Localized microwave-heating (LMH) studies at Tel Aviv University

Eli Jerby

Faculty of Engineering, Tel Aviv University, Ramat Aviv 6997801, ISRAEL
Home-page: www.eng.tau.ac.il/~jerby
Contact E-mail: jerby@eng.tau.ac.il

Abstract

This article presents a two-decade perspective of localized microwave-heating (LMH) research and related studies conducted at Tel-Aviv University (TAU). These contributions included conceptual, experimental and theoretical studies of thermal-runaway instabilities and hotspot formation effects, microwave drilling and cutting, basalt melting, LMH of metal powders for 3D printing, thermite ignition, and dusty plasma ejection in forms of fire-columns and fireballs. Recently we have discovered the effect of DC-LMH synergy in metals, which enables deep cutting of iron bars.

The TAU-LMH lab

Since established in 1991, our research laboratory at TAU has been devoted to microwave-energy studies, in both aspects of power generation and microwave impact phenomena.

The first years were mostly dedicated to research and development (R&D) of high-power microwave (HPM) generators. These mainly included novel versions of fast-wave devices, oscillators and amplifiers, such as cyclotron-resonance masers (CRM's or gyrotrons) [1] and free-electron masers (FEM's or ubitrons, also known as long-wavelength free-electron lasers, FEL's) [2]. Our main paradigmatic idea then was to incorporate slow-wave features (as in traveling-wave tubes, TWT's) into the operating mechanisms of fast-wave CRM and FEM devices [3, 4]. These conceptual combinations resulted in compact hybrid schemes of microwave tubes with potentially improved HPM capabilities. Following our early studies on novel microwave generators, the main challenge facing our work has been naturally shifted toward finding new applications for the generated microwave power.

Consequently, we started to work on more applicative industrial projects, such as microwave drying of rapid ink-jet printing processes, microwave greenhouses for agricultural purposes [5], and microwave drilling [6]. These application-oriented R&D projects have led us into more fundamental studies on localized microwave-heating (LMH) effects, thermal-runaway instabilities, and hotspot formation [7]. These were later embodied in various LMH phenomena and applications, such as the microwave drill [6, 8], plasma ejection in fireball and fire-column forms [9, 10], additive solidification of metal powders toward 3D-printing (3DP) by LMH [11-13], thermite ignition [14, 15], basalt melting [16-18], and microwave-induced breakdown spectroscopy (MIBS) [19]. More recently, our discovery of the DC and LMH synergy has yielded a capability of iron melting and cutting by DC-LMH, as described below.

Microwave drills and solid-state LMH

The high energy-density obtained in the various LMH processes enables HPM-like effects at relatively low levels of microwave input power (even under ~100 W). Therefore, we adopted solid-state generators for LMH applications already in the early 2000's years (mostly LDMOS transistors, used then in cellular base-stations) [20-22].

The solid-state technology opened new possibilities for LMH devices, which seemed to provide compact, low-cost substitutes for laser-based techniques for some applications. The microwave drill, for instance, intentionally utilizes the LMH effect by purposely exciting a thermal-runaway instability [6, 8, 22, 23]. As shown in **Figure 1**, it generates a small hotspot (in the order of 1 mm in diameter, ~10^2 times shorter than the microwave wavelength), which increases the local temperature up to >1,000ºC, in heating rates of >100ºC/s. LMH effects have been demonstrated by microwave drilling and cutting into concrete, as well as melting and drilling effects in ceramics, basalts, glass, polymers, bones [24], silicon, and other materials [25]. Likewise, an LMH doping effect in silicon was demonstrated [26]. It was also shown that LMH may generate dusty plasmas in forms of fire-columns and fireballs, directly from solid substrates to air atmosphere [9, 10], and to produce nano-particles from the substrate materials [27-29].

A theoretical, coupled thermal-electromagnetic model of the sub-wavelength LMH interaction confirmed the hotspot evolution in front of the open-end applicator due to the intentional thermal-runaway instability [23].

The role of the temperature-dependent material properties on the confined heating process was identified, and the consequent variation in the load impedance was quantified, due to the spatiotemporal temperature evolution and the varying geometry. The theoretical analysis provided both, an insight to the physical principles of the LMH mechanism, and a valid model for LMH-applicator design and its operational monitoring.

