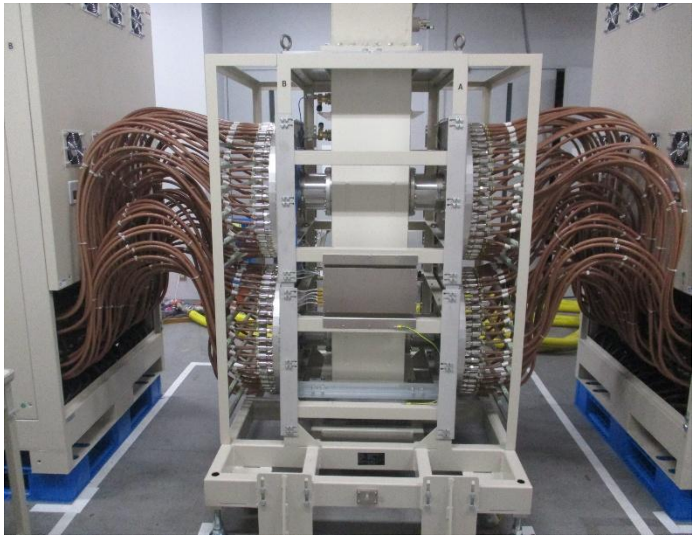
October 7, 2025

Advances in RF Semiconductor Power Amplifier
- Toward Higher Efficiency -

Presented by Reichiro Kobana
R&K Company Limited

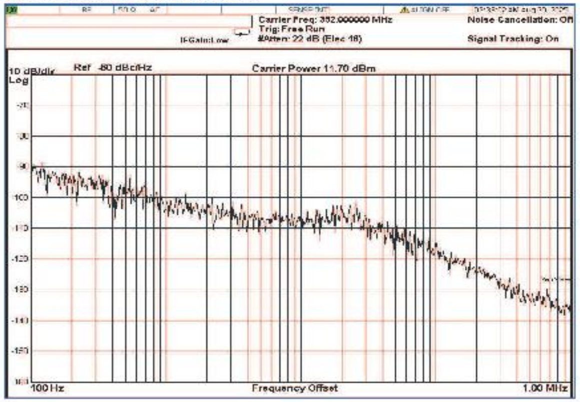
200 kW, then 160 kW SSA – Latest Mass-produced Model (LDMOS)

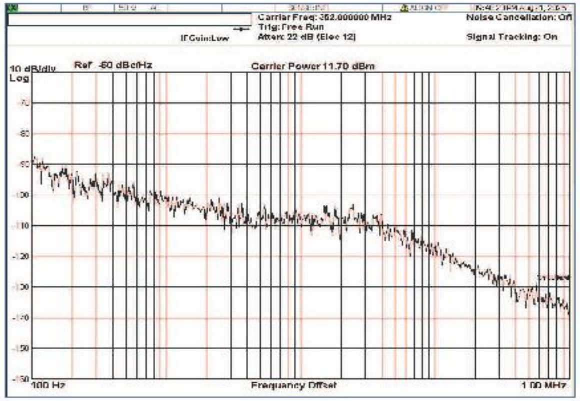
R&K



RF SSPA output signal noise SSB Phase Noise-dBc/Hz

CA352BW2-8282R Phase Noise DATA





RF Synthesizer input signal noise SSB Phase Noise-dBc/Hz

In-depth-analysis of power efficiency

LD-MOS Transistor device(s)

Ampleon BLF978P, ×4×48＝192

Frequency;	352 MHz
Amplifier Gain;	＞+75.0dB
CW RF Power;	＞160kW
DC to RF Device Catalog Efficiency;	＞76.7%
DC to RF Device Linearity-driven −Efficiency;	＞72.0%
AC to DC Efficiency;	＞95.0%
AC to RF Efficiency;	＞61.5%

Estimated RF-Composite Loss

0.72−(0.615÷0.95)＝7.263%

10log(92.737/100)＝—0.32747dB

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The Evolution of RF Power Devices:
From GaAsFET to LDMOS to GaN Devices ①

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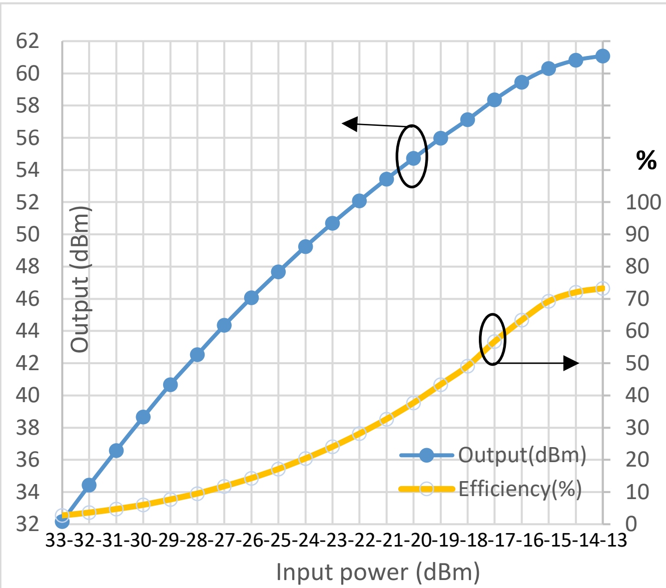
BLF978P/Ampleon TEST DATA (frequency: 352MHz)
Input Signal : CW , Water Temperature : 32℃
Structure : Driver(ALM0105-4748-SMA / Vdd:+12V) + Final (BLF978P / Vdd:+50V , IDQ:150mA)

