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THERMAL PLACEMENT IN HYBRID CIRCUITS— A HEURISTIC APPROACH

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This paper deals with the placement of heat dissipating components in hybrid circuits. An optimum placement is found when the extreme temperatures on the substrate are minimized. Whereas classical techniques such as the gradient method require large computational efforts, a simple and very rapid heuristic method is presented here. The heuristic approach offers the advantage that it can be easily inserted in the design phase of the circuit.

1. INTRODUCTION

Thermal analyses of hybrid circuits made on ceramic substrates have been the subject of several papers.[1–4] Not only steady state in two dimensions, but also three dimensional and time dependent studies have been carried out.[5,6] If the dimensions of the heat sources, such as screen printed resistors are not too small, a two dimensional approach will be sufficient.[1] The agreement between theoretical and experimental results has been proven with infrared thermographic techniques.[7,8]

With a thermal model, the designer can calculate the temperature distribution over the whole substrate. From the thermal point of view, the designer wants to keep the temperatures of all the components as low as possible. Using a thermal model, new designs can be tried in an interactive way in order to find an optimum placement for all the components. In this paper, optimum means the maximum substrate temperature being as low as possible. Some software packages include a thermal module to perform this simulation.[9] Thermal placement of components is directly related to the reliability aspect of hybrid circuits and should also be considered within the more general placement problem.[11,12] Basically, one wants to design circuits with a maximum lifetime. The mathematical model becomes more complicated if components have different failure rates.[12,13,14] Optimizing the lifetime or minimizing the total failure rate is a more general approach.

Another approach is an automatic placement algorithm, which finds an optimum position for all the heat sources on a single substrate. The most popular algorithm turns out to be the gradient method.[15] This technique has the disadvantage of requiring a large amount of computational effort, making it unsuitable to be incorporated in an interactive CAD system. Moreover, thermal placement only involves the heat dissipating components; other components and interconnections are disregarded. The gradient method can also be combined with some heuristic rules to find a better initial position.[16,17]

In this paper, a simple heuristic approach will be presented. It will be proven that the results are quite close to the optimum situation calculated with the gradient method. This proves the method is satisfactory from a thermal point of view. Moreover, the heuristic approach is more suited to be incorporated in the placement phase of a design.

2. THERMAL MODEL

For a ceramic substrate, the thickness t_s being much smaller than the other dimensions, the temperature can be modeled as a two dimensional function. This means that the front and rear side have the same temperature or no thermal gradients exist in the depth of the substrate. Putting (x, y) axes parallel to the substrate, one has[1,2]:

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} - \frac{T}{L^2} = -\frac{p}{\lambda t_s} \tag{1}$$

where:

- T: temperature rise above ambient
- λ: thermal conductivity (in W/m °C)
- α: convection coefficient (in W/m^2 °C)
- t_s: substrate thickness
- $L = \sqrt{\lambda t_s / 2\alpha}$: characteristic length
- p: power density (in W/m^2)

It has been assumed that the substrate is subjected to two-sided cooling with a uniform convection coefficient α. The same equation (1) still holds if both sides of the substrate have different heat transfer coefficients α_1 and α_2. The term 2α in the definition of the characteristic length L has then to be replaced by $\alpha_1 + \alpha_2$. The power density p is, of course, zero outside a heat source.

Several techniques for solving equation (1) have been presented in the literature. We cite Fourier methods,[5,16] finite differences,[1,2,3] and boundary elements methods.[18,19] Note that with a slight modification of the present model, the third dimension and multilayer effects can be included.[5,20]

Radiation can be taken into account approximately by increasing α with the radiation heat transfer coefficient α_r and using $\alpha + \alpha_r$ instead of α. If the exact non-linear radiation is used, and eventually combined with non-linear convection, a more complicated equation than (1) is found, which can be solved by finite difference techniques [2].

