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THERMAL RESPONSE OF LARGE AREA HIGH TEMPERATURE SUPERCONDUCTING YBaCuO INFRA RED BOLOMETERS

Ali E. Khalil*

GE Astrospace Division, Princeton NJ 08543

Abstract:

Thermal analysis of large area high temperature superconducting infra red detector operating in the equilibrium mode (bolometer) is performed. The spatial spread of the heat pulse as a result of the initial thermal excitations due to the incident radiation is modeled using heat conduction. An expression for the temperature coefficient $\beta=1/R(dR/dT)$ in terms of the thermal conductance of the insulating substrate and the thermal time constant of the detector were derived. In addition, the thermal responsivity and the thermal cross talk between different elements of the array as a function of the angular frequency and the spatial modulation frequency of the incident radiation were examined. The results of this theoretical modeling were compared with recent measurements on YBaCuO thin film using YAG laser with clear excellent agreement between theory and experiment. This analysis can be critical for future design and applications of large area focal plane arrays as broad band optical detectors made of granular thin films high temperature superconductors YBaCuO.

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INTRODUCTION

Recent reports of optical interactions of high temperature superconducting (HTS) thin film YBaCuO have demonstrated equilibrium[1] (bolometric) and non-equilibrium[2] (quasi particle excitations) responses. These results have very promising applications for broad band optical detectors from ultraviolet to near infrared. A thin film high temperature superconducting transition edge bolometer can potentially have much better sensitivity for wavelengths greater than 20μm. In addition, utilizing high temperature superconducting thin film technology can lead to the state of the art thermal detectors operating at the theoretical noise limit. A proper choice of the detector backing can result in a flat spectral response at near perfect effeciency for wavelengths out to 250 μm. At these longer wavelengths where detector operations are mostly needed the bolometer area required for efficient coupling to an optical signal increases with the wave length. In addition, the bolometer thickness must also increase with wavelength for good optical efficiency. In general a careful design can provide a control over the thermal conductance between the thin film and the insulating substrate. A wide spectrum of values ranging from 0.005 μW/K to 1000 μW/K can be achieved in order to suit the background noise and or the detector speed requirements[3], while the film thickness can be adjusted to provide absorption over a wide range of wavelengths.

A superconducting transition edge bolometer is a thermistor consisting of a thin film superconducting YBaCuO evaporated into a suitable thermally isolated substrate. The operating temperature of the bolometer is maintained close to the midpoint of the superconducting transition region where the resistance R has a maximum dynamic range. Measurements on the electrical response of YBaCuO thin films to a fast optical laser pulses (100 Ps long) was recently reported[4]. It was found that although the magnitude of the signal corresponds to radiation heating, nonequilibrium energy transport have played a part in distributing the heat through the thickness of the film. Several models have been proposed to explain the experimental observations on optical excitations of the oxide superconductors however, complete understanding of this phenomena remains far from being clear[5].

In this article the performance of a thermal imaging system utilizing HTS thin film detector arrays and using the heat transport mechanism is examined. One of the key aspects of the performance of such system is the thermal response of the array to the incident radiation. These calculations require solving the heat conduction equation in the high temperature superconducting material (HTS) subject to the appropriate boundary conditions. An important feature of the thermal response is the lateral heat conduction which may tend to degrade the performance of the material by introducing cross coupling decreasing the signal to noise ratio. This problem may be particularly severe in a spread sheet configuration. However, a system of linear arrays with discrete detector elements and separate readout for each element will tend to eleviate the thermal spreading problem.

In order to simplify the modeling and numerical calculations it is useful to consider the case of a uniform illumination (heating) of the detector material. An array of detectors without adequate thermal isolation between different elements will experience severe thermal spreading. These effects will be accounted for using heat diffusion modeling in the later part of this article. The analysis does not include non-equilibrium behavior of the superconductor and only operations at the equilibrium conditions where thermal phonons are totally decoupled from the charged particle carriers are modeled.

