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Integrated Simulation of Electrical and Thermal Processes in Optoelectronic Devices Designing

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***Abstract*—The article studies the mutual influence of electrical and thermal processes due to their simultaneous occurrence in the printed circuit assemblies of optoelectronic devices (OEDs) in real operating conditions. An increase in the accuracy of computer modeling of electrical and thermal processes can be achieved by switching from the separate modeling of these processes used in engineering practice to their joint simultaneous modeling according to the proposed unified integrated electrothermal model. The authors use the existing in physics electrothermal analogy of mathematical descriptions of these processes. The resulting loads of heat dissipations power and temperatures of electrical radio products placed on the OED printed circuit boards makes it possible to identify hidden potential failures in them during design. When using integrated digital twin, it is possible to identify pre-failure situations during the operation of the OED.**

Keywords—electrothermal analogy, integrated model, computer modelling, thermal processes, electrical processes, digital twin, laser gyroscopes

I. INTRODUCTION

At present, in OEDs, especially those based on gas and solid-state laser gyroscopes (LG), the circuits and designs of electronic systems of optical emitters, laser pumping devices and printed circuit boards (PCB) for supporting laser radiation and information processing are constantly being improved. Moreover, the main functional part of the OES circuit, including secondary power supplies, stabilizers, generators, sensors, amplifiers and other units, is analog. Therefore, the electrical process in them is modeled using the programs: Micro-Cap, NI Multisim, LabVIEW, Altium Designer, LTspice / SwitcherCAD, EasyEDA, etc. If the OEDs contains analog and digital devices together, Micro-Cap or the popular Proteus computer-aided design system can be used.

For electronics of modern OEDs, in addition to the accuracy of the calculated output characteristics, one of the important parameters is reliability indicators. And one of the main factors affecting the failure of laser sensors and other emitters, as well as electrical radio products (ERP) are electrical and thermal loads on them [1]. During operation, the heating of laser sensors and ERP is caused by thermal processes in OED, caused by the ambient temperature and heat dissipation in the sensors themselves when laser beams pass through them and in the ERP when electric currents flow through them.

The complexity of OED is steadily increasing, and their efficiency, as a rule, is relatively small, therefore, from 50 to 90% of the consumed energy is converted into thermal energy, and this leads to overheating of both laser sensors and ERP on PCB [2]. But even if the ERP temperatures do not exceed the maximum permissible values, all the electrical parameters of the ERP change with an increase in temperature. This leads to changes in currents, voltages and heat dissipation powers at all ERPs included in OED circuit diagrams. Consequently, the thermal process in OED is constantly changing dynamically from changing heat dissipations in the ERP. This also affects changes in the thermal modes of operation of laser sensors.

In the design calculations of electrical circuits and output parameters of laser sensors of LG, not enough attention is paid to the consideration of the relationship between electrical and thermal processes occurring in them [3]. Even when carrying out computer modeling, it is carried out separately for electrical and thermal processes in the OED [4, 5]. Modern computer programs for electrical circuits simulating are not tuned to take into account the effect of temperature increase in ERP as a result of operating currents flowing in them. The simulation is carried out at constant initial set values of the ERP parameters. Although under the influence of thermal processes and heating of the ERP, the initial values of the parameters change. As a result, this leads to the adoption of incorrect design decisions, since the excess of ERP temperatures over the maximum permissible values specified in the technical conditions of their application is not detected.

Moreover, changes in ERP parameters lead to a redistribution of currents flowing through them, and, consequently, to a change in heat dissipations in the ERP. Since heat dissipations in ERP is the input data for OED thermal modeling programs, accounting for temperature changes in ERP parameters could lead to automatic accounting for changes in heat dissipations during thermal modeling. Changes in heat dissipations at the entrance to the thermal modeling program, in turn, leads to the receipt of new changed temperature values on the ERP. The simulation loop is closed.

The task is to take into account the current temperatures on the ERP cases when modeling electrical processes in OED schemes and take into account the current heat dissipations in ERP when modeling thermal processes in OED structures.

