Localized Microwave-Heating (LMH) and the Matthew Effect

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1 Matthew effect

The term Matthew effect, coined by Merton in 1968 [1], represents a universal principle, also known as the accumulated effect of advantages and disadvantages. It explains a variety of different phenomena in diverse scientific areas, and in daily life as well. In particular, various appearances of the Matthew effect in human societies are well characterized in social sciences and humanities, including economics, sociology, theology and education [2]. Referred to Matthew the Apostle who lived in the first century, the eternal wonderment: "Why the rich get richer and the poor get poorer?" [3] has raised one of the ethical dilemmas reflected in this principle, since the biblical profits till our own era and the contemporary globalization issues [4].

In academic life [1], the Matthew effect is clearly seen in the ways that academic prestige (as an asset) is accumulated, and tends to further evolve in distinct focal points considered as centers of excellence. These are for instance the (relatively few) élite academic institutions, which attract a growing number of excellent students from all over the world, and hence continuously elevate their acceptance criteria (and further escalate their attraction and reputation). Another example is the top-ranked scientific Journals, which become more and more desired by many authors, and consequently receive a growing number of submissions and citations (which lead, as a positive feedback, to a further increase of their rejection rates, and hence inflates their scientific ranking).

The system of academic metrics, using over-simplified indices of merit (e.g. impact factors and *h* indices), is not only a means to measure quality, but actually an accelerator for the unstable dynamics associated with this trend, pretended to be a desire for excellence. One of the destructive aspects of the same Matthew-effect mechanism is the continuous deterioration and actually the suppression of the larger middle-class communities of the seemingly mediocre entities (either ordinary people, or second-world countries, or even some glory-less but essential professional and academic organs).

The Matthew effect also impedes the evolution of microwave-heating R&D societies as independent professional communities. One of the expressions of this growing barrier is the increasing difficulties in publishing a Journal dedicated to this niche field (with an inherently lower impact factor).

The universal mechanism of Matthew effect also underlies one of the physical phenomenon of our interest, namely the localized microwave heating (LMH) and hotspot formation. This article presents therefore the LMH paradigm in an analogy to the Matthew effect, and shows the hotspot formation as an accumulated effect of advantages and disadvantages in relation to microwave heating. Several examples and potential applications of this mechanism are reviewed.

2 Localized microwave-heating (LMH)

Microwave heating is commonly utilized in uniformly-distributed volumetric schemes, such as ovens, belt applicators, and furnaces [5]. The heat-affected zone (HAZ) is typically comparable to the microwave wavelength, in the order of ~10^{-1} m. Non-uniform heating patterns may accidentally evolve in such processes, hence rapidly creating local hotspots with significantly high local temperatures. Such localization effects could be harmful in microwave applications that require uniform heating, such as food processing and drying.

The localized microwave-heating (LMH) effect is intentionally utilized (e.g. by microwave drills [6]) by purposely exciting a thermal-runaway instability [7, 8], which generates a hotspot with a sub-wavelength HAZ (in the order of ~10^{-3} m). LMH may occur in materials characterized by temperature-dependent properties, which dictate a faster rate of energy absorption than diffusion [9]. It enables a local temperature increase to above 1,000ºC in a heating rate of >100ºC/s in various materials. The LMH instability is ceased at the material's phase transition, to liquid, gas, or plasma.

The LMH paradigm [10,11], embodied in the microwave-drill concept, is effectively extended for various other applications. LMH effects have been demonstrated in various materials [12], including concrete [13,14], ceramics [15,16], and basalts [17,18]. LMH may also be useful for microwave-assisted mining [19] and concrete-recycling [20] applications. It was also found applicable for glass [21], polymers [22], and silicon [23,24]. A doping effect induced in silicon by LMH was also demonstrated [25]. In this experiment, silver and aluminum dopants were locally diffused by LMH into silicon to form a diode PN-junction.

LMH is also studied for medical applications such as tissue heating [26], bone drilling [27], interstitial treatments [28,29], ablation therapy [30], and DNA amplification [31]. Open-end coaxial applicators are used for direct heating of liquids and for activation of chemical reactions [32,33]. LMH may generate plasmoids, directly from solid substrates [34-36], and produce nano-particles [37-39].