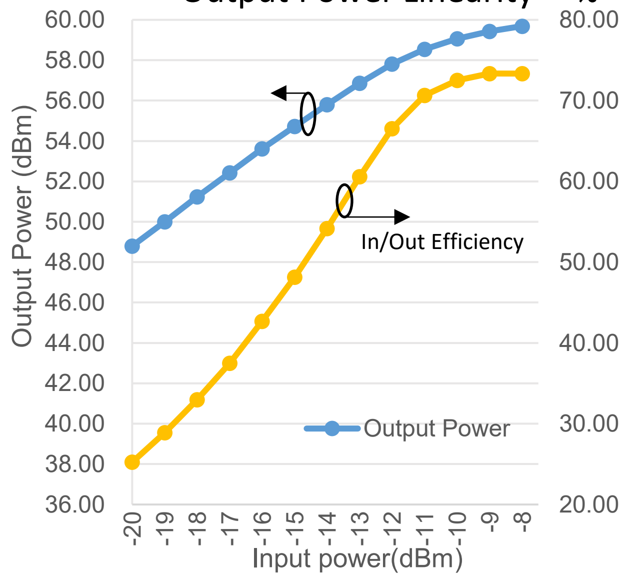
Output Power Linearity



RF Input Power	Driver Output power	RF Output (dBm)	DC-RF Efficiency (%)	Drain Current (A)	RF Power Gain(dB)
-35	14.7	27.93	1.62	0.76	11.23
-34	15.68	29.97	2.14	0.93	12.29
-33	16.68	32.18	2.76	1.20	13.50
-32	17.7	34.43	3.63	1.53	14.73
-31	18.7	36.58	4.74	1.92	15.88
-30	19.69	38.66	6.03	2.44	16.97
-29	20.68	40.68	7.71	3.03	18.00
-28	21.69	42.53	9.53	3.76	18.84
-27	22.7	44.36	11.80	4.62	19.66
-26	23.68	46.07	14.31	5.66	20.39
-25	24.68	47.68	17.16	6.83	21.00
-24	25.69	49.24	20.44	8.21	21.55
-23	26.67	50.7	24.07	9.76	22.03
-22	27.67	52.09	28.15	11.50	22.42
-21	28.69	53.44	32.66	13.52	22.75
-20	29.67	54.72	37.70	15.73	23.05
-19	30.68	55.97	43.39	18.23	23.29
-18	31.67	57.13	49.16	21.01	23.46
-17	32.67	58.37	56.76	24.21	23.70
-16	33.66	59.46	63.38	27.86	23.80
-15	34.65	60.3	69.22	30.96	23.65
-14	35.65	60.82	72.02	33.54	23.17
-13	36.58	61.09	73.26	35.09	22.51

Linearity and DC to RF Efficiency
Device : +D.A. (R&K ALM0105-4748-SMA)
+ F.A. (BLF978P/ Ampleon) single device
Signal : CW RF Power at 500MHz %
DC Power : VDD = +45 Volts, IDQ = 200 mA, at AB, (adjustment for Linearity matching.
Cooling water: +25℃

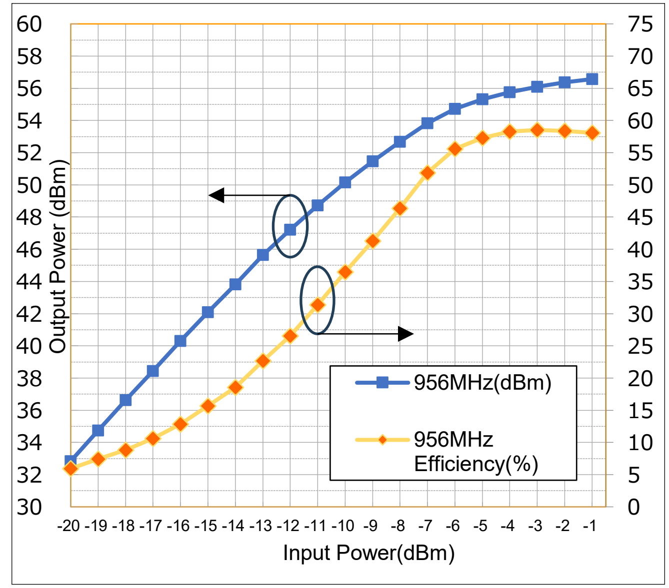
Output Power Linearity



Input Power(dBm)	DA Power	Output Power	Power Gain	Drain Current	Efficiency %
-20.0	26.64	48.80	22.16	6.64	25.23
-19.0	27.55	50.00	22.45	7.65	28.88
-18.0	28.54	51.23	22.69	8.90	32.97
-17.0	29.48	52.42	22.94	10.30	37.47
-16.0	30.46	53.61	23.15	11.90	42.67
-15.0	31.44	54.72	23.28	13.62	48.15
-14.0	32.44	55.80	23.36	15.53	54.15
-13.0	33.42	56.86	23.44	17.72	60.58
-12.0	34.42	57.81	23.39	20.08	66.53
-11.0	35.43	58.54	23.11	22.37	70.63
-10.0	36.45	59.07	22.62	24.60	72.52
-9.0	37.45	59.43	21.98	26.40	73.35
-8.0	38.45	59.69	21.24	28.00	73.34
	(dBm)	(dBm)	(dB)	(A)	(%)

Linearity and DC to RF Efficiency
Device : +D.A. (R&K ALM0510-3846-SMA)
+ F.A. (MRF13750H/NXP) single device
Signal : CW RF Power at 956MHz
DC Power : VDD = +42.5 Volts, IDQ = 100 mA, at AB, +31℃

%



Input Power (dBm)	Driver Output (dBm)	Output Power (dBm)	Drain Current (A)	Efficiency (%)	RF Power Gain (dB)
-20	20.61	32.84	0.76	5.93	12.23
-19	21.61	34.74	0.94	7.43	13.13
-18	22.63	36.63	1.22	8.85	14.00
-17	23.69	38.44	1.54	10.63	14.75
-16	24.65	40.31	1.96	12.85	15.66
-15	25.69	42.09	2.42	15.68	16.40
-14	26.69	43.81	3.04	18.54	17.12
-13	27.79	45.65	3.80	22.66	17.86
-12	28.81	47.21	4.64	26.57	18.40
-11	29.79	48.72	5.56	31.39	18.93
-10	30.81	50.16	6.66	36.50	19.35
-9	31.79	51.47	7.96	41.28	19.68
-8	32.74	52.68	9.36	46.38	19.94
-7	33.75	53.82	10.88	51.85	20.07
-6	34.73	54.72	12.48	55.59	19.99
-5	35.72	55.31	13.86	57.29	19.59
-4	36.70	55.75	15.06	58.29	19.05
-3	37.71	56.10	16.24	58.52	18.39
-2	38.68	56.37	17.30	58.38	17.69
-1	39.62	56.57	18.18	58.06	16.95

