Transistor-Based Microwave Heaters

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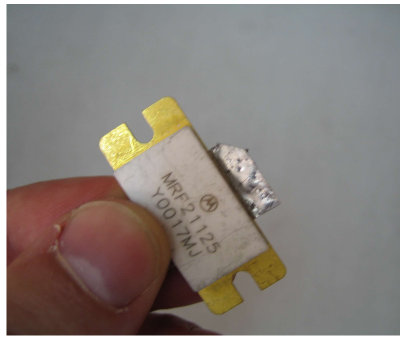
Outline:

- Introduction
  - Solid-state microwave ovens – pioneering studies.
  - High-power RF transistors available today.
- Transistor-based miniature heater
  - Application for biological tests (green-fluorescence protein).
  - Frequency control as a means for an adaptive impedance matching.
  - Active applicator and near-field radiator.
- Open-end applicator (miniature microwave drill)
  - Local melting and erosion of plastic, marble, and glass by transistor-powered applicators.
- Discussion

Microwave Tubes vs. Solid-State Devices

	RF Transistors	2.45 GHz Magnetrons
		
Power	< 150 W	>300 W
Efficiency	< 40 %	>60 %
Cost	>1 $ / W	<0.1 $ / W
Voltage	< 60 V	4 kV
Weight	~0.5 g / W	~5 g / W
Spectral purity	Good	Poor

Transistor-Based Microwave-Oven History

1969 Erwin F. Belohovbek, "Solid state microwave oven,“ RCA No. 812, Jan. 1969.

1971 Bruce R. McAvoy, “Solid state microwave oven,” US patent 3,557,333.

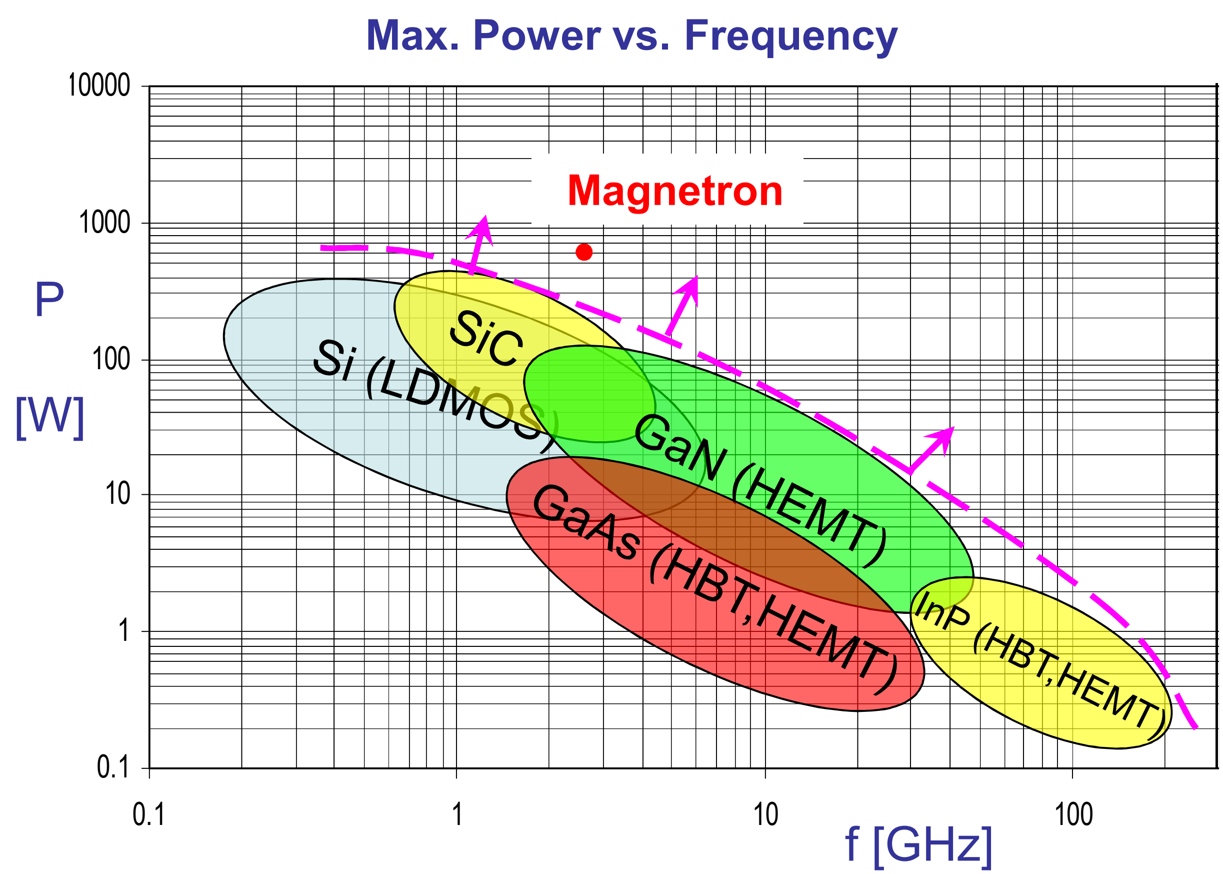
1979 A. Mackay, W. R. Tinga, and W.A.G. Voss, “Frequency agile sources for microwave ovens,” J. Microwave Power 14(1), 1979. [Frequency tuning control as a means for an adaptive matching to varying load].

1986 W.A.G. Voss, “Solid state microwave oven development,” J. Microwave Power. [Transistor near-field radiator arrays at 915 and 2,450 MHz].

Conceptual advantages

- Adaptive matching by frequency tuning, narrower spectral line width.
- Low-voltage operation, smaller size and weight.
- Modular design by combining radiating elements (power summation).

Advanced RF Transistor Technologies



LDMOS - Lateral Diffused Metal-Oxide Semicond.

HBT - Hetero-Junction Bipolar Transistor

MESFET - Metal-Semicond. Field-Effect Transistor

HEMT - High-Electron Mobility Transistor

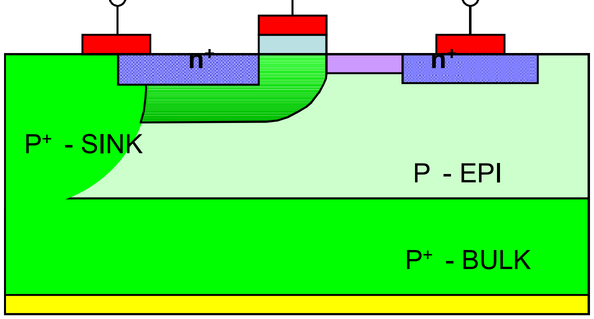
Silicon Carbide Technology -

- Better thermal conductivity than Silicon (4.9 vs. 1.5 W/cm-K).
- Wider band-gap (3.0 vs. 1.1 eV) and higher breakdown field.
- Better immunity but complicated fabrication, defects, etc.

