Practical Consideration for Lock-in Thermography Effective Spatial Resolution

ANNA STOYNOVA, BORISLAV BONEV
Department of Microelectronics
Technical University of Sofia
8 Kliment Ohridski blvd, Sofia
BULGARIA
bonev@ecad.tu-sofia.bg

Abstract: - The aim is to study some factors influence on the contrast decreasing of the ampligram and phasegram obtained after lock-in thermography. It is analysed the effect of delay between excitation source modulated parameter changing and modulated signal. Two software corrections for decreasing the effect of these factors are developed. The offered corrections can be used with different types of excitation sources. In order to evaluate the effect of these corrections, lock-in thermography measurement is performed. Multiple results processing at different correction parameters' values are studied for PCB samples. The contrast dependence from correction parameters in graphical form is presented. Multiple results processing with random correction parameters values using the both corrections are performed for determination of maximum possible contrast An iterative method with less number of results processing for choosing appropriate values of correction parameters using the both corrections is proposed. The effect of this method is presented and compared in tabular and graphic form. The investigated sample is PCB (evaluation of copper layers' adhesion on FR-4).

Key-Words: - lock-in thermography, excitation source, contrast increasing, digital lock-in correlation, Fourier transformation

1 Introduction

In recent years, there has been a growing interest in active thermography methods, particularly lock-in thermography. Active thermographic methods use a forced temperature change (heating or cooling) of the tested object and simultaneously capture the process of temperature change with an infrared (IR) camera [1]. Excitation source is used for temperature change. In lock-in thermography is used a periodic temperature change.

The advantages of the lock-in thermography such as its non-destructivity and contactlessness in some cases, noise suppression and other, are a precondition for its wide application [2].

Any source of heating or cooling that can give or take heat for a long time can be used as excitation source:

- optical excitation sources (halogen lamp, LED, laser);
- mechanical excitation source (ultrasound source);
- electrical (for example – modulating the power supply voltage);

The halogen lamp is one of the most commonly used optical excitation sources for lock-in thermography mainly because of its relatively low cost, high output power, large heated area and relatively easy modulation of the light intensity.

The use of a halogen lamp as excitation source requires some peculiarities in the processing of the received data relating to the thermal inertia of the lamp [3].

A significant disadvantage in the use of a halogen lamp as excitation source is the poor energy efficiency of the measurement process. The efficiency of the halogen lamp is relatively low, which, combined with the long duration of the measurement process, leads to significant electricity consumption.

The energy efficiency of the process can be improve by increasing the sensitivity of the method, i.e., obtaining the same contrast at a lower light intensity of the lamp. Sensitivity is decreasing due to a number of factors whose origin and effect requires thorough analysis and finding ways to reduce their effect on the obtained result.

Other optical excitation sources (such as LED and laser) have better energy efficiency and its inertia is negligible low.

Significant disadvantage of LED is relatively low output optical power. In the resent years, the power of LEDs increases significantly and this is a

precondition of usage of LED as optical excitation source in cases, where it is not needed high output power of excitation source.

If it is needed heating of very small objects or spot of the tested object it can be used laser excitation source. In this case is possible to heating up only the tested object area of interest. As an example can be heated up separate elements in the printed circuit boards (PCB). If it is used focused laser beam in many cases can be heated up very small areas in separate chips in silicon wafer.

2 Problem Formulation

2.1 Principle of lock-in thermography

The principle of the lock-in thermography is based on the principle of synchronous phase detection. The first variants of lock-in thermography used analogue processing of the received signal by synchronous phase detectors. It was used a system with a sensor for infrared radiation and a modulated laser beam. This pair of emitter-receiver scans test surface [1]. Obviously, this system has been very slow. When IR thermal cameras become cheaper, they are used instead of the one receiver and the whole tested object surface is captured at once.

Important step in the lock-in thermography measurement is the determination of measurement parameters:

- excitation source modulation frequency (lock-in frequency);
- measurement duration.

For this purpose is needed simulation of measurement. In many cases simulation of 1D thermal wave propagation in tested object is enough. The temperature change over time contains offset and modulation component, because after turning on the excitation source in addition to the periodic variation of the temperature due to modulation, the temperature average value is increasing. This can be represented with equation (1).

$$T(z,t) = T(z,t)_{offset} + T(z,t)_{mod}, \quad (1)$$

where $T(z,t)_{offset}$ is the offset component and $T(z,t)_{mod}$ is the modulation component.

