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Optically probing sub-nanometer photo-dynamics of solid surfaces

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Abstract

Optical methods to study the laser-matter interactions precisely is of utmost importance. Here, we demonstrate a simple, collinear interferometer with minimum components to study time-resolved thermal deformations induced in solids/thin films with a picometer resolution. We have measured sub-nm deformations in various samples, like red acrylic sheet, when exposed to high-power CW laser source. The displacement measurement from our interferometer was then used to calculate the change in temperature of the solid sample. The minimum temperature change recorded was $(41.96 \pm 5.78)\ mK$. Precise temperature change of solid materials is needed in many applications like in laser heating or cooling experiments. It will be interesting to study the thermal deformation in solids due to ultra-fast nano-second or pico-second laser pulses.

1 Introduction

Precise characterization of various materials and devices has always been a basic necessity to revolutionize technology . Various physical quantities such as optical density, photo-thermal and photo-elastic response of materials, magnetic susceptibility, thermal expansion coefficient etc. rely on measurement of displacements of various objects caused by external fields. Existing techniques for surface analysis of materials such as Scanning Electron Microscopy (SEM) [1], X-Ray Diffraction [2], Atomic Force Microscopy (AFM) [3], Transmission Electron Microscopy (TEM) [4], Raman Microscopy [5], are mostly invasive and change the surface properties. Moreover, implementing these setups in a laboratory is a hefty and a lengthy process to carry out research. So, one requires non-invasive techniques like interferometry [6] to measure the surface displacements and deformations with real-time precision.

In industries [7], interferometry is widely used to measure crystal growth [8], metrology [9],surface topography, surface temperature measurements [10, 11] etc. Since the sample size (in *mm* or *cm*) is much larger than the laser spot size (usually in μm), direct measurement of change in surface temperature due to laser heating is extremely difficult. Here in this paper we discuss non-invasive interferometry technique to measure the thermal fluctuations in solids due to laser with better precision. Detection of sub-nm displacement with interferometry was utilized to measure the real-time change in temperature of solid samples. For this method prior knowledge of coefficient of thermal expansion and the thermo-optic coefficient of the sample is required. This may find its application in studying laser cooling of solids[12, 13, 14].

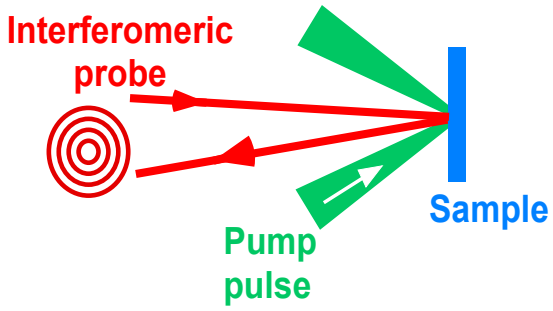

Figure 1. Experimental setup: Schematic of the nanometric probing of solid samples.

2 Experimental Set-up

The schematics of our setup is shown in Fig.1. We used a collimated He-Ne laser (10 mW, $\lambda = 632\ nm$, *and* $1/e^2$ full waist $\approx 1.0\ mm$) as probe and a high power CW green laser as pump. We used a compact and versatile Michelson-like interferometer to obtain fringes directly from the sample surfaces, viz. red acrylic sheet, dried blood drop, and a thin graphene oxide film drop casted on a glass slide. For the reference fringe signal the sample was placed on a 3-axis piezo stage (Thorlabs 3-Axis NanoMax Piezo stage MAX312D). This stage was then given a 5 V voltage corresponding to a movement of $\approx\ 2\mu m$ for measuring the reference minima to maxima signal. The signal was obtained on the oscilloscope via a photodiode with a pin hole. A focused 535 nm laser source of power 300 mW for different shutter duration was overlapped with the probe laser on the sample with a lens of 30 cm focal length to heat the samples. The corresponding change in the interference fringes was then observed in the oscilloscope using a $650 \pm 40\ nm$ band pass filter to avoid the detection of the pump laser. The physical properties of solids, such as sample length, refractive index, etc., changes when heated or cooled due

