Challenges of using Solid-State Sources for Microwave Cooking and Heating Applications

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***Abstract*— This paper outlines some of the challenges encountered when using solid-state sources for microwave cooking and heating applications. To aid this analysis, a cylindrical cavity resonator is characterised in terms of its impedance behavior under variable loading conditions, represented by volumes of water ranging from 0.05-0.12 litres. These variations, due to changes in volume and temperature of the load, are captured and deembedded to the device plane. Although circulators and high power loads are effective in protecting the device against such high VSWR conditions, these compoments are expensive, adding significant cost and due to associated loss, ultimately reducing available power delivered to the load within the cavity.**

For these reasons, it is importantg to consider a 'circulator-less' design, to highlight hostile loading environment within which transistor devices must operate, and which can ultimately limit the use of solid-state technologies for commercial applications.The importance of maintaining a satisfactory impedance match between the source and load is emphasized.

Index Terms — Solid-state, cylindrical cavity resonator, VSWR.

I. INTRODUCTION

Use of solid-State Power Amplifers (SSPAs) in domestic microwave heating applications is an area of growing interest for semiconductor device, for appliance manufacturers and consumers alike. The application includes the use of RF generated power to heat loads in resonant cavities, where the traditional way of generating power for these applications has been through the use of a magnetron. There are several advantages of using SSPAs over traditional magnetron based systems (Table.1) – replacing a large inflexible power generator with smaller, highly controllable sources offers the potential to enhance heating efficiency through power scaling and selective mode excitation.

Magnetron based technology first developed for radar applications in the early 1920-30's has been the technology of choice for these applications due its robustness, power generation capability and very low cost. With the evolution in semiconductor device technology and the emergence of new devices such as LDMOS, HVLDMOS & GaN, higher powers are now possible from a single solid-state device. NXP–MRF13750H, a 750W LDMOS power transistor at 900MHz, and Ampleon BLC2425M8LS300P, a 300Watt LDMOS power transistor for applications at 2.4-2.5GHz – ISM band, are examples of these evolving power levels. The potential to excite multiple modes over a wider bandwidth (~ 100MHz) is far greater with solid-state technology. Realsing this potential requires a coupling structure of an equal or wider bandwidth. The magnetron in comparison, emitting microwaves at 2.45GHz ± 10 MHz [1] has a limited bandwidth.

Table.1 Benefits of solid state microwave generation

Parameter	Comments
Power control	Controlled Temperature Profiles.
Frequency control - Bandwidth Selection	Ensure source continues to operate into optimally matched load, independent of load variations. Excitation of several modes, independently, in a multi-mode cavity
Phase control	Control heating uniformity through field pattern manipulation

SSPA's typically operate into a constant 50Ω load environment, ensuring a smooth transistion of power from generator to the load, and use a circulator and high power load at the output to protect the transistor against impedance mismatches and fault conditions.

The natural impedance environment presented by a resonant cavity is a function of the cavity dimensions but also the load; changes in volume, temperature and material dielectric properties result in different impedances being presented to the generator. Deviations from optimally matched loading conditions results in performance degradation and potential damage to the device. In this paper, the effects of cavity load variations are investigated and presented.

II. THE DEVICE UNDER TEST

Although for domestic heating applications, a multi-mode rectangular cavity is typically used, for the purposes of this study, a single mode-cylindrical cavity, designed to operate over the 900-960MHz frequency band is considered to simplifies analysis. This type of cavity provides a predictable environment where the electric and magnetic field distribution are easily determined and visualized.. A TM_{010} resonant cavity with a single dominant mode in the 0.9 GHz band was fabricated, with a feed port (P_1) comprising an N-type barrel connector and small loop antenna. The cavity is initially loaded with 0.085 litres of water held within a cylindrical quartz tube placed at the center of the cavity, where E field is uniform and at its strongest. The coupling structure comprising of simple loop antenna couples energy into the circulating magnetic (H) field within the cavity, and is adjusted in terms of its position and rotation to ensure critical coupling is achieved for the load used. The measurement arrangement shown in fig.1, is used to chracaterise cavity impedance behaviour. It comprises of a 10 W SSPA as a generator together with a circulator and high power load to protect the SSPA against high VSWR conditions. Forward and reverse power is monitored (with load variation) using a high directivity dual directional coupler and Keysight RPM2 – U2042XA USB peak & average power sensors. Changes in temperature are monitored through apertures in the top and bottom of the cavity using a pyrometer (Micro – Epsilon CT-SF22-C1) .

