MINIATURE TRANSISTOR-BASED MICROWAVE DRILL

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ABSTRACT
This paper presents the implementation of >100-W LDMOS RF transistors in compact generators for miniature microwave drills. The paper reviews the availability of high-power microwave transistors and their applicability for various microwave heating systems in general, and for microwave drills in particular. The current development status of the microwave-drill technology is reviewed, and miniature microwave-drill schemes are introduced. The latter are developed also for medical applications such as microwave drilling of bones. The experimental setup of a transistor-based miniature microwave drill is described, and recent experimental results of drilling 1-mm diameter holes in various materials are presented. The feasibility of compact solid-state microwave generators as substitutes for low-power magnetrons is discussed, and the consequent new design possibilities for microwave drills are presented.

INTRODUCTION
The microwave drill[1)] was presented in 2001 as a novel method of drilling into hard non-conductive materials by localized microwave energy[2)]. The drilling head consists of an open-end coaxial applicator that focuses the radiation into the drilled region. A thermal runaway process is induced intentionally in the focal point in order to enable the soft penetration of the drilling bit into the radiated volume, hence creating the hole. The microwave-drill schemes presented so far where based mostly on magnetrons. However, delicate microwave-drill applications like drilling of bones[3)] or local doping of solid-state wafers[4)] require more gentle and better controlled microwave sources.

Solid-state high-power transistors are commonly used in communication systems. The laterally-diffused MOS (LDMOS) power transistor has become the technology of choice in the last years for wireless base-station applications due to its high gain, efficiency and power, and excellent linearity. Advancements in the development of wide band-gap devices, like Gallium-Nitride (GaN) and Silicon-Carbide (SiC) transistors, have made them appealing as well for communication purposes. Their wider band-gap allows a higher operating voltage due to the higher breakdown threshold. These devices have larger area for given impedance, hence allowing larger RF currents and higher power. Typically, the Silicon LDMOS technology has achieved an output power over 300W with 45% power-added efficiency (PAE) at 900MHz, and 240W with 25% PAE at 2.1GHz; the GaAs FET technology has exceeded 320W with 57% PAE at 2.14GHz; SiC MESFET's have yielded output power of 120W with at 3.1GHz, and GaN HFET's have demonstrated 230W at 2GHz. These technologies are aimed at 300-W base-station transmitters in the frequency range of 1.7–2.2GHz in a target cost of less than 1$/Watt. All these advancements, and in particular the higher power and PAE, and the lower cost, increase the feasibility of solid-state microwave generators for heating purposes[5)].

In this article we present the use of high-power transistors in microwave local heating applicators of a microwave-drill type. Apart from drilling, this applicator enables local heating, melting and even evaporation of various materials (e.g. glass, silicon, and ceramics). The paper presents experimental and theoretical results of transistor-based microwave drilling, and discusses in more general the solid-state technology applicability for microwave heating.

EXPERIMENTAL SETUP
The solid-state microwave generator employed in the setup shown in Fig. 1 consists of an LDMOS common-source amplifier with a closed-loop feedback[5)]. The microwave oscillations are generated when both phase and amplitude oscillations' conditions are satisfied. In our microwave-drill

experiments, we use Freescale's MRF6S21140, 140-W power transistors with ~14dB gain. The electrical length of the feedback line is tuned by stretched coaxial sections to satisfy the oscillations' condition in the frequency range of 2.1–2.2 GHz. The feedback is implemented by a 10-dB coupling of the amplifier output to its input port, thus the rest of the RF output power (~125 W at 2.16 GHz) is available as a useful power, e.g. for the microwave-drill applicator, with an efficiency of ~48%. The circulator and the dummy load isolate the oscillator from the output mismatch reflections.

