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Influence of chirp time-bandwidth on frequency modulated thermal wave imaging based materials characterization technique

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Abstract

An estimation of thermo-physical properties such as thermal diffusivity, thermal conductivity and heat capacity are extremely important for any practical and industrial applications. Contact free and fast measurement approaches using active infrared thermography principles have shown prolific results in this regard. The present study demonstrates frequency modulated thermal wave imaging (FMTWI) as a fast and efficient in-plane thermal diffusivity measurement technique. Here, a novel photo-thermal excitation signal in the form of a chirp is applied on the sample surface and the thermal response is monitored using an infrared (IR) camera. The in-plane thermal diffusivity of any self-sustaining sample can be measured using the multiple phase information extracted from a single run of the experiment. The applied excitation signal is characterized by the chirp bandwidth and time period which are also related to the noise-equivalent temperature (NET) of the IR camera used. The influences of these two parameters on the final thermal diffusivity results have been discussed. Experimental results from measurements done on standard anodic alumina (AAO) templates have been included.

Keywords: Thermal diffusivity, Frequency modulated thermal wave imaging (FMTWI), Chirp bandwidth and time period.

1. Introduction

Thermal characterization of materials using nondestructive system (NDS) approaches has become popular in recent times. It provides fast and non-contact approach in estimating the thermal parameters. Active infrared (IR) thermography techniques such as lock-in thermography [1-4] and pulsed thermography [5-6] are widely used for determination of the thermal conductivity and thermal diffusivity parameters.

The recently proposed frequency modulated thermal wave imaging (FMTWI) [7-10] approach has also emerged as a fast and efficient thermal characterization technique [11]. Here, a novel photo-thermal excitation signal in the form of an up-chirp is applied on the sample surface and the thermal response is monitored using an infrared (IR) camera. The in-plane thermal diffusivity of any self-sustaining sample can be measured using the multiple phase information extracted from a single run of the experiment. This characteristic provides a time efficient approach for thermal measurements using infrared thermography techniques.

The applied excitation signal is characterized by the chirp bandwidth and time period. The present study discusses the influences of these two parameters on the final in-plane thermal diffusivity results. Experimental results from measurements done on empty anodic alumina (AAO) templates are also included.

2. Frequency modulated thermal wave imaging

FMTWI, in essence, can be termed as superposed lock-in thermography, which facilitates extraction of multiple phase and amplitude images from a single run. In this technique, a photo-thermal point source excitation comprising of a linear frequency modulated signal (chirp) is applied close to the center of the sample surface and the thermal response is recorded with an infrared (IR) camera. As per Fourier theorem, a chirp signal may be viewed as a superposition of multiple sinusoidal signals, having frequencies which are integral multiples of the fundamental frequency. As the thermal waves propagate radially outwards, a linear change in phase (Φ) and an exponential attenuation of wave amplitude are observed as a function of radial distance (L) from the point of excitation [3, 12, 13]. Out of these, the phase information is used solely for thermal diffusivity measurements, as it is more immune to the local variations in surface temperature and emissivity of the radiating surface. In FMTWI technique, phase images corresponding to different excitation frequencies are extracted from a single run of the experiment. This minimizes the operational time of the technique and makes it a fast and efficient one. The in-plane thermal diffusivity is finally calculated from the plot of angular excitation frequency (ω) with square of phase image slope (Φ/L) [11].

3. Experimental results

One important consideration in the FMTWI thermal diffusivity measurement technique is the choice of excitation frequency and time period. The requirement is to keep the sample under test, thermally thin, so that the radially outward thermal wave propagation in the samples can be approximated to a one dimensional heat flow equation. From this one may relate the thermal diffusivity to only the phase information. Experiments were performed on empty anodic alumina samples, with thermal diffusion length larger than 60 μm AAO thickness.

3.1 2 second linear chirp with 1 - 3 Hz bandwidth

A 2 second chirp signal of 1-3Hz bandwidth was applied on the same 100 nm pore empty AAO template. The plot of angular excitation frequency with square of the phase image slope showed linear relationship as shown in figure 1 (b), form which the in-plane thermal diffusivity was calculated to be 9.15 × 10^{-7} m^2s^{-1}. The maximum error in this case was calculated to be 4.8% which comes from the uncertainty in the linear fit of the plot.

