Low-power near-field microwave applicator for localized heating of soft matter

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We report a 9 GHz near-field microwave probe for local surface heating of microwave absorbing materials. The probe radiates microwave energy through a narrow slot microfabricated at the apex of the dielectric resonator. The microwave energy is concentrated in a small region close to the applicator, in such a way that the microwave intensity there is very high. A temperature of 60–120 °C can be achieved in a spot size as small as 0.3×0.5 mm², using an input power of only a few watts. The applicator can be used for local heating, coagulation, and melting of various soft-matter mediums. Particularly, we emphasize results on local heating and coagulation of egg-white and albumin which may be used as a “biological solder” for tissue welding applications. © 2004 American Institute of Physics. [DOI: 10.1063/1.1763213]

Microwave heating is widely used in industry and medicine. Most common heating applications, such as microwave ovens, involve large samples and operate with a microwave power of hundreds of watts. Using near-field techniques, more localized heating can be achieved. Recently, a 1 kW near-field coaxial probe has been used to channel 2.45 GHz microwave radiation to a 1 mm² size spot that resulted in the surface temperature of 1000 °C and electric field of 10⁵ V/m. A 2.45 GHz coaxial probe operating at 40–60 W and a 9.2 GHz waveguide probe operating at 30 W are used in medical applications for local heating of human tissues. To heat smaller, micrometer-size spots, laser radiation is most effective. Although it requires significantly less input power, it is usually absorbed in the uppermost layer of the sample while microwave radiation exhibits larger penetration depth and different absorption mechanism. Hence, it is highly desirable to have a microwave applicator which can heat tiny spots with relatively small input power of few watts. Here, we demonstrate a localized heating source based on a microwave near-field microscopic probe. Up to now, such probes have been used mostly for imaging purposes.

Our applicator is based on a cylindrical metal-coated dielectric resonator with a narrow slot in the apex [Figs. 1(a) and 1(b)]. If the apex were flat, then the slot length is \( l = \frac{\lambda}{2\epsilon^{1/2}} \) where \( \lambda \) is the microwave wavelength and \( \epsilon \) is the dielectric constant of the resonator. In our actual design we use a conical or hemispherical apex [Fig. 1(b)]. The slot here is longer and its precise length and the length of the resonator is found using ANSOFT-HFSS software.

The slot fabrication has been described elsewhere and its width can be designed from 1 to 500 \( \mu \)m. The operating frequency is determined by the dielectric constant of the resonator, which can be any low-loss, high-epsilon material. We developed several applicators operating at 26, 9, and 4.5 GHz. Here we emphasize our results on an X-band applicator based on sapphire resonator (\( \epsilon = 10 \)). The length of the resonator is 12 mm, the diameter of the cylindrical part is 8 mm, the slot length is \( \approx 5 \) mm, and the slot width is \( \approx 200 \mu \)m. The microwave energy is supplied to the slot through the specially designed coax-to-waveguide adaptor and a cylindrical waveguide containing a dielectric transducer [Fig. 1(a)]. To tune the probe, we use an HP-8510C network analyzer and vary the air-gap between the transducer and resonator to find the resonance frequency. The \( Q \)-factor of the resonator is 200–1000 and is limited mostly by the radiation losses. In a tuned device a major part of the input power is transmitted to the slot. We very roughly estimate the power density at the slot area as \( P/S \), where \( P \) is the input power and \( S \) is the slot area. For a 1 W input power, this results in \( 10^6 \) W/m². Such high power density exists only in a small volume with the size of the order of the slot width. At larger distances (of few millimeters) from the slot the power den-
sity is significantly lower due to the strong decay and the divergence of the evanescent microwave field. In an actual experiment only the central region of the slot which is closest to the sample is effective in the heating process. For the probe with a hemispherical head, the length of this region is \((2wR)^{1/2}\) where \(w\) is the slot width and \(R\) is radius of curvature of the resonator apex. The field geometry in the slot and in the heated area is such that the microwave magnetic field is mostly parallel to the long dimension of the slot while the microwave electric field is parallel to the sample surface and perpendicular to the slot. Thus the probe presented here provides both electric-field and magnetic-field heating.

