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Active Thermography Diagnostics of Hidden Defects in Multilayer FR-4 Substrates

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Abstract—This paper discusses the applicability of pulsed and lock-in thermography using Fourier transform processing to diagnose specific types of defects in Multilayer FR-4 Substrates. Digital thermal models of test specimens with different types of defects have been created. Based on the obtained results, the methods are compared in terms of applicability and reliability in defect detection. The results show that by these methods can be detected and characterized in terms of geometric dimensions and type of certain types of specific defects arising in the production of FR-4 multilayer substrates. The presented results show that there is no obstacle to the detection of defects in different layers of the multilayer substrate within the same measurement, as well as the possibility of detecting many types of defects.

Keywords—active thermography, hidden defects, multilayer FR-4 substrates, thermal modeling

I. Introduction

MULTILAYER substrates based on FR-4 insulation material are widely used in the manufacture of various electronic products. They are typically used in the production of printed circuit boards, but can also be used in the production of multichip modules. For example, MCM-L multichip modules use a multilayer FR-4 substrate [1].

To ensure high quality and reliability of the manufactured products, a very important stage of production is the effective diagnosis of substrates during their production. To reduce the final cost of the product, it is important that the diagnostic methods used are not expensive, while ensuring high reliability in detecting defects. The result of this diagnosis is expected to be defect-free substrates at a low diagnostic cost.

The types of defects that can occur during the production of such a substrate are many. They can be related both to the topology of the conductive layers (broken paths, shortened paths, paths with reduced cross-section, etc.) and to the insulation layers (e.g. air cavity in the prepreg layer). This variety of defects requires the use of a diagnostic method with wide possibilities. A noteworthy fact is that the defect material may have very opposite thermo-physical characteristics. For example, with an extremely high coefficient of thermal conductivity (copper) to one with very low (air).

In addition, to reduce the cost of the final product, it is important that the diagnostic method does not involve very expensive equipment and does not require any special preparation of the test sample, especially one that uses consumables with a certain resource and is time-consuming.

These conflicting requirements are largely met by infrared thermal diagnostics, which is a widely used method in the study of various materials [2], [3], [4]. To diagnose hidden defects, active thermographic methods are used, in which additional thermal stimulation of the studied sample is performed, its thermal behavior is recorded using an infrared thermographic camera and the obtained data are processed [5], [6]. Infrared thermography is very widely used in the diagnosis of electronic products [7], [8], [9], [10].

The main methods for the implementation of active thermography are pulse, transient and lock-in thermography [11]. All three methods have their advantages and disadvantages. In pulsed thermography, the measurement is very fast, but the thermal stimulation source (excitation source) is more specific and, respectively, more expensive. In transient thermography, there is both easy implementation, cheap excitation sources, and simple processing of the obtained data, but the sensitivity is worse. Lock-in thermography, in general, gives the best results, but it has a more complex implementation, more complex data processing, and the measurements are long.

The quality of the obtained results depends to a large extent on the processing performed on the data obtained from the thermographic study. In general, processing with extraction of a certain frequency component (e.g. Fourier transform) gives the best results in terms of defects located at greater depths. This processing can typically be applied to lock-in or pulse thermography data.

This paper discusses the applicability of pulsed and lock-in thermography using Fourier transform processing to diagnose specific types of defects in Multilayer FR-4 Substrates. Digital thermal models of test specimens with different types of defects have been created. For each type of defect, it is possible to study the influence of the depth at which the defect is located relative to the surface of the sample.

Based on the obtained results, the methods are compared in terms of applicability and reliability in defect detection. The effect of the application of some types of additional data processing has been studied.

II. Thermal Model of Multilayer FR-4 Substrate with Defects

The model is developed using the widely used specialized software product for modelling and simulation of thermographic measurements ThermoCalc 3D [12]. Fig. 1 shows the test specimen layers description - materials used and dimensions.