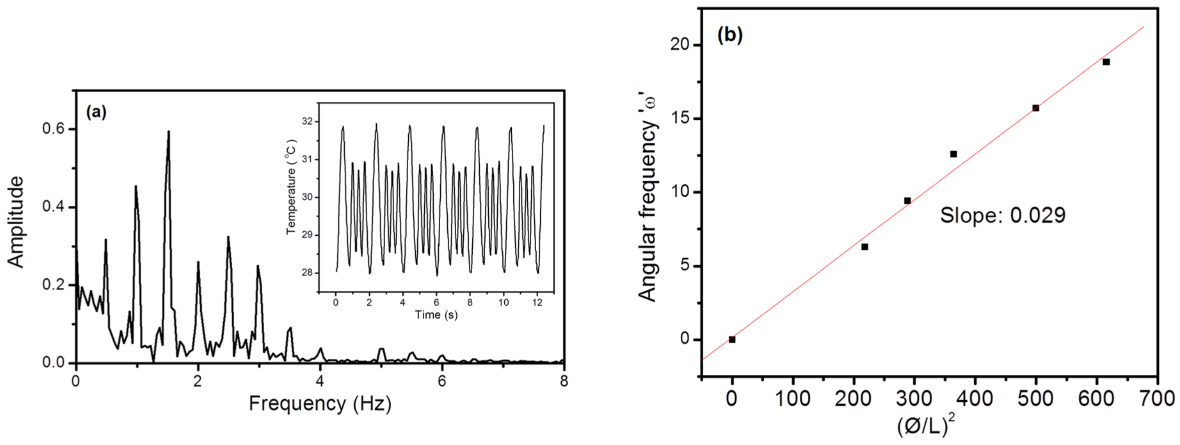

Fig. 1. (a) FFT of the FMTWI IR response for 100 nm pore empty AAO template, inset: temperature – time plot for (2s, 1-3 Hz bandwidth) chirp signal **(b)** Angular excitation frequency plotted against square of phase slope.

3.2 5 second linear chirp with 1 - 3 Hz bandwidth

Next a 5 second chirp signal of 1-3 Hz bandwidth was used as the excitation signal. The FFT analysis showed the different significant harmonic components within the 1-3 Hz bandwidth. It was observed that the components corresponding to 1.6 and 2.4 Hz are missing. This was further supported with the observation that no phase image could be extracted from the FMTWI response, corresponding to the same frequency values.

The slope of the plot of angular excitation frequency with square of phase slope was calculated to be 0.027, from which finally the thermal diffusivity was estimated to be 8.9 × 10^{-7} m^2s^{-1}. The uncertainty in the final result was calculated to be 6.3%.

3.3 5 second linear chirp with 0.5 – 1.5 Hz bandwidth

Next a 5 second chirp signal of 1 Hz bandwidth was applied. The applied excitation maintained the thermally thin sample requirement. The FFT analysis of the IR response showed absence of harmonic component at 1 Hz, with the significant harmonic components lying within 0.5 to 1.5 Hz. As expected, no phase image was obtained corresponding to the 1 Hz frequency component. Distinct phase images corresponding to 0.4 Hz, 0.6 Hz, 0.8 Hz, 1.2 Hz and 1.4 Hz frequency components were obtained from the single FMTWI response. The in-plane thermal diffusivity was calculated to be 8.96 × 10^{-7} m^2s^{-1} with an error margin of 4.3%.

From some of the experimental results of varying applied chirp time bandwidth product, it was inferred that there is minimal influence of the time bandwidth product on the final thermal diffusivity results. The thermal diffusivity values remained nearly close to each other for different applied time bandwidth values, for the range of excitation frequencies satisfying the thermally thin requirement.