Due to the significant energy concentration, the LMH effect can be implemented by a relatively low power (in the order of ~0.1 kW). This feature has led to the development of solid-state LMH applicators [21]. Consequently, the LMH paradigm is also extended to compact microwave heaters, and to new applications such as incremental sintering of metal powders for 3-D printing and additive manufacturing [40], ignition of thermite reactions for material processing and combustion [41] (also in oxygen-free environments such as underwater [42,43] or in space), and to material identification by breakdown spectroscopy (MIBS) [44].

3 The LMH instability as an accumulative effect

The LMH instability can be explained in a figurative manner, as illustrated in Fig. 1 [10]. The open-end applicator is applied to a material of which the dielectric loss factor tends to increase, and the thermal conductivity tends to decrease with temperature. The initial heating of the (originally) uniform material increases the temperature near the electrode tip, hence the spatial distributions of the material properties vary accordingly. The loss factor increases in this vicinity (and the thermal conductivity decreases there), hence more and more power is absorbed there, which leads to an unstable LMH response. This process illustrates the Matthew effect as well. The directed radiation-pattern creates a local “initial advantage” which causes the material there to modify its local properties in a way that further enhances and increases the initial advantage. This positive feedback leads to a confined hotspot.

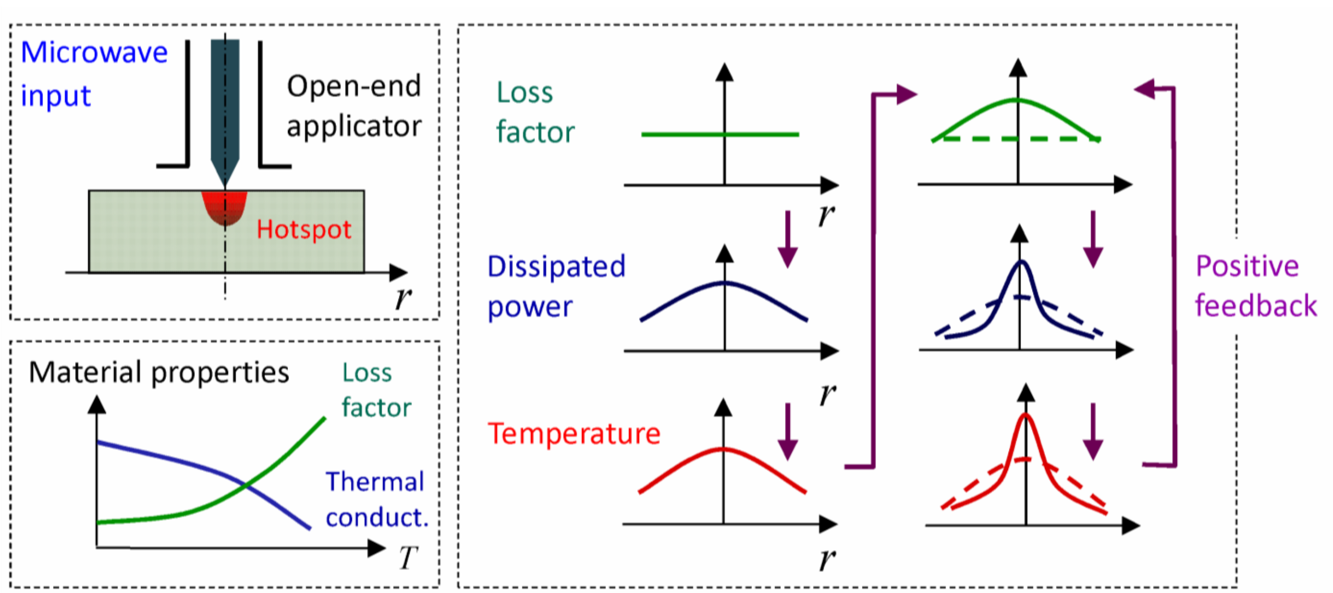

Figure 1: The induced thermal-runaway instability as an accumulated effect [10].

