Missouri University of Science and Technology

Scholars' Mine

Electrical and Computer Engineering Faculty
Research & Creative Works

Electrical and Computer Engineering

01 Jan 2003

Measurement of Mode Patterns in a High-Power Microwave Cavity

Sergey Kharkovsky
Missouri University of Science and Technology

U. C. Hasar

Follow this and additional works at: https://scholarsmine.mst.edu/ele_comeng_facwork

Part of the Electrical and Computer Engineering Commons

Recommended Citation

Measurement of Mode Patterns in a High-Power Microwave Cavity

Sergey N. Kharkovsky, *Senior Member, IEEE,* and Ugur C. Hasar, *Student Member, IEEE*

Abstract—A wet thermal paper method for measuring of mode patterns and heat distributions in a high-power microwave multimode cavity is developed. The exposure time of the paper is evaluated. It is shown that this method allows measuring and recording mode patterns in the loaded and unloaded cavity, and the heat distribution inside the cavity with a load movement. The mode patterns and heat distributions along horizontal and vertical planes of the cavity are presented. Possible applications of the method in medicine and biology are discussed, and a calibration protocol of a microwave oven for microwave radiation exposure on cell cultures in the cavity is given.

Index Terms—Calibration, exposure time, high power, measurement, microwave cavity, mode patterns, wet thermal paper method.

I. INTRODUCTION

HIGH-POWER microwaves are used in industry for heating, drying, etc [1]. Besides, the methods of microwave treatment have been used in medicine and biology for fast fixation [2], denaturation, hybridization [3], sterilization [4], etc. Most of these methods use microwave oven operating at 2.45 GHz.

In principle, the microwave oven is a closed metal rectangular cavity with some means of coupling in power from generator, and the dimensions of the cavity are several wavelengths in three dimensions. Such cavity supports a large number of resonant modes in a given frequency range. Its field distribution is given by the sum of all the modes excited at the given operating frequency. There is, therefore, fundamentally a spatial nonuniform complex distribution of field (mode patterns) within a multimode oven [1].

In practice, the field distribution in the oven is more complicated than indicated above because of the influence of a load. That is why it is important to study the mode patterns with the given load in the cavity.

There are well known methods for the measurement of field distribution in a high-power microwave cavity. A temperature and a power intensity map in the empty cavity were determined by using a fiber optic sensor [5], a probe [1]. These techniques minimally perturb the microwave field, but they are very complex because the cavity is closed. Some methods were used for identifying mode patterns, for example, by using a neon bulb array [2], a water-filled tube array [6], a radar absorbent material that changes color following the microwave absorbency [2], etc. However, these methods only demonstrate the field distributions in the cavity as mode patterns, and these patterns are not recorded. Mode patterns mean here the resulting interference patterns of the main features of the field distributions (shape, size, etc.) in the cavity that are demonstrated by dark and bright bulbs [1], cold and hot water-filled tubes [6], and different colored parts of the absorbent material [2].

In this paper we develop a new simple wet thermal paper method for the measuring and recording mode patterns and heat distributions in a high-power cavity and present some results of these measurements. First, the evaluation of the exposure time of the wet thermal paper and the description of the method are given. Then, the results of measurement of mode patterns and heat distributions along horizontal and vertical planes in the unloaded and loaded cavity are presented. Finally, possible applications of the method in medicine and biology are discussed, and a protocol of the calibration of a microwave oven for a microwave radiation exposure on cell cultures in the cavity is given.

II. WET THERMAL PAPER METHOD

To record the mode patterns of the cavity, a piece of wet thermal fax paper is placed between two pieces of cardboard fixed in special polystyrene (foam) light form and is located inside the cavity. The water on the paper surface heats up the places where there is microwave energy, and the thermal paper changes color with time from white to black in these places. The evaluation of the exposure time is the essential point for measurements and calibration.

A. Evaluation of the Exposure Time

The criterion for evaluation of the exposure time is to heat the water on the paper surface up to 100 °C.

The average power dissipated as heat inside a dielectric is given by [7]

$$P_{av} = \frac{1}{2}\omega\varepsilon_o\varepsilon''_{eff} \int\limits_V \left(\vec{E}^*\vec{E}\right) dV \tag{1}$$

where ω is the angular frequency, ε_o is the dielectric constant of free space, ε''_{eff} is the imaginary part of the effective dielectric permittivity, $\vec{E}$ is the electric field intensity (* refers to the conjugate), and V is the volume of the dielectric material.

