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Abstract

Determination of the in-plane thermal diffusivity of thin film based on the periodic regime local heating†

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Introduction

The in-plane thermal diffusivity of soft materials is critical information for the development of functional thermal materials in nano/microscale integrated devices. Laser induced localized periodic heating and imaging of spatially distributed periodic temperature responses are key techniques for determining in-plane thermophysical properties [1]. However, this method is significantly influenced by the three-dimensional geometry of the sample and the surface conditions (such as vacuum conditions). To avoid these multidimensional effects in thermal analysis, it is necessary to increase the frequency range of periodic heating as much as possible. This is typically limited by the frame rate of the imaging system.

In this study, we performed thermal imaging and analysis of periodic heating responses on the sample surface at frequencies far exceeding the frame rate of the imaging system. (Figure 1). The in-plane thermal diffusivity of thin polymer film was investigated by analyzing the in-plane periodic temperature response induced by a focused near infrared laser (λ = 830 nm) in a broad frequency range exceeding the frame rate of an InSb infrared camera (sensitivity range 3 μm – 5 μm).

Theory

The periodic temperature response at a single point on a sufficiently thin sample is described as follows.

$$T = T_0 \sin\{\omega_1 t + \Delta\theta(\omega_1)\} \quad (1)$$

Here, T_0 is the amplitude of temperature modulation, ω_1 is the angular frequency of the temperature modulation, and $\Delta\theta(\omega_1)$ is the phase delay due to in-plane thermal diffusion. Under the approximation of a thermally thick medium, the phase delay can be described as follows.

$$\Delta\theta(\omega_1) = -\sqrt{\frac{\omega_1}{2\alpha}}d + \beta \quad (2)$$

The amplitude of the temperature modulation is typically sufficiently small to approximate the linear relationship between the signal intensity of infrared camera and temperature. The signal intensity of the temperature modulation measured in the m^{th} image at the camera frame rate of f_2 can be described as follows.

(3)

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$$I_m = I_0 \sin\left\{2\pi \frac{f_1}{f_2} m + \Delta\theta(\omega_1)\right\}$$

$$= I_0 \sin\left\{2\pi \Delta f \frac{m}{f_2} + \Delta\theta(\omega_1)\right\}$$

Here, m is the number of frames (integer), f_1 and f_2 represent the temperature modulation frequency and the image acquisition (frame rate) frequency, respectively, and Δf is the difference frequency ($\Delta f = f_1 - nf_2$), where n is the integer.

During the experiment, the frame rate of the infrared camera was fixed at $f_2 = 80$ Hz, and the difference frequencies of the acquired image series were also fixed $\Delta f = 1$ Hz by keeping relation of $\Delta f = f_1 - nf_2$ and analyzed by Fourier transform analysis.

Experimental

The schematic diagram of the focused laser coupled thermal imaging system is depicted in Figure 1. The diode laser is mounted at diagonal angle to irradiate sample from the side of infrared camera (FLIR, SC6000HS-MID-TH) with microscope objective. The spot size of the laser is approximately 1 μm, which is sufficiently smaller than the pixel size of the thermal imaging (4 μm). Therefore, in this study, it is reasonable to assume a single-pixel heating spot for data analysis, and it is also acceptable to ignore the minute extension of the heating spot along the tilt direction of the laser irradiation.

The sample (polymer thin film) was mounted on the hot stage with slide-in mechanics to the chamber. Main body of the chamber was cooled with the water and the temperature of hot stage as controlled by using the thermocouple reading placed nearby sample position. The diode laser was driven by the function generator (NF, Wave Factory 1942), and the heating frequency was controlled between 0.1 Hz – 1 kHz.

The spatiotemporal temperature response to periodic laser heating on the sample surface was analyzed by Fourier transforming the time dependence of the temperature distribution. The in-plane thermal diffusivity of the sample was analyzed by approximated solution of the periodic regime heating as shown in eq. (2), which is applicable for the temperature response at sufficiently far from the heating position with sufficiently high frequency of the heating.[2]

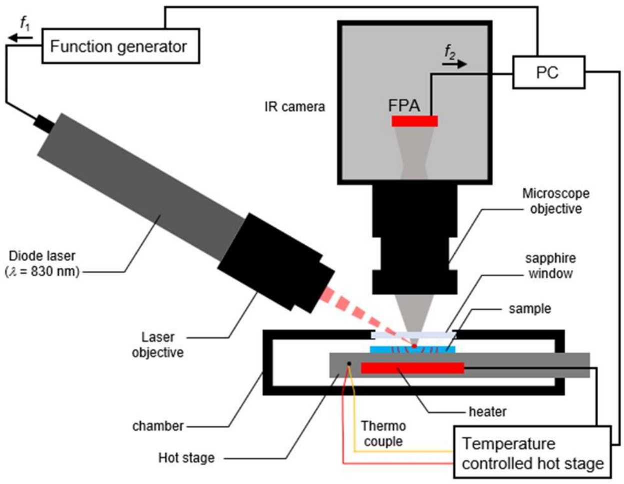

Figure 1. The schematic diagram of the focused laser coupled thermal imaging system. The point periodic heating was generated by the modulated near infrared laser. The microscale spatiotemporal temperature response was recorded by IR camera.