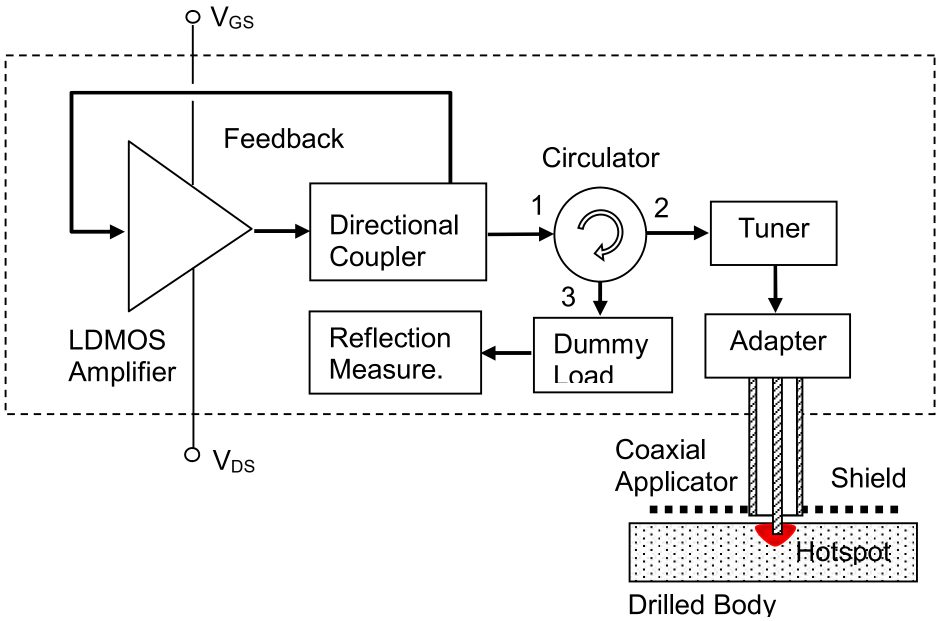

Figure 1. The transistor-based microwave drill scheme.

The drilling head consists of an open-end coaxial applicator with an extendable inner electrode that functions also as the drilling bit[1)]. The safety requirements are satisfied by a proper shielding. This experimental setup enables measurements of the incident and reflected power, the drilled depth, and the temperature (measured by an IR thermal sensor underneath the drilled region). The microwave output power is adjusted in the range of 5–120 W by varying the transistor's drain bias voltage, V_{DS}, in the range of 5–28V with a constant gate bias V_{GS} of 7V. Figure 2 shows the available output power control by the transistor's drain bias voltage as employed in our setup.

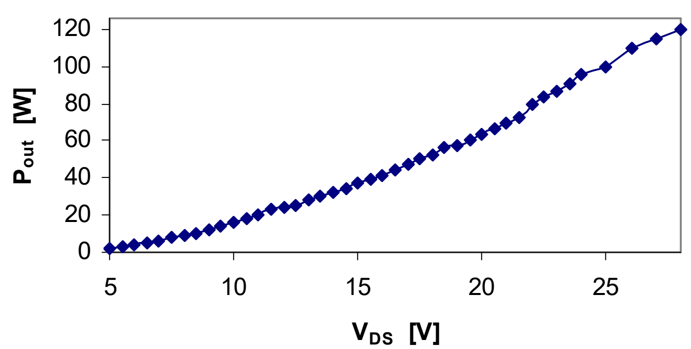

Figure 2. The oscillator available output power control by the transistor's drain bias voltage.

The miniature microwave drill presented here is a compact device (~10-cm long) operating at 28 V_{DC}. It can be easily controlled and integrated with other systems for a variety of applications apart from drilling.

EXPERIMENTAL RESULTS

The miniature transistor-based microwave drill has been tested in this experiment on two main representative materials, namely ceramic tiles and Ertalon-6© plastic. Figure 3a shows a 1-mm diameter, 5-mm deep hole in a ceramic tile drilled by the miniature microwave drill with a 100-W input power generated by the LDMOS oscillator shown in Fig. 1. Figure 3b shows the relative power reflection at a constant tuning setting. The microwave-drill load impedance varies abruptly during the hotspot excitation hence the power reflection is reduced from ~0.95 to ~0.05 for a short time after 5 s in this run, and then increases back and stabilized at ~0.5. This result shows the need for a rapid adaptive impedance matching in order to increase the microwave drilling efficiency.

