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Department of Electrical Engineering and Computer Science

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Electromagnetic-Thermal Analysis Study Based on HFSS-ANSYS Link

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ABSTRACT: In this work, rigorous thermal analysis is done for the first time based on the link between Ansoft HFSS and ANSYS. High-frequency results obtained from HFSS including surface loss density and volume loss density are imported into ANSYS. The thermal analysis run into ANSYS incorporates accurately the non-uniform power distribution in the microwave structure and hence predicts very well the thermal map for high-power applications. Experimental results confirm the developed approach.

KEYWORDS: Ansoft HFSS, ANSYS, finite-element method, packaging, surface-loss density, thermal analysis, volume-loss density

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Abstract

In this work, rigorous thermal analysis is done for the first time based on the link between Ansoft HFSS and ANSYS. High-frequency results obtained from HFSS including surface loss density and volume loss density are imported into ANSYS. The thermal analysis run into ANSYS incorporates accurately the non-uniform power distribution in the microwave structure and hence predicts very well the thermal map for high-power applications. Experimental results confirm the developed approach.

Index Terms—Ansoft HFSS, ANSYS, finite-element method, packaging, surface-loss density, thermal analysis, volume-loss density.

I. INTRODUCTION

The current demands on radio frequency (RF)/microwave planar circuits are pushing towards miniaturization and population of more and more circuits in smaller real estate. This comes at the price of increased heating which possibly limits circuit functionality. Also, for radar and ground station applications, the transmitting-circuit elements are expected to handle high power which requires special dielectric materials with high thermal conductivity and good thermal path to heat sink. Before proceeding to fabrication, mechanical engineer assesses the thermal map within the circuits based on the insertion loss as well as distribution of surface currents supplied by the RF engineer. The current approach of thermal analysis is mainly carried out by mechanical engineer and it is based on the assumption of uniform loss distribution on metallic surfaces. However, this assumption is quite far from real thermal measurements as will be explained later and eventually for packaged structures with dense circuitry this approach is expected to fail.

Recently, the newer versions of ANSYS [1] have the capability to interpret Ansoft-HFSS [2] electromagnetic results and compute steady-state as well as transient temperature response. ANSYS and Ansoft-HFSS are commercial software tools based on finite-element method (FEM). HFSS and ANSYS are two different platforms integrated together to model accurately the thermal-electromagnetic interaction, i.e., finding the thermal map corresponding to power loss distribution within any microwave package. The objectives of this work are: (1) Use HFSS and ANSYS to find the temperature distribution inside packaged radio frequency/microwave components. For this purpose, the temperature dependence of electrical properties such as complex permittivity and electrical conductivity are included in the full-wave electromagnetic model. (2) Study the effect of temperature dependence on the frequency response. (3) Investigate the outcome of electrical properties varying with temperature on power losses. (4) Compute temperature distribution inside packages where it is difficult to access the inside with thermocouple. It is noted that the intrusion of thermal probes inside a closed package is expected to alter the electromagnetic field distribution and hence perturb the optimized-design performance while doing thermal test.

II. HIGH-FREQUENCY ANALYSIS

The microwave circuit considered in this study is shown in Fig. 1. It consists of back-to-back transition between 50-Ω line and 10-Ω load on a Roger RT/Duroid 6006 substrate of thickness 50 mil. Each transition consists of five sections of quarter-wave transformers. The frequency responses obtained at room temperature from simulations using Ansoft HFSS and measurements are shown in Fig. 2. The results show that the insertion loss IL at mid-band frequency 3 GHz is 0.62 dB. An estimate of total power dissipated P_d in the circuit is computed using (1).

$$P_d = P_{in}\left(1 - 10^{-IL/10}\right), \tag{1}$$

where P_{in} is the input power applied to the circuit. It is assumed in (1) that the circuit is well matched at input.