Our experimental setup [Fig. 1(c)] consists of a microwave source (HP-83623A synthesizer) and a medium-power microwave amplifier (M764 Litton Electron Devices, San Carlos, CA). A microwave circulator is used to protect the amplifier from back-reflected waves and the power meter monitors reflection from the sample. The sample is mounted on an XYZ stage and is brought to the distance of 10–200 \(\mu\)m from the probe in order to operate in the near-field regime (or in a contact mode). To record any visual changes resulting from heating we place a video camera below or near the irradiated sample. We have studied the effect of microwave heating on various organic/biological systems including water, egg-white, albumin, plant leaves, and raw meat. In some cases, the biological system was decorated with magnetic nanoparticles to enhance heating by magnetic absorption.

In this letter we emphasize our studies on egg-white and albumin which have similar chemical composition. The temperature distribution upon localized microwave heating is highly inhomogeneous, the maximum temperature being achieved in the area just beneath the probe. To evaluate the average temperature rise during microwave irradiation we placed a 0.5-mm-thick albumin layer on a 0.12-mm-thick microscopic glass slide (Marienfeld, Lauda-Koenigshofen, Germany) and measured the temperature of the layer in a contactless way, using a silver halide IR fiber connected to the radiometer (Fig. 2, inset). Note that the sample was microwave irradiated through the thin glass slide while the IR thermometer is at the back side of the albumin layer, hence the measured temperature is lower than the maximal temperature in the irradiated spot. Figure 2 shows that this average temperature steadily grows upon increasing the input microwave power. At high enough power the albumin coagulates, its thermal properties change, and the temperature rises faster (not shown here). The coagulation allows one to visualize the heating process since the albumin and egg-white layers are transparent at ambient temperature but become opaque upon coagulation.

To study the lateral heating pattern, we irradiated a 0.5-mm-thick egg-white layer sandwiched between two microscopic glass slides and observed the heating dynamics from the backside using a video camera. At the smallest exposure the coagulated area is \(\sim 0.3 \times 0.5 \text{ mm}^2\), which roughly coincides with the slot projection onto the sample while upon increasing exposure, the coagulated area becomes more circular. Figure 3 shows results of a similar experiment. We observe that the coagulated area grows linearly with time, that is characteristic for diffusive heat transport, and that the coagulated area is proportional to the input microwave power. Extrapolation to the horizontal axis indicates that the minimal input power to cause coagulation is \(P_{\text{min}} = 0.2\) W.

The depth of the heated region was measured using the egg-white confined in a 5.5 diam glass tubing. The sample was heated from the top while the coagulation process was observed from the side (see inset in Fig. 4). A thin microscopic glass slide protects the probe from water evaporation from the sample. Figure 4 shows the depth of the coagulated egg-white at 1.6 W input power and for different periods of exposure. The solid line in Fig. 4 shows a model prediction, assuming three-dimensional heat diffusion, \(t = (6kt)^{1/2}\) where \(k = 1.36 \times 10^{-7} \text{ m}^2/\text{s}\) is the heat conductance of the egg-white. Additional evidence for 3D-heat diffusion was achieved by microwave heating of a thick peace of raw meat which turns gray after irradiation. We sliced it and observed a hemispherical heating pattern, as expected.

To find the temperature distribution in the irradiated spot rates after several minutes of irradiation. The inset in Fig. 3 shows that the maximal coagulated area depends linearly on the input microwave power. Extrapolation to the horizontal axis indicates that the minimal input power to cause coagulation is \(P_{\text{min}} = 0.2\) W.