Consider a thin film YBaCuO superconducting bolometer of the geometry defined in Fig.1 with volume specific heat C, thermal conductivity K, mass density γ , and thickness b. The film is at ambient temperature T(r,t) coupled to a heat sink (thermal insulator) of thickness c and temperature T_0 through a thermal conductance G. The thermal equilibrium of the entire system (the film + substrate) can be derived on the basis of the first principles. In the normal mode of operation energy is added to the system by incident photon flux of power density P_i and scene temperature $T_s(r)$ causing the system temperature to rise by an amount ΔT above the ambient. When thermal equilibrium is established the thermal response will depend on the temperature gradient $\Delta T/c$ across the insulator layer. This temperature gradient will cause heat flow per unit area of the thin film surface to the insulating substrate at a rate given by $K\,\Delta T/c$. In the steady state the amount of heat escaping to the insulator is balanced by the rate of heat conduction through the film, the radiation input flux, and the rate of energy loss per unit area out of the insulator to the surrounding, in this case the energy rate equation can be written as,

$$-\Delta TK/c=b\gamma C\delta\Delta T/\delta t+F_0-P_i b \qquad (1)$$

F_0 is the heat conduction loss through the insulator, we assume a blackbody radiation model where this quantity is given by $(4e\sigma T_0^{\,3})\Delta T$. σ is the Boltzman's constant and e is the emissivity of the insulating layer. Equation (1) describes the system response to the initial external perturbation with a thermal time constant t_h and a temperature rise ΔT given by,

$$t_h = bC\gamma/(4e\sigma T_0^3 + K/c) \quad (2)$$

$$\Delta T = (P_i t_h/C\gamma)(1-\exp(-t/t_h)) \quad (3)$$

ΔT is the increase in the detector temperature above the ambient due to a uniform illumination with a source of power density P_i. This temperature rise will saturate reaching a terminal value $P_i t_h/C\gamma$ at the complete phase transition where the superconducting thin film is totally switched to the normal state. For normal bolometer operation the superconducting resistive element of the thermometer is always operated at the midpoint of the transition region for maximum dynamic gain (dR/dT is maximum). In this case the temperature coefficient $\beta = 1/R(dR/dT)$ in conventional bolometer theory can be identified as the inverse of the half-width ΔT of the superconducting transition and,

$$\beta = (G\gamma/P_i)(1-\exp(-t/t_h))^{-1} \quad (4)$$

where $G=C/t_h$ is the thermal conductance between the film and the insulating layer. A superior bolometer performance requires β to be as large as possible[6]. These criteria can only be satisfied within the dynamic operating regime of the bolometer defined by equation (4). On a very short time scale immediately following the initial thermal disturbance and for small values of $t \ll t_h$ the temperature coefficient of the detector β is proportional to $1/t$ and consequently has a very large value (see Fig.2) which corresponds to optimum operating conditions of a thermal bolometer. However, for later times $t \gg t_h$, β is inversly proportional to the detector substrate thickness b and within this dynamic range a thiner detector substrate is preferable to improve the detector responsivity. These conclusions were recently confirmed where measurement on β for thin film HTS reported values much higher than those of low temperature superconductors[6].

Another important factor affecting the detector performance is the thermal coupling and the heat dissipation through the insulating substrate. In the special case when $T_o^3 c \ll K/4e\sigma$, the thermal time constant t_h is proportional to $bc(\gamma C/K)$, a maximum value of β will be reached when t_h is as small as possible. Since, the ratio $(\gamma C/K)$ is fixed by the choice of the superconducting film material the product (bc) should be minimal and the design of a large area array requires in principle that the detector thickness b and the substrate thickness c to be small for optimum thermal response.

In order to check the validity of our analysis a comparison between the theoretical predictions of equation (3) and recent experimental measurement reported in Ref.3 was performed. In the experiment described above a Nd:YAG laser was used as infrared source with pulses of 1.06 μm wavelength and ≈150psec long to illuminate a superconducting YBaCuO granular film of thickness 0.7μm. The authors observed that the voltage rise following laser excitation of the thin film was consistent with a bolometric (thermal) response. This was evident from the dependence of the voltage rise on the laser fluence. We have calculated that dependence using equation (3) together with R aganist T data provided in ref3. We have also used other parameters provided by the same reference for the film thickness, pulse duration,thermal conductivity, density and bias current of the thin film. Results of these calculations together with the measurements of reference3 are shown in fig.5 where clear agreement are evident.