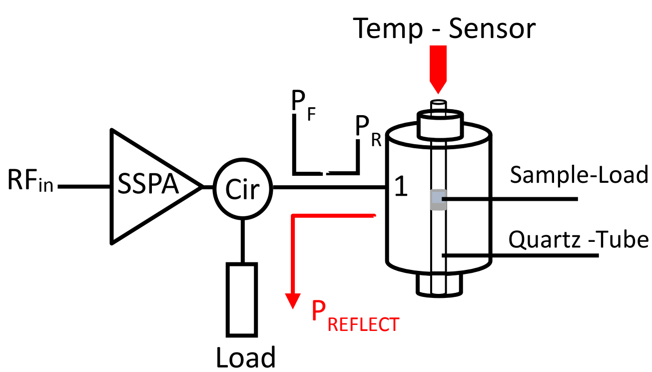
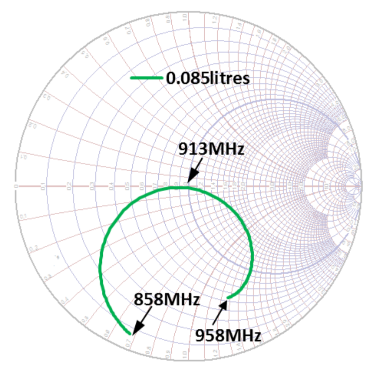


Fig.1. Single Port Measurement Set-up

III. Measurement Observations – Load Variations

From the measurement data, it is observed that the load (0.085litres of water) is critically coupled at 913MHz. Away from this optimal frequency point, the match deteriorates and the level of reflected power begins to rapidly increase. This is demonstrated by the measured refelction coefficient (S_{11}), forward and reflected power, and VSWR measurement data shown figure 2, where the reflected power measuremets follow the s-parameter response. The simple loop coupling has a limited bandwidth (~9MHz) with an acceptable level of match (S11 < -10dB). The VSWR measurement data shows a value of just above 1 at the critically coupled frequency (913MHz) indicating a smooth transfer of available power into the cavity and load. At this frequency of operation, the device operates safely however away from this point the value of VSWR rises (with increasing reflection coefficient) leading to a drop in power delivered to the load and due to high reflection, potential damage to the SSPA. A circulator and high power load is used at the output of the power transistor to protect it against these potentially hostile loading conditions.

The forward, reflected power and power delivery efficiency with a single loop coupling structure are summarised in Table 2; a 10W forward power results in a reflected power of 0.01W at the critical coupled frequency (913MHz), 0.1 W over the 912-915MHz) and 1W at the band edges (909MHz, 918MHz) with power delivery efficiencies of 99.99, 99 and 90 percent respectively. Outside of this bandwidth the levels of reflected power become unacceptable - performance degrades, device reliability is compromised in the absence of a circulator and high power load. An understanding of the load environment and reflected power levels helps select adequatley rated circultaor and high power load.



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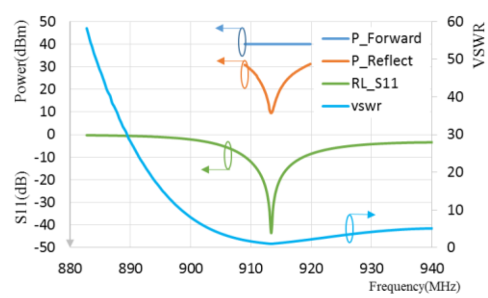

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Figure 2: - Critical Coupling at 913 MHz with a single loop coupling structure - 0.085 *l* of water.