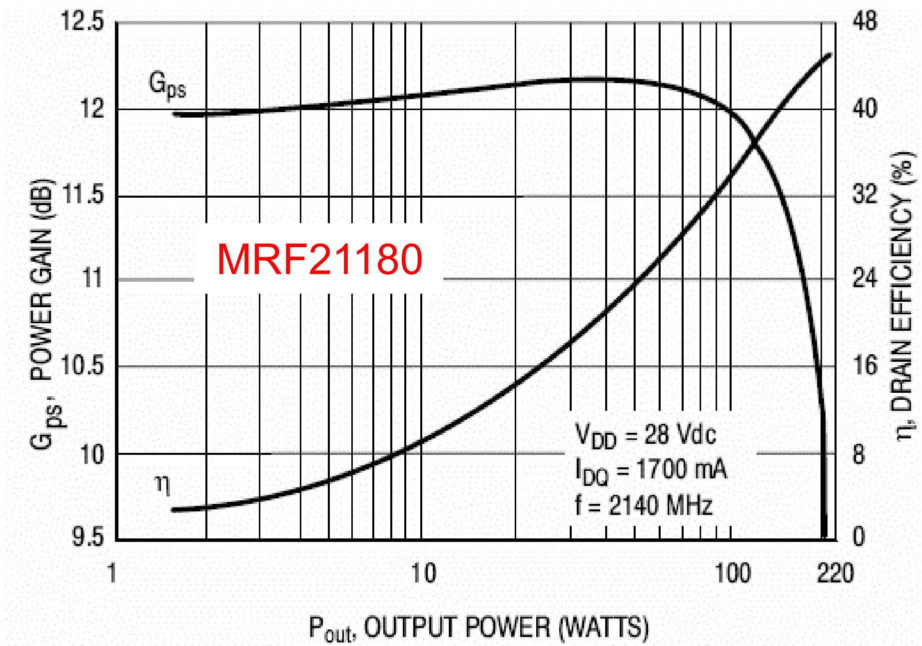
The market needs 300-W transistors @ 1.7-2.2 GHz and < 1 $ / W for cellular applications.

Silicon LDMOS Transistors

- Mature and reliable fabrication technology.
- Monolithic integration with control circuitry.
- 28-Volt operation, ~100-W output, >30% efficiency @ 2.45 GHz.
- Sensitive to electrostatic charge and to reflected waves.
- Commercially available, widely used in cellular base-stations.
- Relatively low-cost (~1 $ / W).
- **A practical choice for miniature heaters.**



Heat sink



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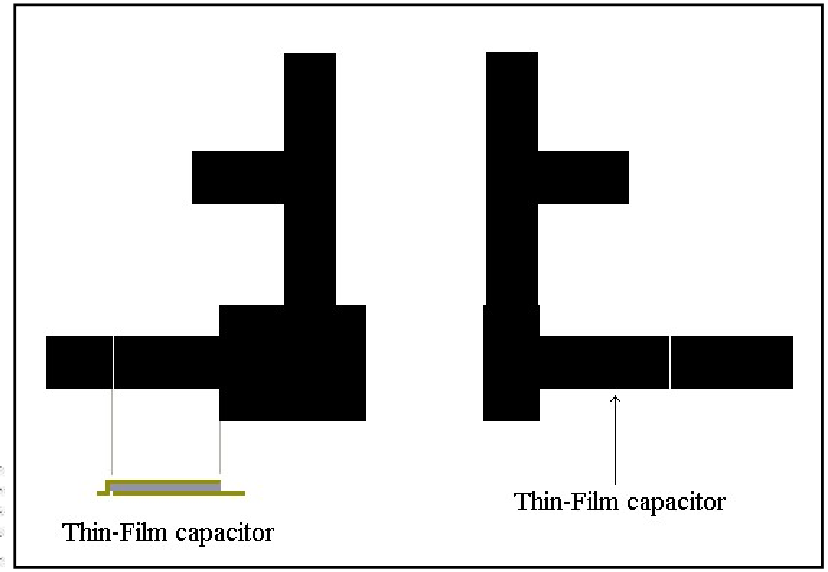
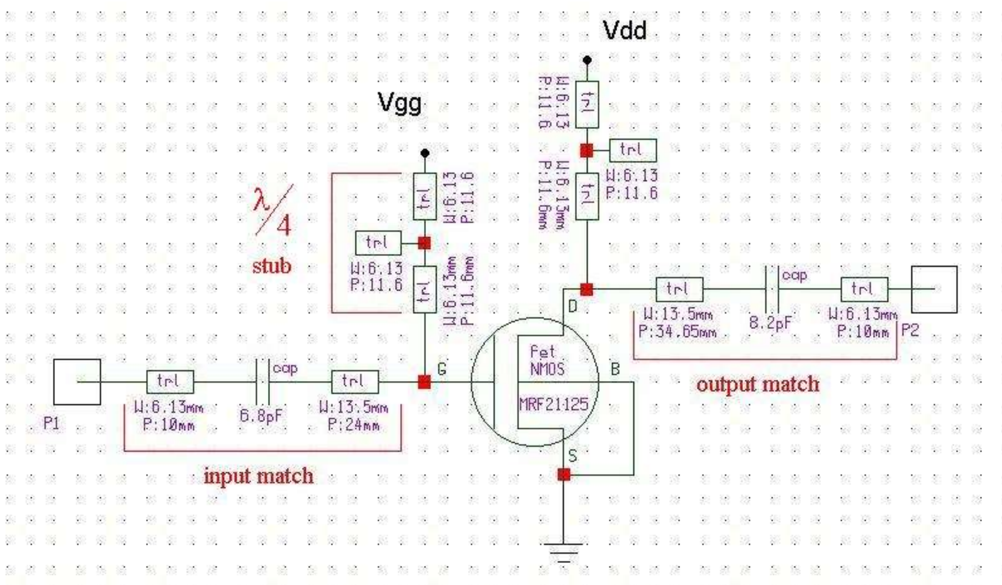
Design Consideration

- Input and output impedance matching.
- Micro-strip transmission line design.
- Isolation between RF and DC paths.
- Stability.





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Examples of Laboratory Solid-State Microwave Sources

EMPOWER RF SYSTEMS, INC.

Solid State General Communication Power Amplifier

GCS4Q5EIN

1800 – 2200 MHz / 60 Watt

The GCS4Q5EIN (SKU # 4020) is suitable for high power PCS and UMTS linear applications. This amplifier utilizes advanced silicon LDMOS power devices that provide high gain, wide dynamic range, low distortions and excellent linearity. Exceptional performance, long term reliability and high efficiency are achieved by employing advanced broadband RF matching networks and combining techniques, EMI/RFI filters, machined housings and qualified components. Empower RF's ISO9001 Quality Assurance Program assures consistent performance and the highest reliability.

