Historical Notes on Solid-State Microwave Heating

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The use of solid-state microwave generators for heating was already proposed in the late sixties of the previous century. In 1971, McAvoy was granted the first patent on the "solid state microwave oven"[1]. This invention was followed in the seventies by several other patents related to the various aspects of solid-state microwave heating. In 1972, Cheng patented the "solid state microwave heating apparatus"[2], in which the cavity walls also functioned as the heatsink of the solid-state devices radiated by dipole antennas. In 1975, Ohtani patented the "hybrid microwave heating apparatus"[3], combining the conventional magnetron as a high-power source with auxiliary solid-state devices in order to attain better heating uniformity.

In 1977, Dehn patented the "microwave heating apparatus with improved multiple couplers and solid-state power source"[4]. This patent presented a cut-off of tubular housing for mounting multiple solid-state oscillators using micro-strip circuitry. The couplers were longitudinally spaced and angularly staggered so that the energy was coupled to different regions. In 1976, Bickel patented the "solid-state microwave oven power source"[5], which incorporated plurality of high-power oscillators. This scheme was the first to employ negative-resistance transistors combined to produce phase-lock operation for heating purposes.

In 1980, Mackay granted two patents referring to "controlled heating microwave ovens using different operating frequencies" [6,7]. These patents presented a frequency agile microwave source for energizing the oven cavity in an optimal spatial pattern. The frequencies at which the oven's cavity was energized were selected by the control system in order to obtain improved heating uniformity by superimposing various heating patterns. These pioneering inventions, already patented by the year 1980, were followed by additional patents as partially listed in Table 1 and illustrated in Figs. 1 and 2.

The first archived papers on solid-state microwave heating were published in 1979 by Mackay, Tinga and Voss[8]. The main obstacles encountered in these early studies were the relatively high cost, low power and poor efficiency of the solid-state generators available then as compared to magnetrons[9].

In the early 2000's, the laterally-diffused metal-oxide semiconductor (LDMOS) technology became mature and cost-effective, in particular for the market segment of cellular communication base-stations. The demands for high-power, low-cost LDMOS transistors for the huge mobile-phone market have also paved the way to embed LDMOS transistors into microwave-heating applications, with the expectation to be almost competitive with the pricing of conventional magnetron systems.

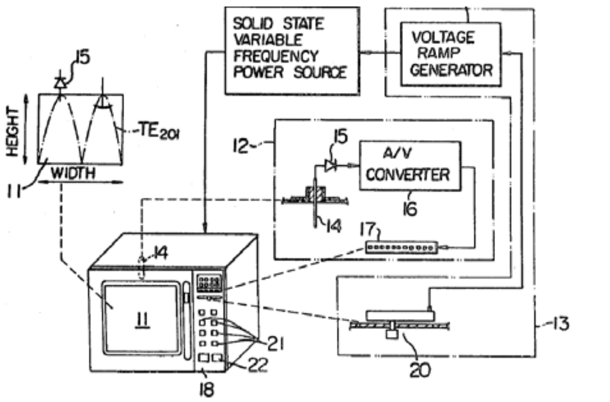

Figure 1. A frequency control scheme for solid-state microwave ovens [Nobue, US pat. 4415789, 1983].

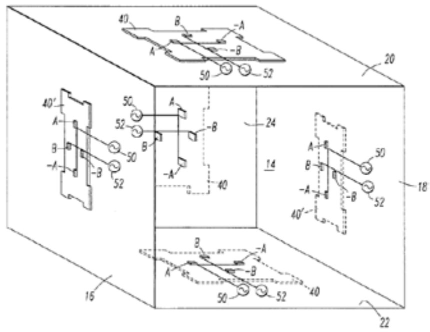

Figure 2. Distributed microwave radiators for heating applications [Page, US pat. 5558800, 1996].

