sponse have been realized. The inductive load single-stage amplifier has a 3-dB bandwidth of 2.5 GHz, a gain of 8 dB, and a noise figure of 2.7 dB with a power dissipation of only 20 mW. Furthermore, it can be operated with single dc supply voltage. The resistive load two-stage amplifier has a 3-dB bandwidth of 2 GHz, a gain of 15 dB, and input and output reflection coefficients of −13 and −21 dB, respectively.

It is expected that these GaAs monolithic amplifiers will effectively improve the performance of UHF-band mobile communication equipment, especially for pocketable telephones. They will also be effective as IF amplifiers for satellite communication equipment.

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## Tolerance Analysis of Shielded Microstrip Lines

S. S. BEDAIR AND M. I. SOBHY

*Abstract*—**A complete analysis of the sensitivities of shielded microstrips is presented. The sensitivity formulas form the basis for studying the effect of tolerances on the performance of these circuits. A set of sensitivity curves are given to help the design procedure. It is suggested that the position of the top cover can be adjusted to compensate for some of the effects of the manufacturing tolerances. Practical examples are given to support the suggested procedure.**

### I. INTRODUCTION

A basic disadvantage of the microstrip circuits lies in the fact that their dimensions cannot be altered after manufacturing, so that the designer has to produce many circuits until he finds the circuit that meets the desired specifications.

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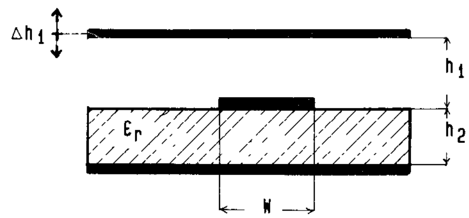


Fig. 1. Shielded microstrip structure with variable shield heights ratio.

In this paper, we suggest the shielded microstrip circuit shown in Fig. 1 with variable shield heights ratio, i.e., the position of the top cover may be changed to compensate for the effect of a given set of manufacturing tolerances. The designer may simply move the top cover up and down until the response of his designed circuit meets the desired specifications. As shown in earlier publications, microstrip parameters are influenced by the frequency $f$ and strip thickness $t$, but they are mainly functions of the strip width $W$, substrate thickness $h_2$, value of the dielectric constant $\epsilon_r$, and shield height $h_1$. Any changes in the values of $W$, $h_2$, $\epsilon_r$, and $h_1$ give rise to corresponding changes in the microstrip parameters. In other words, any manufacturing tolerances in $W$, $h_2$, $\epsilon_r$, and $h_1$ contribute to variations in the parameters of the shielded microstrip circuit.

### II. EFFECT OF MANUFACTURING TOLERANCES

The effect of tolerances on the performance of the shielded microstrip can be analyzed using the sensitivity approach [1], [2]. This is the easiest method of predicting the worst case for the change in $Z_0$ and the relative effective dielectric constant $\epsilon_{re}$, corresponding to a set of tolerances. The change in the values of $Z_0$ and $\epsilon_{re}$ can be evaluated using the following relations:

$$\frac{\Delta Z_0}{Z_0} = \frac{\Delta W}{W} S_W^{Z_0} + \frac{\Delta h_2}{h_2} S_{h_2}^{Z_0} + \frac{\Delta \epsilon_r}{\epsilon_r} S_{\epsilon_r}^{Z_0} + \frac{\Delta h_1}{h_1} S_{h_1}^{Z_0} \quad (1a)$$

$$\frac{\Delta \epsilon_{re}}{\epsilon_{re}} = \frac{\Delta W}{W} S_W^{\epsilon_{re}} + \frac{\Delta h_2}{h_2} S_{h_2}^{\epsilon_{re}} + \frac{\Delta \epsilon_r}{\epsilon_r} S_{\epsilon_r}^{\epsilon_{re}} \rightarrow \frac{\Delta h_1}{h_1} S_{h_1}^{\epsilon_{re}} \quad (1b)$$

where $W$, $h_2$, $\epsilon_r$, and $h_1$ are the tolerances in $W$, $h_2$, $\epsilon_r$, and $h_1$, respectively, and the sensitivity $S_B^A$ is defined as

$$S_B^A = \frac{B}{A} \frac{\partial A}{\partial B}. \quad (2)$$

A complete set of graphs for the sensitivities of $Z_0$ and $\epsilon_{re}$ with respect to $W$, $h_2$, $\epsilon_r$, and $h_1$ ($S_W^{Z_0}$, $S_{h_2}^{Z_0}$, $S_{\epsilon_r}^{Z_0}$, $S_{h_1}^{Z_0}$, $S_W^{\epsilon_{re}}$, $S_{h_2}^{\epsilon_{re}}$, $S_{\epsilon_r}^{\epsilon_{re}}$, and $S_{h_1}^{\epsilon_{re}}$) as functions of the width to height ratio $W/h_2$ for $\epsilon_r = 9.6$ and at different shield heights ratios $h_1/h_2$ are given in Fig. 2(a) to 2(h). The most important facts that can be pointed out are listed below.

