Active-Antenna Approach for Microwave Heating by Solid-State Applicators†

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Abstract

The current technological trend of implementing solid-state amplifiers (SSA's) in microwave-heating applicators is motivated by the SSA's advantages over magnetrons, namely their superior tunability and controllability features. However, the desire for perfection may lead in some cases to too sophisticated and costly design configurations, which may impede the SSA-technology penetration into low-end, low-cost markets. This article presents simplified and potentially low-cost schemes based on the *active-antenna* approach, which integrates the SSA within the antenna. Following our previous studies of miniature solid-state microwave heaters and microwave drills, we present here various schemes of active microwave-heating applicators, using LDMOS transistors. The paper presents preliminary experimental demonstrations of conceptual *active-applicator* schemes, as well as potential unique capabilities (e.g. self-tune and self-stop features) of these schemes.

† A paper presented at AMPERE-2017, Delft, The Netherlands, Sept. 18-21, 2017.

1 Introduction

The present technological trend of implementing solid-state generators (instead of the commonly used magnetron tubes) for microwave heating, has already been proposed and studied for five decades now, since the late 60's of the previous century [1-5]. However, in practice, the progress in the actual insertion of solid-state devices to replace vacuum tubes in microwave heating systems has been impeded till recently by the relatively higher costs and lower efficiencies of the solid-state devices, as compared to the mature magnetron-based systems. Nevertheless, ideas such as employing frequency agility in microwave ovens [3], hence using the frequency-tuning control as a means for adaptive matching to a varying load, were presented already in 1979. The concept of transistorized near-field radiator arrays [4] for microwave heating at 915 and 2,450 MHz was introduced in 1986.

Two common schemes, employing high-power transistors for microwave heating in amplifier and oscillator configurations, are illustrated in Figs. 1a, b. The amplifier scheme includes a controllable low-power exciter, cascaded to a power amplifier. In the oscillator scheme, the amplifier is fed by a positive-feedback loop, hence it tends to self-oscillate in certain conditions. The amplifier scheme is more common since it fully utilizes the controllability features of the solid-state amplifier. The implementation of the oscillator scheme, on the other hand, is cheaper and simpler than that of the amplifier scheme.

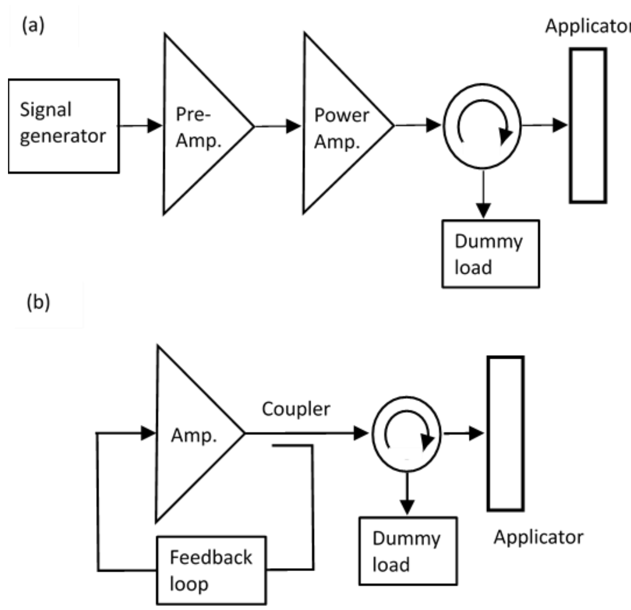

Figure 1: Common design schemes of solid-state microwave heaters, in amplifier (a) and oscillator (b) configurations.

An oscillator-type solid-state microwave heater [6] was demonstrated in 2006 for bio-chemical studies (e.g. of green-fluorescence protein, GFP). In this operational device, shown in Fig. 2, the miniature applicator was embedded within the feedback loop itself and powered by an LDMOS amplifier. It was designed to resonate at a varying frequency while maintaining the liquid-load temperature in a controllable fashion. The frequency tuning and temperature control were achieved by varying the transistor's gate and drain voltages, and by adjusting the cavity mirrors.