Table 1. A partial list of patents on solid-state microwave heating since 1971

Year	Title	Inventor	Patent No
1971	Solid-state microwave oven	Bruce R. McAvoy	US 3557333
1972	Solid-state microwave heating apparatus	Kern K. Cheng	US 3691338
1975	Hybrid microwave heating apparatus	Tetsuro Ohtani	US 3867607
1977	Microwave heating apparatus with improved multiple couplers and solid-state power source	Rudolph A. Dehn	US 4006338
1978	Solid-state microwave oven power source	Samuel H. Bickel	US 4097708
1980	Controlled heating microwave ovens	Alejandro MacKay	US 4196332
1980	Controlled heating microwave ovens using different operating frequencies	Alejandro MacKay	CA 1081796
1983	Microwave oven having controllable frequency microwave power source [Figure 1]	Tomotaka Nobue	US 4415789
1985	Microwave heating apparatus with solid-state microwave oscillating device	Hisashi Okatsuka	US 4504718
1995	Microwave oven, in particular for rapid heating to high temperature	Patrick Jackuault	US 5420401
1995	Solid-state microwave generating array material, each element of which is phase controllable, and plasma processing systems	Jerome J. Cuomo	EP 0459177
1996	Active RF cavity including a plurality of solid-state transistors	Bernard R. Cheo	US 5497050
1996	Microwave power radiator for heating applications [Figure 2]	Derrick J. Page	US 5558800
2004	Microwave heating using distributed semiconductor sources	Peter Handinger	US 20040206755
2010	Microwave oven switching between predefined modes	Ulf E. Nordh	US 20100155392
2011	Microwave heating apparatus [Figure 4]	Tomotaka Nobue	US 20110108548
2013	Microwave oven with antenna array	Ranjit Gharpurey	US 20130175262
2015	Microwave oven using solid-state amplifiers and antenna array	Jose A. Lima	US 20150136760
2016	Versatile microwave heating apparatus	Olle Niklasson	US 9332597

A solid-state microwave heater for loads of ~10-cc volume was presented in 2006 at IMPI-40 by Schwartz et al.[10]. This laboratory heater, shown in Figs. 3a,b, introduced the first use known to the author of an LDMOS amplifier for microwave heating purposes. The positive feedback scheme employed in this device adapts the oscillation frequency to the load variation in the frequency domain due to the temperature increase, as shown in Fig. 3c. This scheme was found also useful for localized-microwave heating (LMH) induced by solid-state applicators, such as various microwave drills[11,12] and metallic fuel igniters[13].

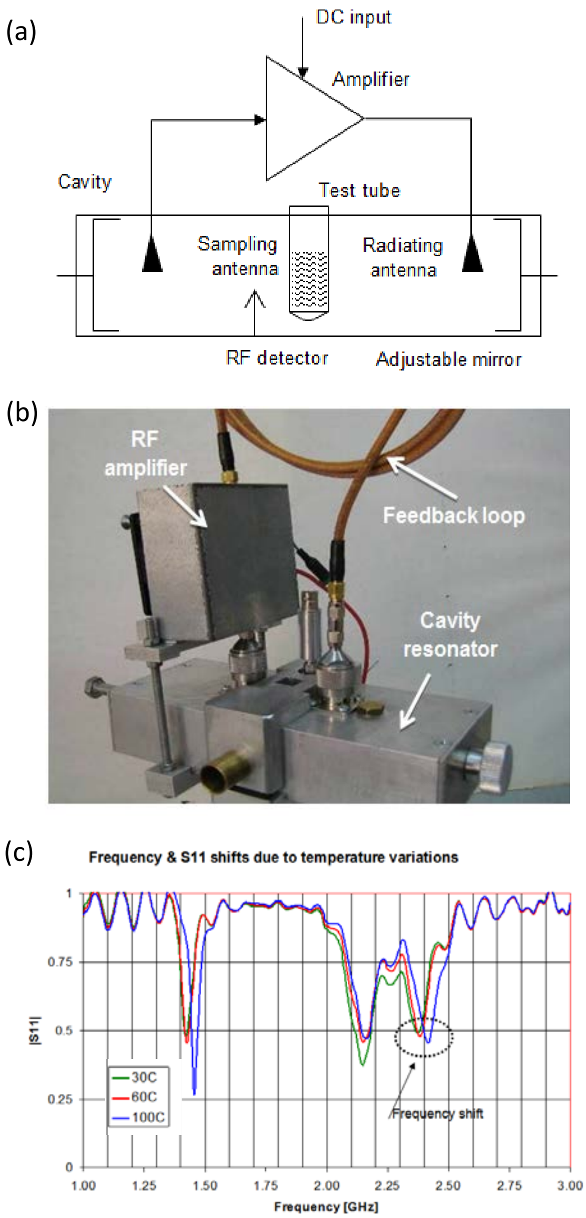

Figure 3. A transistor-based microwave heater[10] [Schwartz et al. 2006]: (a) The positive-feedback scheme, (b) the device, (c) the resonance shift with the temperature.

