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Analysis of the thermal modes of Focal Plane Arrays

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Abstract. Techniques and programs for calculation and modeling of thermal characteristics of MEMS-designs of radiation thermal receivers are offered. Comparative estimates of characteristics of radiation receivers with heatsensitive thin films are executed. Results of researches can be used for development of original programs for modeling of thermal receivers of radiation.

1. Introduction

As it was predicted, in reviews [1, 2], in process of development of opportunities of micron technologies developers of IR-systems began to understand that uncooled thermal detectors, though yield photon and quantum in the extreme parameters, possess a number of characteristics which do them irreplaceable in the extensive field of applications. In particular, it belongs to tasks of observation and recognition of objects at small distances (to 2500 m), infrared microscopy, medical and industrial diagnostics, etc. The main benefit of thermovision systems on multielement thermal detectors in relation to systems with photon and quantum devices, is that their work doesn't require chilling up to the cryogenic temperatures. In English-speaking literature these devices call "uncooled matrix detectors in the focal plane" UFPA (Uncooled Focal Plane Arrays). Calculations of thermal balance form a basis of optimization of a design and execution of thermal detectors of radiation of any types [3-7]. The task of optimization of a design of the detector consists in making heating process by radiation stationary during the time corresponding to shot time.

2. Technique of calculations

As a rule, the corresponding physical models come down to the solution of the linear parabolic differential equations in private derivatives. However simple assessment of time constant of heating of the thermal detector radiation can be received for the following reasons. Let's consider the idealized case in which the receiver with a reference temperature \( T_0 \) represents the thin plate located in vacuum between two planes from which lower is a heatdrain with a fixed temperature of \( T_0 \) and upper is a radiation source from background which temperature jump changed from \( T_0 \) to \( T_b \) (scene temperature), and we will put that the plate is at the room temperature and scene temperature not much more (for example, by one degree) exceeds initial, i.e. \( T_b \approx T_0 \approx 300 \text{ K} \).

Believing that distribution of temperature on amount of a thin plate can be neglected, i.e. that its temperature is identical on all its amount, we determine how the average temperature of a plate \( T \) rather initial \( T_0 \) values changes over time.
The equation of thermal balance describing radiating transfer of heat from more heated plate with a temperature \( T_b \) (or \( T \)) to more colder plate with a temperature \( T_0 \) (or \( T_0 \)), has an appearance:

\[
c_v ShdT = S\left[4\sigma T_0^3 (T_b - T) - 4\sigma T_b^3 (T - T_0)\right] dt,
\]

where \( c_v \) – volume thermal capacity of plate material, \( S \) – its area, \( h \) – thickness.

Here the left part represents the energy acquired by the plate with area \( S \) and thickness \( h \) for \( dt \), and in the right part the first member corresponds to radiation heat exchange between a background and the top surface of a plate, and the second member – to radiation heat exchange with heat drain. In view of \( T_b \approx T_0 \approx 300 \) K and doing substitution \( \theta(t) = T(t) - T_0 \), taking into account an entry condition \( \theta(0) = T(0) - T_0 = 0 \), we receive:

\[
\theta = \frac{(T_b - T_0)}{2}\left(1 - e^{-\frac{A}{2t}}\right),
\]

where \( \tau = \frac{c_v h}{4\sigma T_0^3} \) – the thermal constant of time of radiation exchange process depending on thickness of plate and its heat properties.

At \( T_0 = 300 \) K thermal conductivity of the single site of plate surface (integrated coefficient of radiating heat exchange) \( G = 4\sigma T_0^3 = 6.1 \) W/(m\(^2\)-K) and the value of time constant corresponding to our task in seconds, where \([c_v] = J/(m^3\cdot K)\) and \([h] = m\).

In real thermal detectors it is necessary to consider outflow of heat through design elements at the expense of heat transfer that significantly reduces the average temperature of the detector and, therefore, his sensitivity. The time constant is generally proportional to the attitude of a total thermal capacity \( H_x \) of the detector and elements of design towards total heat conductivity of \( G_x \) of elements through which there is a leakage of heat:

\[
\tau_x = \frac{H_x}{G_x},
\]

For the design of the detector represented in Figure 1 in which thickness of each detector is supposed a lot of smaller than its radius \( R \), for definition of distribution transitional function of temperature in the case under consideration it is possible to consider not depending on coordinate \( x \) (i.e. to consider that the plate evenly heats up on thickness). Then the corresponding thermal task can be reduced to cylindrical, namely to the solution of task on heating by the radiation of a thin edge with radius \( R \) and thickness constant \( b \) on the heat-conducting cylinder with radius.

