National Synchrotron Radiation Research Center

# Fundamental studies of 500MHz Solid-state Amplifier in NSRRC


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*CWRF 2018 workshop, Hsinchu,*


# Outline

- Introduction
- The favorite features of SSPA and the design map in NSRRC
- SSPA module design
- The performance of 20-way power combination
- Investigation the efficiency of a SSPA system
- Conclusion

# Introduction

- Solid-state power amplifier (SSPA) is an interesting, practical and useful technology.
- Some tests and experiments are applied to push the RF power of the transistor to its high limit remaining reliability
- The attention would be put on
  - IR temperature measurement at chip and balun
  - SSPA design with its water cooled heat dissipater
  - The power combining efficiency from the discrepancy between modules
  - The demonstration of module function by 20-way power combination
  - Discussion the efficiency of a SSPA system

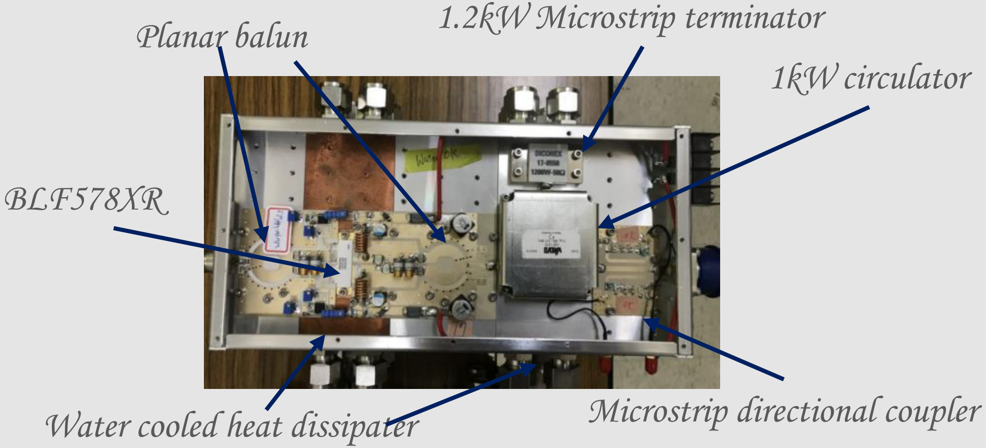
# The favorite features of SSPA and the design map in NSRRC

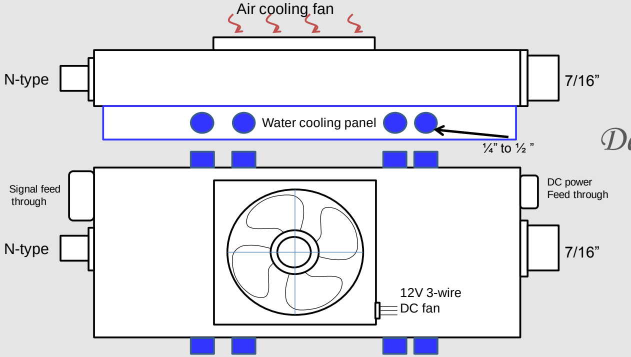
- Favorite features
  - High redundancy
  - No High voltage
  - No radiation
  - Good phase noise
  - Low harmonics
  - No vacuum
  - The technology are continuing improving
  - Assembly in house becomes possible

- The design map
  - Push the output RF power to high limit of transistor to reduce total transistor numbers and system size
  - Remain good reliability:
    - Decrease junction temperature of transistor as low as possible
    - Add forced air cooling for circulator
  - Dual channel cooling for lower total water flow rate
  - Built in high directivity directional coupler to measure reflection RF power at module level

# SSPA module design

- *Design features*
  - *Transistor is screwed mounted for easy disassemble*
  - *Planar balun for easy manufacture*
  - *Integrated dual cooling water channel for better cooling*
  - *Add DC fan to improve module cooling*
  - *Modulator design for each transistor*
  - *Built in high directivity directional coupler*
  - *900W@500MHz output RF power*
  - *Swagelok type water connectors for easy dismount from water manifold*

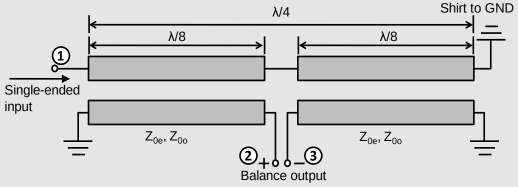



Design view of SSPA module

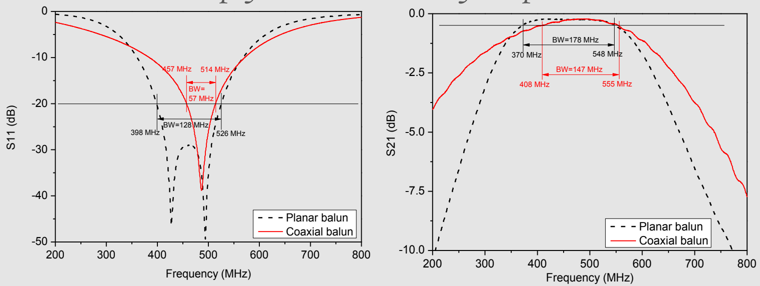
# The planar balun

- The difficulty in soldering the coaxial cable balun is the main motivation to design the planar balun
- The frequency response is similar to typical coaxial balun
- The size is much smaller than coaxial type balun
- The balun can run under 1000W CW (~120˚C) RF power without problem