Results and Discussion

The method was applied to the typical polymer film sample. Exemplary results were shown in Figure 2. The phase image at different heating frequency f_1 were estimated by Fourier transforming the raw image of the temperature response taken at frame rate of f_2=80 Hz. The frequency of the heating was set to ±1 Hz of nf_2 (n : integer), so that FT analysis was always performed at Δf =1 Hz. The phase is linearly delaying as a function of the distance from the heating position. The thermal diffusivity of the sample was mainly estimated from the slope of the distance dependency of the phase.

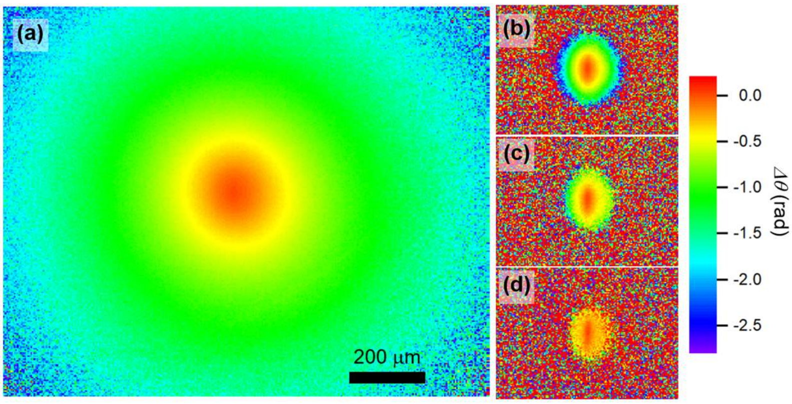

Figure 2. The analysis of the phase distribution around heating position at different frequency (a) f_1 = 1 Hz, (b) f_1 = 81 Hz, (c) f_1 = 161 Hz, (d) f_1 = 319 Hz of the focused laser periodic heating on the polymer thin film, thickness 25 μm. The frame rate of camera was fixed at 80 Hz so that Δf = 1 Hz for all images of analysis.

As the heating frequency f_1 increases, the decay rate of temperature modulation becomes very high, and the amplitude modulation component of the temperature response rapidly decays below the thermal noise revel. As a result, phase analysis becomes scattered when moving a certain distance away from the heating position. The position dependent linear profile was analyzed by averaging the two-dimensional phase distribution along the azimuthal direction (Fig. 3a).

The sample demonstrated in these exemplary results is isotropic, thus the average value around the heating position represents the averaged in-plane thermophysical properties of the sample thin film. Figure 3b shows 3D representation of the amplitude of periodic temperature response. Z axis is the amplitude of 1 Hz component and the x – y axis corresponds to the spatial position around heating spot. The conical surface was obtained for all frequencies showing that the sample has isotropic thermal diffusivity.

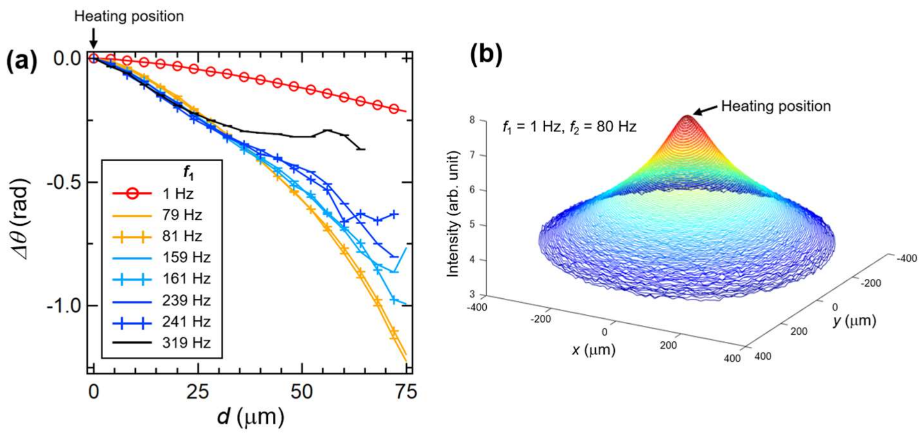

Figure 3. (a) Line profile of the in-plane phase delay averaged along azimuthal angle direction around heating position at 8 different frequency set at ± 1 Hz of nf_2. (b) 3D representation of the amplitude decay of the analyzed periodic component of temperature response around central heating position.

Conclusions

The in-plane thermal diffusivity of some polymer film was investigated by the focused laser coupled thermal imaging technique. The thermal diffusivity of the sample was estimated from the distribution of the phase delay from the point periodic heating by near infrared laser. The method enables non-contact estimation of the thermophysical properties using wide range of heating frequency which can be potentially applied for wide variety of the materials.

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Data Availability Statement: The data that support the findings of this study are available from the corresponding author, J.M., upon reasonable request.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. J. Morikawa, E. Hayakawa, T. Hashimoto, R. Buividas, S. Juodkazis "Thermal imaging of a heat transport in regions structured by femtosecond laser", *Optics Express*, **2011**, *19*(21), 20542-20550
2. Y. Gu, X. Tang, Y. Xu, and I. Hatta, "Ingenious method for eliminating effects of heat loss in measurements of thermal diffusivity by ac calorimetric method," *Jpn. J. Appl. Phys.*, **1993**, *32*, L1365 – L1367