For determination of modulation component is used 1D thermal equation (2) [4].

$$\frac{\partial^2 T(z,t)_{mod}}{\partial z^2} - \frac{1}{\alpha}\frac{\partial T(z,t)_{mod}}{\partial t} = 0, \quad (2)$$

$$\alpha = \frac{k}{\rho c_p}, \quad (3)$$

where $T\,[K]$ – temperature, $\alpha\ \left[\frac{m^2}{s}\right]$ – thermal diffusivity of tested sample material, $k\ \left[\frac{W}{mK}\right]$ – thermal conductivity of tested sample material, $\rho\ \left[\frac{kg}{m^3}\right]$ – density of tested sample material, $c_p\ \left[\frac{J}{kgK}\right]$ – specific heat capacity of tested sample material.

The solution of this equation is represented with equation (4) [2].

$$T(z,t)_{mod} = Ae^{-\frac{z}{\mu}}e^{i\left(2\pi f_{lock-in}t-\frac{z}{\mu}\right)}, \quad (4)$$

$$\mu = \sqrt{\frac{k}{\pi f_e \rho c_p}}, \quad (5)$$

$$A = \frac{p_0}{\sqrt{2\pi f_{lock-in} k\rho c_p}}, \quad (6)$$

where A – amplitude of temperature changing due o modulation, $\mu\ \left[\frac{m^2}{s}\right]$ – thermal diffusion length, p_0 – surface power density.

The offset component is represented with equation (7) [2].

$$T(z,t)_{offset} = T_{ambient} + \Delta T\left(1 - e^{-\frac{t}{\tau}}\right), \quad (7)$$

$$\Delta T = PR_h, \quad (8)$$

$$\tau = mc_p R_h, \quad (9)$$

where τ is time constant.

In cases, where the tested sample has complex geometry it is needed 3D heat transfer simulation with using computational methods.

An important point in the principle of the lock-in thermography is the need to know each thermogram of the sequence at which instantaneous value of generated heat flux by excitation source is captured.

The simplest way to realize this is the synchronization between the modulating signal of the excitation source and capturing thermograms from the IR camera.

2.2 Methods for lock-in processing of thermography results

An ampligram and a phasegram, as well as some other images, are obtained as a result from the lock-in thermography measurement. These are obtained

by processing all or part of the thermograms from sequence.

There are basically two methods for processing the sequence of thermograms - digital lock-in correlation and Fourier analysis.

The principle of digital lock-in correlation is shown on fig. 1.

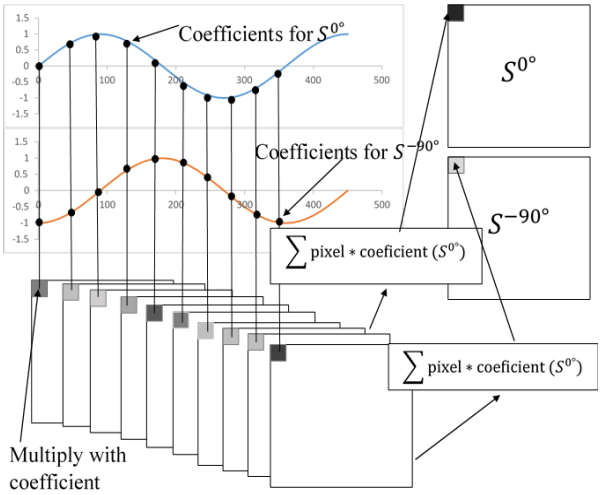


Fig. 1. The principle of digital lock-in correlation.