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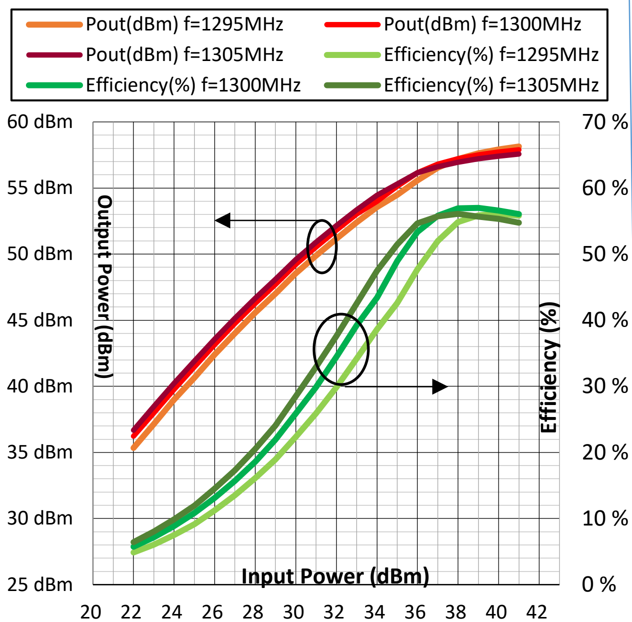
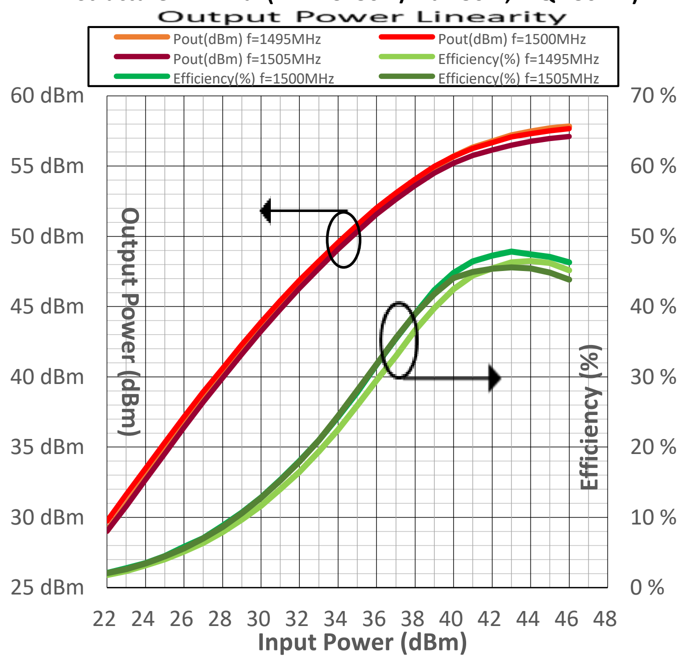
MRF13750H/NXP TEST DATA (frequency: 1300MHz)
Input Signal : CW , Water Temperature : +28℃
Structure : Final (MRF13750H / Vd:+50V , IDQ:150mA)

Output Power Linearity



f=1300MHz				
Vdd=+50.0V, Total Idq=150mA				
Pout(dBm)	Id(A)	Pout(W)	Efficiency(%)	Gps(dB)
+36.23 dBm	1.41 A	4.20 W	5.73 %	14.23 dB
+38.00 dBm	1.71 A	6.31 W	7.15 %	15.00 dB
+39.77 dBm	2.08 A	9.48 W	8.88 %	15.77 dB
+41.48 dBm	2.54 A	14.06 W	10.82 %	16.48 dB
+43.15 dBm	3.09 A	20.65 W	13.11 %	17.15 dB
+44.74 dBm	3.74 A	29.79 W	15.66 %	17.74 dB
+46.27 dBm	4.49 A	42.36 W	18.59 %	18.27 dB
+47.70 dBm	5.30 A	58.88 W	21.92 %	18.70 dB
+49.22 dBm	6.38 A	83.56 W	25.88 %	19.22 dB
+50.54 dBm	7.50 A	113.24 W	29.86 %	19.54 dB
+51.83 dBm	8.75 A	152.41 W	34.47 %	19.83 dB
+53.03 dBm	10.14 A	200.91 W	39.23 %	20.03 dB
+54.00 dBm	11.46 A	251.19 W	43.40 %	20.00 dB
+55.13 dBm	13.19 A	325.84 W	48.93 %	20.13 dB
+56.14 dBm	15.26 A	411.15 W	53.36 %	20.14 dB
+56.80 dBm	16.97 A	478.63 W	55.82 %	19.80 dB
+57.22 dBm	18.30 A	527.23 W	56.93 %	19.22 dB
+57.51 dBm	19.50 A	563.64 W	56.99 %	18.51 dB
+57.72 dBm	20.55 A	591.56 W	56.60 %	17.72 dB
+57.89 dBm	21.50 A	615.18 W	56.05 %	16.89 dB

MRF13750H/NXP TEST DATA (frequency: 1500MHz)
Input Signal : CW , Water Temperature : +28℃
Structure : Final (MRF13750H / Vd:+50V , IDQ:150mA)