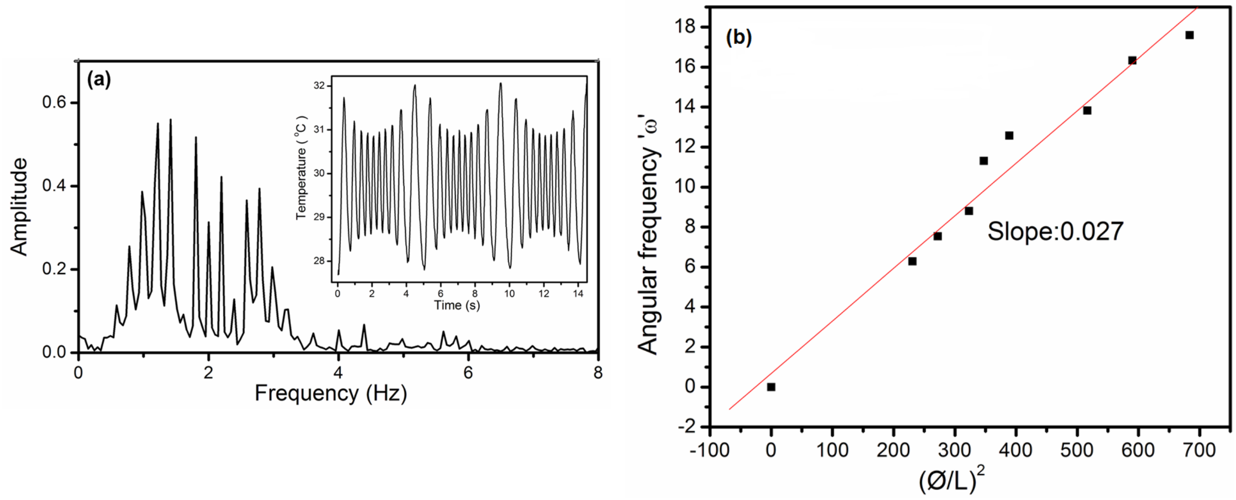

Fig. 2. (a) FFT of the FMTWI IR response for 100 nm pore empty AAO template, inset: temperature – time plot for (5 s, 1-3 Hz bandwidth) chirp signal **(b)** Angular excitation frequency plotted against square phase slope.

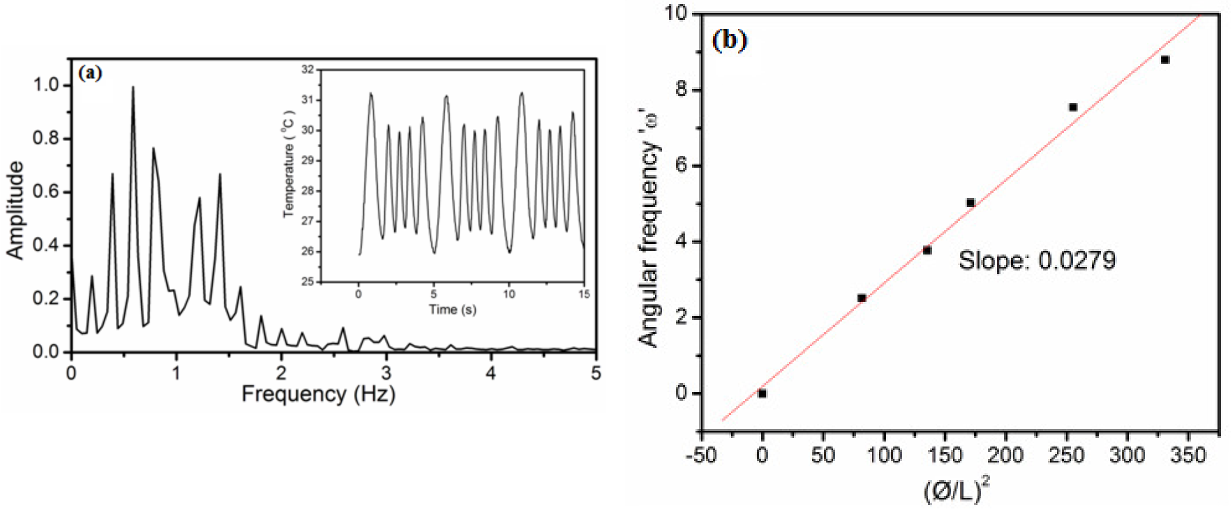

Fig. 3. (a) FFT of the FMTWI IR response from 100 nm pore empty AAO template, inset: temperature – time plot for (5s, 0.5 - 1.5 Hz bandwidth) chirp signal **(b)** Angular excitation frequency plotted against square phase slope.

4. Conclusion

The present study introduces and implements frequency modulated thermal wave imaging (FMTWI) for in-plane thermal diffusivity measurements of self-sustaining thin plate materials. The technique provides a fast and reliable approach for estimating anisotropic thermal diffusivity. In this approach a frequency modulated chirp excitation is applied and the multiple phase image responses corresponding to different excitation frequencies are extracted from the single FMTWI response. The technique shows high sensitivity with maintaining the signal to noise ratio within limits. The technique shows great promise in transforming all lock-in thermography based thermal characterization techniques to fast and speedy ones. The influence of the applied chirp time period and frequency bandwidth on the final thermal diffusivity results were also studied through varying the applied excitation signals. It was observed that the final thermal diffusivity results are independent of the chirp time bandwidth parameters till the excitation frequencies assure the sample under test to be thermally thin.

5. References

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