In the above analysis an expression for the temperature coefficient of HTS bolometer when its dynamical behavior is governed by thermal balance of the system was derived. It was found that the temperature coefficient strongly depends on the geometry of the film and the insulating substrate. In addition, due to the rapid transition from superconducting to the normal state of the material very large values of β can be achieved when the thermal time constant is adjusted to acquire small values.

Thermal Responsivity

A thermal imaging system utilizing discrete HTS thin film detector arrays with solid state readout (CCD or CID) can be constructed. An accurate prediction of the performance of the detector array requires full thermal diffusion analysis with appropriate boundary conditions. Consider one element in the detector array with the configuration shown in Fig (1) and assuming the cross section area A of the thin film is normal to the Z-axis. In the case of a uniform illumination of the detector surface the diffusion equation can be written as,

$$1/k\Delta T-\delta T/\delta t=0 \qquad (5)$$

Δ stands for three-dimensional Laplacians operator

with the boundary conditions,

$$K\delta T/\delta Z= -I_i T \qquad Z=0 \qquad (6)$$

$$K\delta T/\delta Z= I_o T \qquad Z=-b \qquad (7)$$

I_i and I_o are the radiative heat flow at the front and back electrode boundaries, $k=K/C\gamma$ is the thermal diffusity of the substrate. Integrating the Fourier transform of equation (5) over the Z-axis and applying the appropriate boundary conditions (6) and (7) we have,

$$q^2 T_a(s,\Omega)=1/Kb\{I_o T(s,\Omega,-b)+I_i T(s,\Omega,0)\} \qquad (8)$$

and

$$q^2=s^2_x+s^2_y+i\Omega/K$$
$$i=(-1)^{1/2}$$

T_a is the mean temperature change inside the film and is given by

$$T_a=1/b\int_{-b}^{0} T(x,y,z,t)dz$$

the thermal responsivity function of the detector is defined as

$$R_t=T_a(s,\Omega)/I_i T(s,\Omega,0)$$
$$=1/q^2 Kb[1+ I_o T(s,\Omega,-b)/I_i T(s,\Omega,0)] \qquad (9)$$

for a very thin detector of few microns thick the diffusion length of the heat pulse in the Z-direction is much larger than the wafer thickness and $|qb|<<1$, $T(s,\Omega,-b)\approx T(s,\Omega,0)$, in this case equation (9) reduces to,

$$|R_t|=(1+e_o/ei)/Kb(1+\Omega^2/s^2K^2) \qquad (10)$$

e_i and e_o are the respective emissivities at the front and back surfaces of the film. Equation (10) is plotted in fig (3) as a function of the variable $(s/\Omega^{1/2})$ where s is the spatial modulation frequency and Ω is the angular frequency of the incoming radiation. Two graphs were plotted for two different values of the thermal diffusivity k. Inspection of this figure reveals that for the superconducting material with its characteristic diffusivity value, higher chopping frequency results in higher spatial frequency to produce the same thermal response while quadrupling the chopping frequency will require doubling the spatial frequency.

The response of the HTS detector will ultimately be determined by trading off the electrical-thermal gain bandwidth and the noise bandwidth. The bandwidth limits are determined by the thermal time constant t_h and by the electrical time constant t_e, generally $t_h >> t_e$ and the rise time of the signal will be affected by the thermal coupling between the film and the insulator substrate. A current will appear in the HTS material only in response to temperature variations which produces a resistive load in the superconducting element. The temperature variations of the incident radiation flux can be achieved by different types of modulation schemes. Depending on the particular application, chopper modulation of a stationary source can be established. In outer space applications since, a linear or constant velocity scan is necessary when a large field of view is to be covered by a linear array the satellite motion will induce the temperature variation of the covered scene. In most of these applications and due to the large dynamic gain of HTS material (β is large) thermal crosstalk between different elements may degrade the detector response by decreasing the signal to noise ratio.