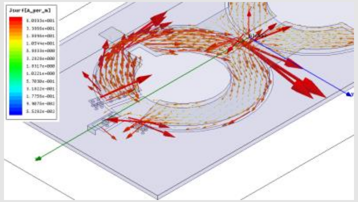



Simplified circuit model of the planar balun

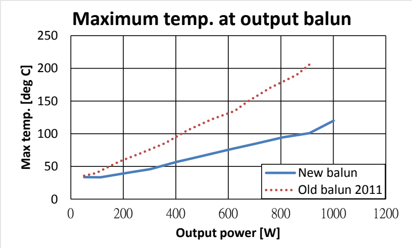
Physical implement




Frequency response of back-to-back connection



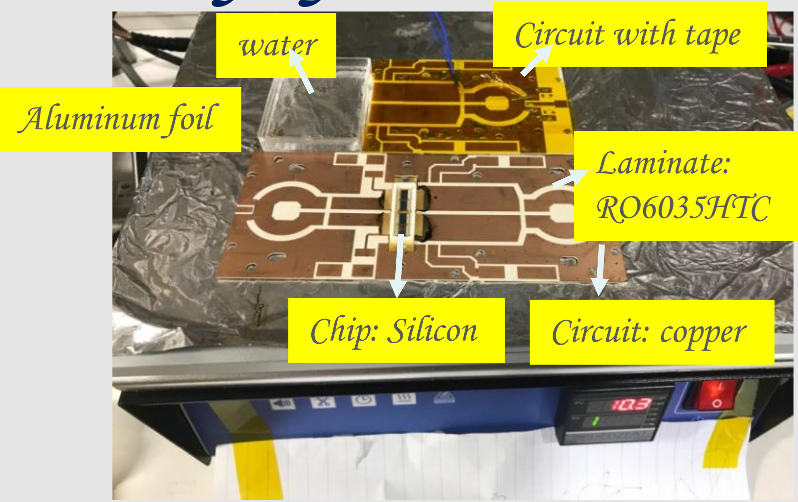
EM simulation

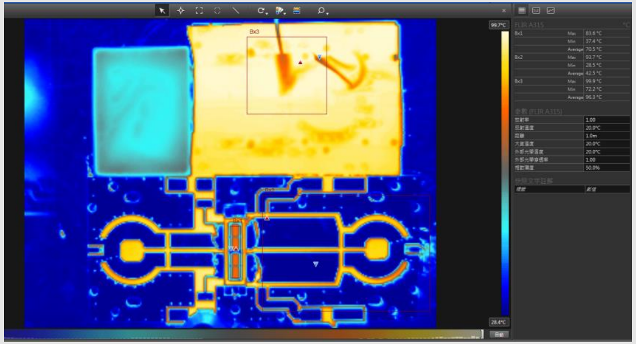



Temperature vs. output RF power

# IR camera and the emissivity of materials

- Different materials have different IR (Infrared) emissivity at various temperature
- Use hot plate to calibrate the emissivity
- Cook to 100°C, the emissivity of the used materials:
  - Copper: 0.03
  - Silicon of transistor: 0.84
  - Laminate: 0.94
  - Adhesive Tape: 0.97
  - Water: 0.95
- The actual temperature of silicon (the junction temperature) can be obtained by IR camera



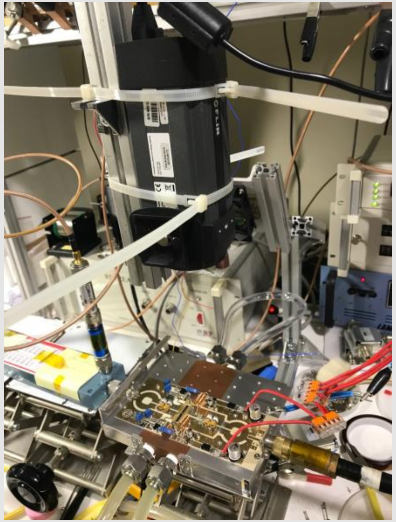



IR view

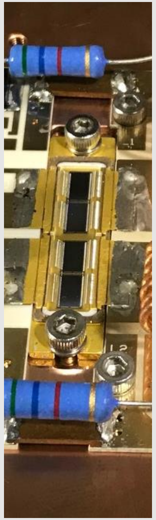
# The durability of planar balun with the capture of thermal images

- The circuit are filmed by transparent painting for better IR view
- Observe the real time temperature variation of high power transistor and circuit

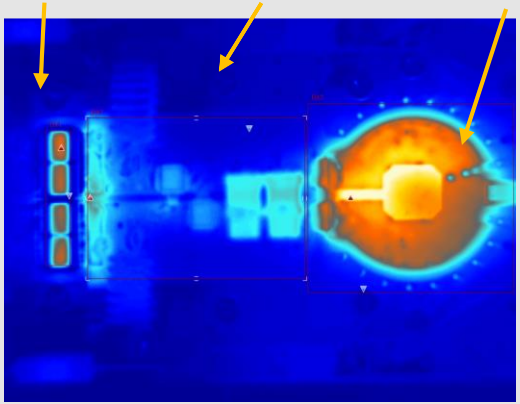
IR camera

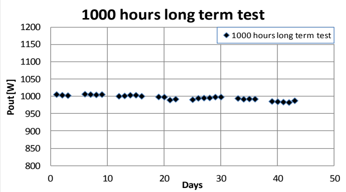


Ceramic cover removed

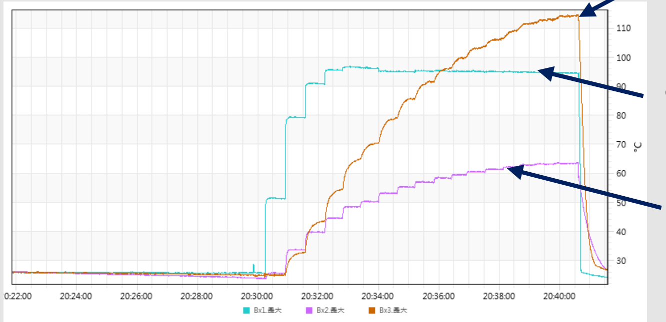


Transistor Matching network Balun






The planar balun can run under 1000W CW for 40days without problem



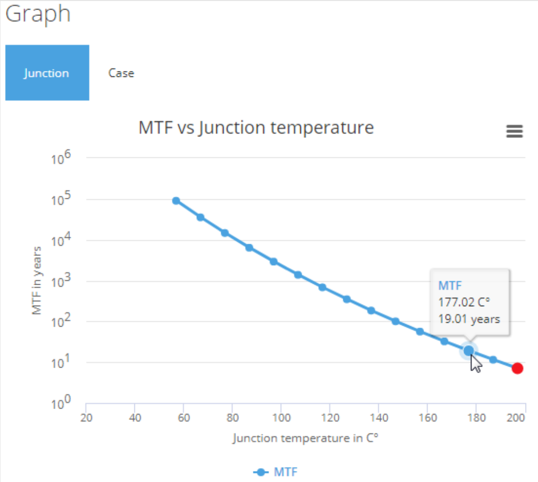

Balun temp

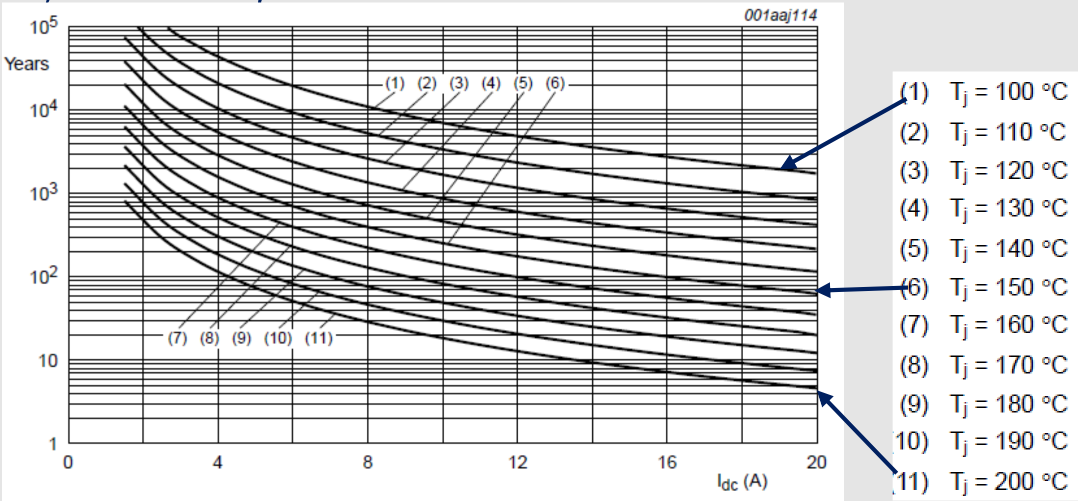
Transistor temp

Matching network temp

# The motivation for better cooling

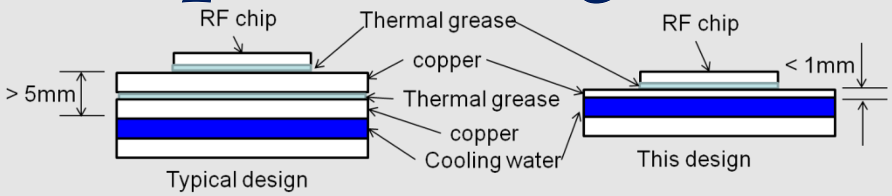
- *To have better reliability of transistor itself*
- *The lifetime of the transistor is mainly determined by the junction temperature*
- *The performance also affected by the junction temperature*