The gradient method is an iterative algorithm to find the optimum position of all the heat sources. One starts with an initial position. The temperature distribution is then calculated by solving (1). In the center of any heat source, the temperature gradient is calculated. The heat sources are then moved over a distance proportional to the local thermal gradient and in a direction opposite to the gradient. Hence, a new placement is obtained and the procedure is done over again. It has to be repeated until sufficient convergence is obtained. As a consequence, equation (1) has to be solved many times, which explains the need for large computation times.

3. ANALYSIS OF A SQUARE SHAPED SUBSTRATE WITH TWO HEAT SOURCES

In order to get a deeper insight in the problem, a very simple case has been studied: a square shaped substrate with two screen-printed resistors. The resistors have the same dimensions and dissipate the same power. It has been proven that the optimum position occurs if the two heat sources are on the diagonal in a symmetric way (Fig. 1). The abcissas are then x and a $-$ x respectively. Thermal simulations have been carried out for different positions x of the resistors and various values for λ and α. The results are shown in Fig. 2. All temperatures have been normalized to the maximum value, i.e., the temperature occuring when the resistors are in the opposite corners or x $= \Delta/2$. From Fig. 2 it is clear that the placement can largely influence the resistors' temperatures. For substrates with a high thermal conductivity such as AlN ($\lambda = 160$), the characteristic length L becomes larger than the substrate dimensions. The whole substrate is then warmed up at an almost uniform temperature, making a thermal placement ineffective.[21] For the widely used Al_2O_3 substrates, the characteristic length is typically 20 mm, i.e., comparable to common substrate dimensions. Another position of the resistors will then influence the temperature distribution as can be seen from Fig. 2.

The most important conclusion from Fig. 2 is that the optimum is not very sharp. One should rather speak about an optimum region than an optimum point. It then

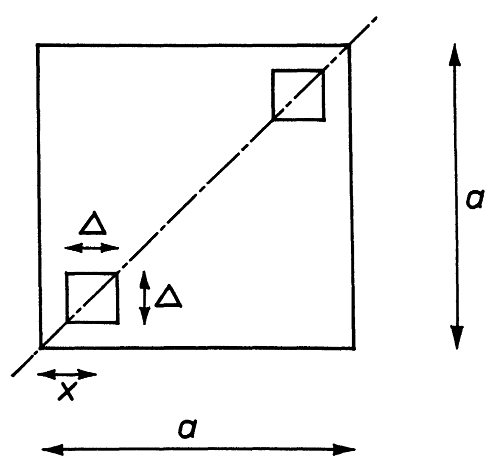


FIGURE 1 Square substrate with two symmetrically placed resistors along the diagonal line.