For one pixel of the images $S^{0°}$ and $S^{-90°}$ is obtained [2]:

$$S^{0°}(x,y) = \frac{1}{Nn}\sum_{k=1}^{N}\sum_{m=1}^{n} F_{k,m}(x,y)K^{0°}, \quad (1)$$

$$S^{-90°}(x,y) = \frac{1}{Nn}\sum_{k=1}^{N}\sum_{m=1}^{n} F_{k,m}(x,y)K^{-90°}, \quad (2)$$

$$K^{0°} = 2\sin\left(\frac{2\pi(m-1)}{n}\right), \quad (3)$$

$$K^{-90°} = -2\cos\left(\frac{2\pi(m-1)}{n}\right), \quad (4)$$

where:

$S^{0°}(x,y)$ – value of the pixel (x,y) from image $S^{0°}$;

$S^{-90°}(x,y)$ – value of the pixel (x,y) from image $S^{-90°}$;

x – row of thermogram;

y – column of thermogram;

N – number of periods for which the calculation is performed;

n – number of captured thermograms per period;

$F_{i,j}(x,y)$ – value of the pixel (x,y) of image i from period j;

$K^{0°}$ - correlation coefficient for computation of $S^{0°}$;

$K^{-90°}$ - correlation coefficient for computation of $S^{-90°}$.

The ampligram and phasegram are obtained from images $S^{0°}$ and $S^{-90°}$:

$$S_A(x,y) = \sqrt{S^{0°}(x,y)^2 + S^{-90°}(x,y)^2}, \quad (5)$$

$$S_P(x,y) = \tan^{-1}\left(\frac{S^{-90°}(x,y)}{S^{0°}(x,y)}\right). \quad (6)$$

When it is used Fourier transformation method for computation of ampligram and phasegram, first it is needed to calculate the first harmonic image:

$$S(x,y) = \frac{1}{Nn}\sum_{k=1}^{N}\sum_{m=1}^{n} F_{k,m}(x,y)K, \quad (7)$$

$$K = exp\left(-j\left(\frac{2\pi m}{n}\right)\right). \quad (8)$$

The ampligram and phasegram are obtained from the first harmonic image:

$$S_A(x,y) = \sqrt{Re(S(x,y))^2 + Im(S(x,y))^2}, \quad (9)$$

$$S_P(x,y) = tan^{-1}\left(\frac{Im(S(x,y))}{Re(S(x,y))}\right). \quad (10)$$

2.3 Contrast decreasing factors

There are lot of specificities in thermogram sequence processing when it is used different excitation source.

In the case of usage of halogen lamp, the direction of the supplied voltage is irrelevant. If it is supplied reverse voltage to the LED, it is off and can be damaged. Therefore, only one polar voltage is applied to halogen lamp and when it is used LED – only forward voltage. In the used experimental setup, halogen lamp voltage has the time diagram, shown on fig. 2.

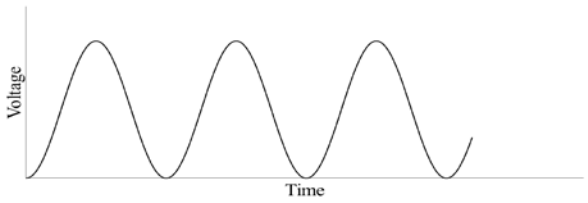


Fig. 2. The voltage waveform applied to halogen lamp.

When it is used digital lock-in correlation method, the closest correlation function to this signal is (1–cos) for computation of image $S^{0°}$ and (1-sin) for computation of image $S^{-90°}$.

In the case of using laser diode as excitation source, also it is needed to apply only one polar and forward voltage to the laser diode.

The contrast of resulting from lock-in thermography measurement images will be the highest in case of the instantaneous values of correlation function are equal to instantaneous values of generated heat flux from excitation source.

One of the most complex case is using electrical power dissipated in electronic elements in circuits as excitation source. This is strongly specific for each measurement. As an example – if it is used power dissipated in MOSFET as excitation source for heating up the MOSFET and the modulated parameter is the drain current of the transistor, depending on the value of the drain current and gate-source voltage, the dependence between power dissipated in MOSFET and modulated parameter (drain current) will be strongly non-linear.

In the halogen lamp, the change in the light intensity does not fully follow the modulation signal, but with some delay due to the thermal inertia of the lamp filament. This delay, however, changes over time - at the start time, when the filament is cold, this delay is greatest. In subsequent periods, this delay is decreasing.

Consequently, it is obvious, that there are in many cases difference between waveform of excitation source modulation signal and generated heat flux from excitation source.

3 Problem Solution

3.1 Lock-in thermography measurement

To study the effect of the factors described above, a lock-in thermography measurement of a one-layer printed circuit board (PCB) was performed.

The halogen lamp and the camera are located opposite the PCB side without paths.