The equation of heat conductivity satisfying this model has an appearance:

\[
K_p \left\{ \frac{\partial^2 \theta}{\partial \rho^2} + \frac{1}{\rho} \frac{\partial \theta}{\partial \rho} - \frac{1}{\chi_p} \frac{\partial^2 \theta}{\partial \rho \partial \rho} \right\} = \frac{G(T_b + T_0 - 2\theta)}{b},
\]

where \( \rho \) – radius in system of cylindrical coordinates; \( \theta(\rho) \) – edge temperature in a point with the coordinate of \( \rho \), \( K_p \) – coefficient of heat conductivity of material of the detector \( \chi_p \) – heat diffusivity coefficient ( \( \chi_p = K_p / c_v \)), \( c_v \) – a volume thermal capacity of detector material.
Passing to dimensionless coordinates and parameters we receive a classical regional task with the mixed Dirichlet and Neumann boundary conditions:

$$\frac{\partial^2 \theta}{\partial \xi^2} + \frac{1}{\xi} \frac{\partial \theta}{\partial \xi} + \beta^2 \theta = \frac{\beta^2}{2} (T_b + T_0),$$

where:

- $\xi = \frac{\rho}{r}$ – dimensionless radius;
- $1 \leq \xi \leq \frac{R}{r}$;
- $\tau = \frac{\chi}{r^2} t$ – dimensionless time;
- $\beta^2 = \frac{2Gr^2}{K_r b}$ – the parameter characterizing radiating heat exchange and design.

The nonstationary solution of the equation (2), i.e. calculation of temperature transitional function can be received by the method of final differences leading to the system of the linear equations describing changes of temperature in splitting grid knots at different timepoints. The example of such calculation of profiles of the specified temperature for this task of the program written in language C++ is given in Figure 2. At the same time the following typical values of parameters have been accepted: heatsensitive material – polivinilidenftorid film ($K_r = 0.13 \text{ w/m-K}$, $c_v = 2.3 \cdot 10^6 \text{ J/m}^3\text{K}$), the sizes of reception element $1 \times 100 \times 100 \text{ um}^3$, diameter of bump contact is $20 \text{ um}$.

Criterion of correctness of the executed calculations is comparison of the stationary decision received by a numerical method with the same decision received analytically. In [3] it is shown that at the analytical decision has an appearance:

$$\theta_s = \frac{1}{2} \left[ \frac{K_1 \left( \beta \cdot \frac{R}{r} \right) I_0 (\beta \xi) + K_0 (\beta \xi) I_1 \left( \beta \cdot \frac{R}{r} \right)}{K_1 \left( \beta \cdot \frac{R}{r} \right) I_0 (\beta) + K_0 (\beta) I_1 \left( \beta \cdot \frac{R}{r} \right)} \right],$$

where $I_0$, $I_1$, $K_0$ and $K_1$ – the modified Bessel functions of zero and first order. This dependence for the same parameter values is provided in Figure 2 by the shaped line. The stationary decision received as a result of calculations by method of grids matches it within $5\%$. 

**Figure 1.** To calculation of the thermal detector with heatdrain in the center.

**Figure 2.** Example of calculation of profiles of the specified temperature for this task of the program written in language C++.
The comparison of different options of detector design given in Figure 3, is an example of application of the developed method of calculation. The specified average temperatures calculated for different types of designs with the heat sensitive polymeric film are given in this drawing. Apparently, the most effective heating happens for the design with the thermal drain in the center. In time about 0.02 s with values of the specified average temperatures of a layer about $10^3...10^2$ K one degree of a scene by, and optimum values of its thickness constitute 1...2 µm are reached. The optimum relation of radius of the separate single detector to radius of the maintaining element of the contact design lies within 5...10. In general these conclusions match the results given in reviews [8, 9].

Figure 2. Change of temperature after inclusion of radiation in heat-sensitive layer in the detector on bump contact with heat drain in the center.

Figure 3. The specified average temperatures and heat conductivity per unit area for different types of designs with the heat sensitive film.
3. Conclusions
The techniques and programs for calculation and modeling of thermal characteristics of MEMS-designs of thermal detectors of radiation based on determination of the transitional functions of average temperature of heat sensitive layers and ratios signal/noise are developed. The offered techniques allow to carry out comparative estimates of characteristics of detectors of radiation on heat sensitive (for example, pyroelectric) thin films. On the basis of developed techniques the analysis of standard options of MEMS-designs is made. It is shown that the design with the film raised over the plate with low heat conductivity, in particular for pyroelectric detectors – films from a polinviniledenotrid or the organic pyroelectricic appears the most effective. General heat conductivity in this case doesn't exceed 0.1...0.05 W/cm²·K in case of the sizes of elements of the detector $1 \times 100 \times 100$ um³ и $1 \times 50 \times 50$ um³
Development of the offered techniques consists in development of original programs of modeling of the thermal detectors of radiation on the basis of universal tools for designing and modeling of MEMS, for example, on the basis of the CoventorWare.

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References