Table.2 Single loop coupling measurements

Frequency	PFORWARD	PREFLECT	Delivery$_{(\%)}$
913MHZ	10	0.01	99.99
912-915MHz	10	0.1	99
909, 918MHz	10	1	90

Impedance variations due to changes in load (volume of water, 0.05-0.12litres) are investigated and presented on a smith chart, figure.4. An increase in the volume of water moves the impedance to the right of 50Ω – (*high Z*) and a decrease in volume moves the impedance towards the left (*low Z)*,. The impedance is reactive in nature and lies in the bottom half of the smith chart – indicating a capacitive load. Changes in volume affect both the real and imaginary componenets of the impedance

Reflection coefficient measurements (fig.5) show that an increase in the volume of water moves the frequency at which load is optimally matched to a lower value whilst a decrease in the volume of water moves the frequency at which the load is optimally matched to a higher value. This information can be used to develop an intelligent methodology (algorithm) to search for frequency points where the load is critically coupled. Inability to locate this new frequency presents an impedance mismatch at the device plane – exposing it to high VSWR conditions (fig.6) with severe implications on cavity efficiency and device reliability. This is undesirable and of concern for device and heating apparatus manufacturers.

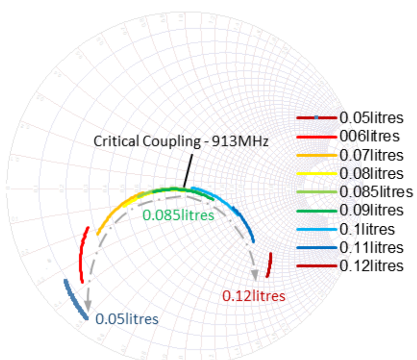


Figure 4:- Impedance variations due to changes in load 0.085-0.12 *l* of water – load.

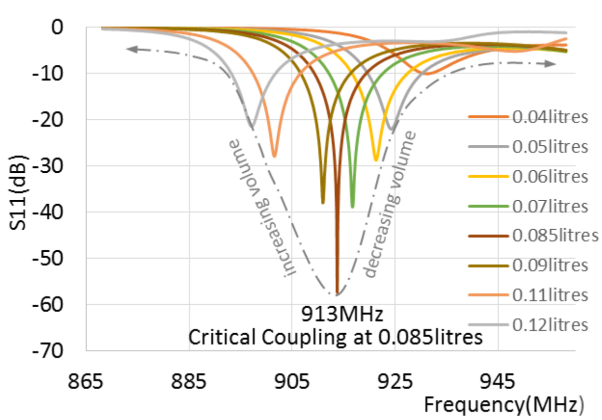


Figure 5:- Reflection coefficient measurements 0.085-0.12 *l* of water – load.

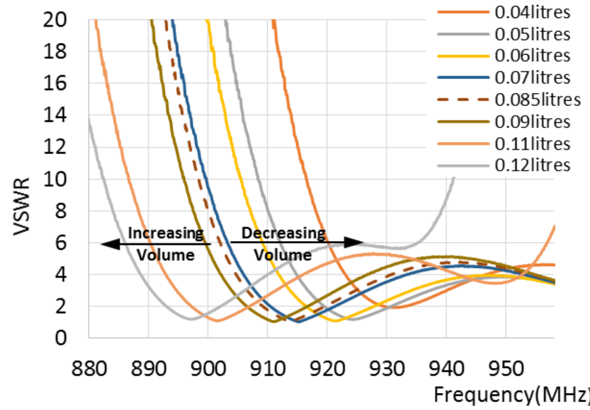


Figure 6:- VSWR measurements 0.085-0.12 *l* of water – load.

IV. MEASUREMENT OBSERVATIONS – TEMPERATURE VARIATIONS

The Dielectric properties of materials vary with temperature [7]. This affects the level of interaction between the material and the electromagnetic energy. In the case of non-ionizing radiation the electric permittivity (ε) describes the interaction of the electromagnetic waves with the material. Permittivity of a material is the ability to absorb, transmit and reflect electromagnetic energy. It is a complex quantity comprising of dielctric constant (ε') and dielctric loss factor (ε''). The real component ε' is related to the capacitance of the substance and its ability to store energy. The imaginary component is related to the absorption mechansims of energy dissipation. Measurements (Fig.7) show the load impedance sensitivity to temperature variations. A rise in temperature increases ion mobility due to dissociation of molecules leading to increased conductivity. At higher temperatures water absorbes and stores less of the available energy. This suggests that both dielectric constant (ε') and dilectric loss factor (ε'') reduce with increasing temperature. The resulting impedance variations with temperature (fig.8) shows that an increase in temperature has moved the optimum match to a new value located higher in frequency, matching at the existing frequency point has deteriorated. This information can be used to devlop a heating profile where the frequency of operation can be adapted to accommodate a detected rise in temperature.