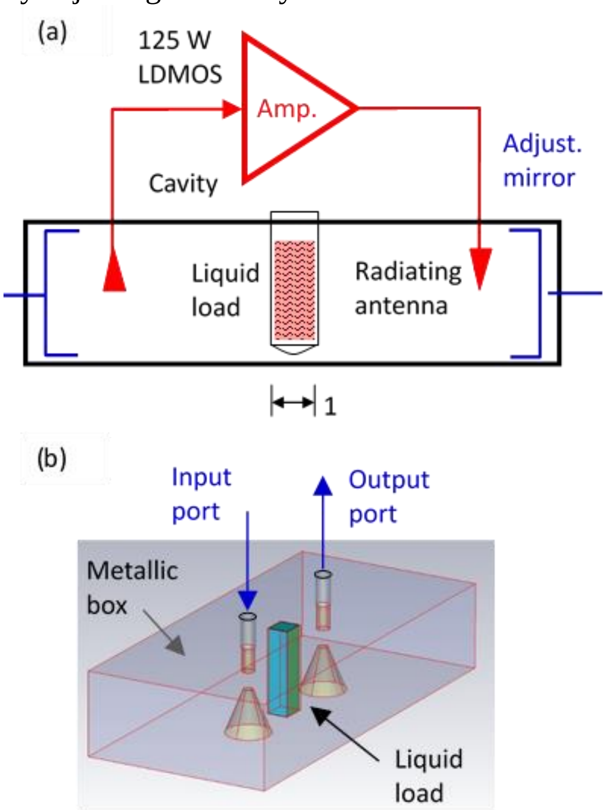

Figure 2: A miniature solid-state microwave heating applicator[6]: (a) A schematic of the load incorporated in the feedback loop of the LDMOS amplifier, and (b) the cavity designed for biochemical studies (e.g. of green-fluorescence protein, GFP).

In another solid-state microwave heater [7], presented in 2008, the LDMOS oscillator (as in Fig. 1b) feeds an open-end applicator, which functions as a delicate microwave drill. The ~0.1-kW power level obtained was proven to be sufficient for local melting of materials, such as glass [8]. Further studies based on the solid-state microwave-drill setup included ignition of thermite powders [9] and 3D-Printing [10].

The integration of both the load and the microwave generator within the microwave-heating applicator [6], and the desire for high level of integration in advanced electronic appliances, have led us to consider the *active-antenna* concept for heating purposes.

Antennas are usually considered as passive devices, in the sense that the microwave generator is separated from the radiating elements; the microwave power is supplied to the antenna via its input port. As an exception, the active-antenna concept [11] inherently incorporates the radiating and the active elements into an integrated device. Reciprocally, a similar approach applied to the receiving element is known as the *rectenna* [12] (an antenna integrated with a rectifier).

The active antenna can be regarded as a microwave circuit where the input port is the DC supply, and the output port is the radiation to free space, as illustrated in Fig. 3. The active antenna incorporates the transmitter functions, and hence it may exhibit advantages such as smaller dimensions, lower cost and better efficiency, as compared to modular design. The active-antenna technology is quite mature and is commercially available for far-field transmit-receive applications in radar and communication applications.