More recently, techniques for efficiency improvement were investigated by Korpas[14], and by Imiatez[15] for healthcare applications. Advanced techniques, applying algorithms to control the frequency and phase in order to optimize the efficiency, were studied in GaN[16]. Multiple source analyses, in order to control the heating pattern, were presented by Yakovelev[17].

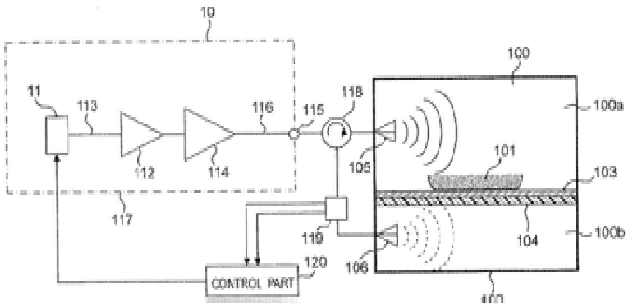

Figure 4. A two-stage microwave oven scheme [Nobue, US pat. US 20110108548, 2011]

Despite the evident technological feasibility of the solid-state technology for microwave heating, as reflected in the literature since the first patent in 1971, the magnetron vacuum tube has dominated this field for over five decades. Only recently, the potential market value of solid-state microwave heating systems, in particular for domestic microwave-ovens, triggered several companies to develop, patent and commercialize this technology. In 2013, RF Dynamics Ltd. (renamed to Goji) reported the development of a solid-state microwave oven and claimed then to achieve a quick, precise and efficient cooking system[18]. A commercial demonstrator of a solid-state oven was also announced in 2015 by Freescale/NXP[19,20].

Although LDMOS technology is the most commonly used for high power solid-state devices, the noticeable performance advantages of the continually improving and growing GaN technology is being the trigger to pursue for low-cost high-volume manufacturing. Lately, at the IMS-2016 exhibition in San Francisco, several companies presented mature GaN devices; MACOM presented a GaN-on-silicon amplifier for 2.45-GHz CW ISM applications, with 300-W saturated power and manufacturing capabilities for 8” wafers. Other GaN devices from AMPLEON, QORVO, INFINEON, NXP, and RFHIC, have also been presented. Heating applicators based on GaN devices, presented mostly for cooking, are yet not available for consumers and high-volume manufacturing, but they indeed demonstrate the technological capabilities. NXP presented 900-mL battery-operated portable heater based on a 200-W LDMOS device. MACOM and MIDEA also presented a microwave-oven based on a 300-W GaN device, designed to provide homogeneous field pattern inside the cavity.

It appears that the solid-state microwave heating technology is promising and compelling to replace the conventional magnetron tubes sometime in the near future. This trend is justified mainly by the small form factor, the low operating voltage, and the ability to precisely control the phase and frequency in order to obtain better heat distribution.

GaN devices present noticeable advantages over the LDMOS technology especially at 2.45-GHz and higher frequencies, and it seems to be the dominant device for solid-state heating applications in future. Its main advantages are the high breakdown voltage, higher efficiency, and higher gain and power density. Its main obstacle is yet the high price, though it is gradually being reduced. These days, according to MACOM, the GaN price is becoming competitive to the common LDMOS costs.

The goal of having a significant market share for the solid-state heating systems will be achieved by reducing the price gap between the magnetron and the LDMOS/GaN devices. Once this cost target will be achieved, the microwave heating technology will become ubiquity. The heating and cooking with solid-state microwave ovens will be more precise, more controllable, and much more fascinating.

For further reading:

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Eli Schwartz received his M.Sc. degree in electrical engineering at Tel Aviv University. He worked on solid-state microwave heaters under the supervision of Prof. Eli Jerby in the years 2005-2006. Mr. Schwartz is currently a senior RFIC engineer at DSP Group in the R&D division, working on next-generation mobile wireless solutions such as CMOS RF power amplifiers. Prior to that, he held various RFIC positions at Intel, working on millimeter-wave circuits.