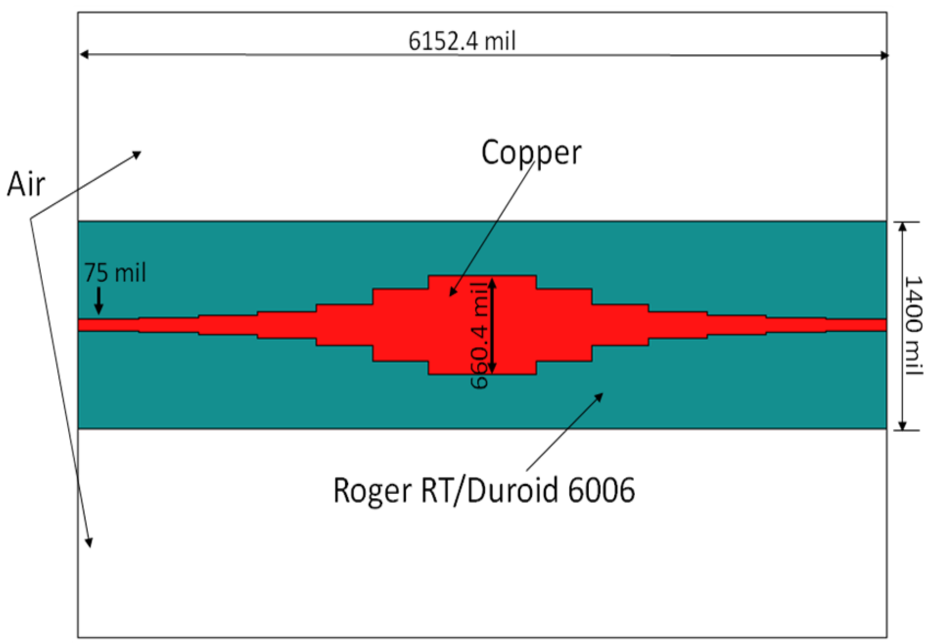


Fig. 1. Top view of back-to-back microstrip transition consisting of 5 sections of quarter-wave transformer.

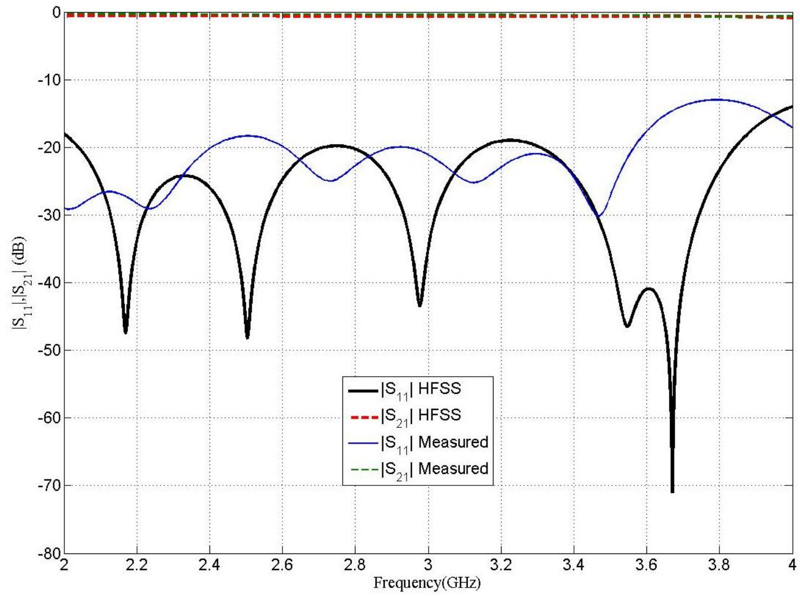
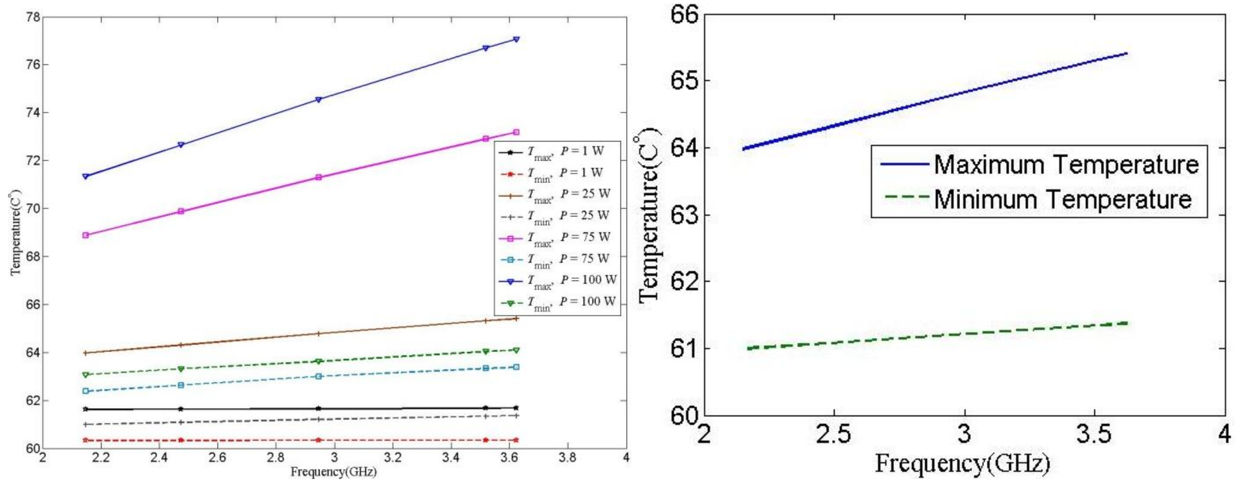


