Two Port Cylindrical Cavity Enables Efficient Power Delivery-Through Power Combining & Scaling in a Solid State System

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***Abstract*— There is a growing interest in using solid-state, power transistor based technology as an alternative to traditional magnetron-based power generation in microwave cooking and heating. The power available from a single solid-state power amplifier 'module' is generally limited by the maximum power rating of the transistors used however, and in most cases, a single module will be insufficient. In such instances, power combining becomes a key requirement, and at power levels greater than 250 Watts, this becomes a difficult task to accomplish in a cost effective way at the printed circuit board level. The use of the microwave cavity itself for direct power combination offers a possible solution, but it requires the use of multiple ports and feed structures.**

The cavity's operational impedance environment is a function of loading conditions, where each of the power amplifier modules will experience potentially high or even very high voltage standing wave ratio's (VSWR) and must operate reliably and without performance degradation. Monitoring, capturing, managing and manipulating the impedance invironment at each of the excitation ports is a key requirement in ensuring safe, reliable and efficient operation. For solid-state solutions to be viable in mass-market applications, there is a need to reduce the PA module cost to the point where they can be competitive with the magnetron based systems. Removing the need for the traditional circulator will help achieve this goal, however high VSWR and device reliability remains a concern. In this paper, the impact on device reliability in a 2-port systems is considered and presented.

Index Terms—Microwave Cavity, Power Combining, Safe and Reliable Operation, Solid-State, VSWR

I. INTRODUCTION

The operational impedance environment presented to a solid state source by a microwave cavity is heavily influenced by the variable loading conditions determined by the cavity itself, together with parameters such as the sample's volume, dielectric properties, placement within the cavity as well as variations in sample temperature. A solid-state power amplifier (PA) coupling radio frequency (RF) power into such a cavity must therefore be able to tolerate these 'hostile' loading conditions without stress or failure. Semiconductor device manufacturers traditionally describe the reliability of a device in terms of the voltage standing wave ratio (VSWR) it can tolerate. A VSWR test involves stressing the power transistor to a known and typical worst case mismatch, for example, 10:1 - with phase rotation through 360 degrees for a specified amount of time. Failure or degradation can generally be identified through "before and after" performance measurements and also, in some cases, visual inspection. Visual inspection involves careful analysis of the bond wires and die structures under a high magnification microscope and usually requires de-capping of the device. Such analysis can determine if a failure has occurred, but not necessarily why, as it is difficult to identify the exact transistor operating conditions in terms of the intrinsic voltages and currents that will have caused the failure in the first place. As a consequence, the VSWR stated in the data sheet needs to be considered on an application specific basis.

LDMOS is considered as the technology of choice for these applications due to its high power capability and cost, however, for future applications, it is prudent to consider GaN on Si technology, where achievable power levels are similar to LDMOS. Due to higher breakdown voltages, this technology promises to offer improved reliability and potentially, simplified design. Typical mechanisms leading to device breakdown have been discussed in previous work [1]-[4] and are generally attributed to high reverse or reflected power, bias conditions, excessive input drive and excessive junction temperature. High reverse power leading to the generation of excessive peak voltage and current waveforms at the.intrinsic device plane are considered to be the most troublesome in circulator-less PAs for microwave cavity applications, especially where multiple sources are used to deliver power into the same cavity. This application therefore demands a more detailed investigation into the potentially hostile conditions imposed on devices within power amplifiers where two or more sources are used to deliver power into a single, variable load cavity, and the reliability implications that result.