The model has dimensions of 45 mm × 30 mm. It consists of 11 layers - 9 insulation layers (FR-4 and prepreg), copper layers (where there is a path) and layer of flexible PVC. The last layer is an insulating tape, which is needed in real measurement for emissivity correction.

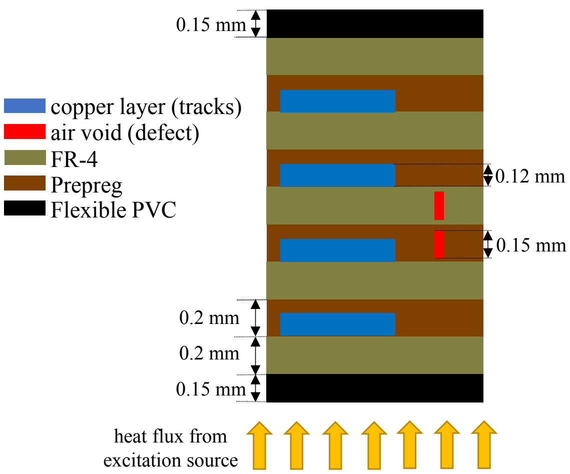

Figure 1. Description of test sample layers

The topology of the hidden layers is shown in Fig. 2. The types of artificial defects in copper layers are described. The location of the defects in the prepreg layer (red squares) is shown. The thermal-physical parameters of the individual layers are presented in Table. 1.

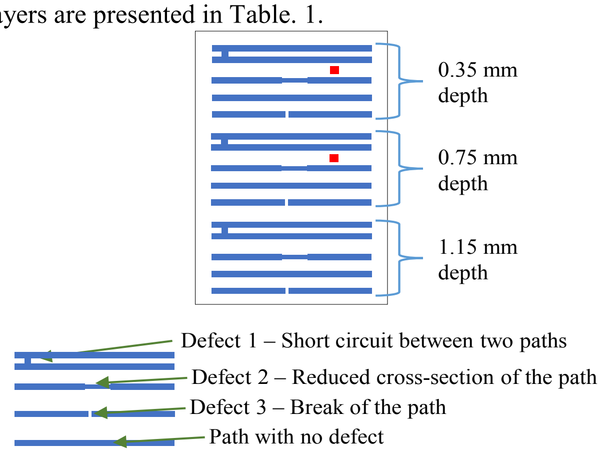

Figure 2. Topology of the hidden layers and description of the types of defects embedded in the test specimen

Table 1. Thermal-physical properties of materials used in the test sample (properties taken from [13], [14], [15], [16], [17])

parameter	value for FR-4	value for copper	value for prepreg	value for air	value for flexible PVC
thermal conductivity k [W m^{-1} K^{-1}]	$0.25_{x,y}$ 0.17_z	400	$2_{x,y}$ 0.6_z	0.024	0.155
density ρ [kg m^{-3}]	2100	8920	1500	1.276	900
specific heat capacity c_p [J kg^{-1} K^{-1}]	570	385	850	1006	1225

The created thermal model of the test sample in the environment of ThermoCalc 3D is shown in Fig.3. Two different views of the test sample model are shown. The horizontal and vertical location of the defects is shown.

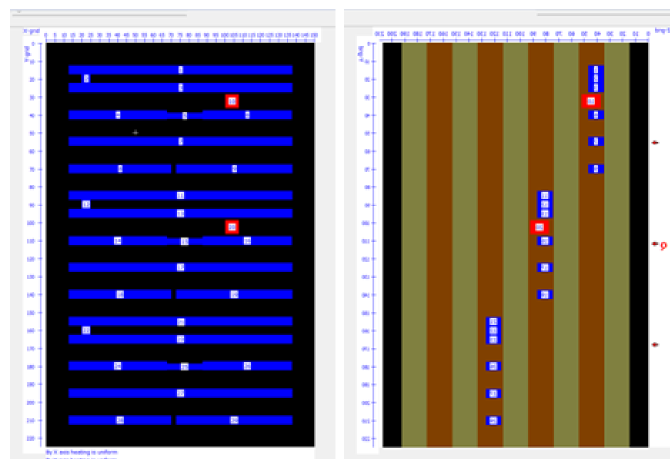

Figure 3. The created thermal model of the test sample in the environment of ThermoCalc 3D

III. Active Thermography Study and Post-Processing Methods

The research was performed by using two different methods for the implementation of active thermography in relation to the method of thermal stimulation - pulse and lock-in. The simulated measurements were performed in the environment of ThermoCalc 3D. The data obtained from the simulated measurements were processed by extracting the frequency component using the Fourier transform method.