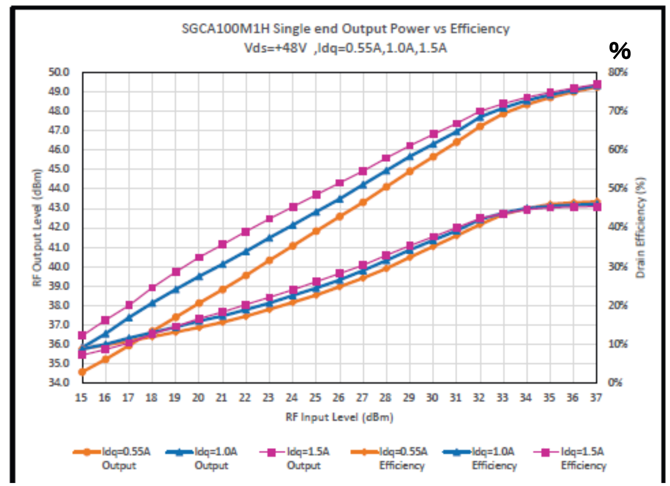
f=1500MHz				
Vdd=+50.0V, Total Idq=150mA				
Pout(dBm)	Id(A)	Pout(W)	Efficiency(%)	Gps(dB)
+29.73 dBm	0.75 A	0.94 W	2.08 %	7.73 dB
+31.61 dBm	0.91 A	1.45 W	2.75 %	8.61 dB
+33.48 dBm	1.13 A	2.23 W	3.50 %	9.48 dB
+35.34 dBm	1.39 A	3.42 W	4.47 %	10.34 dB
+37.16 dBm	1.65 A	5.20 W	5.82 %	11.16 dB
+38.92 dBm	2.07 A	7.80 W	7.05 %	11.92 dB
+40.62 dBm	2.48 A	11.53 W	8.79 %	12.62 dB
+42.29 dBm	3.02 A	16.94 W	10.69 %	13.29 dB
+43.89 dBm	3.66 A	24.49 W	12.84 %	13.89 dB
+45.42 dBm	4.38 A	34.83 W	15.33 %	14.42 dB
+46.88 dBm	5.24 A	48.75 W	18.00 %	14.88 dB
+48.25 dBm	6.18 A	66.83 W	20.98 %	15.25 dB
+49.57 dBm	7.25 A	90.57 W	24.29 %	15.57 dB
+50.82 dBm	8.46 A	120.78 W	27.81 %	15.82 dB
+52.02 dBm	9.79 A	159.22 W	31.71 %	16.02 dB
+53.09 dBm	11.21 A	203.70 W	35.45 %	16.09 dB
+54.08 dBm	12.81 A	255.86 W	38.96 %	16.08 dB
+54.98 dBm	14.50 A	314.77 W	42.32 %	15.98 dB
+55.69 dBm	16.10 A	370.68 W	44.81 %	15.69 dB
+56.27 dBm	17.70 A	423.64 W	46.45 %	15.27 dB
+56.68 dBm	19.03 A	465.59 W	47.27 %	14.68 dB
+57.07 dBm	20.46 A	509.33 W	47.84 %	14.07 dB
+57.31 dBm	21.64 A	538.27 W	47.43 %	13.31 dB
+57.52 dBm	22.65 A	564.94 W	47.09 %	12.52 dB
+57.67 dBm	23.53 A	584.79 W	46.32 %	11.67 dB

Linearity and DC to RF Efficiency
Device : F.A. (SGCA100M1H / SEDI) single device
Signal : CW RF Power at 3900MHz
DC Power : VDD = +48 Volts, IDQ = 0.55A, 1.0A, 1.5A at AB, (adjustment for Linearity matching.)
Cooling water: +25℃

Output Power Linearity

⑦ Output Power vs Efficiency Efficiency%=Output Power/(+48V*Current)*100

	3900MHz								
Input	Idq=0.55A Output	+48V Drain Current	Idq=0.55A Efficiency	Idq=1.0A Output	+48V Drain Current	Idq=1.0A Efficiency	Idq=1.5A Output	+48V Drain Current	Idq=1.5A Efficiency
+15dBm	+34.58dBm	0.67A	8.9%	+35.84dBm	0.91A	8.8%	+36.45dBm	1.27A	7.2%
+16dBm	+35.23dBm	0.71A	9.8%	+36.55dBm	0.94A	10.0%	+37.25dBm	1.27A	8.7%
+17dBm	+35.94dBm	0.75A	10.9%	+37.38dBm	0.98A	11.6%	+38.00dBm	1.27A	10.4%
+18dBm	+36.67dBm	0.81A	11.9%	+38.13dBm	1.04A	13.0%	+38.92dBm	1.29A	12.6%
+19dBm	+37.40dBm	0.87A	13.2%	+38.83dBm	1.10A	14.5%	+39.73dBm	1.34A	14.6%
+20dBm	+38.12dBm	0.94A	14.4%	+39.50dBm	1.16A	16.0%	+40.48dBm	1.40A	16.6%
+21dBm	+38.82dBm	1.01A	15.7%	+40.13dBm	1.24A	17.3%	+41.14dBm	1.48A	18.3%
+22dBm	+39.55dBm	1.09A	17.2%	+40.79dBm	1.32A	18.9%	+41.81dBm	1.56A	20.3%
+23dBm	+40.32dBm	1.18A	19.0%	+41.48dBm	1.42A	20.6%	+42.46dBm	1.66A	22.1%
+24dBm	+41.07dBm	1.28A	20.8%	+42.14dBm	1.51A	22.6%	+43.08dBm	1.76A	24.1%
+25dBm	+41.83dBm	1.40A	22.7%	+42.82dBm	1.63A	24.5%	+43.70dBm	1.87A	26.1%
+26dBm	+42.58dBm	1.52A	24.8%	+43.49dBm	1.75A	26.6%	+44.31dBm	1.99A	28.2%
+27dBm	+43.31dBm	1.65A	27.1%	+44.22dBm	1.90A	29.0%	+44.92dBm	2.13A	30.4%
+28dBm	+44.11dBm	1.82A	29.5%	+44.95dBm	2.06A	31.6%	+45.59dBm	2.29A	33.0%
+29dBm	+44.91dBm	1.99A	32.4%	+45.67dBm	2.24A	34.3%	+46.23dBm	2.47A	35.4%
+30dBm	+45.66dBm	2.18A	35.2%	+46.31dBm	2.42A	36.8%	+46.81dBm	2.65A	37.7%
+31dBm	+46.41dBm	2.40A	38.0%	+46.95dBm	2.63A	39.2%	+47.37dBm	2.84A	40.0%
+32dBm	+47.22dBm	2.69A	40.8%	+47.70dBm	2.91A	42.2%	+48.00dBm	3.10A	42.4%
+33dBm	+47.88dBm	2.94A	43.5%	+48.17dBm	3.12A	43.8%	+48.39dBm	3.29A	43.7%
+34dBm	+48.35dBm	3.17A	44.9%	+48.56dBm	3.32A	45.0%	+48.72dBm	3.47A	44.7%
+35dBm	+48.71dBm	3.36A	46.1%	+48.85dBm	3.51A	45.5%	+48.97dBm	3.64A	45.1%
+36dBm	+49.00dBm	3.56A	46.5%	+49.10dBm	3.69A	45.9%	+49.19dBm	3.81A	45.4%
+37dBm	+49.25dBm	3.75A	46.7%	+49.33dBm	3.87A	46.1%	+49.39dBm	3.98A	45.5%