II. DEVICE UNDER TEST

Although for domestic heating applications, a multi-mode rectangular cavity would typically be used, a single mode-cylindrical cavity designed to operate over the 900MHz - 960MHz frequency band has been used to provide a predictable envorinment, deterministic electric field distribution and to simplify analysis. A cylinderical cavity was designed to provide a single TM_{010} resonant mode was fabricated, with two coupled ports, port-A and port-B located opposite each other, each with a collar designed to accept a modified N-type barrel connector. The cavity was loaded through placement of a cylindrical quartz tube containing 50 ml of water, placed in the center of the cavity where the E field is strongest. The coupling structures comprising a simple loop at each of the ports were adjusted in terms of their orientation relative to the circulating H-field, to ensure the 50 Ohm sources were properly matched (critically coupled) to the load. The achieved match at port B was similar to that of port A. RF generated power from two separate power amplifiers was then injected into the cavity simultaneously via port-A and port-B, forward and reflected power measurements were made using dedicated directional couplers at both ports, under different loading conditions. The power delivery into the cavity was controlled in terms of the phase and amplitude of the input signal and also by ensuring both paths were of equal length.

III. MEASUREMENT PROCEDURE

Forward and reverse power measurement using high directivity dual directional couplers and power sensors captured any changes in reflected power behavior at each of the ports caused by impedance mismatch. Using these basic measurement techniques, amplifier performance was monitored and analyzed under variable loading conditions, as the fundamental load moved away from its ideal 50 Ohm environment. It is shown that a simple loop coupling with narrow band characteristics does not present optimum loading conditions over the entire frequency band of interest and as a consequence, device reliability may be compromised.

The introduction of a second, active, phase coherent source via port-B further influences the impedance seen by the first source at port-A. In-order to ensure that both sources are matched / critically coupled to the cavity load, each of the coupling structures needed to be physicaly adjusted to account for the the presence of the other. Simple equivalent cavity model simulations have shown that under certain, ideal and worst-case loading and phase alignment conditions, a power level equal to the total (port-A + port-B) transmit power can appear at *port A* or *port B, w*ereas under optimum loading conditions, power from both sources is absorbed by the load resulting in little or no reflected power at the both device's output planes.

In this paper, the forward and reflected power signals were measured directly at the cavity's *port A* and *port B*, which allows for direct observation of the mismatch at the device package planes. A novel broadband coupling structure captures the optimum impedance points across the frequency band of interest ensuring that the source is always operating into a near matched load. As well as improving efficiency, this methodology helps avoid the hazardous phase alignment scenario's, reflected travelling waves and the associated voltage and current maxima. Maintaining an optimum matched condition ensures that transmitted power is absorbed by the load and sustenance of this condition ensures that little or no power is reflected.

IV. MEASUREMENT OBSERVATIONS

Consider firstly, the measurement at Port-B under conditions 1 and 2 stated below:

1. In the presence of a coupling structure at port-A, with Source-A switched off.
2. In the presence of a coupling structure at port-A, with Source A switched ON. The input phase and path lengths are kept constant to maintain phase coherence.

The ratio of reflected power to forward power is low where the source is optimally matched to the load over a narrow band of frequencies, gradually worsening as the frequency of operation changes from where it is optimally matched. Fig. 1a and 1b show the corresponding absolute reflected power measurement data at port-B and port-A respectively for the stated conditions 1 and 2. It is observed that the level of reflected power is low at 944MHz – at this frequency both the sources are optimally matched to the load. A forward power of 5 watts results in a reflected power of 0.1Watts - 98 percent of the generated power is delivered into to the cavity. The results show that at this frequency of operation, the device will operate reliably with little or no stress and the potential for breakdown is minimal.

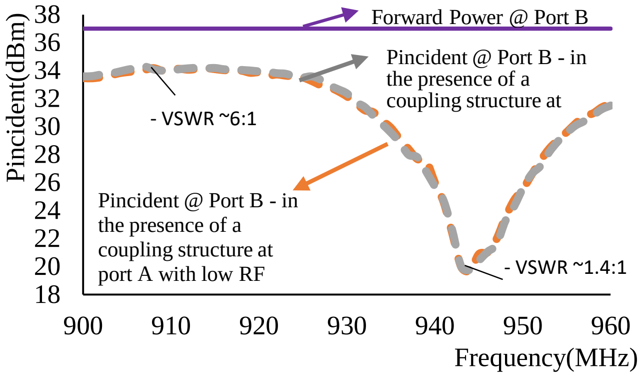

Fig 1a – Shows incident power measurements at port B - (i) in the presence of a coupling structure at port A (ii) In the presence of coupling structure at port A with low RF power.