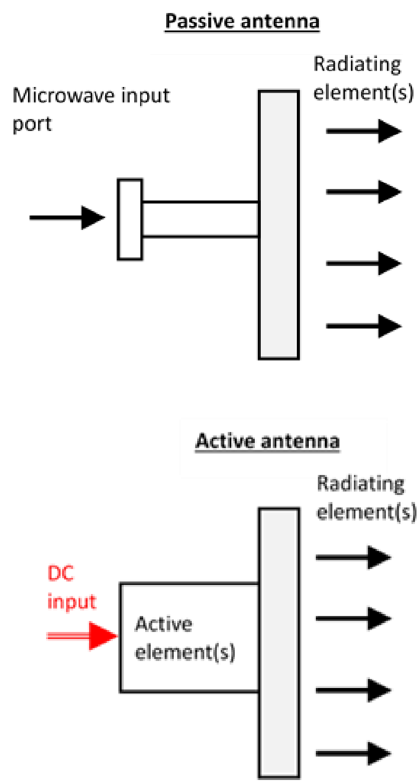

Figure 3: Simplified schematics of active vs. passive antenna configurations for far-field radiation.

This study imports ideas and conceptual schemes of the active-antenna concept, and explores ways to incorporate them for solid-state microwave heating. The main challenge here is to integrate the high-power solid-state module within the radiator (or the applicator structure) itself, so they would be interactively coupled with the load as the heating process evolves. This active-applicator approach is introduced here with several examples, including preliminary experimental and numerical feasibility studies. Unique features such as self-tune and self-stop are identified and discussed, and a path for our future studies in this regard is drawn.

2 The active-applicator concept

The *active-antenna* concept can be adapted for microwave heating purposes, in an *active-applicator* approach. Various ways could be conceived to embed the load within an integrated structure of the radiating and active elements. In the *active-radiator* scheme, shown in Fig. 4a, the coupling between the two antenna ports is affected by the variation in the load's dielectric properties during the heating process. Another scheme is the active-applicator shown in Fig. 4b, in which the load itself is closing the loop in a bi-static mode, and determines the oscillation conditions.

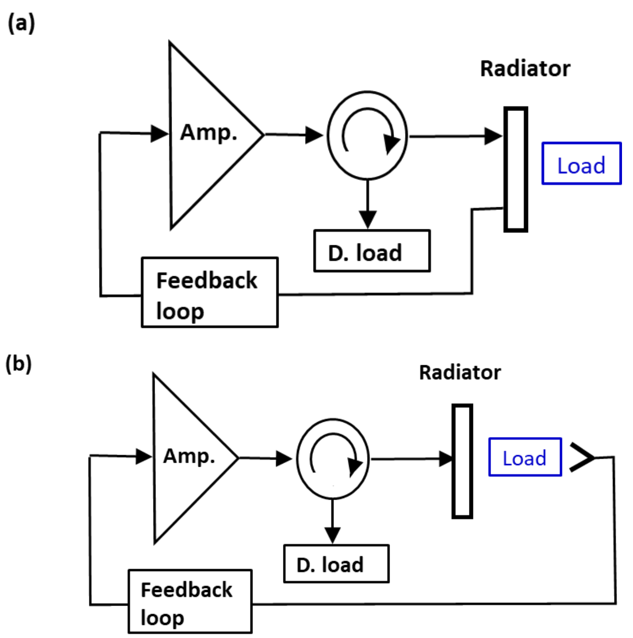

Figure 4: Active-applicator schemes for microwave heating in (a) an active radiator (monostatic) and (b) an active applicator (bi-static) configurations, in both the oscillation conditions are affected by the load status.

The latter scheme is more relevant for industrial processes in which the heated objects are repeatedly the same, and the process is predicable. The hypothesis of this study [13] is that the oscillation condition can be affected by the load status (amount, temperature, etc.) in a way that their mutual adaptation could be used in order to tune and optimize the heating process.

2.1 Active-radiator implementation

The active radiator constructed for this study consists of a patch array antenna inside a metallic chamber, fed by a 140-W LDMOS amplifier configured as shown in Fig. 4a. The load inside the chamber is a water container, as shown in Fig. 5a. A probe antenna situated on the same antenna board provides the feedback loop, hence the antenna array functions as both the radiating elements and the feedback sensor. In the experiments, the feedback signal is also sampled by a frequency-time domain analyzer (Tektronix RSA306B), hence frequency variations over time and the spectral power density evolutions are detected.