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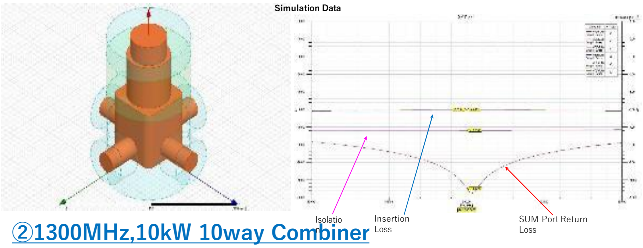
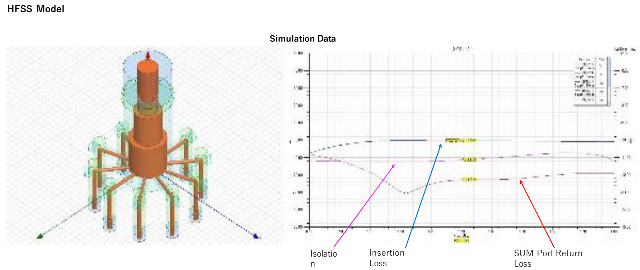
3D Simulation: Mastery and the Art of Spatial Symmetry

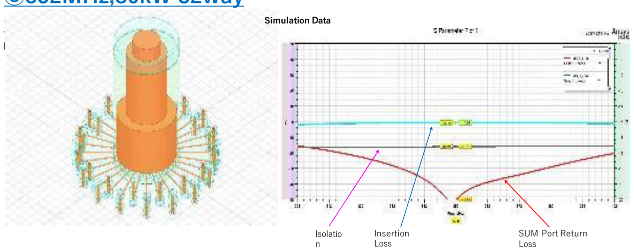
①500MHz,350kW(Pulse) 4way



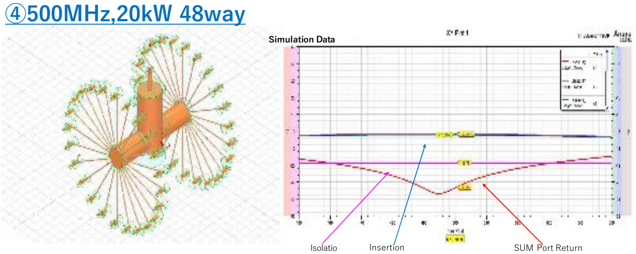
②1300MHz,10kW 10way Combiner



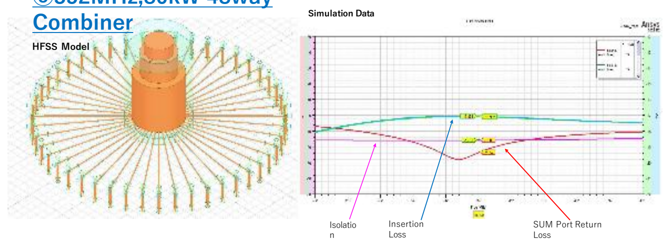
③352MHz,80kW 32way



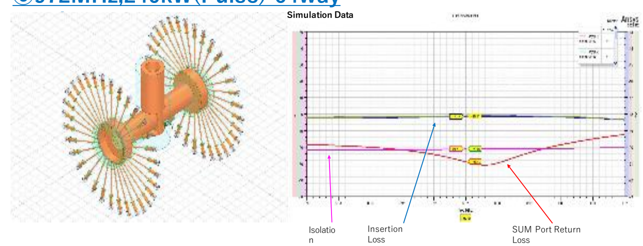
④500MHz,20kW 48way



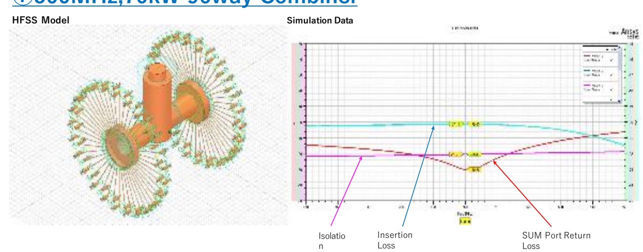
⑤352MHz,80kW 48way Combiner



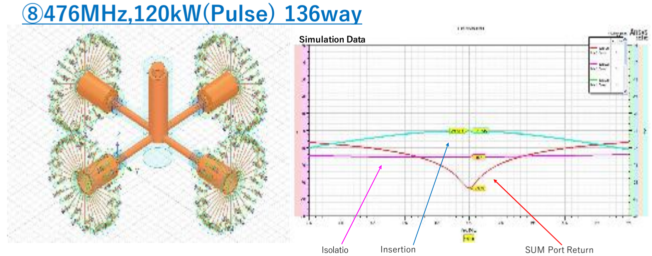
⑥972MHz,240kW(Pulse) 64way



⑦500MHz,70kW 96way Combiner



⑧476MHz,120kW(Pulse) 136way



※ Low power consumption,
※ high efficiency
※ low cost,

are all realized with following rugged radial power combiner circuits by HFSS and COMSOL simulation design.

◎ Odd, Even, and Prime ports design are all available.
◎ Max power is only limited up to the connector design.
◎ Isolation to adjacent ports are achieved by the number of branches.
◎ Max. insertion loss is only -0.05dB to -0.15dB max. with very broadband.
◎ RF Power Combiner using cavity resonators have high Q and low loss, but this method has a very low Q, so the temperature characteristics are very stable and the loss is relatively low.
In particular, most RF losses are caused by coax-cables, so the power combining method of the future will likely shift “coax with waveguide cascaded combiners”.