In most cases, $\vec{E}$ is not a constant quantity but varies in space within the microwave applicators. In special cases, where the

electric field can be assumed constant, with the usage of the property $\vec{E}^*\vec{E} = E^2$, (1) yields

$$P_{av} = \omega \varepsilon_o \varepsilon''_{eff} (E_{\mathrm{rms}})^2 V \qquad (2)$$

where E_{rms} is the root mean square of electric field intensity.

As the material absorbs the microwave energy, its temperature increases at a rate depending upon a number of distinct parameters. The power required for raising the temperature of a mass M_a (kg) of the material from T_0 °C to T °C in t seconds is given by [1]

$$P = \frac{Q_h}{t} = M_a c_p \frac{(T - T_0)}{t} \qquad (3)$$

where Q_h is the external heat supplied to the system and c_p is the specific heat of the material at constant pressure. The specific heat of a material is the amount of heat required to raise the temperature of its 1 kg by 1 °C.

Substituting (2) into (3), we can obtain the needed exposure time as

$$t = \frac{M_a c_p (T - T_o)}{\omega \varepsilon_o \varepsilon''_{eff} (E_{\mathrm{rms}})^2 V}. \qquad (4)$$

For our case, $c_p = 4.18 \times 10^3$ J(kg °C)$^{-1}$, $T = 100$ °C, $T_o = 23$ °C, $\varepsilon''_{eff(av)} \approx 7$, $M_a = 3.8 \times 10^{-3}$ kg, $\varepsilon_o = 10^{-9}(36\pi)^{-1}$ F/m. If we use a standard microwave oven the electric field intensity will be $E_{\mathrm{rms}} = 3 \times 10^3$ Vm^{-1}. In addition, if we assume that the volume of the water is the same as that of the thermal fax paper, the volume of the water is estimated as $V \approx 5 \times 10^{-6}$ m^3.

Then, the exposure time t is calculated, and the result is 30 s. The estimated exposure time is suitable because, on the one hand, it is greater than the transition time for steady-state regime of the high-power oscillator operating. On other hand, this time is short enough to avoid an influence of hot water flow to "cold" places, especially when measuring the mode pattern along the vertical plane. But this assumption can be checked by only experiment.

After the evaluation of the exposure time measurement setup is arranged.

B. Measurement Arrangement

The schematic view of the cavity with coupling element is shown in Fig. 1. The dimensions of the cavity are a = 31.3 cm, b = 31.5 cm and c = 31 cm. There is a rotary plate on the bottom of the cavity as shown in Fig. 1. The cavity is fed by a microwave oscillator the output power of which can be varied from 90 to 900 W.

The cardboard pieces with the wet thermal fax paper are located inside the cavity at the horizontal or vertical plane. The load used is a glass of water (100–200 ml).

When the wet paper is irradiated for several seconds, the water on the paper surface is heated in places, where the microwave intensity is the highest. In that time, the thermal paper changes its color from white to black in these places. Dark spots ("hot spots") on the paper correspond to the location of the microwave field. Water in the "cold" places of the paper vapors at the air. Therefore, we have the dry paper with dark spots cor-
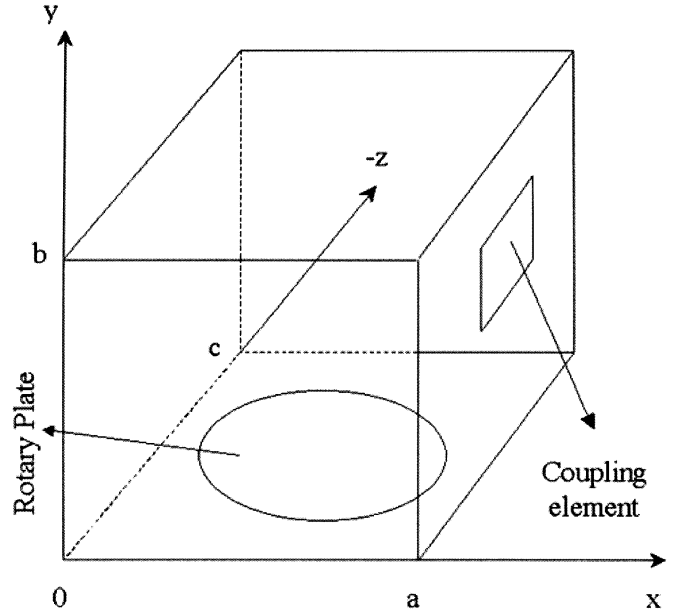