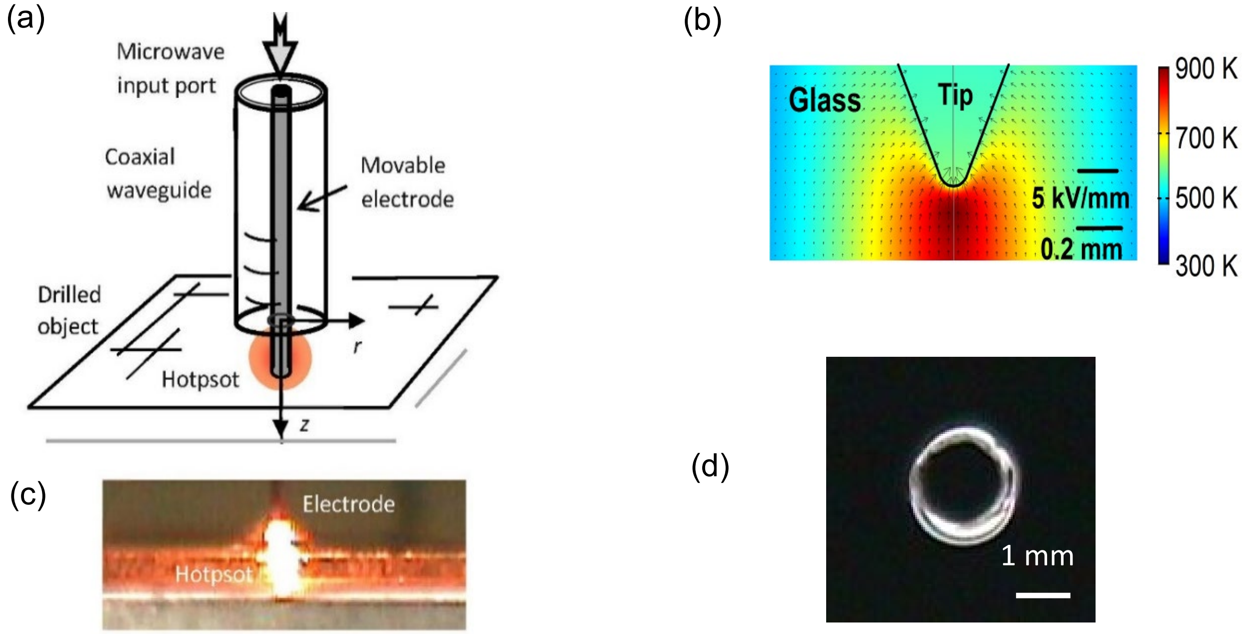

Figure 1. The microwave-drill [6, 22]: (a) A simplified illustration of a basic microwave-drill applicator, consisting of a coaxial waveguide and a moveable center electrode. (b) A simulation of the spatial temperature and electric-field distributions at the hotspot in front of an LDMOS-based microwave-drill. (c) A hotspot created in a glass plate by a 1-mm^{Ø} electrode microwave-drill. (d) A ~1.6-mm^{Ø} hole made by a microwave drill in glass.

Advanced microwave-drill schemes enable wider operating ranges, including hole diameters from ~0.5 mm in glass up to 12 mm in concrete (the latter in >20 cm hole depths) [30], as well as cutting of concrete and iron rebars [31, 32]. Microwave drilling has also been demonstrated on various ceramics (e.g., low-purity alumina, mullite-cordierite, glass-ceramics and thermal-barrier coating) [33, 34].

LMH in cavities, hotspot excitation, basalt melting, and miniature volcano's

LMH intensification due to temperature-dependent material properties has also been demonstrated by irradiating basalts in a microwave cavity [16-18, 35].

The LMH effect is clearly seen as the basalt brick is melted inside, while its outer surface remains solid, as shown in **Figure 2**. The molten core ejects lava outside the brick, which leaves a void inside (whereas the outer surface of the brick remains solid). A numerical simulation agreed well with the temperature profiles measured on the basalt-brick faces. Similar demonstrations were also conducted with naturally shaped basalt stones, to mimic various volcanic phenomena in a laboratory scale. This LMH effect can be further used in order to intensify processes of mineral extraction from rocks.

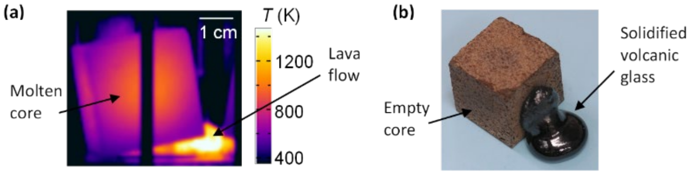

Figure 2. A basalt brick irradiated in a microwave cavity [17]: (a) The intensified LMH melts only the core, as observed through the porous surface, which remains solid. The lava flow ejected from the core tilts the brick in the cavity. (b) The hollow brick with the lava solidified to volcanic glass (obsidian).