Shown with Option Package 05

AET ADVANCED ELECTRONICS TECHNOLOGY http://www.aetjapan.com

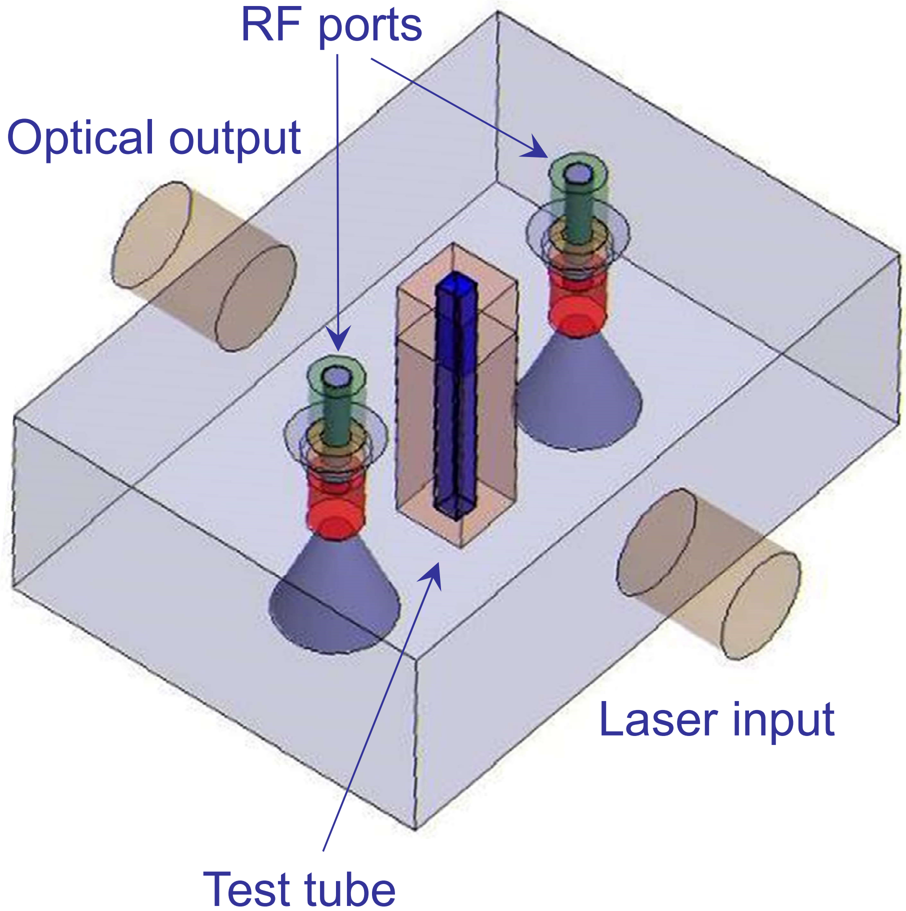
Sairem GMM 012

120 W @ 2.45 GHz

Model	APRF100-04-2450
Frequency	2450MHz
Input signal	CW/pulse
Output power	100W (min.)/@12.5W – 100W variable
Input/Output impedance	Nominal 50Ω

Miniature Microwave Heater for Biological Tests

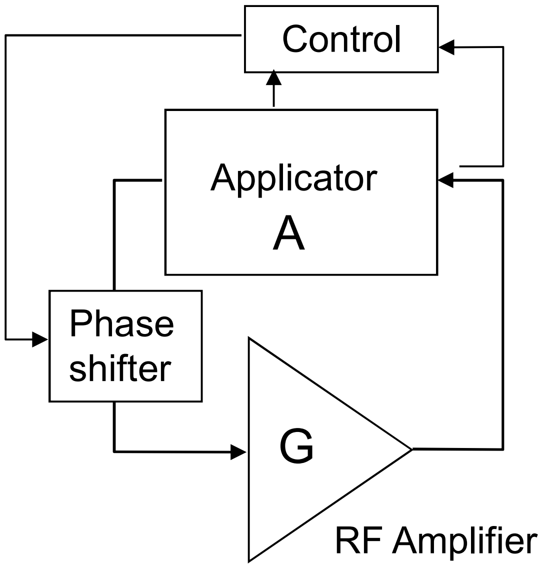
- An applicator for Green-Fluorescence-Protein (GFP) studies*.
- Non-thermal microwave effect (could be significant to safety standards).
- CW and pulsed microwaves.
- Temperature control up to 40°C, to avoid the protein damage.
- The device shall be embedded in a large optical-biology laboratory setup.



* Hupert et al., Copty et al.

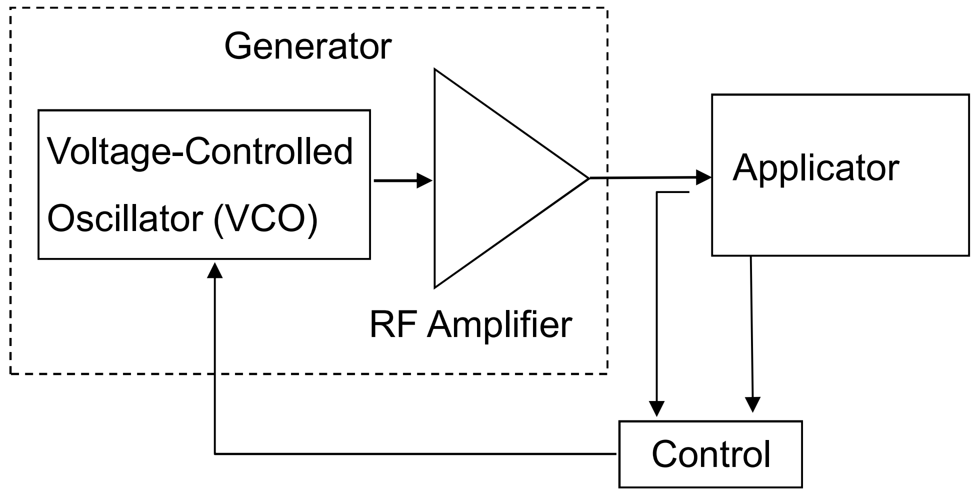
Active Applicator Schemes

Oscillator



- Self oscillations if $|GA| = 1$
  and $\angle GA = 2n\pi$
  (Barkhausen condition)
- Simple and compact design.