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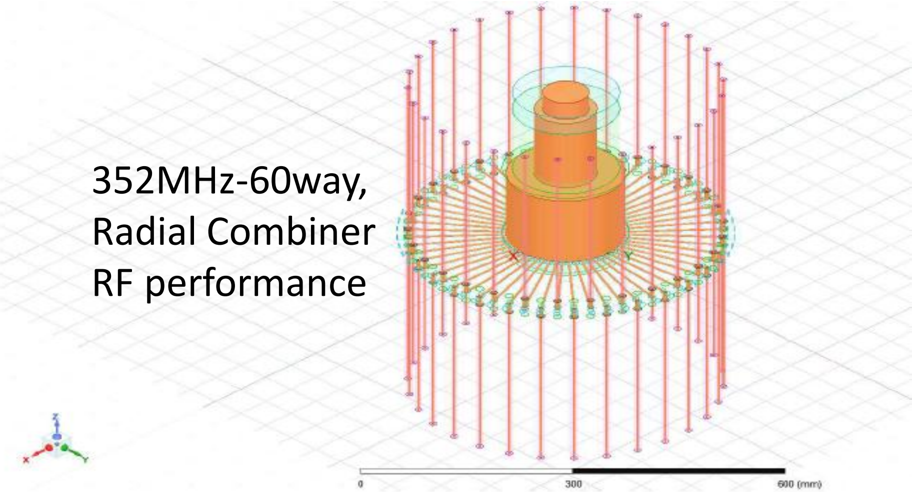
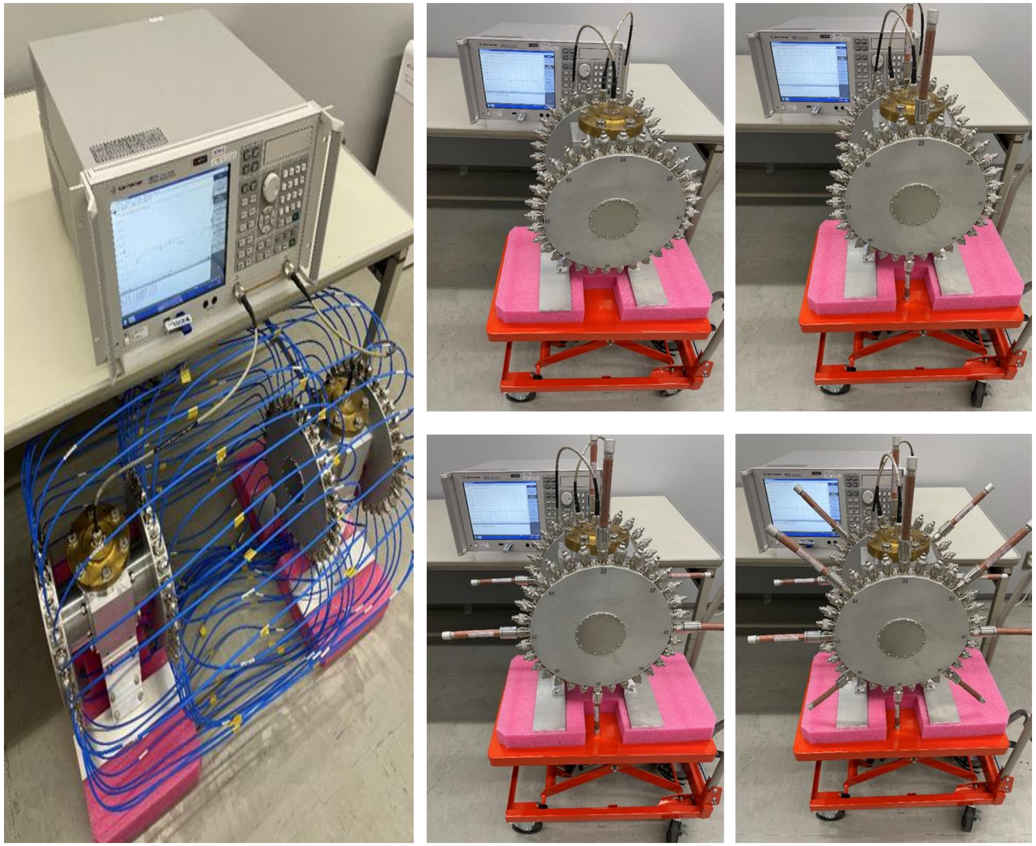
Perfect Restoration of Missing Regularity through 3D Spatial Symmetry ①

New techniques for achieving optimal Power and Efficiency via adjustments to terminal synthesis "Numbers" of Radial Combiners. Quadrature short.

Single structure, but Multiple ports RF Power Combiner, at 972MHz＞240kW-Pulsed RF, 64/60/56/48way design.

352MHz-60way, Radial Combiner RF performance





352MHz Data

	60way	58way	56way	54way	50way	40way	
Input Return Loss	-1.24	-1.09	-1.08	-1.09	-1.12	-1.12	(dB)
Output Return Loss	-20.24	-21.86	-23.78	-26.28	-32.46	-19.24	(d B)
Isolation	-13.34	-12.87	-12.88	-12.89	-12.77	-12.13	(dB)

352MHz Insertion Loss

	60way	58way	56way	54way	50way	40way	
Theoretical loss	-17.78	-17.63	-17.48	-17.32	-16.99	-16.02	(dB)
Loss	-17.86	-17.52	-17.52	-17.4	-17.08	-16.18	(dB)