Metal powder LMH, additive manufacturing (AM), and thermite ignition

In metal powders, the LMH effect is also associated with internal micro-plasma breakdowns between the particles, which expedite the local melting and solidification of the metal powder. This effect enabled LMH-based techniques for stepwise or continuous 3DP and AM of metal parts from various powders [11-13], as shown in **Figure 3**.

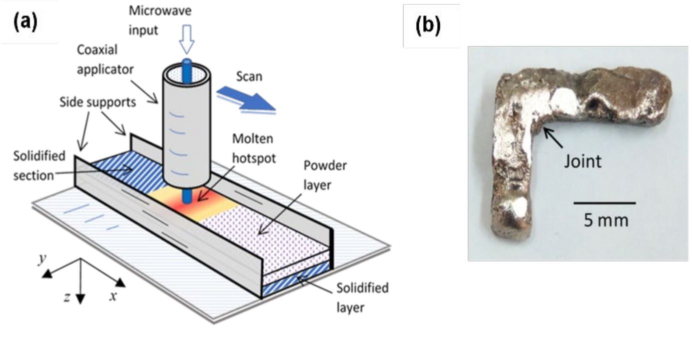

Figure 3. LMH-AM experimental [13]: (a) A conceptual scheme of the experimental 1D scanning-LMH-AM process. The powder is applied in layers, each is scanned and solidified by the LMH applicator, and bonded to the underlying, previously solidified layers. (b) An L-shape metal rod fabricated by two straight rods, each produced by scanning LMH-AM and joined together by a powder-batch LMH.

Powder mixtures, as made of pure aluminum and magnetite (or hematite), may generate energetic thermite reactions, as shown in **Figure 4**. These effects could be useful for a variety of combustion and material processing applications. However, their usage was limited by the difficult ignition of these reactions. We found that ignition of thermite reactions could be feasible by intensified LMH in air [14] as well as underwater [15].

In our LMH-ignition experiments, the power required for thermite ignition, ~0.1-kW for a ~3-s period, was provided by a solid-state microwave generator. Our experiments also demonstrated the feasibility of cutting and welding by relatively low-power LMH.

The initiation of the intense exothermic reaction in thermites also demonstrated an example for LMH ignition of other self-propagating high-temperature syntheses (SHS). Due to their zero-oxygen balance, exothermic thermite reactions also occur underwater. This feature was also impeded by the hydrophobic properties of the thermite powder and its tendency to agglomerate on the water surface, rather than to sink into the water. However, we discovered a bubble-marble (BM) effect that enabled the insertion and confinement of a thermite-powder batch into water by a static magnetic field, and its ignition by LMH underwater [15]. Potential applications of this underwater combustion effect may include wet welding, thermal drilling, detonation, thrust generation, material processing, and composite material production. All these could be implemented as well in other oxygen-free environments, such as the outer space. Chemical reactions applied by LMH for surface treatments also include thermite reactions for the conversion of rust, to iron and alumina [14].

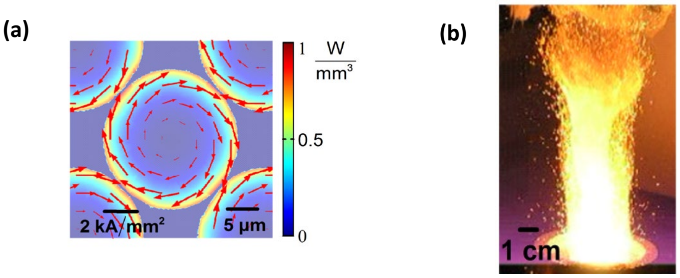

Figure 4. LMH of metal powders: (a) Eddy currents induced in copper powder by LMH. (b) A thermite flame ignited by LMH intensification [14].

Dusty plasma and fireball ejection by LMH

Dusty plasmas in forms of fireballs and fire-columns, as shown in **Figure 5**, were found to be ejected by LMH directly from hotspots evolved in solid substrates, as presented in [10, 18, 27-29] for various dielectric and metallic materials.