To address the problem of the thermal cross talk between different detector elements we assume a monolithic HTS detector array with a row of square elements of dimensions 2a and CCd or CID readout electronics. We define the thermal spread function of two detector elements to be given by,

$$W_s = |R_1/R_2| \qquad (11)$$

W_s describes the noise effects of the element 1 which is adjacent to element 2 in the array due to the same input pulse and R_i is proportional to the voltage response of an element i to the thermal excitations, this function is defined as,

$$R_i = 1(/2\pi)^2 \int d^2k T_a(k,\Omega) S_i(k) \qquad (12)$$

and

$$S_i(k) = (\sin k_x a / k_x a)\ (\sin k_y a / k_y a)\ \exp(i k_x x_o + i k_y y_o)$$

$S_i(k)$ is the spatial transform function of a detector element i centered at (x_o, y_o), the element electrode is defined to have a uniform thermal response in the electrode area and zero outside this area. The thermal spread function of equation (11) was calculated for different spacings between the elements. The results are plotted in Fig.4 as a function of the parameter $a(\Omega/k)^{1/2}$. These curves reveal that the thermal cross talk decreases rapidly with increasing the spacing between elements in the array while decreasing the thermal diffusivity of the material may improve the overall array performance. It is important to realize that If phase sensitive detection is employed then W_s has to be multiplied by cosine the phase difference between the signals from two adjacent elements.

In this article a theoretical model was developed to describe thermal excitations of large area high temperature superconducting thin film bolometers. As a result of this analysis it was found that large values of β (temperature coef.) can be achieved and for optimum array performance a superconducting thin film is preferable in constructing array configurations to thick films. Although the results of the second part of the analysis are generic in nature and applicable to any focal plane array configuration it shows that thermal cross talk can be minimized by increasing the element spacing in the array or increasing the spatial chopping frequency of the incoming radiation. The results of these calculations together with recent measurements on laser excitations of thin film agree reasonably well. This modeling can be utilized in future design of hyprid focal plane array IR detectors using HTC technology.

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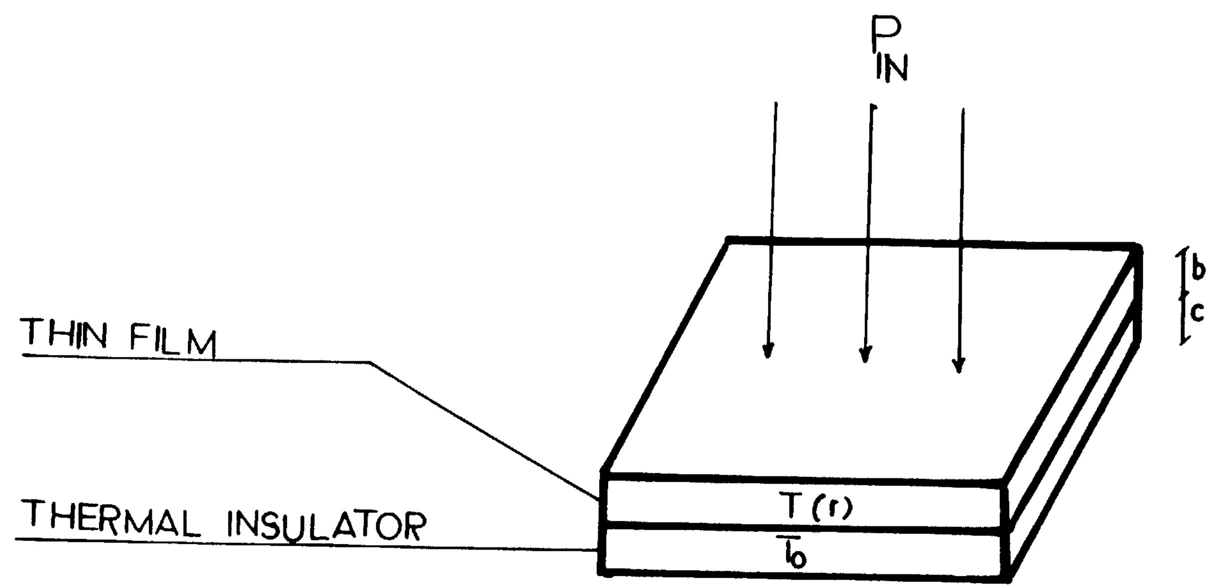

Figure 1: Detector-insulator configuration.