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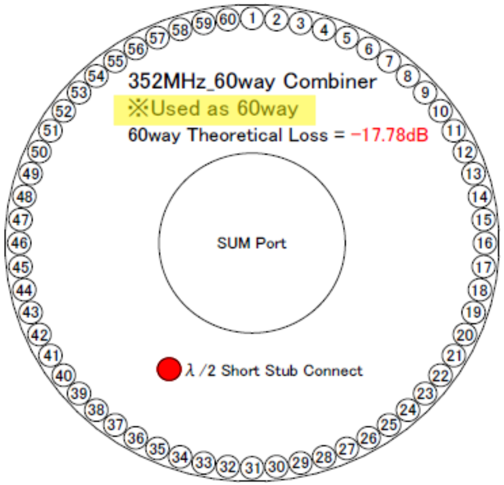
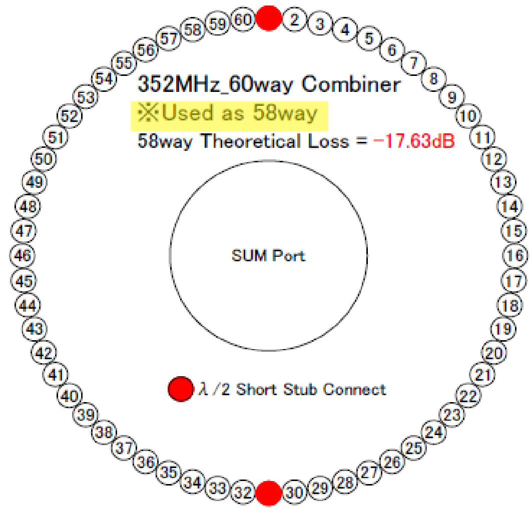
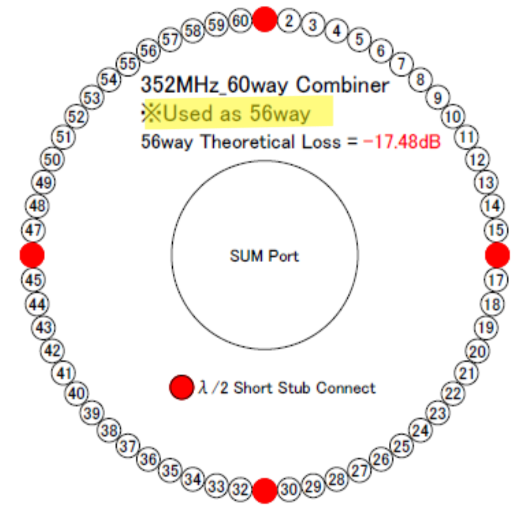
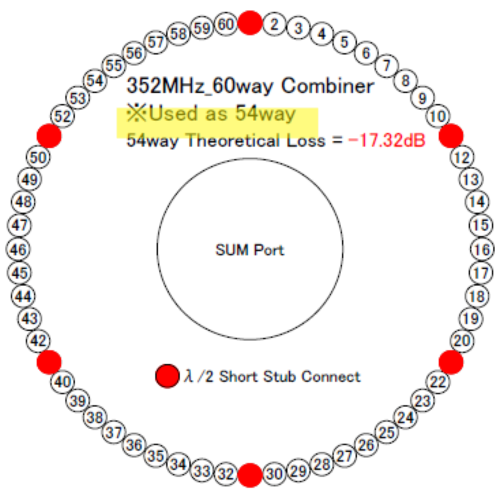
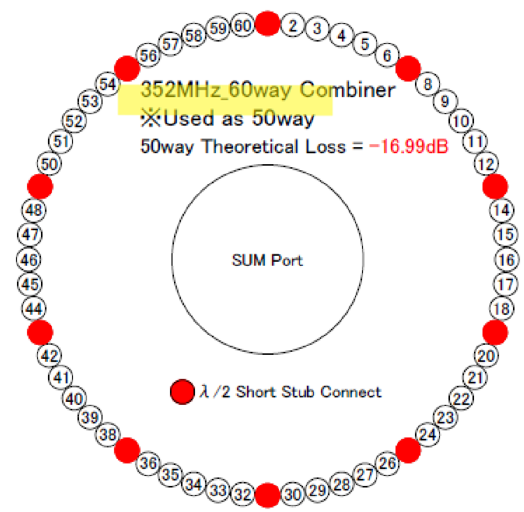
Perfect Restoration of Missing Regularity through 3D Spatial Symmetry ②

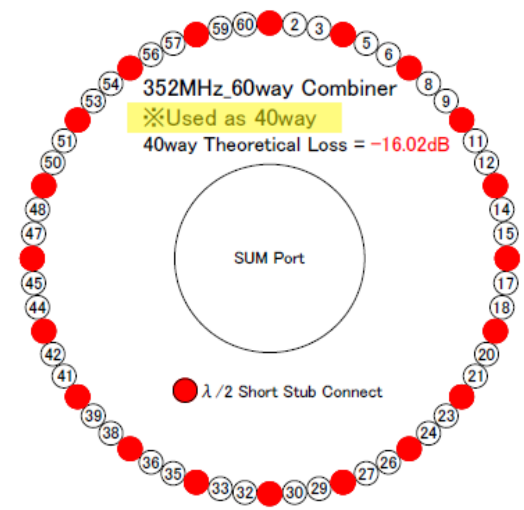












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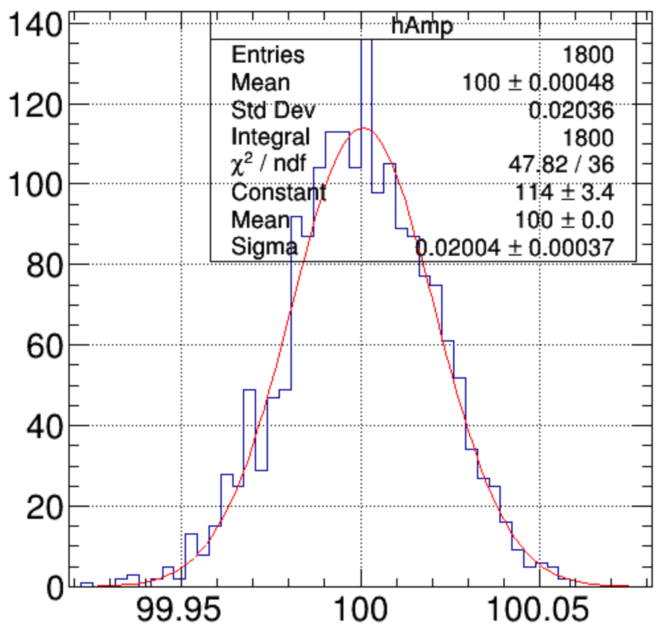
R&K 476MHz SSA for SACLA - pulse by pulse stability

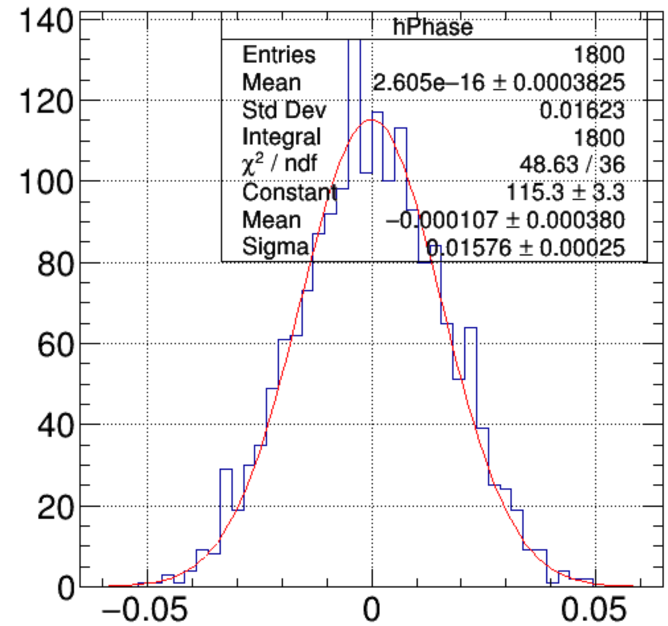
R&K

Stability (short term)

- RF-out @ 100kW @476MHz
  0.020% , 0.016deg (sigma)

I would like to express my sincere gratitude to the RIKEN team for giving us the opportunity to collect "phase and level stability data under free-running conditions of RF over 100kW".
For a long time, cost, reliability, and power efficiency came first, and it has been difficult for us to obtain such fulfilling stability data.
Conventional vacuum tube amplifiers always have an electron transit time, and they are extremely sensitive to the thermal noise. They are noise source.
However, as shown here, solid-state amplifier is now possible to achieve this level of stability even without locking the signal by LLRF.





