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► To cite this version:

U. Netzelmann. Non-linearity in photothermal radiometric imaging. Journal de Physique IV Proceedings, 1994, 04 (C7), pp.C7-55-C7-58. 10.1051/jp4:1994714 . jpa-00253195

HAL Id: jpa-00253195

<https://hal.science/jpa-00253195>

Submitted on 1 Jan 1994

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Non-linearity in photothermal radiometric imaging

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Abstract: Non-linear effects occurring in photothermal microscopes based on principle of photothermal radiometry are studied as a function of the laser power and of the modulation frequency. For stainless steel, a second harmonic component of up to 11 % of the fundamental amplitude is found. Phase shifts of up to 20 degrees are observed as a function of the modulation frequency. The nonlinearity is mainly due to Stefan-Boltzmann's law. The experimental results are in good agreement with a theoretical model based on the static and oscillating temperature distribution.

1. INTRODUCTION

Thermal wave microscopy finds new applications in various fields of industrial nondestructive testing. Fast scanning speeds and therefore high signal-to-noise ratios are often required. A common way to improve the signal-to-noise ratio is to increase the laser power applied. When detecting infrared radiation from a periodically heated spot on a surface, Stefan-Boltzmann's law leads to an inherent nonlinearity of the detection, which is normally neglected by assuming small temperature changes. For higher laser powers, this is no longer possible (¹), in particular for highly focused photothermal microscopes, where the radial distribution of the local static temperature can have significant effects on the detected photothermal signals.

2. THEORETICAL MODEL

A modulated heating beam with a radius r_H is assumed to fall onto a half-space with surface absorption and a thermal diffusion length μ_s (Fig. 1). The heated spot is observed by an infrared detector with a gaussian sensitivity profile with radius r_D and with constant sensitivity in the wavelength range $\lambda_{\min}$ to $\lambda_{\max}$. For the material under study, a possible temperature and wavelength dependence of the surface emissivity will be ignored. Then the harmonic part of the detector signal is proportional to:

$$S = 2\pi \int_0^{\infty} e^{-\left(\frac{r}{r_D}\right)^2} \left[\int_{\lambda_{\min}}^{\lambda_{\max}} \frac{\partial \mathcal{R}_{bb\lambda}(T_0 + T_{dc}(r))}{\partial T} d\lambda \right] g(r) r dr \quad , \quad (1)$$

Fig. 1: Sketch of the experimental situation

where $R_{bb\lambda}$ is the spectral radiant emittance, T_0 the ambient temperature, T_{dc} the steady-state temperature increase, ϑ the temperature oscillation at the sample surface. It is assumed that still $T_0 \gg T_{dc}, |\vartheta|$. For a sample extending into a half-space and using Hankel transforms ⁽²⁾, the radial distribution of the surface temperature due to an absorbed power P_0 on a material surface with a thermal conductivity λ_s can be shown to be given by:

$$\vartheta(r) = \frac{P_0}{2\pi_0} \int_0^\infty \frac{1}{\lambda_s \sigma_s} e^{-\frac{r_H^2 q^2}{4}} J_0(qr) q dq \quad , \text{ where } \quad \sigma_s^2 = q^2 + i \frac{2}{\mu_s} \quad (2)$$

$$T_{dc}(r) = \frac{P_0}{2\sqrt{\pi}} \frac{1}{\lambda_s r_H} e^{-\frac{r^2}{2r_H^2}} I_0\left(\frac{r^2}{2r_H^2}\right) \quad (3)$$

An analysis of (2) and (3) shows, that for $r_H \ll \mu_s$, $T_{dc}(r)$ and $|\vartheta(r)|$ are very close to each other in the illuminated region of the sample. Both amplitude and phase of ϑ as well as T_{dc} are monotonously decreasing with r . Considering the integral (1), the distribution of the static temperature increase $T_{dc}(r)$ emphasises signal contributions from the centre of heating spot, which have a more positive phase than that from more distant regions. This is the mechanism for the power dependent phase shifts we have observed experimentally.

3. EXPERIMENTS

In a first experiment, the photothermal signal of a freshly polished, thermally thick plate of stainless steel ($\mu_s(1 \text{ kHz}) = 35.4 \text{ } \mu\text{m}$) was measured by an ALADIN P1 photothermal microscope (Siemens KWU, Offenbach), which uses a Nd-Yag laser as heating source and which is detecting the infrared emission of the sample in the 1 to 5.5 μm wavelength range. On a very homogeneous area of the surface, signal amplitude and phase were recorded as a function of the applied laser power for different modulation frequencies (Fig. 2). A non-linear increase of the signal amplitude with laser power is observed, containing a second harmonic amplitude signal of up to 11 %. Signal phase is increasing with laser power for more than 20 degrees.

