. of JSME, Vol.79, No. 799 (2013), pp.229–233, (in Japanese).

DeWilde, Y., Formanek, F., Carminati, R., Gralak, B., Lemoine, P.-A., Joulin, K., Mulet, J.-P., Chen, Y. and Greffet, J.J., “Thermal radiation scanning tunnelling microscopy”, Nature, Vol. 444 (2006), pp. 740-743.

DiMatteo, R. S., Greiff, P. and Finberg, L. L., “Micron-gap ThermoPhotVoltaics (MTPV)”, Thermophotovoltaic Generation of Electricity, 5th Conference, (2002), pp. 232-240.

Francoeur, M. and Megnüç P., “Role of Fluctuational Electrodynamics in Near-Field Radiative Heat Transfer”, J. of Quantitative Spectroscopy and Radiative Transfer, 109, (2008), pp.280-293.

Francoeur, M., Vaillon, R. and Megnüç P., “Thermal Impacts on the Performance of Nanoscale-Gap Thermophotovoltaic Power Generators”, IEEE Transactions on Energy Conversion, Vol. 26, No. 2 (2011), pp. 686-698.

Hanamura, K., Fukai, H., and Srinivasan, E., “Photovoltaic Generation of Electricity Using Near-Field Radiation”, ASME/JSME 2011 8th Therm. Engng. Joint Conf., No.AJTEC2011-44513, (2011), pp.1-5.

Hanamura, K. and Hirashima D., “Spectral Control of Near-Field Radiation through Surface Plasmon Polariton Interference”, Proc. of the ASME 2013 Heat Trans. Summer Conf., ASME, HT2013, (2013), 17601.

Hirashima, D. and Hanamura, K., “Simulation for Thermal Radiation Emitted from Functional Surface”, Trans. of JSME, Vol. 77, No. 782, (2011), pp.1978–1983, (in Japanese).

Hoorn, C. H., Chavan, D. C., Tiribilli, B., Margheri, G., Mank, A. J. G., Ariese, F. and Iannuzzi, D., “Opto-mechanical probe for combining atomic force microscopy and optical near-field surface analysis”, Opt. Lett. 39 (2014), pp. 4800-4803.

Hu, L., Narayanaswamy, A., Chen, X., and Chen G., “Near-field thermal radiation between two closely spaced glass plates exceeding Planck’s blackbody radiation law”, Applied Physics Letters, Vol. 92, (2008), pp. 133106.

Kittel, A., Müller-Hirsch, W., Parisi, J., Bihs, S.-A., Reddig, D. and Holthaus, M., “Near-Field Heat Transfer in a Scanning Thermal Microscope”, Physical Review Letters, Vol. 95, (2005), pp. 224301.

Kittel, A., “Probing near-field thermal radiation”, Nature Photonics, Vol. 3, (2009), pp.492-494.

Ottens, R.S., Quetschke, V., Wise, S., Alemi, A.A., Lundock, R., Mueller, G., Reitze, D.H., Tanner, D.B. and Whiting, B.F., “Near-field radiative heat transfer between macroscopic planar surfaces”, Physical Review Letters, Vol. 107, (2011), pp.014301.

Rousseau, E., Siria, A., Jourdan, G., Volz, S., Comin F., Chevrier, J. and Greffet, J.J., “Radiative heat transfer at the nanoscale”, Nature Photonics, Vol.3, (2009), pp. 514-517.

Shen, S., Narayanaswamy, A. and Chen G., “Surface Phonon Polaritons Mediated Energy Transfer between Nanoscale Gaps”, Nano Letters, Vol. 9, No. 8, (2009), pp. 2909-2913.