Amplifier

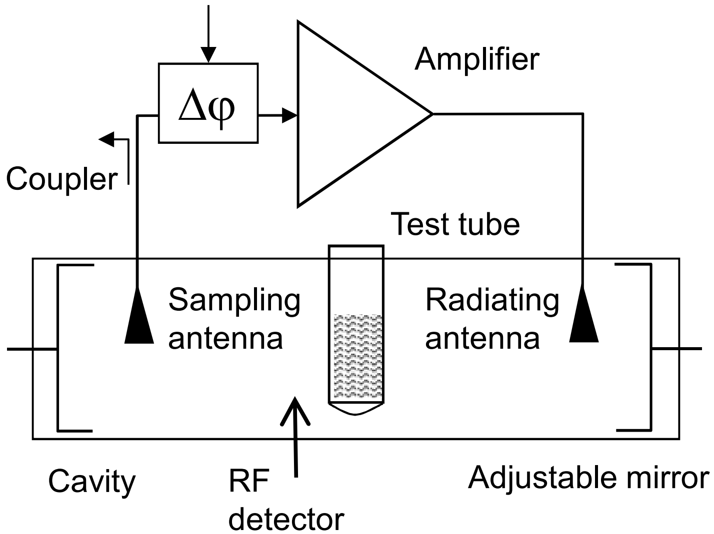


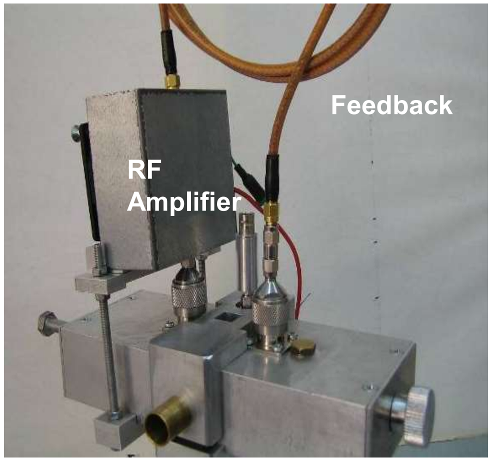
- Better control (a separable system).
- More expensive and larger.

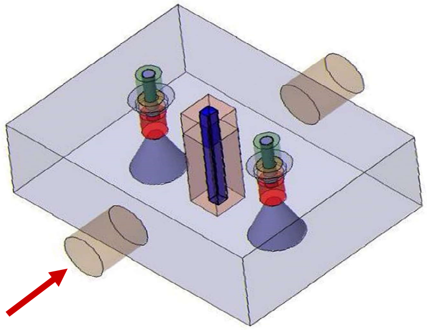
Test-Tube Microwave Heater - Oscillator Scheme

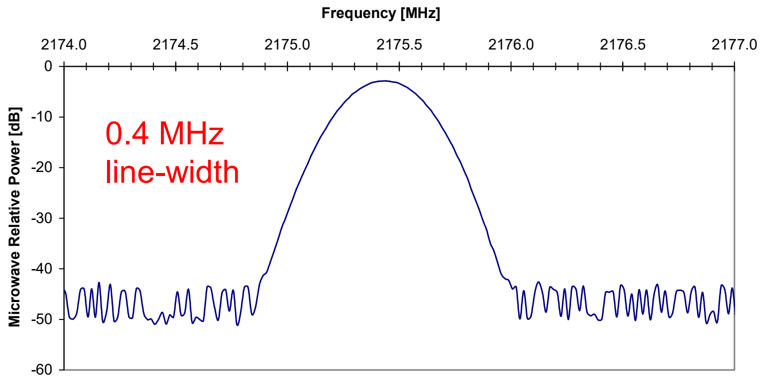
Heating a 3-cc test-tube to 40°C

at 5 Watt microwave power.

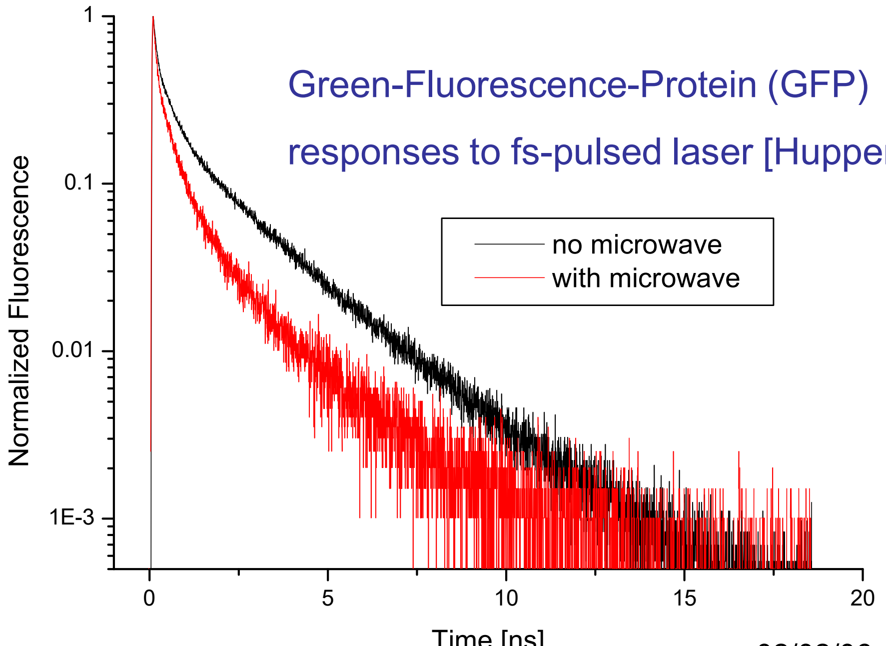




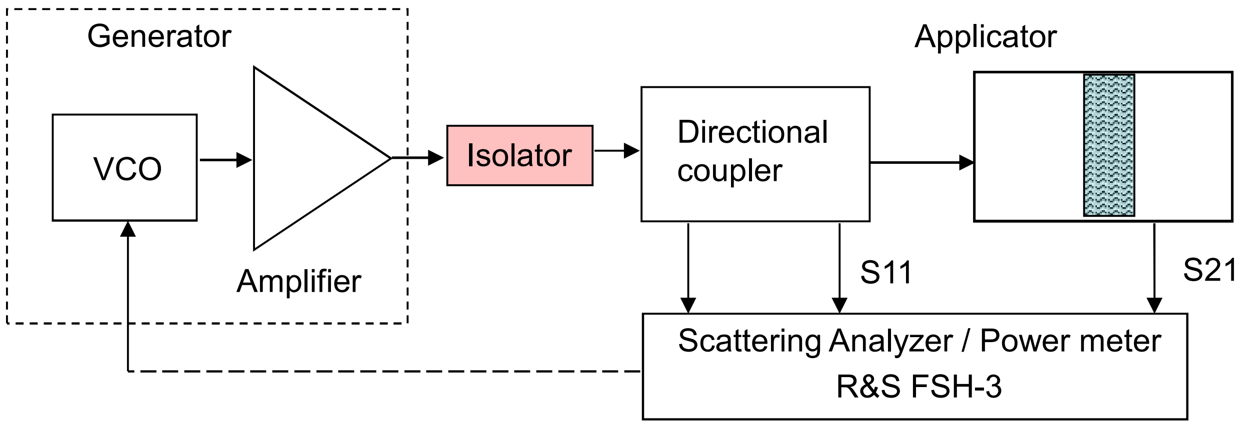




Green-Fluorescence-Protein (GFP) responses to fs-pulsed laser [Huppert].