It was found however that when using a single, static coupling loop, the operational bandwidth is limited (9MHz) and even relatively small (20°C) rises in load temperature can cause significant mismatch and high-reflective states to exist. Using this cavity, achieving optimal match by locating the new operating frequency beyond this 10MHz bandwidth and 20 degree temperature rise requires a physical adjustment of the coupling loop through electromechanical or other means, which can be problematic.

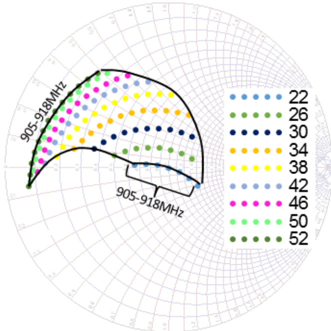


Figure 7:- Impedance variations due to changes in temperature 0.085 *l* of water – load.

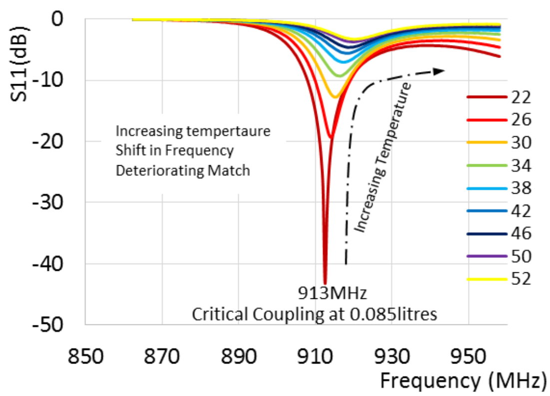


Figure 8:- Reflection coefficient measurements with temperature variations (°C) - 0.085 *l* of water – load.

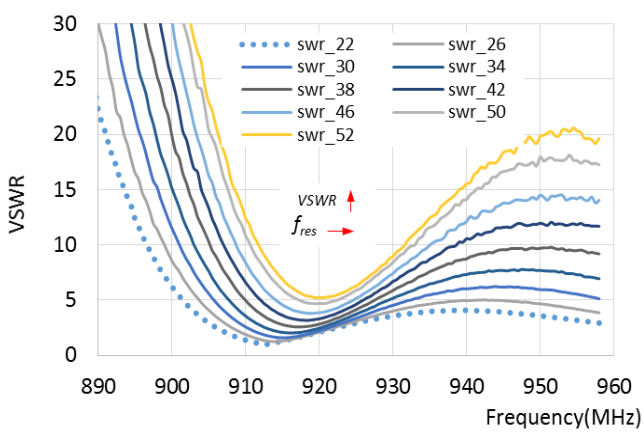


Figure 9:- VSWR measurements 0.085-0.12 *l* of water – load.

This is further shown in fig.9, where VSWR over a 30°C temperature range, deteriorates from 1.01:1 at 22°C for 913 MHz to 5.2:1 at 52°C for 920MHz. This has adverse implications on both device reliability and heating efficiency. Ensuring safe and reliable SSPA operation requires cavity impedance characterisation under variable loading conditions and with temperature variation.

These changes in the complex permittivity of the load require a physical re-alignment of the coupling loop to locate the new optimally matched state. This typically involves adjusting the mutual coupling into the magnetic field through a "back and forward" movement in the horizontal direction and a rotation around the axis until a matched, or critically coupled condition is located. Once matched, the coupling structure is locked in place and the process is repeated with a new load.. Efficient and reliable SSPA design requires a matched state, typically where return loss (S_{11}) is limited to 10dB and a vswr ~ 2:1 For this work, achieving this level of match is considered as the minimum requirement. Under normal operating conditions, values exceeding this are deemed unacceptable, however under extreme – "fault" conditions vswr values of up to 10:1, for short periods may be permited. As an exampole, table 2 listes VSWR values and operating conditions for the NXP-MHT1003NR3 power transistor. There is a general requirement for SSPAs to operate contiuously into a matched load, ensuring most of the available power is transferred to the cavity, maintaining heating efficiency whilst preserving device reliability.