A second experiment was performed in order to distinguish between the non-linear mechanism discussed above and possible other sources of non-linearity, as reported in literature ^(3,4,5). The photothermal microscope is measuring the signal through the window of a photoacoustic cell ⁽⁶⁾ with the sample as the bottom wall (Fig. 3). The cell window consists of CaF_2 and is therefore sufficiently transparent for the 1.064 μm radiation of the heating beam as well as for the thermal infrared. This arrangement allows to record the photothermal radiometry (PTR) and the photoacoustic (PA) signal of the sample simultaneously and exactly at the same position.

Fig. 2: Theoretical (solid lines) and experimental (squares) photothermal amplitude (left) and phase (right) as a function of the incident laser power for several modulation frequencies

Fig. 3: Arrangement used for simultaneous recording of photothermal radiometry (PTR) and photoacoustic (PA) signals

Fig. 4: PTR and PA fundamental (1f) and second harmonic (2f) signals as a function of the laser power.

Fig. 4 shows the results on the same sample for a modulation frequency of 1 kHz as a function of an applied laser power of up to 100 mW focused to the surface. The fundamental (1f) as well as the second harmonic (2f) signals have been recorded. All amplitude signals are normalised with respect to the 1f-PTR signal amplitude at 100 mW. The 2f signals are multiplied by a factor of 10 for clarity of representation. Where the PTR signal shows a non-linear dependence of the signal amplitude on laser power and power dependent phase shifts, the PA-signal is increasing linearly with frequency and its phase is constant. The 2f-component is much smaller for the PA-signal than for the PTR signal.

4. DISCUSSION

The PA-signal is depending on optical absorptivity and thermal properties of the sample and on the gas properties in the cell. Its linearity as a function of the laser power shows, that none of these properties is source of a notable non-linearity for this particular sample (a small 2f-component of the same relative size as found in the PA-signal can also be detected in the excitation light due to an imperfection of the modulation). The remaining sources of the non-linearity of the PTR-signal are Stefan-Boltzmann's law and a temperature dependent emissivity. In the temperature range considered here, the latter will usually have a smaller influence than the first.

These results justify to compare the experimental data of the first experiment with a theoretical calculation based on the relations (1)-(3). The factor describing the efficiency of the infrared emission (square bracket in (1)) is calculated using $T_0 = 295$ K and T_{dc} from (3), as well as a heating beam radius of $r_H = 3.5$ μ m and an optical reflectivity of the steel surface of 0.5. For example, in the case of an absorbed laser power of 10 mW, the emission efficiency in the centre of the beam is nearly a factor of 4 higher than in the outer zones of the heated spot. The integration under consideration of a detection profile of $r_D = 200$ μ m (determined experimentally) finally gives the solid lines in Fig. 2, which have been fitted to the experimental data by frequency dependent phase offsets and amplitude factors at $P = 20$ mW correcting for the unknown overall system response. The agreement with the experimental data is good.

5. CONCLUSION

Our experiments show that non-linearity in photothermal radiometric imaging due to Stefan-Boltzmann's law influences not only signal amplitudes but also signal phases. These effects easily occurring when working with highly focused excitation beams must be separated from phase shifts to be used for the analysis of layer thicknesses, defect sizes or thermal resistances.

As a useful consequence of non-linearity we have found in accordance with previous results by mirage detection (3), that the contrast of surface cracks in thermal images is improved.

REFERENCES

- [1] Busse, G., in: Physical Acoustics, Vol.18, Mason, W., and Thurston, R. (eds.) (Academic Press, San Diego 1988) p. 403
- [2] Opsal, J., Rosencwaig, A., and Willenbourg, D., *Appl. Optics* **22** (1983) 3169
- [3] Rajakarunayake, Y. N., and Wickramasinghe H. K., *Appl. Phys. Lett.* **48** (1986) 218
- [4] Wetsel, G. C., and Spicer, J. B., *Can. J. Phys.* **64** (1986) 1269
- [5] Gusev, V., Mandelis, A., and Bleiss, R., *Int. J. Thermophys.* (in press)
- [6] Gissinger, S., Diploma Thesis, (ENSIMEV Valenciennes and IzfP Saarbrücken, 1993)