Fig. 1. Schematic view of the cavity with the coupling element (rectangular aperture) and rotary plate.

responding to the mode pattern of the cavity. In the case when the wet paper rotates by means of a rotary plate, dark places on the paper show the heat distribution on the rotary plate. The optimum exposure time and amount of water are determined experimentally. If we repeat the measurement procedure carefully, we get the same pattern or the same heat distribution every time.

The measurements are conducted at two different planes, horizontal and vertical.

### III. MEASUREMENT RESULTS

A. Horizontal Plane

We have investigated the distribution of microwave field a little above the bottom of the cavity. In fact, the form containing wet thermal paper is located on the rotary plate of a diameter of 300 mm.

The views of the thermal papers irradiated without rotation of the plate in the unloaded and loaded cavity are shown in Fig. 2. It can be seen from Fig. 2(a) that the mode patterns in the unloaded cavity is nonuniform, however, there is at least one symmetry plane here. The location of the load in the cavity changes this field distribution significantly [Fig. 2(b)]. It becomes more nonuniform. The load in the cavity not only changes the field distribution but also reduces the amplitude of field intensity.

Fig. 3 shows views of the thermal paper irradiated with the rotation of plate in the unloaded [Fig. 3(a)] and loaded [Fig. 3(b)] cavity. The location of wet thermal paper is the same as described in Fig. 2. Here, dark areas show the heat distribution as a result of the field influence in different places of the paper because both the thermal paper and the load move through maximum and minimum (nodes) of the microwave field. We can see that the heat distribution in the unloaded cavity [Fig. 3(a)] is uniform with a circular symmetry, and the field is absent at the cavity center. The load does not markedly change the heat distribution but rather reduces the field intensity [Fig. 3(b)].
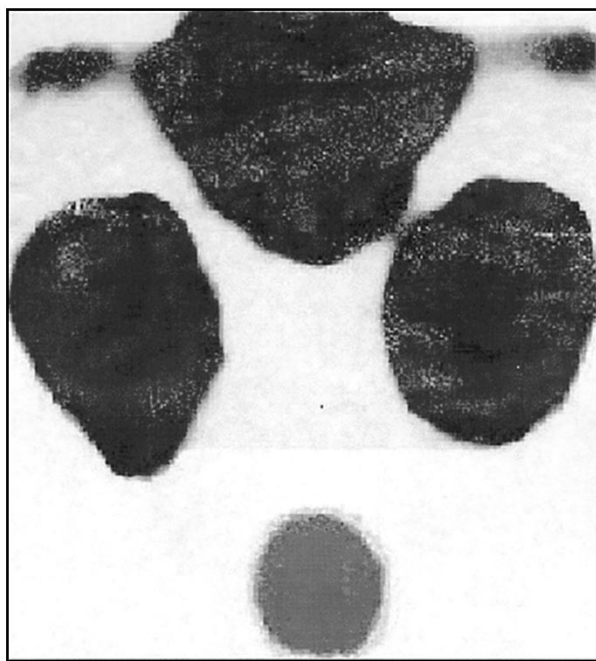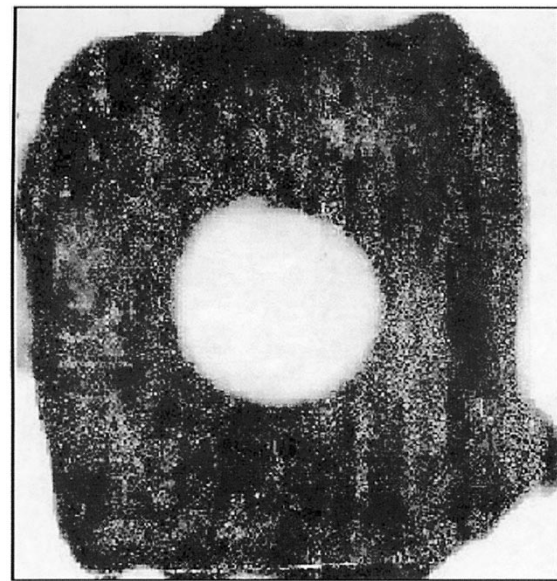
(a)
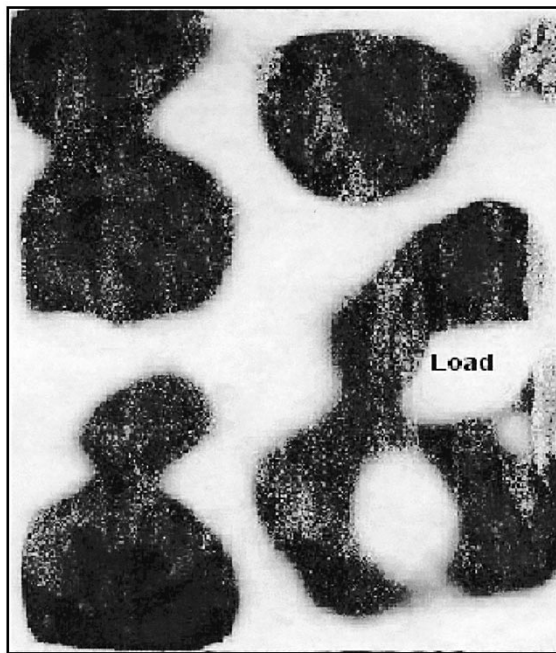
(b)