Fig. 2. Frequency responses of the circuit shown in Fig. 1 as obtained from HFSS and microwave measurements at room temperature 22 °C.

III. THERMAL-ELECTROMAGNETIC INTERACTION

A material is heated using electromagnetic signal. This is attributed to the presence of inherent metallic and material losses. Material losses can be due to dielectric losses for dielectric materials or magnetic losses for magnetic materials. Herein, in this work, it is reasonable to assume that magnetic losses are neglected as we are dealing with non-magnetic materials. The electromagnetic signal interacts with the material on the molecular level and leads to temperature heating as power is absorbed within lossy material. For material losses, the temperature rise is linearly proportional to operating signal frequency and quadratically proportional to signal amplitude. To study the effect of power and frequency, first HFSS is used to compute the high-frequency electromagnetic response of structure. HFSS gives as output the two types of loss quantities: (i) surface loss density (W/m^2) which comes from metallic losses: $P_{Lc} = \frac{R_s}{2}\int_s \left|\vec{H}_t\right|^2 ds, R_s = \sqrt{\frac{\omega\mu_0}{2\sigma}}$ where P_{Lc} is average conductive-power loss, R_{s} is surface resistance, ω is angular frequency, μ_0 is the permeability of free space, σ is metal conductivity, $\vec{H}_t$ denotes tangential magnetic field, and S is the surface of conductor and (ii) volume loss density (W/m^3) attributed to dielectric losses: $P_{Ld} = \frac{1}{2}\omega\varepsilon_0\varepsilon_r^{"}\int_V \left|\vec{E}\right|^2 dV$, where P_{Ld} is average dielectric-power loss, ε_0 is the permittivity of free space, $\varepsilon_r^{"}$ is the imaginary part of material permittivity and it represents losses, $\vec{E}$ denotes electric field, and V is the volume of dielectric. Second, the electrical results including losses are imported into ANSYS which performs mechanical simulations and gives thermal-dependent properties corresponding to losses which are function of frequency and the power level of input microwave signal. The graphs in Fig. 3 give the variation of temperature versus frequency at different power levels for the microwave circuit shown in Fig. 1.



(a) (b)

Fig. 3. (a) Maximum and minimum steady-state temperature recorded on the top surface of the heated microwave circuit shown in Fig. 1 versus the frequency of applied input signal at different input power levels. (b) Zoom on temperature variation versus frequency at input power level of 25 W.

