Optimal Modelling of Planar Thermal Converter Device

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Abstract— The root mean square (rms) measurement of alternating voltage of any waveform is frequently done by means of thermal transfer instruments. The principle of these thermal rms converters is to transfer the heating energy of resistive load to a temperature-sensing element. The dc voltage output of the sensor reflects the amount of electrical power (ac or dc) applied to the input. This paper is addressing the modelling of a thermal converter device in planar technology using finite element platform. The original approach of this study capitalizes on introduction of a resistive thermal sensing element of a planar type to provision the thermal-conversion response to the active power dissipated on the 3D stratified non-reactive heater structure. Through iterative multi-physics simulations, model properties and dimensions have been evaluated and optimized.

Keywords— Thermal converter, thermoelectric sensor, thermal transfer, solid state device.

1. Introduction

The ac-rms is the equivalent to the dc heating value of a particular waveform. Effective values measurements have been reported in early years based on electrodynamic instruments [1].

Thermocouple was the first temperature sensor used. It provides a direct conversion between temperature and voltage with good linearity and sensitivity of up to 68 μV/°C with relative low stability in time. The advent of thin-film technology did see introduction of “multijunction” meaning a large number of thermocouple have been connected in series to increase the sensitivity [2]. Further research shows introduction of 64 Si-Bi micro-thermocouples deposited on a poly-amide film in conjunction with a Ni-Cr heater sputtered on a 2 mm × 8 mm AlN (Aluminum Nitride) chip [3]. Technology of planar thermocouple design and deposition is quite complex and requires special tooling that motivates for investigation of alternative sensor techniques.

This study is a continuation of the analysis presented in [10].

2. RMS-DC Conversion Standards and Their Applications

As the definition states, the rms value assigned to an ac voltage is the amount of the dc voltage required to produce equivalent amount of heat on the same load. Hence, the ac voltage is compared with the dc voltage by alternately applying them to the same heater and measuring the temperature rise. Mathematically, it involves squaring the signal, taking the average and obtaining the square root. For any form of voltage waveform $v(t)$, the basic definition of the true rms conversion is [5], [6]:

$$V_{\mathrm{rms}} = \sqrt{\frac{1}{T}\int_0^T v^2(t)\,\mathrm{d}t}\,, \qquad (1)$$

where T is the period of the input signal.

Based on this definition a few solutions exist at present:

- Analog circuit to perform calculation where the integration depend on an additional capacitor. Hence it has problems for low frequencies as well as for high frequencies.
- Thermal ac-dc converter, as studied in this paper.

Fig. 1 shows the basic principle of a solid state rms-dc thermal converter. The method compares the heating response of an unknown ac voltage to the heating response of a known dc reference, which is calibrated in the laboratory to an SI-traceable standard.

In early years, when the measurements were of interest up to 20 kHz, the heater was in a form of resistive wire with relatively low inductive component [1]-[3]. The moment higher frequencies came under scrutiny the heater became impedance depending on the input frequency signal.

The solution was building the heater within thin-film technology with a specific geometry that reduces inductivity and using resistive materials with low temperature coefficient such as the alloys base of Cu and Ni [6], [8].

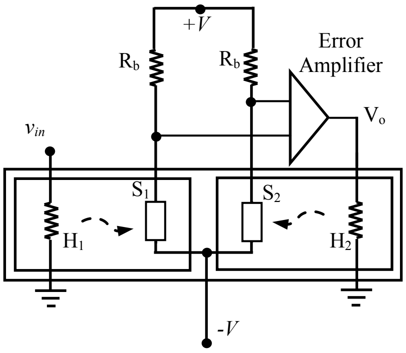


Fig.1 Thermal rms conversion – basic principle

For the thermal sensor, Pt100 and Pt1000 are taken in consideration. Platinum elements are characterized by reliability, long time stability and very good linearity in operational temperature range of rms-dc converter. The use of a Pt1000 in thin-film technology is a good compromise between the cost and the measurements accuracy.

3. Model Configuration and Design Flow Analysis

The heater-sensor (H and S from Fig.1) joint constitutes a fundamental component of a thermal converter that implements non-conductive rms energy mapping from the measured load to the gauging equipment, i.e. digital voltmeters and comparators. In the process of design of the optimal rms-dc thermal converter it is generally necessary to ensure flatness of the frequency response in the operational band, i.e. to obtain satisfactory resistance/reactance ratio of the heater, and to adopt a sensing element which would have a good sensitivity to the heat flow change, e.g., Pt1000 resistive elements are seen more favorably than the Pt100 resistive elements would be albeit their higher cost.

Fig. 2 presents the proposed design topology which ensures uniform heat flow distribution in the vicinity of the thermal sensing element. The ceramic (Al_2O_3) package walls ensure adiabatic thermal isolation of the chip structure. AlN substrate layers provision for good thermal conductance and high dielectric strength.