A. Lock-in thermography study

Fourier transform (FT) was used as a method for processing the results from lock-in thermography studies. The defects are characterized by the amplitude and the phase of the corresponding temperature signals. When processing data from lock-in thermography, compensation of the temporal mean component [18], [19] is often performed, which partially eliminates the dependence of the calculated amplitude and phase on the non-stationarity of the thermal regime. Since the main goal of the specific study is to detect the defect and estimate its geometric dimensions, without using the specific value of the amplitude or phase, results are presented in both cases - with compensation and without compensation.

The amplitude/phase of the temperature signal for each pixel are calculated as follows [20]:

$$S^F = \frac{1}{I_{last} - I_{first} + 1} \times \sum_{k=I_{first}}^{I_{last}} F_k \times K^F, \tag{1}$$

$$K^F = -2 \times e^{-j\frac{2\times\pi\times(k-1)}{n}}, \tag{2}$$

$$n = \frac{1}{f_{lock-in}} \times f_{frame}, \tag{3}$$

$$I_{last} = n \times N, \tag{4}$$

$$I_{first} = I_{last} - n \times N_{comp}, \tag{5}$$

$$\mathrm{A} = \sqrt{Re(S^F)^2 + Im(S^F)^2}, \tag{6}$$

$$\Phi = \tan^{-1}\frac{Im(S^F)}{Re(S^F)}, \tag{7}$$

where F_k is the k-th time value of the temperature signal, I_{first} and I_{last} are the first and last index of temperature signal values, on which the processing is performed, n is the number of signal time values for one lock-in period, $f_{lock-in}$ is the lock-in frequency, f_{frame} is the camera frame rate, N is the number of periods, N_{comp} is the number of periods used in computation, A is the calculated amplitude and Φ is the calculated phase.

The parameters of lock-in thermography simulated measurement are presented in Table 2.

B. Pulse thermography study

Although the Fourier transform is typically used in the processing of data obtained from lock-in thermographic measurements, it can also be used in pulsed thermography data - e.g. pulse-phase thermography [21]. The processing is performed in the same way as for data from lock-in thermography, as the selected lock-in frequency is actually the frequency of the extracted frequency component.

The parameters are presented in Table 3.

Table 2. Parameters for lock-in thermography study

parameter	value
lock-in frequency $f_{lock-in}$ [Hz]	0.2 (0.1)
frame rate f_{frame} [fps]	10 (5)
number of periods N	10 (10)
number of periods used in computation N_{comp}	7 (7)
average heat flux though test sample $q_{excitation}$ [W m^{-2}]	1000
image resolution [pixels]	150 × 225

Table 3. Parameters for pulse/transient thermography study

parameter	value
pulse width t_{pulse} [s]	0.005
frame rate f_{frame} [fps]	200
excitation energy $E_{excitation}$ [kJ m^{-2}]	6000
image resolution [pixels]	150 × 225
extracted frequency component (FT) $f_{extracted}$ [Hz]	1

IV. Results

A. Results from lock-in thermography

The results from the lock-in thermographic study at 0.2 Hz are shown in Fig. 4 and Fig. 5. Normalized values for the phase and amplitude of the respective copper path (amplitude/phase profile, which gives amplitude/phase values for each pixel from left to right side of the copper path) are shown for different depth of the defect for paths with defects 1-3 and the defect-free path, as well as for defect 4 (air void in prepreg layer).

