Localized Microwave-Heating by a Solid-State Applicator

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The localized microwave-heating (LMH) effect may accidentally occur, for instance in microwave ovens, when a local thermal instability is evolved in a form of a confined hotspot (instead of the uniform volumetric heating intended). The local temperature within the hotspot may rise much faster and higher than the surrounding, and possibly damage the heated object.

In the contrary, in our studies at Tel Aviv University, the LMH effect is intentionally induced in a specific position on the object's surface, in order to achieve the localized rapid heating on purpose[1]. The intentional LMH effect is further accelerated by the thermal-runaway instability caused by the temperature-dependence of the material properties[2]. The localized unstable heating obtained is leading – on purpose - to a phase transition, to liquid, gas, or plasma[3] state at the induced hotspot.

In practice, the LMH can be applied to the substrate by an open-end coaxial applicator fed by a solid-state generator[4-6], as illustrated in Fig. 1. Such a compact solid-state LMH applicator may have a variety of potential applications in solids, powders and plasmas. One of them is the microwave drill[1], which is applicable for various materials[7], such as concrete, glass, ceramics, basalts, polymers, silicon, and bones[8].

Both experiments and theory show that the thermal-runaway instability can be excited also by relatively low microwave power, in the range ~10-100 W, hence by solid-state sources rather than magnetrons[6]. Local melting may occur then in a millimeter scale within seconds in the various materials mentioned above[4]. The relatively low power needed for open-end coaxial applicators to excite LMH effects in millimeter scales (typically below ~0.2 kW) makes the solid-state generators (e.g. LDMOS) suitable sources for LMH applicators[4-6]. This compact solid-state scheme enables a new range of portable LMH applications.

The experimental LMH device[4] employs an LDMOS amplifier in a positive-feedback oscillator scheme[6], and a miniature microwave-drill applicator as illustrated in Fig. 1. It is made by a coaxial open-end applicator with a 1-mm∅ movable electrode. The LDMOS-FET amplifier (Freescale MRF 6S21140 evaluation board) is tuned by the feedback loop to oscillate at 2.1 GHz. It can generate up to 140-W CW power, controlled by the V_{GS} and V_{DS} voltages. The transistor is protected from the microwave reflections by an isolator. The incident and reflected waves are detected by a reflectometer, which consists of a directional coupler and Schottky diodes.

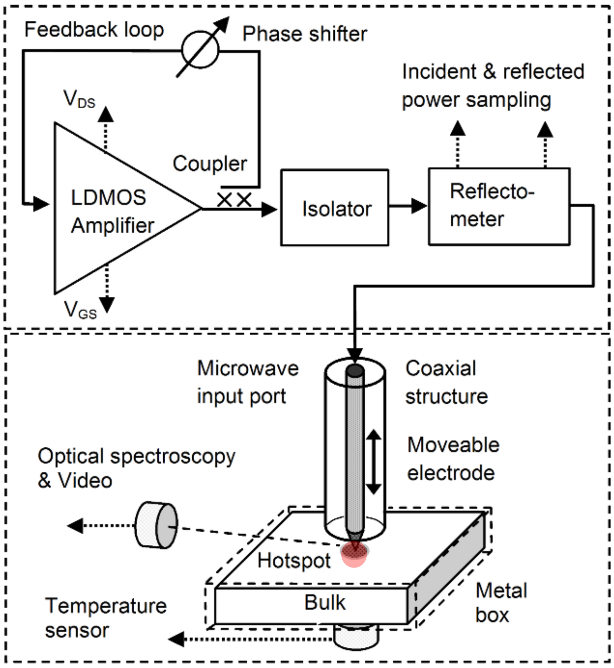

Figure. 1. A solid-state LMH applicator[4] consisting of a open-end coaxial waveguide with a movable center electrode which penetrates into the softened hotspot. The solid-state generator consists of an LDMOS amplifier with a positive feedback loop[5,6].

The molten hotspot is observed e.g. in a glass plate also via its rear surface. The temperature profile evolved is detected there by a thermal camera (FLIR E40) positioned as the temperature sensor in Fig. 1. The theoretically computed temperature profiles[4] at the tip and rear planes are shown for comparison. The difference between the curves demonstrates the thermal diffusion through the 1-mm thick glass plate. The hotspot confinement effect is clearly seen in Fig. 2 and in Figs. 3a and b. The experimental drilling results verify the rapid heating effect, in agreement with the theoretical model shown in Fig. 3a.