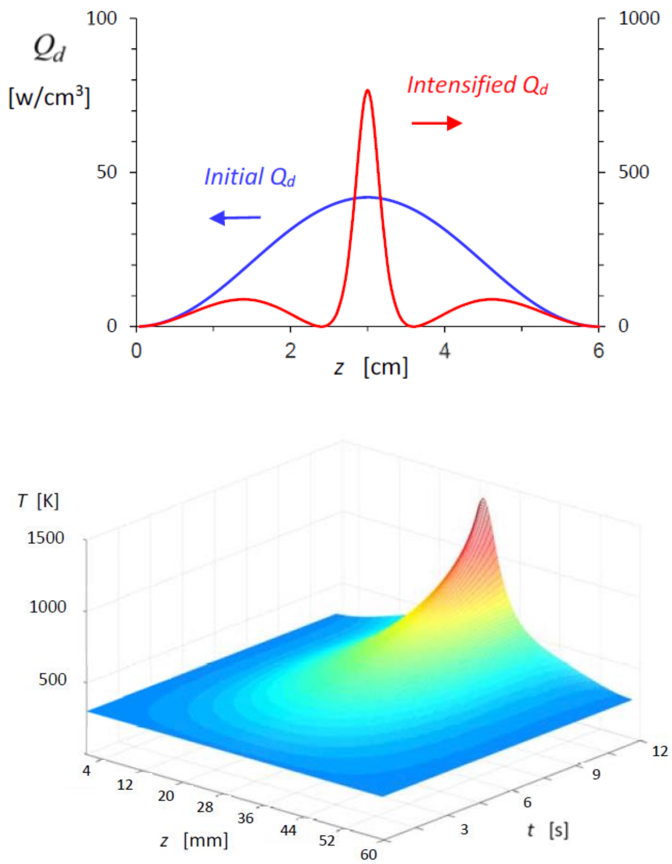

Figure 2: A numerical example of an accumulative LMH effect in a 1-D cavity [11]: (top) The initial and final profiles of the dissipated power density Q_d along the cavity, from a sine-squared to a sharper profile. (bottom) The localized temperature profile along the cavity, and the hotspot evolved.

As an example for the LMH intensification effect, Ref. [11] shows a model of a 1-D resonator filled with a dielectric medium. The complex dielectric constant $\varepsilon_r(T)$ has nearly parabolic temperature dependence as illustrated in Fig. 1. The ~6-cm long resonator is excited by a 2.45-GHz, ~1 kW power, at the fundamental axial mode. The coupled solution of the wave and heat equations shows that higher-order modes are dynamically evolved during the non-uniform microwave heating [11]. The temperature-dependent dielectric permittivity is being modified along the resonator, and coupled to the higher-order modes. This mode dynamics modifies the EM dissipated power $Q_d(z,t)$ initially distributed as the original fundamental-mode (sine-squared) profile. As the LMH instability proceeds, Q_d becomes significantly intensified and confined at the sub-wavelength hotspot region, as shown in Fig. 2 (top). The temperature rise is accelerated, and its localized profile is sharpened accordingly, hence the hotspot is intensified as shown in Fig. 2 (bottom).

In another example [10], a similar arbitrary material is placed in front of a waveguide aperture. The LMH effect is seen in Fig. 3 by the temperature profile and also by the focusing-like convergence of the Poynting vector towards the hotspot. This focusing also demonstrates the negative aspect of the Matthew effect, namely the suppression of the depleted vicinity surrounding the favorite spot.

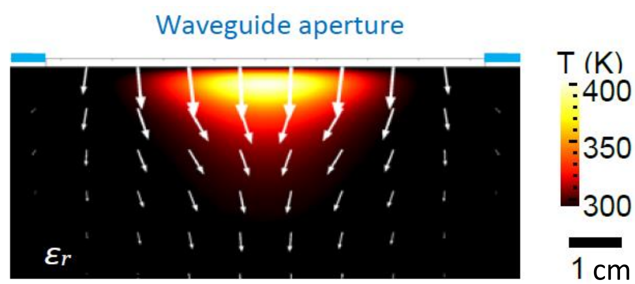

Figure 3: A numerical simulation of a hotspot evolved in an arbitrary material placed in front of a waveguide aperture [10]. The LMH effect is evident by the temperature profile, as well as the focusing-like convergence of the Poynting vector (denoted by the white arrows).