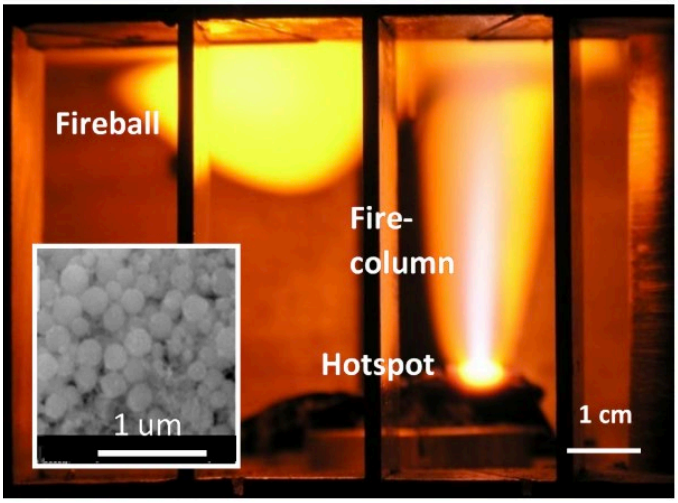

Figure 5. Plasmoids ejected from an LMH hotspot in glass [29], including the intensified hotspot in the solid substrate, the fire-column ejected, and the secondary fireball evolved (all were captured together, but each may solely exist in its own operating mode). The inset shows nano-particles produced by LMH generated dusty plasma, as observed by SEM.

The intensified LMH-plasma process begins with a hotspot formation as in microwave drilling. However, for plasma ejection, the electrode is lifted up (rather than pushed in) in order to detach the molten drop from the surface and to further inflate it to a form of a buoyant fireball.

Beside their resemblance to natural ball-lightning phenomena, fireballs and fire columns, may also have a practical importance, for instance as means to produce nano-particles directly from various substrate materials (silicon, glass, ceramics, copper, titanium, etc.) [27-29].

Nanoparticles were observed in these experiments by both, *in-situ* synchrotron small-angle X-ray scattering (SAXS) of the dusty plasma, and *ex-situ* SEM observations of the nano-powders collected after the processes. The LMH generated plasma-column, ejected from the hotspot induced in the substrate material, can also be used for atomic emission spectroscopy of the light emitted by the plasma. Hence, we proposed the microwave-induced breakdown spectroscopy (MIBS) technique [19], similar to the laser-induced (LIBS) identification technique (except that the plasma is excited by LMH rather than by laser).

LMH of silicon-wafer experiments yielded heating rates of >200 K/s up to the melting point [29]. This enabled localized thermal processes in silicon, including joining, welding, drilling, and doping. The latter was demonstrated by local doping of silicon substrates by LMH, using silver and aluminum dopants [26]. The dopant was incorporated in these processes in the electrode tip, and locally diffused into the heated wafer to form a sub-micron PN junction.

DC-LMH hybrids, iron melting and cutting, and natural lightning effects

Following our previous LMH studies, we have recently discovered that adding a relatively small direct-current (DC) to LMH may catalyze a hotspot effect in bulk iron, up to a local melting (and even further to ablation and dusty-plasma ejection) [32].

This combined DC-LMH effect has been demonstrated for instance by cutting an 8-mm$^{\varnothing}$ iron rebar (carbon steel) without any susceptor added. Such a deep melting effect as shown in **Figure 6** is not feasible otherwise in these conditions, neither by sole microwaves nor by sole DC.

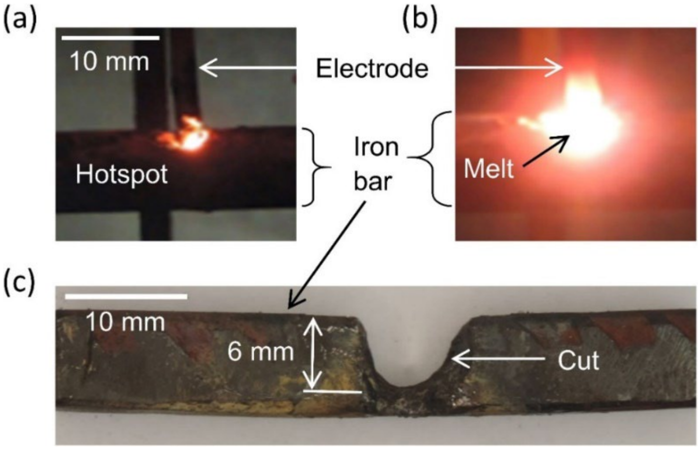

Figure 6. Iron melting and cutting by DC-LMH [32]: (a) The hotspot formed by the combined LMH and DC in the iron rebar; (b) the deeper melting obtained, and (c) the cut performed by DC-LMH in the iron rebar (the joint was intentionally remained).