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II. Problem Solution of Interconnected Simulation of Electric and Thermal Processes in Optoelectronic Devices

Let us consider two possible approaches to solving the problem of interrelated modeling of electrical processes in circuits and thermal processes in structures on which this OED electrical circuit is implemented.

The first approach consists in the joint sequential use of two programs for separate electrical and thermal modeling, which implies iterative data transfer from one calculation to another [4]. In this case, after the electrical simulation, the files with heat dissipation in the ERP are transferred to the OED thermal simulation. The temperatures of the ERP cases are transferred back from the thermal model to the electrical model, from which new values of the ERP electrical parameters are calculated in accordance with the formulas for the dependences of these parameters on the temperature of the ERP cases.

At the second step, after iterative modeling of electrical processes, the obtained new values of the heat dissipations in ERP are again transferred to the thermal modeling program. This approach involves several iterations of calculations until the required accuracy of the results of step-by-step modeling is achieved. To stop iterations, the values of the output characteristics (heat dissipations and ERP temperature) at the next iteration step must differ from the values of the previous step by a predetermined small value. In this case, the total number of iterations can be large. The modeling process can be cumbersome and time-consuming.

This paper proposes a more accurate approach to solving the problem of electrical and thermal modeling of OED by using a single electrical modeling program for both electrical and thermal modeling. Such an approach is the preliminary construction of an integrated electric thermal model OED in the form of a single topological circuit consisting of nodes (vertices) and branches (edges) of the model connecting them. That is, the thermal submodel is presented in the form of an equivalent circuit built on the basis of a structural analogy of the records of mathematical equations describing thermal and electrical processes [6 – 8].

The process of heat energy transfer (heat flow) is described by the Fourier equation:

$$\vec{q} = -\lambda \ \mathrm{grad}\ T, \tag{1}$$

where q is the heat flow density, λ is the thermal conductivity of the medium, and T is the temperature.

The process of transferring an electric charge (electric current) is described by Ohm's law:

$$\vec{j} = -\gamma \ \mathrm{grad}\ \varphi, \tag{2}$$

where j is the current density, γ is the electrical conductivity of the medium, φ is the electrical potential, i. e. equation (2) is completely identical to equation (1).

The correspondence of variables and parameters in the electrothermal analogy is shown in Table 1 and Table 2.

TABLE I. Electrothermal Analogy

Submodel type	**Potential characteristic of a submodel node**	**Potential characteristic of a submodel branch**	**Flow characteristic of a submodel branch**
Electrical	Potential	Potential difference	Current
Thermal	Temperature	Temperature difference	Heat flow

TABLE II. Passive Parameters in the Electrothermal Analogy

Electrical submodel	**Thermal submodel**	**Physical characteristic of the parameter**
Electrical conductivity	Thermal conductivity	Dissipative parameter of the branch
Electric capacity	Thermal capacity	Conservative parameter of the 1st kind
Electrical inductance	–	Conservative parameter of the 2nd kind

Building a single, integrated OED model makes it possible to simulate electrical and thermal processes simultaneously using a single electrical simulation program, such as MicroCap, Altium Designer, or another program that will provide end-to-end CAD design for OEDs based on PCB and programmable logic integrated circuits.

When a thermal submodel is introduced into the selected electrical modeling program in the form of a circuit of thermal resistances of individual sections of the OED structure, the engineer imagines it in this case as an electrical circuit. At the same time, he understands virtually that the calculated electrical potentials of the nodes of the thermal submodel are the numerical values of the temperatures of the sections of the structure or the ERP temperature installed on the PCB.

An important feature of the proposed method is how to connect the circuit of the electrical submodel with the thermal submodel in the form of an equivalent circuit, which becomes a continuation of the electrical submodel. As a result, the electrical and thermal circuits become, as already indicated above, related submodels of a single integrated model. Links between submodels are made when building an integrated model. On the one hand, with the help of dependent current sources supplied in the thermal submodel, it is possible to implement the transfer of heat dissipations in ERP from the electrical submodel to the thermal submodel.