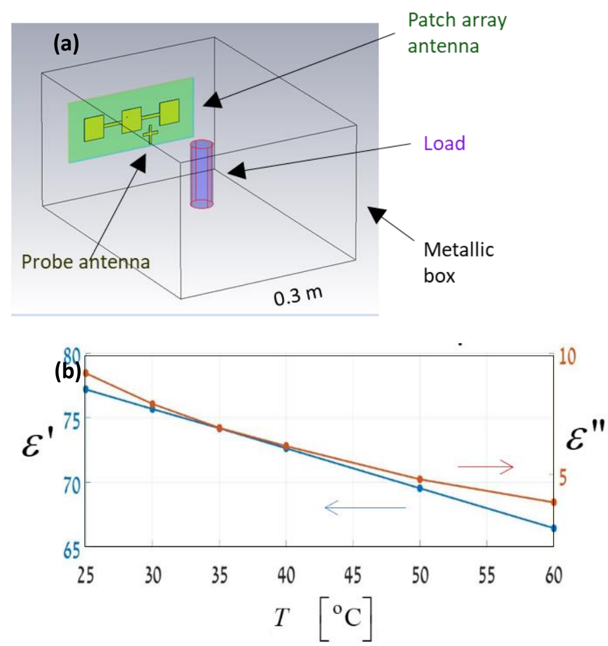

Figure 5: (a) an example for an active-radiator scheme implemented by a patch array antenna inside a metallic chamber with water load inside. A sampling probe on the same antenna board closes the feedback loop as in Fig. 4a, and enables oscillations. A 140-W LDMOS amplifier and a frequency-time analyzer (Tektronix RSA 306B) are employed in this experiment. (b) The temperature-dependent dielectric permittivity of water [13].

The water load varies during the heating process due to the temperature dependence of its dielectric properties [14], as shown in Fig. 5b. Therefore, a variation in the oscillating frequency is expected due to changes in the load conditions. Simulation results of the cavity scattering parameters (using CST MW studio®) show a frequency shift as the temperature rises (due to the temperature dependence of the dielectric permittivity) as presented in Fig. 6a. Preliminary experimental results confirm the oscillating frequency shift, as shown in Fig. 6b, in accord with the temperature increase. This frequency variation inherently improves the matching and power transfer to the load, and it may also provide an indirect measure of the load temperature. This variation pattern offers possibilities for *self-tune* and even *self-stop* mechanism inherently incorporated in the heating process.

2.2 Dispersion-controlled active-applicator

The active-applicator scheme implemented in this experiment demonstrates the feasibility of an adaptive self-controlled process, using the varying dispersion of the load during heating. Furthermore, this heater operates only in the presence of sufficient load in it.

The device shown in Fig. 7 was constructed as a modified version of the miniature solid-state heater [6] presented in Fig. 2. The difference here is the center section added to the cavity, which blocks its transmission when empty, as a waveguide section in cutoff. Therefore, the cavity functions as an *adaptive feedback*, since it varies the oscillation condition with respect to the loading condition. In the absence of load (or insufficient loading), the oscillation conditions are not met and no microwave power is generated at all. In different amounts of the liquid or different temperatures, the oscillation conditions adapt and self-tuned to the optimal frequency.

Measurements of the active-applicator's open-loop gain were conducted in various conditions using a vector network analyzer. As shown in Figs. 8a, b, varying the load's amount has revealed that the oscillation threshold is satisfied only when the tube is sufficiently filled with liquid. At smaller amounts, the open-loop gain is lower than the threshold. Figure 8c shows that the gate-source voltage of the LDMOS amplifier also controls the oscillation conditions. Referring to the load temperature, simulations show that the insertion loss increases and the frequency is shifted higher as the temperature rises (Fig. 10d). These results also indicate that a self-stop feature could be activated when the open-loop gain is reduced below unity.