The terms P_{inc}, P_{del} and P_{ref} are used to quantify the incident, forward and reflected powers throughout this document and the exact definition for each of these terms is given below:

P_{inc} = Incident Power at (port-A, port B)
P_{del} = Percentage of power delivered to the cavity
P_{ref} = Percentage of power reflected back to the to the port.

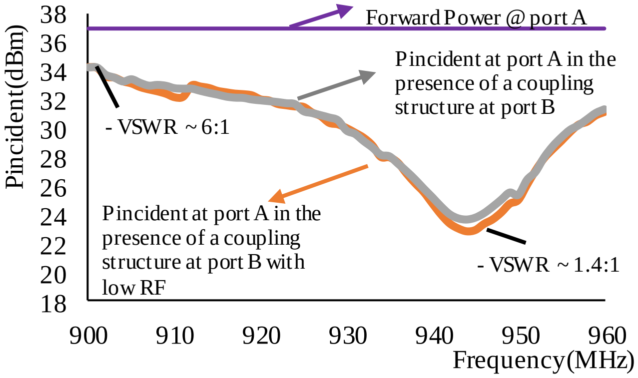

Fig 1b – Shows P_{inc} measurements at port A - (i) in the presence of a coupling structure at port B (ii) In the presence of coupling structure at port B with low RF power.

It can be seen that in the presence of low levels of RF at *port A*, there is little or no influence in the reflected power at port B. This shows that under operating conditions where the power from a single source (source B) is considered sufficient to heat the load, maximising system efficiency, source-A can be switched off or left to stand in idle mode.

It is further observed that away from this optimally matched frequency, the amount of reflected power at each of the ports begins to increase. This is of course no suprise but does mean that the PAs could potentially experience high levels of reflected power, and in circulator-less designs, this could lead to device damage. For completeness, the relationship between reflected power and VSWR is given opposite by equations 1 to 2 and summarized below in table 1. Using the forward and reflected powers from figures 1a and 1b it can be seen that the VSWR varies from 1.4:1 at the optimally matched frequency points to 6:1 at the band edges where 50 percent of the generated power is refelcetd back.

Return Loss	VSWR	Transmission Loss	P_{del}	P_{ref}
(dB)		(dB)	(%)	(%)
-	1.00	0.00	100.00	0.00
-19.00	1.25	0.05	98.80	1.20
-9.50	2.00	0.51	88.90	11.10
-6.00	3.00	1.25	75.00	25.00
-2.90	6.00	3.10	49.00	51.00

Table 1 –Theoretical values and relationship between Return Loss, VSWR, Transmission loss, P-Transmit and P-Reflect in tabular form

$$\text{Reflected Power (\%)} = 100 * |\Gamma|^2 \qquad (1)$$

$$\text{Reflected Power (dB)} = 10 * \log(|\Gamma|^2) = 20 * \log(|\Gamma|) \qquad (2)$$

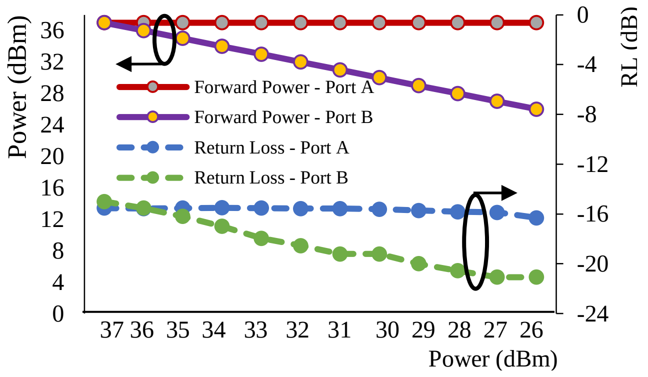

Fig 2a – Shows P_{del} and P_{ref} measurements at port A & port B where the forward power at port A is set to 37dBm and the forward power at port B is varied between 37 and 26 dBm in 1 dB steps.