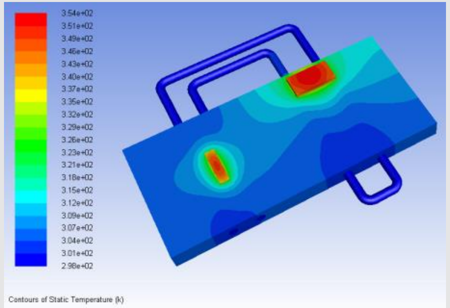



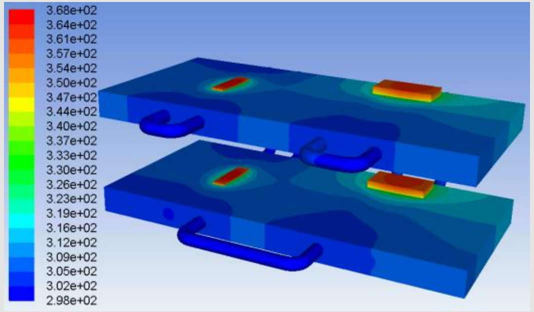

https://www.ampleon.com/design-tool/BLF578.html?caseTemp=80

# Water cooled heat dissipater design

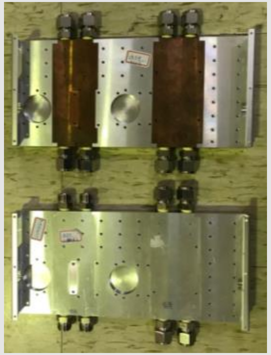



- *Features*
  - *Transistor contact water cooled heat dissipater directly*
  - *Dual water channel under chip and load*
  - *Natural heat exchanger to average the chip temperature as the SSPA modules are in series connection*

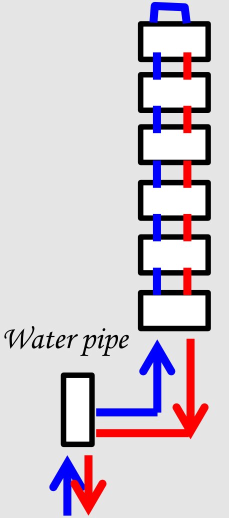



*Cooling capability simulation by Fluent: verify the averaging effects of chip temp in series connection of water channel*



*Material of Cu and AL for water cooled heat dissipater*

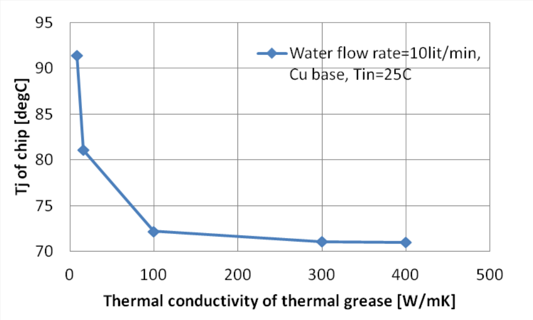


# The factors for cooling efficiency

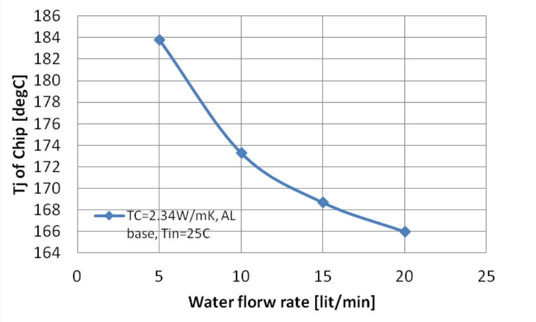
- *Four factors can affect the cooling capability*
  - *Base material: copper or aluminum*
  - *Thermal grease thermal conductivity: W/m·K*
  - *Water flow rate: lit/min*
  - *Structure of heat dissipater*

*Table: Thermal conductivity of common materials*

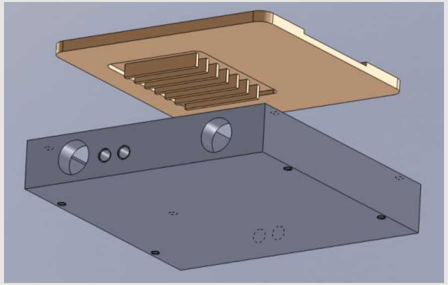
| *Material* | *Thermal conductivity [W/m·K]* |
| --- | --- |
| Diamond | 2300 |
| Silver | 429 |
| *Copper* | *401* |
| Gold | 317 |
| *Aluminum* | *237* |
| Iron | 80.2 |

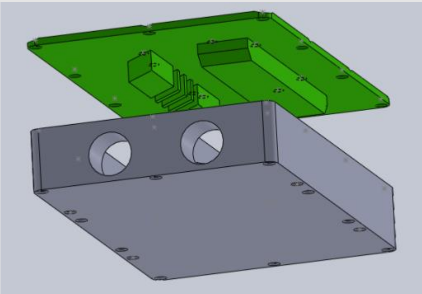



*Thermal conductivity of thermal grease vs. junction temperature of transistor*




*Water flow rate vs. junction temperature of transistor*

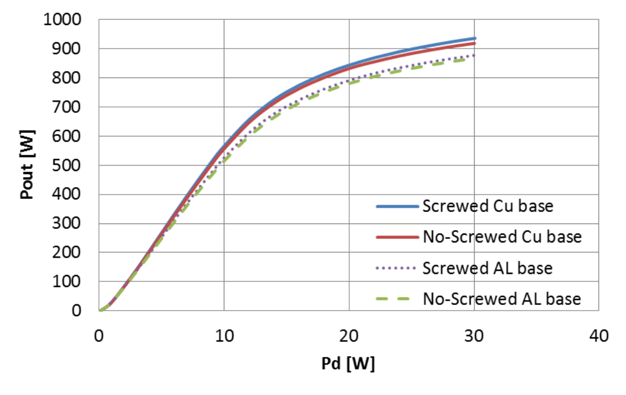


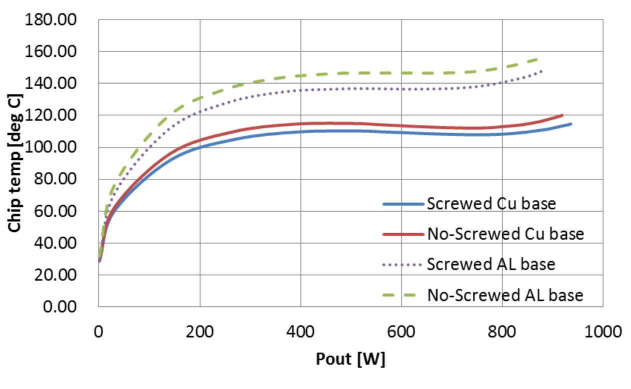


*The mechanical structure also affects the cooling capability*

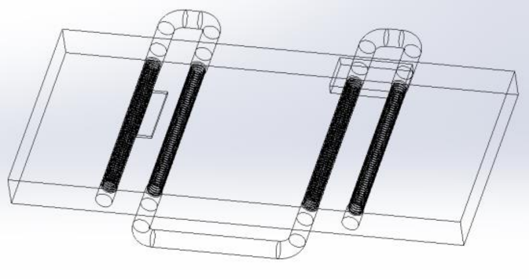
# Aluminum or copper as heat dissipater?