On the other hand, by setting variable resistances instead of constant resistances in the electrical submodel, it is possible to reflect the dependence of these resistances on the temperatures corresponding to the ERP to which these resistances belong. Here we mean, the resistance can belong to a resistor or be, for example, the collector resistance of a transistor. The numerical values of the temperature of the resistor or transistor appear in the corresponding nodes of the thermal submodel during the OED computer thermal simulation.

In the thermal submodel, flow sources of thermal power are introduced for each part of the OED structure, primarily related to emitters of an optical signal, for example, a laser. Then a branch with a dependent heat source is installed in each node, which corresponds to the ERP, in which the flowing current causes a significant power of this heat dissipation.

For example, the dependence of the power P of the heat source on the resistor and on the input resistances R of the integrated circuits through which the current I flow should have the known form (3):

$$P = I^2 R. \tag{3}$$

In turn, instead of a constant resistance, a variable resistance is introduced into the electrical submodel, which changes during the electrical simulation in accordance with the change in the current value T of the ERP temperature according to (4):

$$R_T = R_{25} \cdot (1 + \alpha\,(T - 25)), \tag{4}$$

where α is the temperature coefficient of resistance R. Temperature corrections for other ERP parameters are also introduced.

The structure and connections in the proposed integrated electrothermal model are clearly shown in Fig. 1. In the integrated model, there are no simulation iterations, that is, there are no transitions from the electrical submodel to the thermal submodel and vice versa, since the dynamic link between the submodels is implemented before simulation, as described above.

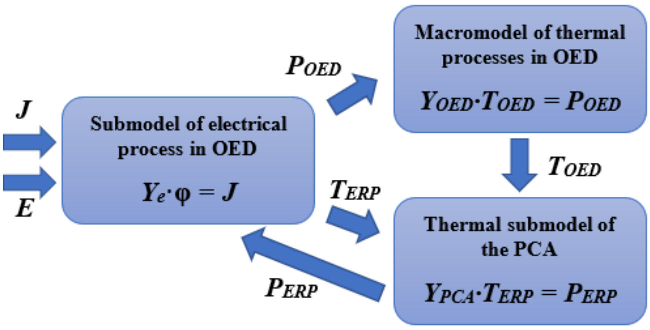


Fig. 1. The device structure of the integrated electro thermal model of the optoelectronic

Fig. 1 introduced the following notation:

J is the vector of input current sources of the OED electrical circuit,

E is the vector of input voltage sources of OED electrical circuit,

Y_e is the OED electrical circuit conductivity matrix,

φ is the vector of electrical potentials at the nodes of the electrical circuit of OED,

T_a is the ambient temperature,

Y_{OED} is the thermal conductivity matrix of OED,

T_{OED} is the vector of design temperatures of structural parts of OED including printed circuit assemblies (PCA) and internal air volumes,

P_{OED} is the vector of heat dissipation power in structural parts of OED including PCA,

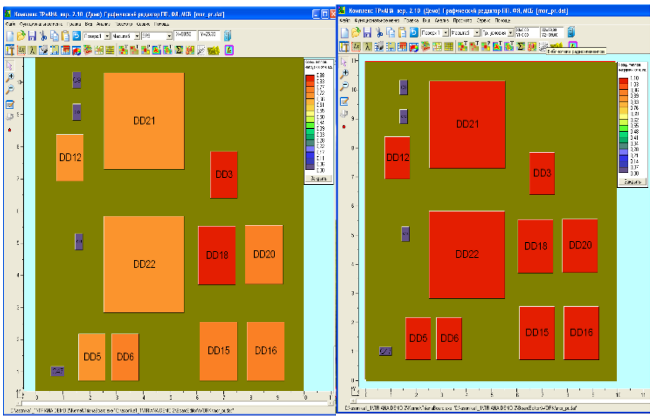
P_{ERP} is the vector of heat dissipation power in ERP of PCA,

Y_{PCA} is thermal conductivity matrix of PCA,

T_{ERP} is the vector of ERP temperatures.