The thermal-electromagnetic interaction is a closed-feedback process. Electromagnetic power is applied to the microwave circuit to be tested. Initially, at room temperature a well-designed microwave circuit has minimum insertion losses which are the inherent losses of the circuit itself. As the amount of power input to the circuit increases, each element of circuit dissipates partial amount of electromagnetic energy which transforms to heating energy and a corresponding rise of temperature that may differ from one point of the circuit to another depending on the layout of circuit. The electrical properties of circuit elements are changing as it is heating up as indicated by the following equation:

$$x(T) = x(T_0)\left[1 + C_1(T - T_0) + C_2(T - T_0)^2\right], \tag{2}$$

where x is any electrical property such as: dielectric constant, loss tangent, and resistivity. T_0 is the ambient temperature, T is the temperature of heated circuit which is position dependent if circuit is not heated homogenously, and C_1 and C_2 are linear and quadratic expansion coefficients, respectively. In real world, all elements are continuously varying which is equivalent to a varying output response until steady state condition is reached. This is the reason why the approach of uniform power distribution followed by mechanical engineer fails. Moreover, edge effects are not taken into account. It is noted that while circuit elements are heating there are three different mechanisms of heat transfer: (i) conduction takes place in metallic/dielectric parts and it is controlled by their thermal conductivities, (ii) convection occurs in fluids and the corresponding convection coefficient need to be evaluated accurately. Convection mechanism is divided into two categories: natural and forced. Natural convection coefficient varies from 1 to 25 W/m^2.°C. It is obtained from iterative numerical process in ANSYS as shown in Fig. 4 where the results indicate that no significant change of temperature as long as convection coefficient is less than 25 W/m^2.°C. (iii) Radiation is electromagnetic radiation emitted from heated material.

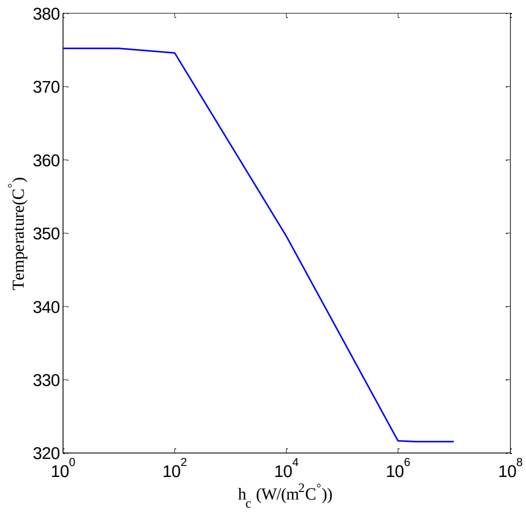


Fig. 4. Variation of temperature versus convection coefficient used in ANSYS model.

The thermal results obtained from ANSYS are imported back to HFSS for re-computation of new losses and this process is repeated for several iterations until a convergence criterion is satisfied as clarified by the decision chart shown in Fig. 5.