4 The microwave drill

An example of a practical LMH implementation is for instance a silent microwave-drill developed for concrete [14] (capable of drilling >25-cm deep, 12-mm diameter holes). More delicate microwave drilling operations were also demonstrated in ~1-mm diameter, for instance by relatively low-power (~0.1 kW) LMH applied to soda-lime glass plates (of 1-4 mm thickness) [21]. A simulation of the LMH evolution in these cases agrees well with the experimental measurements. Figure 4 shows for instance a simulated hotspot profile, and an LMH-drilled hole in glass [21].

The relatively low power needed for open-end coaxial applicators to reach LMH intensification in millimeter scales (typically below ~0.2 kW) makes solid-state generators (e.g. LDMOS [21]) suitable as sources for LMH applicators. These compact schemes enable a new range of portable LMH intensifiers.

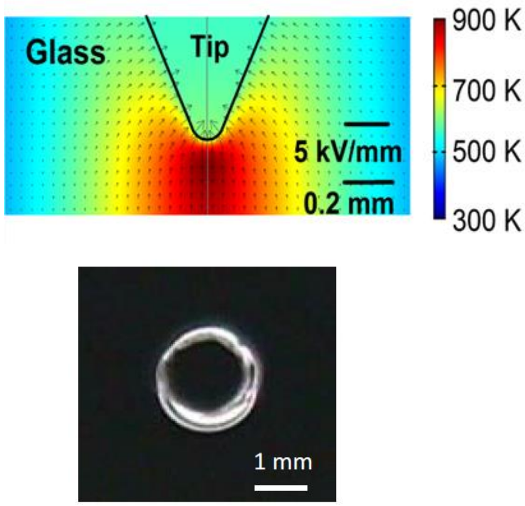

Figure 4: LMH effect in glass irradiated by a coaxial open-end applicator using an LDMOS-based microwave-drill [21]: (top) The simulated spatial temperature and electric-field distributions at the hotspot, and (bottom) a ~1.6-mm$^{\varnothing}$ hole made by LMH in glass.

5 Plasma ejection from solids

Dusty plasmas in forms of fireballs and fire-columns as shown in Fig. 5 can be ejected by LMH directly from hotspots evolved in solid substrates made of various dielectric and metallic materials [34-39]. The LMH-plasma process begins with a hotspot formation as in microwave drilling. For plasma ejection however, 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.

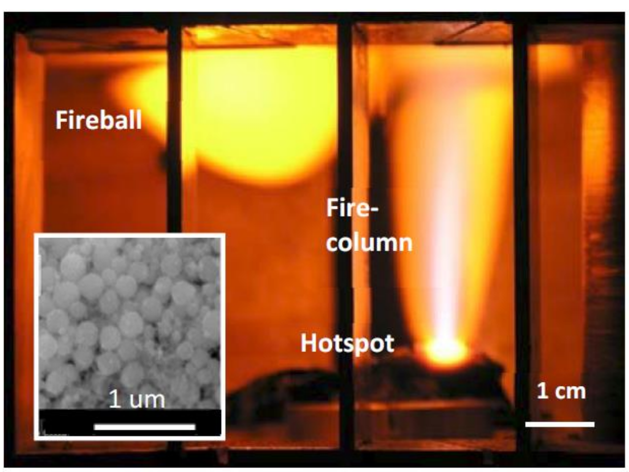

Figure 5: Plasmoids ejected by LMH from a hotspot in glass [35,36]: The hotspot in the solid substrate, the fire-column ejected, and the secondary fireball evolved. The inset shows nano-particles produced by LMH generated dusty plasma.

Beside their resemblance to natural ball-lightning phenomena, fireballs and fire-columns as shown in Fig. 5, may also have practical importance, e.g. as means to produce nano-particles directly from various substrate materials, such as silicon, glass, ceramics, copper, and titanium [35-39]. Nanoparticles were observed in these and other materials, both by in-situ synchrotron small-angle X-ray scattering (SAXS) of the dusty plasma, and by ex-situ SEM observations of the nano-powders collected after the processes. Particle of various sizes, shapes, and number densities have been obtained (typically of <0.1 µm size and $\sim 10^{16}$ m^{-3} number density within the dusty plasma). The LMH generated plasma can also be used for material identification [44] by atomic emission spectroscopy of the light emitted by the plasma ejected from the hotspot (similarly to the laser induced breakdown spectroscopy (LIBS)).