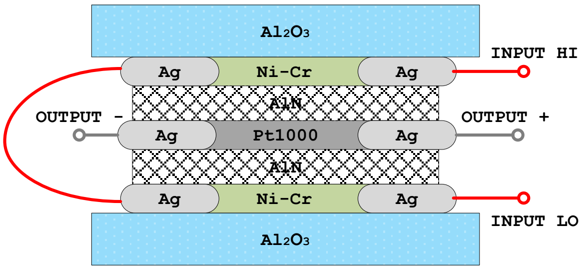


Fig. 2. Stratified design topology of the planar thermal converter

This paper considers two candidate heater designs: metal foil U-shape (similar to [3]) and stripline elliptic Fermat spiral form (Fig. 3) [4].

The design of the planar sensing element is implemented in the form of an elliptic spiral similar to the latter heater design that allows optimizing sensor placement on the substrate and obtaining the required resistance by varying the cross-section of the spirally shaped stripline [7]-[9].

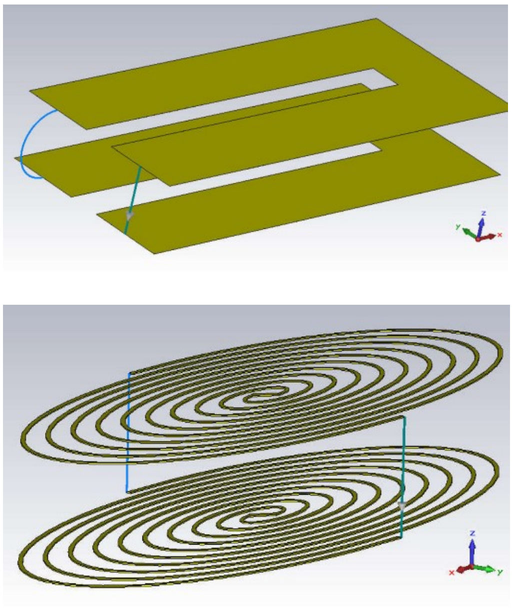


Fig. 3. Two variants of heater design

A. *Electromagnetic Modelling*

It is beneficial to reduce the dimensions of the planar structure as much as possible to minimize the impact of the materials imperfection on the electromagnetic field and heat flow while preserving the required sensitivity level.

The designed planar structure was sized to fit in a typical dual-in-line IC package with 16 pins. The length of the substrate was selected to be no more than 6.5 mm and the width – no more than 2.7 mm. The IC package cavity height also dictates restriction to keep the multi-layer structure less than 1 mm thick.

The 0.05-µm thick U-shape heater design is compared with the 10-µm thick spiral design (Fig. 3). Both structures effectively span horizontal area of the substrate and have about the same resistances.

The electromagnetic simulation model was implemented in the CST Microwave Studio software. The model accounts for the physical properties of the conductor and substrate materials. The model was defined in terms of a full-wave problem with application of a low-frequency frequency domain solver. All the components of the model were constructed in the 3D geometry and mesh composition of multiple tetrahedral cells. The mesh structure for some of the planar components is shown in Fig. 4 (spiral heater example).

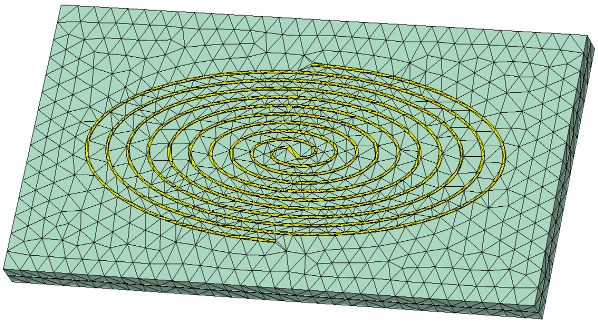
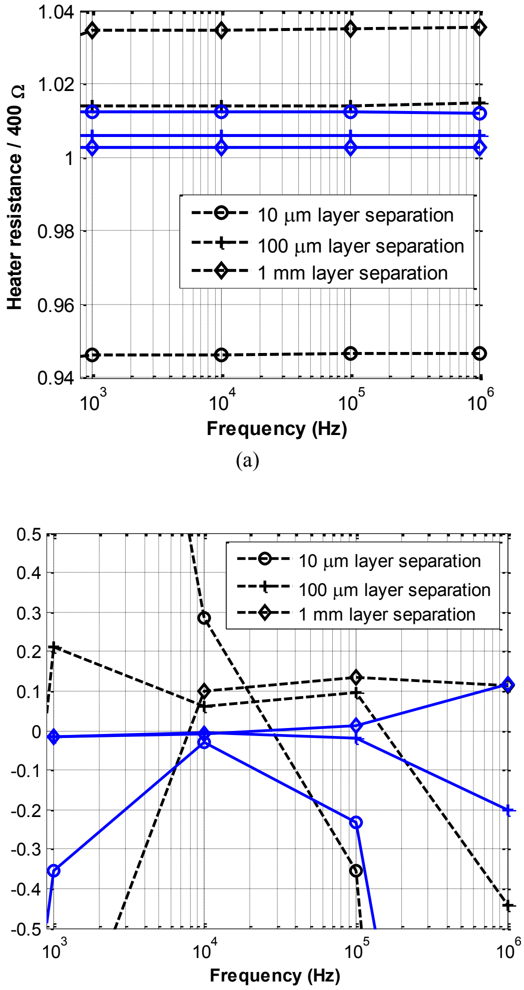