TABLE 2
MHT1003NR3 – Load Mismatch/Ruggedness

F_{MHz}	S_{TYPE}	VSWR	P_{IN} (W)	V_{DS}	Comment
2450	CW	>10:1 at all Phase Angles	14 3dB Overdrive	32	No Device Degradation

V. SYSTEM OPTIMISATION

It has been identified through this work, that, in order to efficiently transfer solid-state generated power into a load within the single-mode resonant cavity, under variable loading conditions, some form of adaptive coupling approach is required. This may be through electromechanical adjustment of the coupling or through adaptation of the excitation frequency, or both, which is problematic.

An alternative approach is presented that involves modifying the single loop launch for extended bandwidth operation, without the need for mechanical adjustment. The impedance traces in fig.10 show comparisons between single loop and proposed wideband coupling approach. The impedance trace with the proposed approach encircles the 50Ω point. S-parameter data (fig.11) shows a return loss of better than -15 dB over a 70MHz operational bandwidth. The VSWR data in figure.12 shows that with the proposed approach, the SSPA will continue to operate efficienctly and safely into a matched load over the operational bandwidth, and without physical adjustment, which is in contrast to the high-Q single loop structure's limited operational bandwidth. The proposed technique is tolerant to load and temperature variations, which is important when considering isolator-less power amplifier designs for low-cost microwave heating applications.

With the proposed approach, a return loss of 15dB at the optimal frequency is equivalent to a delivery efficiency of 97%, compared to a return loss of 42dB and a delivery efficiency 100% when using the single loop. This loss in cavity efficiency (3%) is relatively small and worth sacrificing for the gains made in operating bandwidth. With the proposed approach the efficiency remains relatively constant (> 90% over 890-960MHz), it tapers off to below 50% with the single loop. This is illustretaed in the measurement data of fig.13 and 14.

Whilst the benfits may not be that significant for a single mode cavity, the concept has a huge potential for use in multi-mode cavity operation where many modes are scattered over a larger bandwidth. The approach can be adapted to achieve a desired response according to the nature and range of loads.

In the single mode cavity used, impedance variations due to load temperature rise can also be accommodated by setting the initial optimally matched frequency point at the lower end of the operational bandwidth (909MHz). As the temperature of the load increases, increasing the heating frequency ensures high delivery efficiencys and a continuous and acceptable match over the operating bandwidth, without physical realignment of the coupling structure. The measurement data (fig.15) shows that the approach is less sensitive to changes in temperature - S_{11} continues to be better than -10dB over a lage portion of the operating bandwidth.

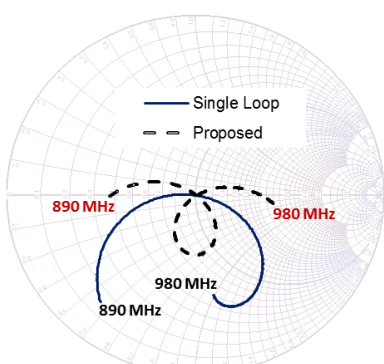


Figure 10:- Coupling with single loop and proposed approach - 0.085 *l* of water – load.

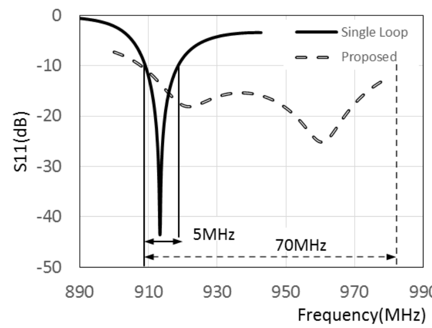


Figure 11:- Reflection coefficient measurements for the two coupling structures for 0.085 *l* of water – load.