The calculation of the final heat dissipations in ERP and temperatures of the OED and ERP structural parts will occur using the same electrical simulation program, which is much faster than iterative simulation. There is a time gain for fully automated integrated modeling over iterative modeling with manual data transfer from one step to another. At the same time, there is a gain in the systemic identification of latent both electrical and thermal overloads of the ERP, if they are present in the design of the OED. With separate electrical and thermal modeling of the OED, latent overloads may not be detected as a result of modeling errors due to neglect of the dynamic interconnection of the ongoing electrical and thermal processes.

The appearance of latent thermal overloads in this work was tested on the example of one of the PCB. The results of separate thermal modeling and combined modeling with electrical modeling are shown in Fig. 2.



a) b)

Fig. 2. Comparison of thermal load factors of ERP with separate thermal modeling (a) and with integrated (b) electrical and thermal modeling of the same PCB

Fig. 2a shows the ERP temperature in a separate thermal simulation of the PCA at constant values of heat dissipations in ERP, previously obtained in a separate electrical simulation of a schematic diagram, which is implemented on a given PCA. As you can see, ERP DD3 and DD18 have the highest thermal loads. Moreover, the load factors are 0.88, i. e. the PCA passes the thermal load requirements.

In Fig. 2b, the same PCA was simulated by integrating the electrical and thermal models. The simulation results showed that the load factors of ERP DD3, DD5, DD6, DD12, DD15, DD16, DD18, DD20, DD21, DD22 became equal to 1.1, i. e. all ERPs have an overload of about 10%. Thus, the integrated modeling made it possible to reveal latent thermal overloads and it is necessary to make changes to the PCA design in order to provide an additional heat sink from the ERP. This could be a thermal bus that completely covered the PCB area.

We emphasize that the identification of hidden places of potential PCA failures occurred at an early stage of the OED design, which includes this PCA. If a failure was revealed during the OED tests, then changes would have to be made not only in the PCA, but possibly in the OED supporting structure as a whole. This would require additional funding, and there would be an increase in the design time of the OED.

The electrical submodel is not shown in this work, since the heat dissipation power in ERP during integrated modeling increased, but remained within the acceptable limits stipulated in the technical specifications. But for the OED designers, it is important that this simulation at an early stage of the design showed the functionality of the circuit diagram even under thermal influence. In other cases, even with electrical, but separate modeling, it often happens that it is only during thermal tests that the designer of the circuit finds out that it is not operational.

Thus, the integrated electrothermal model, built using the same unified designations for both submodels [9], can be calculated by any electrical simulation program. This facilitates the implementation of the digital twin of the OED, which is necessary for diagnosing and maintaining the operability of the OED installed in complex systems of avionics and space equipment [10].

Digital twin is a digital recording in the on-board computer of the simulation results of the electrothermal process, which helps to quickly detect physical problems in the operation of an OED operating on board an aircraft or spacecraft. These results play the role of reference values and their comparison with the results of periodic or continuous diagnostics of on-board electronic equipment in flight of an aircraft or spacecraft may show that some of their current values approach or exceed the maximum permissible values. Thus, diagnosing an OED using a digital twin reveals trends in possible electronic failures.

III. CONCLUSION

The construction and using an integrated electrothermal model in the early stages of creating and working out circuitry and design solutions gives designers a quantitative idea of how the most important processes in the OED interact. Integrated modeling is needed to identify potential faults, eliminate their identified causes, and ultimately improve the performance of the OED at different ambient temperatures.

Considering the dynamics of the mutual influence of dissimilar electrical and thermal processes occurring in OED through dependent characteristics and parameters on each other, it is possible to significantly increase the guarantee of obtaining high reliability of the designed products. This occurs, on the one hand, by connecting the electrical model of the OED with its thermal model and, on the other hand, by using only one electrical simulation program (as opposed to the usual use of two programs, both electrical and thermal simulation).

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