Fig. 2. The mode patterns on the thermal paper irradiated along the horizontal plane (at $y = 2$ cm) of the unloaded (a, $P = 360$ W, $t = 30$ s) and loaded (b, $P = 900$ W, $t = 30$ s, 100-ml load) cavity.

B. Vertical Plane

As mentioned above, the possibility of the method to measure and record mode patterns along the vertical plane must be tested. The hot water flow across the thermal paper under the influence of gravity might change its color in "cold" places and results could be false.

Fig. 4 shows mode patterns in the cavity near its wall where the coupling element is placed.

The dark spot in the center of the Fig. 4(a) corresponds to the location of the coupling element.


(a)
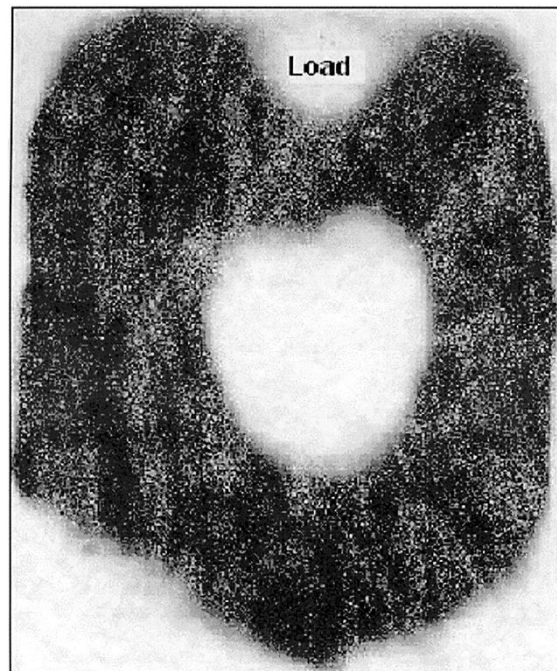
(b)

Fig. 3. The heat distributions on the thermal paper irradiated along horizontal plane (at $y = 2$ cm) of the unloaded (a, $P = 360$ W, $T = 30$ s) and loaded (b, $P = 360$ W, $t = 45$ s, 100 ml load) cavity with rotation of the plate.

As can be seen from Fig. 4(a), the assumption that the hot water flow down caused by gravity would not affect the change of the spot size has been confirmed. It means that the exposure time is really suitable for measuring mode patterns along the vertical plane.

Fig. 4(b) shows the effect of load on mode pattern. It can be seen from Fig. 4(b) that the load changes mode patterns, and the location of the coupling element is determined not so clear.