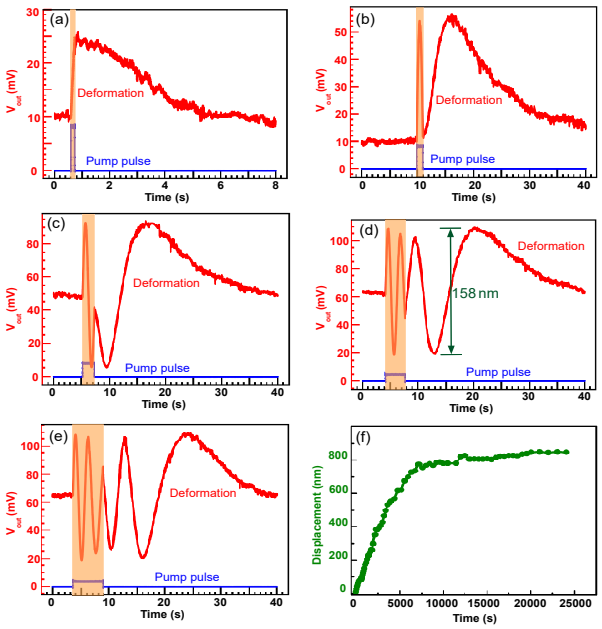

Figure 2. Time-resolved laser induced deformation for red acrylic sheet for shutter duration of (a) 100 *ms*, (b) 1 *s*, (c) 2 *s*, (d) 3.4 *s*, (e) 5.2 *s*. (f) net displacement in the sample with shutter duration.

to change in temperature. The optical path displacement, x, of the sample can be calculated using the equation:

$$x = n\lambda/2 \tag{1}$$

Where, n is the number of fringes evolved and λ is the wavelength of the laser used to obtain interference fringes. For the length of the sample, L and it's refractive index, η, is related with the optical displacement as:

$$x = L(\eta - 1). \tag{2}$$

The change in optical path length with temperature change of the sample is then given by,

$$\Delta x = L\frac{d\eta}{dT}\Delta T + \eta\frac{dL}{dT}\Delta T - \frac{dL}{dT}\Delta T. \tag{3}$$

With the prior knowledge of coefficient of linear thermal expansion, $\alpha = \frac{1}{L}\frac{dL}{dT}$, and the thermo-optic coefficient, $\frac{\eta}{dT}$ of the sample, the change in temperature at the sample surface can be calculated and rearranging the terms in eqn(3), we get,

$$\Delta T = \frac{n\lambda}{L\eta(\gamma - \frac{\alpha}{\eta})} \tag{4}$$

where, $\gamma = \frac{1}{\eta}\frac{d\eta}{dT} + \alpha$.

Fig. 2(a-e) shows the deformation of red acrylic surface when exposed to high power (300 mW) green laser for different time duration. We collected data at different exposure times (40 ms to 30 s) showing larger deformation for longer exposures. We observed that the fringes evolved faster initially and slowed down gradually with time during the shutter ON time. This can be seen evidently during the large pump laser time in Fig. 2(d-e). Using eqn. (1) the refractive index of red acrylic sheet of length 4 mm was found to be 1.47, which is consistent with the literature. As the sample surface temperature increases its refractive index decreases. For acrylic the values of α and $d\eta/dT$ (taken from literature [15, 16]) is $7\times10^{-5}\ K^{-1}$ and $-8.5\times10^{-5}\ K^{-1}$ respectively, thus $\gamma = 8.36\times10^{-6}\ K^{-1}$. For the data shown in Fig. 2(f), using eq. (4), we found a temperature change of $(41.96\pm5.78)\ mK$. The error bar in the calculation corresponds to the fluctuations in the data. Fig.2(f) shows the net displacement in the sample during different shutter duration. We also observed that the net displacement saturates after a certain shutter duration. At this point the sample has attained its maximum temperature and beyond this point a permanent damage to the sample can be observed in the form of a dip (or bulge).

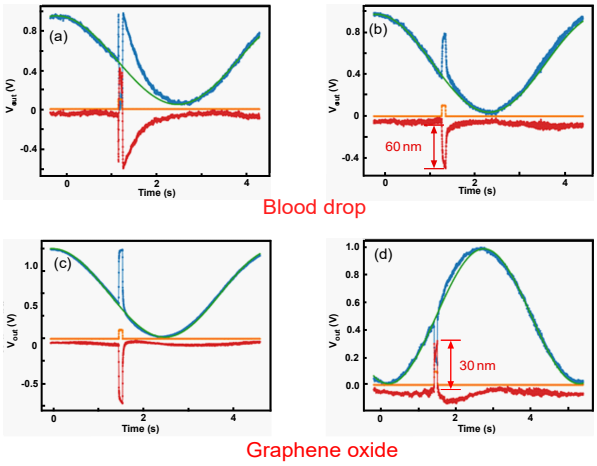

Figure 3. Time-resolved laser induced deformation for (a-b) a dried blood drop on slide, (c-d) a graphene oxide film drop casted on a glass slide.