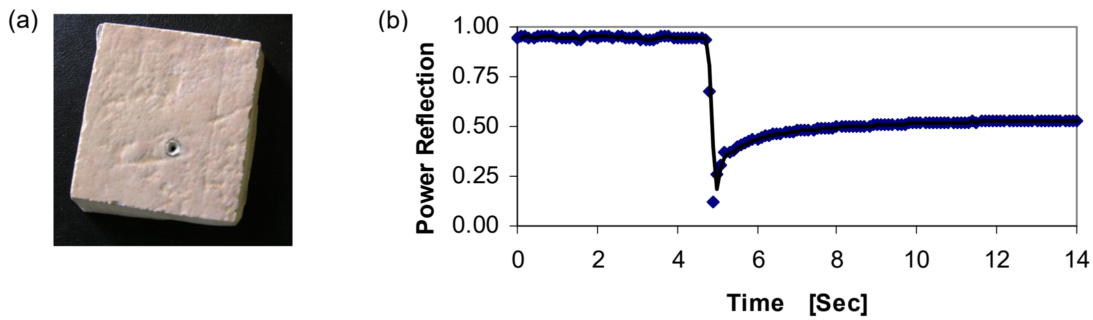

Figure 3. A 1-mm diameter hole made by the 100-W input miniature microwave drill in a ceramic tile (a) and the relative reflected power during the drilling process (b).

Figure 4a shows a 1-mm diameter hole in an Ertalon-6© plastic slab by a 25-W input power applied to the miniature microwave drill. The 9-mm deep hole is done in ~15 seconds in this case. A longer operation leads to evaporation and widening of the hole.

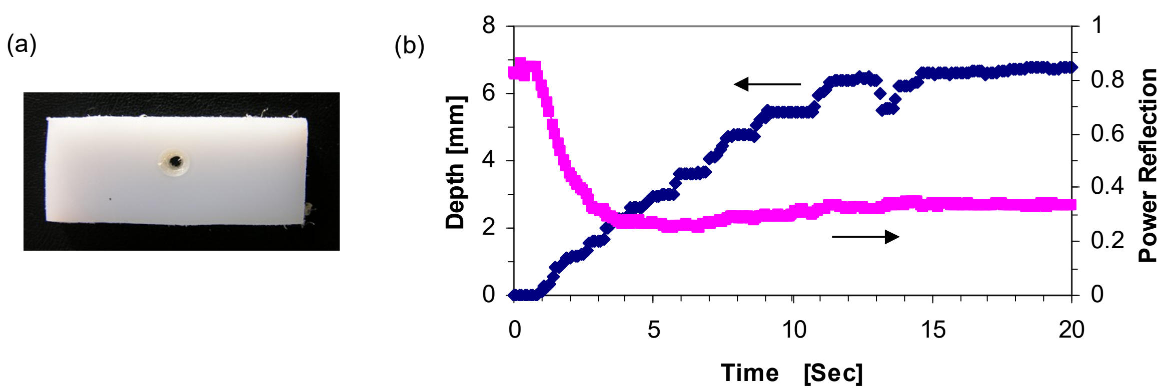

Figure 4. A 1-mm diameter hole made in an Ertalon-6© plastic slab by a 25-W input power applied to the miniature microwave drill (a), and the relative reflected power during the drilling process (b).

These typical results demonstrate the capabilities of the miniature microwave drill in making ~1-mm diameter holes of up to ~8-mm depth in various materials.