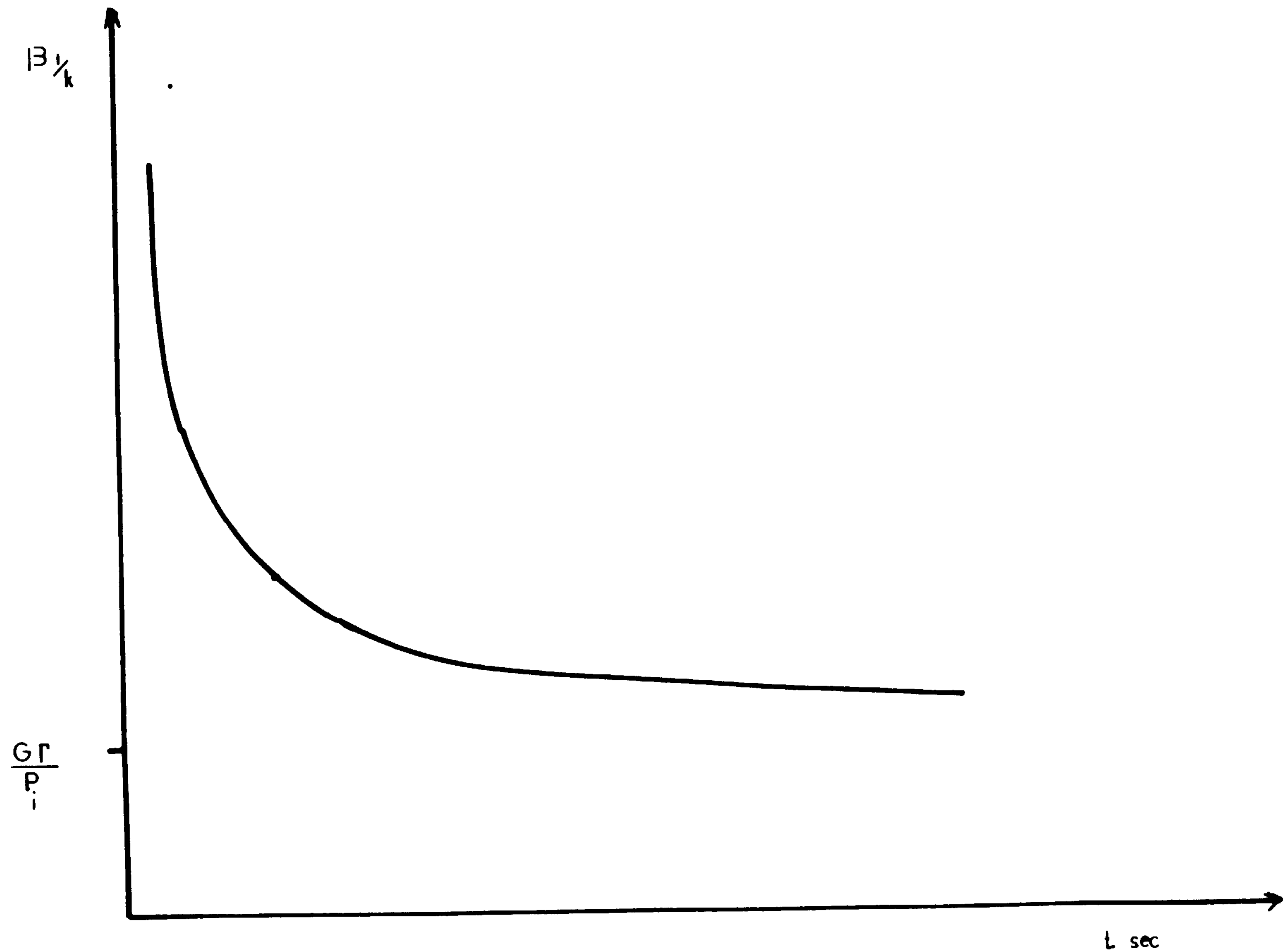

Figure 2: Temperature coefficient β as a function of time.