Similar experiment was then performed on a dried blood drop and on a graphene oxide film drop casted on a glass slide. We observed a displacement of 60 nm and 30 nm respectively with a precision of 200 pm for each sample as shown in Fig. 3. For the given values of the thermal expansion coefficient and thermo-optic coefficient the change in temperature of these samples can be calculated in a similar way discussed above.

3 Results and Discussion

In conclusion, we report a simple and versatile optical technique to measure time-resolved optical displacement with picometer resolution using high contrast fringes produced by the michelson-like interferometer. By analyzing dynam-

ical fringes when the test surface is modulated we measured its displacement in self-calibrating way with a resolution of $\lambda/3000 \approx 200$ *pm*. Application of our technique to observe time-resolved fast dynamics occurring in bodies and to measure reversible and irreversible dynamics of laser heating (or cooling) and subsequent nano-scale mechanical response of various solids is demonstrated. A temperature change of (41.96 ± 5.78) *mK* was observed on the surface of red acrylic sheet.

It would be interesting to study the variations in the profile of solid surfaces due to ultra-fast nano-second or pico-second laser pulses. We can then investigate the change in properties of the sample due to electron transition as the pulse time duration will be of the order of electronic transition from the higher state to lower state. Furthermore, the technique can be adapted to measure sub-nm deformations and temperature changes on liquid surfaces subjected to external fields.

4 Acknowledgements

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References

[1] J. I. Goldstein, D. E. Newbury, J. R. Michael, N. W. Ritchie, J. H. J. Scott, & D. C. Joy, "Scanning electron microscopy and X-ray microanalysis", *Springer*, 2017.

[2] B. E. Warren, "X-ray Diffraction", *Courier Corporation*, 1990.

[3] C. R. Blanchard, "Atomic force microscopy", *The chemical educator*, **1**(5), 1-8, 1996.

[4] P. M. Kelly, A. Jostsons, R. G. Blake, & J. G. Napier, "The determination of foil thickness by scanning transmission electron microscopy", *Physica status solidi (a)*, **31**(2), 771-780, 1975.

[5] A. Hartschuh, E. J. SÃąnchez, X. S. Xie, & L. Novotny, "High-resolution near-field Raman microscopy of single-walled carbon nanotubes", *Physical Review Letters*, **90**(9), 095503, 2003.

[6] A. Michelson, âĂIJMichelson-Morleys experimentâĂİ, *Phil. Mag*, **5**, 1887.

[7] A. Wada, M. Kato, & Y. Ishii, "Multiple-wavelength digital holographic interferometry using tunable laser diodes", *Applied optics*, **47**(12), 2053-2060, 2008.

[8] Y. K. Kim, B. R. Reddy, T. G. George, & R. B. Lal, "Optical heterodyne interferometry technique for solution crystal growth rate measurement", *Optical Engineering*, **37**(2), 616-622, 1998.

[9] T. Yoshizawa, "Handbook of optical metrology: principles and applications", *CRC Press*, 2015.

[10] F. Meriaudeau, "Real time multispectral high temperature measurement: Application to control in the industry", *Image and Vision Computing*, **25**(7), 1124-1133, 2007.

[11] C. W. Farley, III & B. R. Reddy, Interferometric measurement of laser heating in praseodymium-doped YAG crystal", *Applied optics*, **50**(4), 526-531, 2011.

[12] M. SheikâĂŘBahae, & R. I. Epstein, "Laser cooling of solids", *Laser & Photonics Reviews*, **3**(1âĂŘ2), 67-84, 2009.

[13] D. V. Seletskiy, S. D. Melgaard, S. Bigotta, A. Di Lieto, M. Tonelli, & M. Sheik-Bahae, "Laser cooling of solids to cryogenic temperatures", *Nature Photonics*, **4**(3), 161, 2010.

[14] G. Nemova, & R. Kashyap, "Laser cooling of solids", *Reports on Progress in Physics*, **73**(8), 086501, 2010.

[15] S. N. Kasarova, N. G. Sultanova, & I. D. Nikolov, "Temperature dependence of refractive characteristics of optical plastics", *In Journal of Physics: Conference Series, IOP Publishing*, **253**(1),012028, 2010.

[16] https://www.carvilleplastics.com/latest_news/key-properties-cast-acrylic-pmma/ (as viewed on October 24, 2018).