a) The sensitivity curves for $Z_0$ and $\epsilon_{re}$ are free from any discontinuities.

b) $S_W^{Z_0}$, $S_{\epsilon_r}^{Z_0}$, and $S_{h_2}^{\epsilon_{re}}$ are negative.

c) High-impedance shielded microstriplines ($W \leqslant h_2$) are more sensitive to tolerances in $\epsilon_r$ than tolerances in $W$, $h_1$, and $h_2$.

d) Low-impedance shielded microstriplines ($W \geqslant h_2$) are less sensitive to tolerances in $\epsilon_r$ than tolerances in $W$, $h_1$, and $h_2$.

e) For unity shield heights ratio $h_1/h_2 = 1$, the sensitivities $S_r^{Z_0}$, $S_r^{re}$, and $S_W^{re}$ have the following values:

$$S_{\epsilon_r}^{Z_0} = -\epsilon_r/(2+2\epsilon_r) \quad (3a)$$

$$S_{\epsilon_r}^{\epsilon_{re}} = \epsilon_r/(1+\epsilon_r) \quad (3b)$$

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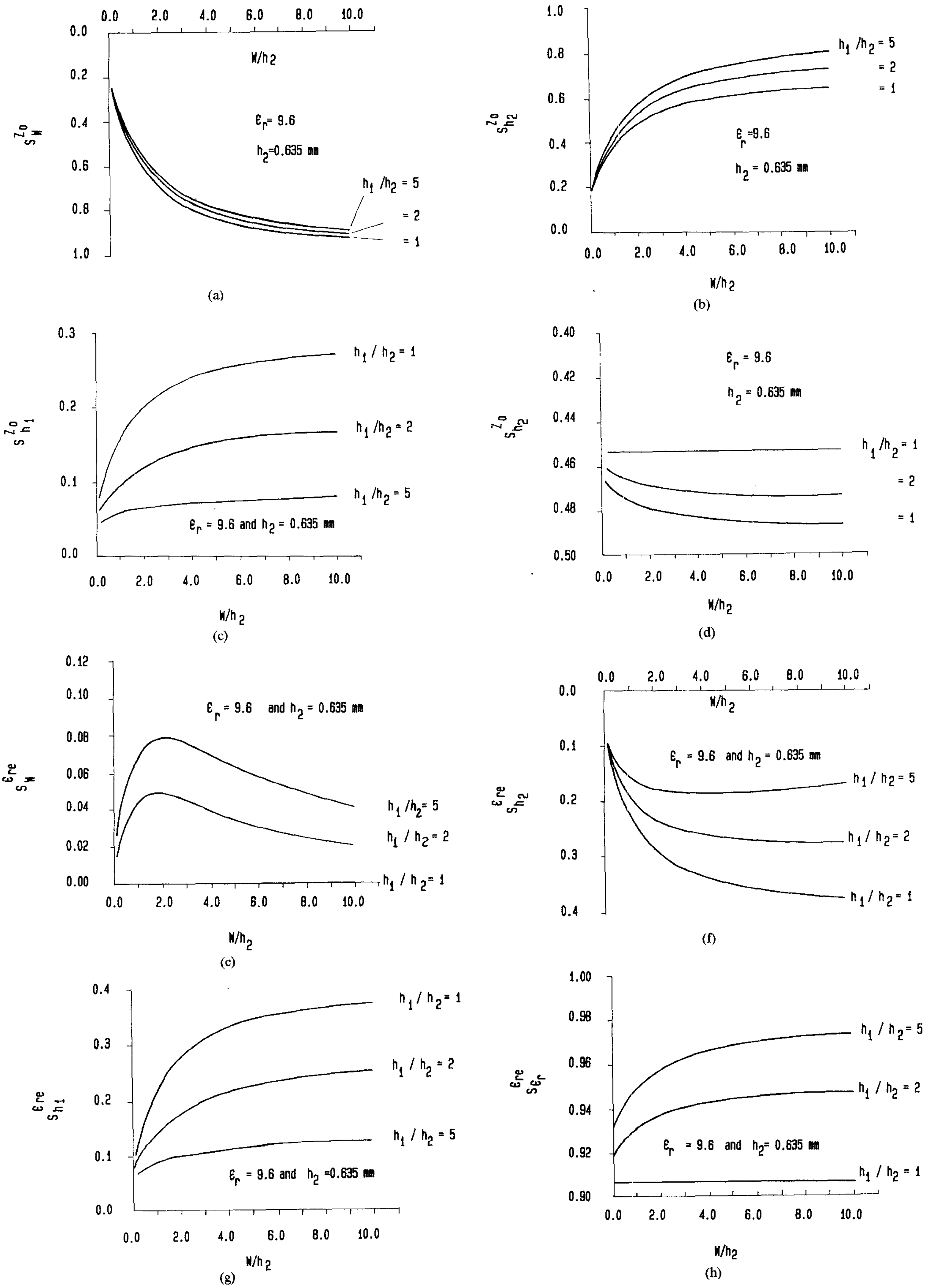