Results are shown for two cases - without compensation of the temporal mean component and after compensation of the temporal mean component.

The results after compensation of the temporal mean component are shown with a dotted line, and the letter "C" is marked in the legend.

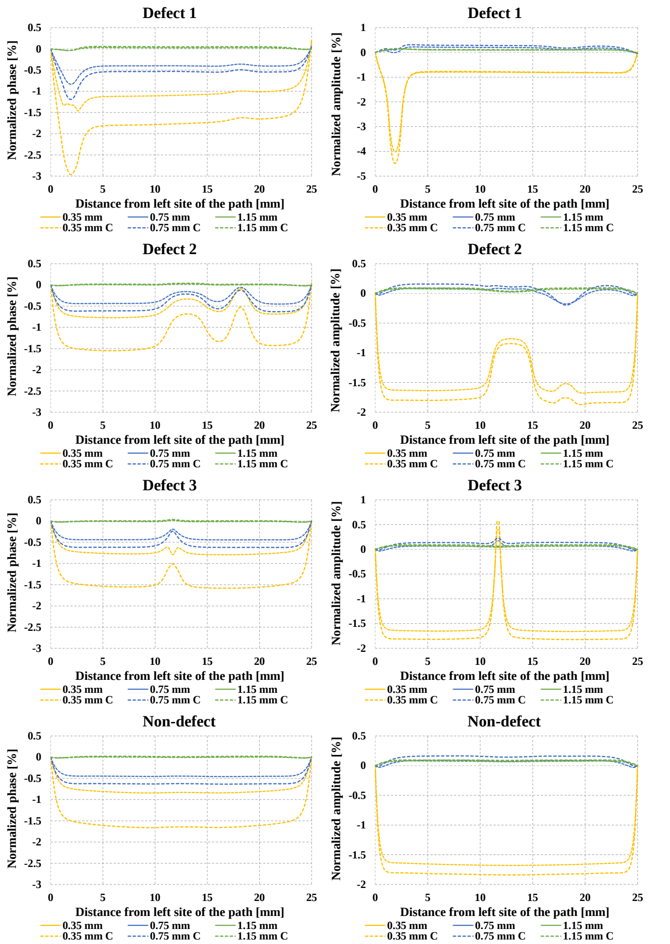

Figure 4. Results for copper layer defects from the lock-in thermographic study at 0.2 Hz

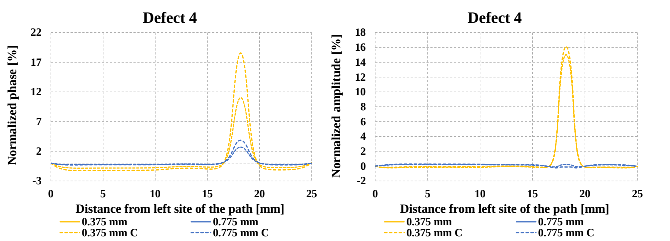

Figure 5. Results for prepreg layer defect from the lock-in thermographic study at 0.2 Hz

The results show the applicability of lock-in thermography in the detection of this type of defects in this case.

In the case of defects located at a depth of 0.35 mm, all types of defects are successfully detected, both through the amplitude profile and through the phase profile. In general, compensation of the temporal mean component leads to better results, improving the ability to estimate the geometric dimensions of the defect and its location, as well as the signal-to-noise ratio.

For defects located at a depth of 0.75 mm, all types of defects are successfully detected by the phase profile. In the amplitude profile, the signal-to-noise ratio is quite low and it is likely that in real measurement, defects cannot be detected. In general, compensation of the temporal mean component leads to better results in the phase profile. Regarding the amplitude profile, no positive effect of compensation of the temporal mean component is observed.

For defects located at a depth of 1.15 mm, the detection is practically impossible for most defects both in phase profile and in amplitude profile. No positive effect of compensation of the temporal mean component was observed.

In general, the defect in the prepreg (defect 4 - air void) is detected much better than the defects in the tracks.