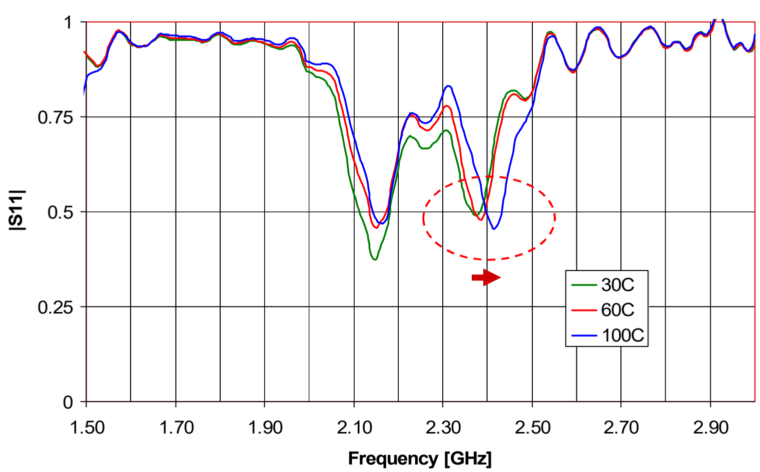


Amplifier Experimental Scheme



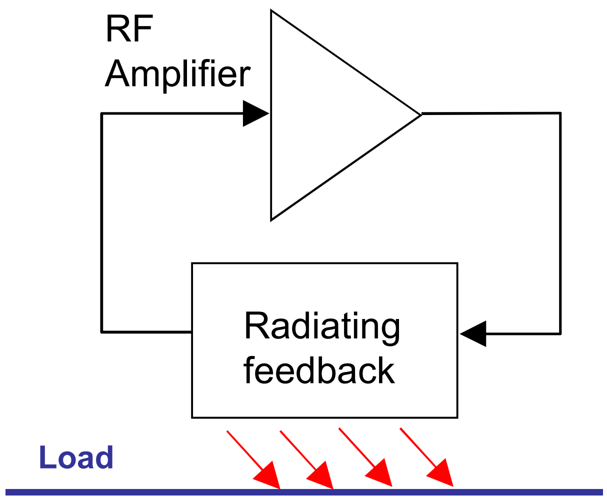
Heating a 3-cc test-tube from 23 °C to 100°C (boiling) at ~30 Watt effective microwave power:

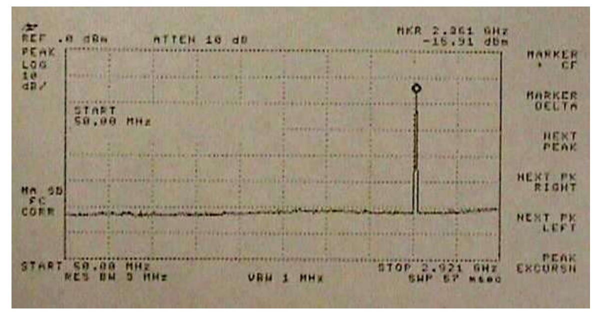
S11 vs. Frequency at Various Temperatures



- Due to temperature increase, the resonance frequency shifts by >50 MHz.
- A similar shift occurs due to different quantities.
- Frequency tuning during the heating process shortened the time to boil (TTB) by ~40%.
- An adaptive tracking of the resonance during the heating process may improve efficiency.

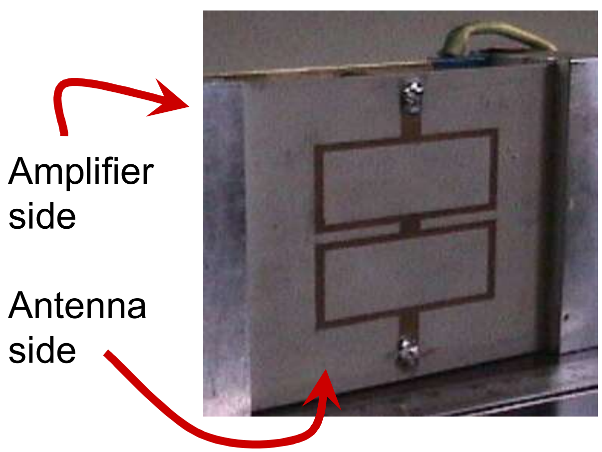
Active Applicator Module for Near-Field Ink-Jet Printer Dryer

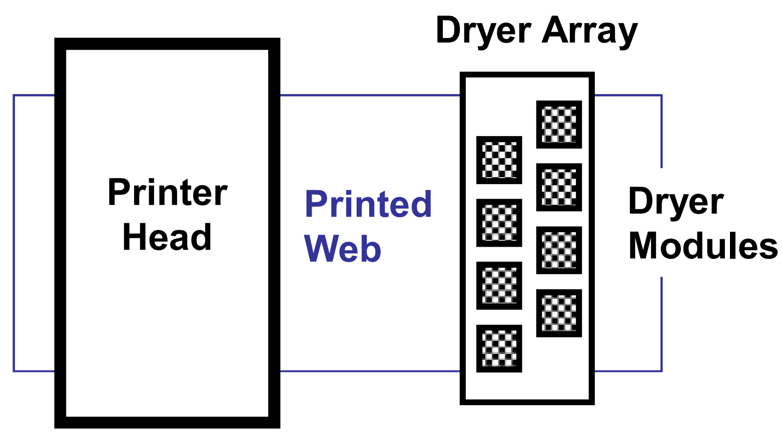




Coherent 5 Watt emission (in the year 2001)

A “leaky” strip-line Near-field antenna:



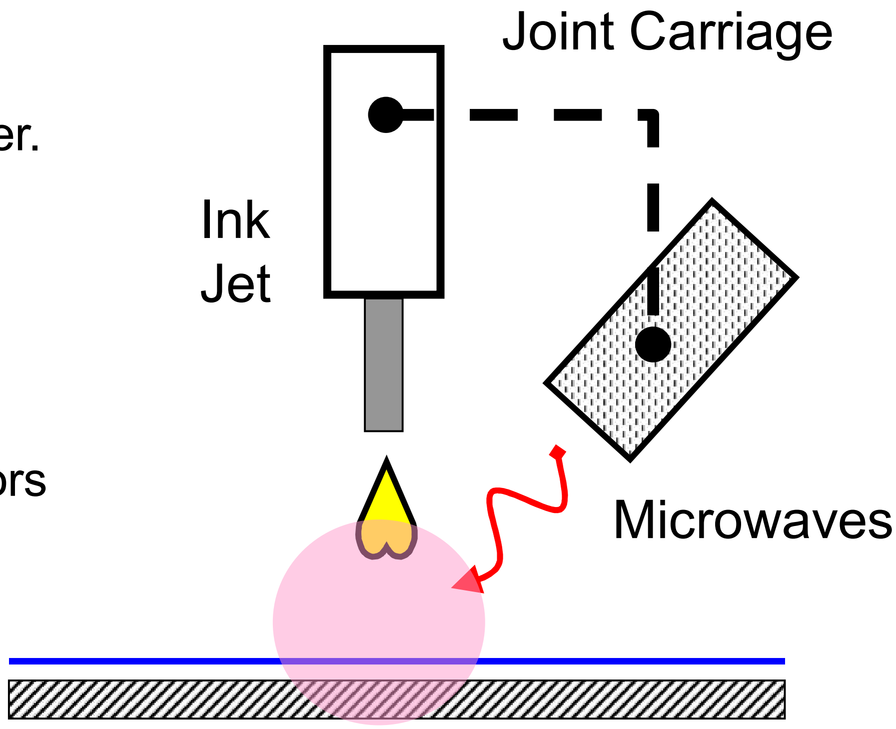


In 2002, a magnetron-based solution of a dual slotted waveguide was preferred for this project.