- Test heat dissipater of RF power transistor usually using aluminum (AL) and copper (CU)
- The water channels are smooth and screwed separately for each material
- Use the same circuit, transistor and thermal grease, at the same RF output power, the measured chip temperature difference can reach 33˚C between CU and AL base.
- The simulated chip temp difference between Cu and AL is about 27 ˚C (the same setting)
- Provide additional disturbance of water flow can also improve cooling capability



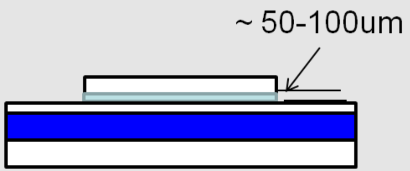




Inlet water temp: 20 ˚C
Water flow rate:10 Lit/min
TC of thermal grease: 16 W/m·K

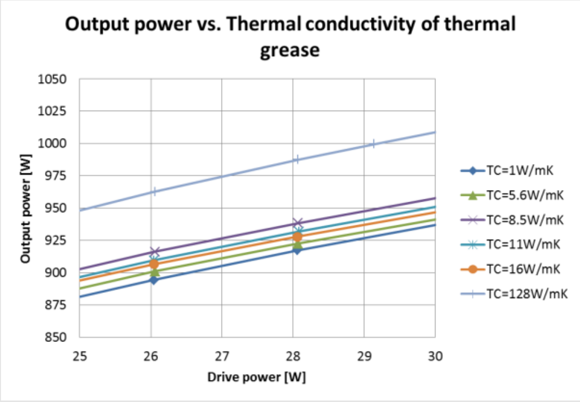


Screwed water channel

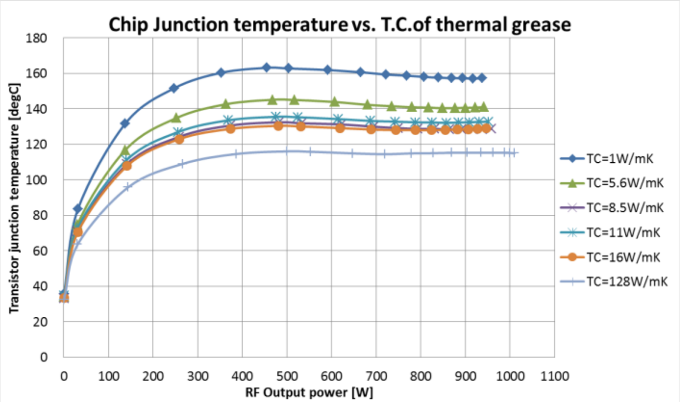
# Does 50μm matters?



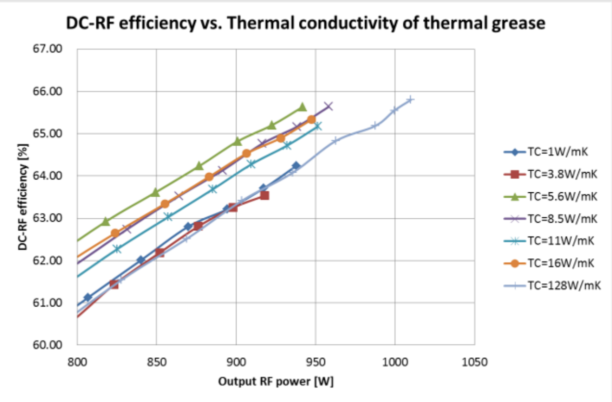

- The thickness of the thermal grease between chip and heat dissipater usually has thickness of 50 μ m-100μm
- Use various thermal conductivity of thermal grease (TC in W/m˙K) to experimentally test the performance change of the same chip and circuit
- Obviously, the performance of the transistor affected by the temperature
- 40°C temp difference is observed between TC=1W/mK to 128W/mK




RF Drive power versus output power



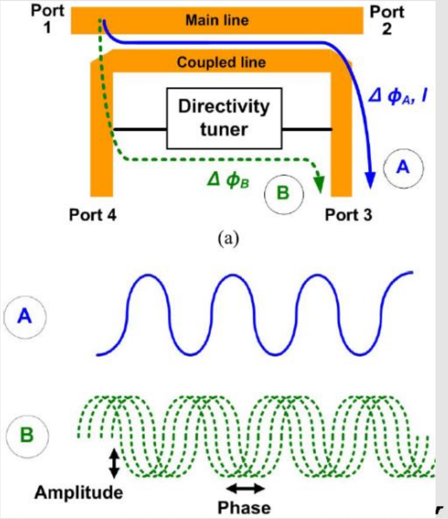

Junction temperature of transistor by various thermal grease

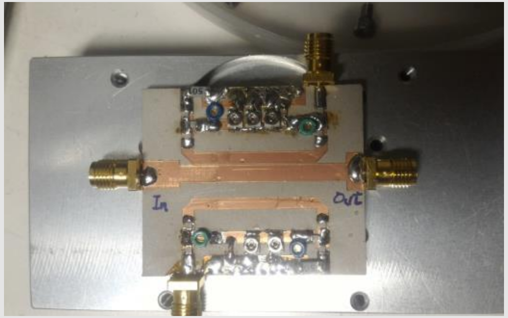



DC-RF efficiency of various thermal grease

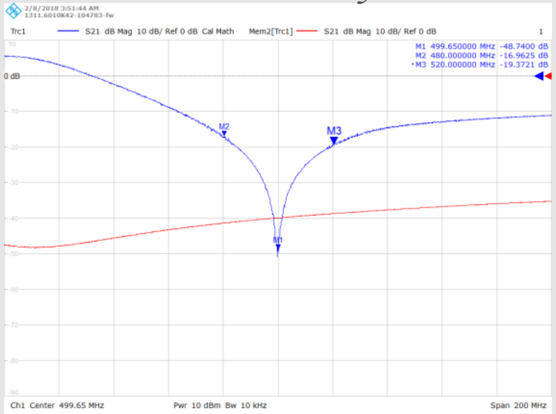
# *Measure reflection power at modules level: High directivity microstrip directional coupler*

- *Microstrip directional coupler can be small but with less directivity*
- *With the aids of trimming capacitors and resistors, the unwanted signals can be suppressed at the isolated port.*
- *The result shows that better than 40 dB directivity can be got at the specified frequency.*