![FIG. 2. Saturation temperature of the 0.5-mm-thick albumin layer as measured by the IR thermometer from the back side. Inset shows the measurement setup. Microwave frequency is 9 GHz, slot width is 180 \(\mu\)m, conical probe head.](#)

![FIG. 3. Coagulated area of a 0.5-mm-thick egg-white layer vs time at different input powers. The time to reach saturation is lower for higher input powers. Inset shows linear relation between the maximal coagulated area and the input microwave power. Extrapolation to the horizontal axis yields a minimum input power for coagulation. A hemispherical probe has been used here with a 200-\(\mu\)m-wide slot.](#)
we use a model developed by Lax\textsuperscript{9} in the context of laser heating. This model assumes that the electromagnetic radiation is absorbed in a small spot with a lateral size equal to the size of the laser beam, and then heat spreads into adjacent regions through thermal conduction. Assuming a circular beam with the diameter \( w \), thick sample and moderate absorption, \( \alpha \ll w^{-1} \), Lax finds the maximal temperature in the center of irradiated spot and in the steady state as

\[
T_{\text{max}} = T_{\text{ambient}} + \frac{P \alpha}{2 \pi K} \ln \left( \frac{2}{\alpha w} - \frac{\gamma}{2} \right),
\]

where \( P \) is the input power, \( \alpha \) and \( K \) are the microwave absorption coefficient and thermal conductivity of the sample, correspondingly, and \( \gamma = 0.5772 \) is Euler’s constant. Reference \textsuperscript{10} extended this model to a focused laser beam, while Refs. \textsuperscript{11} and \textsuperscript{12} took into account the change of thermal and absorptive properties of the sample upon heating. We apply the original model\textsuperscript{9} to estimate the minimal input power \( P_{\text{min}} \) to start coagulation of the egg-white. When the input power is small, i.e., \( P < P_{\text{min}} \), the temperature is below coagulation threshold and the thermal properties of the sample are spatially uniform. At \( P > P_{\text{min}} \) there is a small area beneath the probe where the temperature exceeds coagulation threshold, i.e., \( T_{\text{max}} > 65^\circ\text{C} \). At \( P = P_{\text{min}} \), \( T_{\text{max}} = 65^\circ\text{C} \). Since the microwave energy is concentrated in a very small spot, three-dimensional heating may be neglected. The relevant parameters of egg-white are: \( K = 0.54 \text{~W/mK} \), loss tangent \( \tan \delta = 0.5 \), dielectric permittivity \( \epsilon_r = 35 \). For \( f = 9 \text{GHz} \) we find \( \alpha = (2\pi f/c)(\epsilon_r)^{1/2} \tan \delta = 560 \text{~m}^{-1} \). Although microwave absorption in egg-white is very high, the beam size is very small, \( w = 200 \mu\text{m} \), hence the condition of moderate absorption is satisfied. Then Eq. (1) yields \( P_{\text{min}} = 0.1 \text{~W} \). The coagulation in our experiments starts at \( P = 0.2 \text{~W} \) (Fig. 3) which is higher than the estimate based on Eq. (1). This is not surprising since a considerable part of the microwave radiation exits through the extremities of the slot and does not contribute to heating.

By scanning the sample, regulating the power and the irradiation time we are able to perform microwave heating of various prescribed patterns with controlled temperature, lateral size, and depth. At high enough input power, there are additional effects such as sparking and excessive heating of the probe itself due to dielectric losses in the resonator and conduction currents in its metal coating. To operate our probe at such high powers we used a pulse mode.

Impregnated materials containing metallic or magnetic particles embedded in a dielectric matrix may also be heated with our probe through microwave induction.\textsuperscript{13} These structures are characterized by enhanced nonresonant absorption. In this case, it is the microwave magnetic field that is responsible for the heating. If the embedded particles are paramagnetic, there appears an additional absorption due to magnetic resonance which we discuss elsewhere.\textsuperscript{14} To demonstrate “magnetic heating” we have studied the temperature of a plant leaf upon irradiation with the same microwave power before and after decoration with magnetite nanoparticles. We found that the decoration leads to a 30°C temperature increase at an input power of 1.6 W.

We conclude that our 9 GHz near-field probe may heat locally and contactlessly the microwave absorbing materials using an input power of only few watts. Heating can be significantly enhanced by decorating the substance with magnetic and/or metallic particles. The small operating power does not raise safety precautions and in principle may be achieved by solid-state amplifier. Our soft solder may be useful for mild tasks, such as selective heating of biological materials, where surface temperature of \( \sim 100^\circ\text{C} \) is more than enough. In particular, it may be used for tissue welding as an alternative to lasers.\textsuperscript{15}

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