Fig. 5 shows mode patterns along different vertical planes of the cavity. We can see that there is no field at the bottom of cavity center [Fig. 5(a)]. Besides, the rotation of the plate with the paper provides approximately uniform heat distribution in the center of the cavity (Fig. 6).
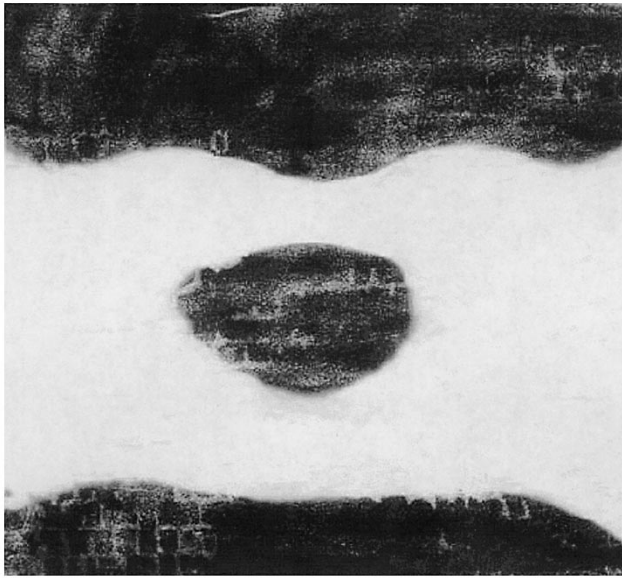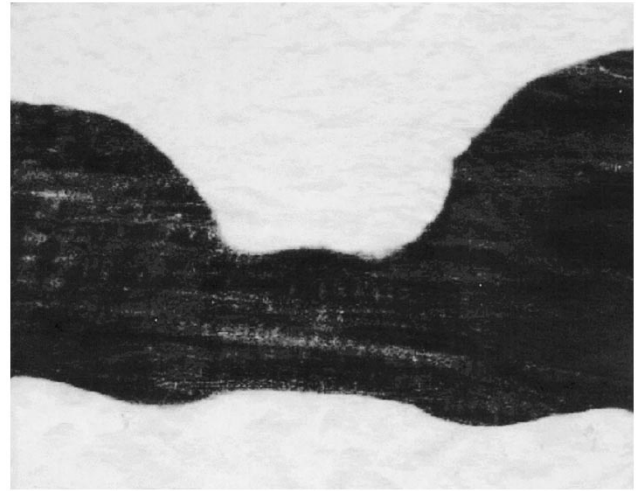
(a)
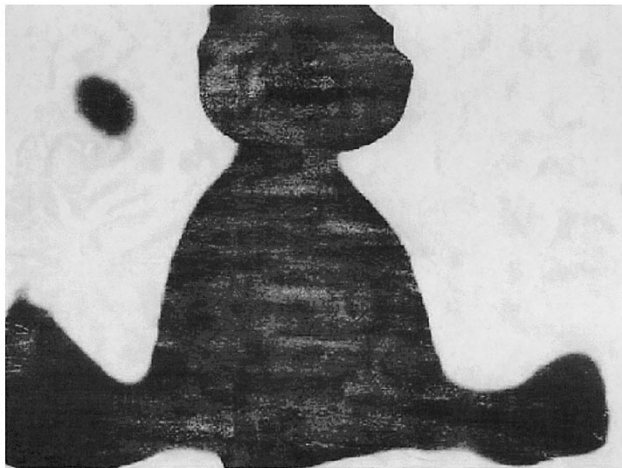
(b)

Fig. 4. The mode patterns on the thermal paper (17×23 cm^2) irradiated along the vertical plane (at $x = 31$ cm) of the unloaded (a, $P = 600$ W, $t = 25$ s) and loaded (b, $P = 600$ W, $t = 30$ s, 200 ml load in the center of the cavity bottom) cavity.

## IV. Discussion of Possible Applications and Calibration Protocol

It is possible to use the developed method and the obtained results for specific applications. For example, for applications of the microwave oven in medicine and biology, the cavity has to assure a uniform field distribution with a controlled intensity at the location of the samples [2].

The use of the microwave oven for biological studies of microwave effects without its calibration often causes irreproducible results because of nonuniform field distribution, the effect of load, and features of the sample (small size, the presence of water and different medium, etc.). The composition of the sample container and the volume of solution around the sample are among the most important determinants of uniform microwave irradiation.