Miniature Microwave Dryer Head

Integrated with Ink Jet ?

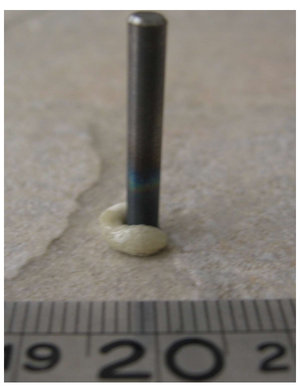
- Drop-on-Demand (DoD) ink-jet.
- Microwave-on-Demand (MoD) dryer.
- Synchronized with the drop.
- Compact scheme.
- Enhanced efficiency.
- Could be feasible with RF transistors (not with magnetrons).

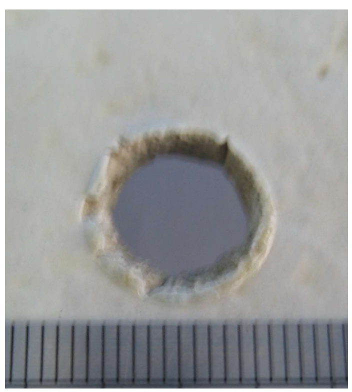


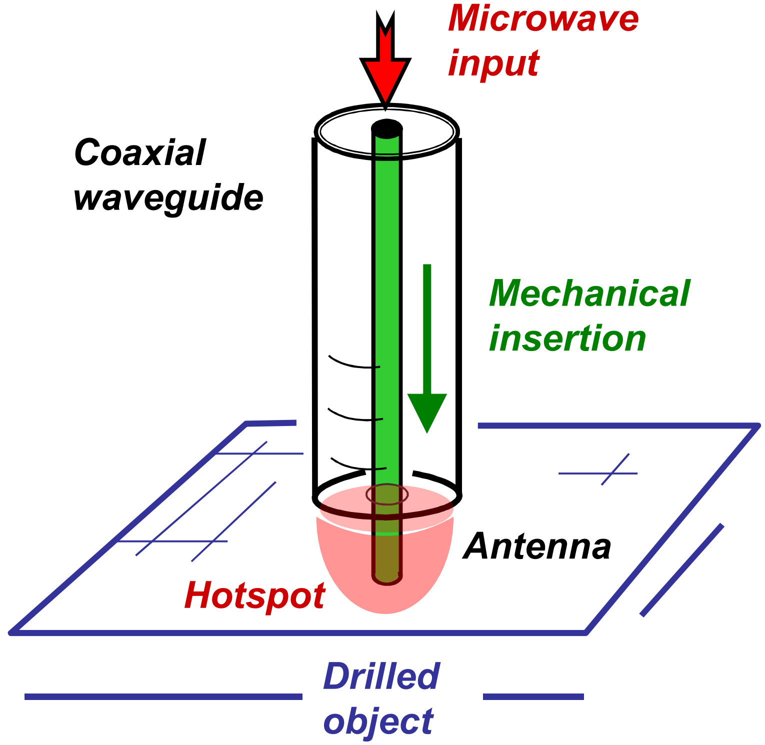
Application to the Microwave Drill