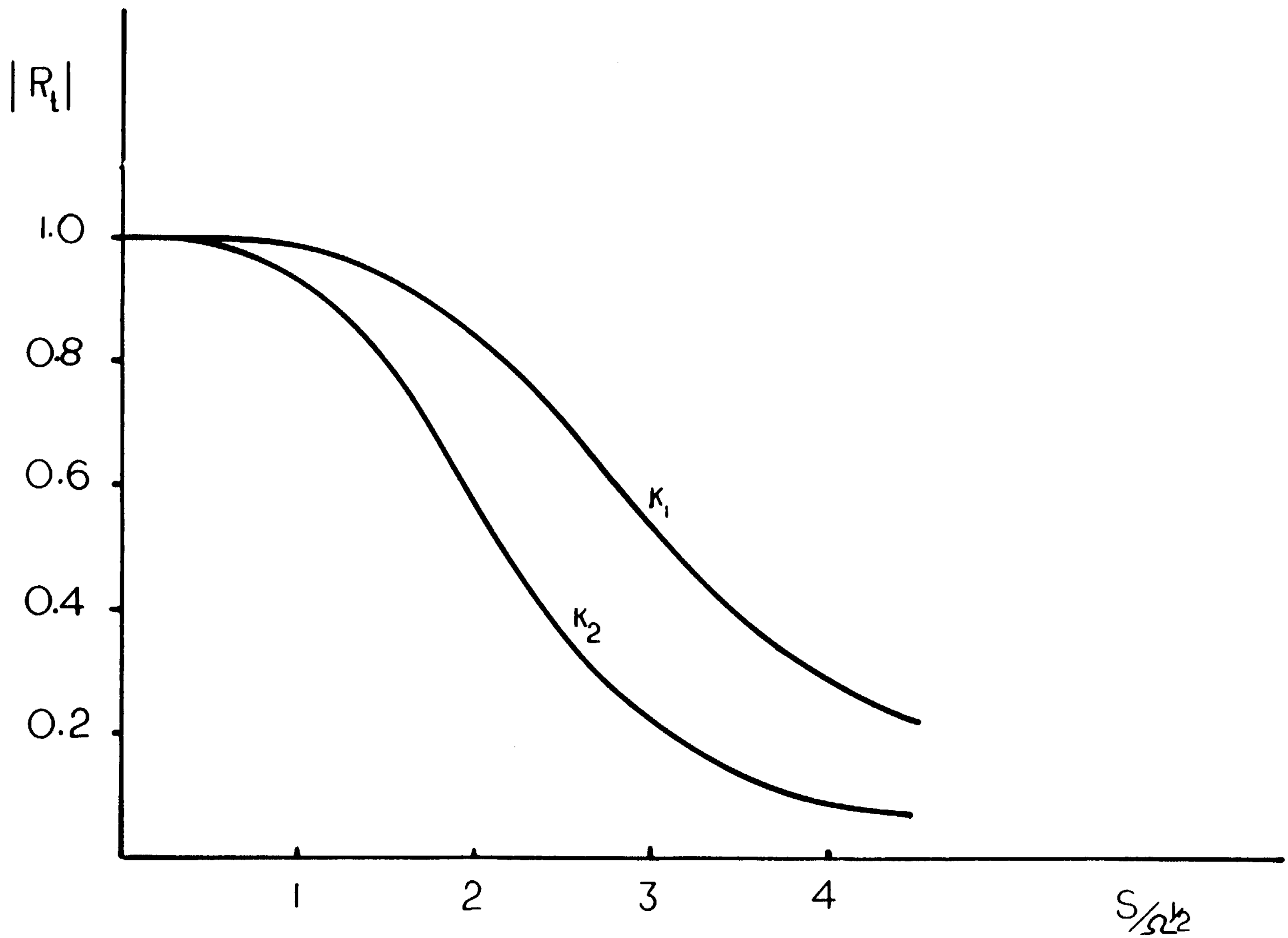

Figure 3: Thermal responsivity as a function of $S/\Omega^{1/2}$ and different values of thermal conductivities. $K_2/K_1=4$.