DISCUSSION

The feasibility of a miniature transistor-based microwave drill has been demonstrated in this study using a 140-W LDMOS transistor imported from the cellular base-station technology. The ceramic tile experiment (Fig. 3) demonstrates how the microwave-drill focusing effect enables reaching a temperature of >800°C in a ~1-mm diameter hotspot within a few seconds by only ~100-W applied.

This effect was verified by a numerical FDTD simulation[2)] for microwave local heating by the microwave drill apparatus in mullite, in conditions similar to the experiment presented in Fig. 3. The simulation results shown in Fig. 5 for a 100-W input power demonstrate the creation of a hotspot that exceeds 1200°C in ~6 s and the corresponding self-impedance-matching during the heating process.

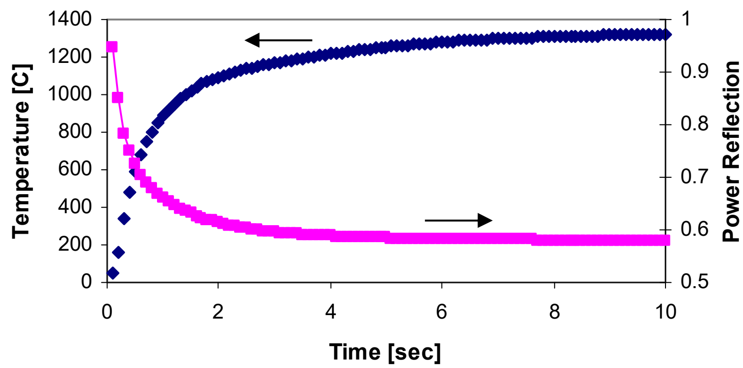

Figure 5. FDTD simulation[2)] results for mullite local heating by a 100-W input microwave drill.

The controllability and the compact size of the miniature transistor-based microwave drill scheme presented here may be useful in various fields, including medical applications and in particular drilling of bones in orthopedic operations[3)]. The concept of miniature microwave drilling can be extended also to characterization of materials by probing their localized responses in wide ranges of local temperatures.

In view of the advancements in cellular technologies, miniature solid-state microwave heaters seem feasible in the near future also in power levels above 100W. Such solid-state generators have several advantages over magnetrons operating in the range of few hundred watts. Solid-state generators are significantly smaller, and can be integrated in arrays for larger power and for improved radiation patterns. They do not require high voltage power supplies, and can be operated at lower voltages (e.g. $28V_{DC}$). Furthermore, the solid-state generators are more coherent than magnetrons, they are frequency tunable (e.g. by varying the feedback length in the scheme shown in Fig. 1), and their output power is controllable (as in Fig. 2). On the other hand, magnetrons are still considered to be more reliable and rigid sources, with less sensitivity to load impedance mismatch, larger efficiency, and lower cost. Therefore, the solid-sate generators are considered mostly for delicate microwave heaters like the miniature microwave drill in power ranges up to ~300 W.

ACKNOWLEDGEMENT

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REFERENCES

1) E. Jerby, V. Dikhtyar, O. Aktushev, and U. Grosglick, *Science* **298** (2002) 587-589; For more publications and patents, see www.eng.tau.ac.il/~jerby
2) E. Jerby, V. Dikhtyar and O. Aktushev, *Jour. Appl. Phys.* **97** (2004) 034909.
3) Y. Eshet, R. Mann, A. Anaton, T. Yacoby, A. Gefen, and E. Jerby, *IEEE Trans. Biomedical Eng.* 53 (2006) 1174-1182.
4) E. Jerby, P. Livshits, A. Shahadi, V. Dikhtyar, and A. Inberg, in these Proceedings.
5) E. Schwartz, A, Anaton, D. Huppert, and E. Jerby, *Proc. IMPI 40th Ann. Int'l Microwave Symposium* (2006) 246-249. https://www.eng.tau.ac.il/~jerby/Transistor_based_microwave_heater_Jerby.pdf