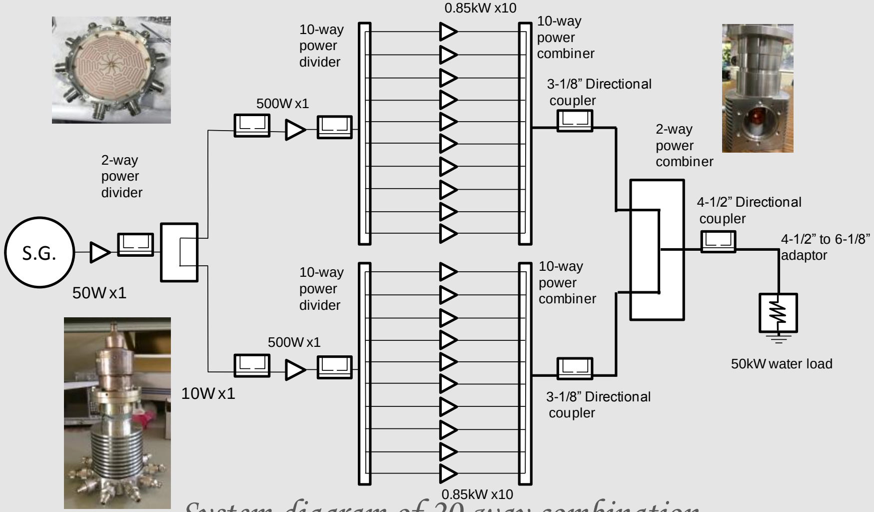




*48dB directivity*

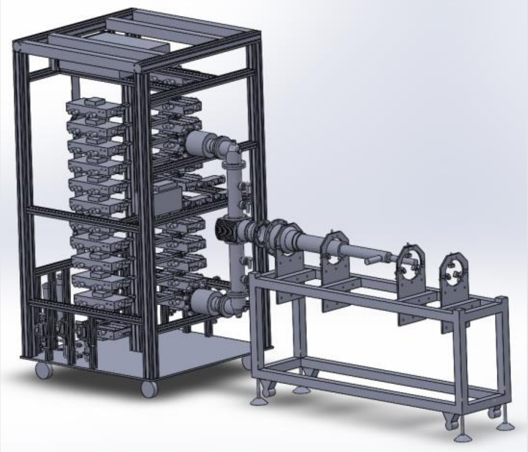


# Demo the SSPA module design: 20-way power combination

- To validate the SSPA module design, a 20-way power combination test stand is implemented.
- Design target is 17kW with the average 850W power of modules
- $P_{sat}$ is 18kW with 900Wx20 of power combination



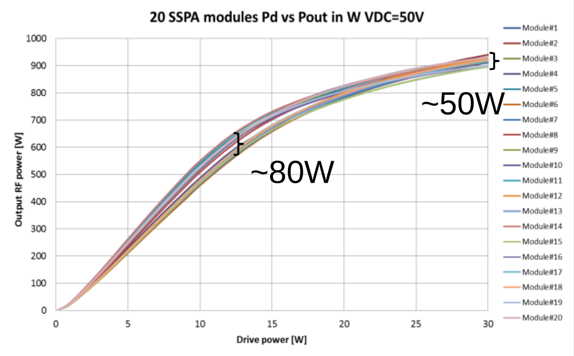

System diagram of 20-way combination



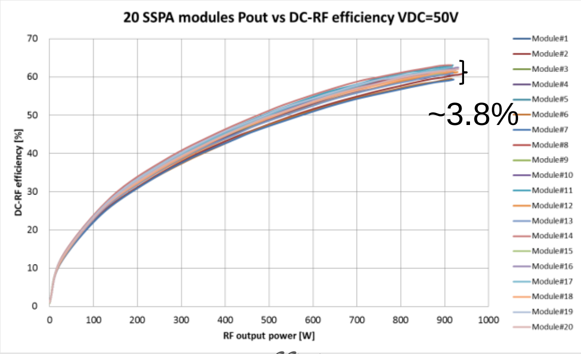
Layout of 20-way power combination

# Statistic data of 20 modules

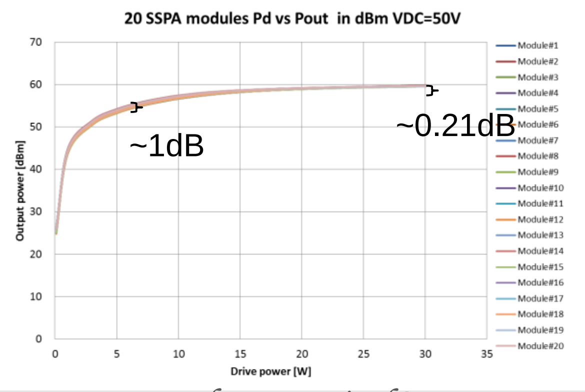
- *Amplitude can be well controlled through the trimming capacitors*
- *The phase has larger variation in10 deg*



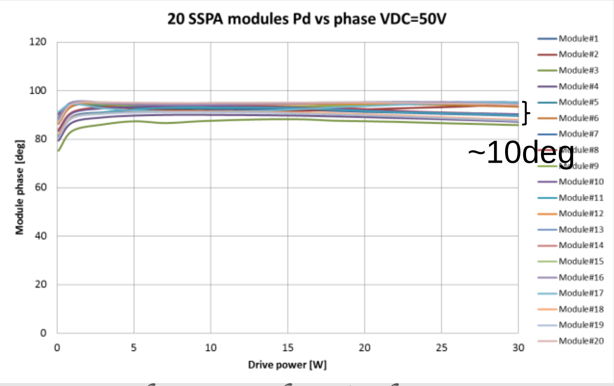

*Pd vs. Pout in W*




*Pout vs. efficiency*




*Pd vs. Pout in dBm*

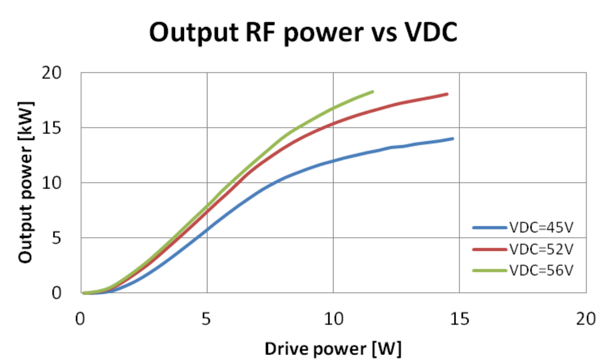


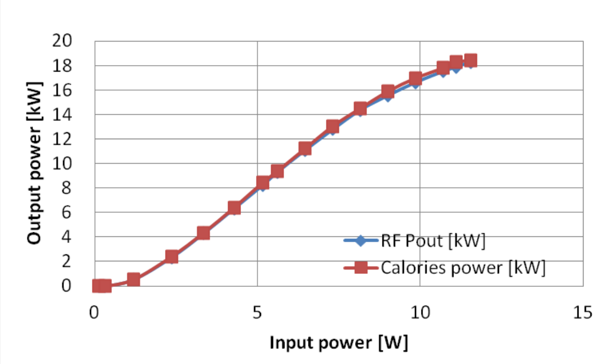

*Pd vs. S21 phase in deg*

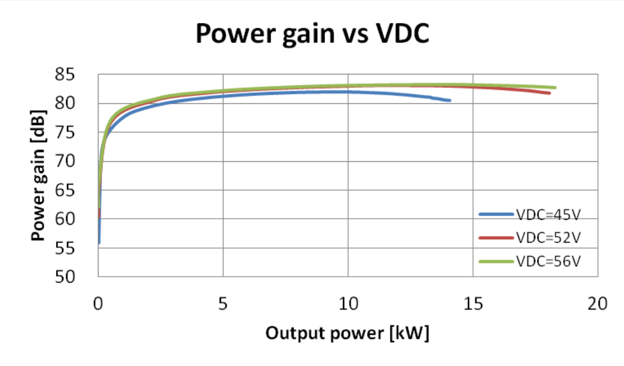
# Power combine results

- *18kW output is confirmed by calorimetric method*
- *The RF output power would be limited by the circulator (1kW maximum, 950W for operation limit)*