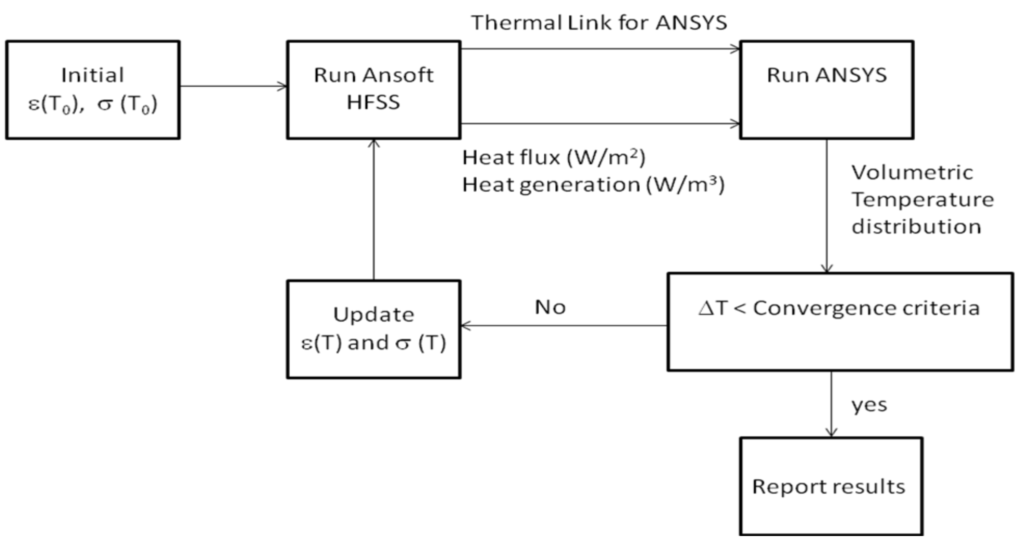


Fig. 5. Decision chart showing the main steps for running HFSS-ANSYS.

The validity of simulation results are verified versus experimental results for input power levels up to 25 W as shown in Fig. 6. It is noted that the discrepancy between the simulation and measurement is due to the fact that substrate surface was not flat against the hot plate which creates air pockets between the RF ground plane of circuit and hot plate. The presence of air gaps becomes more pronounced as the input power level increases. Temperature profiles on the top surfaces of dielectric and metallization as obtained from ANSYS are illustrated in Fig. 7 (a) and (b), respectively for the case of 1 W applied input power at frequency 2.148 GHz (first resonant frequency obtained at room temperature). The thermal map helps to visualize clearly the locations of hot and cold spots in the structure and hence find possible solution to have drastic increase of temperature in critical areas.

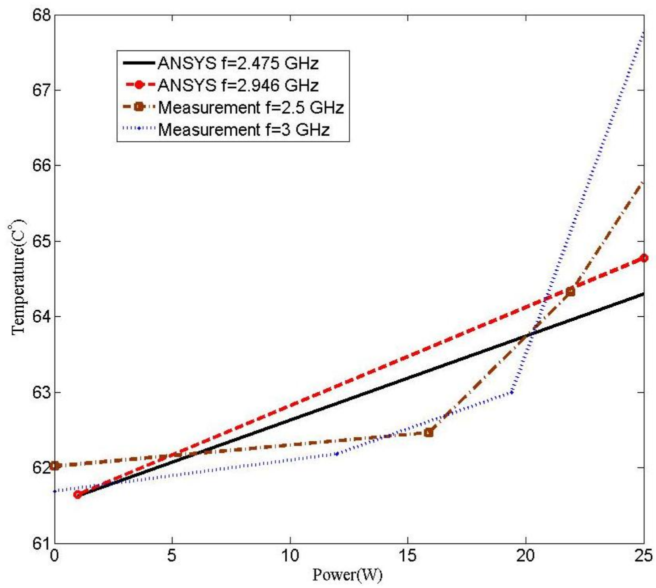


Fig. 6. Steady state temperature versus power level at different frequency as obtained from measurements and simulations using ANSYS.

After getting the temperature profile as shown in Fig. 7, the change of electrical parameters can be determined as follows. For dielectric substrate used in this case study: C_1 = -410 × 10^{-6} °C^{-1}, C_2 = 0, T_0 = 22 °C, T = 65 °C, $\varepsilon(T_0)$ = 6.15, substituting these parameters in (2) gives $\varepsilon(T)$ = 6.0416. For conductor metallization, the following equation is used:

$$\sigma(T) = \sigma(T_0)\left(1 + a_1(T - T_0) + a_2(T - T_0)^2\right)^{-1}$$

For copper metallization using the following parameters: a_1 = 4.29 × 10^{-3} °C^{-1}, a_2 = 0, T_0 = 22 °C, T = 65 °C, and $\sigma(T_0)$ = 5.8 × 10^7 S/m gives $\sigma(T)$ = 4.897 × 10^7 S/m.