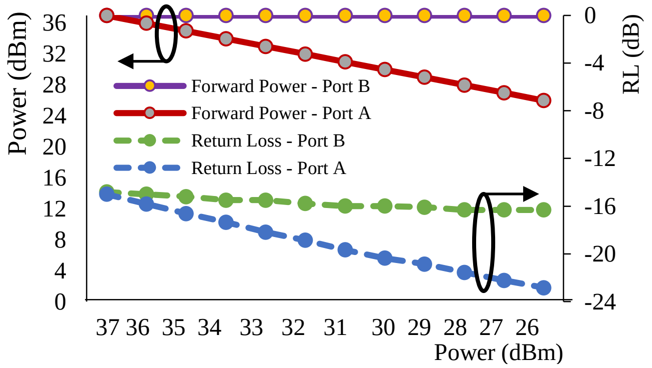

Fig 2b – Shows P_{del} and P_{ref} power measurements at port A & port B where the forward power at port B is set to 37dBm and the forward power at port A is varied between 37 and 26 dBm in 1 dB steps.

The results show that at set output power levels (37dBm) and under optimally matched loading conditions, the degree of reflected power at both the ports is similar ~ 22dBm, equivalent to a return loss of approximately -15dB's. However as the power at one of the ports - *port A* is scaled down (37dBm to 26dBm) the reflected power at this port also begins to reduce as shown in *figures 2a and 2b*. The reflected power reduces linearly with a gradient of ~0.5 across this range. There is also a small reduction in the incident power at *port B* – this suggests that the total amount of reflected power at port *B* is due largely to the matching condition at this port with a small contribution from the second port, *port A*. While this information will allow system characterization to be made, it suggests that there is a need for careful alignment of the coupling structure to determine the frequency at which the source is optimally matched to the load.

The full bandwidth of the amplifier (900MHz – 960MHz) cannot be fully utilized as deviation from the optimum frequency results in a mismatch at the device package plane – leaving the PA vulnerable to high VSWR conditions and potential breakdown.Variations in the load will have the effect of moving the optimum load condition to a different frequency point. This typically requires a manual readjustment of the simple loop coupling structure to determine the new operating frequency. There exists a need for a broadband coupling structure which enables the capturing of the optimum impedance points over the operating frequency of the power amplifier.

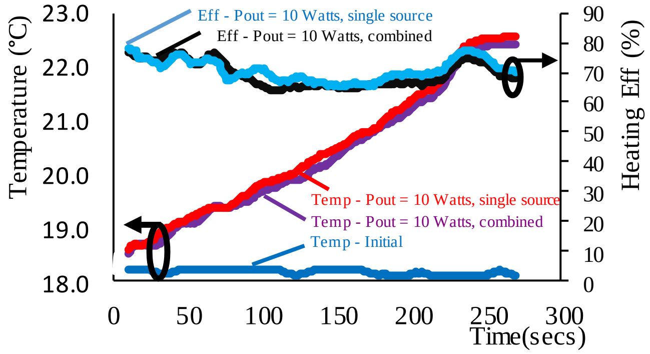

Fig 3 – Shows the rise in temperature with the forward single channel power of 40dBm at port A. The measurement is repeated with the power at Ports (A + B) set to 37dBm to give a combined power of 40dBm.