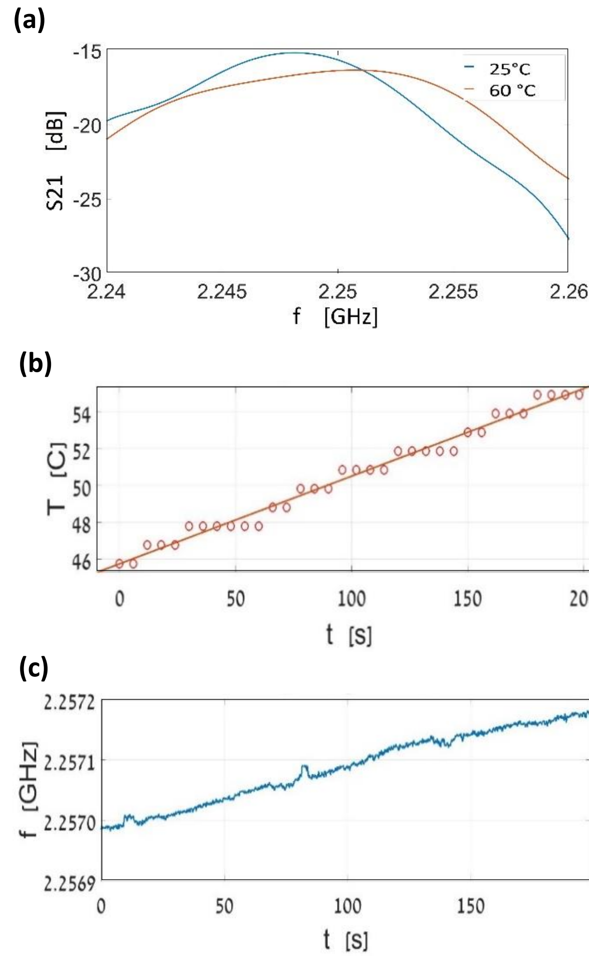

Figure 6: (a) Simulations of the applicator's scattering parameter S_{21} show variations with temperature; the insertion loss increases and the frequency peak is shifted higher as the temperature rises. (b) Experimental measurements during the temperature increase reveal the consequent oscillating frequency increase (c).

In the active-applicator experiments, the frequency and power were acquired using a frequency-time analyzer (Tektronix RSA306B) by adding a probe to the cavity shown in Fig. 7, and sampling the signal evolved inside. The temperature was detected by a PIR detector connected to a PC. Preliminary experimental results presented in Fig. 9a show that the oscillating frequency of the active applicator tracks the temperature as it rises. This ~4-MHz shift in the oscillation frequency during the heating is attributed to the change in the load dispersion within the feedback loop. The variations in the complex dielectric constant of the water during heating, as shown in Fig. 5b, modify the oscillation conditions, and hence the frequency shifts as shown in Fig. 8d.