The dielectric constant drops from 6.15 at 22 °C to 6.0416 at 65 °C, i.e., $\varepsilon(T) < \varepsilon(T_0)$. This leads to the change of a resonant frequency according to the following relation: $f_r = \frac{c}{4l\sqrt{\varepsilon(T)}}$, where c is the speed of light and l is the physical length of each quarter-wavelength section. The resonant frequencies of the initial frequency response shown in Fig. 2 are shifted 25 MHz up as shown in Fig. 8. This shift of resonant frequencies can cause severe effects on the frequency response of narrow-band components.

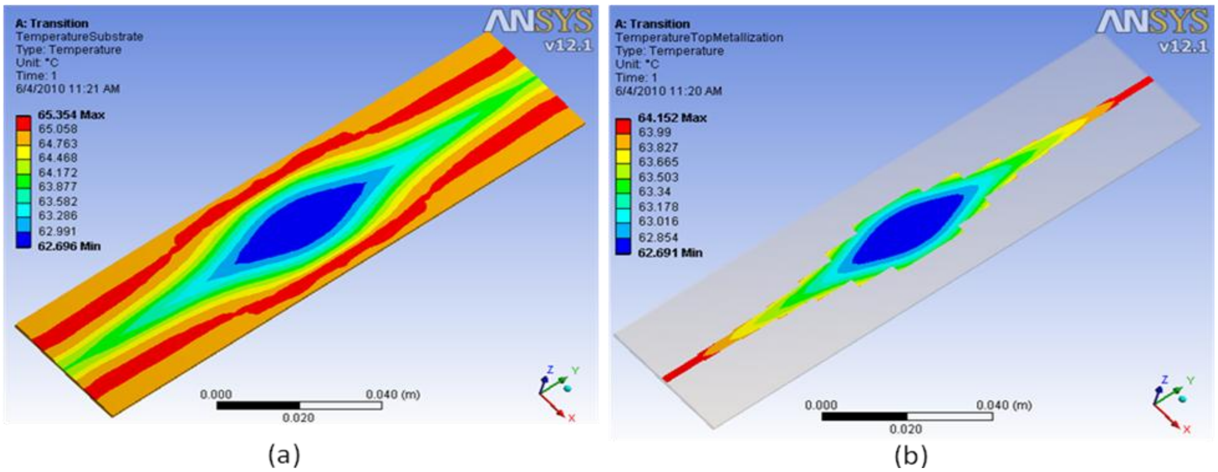


Fig. 7. Temperature distribution on the top surface of the back-to-back transition shown in Fig. 1 as obtained from ANSYS software for the case of 1 W applied input power at frequency 2.148 GHz. (a) Temperature plot on dielectric surface. (b) Temperature plot on metallization surface.

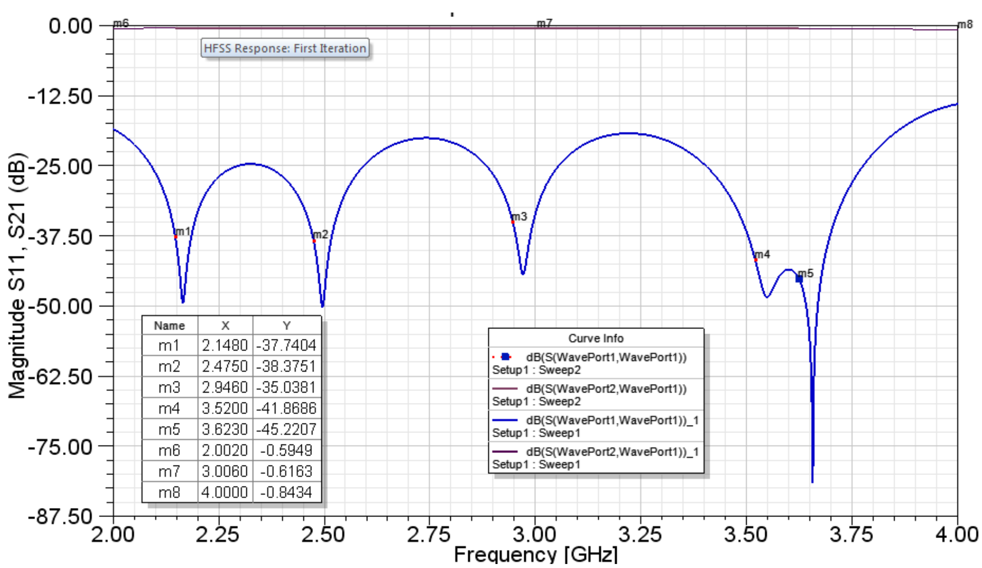


Fig. 8. Frequency response obtained from HFSS after importing the temperature profile from ANSYS. Resonant frequencies are shifted up by 25 MHz due to temperature increase and change of electrical parameters.