Characteristics of PCB:

- material – FR4;
- thickness – 1 mm;
- material of PCB paths – copper;
- thickness of PCB paths – 35 μm.

Approximately calculation of the lock-in thermography measurement parameter is performed by using software Automation Technology IrNDT. A frequency of 0.2 Hz is chosen. At this frequency the heat wave penetration is approximately the thickness of the board [5].

The lock-in measurement is controlled by IRX-Box hardware and IR-NDT software of Automation Technology. The thermogram sequence is processed by own developed software in the environment of Matlab.

The used IR camera is FLIR SC640 with resolution of 640 × 480 pixels and frame rate of 30 frames per second.

The parameters of measurement are:

- lock-in frequency – 0.2 Hz (5s period);
- measurement duration – 50s (10 lock-in periods);
- frame rate of IR camera – 10 frames per second.

It is not used all lock-in periods for computation of ampligram and phasegram, because the thermal process during the first few periods is far from thermal equilibrium and this leads to decreasing of contrast.

To determine the influence of the described error sources, a comparison of the contrast between two areas of the phasegram at different values of the percentage frequency change and delay time is performed. The areas used for contrast computation are shown on fig. 3.

The contrast is calculated using equation (11).

$$C = \frac{1}{10}\sum_{k=1}^{10}\left(S_P(a_k)\right) - \frac{1}{10}\sum_{k=1}^{10}\left(S_P(b_k)\right), \quad (11)$$

where:

$a_1, a_2, \ldots, a_{10}$ – pixel of area (a);

$b_1, b_2, \ldots, b_{10}$ – pixel of area (b).

The averaging of 10 pixels is used for decreasing of noise.

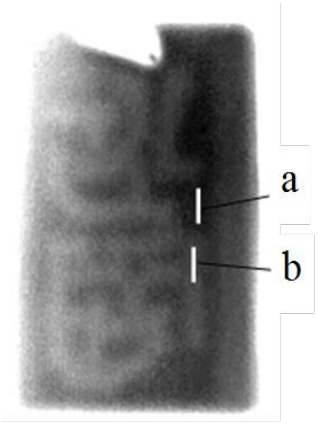
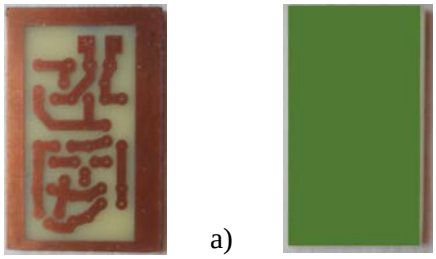


Fig. 3. Areas used for contrast computation.

The photos of the studied PCB sample are shown on fig. 4 - the site copper layers (a) and the site FR-4 (b). The reflection mode lock-in thermography is applied – the infrared camera capture thermograms from the site of FR-4.



a) b)

Fig. 4. The photos of the examined PCB sample.

3.2 Contrast increasing methods

As mentioned above, it is necessary to know the instantaneous value of the heat flux generated from excitation source for each thermogram of the sequence capturing time. The best way is to determinate with simulation the instantaneous values of heat flux generated from excitation source. But in many cases it is needed a lot of time for modeling. Possible solution is to adding more parameters in the correlation function (initial delay of function, percentage change of frequency). Initial delay of function compensates delay between changing of heat flux generated from excitation source and changing of modulation signal. Percentage change of frequency compensates changing of delay during measurement.

Equations (3) and (4) are changed as follows:

$$K^{0^\circ} = 1 - \cos\left(\frac{2\pi(100+d)(m-1)}{100n} - 2\pi t_d f_l\right), \quad (12)$$

$$K^{-90^\circ} = 1 - sin\left(\frac{2\pi(100+d)(m-1)}{100n} - 2\pi t_d f_l\right), \quad (13)$$

where:

t_d – delay time;

f_l – excitation source modulation frequency;

d – percentage change in frequency.

Automated determination of the most appropriate values for delay and percentage change of frequency can be realized. An indication that the most appropriate values for delay and percentage change of frequency are chosen is to achieve maximum contrast between two points or areas of the ampligram or phasegram. This includes multiple results processing and contrast comparison.

This can be applied in the case that in the results has a contrast, albeit low between the areas of the image. In this case, by varying the delay and frequency deviations, the contrast of the image can be increased.