An Open-End In-Contact Applicator

Magnetron-based microwave drill

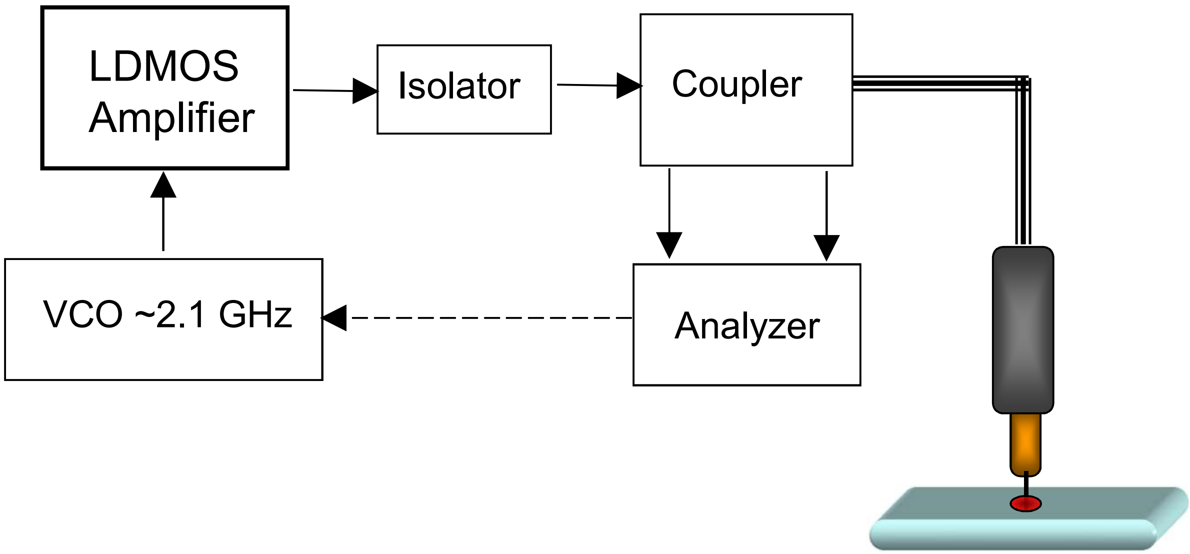






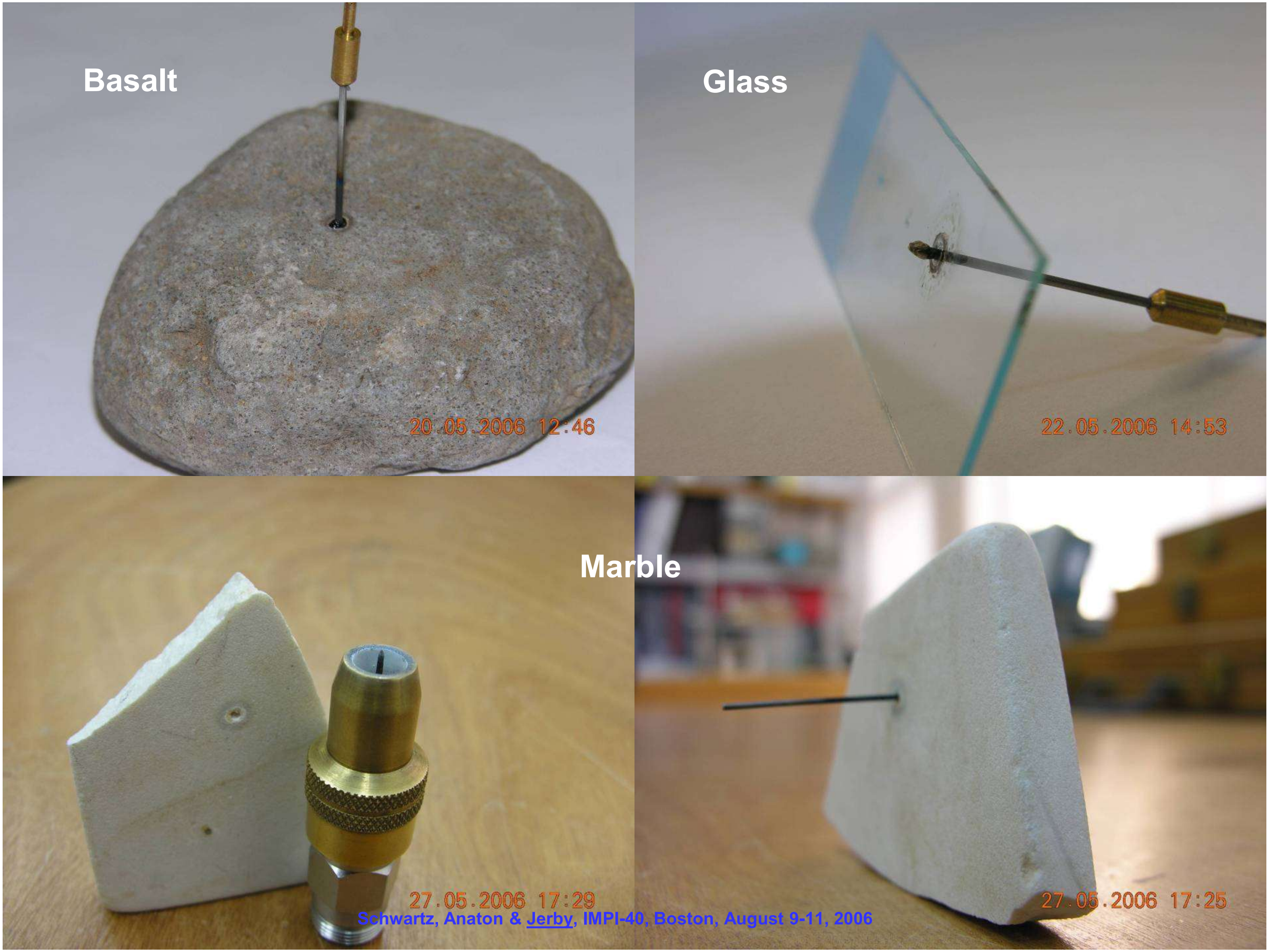
Transistor-based microwave drills ?

Transistor-Based Microwave-Drill Experiments

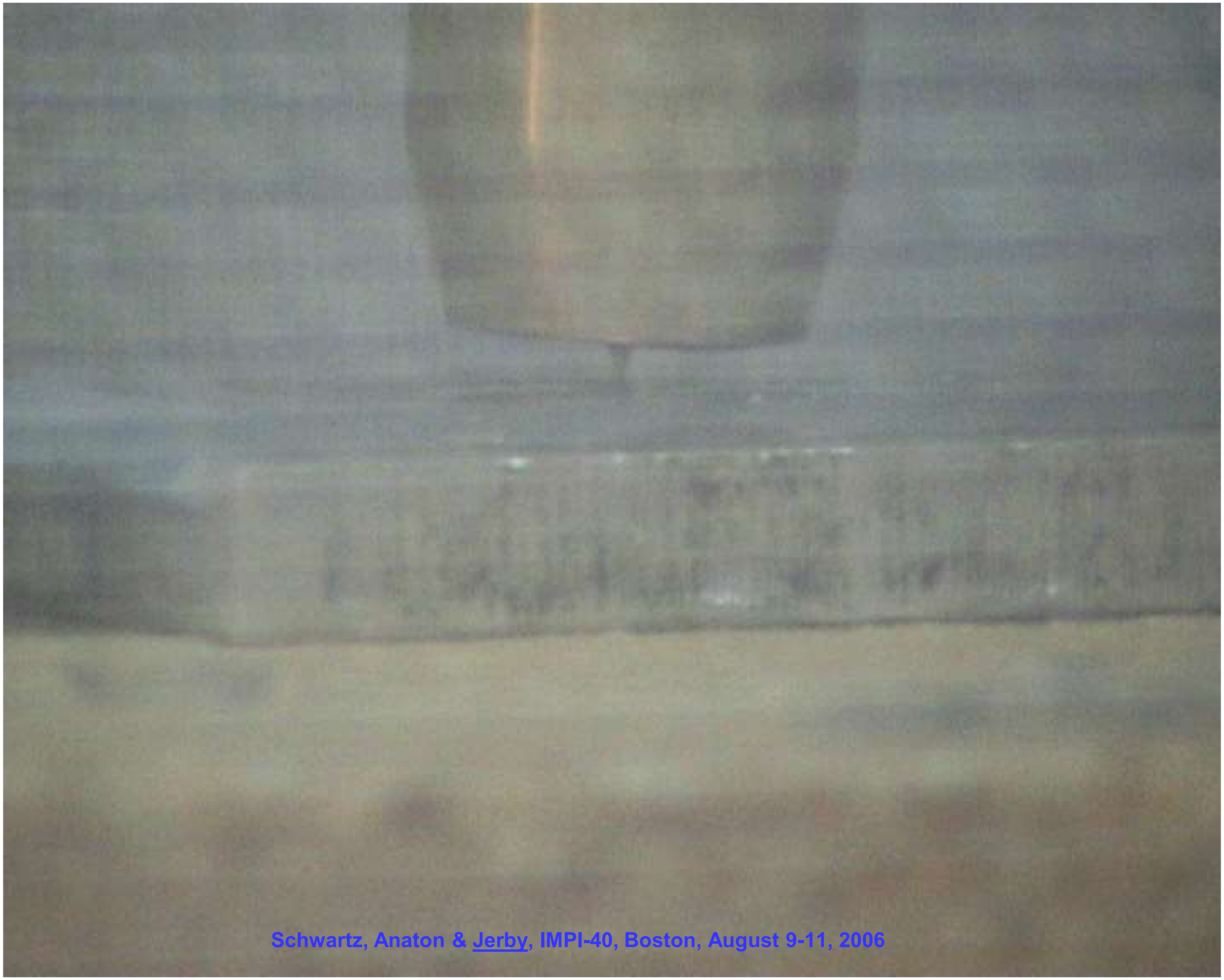


Material	P_{eff} before melting [W]	P_{eff} after melting [W]	TTM [sec]	Drilling speed [mm/sec]
Glass	17.8	34.5	<1	~1
Plastic	18.7	24.8	<1	~1
Marble	24.1	47.9	~3	~0.5