We have used the thermal paper method to predict the heating of a biological sample (the cancer cell line of human containing

(a)
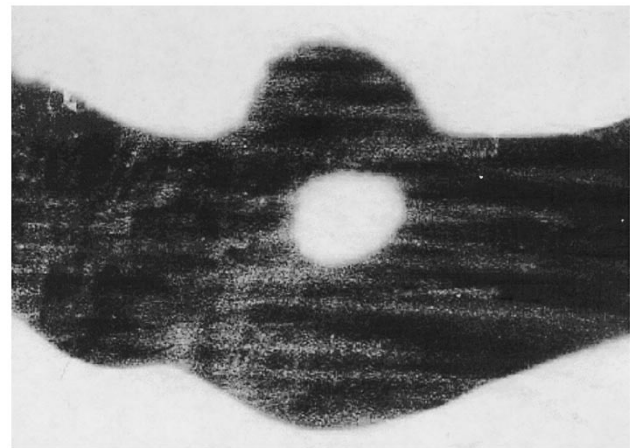
(b)

Fig. 5. The mode patterns on the thermal paper (17×23 cm^2) irradiated along the different vertical planes of the unloaded cavity ($P = 500$ W, $t = 25$ s): $a - x = 16$ cm, $b = 9$ cm.
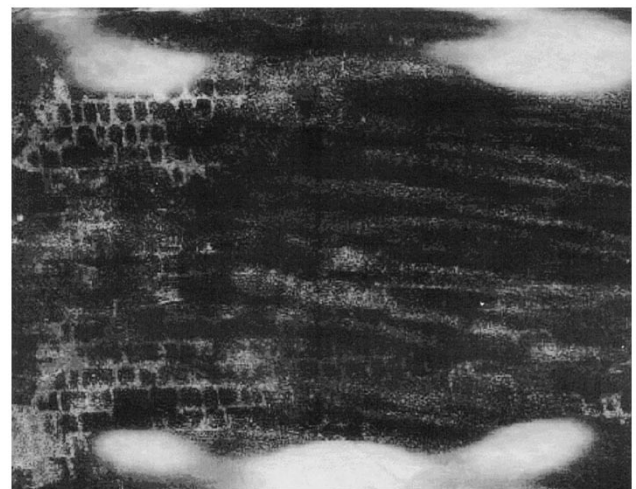

Fig. 6. The heat distribution on the thermal paper irradiated along the vertical plane (at $x = 15.7$ cm) of the unloaded cavity ($P = 600$ W, $t = 30$ s) with rotation of the plate.

in medium EMEM) in a standard microwave oven. Requirements for an experiment are the following.

I) The final temperature of the sample must be less than 50 °C.

II) The volume of the sample must be approximately equal to 2 ml.

III) The container must be a metal-free glass tube.

IV) Several tubes with the sample are irradiated at the same time.

As a result of these investigations, we can give the calibration protocol as follows.

1) The power of the microwave oven is set to a minimum (90 W).

2) The load (100 to 200 ml of water in glass) is located on the rotary plate of the oven, which is then pre-warmed for 1–2 min.

3) The mode pattern of the empty cavity of the oven is determined by using the wet thermal paper, which is located on its rotary plate.

4) The load (200 ml of water in a glass at room temperature) and the required number of tubes, each of those containing about 2 ml of the medium which will be used for cell culture, are uniformly located on the plate of the oven where microwave power exists according to the figure recorded in step 3) on the new wet thermal paper.

5) The microwave field distribution in the cavity with the load and the samples is determined by using the thermal paper. This paper can also be used to evaluate the time delay between turning on the oven (i.e., the paper is clean) and the beginning of the microwave influence (i.e., dark spots arise on the paper).

6) The dependence of the medium temperature on the exposure time is determined by using temperature measurements of the medium after exposure.

7) The locations where the cell culture samples should be placed are identified by determining the regions of the cavity plate that give the most uniform and the same type of fields in the area of each sample and the need to increase the medium temperature from 20 to 50 °C according to step 5) and 6).

The temperature of one of the tubes filled with medium (without cell) is measured after the microwave irradiation for checking.