On fig. 5 is shown block algorithm of iterative method for determination of values of delay time and percentage frequency change. With using this method the number of iterations is lower than two parametric optimisation. If it is used two parametric optimisation the contrast at many combinations will be lower. As an example - if the delay between heat flux generated from excitation source and modulation signal is high but there are no changing this delay during measurement, combination of low delay and high frequency change will resulting lower contrast. If it is used the presented on fig. 4 iterative method will be executed only the first loop of the algorithm (increasing delay – calculate phasegram).

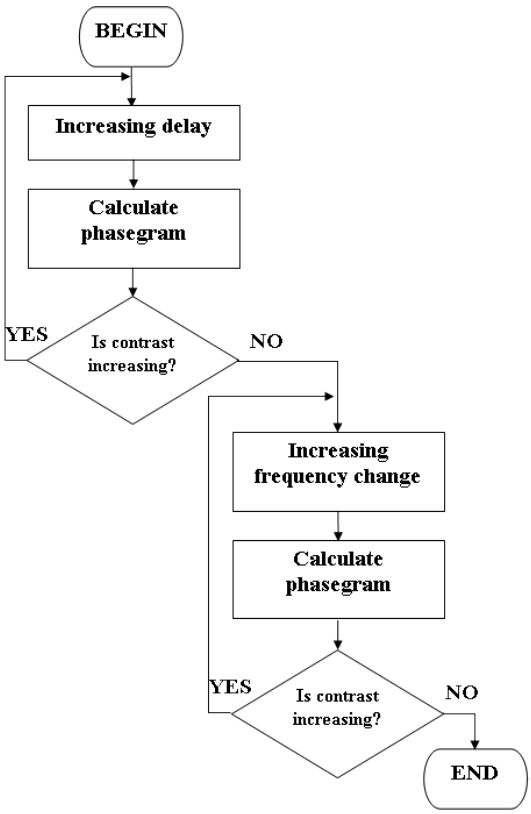


Fig. 5. Block algorithm of method for contrast increasing.

When it is used Fourier method can also be used percentage frequency change correction. Equation (8) is changed as follow:

$$K = exp\left(-j\left(\frac{2\pi m\,(100+d)}{100n}\right)\right) \quad (14)$$

3.3 Comparison of the methods effect and discussion

First it is presented the effect of separate methods.

The dependence between contrast and delay time is shown on fig. 6. It can be seen that the contrast depends on the phase angle of the correlation

function, as the output voltage in the synchronous phase detector depends on the phase angle between the reference signal and the frequency component of the input signal, the frequency of which is equal to the frequency of the reference signal. It can be seen that the maximum is not at zero delay, due to the delay between the change of the lamp light intensity and the modulation signal.

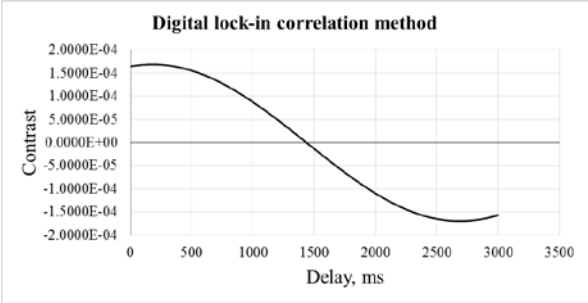


Fig. 6. Dependence between contrast and delay.

The dependences between contrast and percentage change in frequency are shown on fig. 7. It is seen that the maximum is not at the frequency of the modulation signal. This is due to the variations in the delay between changing the light intensity of the lamp and the modulation signal.