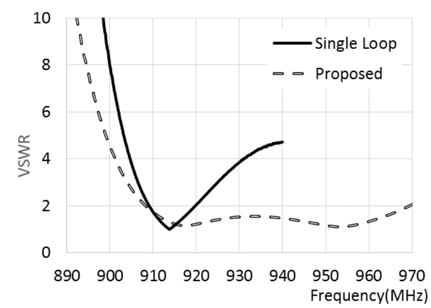
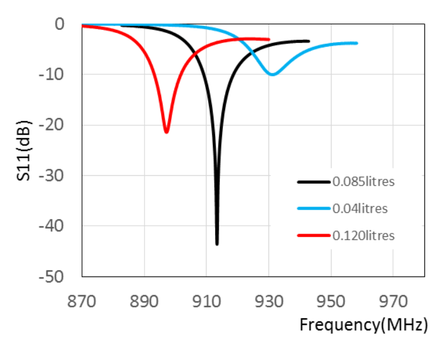


Figure. 12. :- VSWR measurements 0.085 *l* of water – load



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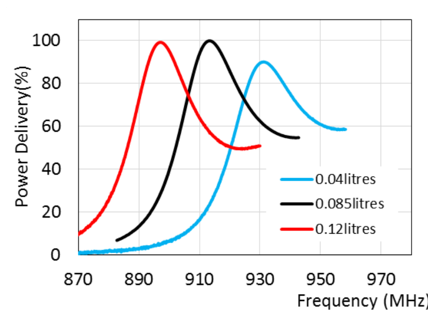

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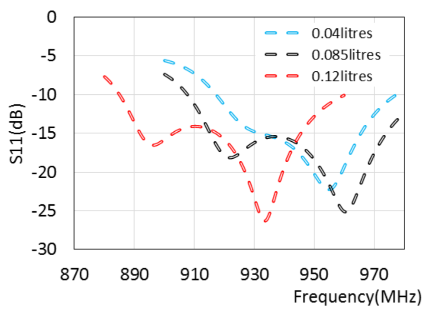
Figure 13: (a) - S_{11} and (b) - delivery efficiency - single loop - 0.085litres of water – load.



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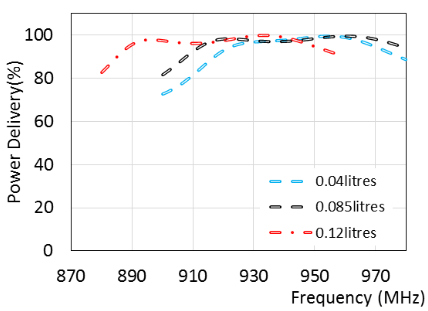

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Figure 14: (a) - S_{11} and (b) - delivery efficiency - proposed approach - 0.085litres of water – load.

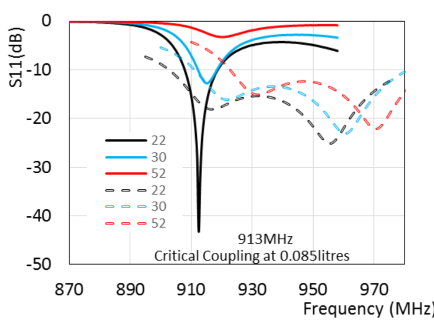

Figure. 15: S_{11} (single mode vs proposed) with temperature (22°C, 30°C and 52°C) - 0.085litres of water – load

VI. CONCLUSION

This paper presents the challenges of using SSPAs for microwave heating applications where the loading conditions are non-constant. To investigate this, a cylindrical cavity has been measured and its impedance behavior characterised under variable loading conditions of volume and temperature. It is demonstrated that such variations in load present different impedances at the generator plane leading to high reflective states, typically requiring a realignment (re-positioning) of the single loop coupling structure.

An alternative coupling structure is presented that demonstrates how it is possible to accommodate these changes over a wider bandwidth (70MHz) and adapt the SSPA frequency of operation to ensure a power delivery efficiency of greater than 97%. This is based on the reflection coefficient measurements of better than -15dB across the operational bandwidth. Using this technique and methodology, a power amplifier can continue to operate into a suitably matched load. The ability to constrain the match to within a vswr of 2.:1 ensures device reliability is not compromised, and raises the possibility of reducing cost of SSPA modules by removing the need for circulators and other associated hardware.

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