TTM – Time To Melt


Basalt
20.05.2006 12:46
Glass
22.05.2006 14:53
Marble
27.05.2006 17:29
27.05.2006 17:25

Transistor-Based Drilling in a Glass Plate



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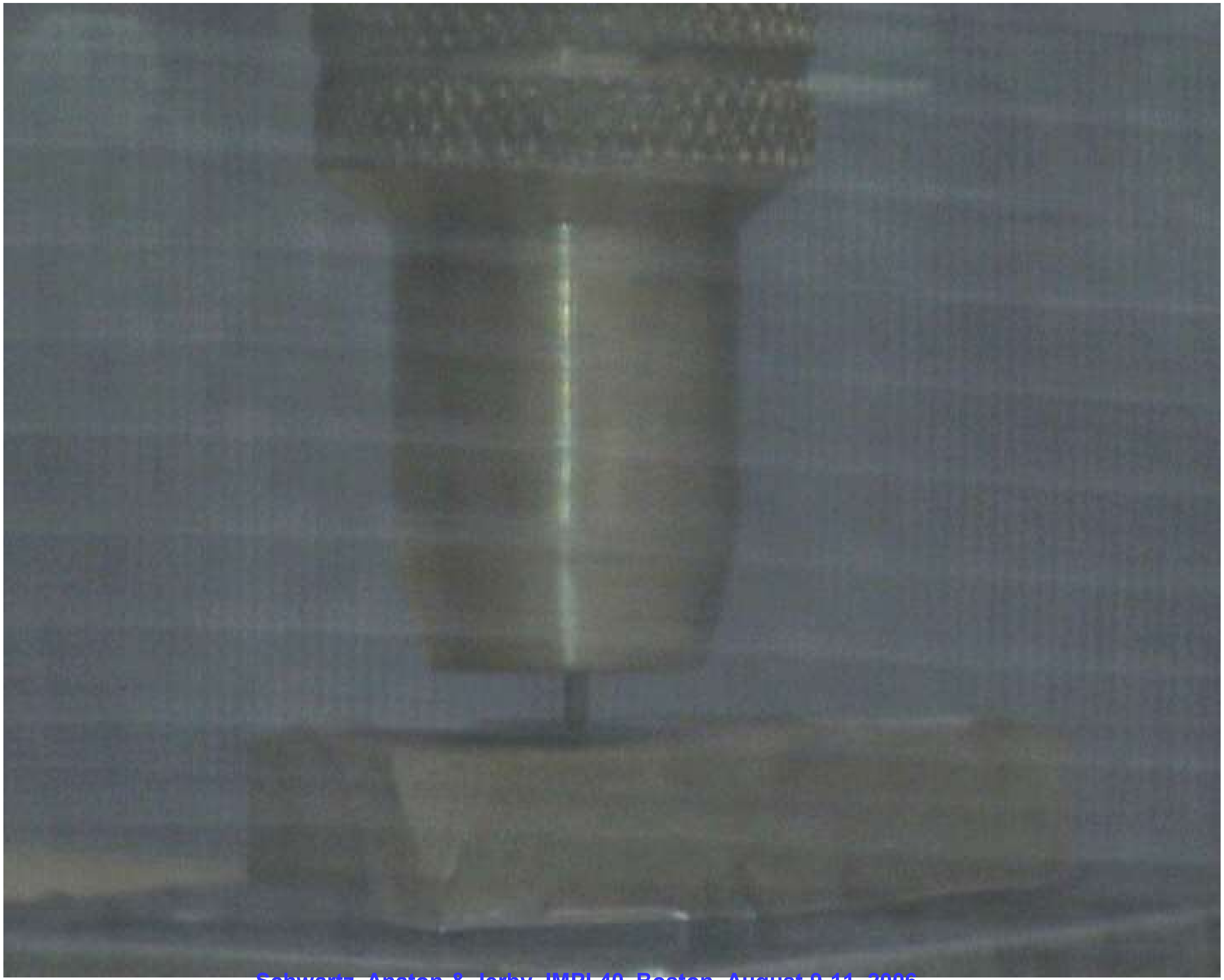
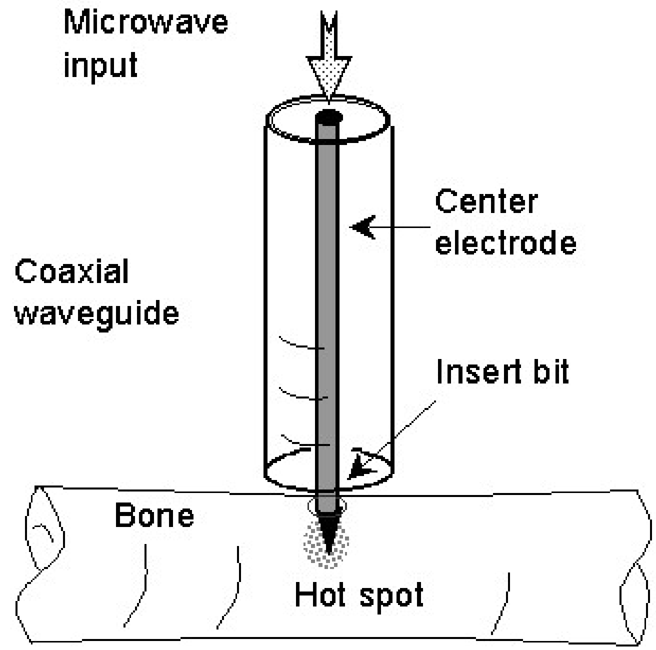
Transistor-Based Drilling in a Tile



Microwave Drilling of Bones

- No rotating / vibrating parts.
- Does not produce debris.
- ~100-W, 2-seocnd operation.
- Immediate fusion of crossing vasculatures.
- Less expensive than any laser drill.
- Next step – in vivo experiments.



Summary and Discussion

- There are needs for <200-W heaters, which can be satisfied by transistors.
- Solid-state microwave heaters are more coherent than magnetron, and their frequency can be tuned during the heating process to follow the load variation.
- Transistor-based microwave heaters are compact and controllable. They can be integrated in arrays, and with other electronic circuits.
- Following the radar evolution, the concepts of phased-array antennas, adaptive phased-arrays, and active-antennas, can be adopted for near-field microwave heating. These can be applied also for >200-W systems by power summation.
- Sensing the load response may enable an adaptive spatial power distribution and radiation-pattern synthesis.
- Future developments in communication-oriented technologies may open new possibilities for microwave heating as well.