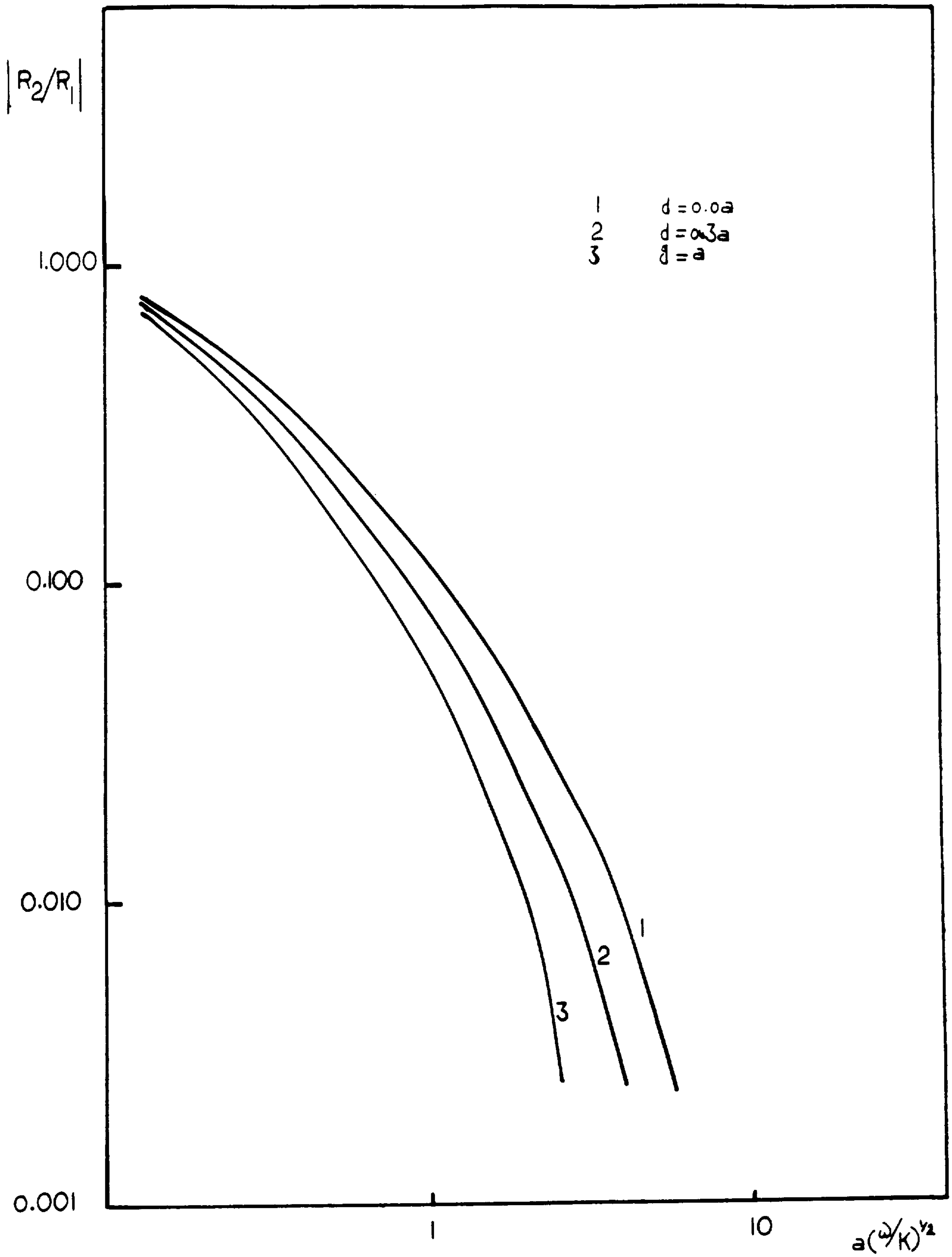

Figure 4: Variation of thermal spread function with $a(\Omega/K)^{1/2}$ for three different values of spacing between elements d.