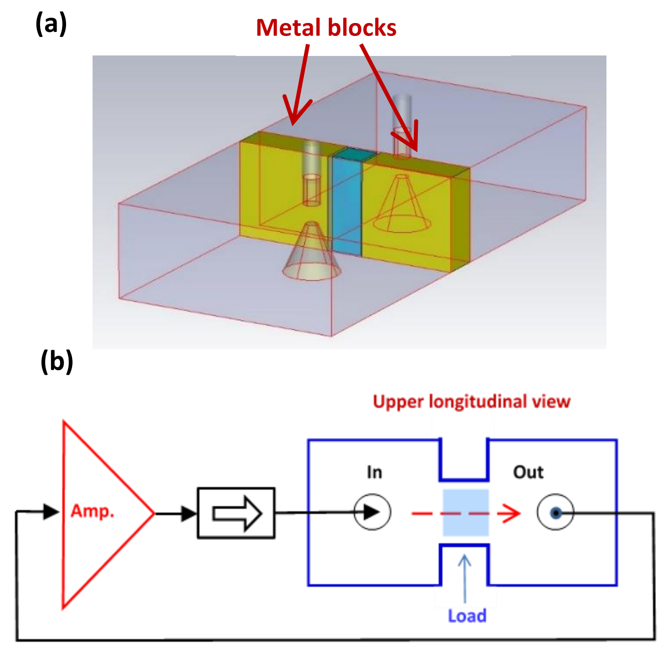

Figure 7: An active applicator scheme: (a) The miniature solid-state microwave heater6 shown in Fig. 2 with additional metallic blocks that enforce cutoff in the absence of load in the cavity. (b) The dispersion-controlled feedback loop of the active applicator (in cutoff except for preset loading conditions which enable oscillations).

Furthermore, when the water starts to boil, the effective dielectric constant of the water becomes too small to maintain the blocked section of the cavity (Fig. 7) above cutoff, and hence the feedback transmission drops. As demonstrated in Fig. 9b, the microwave power generation ceases abruptly at this target temperature. The *dispersion-controlled feedback loop* enables to tune the active applicator to self-stop in other temperatures, designed according to the characteristics shown in Figs. 8a-d. Consequently, another useful feature associated here is that this microwave heater only operates in the presence of a sufficient load inside. These inherent control features may require some more attention in the design stage, but they may significantly simplify the system by incorporating the sensing functions within the heating process itself.