More simulation analyses have been carried out at different power levels and different frequencies (see results in Fig. 3). The temperature profiles on the top surfaces of dielectric and metallization as obtained from ANSYS are illustrated in Fig. 9 (a) and (b), respectively for the case of input power equal to 75 W applied at frequency 2.148 GHz.

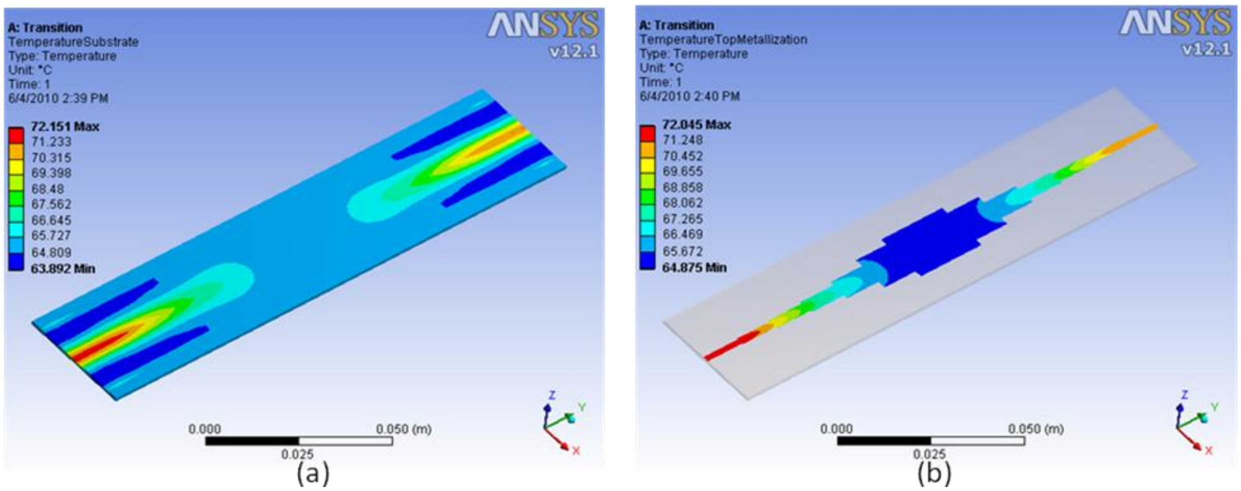


Fig. 9. Temperature distribution on the top surface of the back-to-back transition shown in Fig. 1 as obtained from ANSYS software for the case of 75 W applied input power at frequency 2.148 GHz. (a) Temperature plot on dielectric surface. (b) Temperature plot on metallization surface.

IV. CONCLUSIONS

In this work, the thermal-electromagnetic link is analyzed using HFSS and ANSYS. The high-frequency simulation results including surface and volume loss densities are imported into ANSYS where appropriate thermal boundaries are applied. The thermal results are imported back into HFSS to model the effect of changed temperature-dependent electrical parameters on the frequency response. This modeling approach involving both the RF and thermal analysis gives more rigorous results without the need to do any approximation. The accurate thermal maps obtained from ANSYS help to make the right choice of materials in the early stages of design and to avoid any failure of the final product.

References

[1] ANSYS Workbench, ANSYS Inc., Canonsburg, PA. Ver. 12.1, 2009.
[2] High Frequency Structure Simulator (HFSS), Ansoft Corporation, Pittsburgh, PA. Ver. 12.1, 2010.