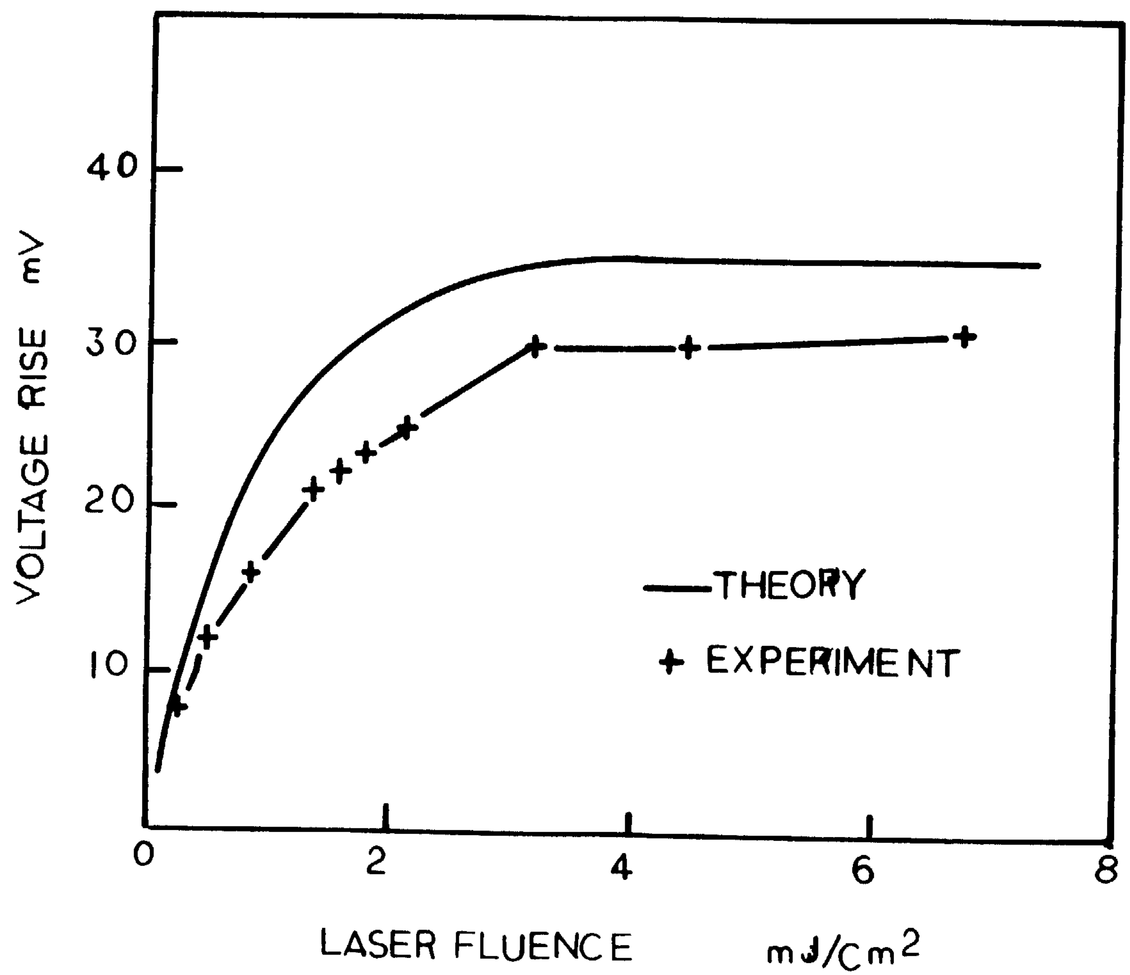

Figure 5: Comparison between experimental measurements of Ref.3 and theoretical calculations of our model. Different parameters were taken from Ref.3.