6 Doping and surface treatment by LMH

The feasibility of local doping of silicon by silver and aluminum using an LMH process was demonstrated in experiments in which the dopant material was incorporated in the electrode tip [25]. Its diffusion into the locally heated bulk was utilized in order to form a sub-micron junction. The doping depth was determined by the applied microwave power. Oxidation effects were also observed in these experiments, conducted in air atmosphere.

Chemical reactions excited by LMH for surface treatment also include thermite reactions for rust conversion to iron [41]. These LMH techniques open new possibilities for a variety of surface treatments and local surface processing.

7 LMH of metal powders

Coupling mechanisms of microwaves and metal powders are known in the literature in various volumetric schemes [45]. Experiments also show that metal powders with negligible dielectric losses can be effectively heated, and incrementally solidified by localized microwaves [40]. This LMH effect is attributed to the magnetic component of the EM field, and to the eddy currents induced in the metal-powder particles, as illustrated in Fig. 6 [45]. This effect, intensified by the micro-powder geometry, also occurs in diamagnetic metals such as copper. The heat is generated due to the metal electric resistivity, which impedes the eddy currents. This magnetic-like LMH effect is not characterized by thermal-runaway instability since the temperature tends to stabilize at ~700 K due to the particle necking and consolidation.

8 LMH ignition of thermite reactions

Powder mixtures, such as pure aluminum and magnetite powders, may generate energetic thermite reactions. These reactions are useful for a variety of combustion and material processing applications. However, the usage of these reactions is yet limited by the difficult ignition. We found that an easier ignition of thermite reactions as in Fig. 6 (right) is feasible by intensified LMH [41]. The power required for thermite ignition by LMH is ~0.1 kW for a ~3-s period, provided by a solid-state microwave generator. These experiments also demonstrate the feasibility of cutting and welding by relatively low-power LMH.

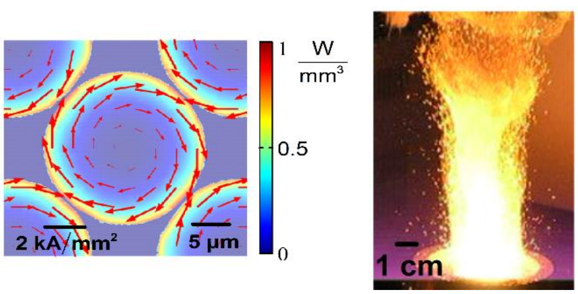

Figure 6: LMH of metallic powders: (left) Eddy currents induced in copper powder [45]. (right) A thermite flame ignited by LMH [41].

Due to their zero-oxygen balance, exothermic thermite reactions may also occur underwater. However, this feature is also difficult to utilize because of the hydrophobic properties of the thermite powder. The bubble-marble (BM) effect [42] enables the insertion and confinement of a thermite-powder batch into water by a static magnetic field, and its ignition by LMH underwater [43]. Potential applications of this underwater combustion may include wet welding, thermal drilling, detonation, thrust generation, material processing, and composite-material production. These are applicable to other oxygen-free environments as well, such as the outer space.

9 LMH potential for 3D printing

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. This effect enables a potential technique for stepwise 3D printing and additive manufacturing (AM) [40]. The solidified drop of metal powder is placed in this technique as a building block on top of the previously constructed block in a stepwise AM process, illustrated in Fig. 7a. A rod constructed by LMH-AM from bronze-based powder is shown in Fig. 7b [40]. Magnetic fixation of iron powder for LMH-AM was also demonstrated [46].