In order to demonstrate that power can be effectively combined within the cavity using multiple sources attached to multiple ports, an experiment was conducted where 10 ml of water was heated and its temperature was measured using a pyrometer (Micro-Epsilon CT-SF22-C1). With reference to Fig.3 the "*temp-initial*" measuremet is the temperature of water under no power conditions and is used as a reference, room temerature case. Source-A is than switched on to deliver 5 watts Watts of RF power into the cavity over 260 seconds. Following cooling to the reference temperature, source-A is combined with source-B to deliver a further 5 Watts (10 Watts combined). This measurement is than repeated with a single source delivering 10 Watts into the cavity. The measurements show similar temperature profiles for both 10 Watt scenarios – a single 10 watt source and two 5 watt sources showing that power combining has been successfully achieved. The heating efficiency of ~ 70 percent is calculated using equations 3,4 and 5 and a plot of efficiency verses time is shown in figure 3.

Energy Absorbed by water(j) = (3)

Vol(g)* Δt*(4.18J/g.°C)

Energy released by source(J) =
P(watts) * Time * ((1j/s)/1Watt) (4)

Heating Efficiency (%) =
(Energy Absorbed /Enegy released) (5)

The main element contributing to the efficiency and reliability of a solid state heating system is the coupling structure. It determines the power delivered P_{del} to the cavity and the power reflected P_{ref} back at port(A and B). An optimally designed coupling structure will ensure that almost all of the generated power is delivered to the cavity and maintain very high power delivery efficiency. The heating efficiency is than calculated by determing the total proportion of energy absorbed by the load using equation 5 and is generally expected to be lower than the delivery efficiency due to some of the power being absorbed by the container. Hence the choice of container is critical in maintaining high levels of heating efficiency.

The overall system efficiency of a solid state system is determined by the efficiency of P_{del} into the cavity, the heating efficiency and the efficiency of the source (PA). The PA efficiency is dependent on the semiconductor device, class of amplification, power level and the choices made during the product design cycle, especially those relating to minimizing path losses and thermal cooling.

V. BANDWIDTH OPTIMISATION

Consider now the scenario where due to the load variations within the cavity the optimum match condition starts to drift in frequency from its original position (due to temperature, position, etc). This require a physical realignment of the simple loop coupling structure and a change in the operating frequency of the power amplifier. A source matched across its full operating bandwidth stated at 900-960MHz in this example, ensures that return loss is maintained below -10dB or less across the operating bandwidth, therby ensuring that a change in the PA's operating frequency does not result in operating conditions where the transmitted power is reflected .

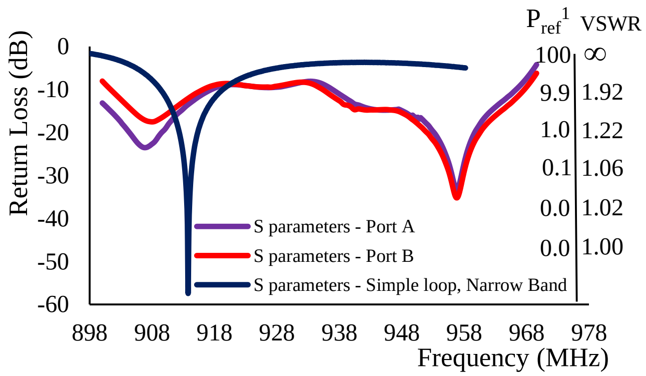

Fig 3a – Shows the impedance match (S11) at port A & port B for a defined load – 50ml of water.

In Fig.3a,broadband matching is achieved by modifying the simple loop coupling structure using a novel, coupling technique. This clearly highlight the benefits of broadband matching networks which ensures that the solid state source continues to operate into a matched load and importantly, is not subjected to high VSWR conditions caused by the simple narrow-band coupling.The percentage of refelected power (P_{ref}) and vswr for both narrow and broadband structures is shown by the scale on the right hand side in figure 3.