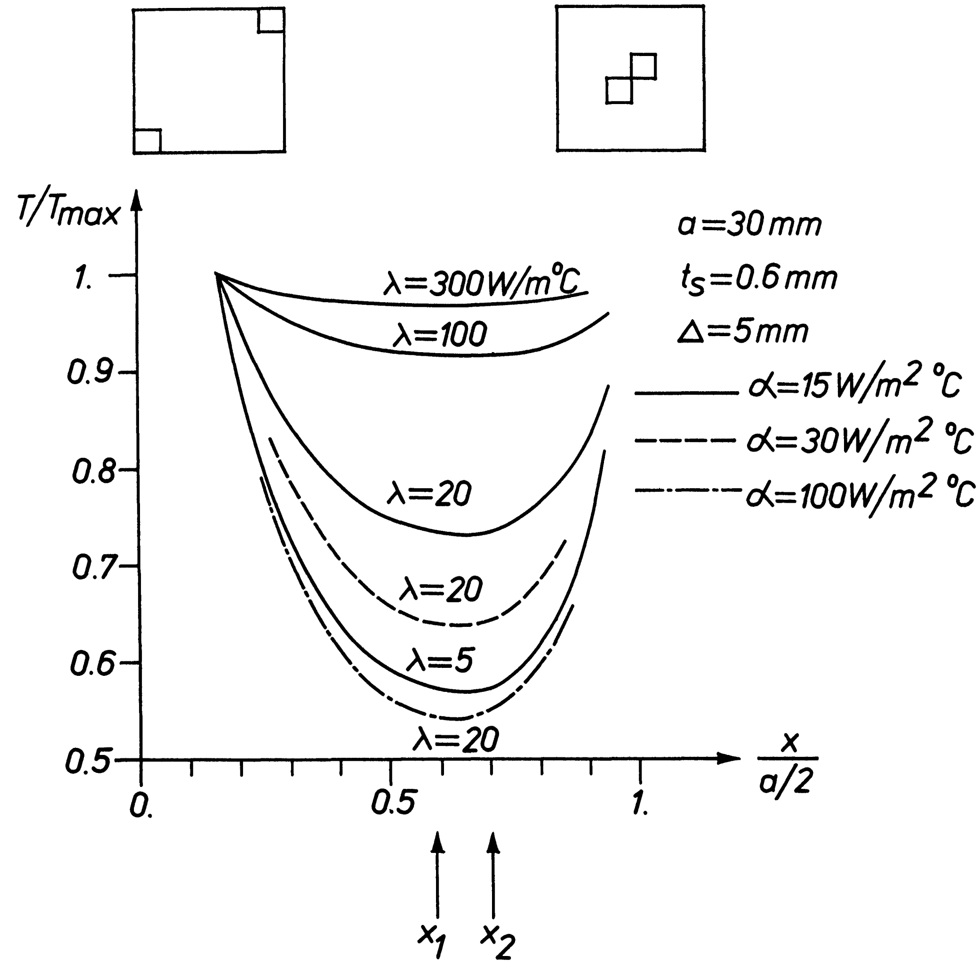


FIGURE 2 Resistor temperature as function of position for the case of Fig. 1. Temperatures are normalised to the value T_{max} occuring when the resistors are placed in the corners.

becomes easier to give a geometrical interpretation. Due to its relatively high thermal conductivity, a ceramic substrate can be considered as a cooling fin for the resistors screen printed on it. If one solves the equation (1) in the one dimensional case,[7] one obtains a solution of the form:

$$T(x) = T_0 e^{-x/L} \qquad (2)$$

Eqn. (2) gives another interpretation of the characteristic length. Around each heat source, a zone with dimension L will be warmed up. It is then easy to understand that, taking the typical values for L into account, the whole substrate will help for cooling. It is then obvious to attach a part of the substrate to each heat source. Every dissipated Watt should have the same substrate area at its disposal for cooling.

For the case of two equal resistors on a square substrate, some possible solutions are shown on Fig. 3. in Fig. 3a, it is assumed that heat propagates in a circular zone around a resistor. Hence, two tangent circles with maximum radius are drawn, yielding a value:

$$x_1 = \frac{2 - \sqrt{2}}{2} a = 0.2928a \tag{3}$$

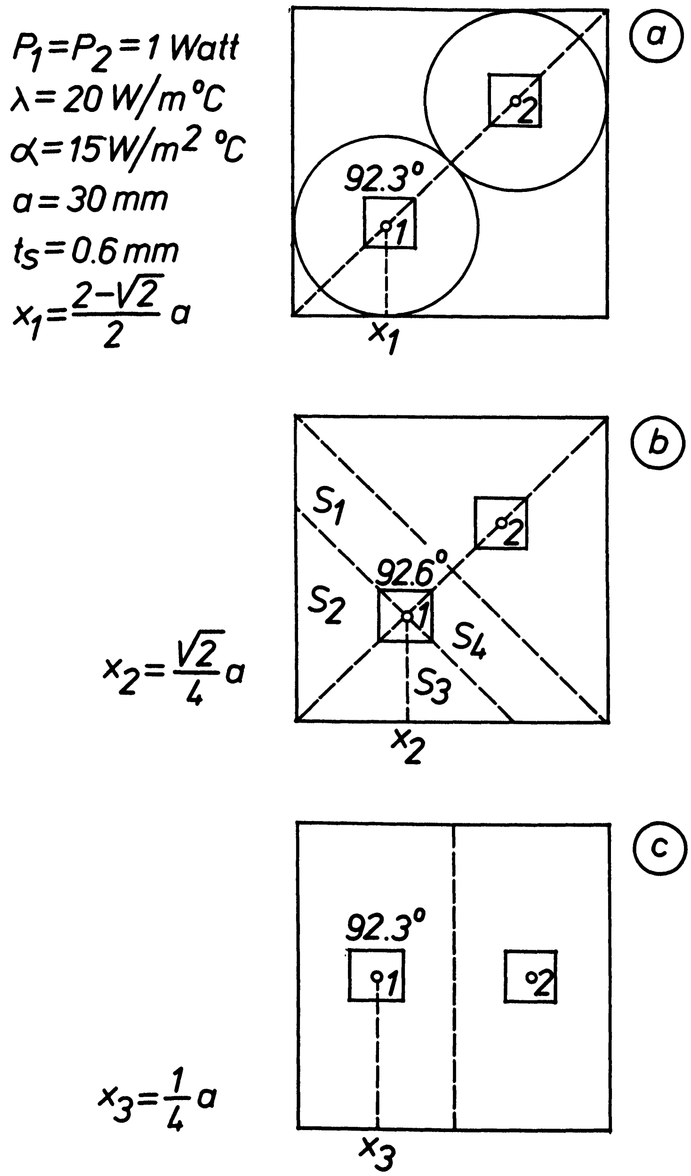


FIGURE 3 Geometrical interpretation of results shown in Fig. 2.

In Fig. 3b, the position was chosen in such a way that the areas S_1, S_2, S_3, and S_4 are equal. This gives:

$$x_2 = \frac{\sqrt{2}}{4} a = 0.3535a \tag{4}$$

Finally, Fig. 3c shows the most obvious solution. The substrate is divided into two equal parts and the resistors are placed in the center points. The most remarkable result of Fig. 3 is that the resistors' temperatures are nearly identical, which proves again the optimum solution is not very critical. This can also be seen on Fig. 2 where x_1 and x_2 are indicated.

4. HEURISTIC APPROACH

From the data outlined in the previous section, a heuristic approach to the placement problem can be put forward. At first, it is clear that the optimum is not very critical. In other words, a different position of the heat sources will have a minor influence on the temperature values. Only extreme situations such as placing two heat sources next to each other should be avoided. A second conclusion is that the optimum corresponds to the case where all heat sources are surrounded by equal parts of the substrate. This idea can be extended to resistors with different heat dissipations. The substrate has then to be divided into pieces with areas proportional to the heat dissipations in the corresponding resistors. This idea is the basis of our heuristic approach.

The practical implementation can be done as follows. The substrate is divided into a number n of equal subareas. If P is the total dissipated power, an amount P/n is attributed to each subarea. It is necessary that n be sufficiently large that all the powers $P_1, P_2, \ldots, P_n$ of the heat sources are integer multiples of P/n. If $P_1 = P/n$, for example, a single subarea is chosen and resistor 1 will be placed in the center. If $P_2 = 4P/n$, four neighboring subareas are grouped together and the second resistor is placed in the gravity center of this group. There are, of course, several possibilities to make clusters of subareas. Therefore, a set of illustrative examples will be discussed now.

Fig. 4 shows the situation with two resistors with powers 0.5W and 1.5W. The substrate is divided into four equal subareas, 0.5W each. The 0.5W resistor is placed in the center of a subarea. The other resistor is put in the gravity center of the remaining three subareas. It is remarkable, though not surprising, that the optimum placement calculated with the gradient method coincides perfectly with the layout on Fig. 4.