This synergic effect is attributed to a combined thermal skin evolution, which jointly forms a hotspot by a mutually intensified DC-LMH thermal-runaway instability, and inherently deepens the microwave penetration into the bulk iron.

The DC-LMH effect in metals is hypothesized in general as conceptually illustrated in **Figure 7** [32]. In this scheme, a bulk of metal, with a temperature-dependent electric conductivity, is subjected to both microwave irradiation and a DC flow (I_{DC}) across it.

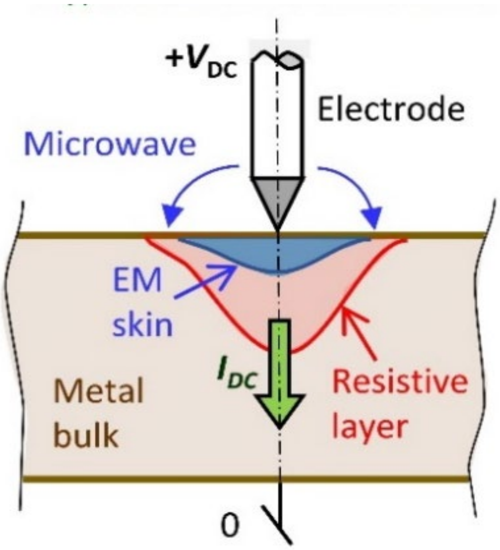

Figure 7. The hypothesized DC-LMH combined interaction in metal bulks [32].

The microwave is guided by a perpendicular electrode towards the metal plate (as in a microwave drill [6]). In this scenario, neither the DC alone nor the sole microwave irradiation (in equivalent power levels) may heat up the metal bulk. However, by combining the two, the heat energy dissipated in the EM skin region is diffused into the bulk beyond the skin depth, and further reduces its electric conductivity. Therefore, the initial microwave heating confined within the EM skin depth creates a deeper thermal resistive layer for the DC, due to the elevated resistivity of the hotter metal region. The deeper resistive layer, broadened beyond the EM skin-depth, absorbs more of the DC power and hence expedites the further expansion of this layer. The DC Joule heating is dissipated deeper than the EM skin, and further rises the temperature therein (which enables a deeper penetration of the microwave heating and hence a hotspot formation by a synergic DC-LMH thermal-runaway instability).

This synergic DC-LMH effect may intensify the combined heating process in a positive-feedback fashion, namely by a joint thermal-runaway instability, and hence forming a molten hotspot deeper in the metal bulk.

DC-LMH synergy is also obtained in dusty-plasma ejection from basalt [18]. In this experiment, after the initial stage of LMH ignition, the plasma is gradually transferred to a form of a stably sustained, long-lived fire-pillar, solely maintained by the DC supply. A stepwise transitional process was applied in order to initiate a steady column, as shown in **Figure 8** [18].

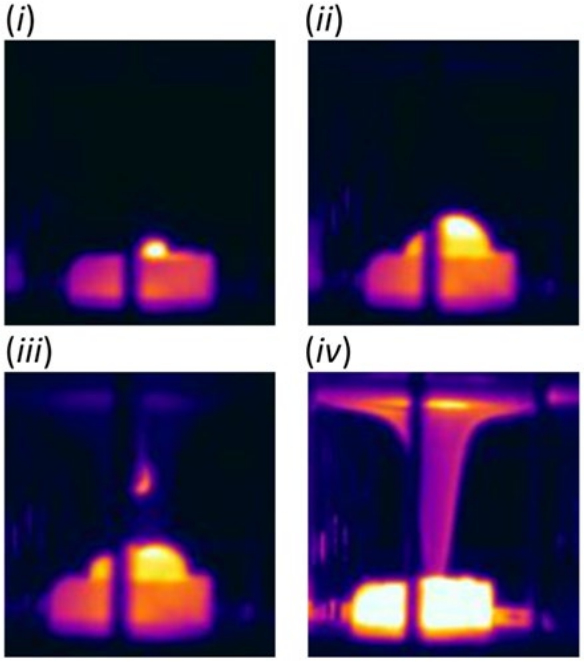

Figure 8. Thermal images of the LMH-to-DC transition in basalt [18]: The hotspot evolution by LMH (*i, ii*) is intensified by DC (*iii*). The ejected plasma column is solely sustained by DC (*iv*).