Fig. 2. Variation of the sensitivity as a function of the shielded microstrip physical dimensions. (a) $S_W^{Z_0}$. (b) $S_{h_2}^{Z_0}$. (c) $S_{h_1}^{Z_0}$. (d) $S_{h_2}^{Z_0}$. (e) $S_W^{\epsilon_{re}}$. (f) $S_{h_2}^{\epsilon_{re}}$. (g) $S_{h_1}^{\epsilon_{re}}$. (h) $S_{\epsilon_r}^{\epsilon_{re}}$.

and

$$S_W^{\epsilon_{re}} = 0. \tag{3c}$$

f) The characteristics of shielded microstrip ($Z_0$ and $\epsilon_{re}$) are, in general, more sensitive to the changes in the shield height $h_1$ for smaller values of the shield heights ratio $h_1/h_2$.

g) The sensitivity of the effective dielectric constant with respect to the strip width $W$ is less than 10 percent.

The characteristic impedance $Z_0$ and the relative dielectric constant $\epsilon_{re}$ are given by

$$Z_0 = [c\sqrt{CC^a}]^{-1} \quad \text{and} \quad \epsilon_{re} = C/C^a$$

where $c$ is the phase velocity in free space, and $C$ and $C^a$ are the capacitance per unit length of the structure with and without the dielectric, respectively. In the limiting case, as $h_1$ approaches zero, both $C$ and $C^a$ approach infinity, $\epsilon_{re}$ approaches unity, and $Z_0$ approaches zero. Thus, both $\epsilon_{re}$ and $Z_0$ decrease with decreasing $h_1$, and $S_{h_1}^{Z_0}$ and $Z_{h_1}^{\epsilon_{re}}$ have the same sign. Since $S_W^{Z_0}$ and $S_W^{\epsilon_{re}}$ have opposite signs, it is not possible to simultaneously compensate for changes in $Z_0$ and $\epsilon_{re}$, resulting from variations in $W$, by adjusting $h_1$. Similarly, the same is true for changes in $Z_0$ and $\epsilon_{re}$, resulting from variations in $h_2$. However, this is not a serious drawback of the suggested methods of compensation as the circuit performance will depend on the value of $Z_0$, and thus, in most cases, compensating $Z_0$ will be the primary target.

The values of sensitivities by themselves are not sufficient to determine the change in the characteristics of the shielded microstrip. The contribution of each of these sensitivities to the characteristics also depends on the weight function $\Delta B/B$, as given in (2). The above analysis of the effect of tolerances may be used to predict the maximum error in $Z_0$ and $\epsilon_{re}$ due to corresponding errors in the physical parameters $W$, $h_2$, $\epsilon_r$, and $h_1$. Moreover, it shows that the change in the shield height $h_1$ may be used to compensate for the effect of the other tolerances or even for the effect of dispersion and finite strip thickness. The maximum expected change $\Delta h_1$ in the shield height in order to set (1a) and (1b) to zero is

$$\Delta h_1(\Delta Z_0 = 0) = \frac{\Delta Z_0(W, h_2, \epsilon_r)}{Z_0} \left| \frac{h_1}{S_{h_1}^{Z_0}} \right| \tag{4a}$$