Fig. 5 gives another example with two resistors of 2W and 2.5W respectively. The substrate is divided into nine subareas, each corresponding to 0.5W. Four neighboring subareas are grouped for the 2W resistor whereas the 2.5W resistor is placed in the remaining group of five subareas. Fig. 5 shows several possibilities. The optimum position obtained by the gradient method is also drawn and corre-

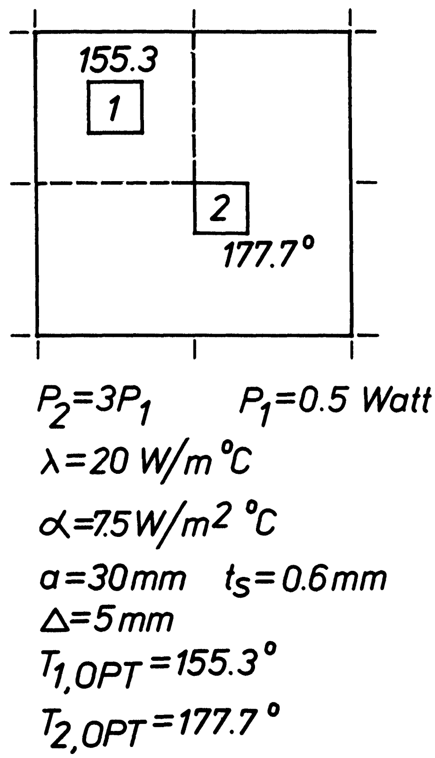


FIGURE 4 Example with two resistors of 0.5W and 1.5W.

sponds with the situation of Fig. 5b. Even when the other layouts differ from the optimum case, the influence on the temperature is rather minimal.

Fig. 6 shows seven possible arrangements if three resistors of 0.5W, 1W, and 3W are involved. It is clear that the best situation is found when the perimeter of a grouped subarea is as small as possible. The situations of Fig. 6b and Fig. 6g give a rather irregular shape for the group of subareas belonging to the 3rd resistor. Hence, the temperatures are somewhat higher as compared to the optimum case (Fig. 3a). Nevertheless, the maximum temperature always remains close to the optimum value.

Fig. 7 shows an example with 10 resistors on one substrate. The optimum temperatures are quite close to the actual values even when the optimum position differs from our heuristic placement (resistors 9 and 10 are interchanged).

In the examples mentioned so far, all resistors have the same dimensions. The influence on the temperature distribution is rather limited as long as the characteristic length L appearing in equation (1) is large enough, a condition usually fulfilled for ceramic substrates. If the dimensions of the resistors become very small, three dimensional effects are no longer negligible and the present model may be questioned [5].