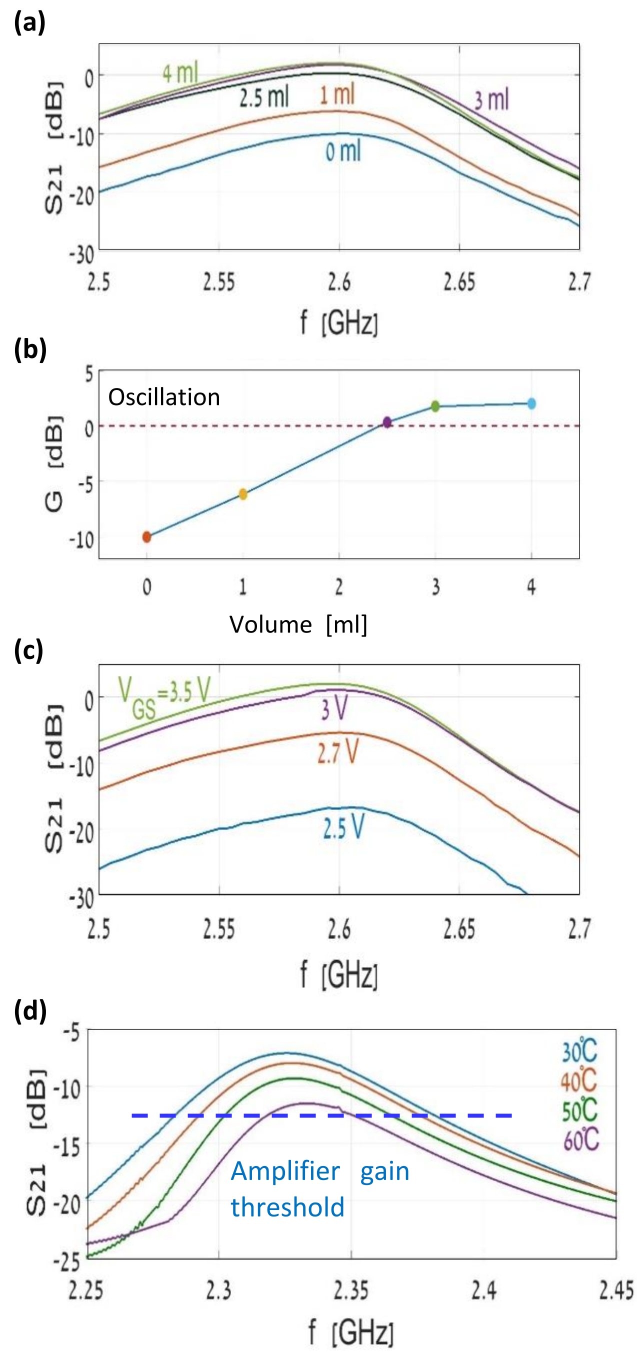

Figure 8: The open-loop gain S_{21} of the active applicator shown in Fig. 7, in various conditions: (a-b) The effect of the load volume on the open-loop gain, and the oscillation condition. (c) The effect of the transistor gate voltage on the open loop gain. (d) A simulation of the cavity insertion loss, showing that the loss increases and the frequency peak is shifted higher as the temperature rises.

3 Additional active-antenna schemes

The implementation of the active-antenna concept for microwave heating application could be considered in various other ways, as demonstrated by the following examples taken from our ongoing studies.

An integrated active-antenna was developed for our preliminary ink-drying experiments as a compact module [15] with an antenna printed on one side, and the LDMOS amplifier circuit (including the matching elements) on the other side, as shown in Fig. 10. This module is fed by 28V DC, and radiates at 2.2 GHz into a chamber. This modular approach preserves some of the magnetron's advantages, such as the design simplicity and low cost (hence we name it a solid-state magnetron).

The modular approach also motivates the rigid "no-PCB" design developed in our laboratory, which employs a suspended metallic strip-line structure for the transistor, as shown in Fig. 11. The wing-like tapers ensure the matching of the directly-mounted transistor to the metallic structure. Preliminary experiments have already shown self-oscillations of this device at ~2.2 GHz.

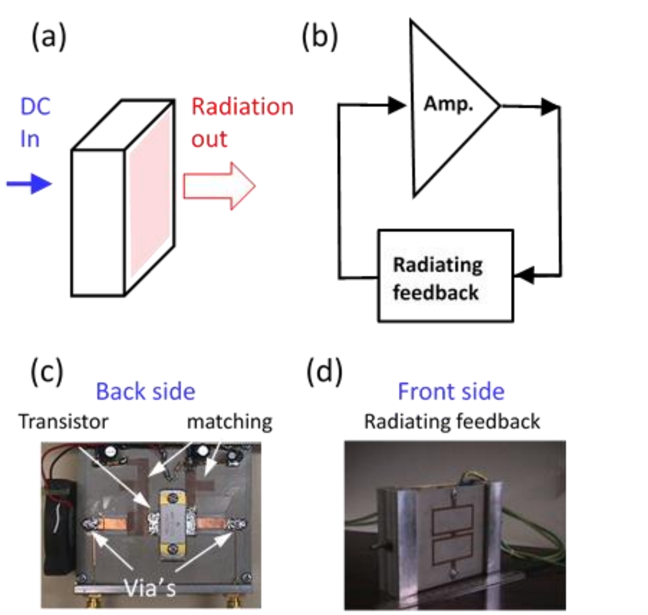

Figure 10: An integrated active-antenna module for microwave heating applications: (a, b) The modular scheme with the radiating element incorporated in the feedback loop of the amplifier, and (c, d) its implementation by an LDMOS transistor directly mounted in the back side of a suspended strip-line structure with the radiating feedback on the front [15]

Another study, yet in a preliminary stage, is the high-efficiency (H-type) active applicator, as conceptually illustrated in Fig. 12. In this scheme, the positive feedback loop maintains the oscillation conditions in saturation. Using a high-class amplifier in a nearly On-Off switched mode, the rich harmonic content generated is separated to various radiating elements, each tuned to another harmonic frequency. The overall efficiency of the radiated power, as well as the heating quality due to the multi-frequency radiation, could be significantly improved