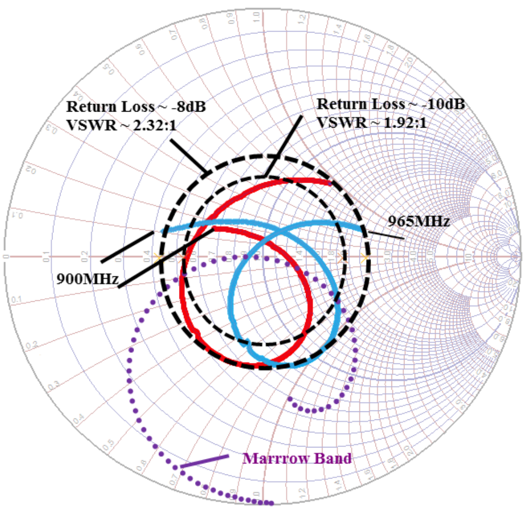

Fig 3b – Shows the impedance match (S11) constrained within the VSWR of 2.32:1 for the entire band at port A & port B for a defined load - 10mili-litres of water.

As stated earlier, power delivery into a cavity resonator is typically achieved through a simple loop structure where efficient power delivery (Pdel) is only possible at a single frequency. Due to the high-Q nature of the cavity, efficient power delivery is only possible at a single frequency as shown by the 'narrow band' impedance response above in figure 3. In order to utilize the full operational bandwidth of the solid-state amplifier, the coupling structures needs to be able to deliver power at any of the frequency points within the band of interest The results in figure3b, show that by carefully manipulating the coupling structure it is now possible to constrain the impedance match to a VSWR of 2.3:1 for the entire operating bandwidth whilst having optimally matched points (nulls) within the band.

VI. MEASUREMENT SETUP

The measurement setup used during the course of this investigation is shown in figure 4. It comprises of a two port cylindrical cavity, two rf sources and dual directional couplers to monitor the forward and reflected power at each of the ports (port-A & port-B).The load is placed in a quartz tube which is positioned in the centre of the cavity and the rise in temperature is measured using a pyrometer from the top as indicated bleow.

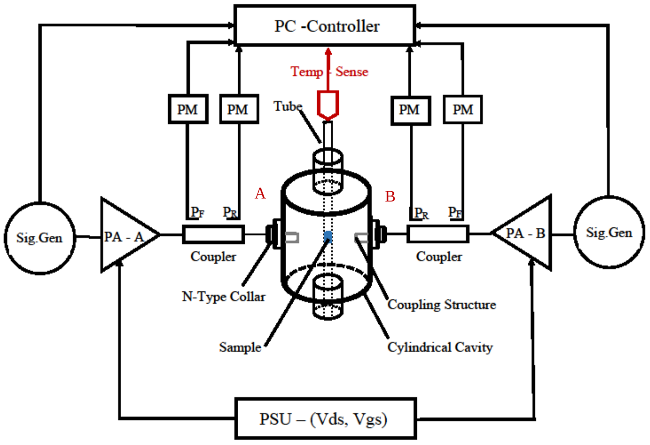

Fig 4 – Measurement set-up used for monitoring the forward, reflected power and temperature rises inside a 2 port cylindrical cavity.

VII. CONCLUSION

This paper presents an approach to free-space power combining for attaining high power and efficient power delivery into a single mode cylindrical cavity. It has been experimentally shown that for a two-port system, power combining has been successfully attained. The results for the two-port system – using a novel broadband coupling structure show that it is possible to sweep the entire frequency band of interest (902 – 928MHz) in order to determine the optimum matching condition for each of the sources ensuring power efficiency (delivery into the cavity) of greater than 98 percent. This is based on the reflection coefficient measurements of better than -20dB. Using this technique and methodology both the power amplifiers continues to operate into a safe operating load. The ability to constrain the match to within 2.3:1 VSWR contours ensures that device reliability is not compromised, furthermore having both sources operating at the same frequency enables frequency and phase locking which ensures that no distortion products will be generated.

VIII. REFERENCES

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