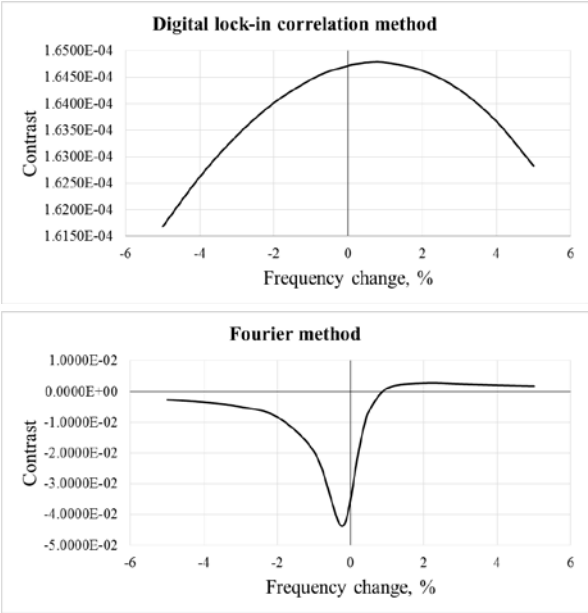


Fig. 7. Dependence between contrast and percentage frequency change (a – digital lock-in correlation method, b – Fourier method).

The combination of the both corrections (delay and percentage change of frequency) can increase the contrast of phasegram more than if it is used one correction.

To determine the effect of the both corrections on the contrast, 50 phasegram calculations were performed using the digital lock-in correlation method at different random combinations of the delay and percentage frequency change values. A highest contrast is obtained at delay of 600 ms and percentage frequency change of 19 % - $1.7999.10^{-4}$. Since the contrast depends on many factors such as lamp parameters, thermal parameters of the tested object, etc., the definition of dependence on which the values of delay and percentage frequency change can be calculated is difficult and the accuracy will be low. In this case can be used iterative method, whose block algorithm is shown on fig. 5. The obtained values in this method are 200 ms for delay and 7 % for percentage frequency change (the step for delay is 50 ms and for percentage frequency change – 0.5 %) after 18 computations of the phasegram and the obtained contrast is $1.7362.10^{-4}$. The contrast without correction is $1.6472.10^{-4}$. The comparison of obtained contrast at different values of delay and percentage frequency change is presented in table 1.

Table 1. Comparison between corrections.

Correction	Number of computations	Contrast
Without	1	$1.6472.10^{-4}$
200 ms 7 %	18	$1.7362.10^{-4}$
600 ms 19 %	50*	$1.7999.10^{-4}$

* This is a number of computations at random values of parameters. At other values it can be needed more computations for obtain the same contrast.

The phasegrams before and after using this method are shown on fig. 8.

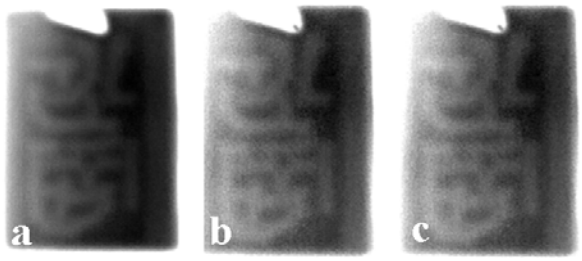


Fig. 8. Phasegrams before (a) and after using method for contrast increasing (b – 200 ms, 7 % and c – 600 ms, 19 %).

The phasegrams before and after using percentage frequency change correction at Fourier method using equation are shown on fig. 9. The contrast without percentage frequency change correction is $-3.5213.10^{-2}$ and with correction - $-4.3634.10^{-2}$ at percentage frequency change 0.2 %.

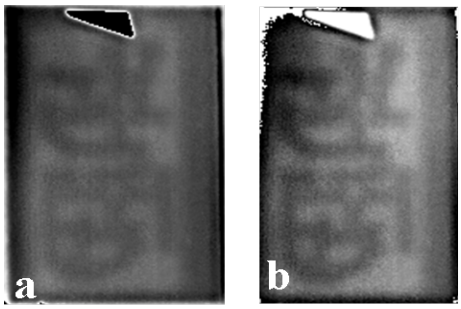


Fig. 9. Phasegrams before (a) and after (b) using percentage frequency change method at Fourier method.

It can be seen, that the contrast increasing with approximately 10 %. Consequently, for obtaining the same contrast as without correction it is needed lower average power of excitation source. As an example – the used block of halogen lamps as excitation source has high power (typically 1 kW per lamp). In this case can be realized significant energy saving, as well as prolongs the life of the lamp.

4 Conclusion

The described methods for contrast increasing is suitable in case of using different excitation sources (optical or electrical) and it is not needed simulation of measurement process. The choice of a particular approach depends on the thermo-physical and constructive parameters of the tested samples and the evaluated defects. Studies in this direction continue and concrete results will be discussed in a subsequent publication.

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