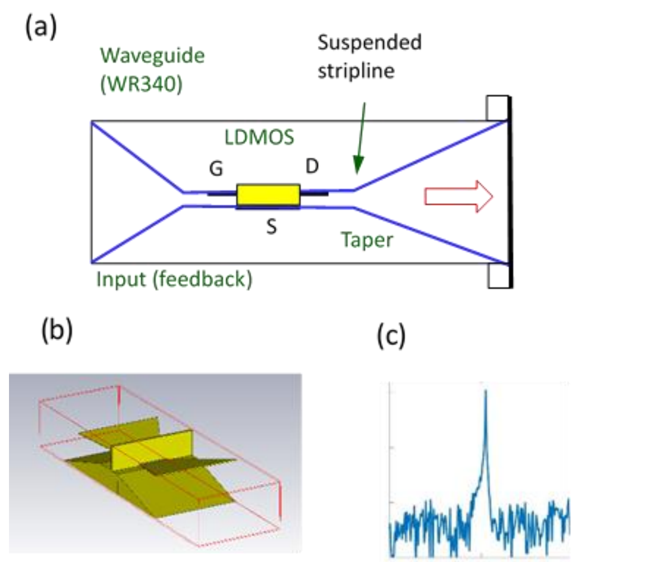

Figure 11: A prototype of a rigid active-antenna module for microwave-heating applications: (a) The suspended strip-line ("no-PCB") structure incorporated in a WR340 rectangular waveguide. (b) The wing-like tapers enabling the matching of the transistor directly-mounted to the metallic structure. (c) A ~2.2 GHz microwave output detected in a preliminary experiment of the device.

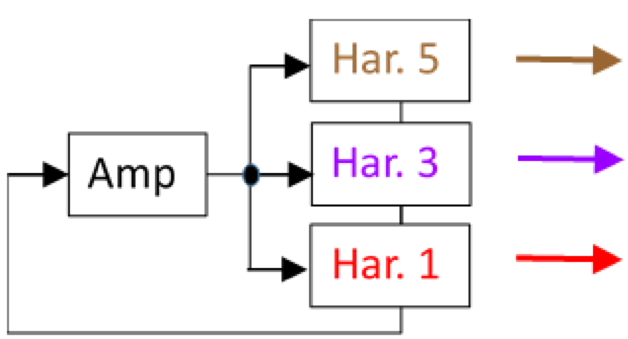

Figure 12: An *H-type* active-applicator scheme for high-efficiency, multi-harmonic microwave-heating operation.

4 Conclusions

The active-antenna concept, adapted for near-field microwave heating purposes, may present a realization of the modular integration approach in future developments of compact, low-cost, solid-state microwave heating devices. The simple-to-apply radiating module, incorporating the microwave generator with the antenna in a single integrated unit fed by a DC voltage, may preserve some of the magnetron's flavor, as a stand-alone, rigid and low cost module.

Furthermore, active applicators can be specifically tailored for heating processes in which the material characteristics previously known, such as in industrial production lines. In these cases, the active-applicator concept introduces additional new features using the previously known load dispersion variations. By tracking the spectral evolution and the load-applicator interaction during the heating process, one can also utilize the active applicator as a sensor enabling detection of the microwave-processing status. The previously known (temperature-dependent) physical properties of the materials may also provide inherent mechanisms for self-tuning and self-control of the process, instead of using arrays of sensors and detectors in external feedback loops. The self-stop mechanism for instance, can be valuable for instance in cases where the microwave processing stage is incorporated in an automatic production line.

The active-applicator approach could be further developed to high-class, high-harmonic, and high- for near-field radiation-beam steering. Periodic structures in 1, 2 or 3 D incorporated in active-applicator arrays [16] may provide the dispersion sensitivity required for self-controlled operation of such high-power applicators.

In conclusion, the active-applicator concept, in its various potential implementations, may lead to advanced capabilities of microwave-heating systems (such as self-tuning, self-optimization and conditional operation) as well as higher efficiency, compactness and modularity.

Acknowledgment

This study is supported by the Israel Science Foundation (ISF), Grant No. 1869/16.

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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; and 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

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