V. CONCLUSION

The results of the mode pattern and heat distribution measurements in the high-power microwave cavity by using the wet thermal paper method show the workability of this method. The evaluated exposure time and the determined optimum exposure time in experiments are in good agreement. The wet thermal paper method allows for quick and easy measuring and recording not only of mode patterns in the unloaded and loaded cavity but also of heat distribution above the rotary plate inside it. The influence of the load and the coupling element on the mode pattern and heat distribution along both horizontal and vertical planes of the cavity can be investigated by using this method. It can be useful in the case of the application of the standard microwave oven, for instance, in medicine and biology. The calibration of the oven is needed in this case, and measurement of the mode patterns of the oven cavity is a very important part of the calibration.

REFERENCES

[1] A. C. Metaxas and R. J. Meredith, *Industrial Microwave Heating*. London, U.K.: Peter Peregrinus, 1988.

[2] G. R. Login and A. M. Dvorak, "Methods of microwave fixation for microscopy. A review of research and clinical applications: 1970–1992," *Prog. Histochem. Cytochem.*, vol. 27, no. 4, pp. 1–127, 1994.

[3] M. Durm, F. M. Haar, M. Hausmann, H. Ludwig, and C. Cremer, "Optimized fast-FISH with alpha-satellite probes: acceleration by microwave activation," *Braz. J Med. Biol. Res.*, vol. 30, no. 1, pp. 15–23, Jan. 1997.

[4] S. K. Young, D. C. Graves, M. D. Rohrer, and R. A. Bulard, "Microwave sterilization of nitrous oxide nasal hoods contaminated with virus," *Oral Surg. Med. Oral Pathol.*, vol. 60, no. 6, pp. 581–585, Dec. 1985.

[5] M. K. Sun, K. A. Wickersheim, A. Kamal, and W. R. Kolbeck, "Fiberoptic sensor for minimally-perturbing measurement of electric fields in high-power microwave environments," in *Microwave Processing of Materials 11*, W. B. Synder, W. H. Sutton, M. F. Iskander, and D. L. Johnson, Eds. Pittsburgh, PA: Materials Research Society, 1991, vol. 189, pp. 141–145.

[6] L. L. Germash and E. D. Shlifer, "Device for an evaluation of the electromagnetic field distribution in microwave ovens" (in Russian), *Electron. Tech., Microwave Electron.*, pp. 44–46, 1982.

[7] D. M. Pozar, *Microwave Engineering*. Reading, MA: Addison-Wesley, 1993.

Sergey N. Kharkovsky (M'01–SM'03) was born in Caucasus region, Russia, in 1952. He received the degree in electronics engineering from the Kharkov Institute of Radioelectronics, Kharkov, Ukraine, in 1975, the Ph.D. in radiophysics from Kharkov State University, Kharkov, in 1985, and the D.Sc. degrees in radiophysics from the Institute of Radio-Physics and Electronics (IRE), National Academy of Sciences of Ukraine, Kharkov, in 1994, respectively.

He received a Senior Scientist title in radiophysics in 1991. He was a member of the Research Staff at IRE from 1975 to 1998, he was a Professor at Kharkov Technical University of Radioelectronics. Kharkov, from 1994 to 1996, and he was a Professor in the Electrical and Electronics Engineering Department, Cukurova University, Adana, Turkey, from 1998 to 2002. He is now a Visiting Associate Professor at the University of Missouri, Rolla. His current areas of research are nondestructive testing and evaluation of composite structures using microwaves and development and investigation of new techniques for microwave and millimeter wave measurements of dielectric properties of materials, including dielectric resonators with whispering gallery modes and solid-state oscillators.
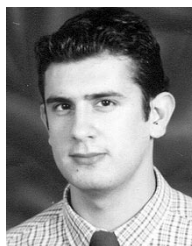
Ugur C. Hasar (S'00) was born in Kadirli, Adana, Turkey, in 1977. He received the B.Sc. and M.Sc. degrees in electrical and electronics engineering from Cukurova University, Adana, in 2000 and 2002, respectively. He is currently pursuing the Ph. D. degree at Cukurova University.

He has been a Research and Teaching Assistant at Cukurova University since 2000. His current areas of research involve nondestructive testing and measurement of materials using microwaves. He is currently seeking new methods for nondestructive characterization of dielectric properties of materials.