In **Figure 8**, the hotspot is formed by an LMH thermal-runaway effect (*i*), and the inner basalt core is molten (*ii*). Then, the hotspot is further intensified by applying a DC current (by an electrode) to the conducting molten channel formed inside the isolating solid substrate (*iii*). Once the DC channel is established, a plasma column is ejected from the molten hotspot to the air atmosphere, and the electrode is lifted upwards whereas the dusty-plasma section interacts with the microwave irradiation and closes the DC-circuit loop. Finally, the microwave is turned off, leaving a stable DC current in the serial circuit (*iv*). This LMH ignition process creates a self-sustained, steady dusty-plasma column, in a form of a fire-pillar, solely maintained by a DC supply.

We have studied this finding [18] with respect to two different themes. One refers to material-processing aspects of rocks and minerals using microwave-assisted techniques. The other theme is related to the resemblance of microwave-excited fireballs to rare ball-lightning (BL) phenomena (also associated with volcanic eruptions).

The known resemblance between microwave-excited plasmoids and BL phenomena is further confirmed here by the LMH-to DC transition effect [18], since DC sources are more readily available in nature, as provided for instance by charged clouds with similar electric-field intensities (in the range $>10^3$ V/m), as illustrated in **Figure 9** [18].

The LMH-to-DC-transition applied here may provide a more comprehensive analogy between laboratory observations and natural phenomena (compared to sole RF models). It may suggest a merge of internal and external energy theories for BL (possibly with another local heat source as a starter).

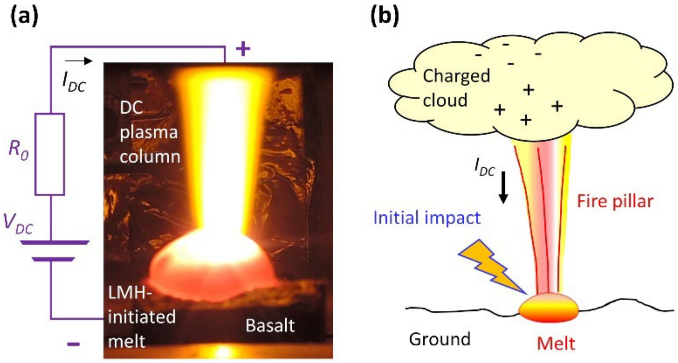

Figure 9. Analogy to rare lightning effects [18]: A seeming analogy between (a) the experimental, DC-sustained dusty-plasma column emitted from basalt, initiated by an LMH-to-DC transition, and (b) a natural, fire-pillar-like lightning, sustained between an electrically-charged cloud and a melt on the ground (initially caused, for instance, by a normal-lightning impact, which may create a ball lightning [18]).

LMH vs. lasers, and concluding remarks

The LMH intensification technique can be considered, to some extent, as a low-end substitute for laser-based processes, such as drilling and cutting, joining, surface treatment, material identification, and additive manufacturing.

While LMH may provide low-cost, compact and efficient solutions in this regard, it requires a physical contact with the object (unlike the remote laser), and its resolution (~1 mm) is yet inferior with respect to lasers. Therefore, one may deduce that LMH applications, such as the microwave drill, are more relevant to operating regimes of relatively large volumes and rough processes, or as complementary means to the more accurate and expensive laser-based systems. Nevertheless, LMH and DC-LMH concepts, and the research outcomes of their further investigations, may form new paradigms of hybrid thermal processing of various materials, in solid, powder, and plasma phases.

Acknowledgements

The LMH studies described here were supported by the Israel Science Foundation (ISF) and the Israeli Ministry of Science and Technology (MOST). The valuable contributions of research students, partners and colleagues (as indicated below in the references' authorship) are warmly acknowledged. The author also thanks the AMPERE-Newsletter's Editors for the invitation to present this summary.