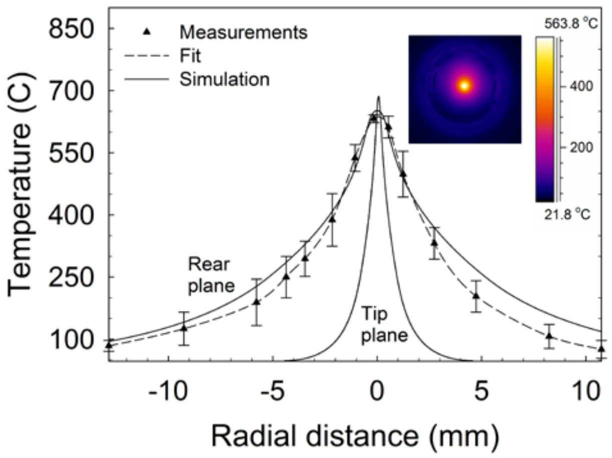

Figure 2. The temperature profile detected on the rear surface of a 1-mm thick glass plate by a thermal camera (FLIR E40). The solid curves show the numerical simulation result for the temparture profiles at the tip and rear planes. The inset shows the FLIR image.

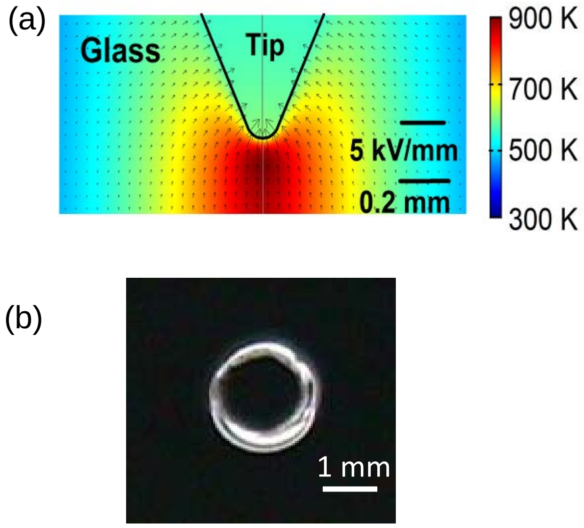

Figure 3. LMH in glass irradiated by a coaxial, LDMOS-based microwave-drill applicator: (a) The simulated spatial temperature and electric-field distributions at the hotspot. (b) A ~1.6-mm$^{\varnothing}$ hole made by LMH in glass.

Similar results were obtained for various other material-processing applications by low-power LMH devices, including local melting (for surface treatments, chemical reactions, joining, etc.), delicate drilling (e.g. of bones in orthopedic operations), local evaporation, ignition, and plasma ejection (e.g. in microwave-induced breakdown spectroscopy (MIBS) for material identification[9]).

Recent experiments in our laboratory also show that metal powders can be effectively heated by LMH[10,11]. Metal powder mixtures, such as of pure aluminum and magnetite (or hematite), may generate highly energetic thermite reactions, which could be useful for a variety of combustion and material processing applications. However, their usage has been limited by the difficult ignition of these reactions. We recently found that LMH ignition of thermite reactions is feasible and effective[10]. The power required for thermite ignition by LMH as demonstrated in Fig. 4 is ~0.1-kW for a ~3-s period. This power level can be easily provided by a solid-state microwave generator. Furthermore, in virtue of their zero-oxygen balance, exothermic thermite reactions may also be ignited by LMH underwater[12,13].

Figure 4. A flame ignited by solid-state LMH from thermite powder[10].

Surface treatments by LMH may also include thermite reactions for the conversion of rust to iron and alumina[11], and local doping of silicon substrates by LMH[14] (where the dopant material, silver or aluminum, is incorporated in these processes in the electrode tip, and diffuses into the locally heated bulk, to form a sub-micron PN junction). These shallow-LMH techniques open new possibilities for a variety of surficial treatments and local surface processing.

The LMH effect in metal powders is also associated with internal micro-plasma breakdowns between the particles, which leads to local melting and solidification of the metal powder. These effects enable a potential LMH technique for stepwise 3-D printing and additive manufacturing (AM)[11].

The solid-state implementation in LMH systems is the natural choice due to the inherent energy concentration and high-power density obtained. The solid-state incorporation reduces the size, weight and operating voltage of the LMH systems, and improves their spectral characteristics, tunability and controllability. Solid-state LMH can be implemented by transistor-based microwave heaters as demonstrated by LDMOS microwave-drill[4], and it may provide in some case a low-cost substitute for laser-based techniques.

To conclude, the solid-state LMH technology opens new possibilities for compact devices, which could be useful for local melting, ignition[10], joining, powder production[15], additive manufacturing and 3D-printing[10], material identification[9], and many other applications included in the LMH paradigm[16].

Acknowledgements

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About the Author

Yehuda Meir was born in Bat-Yam, Israel, in 1983. He received the Ph.D. degree in electrical and electronic engineering from Tel Aviv University, Tel Aviv, Israel, in 2016, at the Department of Physical Electronics under the supervision of Prof. Eli Jerby. He studied the Localized Microwave Heating effect that include microwave-drill technology, thermite ignition, fireballs, and plasmoids in both scientific and technological aspects. He was awarded the Colton Scholarship in 2012 for his Ph.D. studies. He received the Best Poster Award at the 13th AMPERE International Conference on Microwave and High Frequency Heating, Toulouse, France, September 2011, for his study on rapid heating by localized microwaves.