| AC-RF efficiency |
| --- |
| ~54% @ 50VDC |



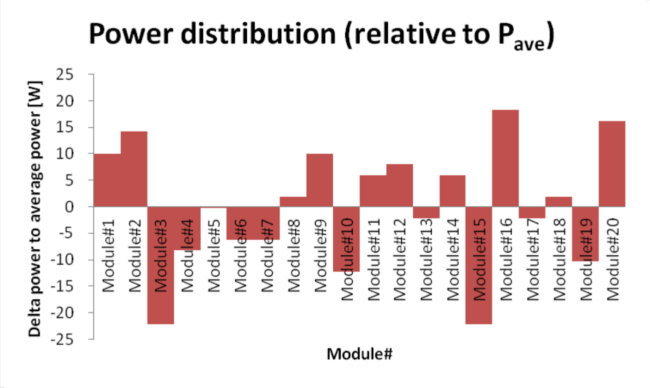



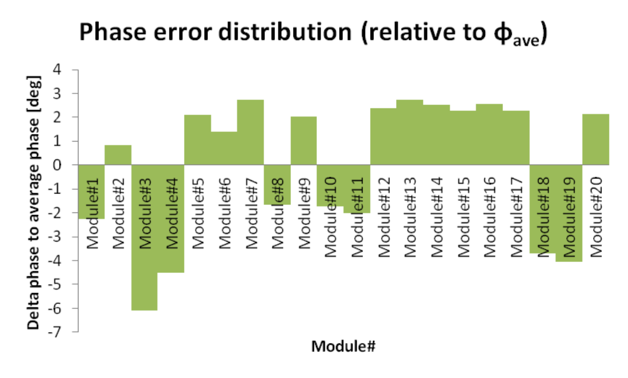



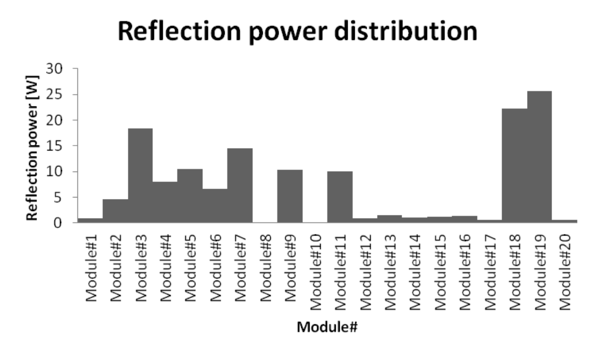
# Property distribution of 20 modules

- *The maximum output power difference is 40.48W (0.2dB) and the standard deviation σ is 11W*
- *The maximum phase difference is 8.82 deg and the standard deviation σ is 3.35˚*
- *The total measured reflection power is 140W*
- *The measured total output power is 17.26kW*
- *The ideal total output power is 17.6 kW*
- *The power combination efficiency is 98.1% (including cable loss)*

| Max. Δ Pout | σ of Δ Pout | Max. Δ ϕ | σ of Δ ϕ | Total Pr | $P_{total}$(measured) | $P_{total}$(ideal) | Power combination efficiency (including cable loss) |
|---|---|---|---|---|---|---|---|
| 40.48 W (0.2dB) | 11W (0.07dB) | 8.82˚ | 3.35˚ | 140 W | 17.26 kW | 17.6 kW | ~98.1% |

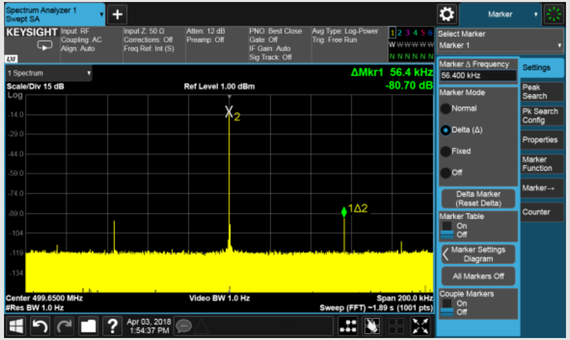


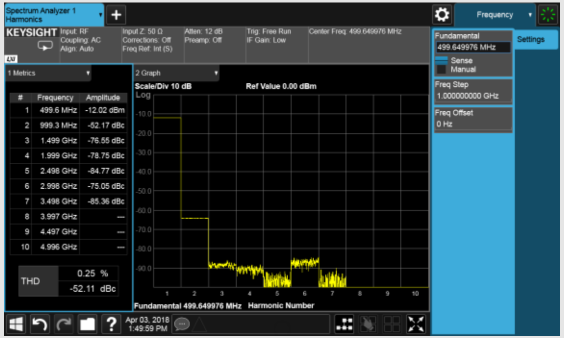



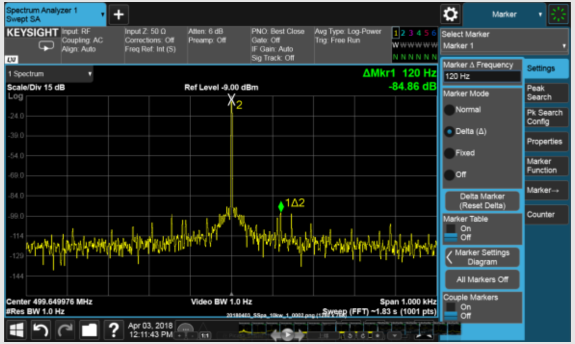



# RF power quality: harmonic and phase noise

- Sampled at saturation output power (18kW)
- Sideband noise:
  - -84.86dBc@120Hz
  - -80.70dBc@56.4kHz
- Harmonics:
  - -52.17dBc@2nd harmonic
  - -76.55dBc@3rd harmonic
- Phase noise:
  - -91.41dBc/Hz@120Hz
- The quality is quite satisfying.