For further reading

1. E. Jerby, A. Shahadi, R. Drori, M. Korol, M. Einat, I. Ruvinsky, M. Sheinin, V. Dikhtyar, V. Grinberg, M. Bensal, T. Harhel, Y. Baron, A. Fruchtman, V. L. Granatstein, and G. Bekefi, "Cyclotron resonance maser experiment in a non-dispersive waveguide," *IEEE Trans. Plasma Science*, Vol. 24, pp. 816-824, 1996.
2. R. Drori and E. Jerby, "Tunable fluid-loaded free-electron-laser in the low electron-energy and long-wavelength extreme," *Physical Review E*, Vol. 59, pp. 3588-3593, 1999.
3. E. Jerby, "Linear analysis of a periodic-waveguide cyclotron maser interaction", *Physical Review E*, Vol. 49, pp. 4487-4496, 1994.
4. E. Jerby, "Traveling wave free electron laser", *Physical Review*, Vol. 44, pp. 703-715, 1991.
5. M. Teitel, A. Shklyar, V. Dikhtyar, E. Jerby, and Y. Elad, "Development of a microwave system for greenhouse heating," *Acta Horticulturae*, Vol. 534, pp. 189-196, 2000.

6. E. Jerby, V. Dikhtyar, O. Actushev, and U. Grosglick, “The microwave drill,” *Science*, Vol. 298, pp. 587-589, Oct. 18, 2002.
7. Y. Alpert and E. Jerby, “Coupled thermal-electromagnetic model for microwave heating of temperature-dependent dielectric media,” *IEEE Trans. Plasma Science*, Vol. 27, pp. 555-562, 1999.
8. E. Jerby, O. Aktushev, and V. Dikhtyar, "Theoretical analysis of the microwave-drill near-field localized heating effect," *Jour. Applied Physics*, Vol. 97, Art. No. 034909, pp. 1-7, 2005.
9. V. Dikhtyar and E. Jerby, "Fireball ejection from a molten hot-spot to air by localized microwaves," *Physical Review Letters*, Vol. 96, No. 045002, 2006.
10. E. Jerby, "Microwave-generated fireballs," *Encyclopedia of Plasma Technology*, Taylor and Francis, 2017, pp. 819-832.
11. E. Jerby, Y. Meir, A. Salzberg, E. Aharoni, A. Levy, J. Planta Torralba, and B. Cavallini, “Incremental metal-powder solidification by localized microwave-heating and its potential for additive manufacturing”, *Additive Manufacturing*, Vol. 6, pp. 53–66, 2015.
12. A. Shelef and E. Jerby, “Incremental solidification (toward 3D-printing) of metal powders by transistor-based microwave applicator”, *Materials and Design*, Vol. 185, Art. No. 108234, 2020.
13. Y. Shoshani, T. Weinstein, Z. Barkay, and E. Jerby, “Sequential solidification of metal powder by a scanning microwave applicator”, *Materials*, Vol. 16, Art. No. 1136 (14 pages), 2023.
14. Y. Meir and E. Jerby, "Thermite-powder ignition by electrically-coupled localized microwaves", *Combustion and Flame*, Vol. 159, pp. 2474–2479, 2012.
15. Y. Meir and E. Jerby, "Underwater microwave ignition of hydrophobic thermite powder enabled by the bubble-marble effect", *Applied Physics Letters*, Vol. 107, 054101, 2015.
16. E. Jerby, V. Dikhtyar, and M. Einat, “Microwave melting and drilling of basalts,” *AIChE Annual Meeting*, Austin, Texas, Nov. 4-7, 2004.
17. E. Jerby and Y. Shoshani, “Localized microwave-heating (LMH) of basalt – Lava, dusty-plasma, and ball-lightning ejection by a “miniature volcano”, *Scientific Reports*, Art. No. 12954, 2019.
18. Y. Shoshani and E. Jerby, “Microwave-ignited DC-plasma ejection from basalt: Powder generation and lightning-like effects”, *Applied Physics Letters*, Vol. 120, 264101, 2022.
19. Y. Meir and E. Jerby, “Breakdown spectroscopy induced by localized microwaves for material identification”, *Microwave Optics Technology Letters*, Vol. 53, pp. 2281-2283, 2011.
20. E. Schwartz, A. Anaton, D. Huppert, and E. Jerby, “Transistor-based miniature microwave heater”, Proc. *IMPI 40th Annual Int'l Microwave Symp*., Boston, pp. 246-249, 2006.
21. O. Mela and E. Jerby, “Miniature transistor-based microwave drill”, *Proc. Global Congress Microwave Energy Applications* (GCMEA), Otsu, Japan, pp. 443-446, 2008.
22. Y. Meir, E. Jerby, “Localized rapid heating by low-power solid-state microwave-drill”, *IEEE Trans. Microwave Theory and Techniques*, Vol. 60, pp. 2665-2672, 2012.