Fig. 4. Mesh structure for the model of the thermal converter with the spiral heater

The electromagnetic simulation scenarios were configured to compute impedance of the heater conductor structure. The stimulus signal frequency ranged from 1 kHz to 1 MHz and the amplitude was set to 1 V (rms).

Fig. 5 shows frequency dependence of the impedance components. The resistance of the continuous metal film structure (U-shape heater variant) tends to lower when the heater layers are closest to each other (10 µm). Resistance increase due to the skin effect is noticeable in case of the U-shape design at frequencies above 100 kHz. In contract to that, the resistance of the spiral structure showed no variation with frequency and very low dependence on the layer separation. The reactance frequency characteristic also favors the spiral design and point at the optimal heater layer separation in the range from 100 µm to 1 mm.



(a)

(b)

Fig. 5. Frequency dependence of the resistance and reactance for the three cases of separation between the planar heater layers (dotted line correspond to the U-shape heater design, and solid lines – to the spiral design):

(a) Heater resistance normalised to 400 Ω;

(b) Heater reactance.

B. *Electrothermal Modelling*

The results of the thermal distribution of heat power were obtained in the course of the coupled electromagnetic and thermal simulations in the CST Multiphysics Studio. The thermal model shared the same meshing structure and was supported by the same solver type. The boundaries of the model were defined to be in the isothermal state corresponding to 23 °C.

Below is the representation of the 3D design to facilitate thermal flow concentration in the region of the sensing element. Fig. 6 shows the heat flow distribution within the chip structure.

One can observe that the sensing spiral (shown in black color) is placed on the center of the heat flux originating from the bottom heater.

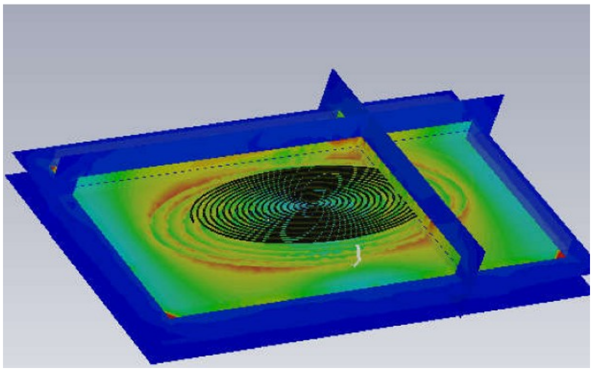


Fig. 6. Heat flow distribution inside the chip structure

Fig. 7 shows the steady-state distribution of the thermal potentials across the chip layers. One can see that the thermal field covers entire zone surrounding the sensing element. Margins of the substrate volume ensure a sufficient gradient to established equilibrium with the controlled ambiant temperature.

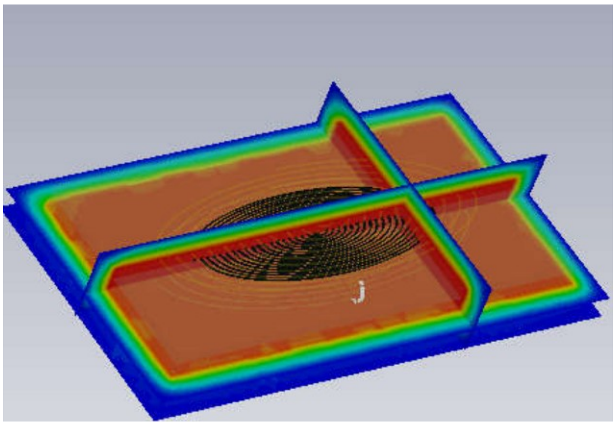


Fig.7. Thermal map of the chip cross-section

4. Conclusions

In this study, we managed to conduct a combined simulation of electromagnetic and thermal processes which lie in the basis of rms-dc converter realization. The small micro-structure allows breakdown of complex shapes channeling electromagnetic/thermal energy into elementary components which have trivial mathematical description and allow for optimal planar structure design with a great degree of integration and loss minimization.

It should be noted that the results derived in this study rely on the accuracy of the low-frequency frequency domain solver that has limitations in the sub-kHz analysis region. To extend the lower frequency margin, it would be necessary to redefine the model specification and configuration to suit the low-frequency time-domain solver use.

Implementation of the heater and sensor in the elliptic spiral form has not yet been reported in literature to the best knowledge of the authors, and the proposed concept could potentially enable production of the planar thermal conversion devices using legacy technological processes.

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