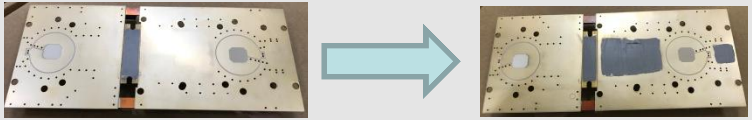


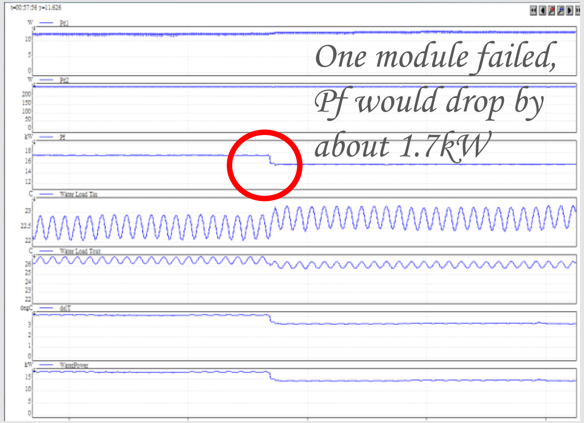



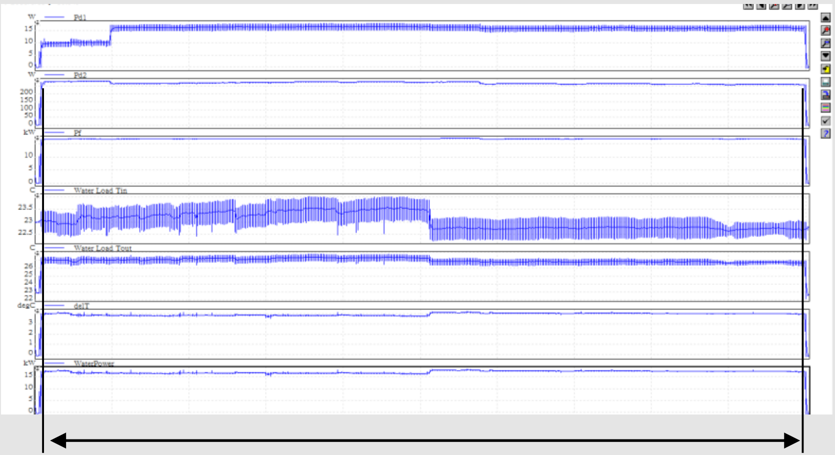

# Simple Reliability test

- Long term reliability with full forward power run at matched load for 240 hour has been tested without any fault of modules after improving the heat dissipation of output circuit.



Add thermal grease under output PCB




Drive power

Preamplifier power

Forward power

Inlet water temp

Outlet water temp

Del T of inlet and outlet water

Power by calorimetric method

# *The efficiency of a SSPA system*

- *Can be roughly divided as four parts:*
  - *AC-DC conversion efficiency: the DC power supply: $Eff_{AC\text{-}DC}$, usually > 90%*
  - *DC-RF conversion efficiency: the SSPA DC-RF efficiency: $Eff_{DC\text{-}RF}$, usually > 60%*
  - *Combination efficiency: due to discrepancy of SSPA modules: $Eff_{combi}$, usually > 98%*
  - *Combiner loss: Insertion loss of RF output cables and combiners : IL, usually < 3%*

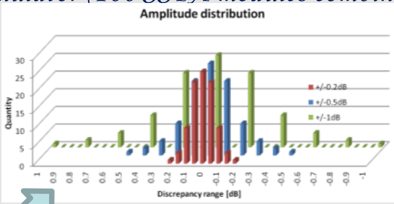
$$Eff_{total} = Eff_{AC-DC} \times Eff_{DC-RF} \times Eff_{combi} \times (1 - IL)$$

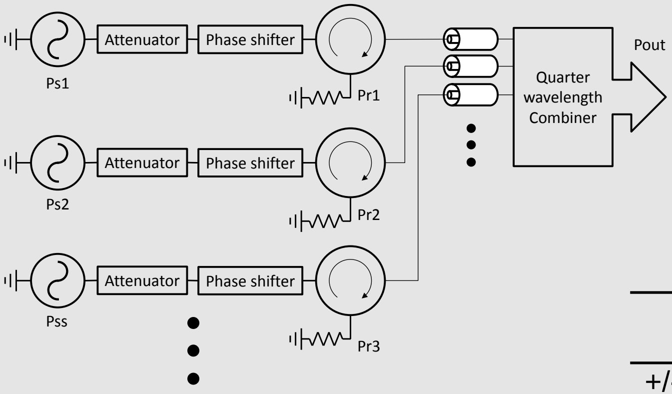
| | $Eff_{AC\text{-}DC}$ | $Eff_{DC\text{-}RF}$ | IL | $Eff_{combi}$ | $Eff_{total}$ | |
|---|---|---|---|---|---|---|
| #1 | 90% | 62% | 2% | 99% | 54.14% | ← *General condition* |
| #2 | 95% | 62% | 2% | 99% | 57.14% | ← *Better power supply* |

*The remaining item that can be improved* (pointing to the $Eff_{DC\text{-}RF}$ column)

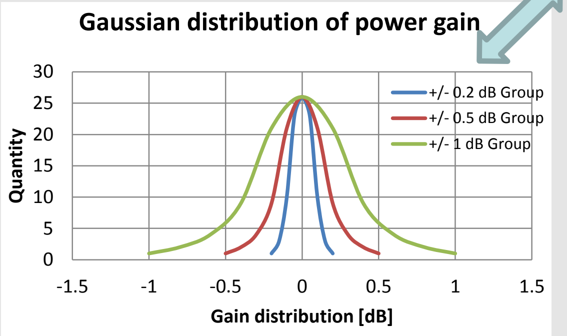
# The efficiency of power combination

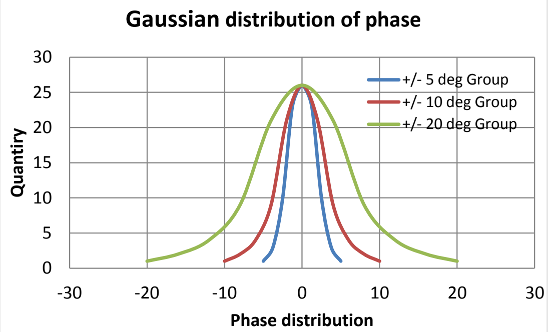
- *The power combining efficiency from the discrepancy of SSPA modules is analyzed by circuit simulator (100 SSPA modules combined at one combiner)*
- *The combiner used here is symmetrical quarter wavelength combiner*
- *It's surprising that the power combination is quite robust to the discrepancy of modules*
- *This shall be the key factor that leads to the success of high power SSPA*




The circuit model in simulator

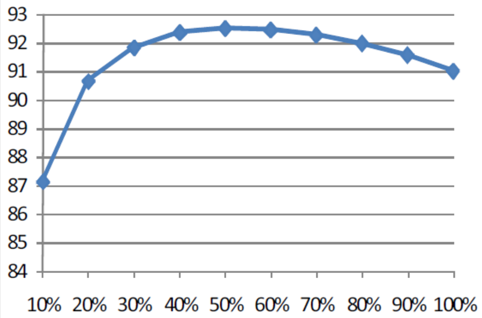



| | Standard Deviation | **Combination efficiency** | Note |
|---|---|---|---|
| +/- 0.2dB & +/- 5˚ (#1) | 0.073dB/1.82˚ | 99.79% | 0.2dB=4.7% |
| +/-0.5dB & +/-10˚ (#2) | 0.173dB/2.33˚ | 99.49% | 0.5dB=12.2% |
| +/-1dB & +/-20˚ (#3) | 0.346dB/4.66˚ | 98.29% | 1dB=25.9% |