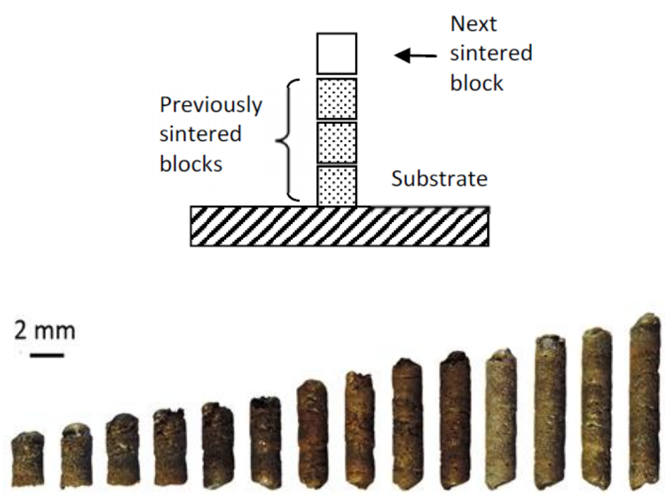

Figure 7: Additive manufacturing (3D printing) of metal powders by LMH [40]: (top) A conceptual scheme of the stepwise LMH-AM process. (bottom) A 2-mm$^{\phi}$ rod constructed in 14 consequent steps from bronze-based powder.

10 Discussion

The LMH paradigm, presented here in the context of Matthew effect, enables microwave heating in HAZ sizes much smaller than the microwave wavelength. The microwave radiation is self-focused intentionally into a millimeter-size hotspot. Further to melting and evaporation, dusty plasma rich of nanoparticles can also be directly ejected from the hotspot.

The LMH paradigm incorporates the theory of induced thermal-runaway instability together with experimental studies and various applications. LMH is applicable to dielectrics and metals as well (in solid and powder forms), and to biological tissues.

Figure 8 shows a conceptual scheme of the LMH relevance to solid, powder and plasma states, as well as their transitions and related applications.

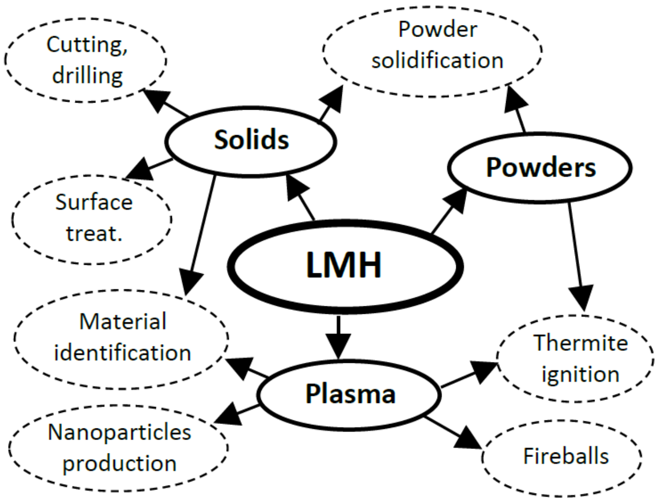

Figure 8: The LMH relevance to solid, powder and plasma states; their transitions, and related applications [10].

The LMH paradigm is presented here in the wider context of the Matthew effect. The intuitive analogy illustrated here may provide a better insight of the LMH instability, and a non-mathematical heuristic explanation of its non-linear dynamics. For those who are interested in Matthew effects in other disciplines, the LMH phenomena and hotspot formation may provide a visual demonstration of the accumulated effect of advantages and disadvantages. In particular, the damage caused by unintentional LMH may exemplify the destructive potential of Matthew effects, e.g. to the contemporary academic system and to the society in general.

Acknowledgements

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For further reading

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Eli Jerby received his Ph.D. degree in Electrical Engineering from Tel-Aviv University (TAU) in 1989. As a Rothschild and Fulbright post-doctoral fellow, he worked at MIT with the late Prof. George Bekefi on free-electron maser (FEM) and cyclotron-resonance maser (CRM) studies. Since his return to TAU in 1991 as a faculty member, Prof. Jerby has studied novel schemes of FEM's and CRM's, as well as localized microwave-heating effects and their applications (e.g. the microwave-drill invention, additive-manufacturing schemes), microwave-generated plasmas and fireballs, thermite reactions and metallic-fuel ignition by localized microwaves. Besides his scientific work, he has conducted in his TAU laboratory several projects for the industry, government, and start-up initiatives. Prof. Jerby served as a program committee member of int'l conferences and workshops in the fields of plasma, radiation sources, microwave heating, 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