and

$$\Delta h_1(\Delta \epsilon_{re} = 0) = \frac{\Delta \epsilon_{re}(W, h_2, \epsilon_r)}{\epsilon_{re}} \left| \frac{h_1}{S_{h_1}^{\epsilon_{re}}} \right| \tag{4b}$$

where

$$\frac{\Delta Z_0(W, h_2, \epsilon_r)}{Z_0} = \left| \frac{\Delta W}{W} S_W^{Z_0} \right| + \left| \frac{\Delta h_2}{h_2} S_{h_2}^{Z_0} \right| + \left| \frac{\Delta \epsilon_r}{\epsilon_r} S_{\epsilon_r}^{Z_0} \right| \tag{4c}$$

and

$$\frac{\Delta \epsilon_{re}(W, h_2, \epsilon_r)}{\epsilon_{re}} = \left| \frac{\Delta W}{W} S_W^{\epsilon_{re}} \right| + \left| \frac{\Delta h_2}{h_2} S_{h_2}^{\epsilon_{re}} \right| + \left| \frac{\Delta \epsilon_r}{\epsilon_r} S_{\epsilon_r}^{\epsilon_{re}} \right|. \tag{4d}$$

In fact, it is not possible to set (1a) and (1b) to zero for the same value of $\Delta h_1$ due to the uncertainty in the changes in $Z_0$ and $\epsilon_{re}$ arising from the tolerances. However, it is always possible (within small tolerances) to get a suitable change in the shield height $h_1$ that minimizes $\Delta Z_0$ or $\Delta \epsilon_{re}$. To illustrate the above-mentioned fact, the following examples are introduced.

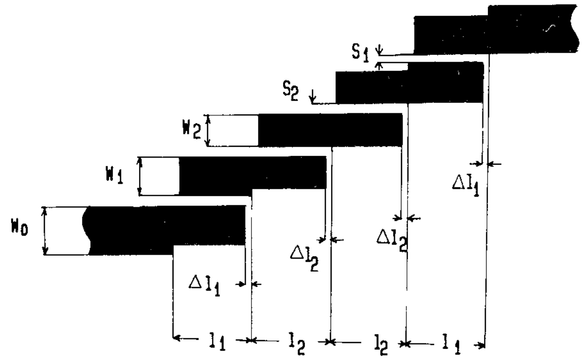


Fig 3. Bandpass parallel-coupled filter of [3].

TABLE I

| i | $W_i$ | $S_i$ | $l_i$ | $\Delta l_i$ |
|---|---|---|---|---|
| 0 | 1.94 | - | 7.4 | - |
| 1 | 1.644 | 0.11 | 9.0 | 0.27 |
| 2 | 2.1 | 0.66 | 9.0 | 0.29 |

All dimensions are in millimeters. $\epsilon_r = 2.33$ and $h_2 = 0.762$ mm.

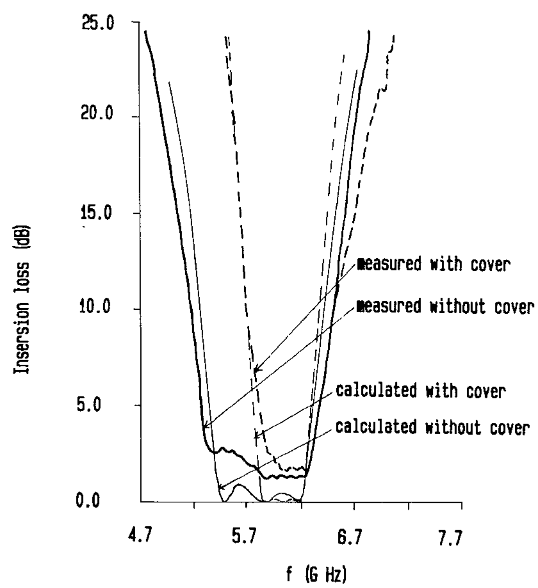


Fig. 4. Response of the filter of example 2.

## III. Practical Examples

In this section, two examples are introduced.

*Example 1*

In this example, we have built a 50-Ω shielded microstripline on alumina substrate of thickness $h_2 = 0.635$ mm and dielectric constant $\epsilon_r = 9.6$. The top cover is at a position such that $h_1 = 1.27$ mm (i.e., $h_1/h_2 = 2$) with a corresponding width $W = 0.579$ mm (as obtained from [3] or [4]). The line was then terminated by a 50-Ω matching load. The reflection coefficient of the line was then measured using an 8410B HP network analyzer. As we expected, the measured reflection coefficient was not zero (i.e., the value of the characteristic impedance of the manufactured line is not 50 Ω, as we desire). This, of course, is due to the effect of manufacturing tolerances. The top cover was then moved up and down until matching was obtained.