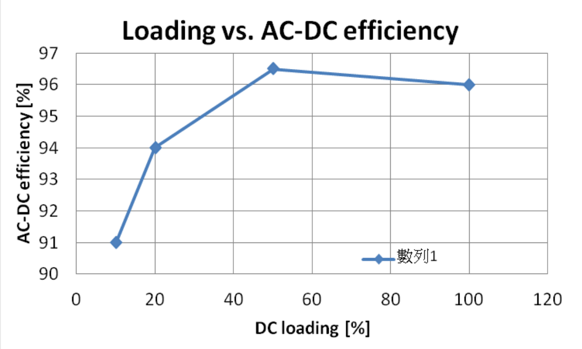
# Higher efficiency cost

- Take modular power supply as example
  - In Taiwan local company:
    1kW 92% efficiency cost=15000NTD/500USD/405EUR
  - USA company:
    1kW 96% efficiency cost=21000NTC/700USD/567EUR
- 40% cost added by only 4% Eff. improvement




RCP-2000

GP100



# The possibility of higher efficiency of SSPA@500 MHz

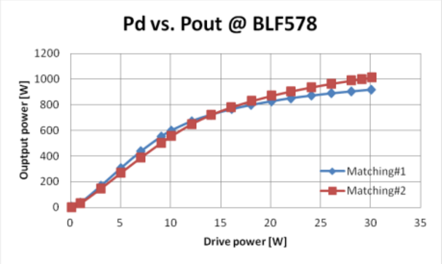
- Use copper heat dissipater and higher thermal conductivity material (128W/m·K) can apparently lower the junction temperature of the transistor
- The higher efficiency of SSPA circuit at 500 MHz becomes possible
- Change the matching point can improve the efficiency from 65%/1010W→ 70%/915W
- Much lower junction temperature of the transistor: 115 ℃→ 88 ℃
- If we can improve the transistor efficiency to its theoretical maximum -- Class AB: ≦ 78.5%: the efficiency of overall SSPA system can reach higher than 70%

| | $Eff_{AC\text{-}DC}$ | $Eff_{DC\text{-}RF}$ | IL | $Eff_{combi}$ | $Eff_{total}$ |
|---|---|---|---|---|---|
| #1 | 90% | 62% | 2% | 99% | 54.14% |
| #2 | 95% | 62% | 2% | 99% | 57.14% |
| #3 | 95% | 70% | 2% | 99% | 64.52% |
| #4 | 95% | 78.5% | 2% | 99% | 72.38% |

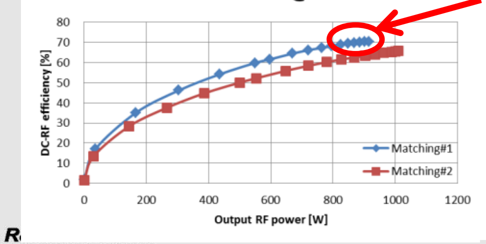
**Present** → #3

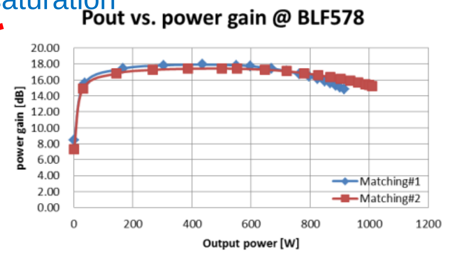
**Dream target** → #4

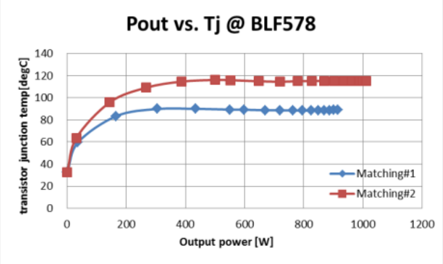
Inlet water temp: 20 ℃
Water flow rate: 15 Lit/min
TC of thermal grease: 128 W/m·K




70% at saturation



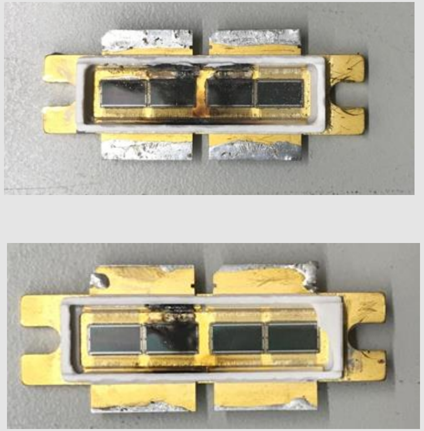



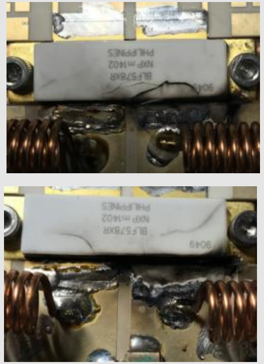
# The faulty cases

- Four categories of faulty type:
  - The melt of ceramic capacitors
  - The arc at metal capacitor
  - The arc at transistor
  - The melt at transistor lead

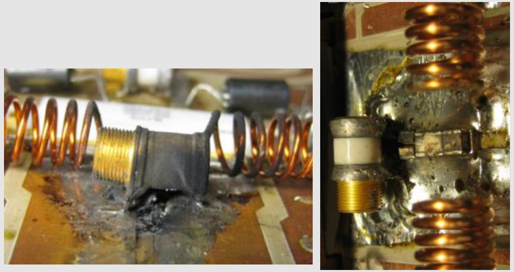

Overdrive



The arc of transistor due to output mismatching or oscillation



Poor cooling of output PCB and causing the melting of transistor lead



Ceramic capacitor over heat

Poor solder of metal cap to cause arc

# Conclusion

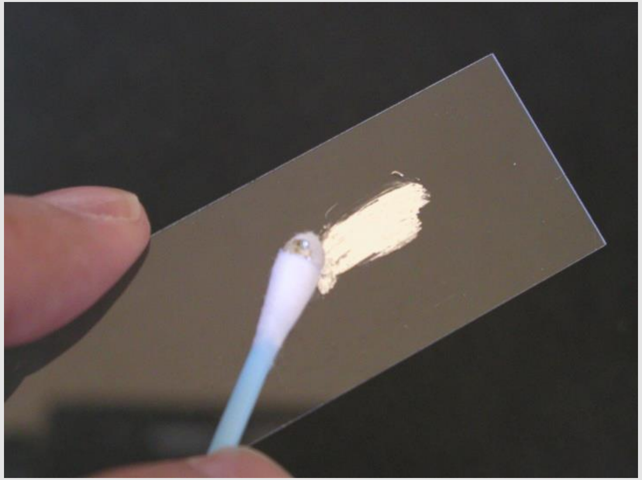
- The temperature of the transistor and circuit were observed and calibrated through IR camera
- The material of heat dissipater and the thermal conductivity of thermal grease also affects the junction temperature of the transistor obviously
- A 20-way power combination test stand is constructed to demonstrate the power combination efficiency and the reliability of the design modules with the water cooling dissipater
- The power combination efficiency is quite robust to the discrepancy of SSPA modules
- The junction temperature affects both the efficiency and output power of the transistor
- Higher efficiency of SSPA system is possible by improving the cooling system and using better DC power supply

End

# THANKS FOR YOUR ATTENTION

# Appendix I Liquid metal

- 128 W/m·K liquid metal
- The alloy of Ga, In and Sn metals

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