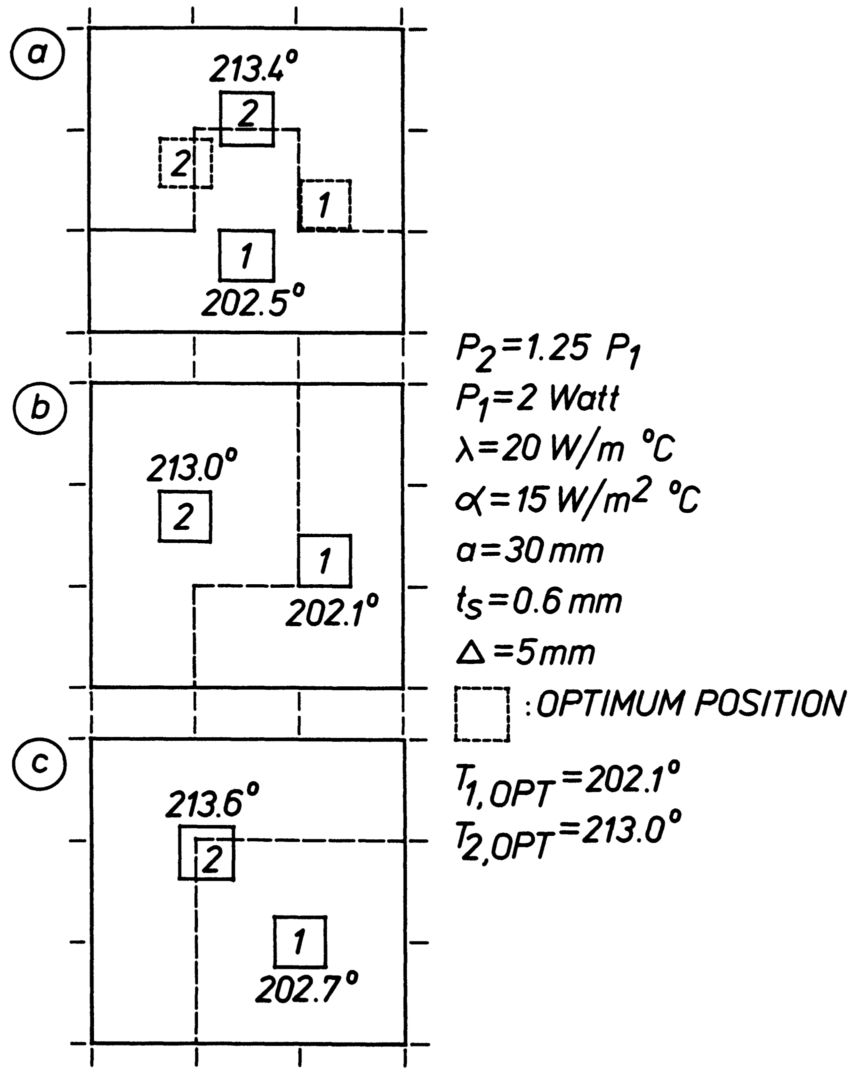


FIGURE 5 Example with two resistors of 2W and 2.5W.

5. CONCLUSION

In this paper, a heuristic approach to the thermal placement in hybrid integrated circuits has been presented. Several examples have been presented and compared with the optimum case, calculated with the gradient method. It was found that the temperatures are very close to the optimum values, proving the validity of our heuristic approach.

Another important conclusion is that the optimum situation is not very critical. The good thermal conductivity of ceramic substrates used for hybrid circuits gives