Results of the lock-in thermographic examination at 0.1 Hz are shown in Fig. 6 and Fig. 7. Similarly to Fig. 4 and Fig. 5 - normalized values for the phase and amplitude of the respective profile are shown for different depth of the defect for tracks with defects 1-3 and the defect-free track, as well as for defect 4 (air void in prepreg layer).

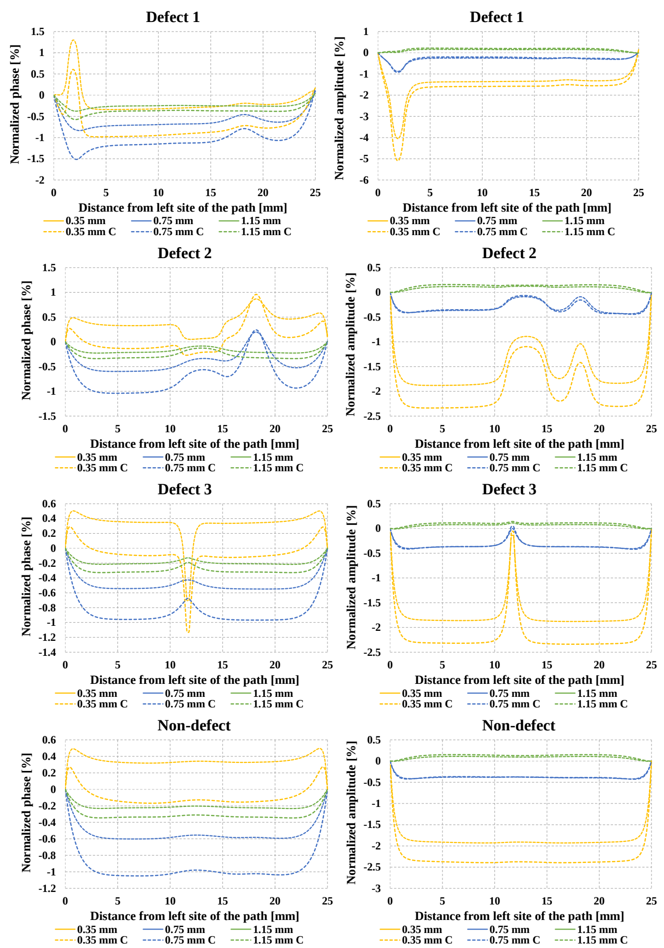

Figure 6. Results for copper layer defects from the lock-in thermographic study at 0.1 Hz

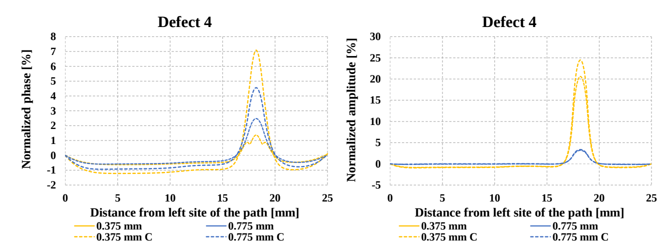

Figure 7. Results for prepreg layer defect from the lock-in thermographic study at 0.1 Hz