It may be pointed out that it is not easy, in practice, as it seems from this example, to compensate for the effect of manufacturing tolerances because, in practice, actual circuits contain more than one line, each having different manufacturing tolerances.

*Example 2*

The bandpass parallel-coupled filter of [3], and shown in Fig. 3, is redesigned for the same specifications, but the response is optimized for a shield height ratio $h_1/h_2 = 2$ using the state-space method of [5]. The new circuit dimensions are given in Table I. Both the computed and measured responses, with and without the top cover, are shown in Fig. 4. Measured and calculated responses show that, in shielded microstrip circuits, the response may be controlled by varying the position of the top cover. It may be pointed out that the theoretical response, with the presence of the top cover, is calculated at a shield heights ratio $h_1/h_2 = 2$. While the measured response, with the presence of the top cover, is obtained by moving the top cover up and down until we obtain a response that meets our desired specifications (i.e., not necessarily at shield heights ratio $h_1/h_2 = 2$).

From the foregoing examples, we suggest a shielded microstrip circuit with a variable shield heights ratio that can be used for a mechanical tuning of a given shielded microstrip circuit.

Special substrate holders (fixtures) with variable shield heights ratios have been manufactured for use during the above-mentioned measurements.

## IV. Conclusion

It should be pointed out that the shielded microstrip circuit with a variable shield heights ratio will not perform magic. It is not expected to be able to compensate for any and all possible manufacturing tolerance combinations. However, an experienced designer can make use of this construction to improve the performance of his designed circuit. It also should be pointed out that we do not call for production of shielded microstrip circuits with variable shield heights ratios for normal usage. We only call for manufacturing circuits with variable shield heights ratios during the prototype stage of testing the designed circuit. The position of the top cover is then varied until the response of the prototype meets the desired specifications. Then the final circuits should be manufactured according to the prototype.

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# Heating Pattern in a Multi-layered Material Exposed to Microwaves

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***Abstract*—The electromagnetic-induced heating pattern in a multi-layered slab material exposed to uniform plane microwaves is studied. A general expression taking into account the multiple reflections at the interfaces is derived for the power dissipated per unit volume in the medium. A numerical method is developed for solving the heat transport equation describing the temperature distribution in this material. A steady, as well as a transient solution is obtained for either a Dirichlet- or a Neumann-type of boundary condition. The effect on the temperature distribution of a cooling fluid circulating inside the slab is considered.**

**The method is applied to the special case of a three-layered material having characteristics similar to those of a biological structure. The possibility of achieving a preferential heating of one of the layers by means of standing waves created with the aid of a flat reflector is demonstrated.**

## I. Introduction

The electromagnetic-induced heating pattern in a slab material exposed to a uniform plane microwave may be obtained from the one-dimensional heat transport equation (HTE). In the presence of a circulating cooling fluid in the material this equation is [1]

$$\rho_m c \frac{\partial T}{\partial t} = k_t \frac{\partial^2 T}{\partial x^2} - Vs(T - T_0) + Q(x,t) \tag{1}$$

where

$\rho_m =$ material density,
$c =$ specific heat,
$k_t =$ thermal conductivity,
$Vs =$ product of flow and heat capacity of the cooling fluid,
$T =$ material temperature,
$T_0 =$ temperature of the fluid entering the material, and
$Q(x,t) =$ electromagnetic power dissipated per unit volume.

An analytical steady-state solution of this equation can be found in [2] for the case of a single finite or semi-infinite layer. Foster, Kritikos, and Schwan [1] obtained a transient solution for a semi-infinite single-plane layer and applied it for determining the temperature distribution in living tissues exposed to microwave radiation. In their equation, the term $Vs(T - T_0)$ represented the contribution of the blood convection to the heat dissipation in the tissue.[1]

More recent attempts to solve the steady-state heat-transport equation by numerical methods are described in [4] and [5]. Numerical calculations of energy deposition and temperature distribution in biological tissues exposed to plane electromagnetic waves are reported in [6] and [7].

In what follows, a numerical method for solving the transient heat transport equation in a multi-layered material, with either a Dirichlet- or a Neumann-type of boundary condition, is presented. The cooling effect due to a fluid circulating through the

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[1]A more correct approach to evaluating this contribution was proposed by Wulff [3].

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