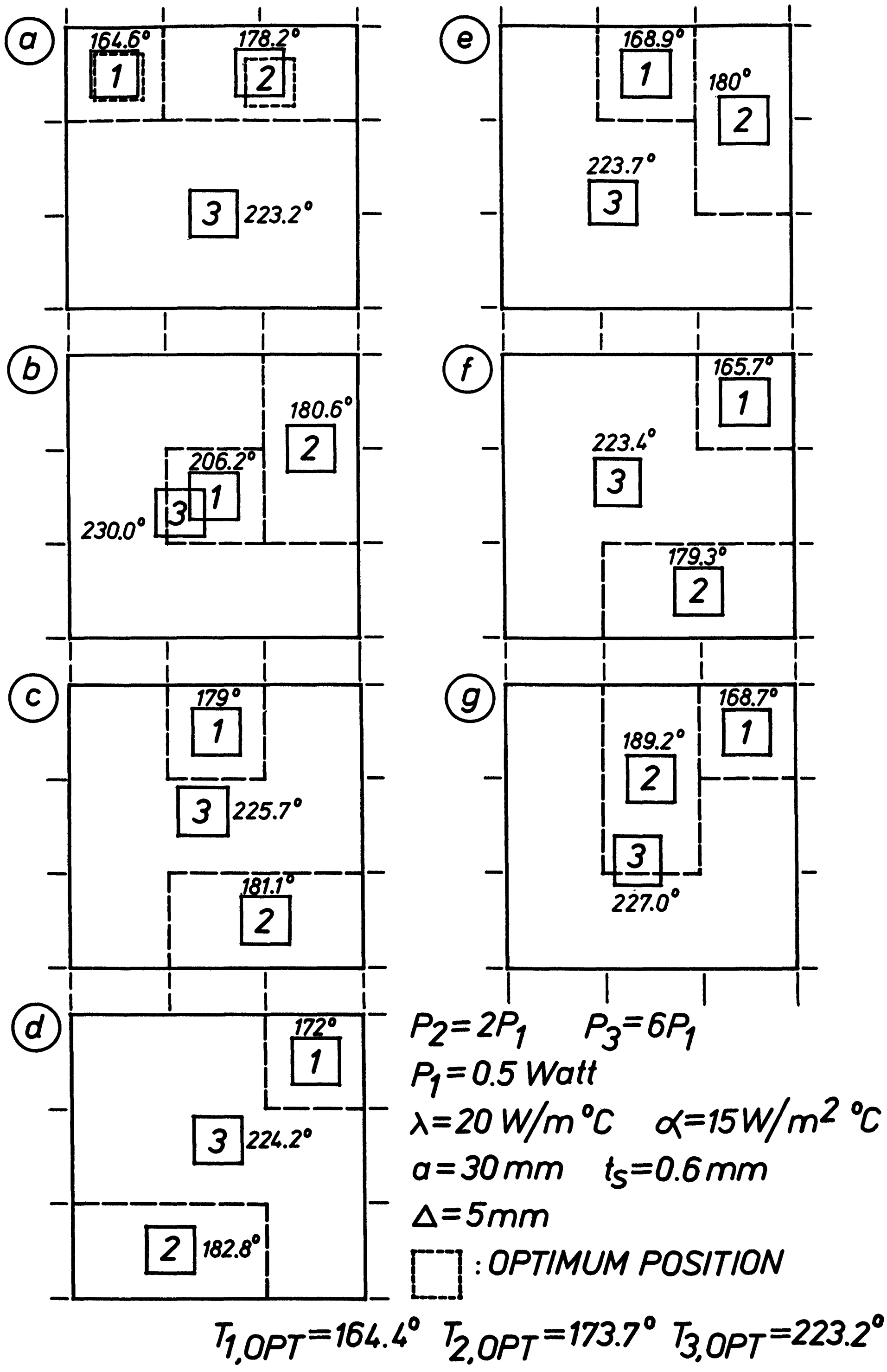
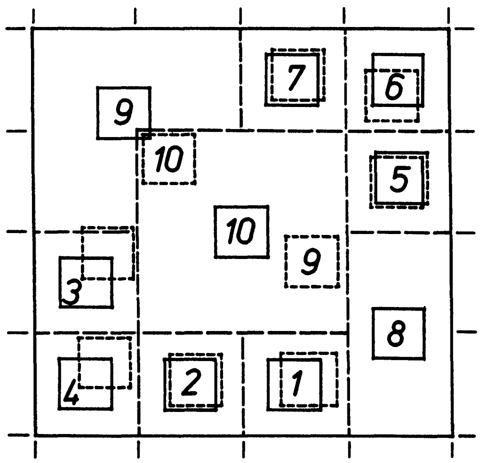


FIGURE 6 Example with three resistors of 0.5W, 1W and 3W.



#	T	T_{OPT}
1	169.2	165.5
2	168.8	164.1
3	167.4	157.3
4	168.2	160.2
5	167.1	167.0
6	167.2	167.1
7	166.8	165.6
8	178.9	178.9
9	189.3	188.3
10	200.8	198.2

$P_1 = P_2 = P_3 = P_4 = P_5 = P_6 = P_7 = 0.5$ Watt

$P_8 = 2P_1 \quad P_9 = 3P_1 \quad P_{10} = 4P_1$

$\lambda = 20\,W/m\,°C \qquad \alpha = 15\,W/m^2\,°C$

$a = 40\,mm \quad t_s = 0.6\,mm$

$\Delta = 5\,mm$

[dashed box] : OPTIMUM POSITION

FIGURE 7 Example with 10 resistors.

rise to a good heat spreading. A slight modification of the layout will hardly influence the resistors temperatures, so that other restrictions due to routing, e.g., can be easily met.

It must be emphasized again that a complete optimization also requires the modeling of the reliability aspects and not only the temperature distribution. Nevertheless, our approach has the advantage of its simplicity so that it can be easily included in the design phase of a hybrid circuit.

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