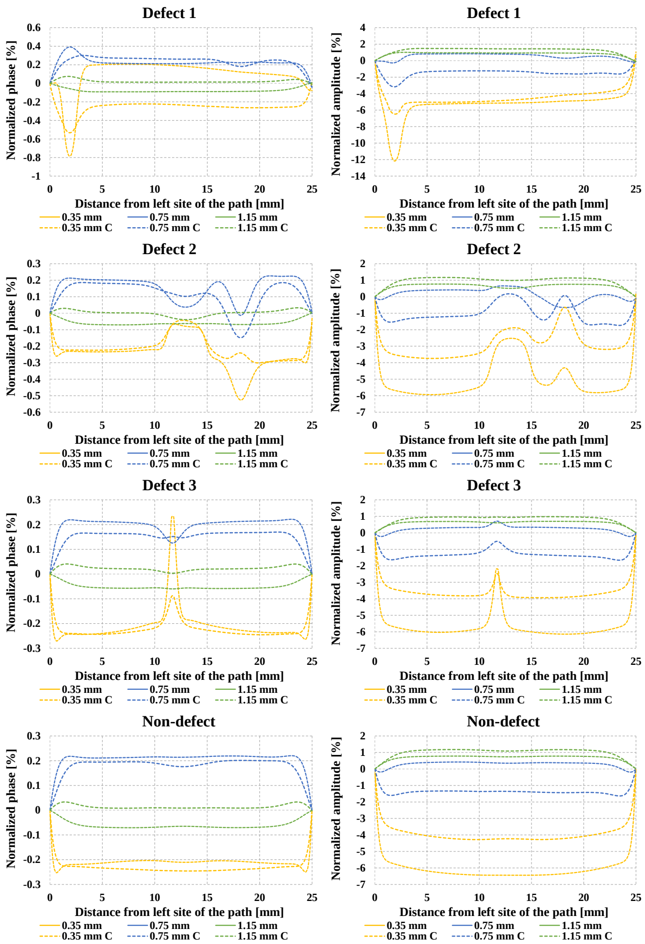

Figure 8. Results for copper layer defects from the pulsed thermographic study

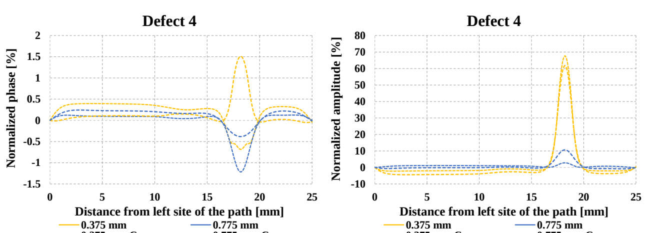

Figure 9. Results for prepreg layer defect from the pulsed thermographic study

Results are shown for two cases - without compensation of the temporal mean component and after compensation of the temporal mean component. The results after compensation of the temporal mean component are shown with a dotted line, and the letter "C" is marked in the legend.

The results obtained are similar to the frequency 0.2 Hz, but in this case a slightly better detection of defects located at a depth of 1.15 mm is observed. It is still very low, but now the probability of finding defects at such a depth is a little higher.

In this case, the positive effect of compensating for the temperature drift is also observed, as its effect is already noticeable in the case of defects located at a depth of 1.15 mm. In terms of amplitude, there is also increased detectability.

B. Results from pulsed thermography

The results from the pulsed thermographic examination are shown in Fig. 8 and Fig. 9. Normalized values for the phase and amplitude of the respective profile for different depth of the defect for paths with defects 1-3 and the defect-free path, as well as for defect 4 (air void in prepreg layer) are shown. They are shown for two processing variants. The dotted graphs are when processing 1/3 of the sequence (marked with the letter "C"), and the rest - at 2/3.

The results obtained are analogous to the lock-in thermographic measurement. Detectability is similar, again there is a problem in detecting most of the defects located at a depth of 1.15 mm.

V. Conclusion

The applicability of pulsed thermography and locking thermography in detecting specific defects in multilayer FR-4 substrates has been studied. The results obtained show that by these methods can be detected and characterized in terms of geometric dimensions and type of certain types of specific defects arising in the production of FR-4 multilayer substrates. The results obtained show that there is no obstacle to detecting defects in different layers of the multilayer substrate within the same measurement, as well as very different types of defects - for example short circuit in copper layer and air void in prepreg layer. Therefore, active thermography can be used both to look for defects in the structure and as an additional control to the electrical test. For example, an electrical test is unlikely to detect a reduced cross-section, as well as very close conductive paths, but without a short circuit. Such problems will potentially lead to a defect in the future. As a future work it is necessary to study the possibilities for classification of the type of defect, as well as its automatic detection and characterization.

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