23. E. Jerby, O. Aktushev, and V. Dikhtyar, "Theoretical analysis of the microwave-drill near-field localized heating effect", *Jour. Applied Physics*, Vol. 97, Art. No. 034909, pp. 1-7, 2005.
24. Y. Eshet, R. Mann, A. Anaton, T. Yacoby, A. Gefen, and E. Jerby, “Microwave drilling of 8 bones”, *IEEE Trans. Biomedical Engineering*, Vol. 53, pp. 1174-1182, 2006.
25. E. Jerby, “Microwave drilling in sub-wavelength diameters”, Chapter 3, *Advances in Microwave Processing for Engineering Materials*, A. Bansal and H. Vasudev (Eds.), CRC Press, 2023.
26. P. Livshits, V. Dikhtyar, A. Inberg, A. Shahadi, and E. Jerby, "Local doping of silicon by a point-contact microwave applicator", *Microelectronic Engineering*, Vol. 88, pp. 2831-2836, 2011.
27. J. B. Mitchell, J. L. LeGarrec, M. Sztucki, T. Narayanan, V. Dikhtyar, E. Jerby, "Evidence for nanoparticles in microwave-generated fireballs observed by synchrotron X-ray scattering", *Physical Review Letters*, Vol. 100, Art. No. 065001, pp. 1-4, 2008.
28. E. Jerby, A. Golts, Y. Shamir, S. Wonde, J. B. A. Mitchell, J. L. LeGarrec, T. Narayanan, M. Sztucki, D. Ashkenazi, Z. Barkay, "Nanoparticle plasma ejected directly from solid copper by localized microwaves", *Applied Physics Letters*, Vol. 95, Art. No. 191501, 2009.
29. Y. Meir, E. Jerby, Z. Barkay, D. Ashkenazi, J. B. A. Mitchell, T. Narayanan, N. Eliaz, J.-L. LeGarrec, M. Sztucki, O. Meshcheryakov, “Observations of ball-lightning-like plasmoids ejected from silicon by localized microwaves”, *Materials*, Vol. 6, pp. 4011-4030, 2013.
30. E. Jerby, Y. Meir, Y. Nerovny, O. Korin, R. Peleg, and Y. Shamir, “Silent microwave-drill for concrete”, *IEEE Trans. Microwave Theory and Techniques*, Vol. 66, pp. 522-529, 2018.
31. Y. Shoshani, T. Levin, E. Jerby, "Concrete cutting by a solid-state, localized microwave-heating (LMH) applicator", *IEEE Trans. Microwave Theory and Techniques*, Vol. 69, pp. 4237-4245, 2021.
32. Y. Shoshani, and E. Jerby, “Local melting and cutting of iron bulks by a synergic microwave-DC thermal skin effect”, *Applied Physics Letters*, Vol. 118, Art. No. 194102, 2021.
33. E. Jerby, V. Dikhtyar, and O. Aktushev, “Microwave drill for ceramics”, Amer. Ceramic Society Bulletin, Vol. 82, pp. 35-37, 2003.
34. E. Jerby and A.M. Thompson, “Microwave drilling of ceramic thermal barrier coatings”, *Jour. American Ceramic Society*, Vol. 87, pp. 308-310, 2004.
35. E. Jerby, "Localized microwave-heating intensification – A 1-D model and potential applications”, *Chemical Engineering and Processes* (CEP), Vol. 122, pp. 331-338, 2017.

About the author

Eli Jerby received his Ph.D. degree in Electrical Engineering from Tel Aviv University (TAU) in 1989. He worked then at MIT as a Rothschild and Fulbright post-doctoral fellow with Prof. George Bekefi. In 1991, Dr. Jerby joined TAU as a faculty member. His studies there included novel schemes of free-electron lasers (FEL's) and cyclotron-resonance masers (CRM's), as well as localized microwave heating (LMH) effects and their applications. Among the latter are the microwave-drill invention, LMH of metal powders, additive-manufacturing (3D-printing), fireballs and microwave generated plasmas, thermite reactions, and metallic-fuel ignition by localized microwaves. Besides his scientific studies, he has initiated and conducted several projects with governmental, industrial, and start-up partners. Prof. Jerby has served in the program committees of int'l conferences and workshops worldwide, in the fields of plasma, radiation sources, microwave heating and applications, and microwave discharges. He also served as the Editor of JMPEE, the Journal of Microwave Power and Electromagnetic Energy (2006-2009) and of AMPERE Newsletter (2015-2017). More information and his publications are available at http://www.eng.tau.ac.il/~jerby