Level vector stability σ A/A [%]

Phase vector stability σ phase [deg]

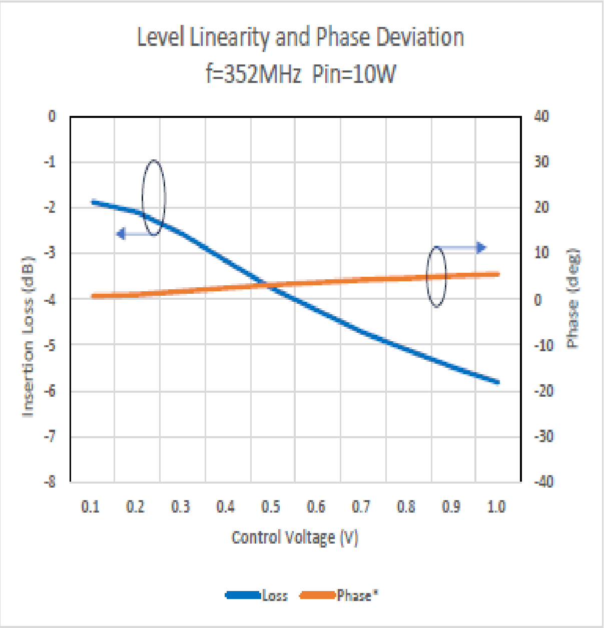
JASRI/RIKEN Eito Iwai, 2024, Private Communication

R&K Analog RF Phase & Level Controller

②Level Control Voltage =0.1-1.0V (Phase Control Voltage=0.7V fix)

Control Volt	Loss	Phase*
0.1	-1.86	0.78
0.2	-2.09	1.04
0.3	-2.56	1.78
0.4	-3.17	2.57
0.5	-3.76	3.27
0.6	-4.24	3.78
0.7	-4.72	4.30
0.8	-5.11	4.69
0.9	-5.49	5.16
1.0	-5.82	5.51

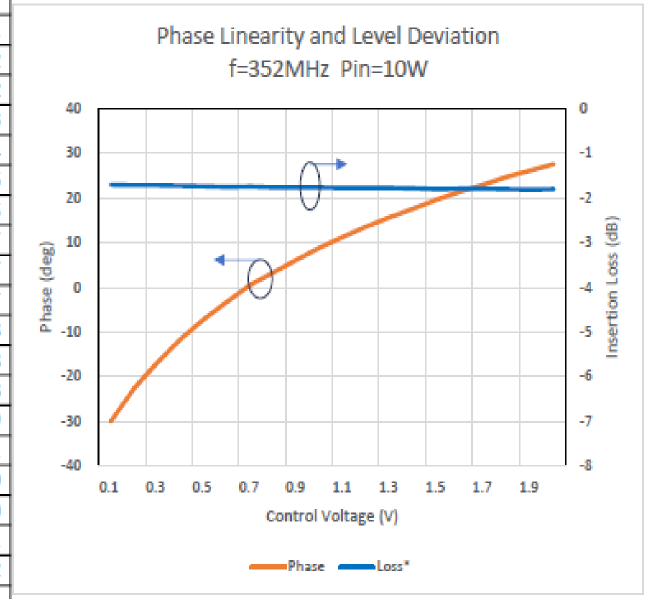
*0.7V fix

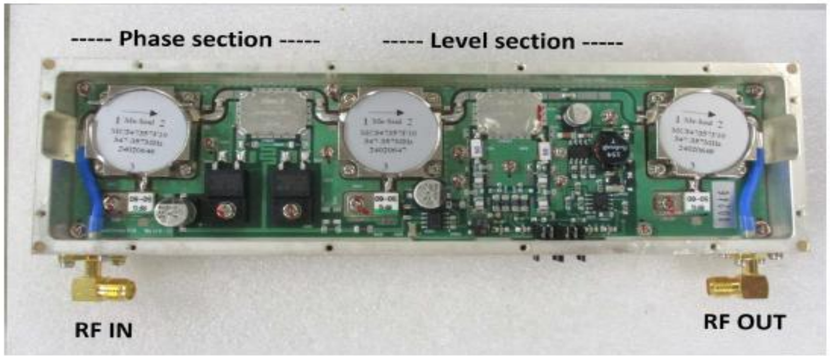


①Phase Control Voltage =0.1-2.0V (Level Control Voltage=0V fix)

Control Volt	Phase	Loss*
0.1	-30.00	-1.71
0.2	-22.65	-1.72
0.3	-16.90	-1.72
0.4	-11.60	-1.73
0.5	-7.10	-1.74
0.6	-3.20	-1.76
0.7	0.60	-1.75
0.8	3.36	-1.77
0.9	6.24	-1.77
1.0	8.95	-1.77
1.1	11.32	-1.78
1.2	13.61	-1.78
1.3	15.71	-1.78
1.4	17.63	-1.79
1.5	19.62	-1.81
1.6	21.39	-1.80
1.7	23.00	-1.80
1.8	24.68	-1.81
1.9	26.12	-1.82
2.0	27.52	-1.81

*0V fix





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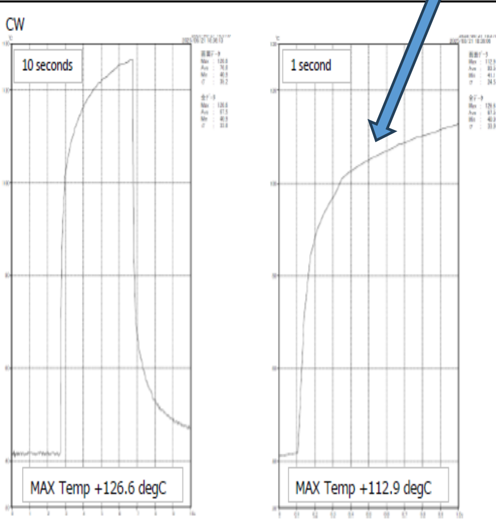
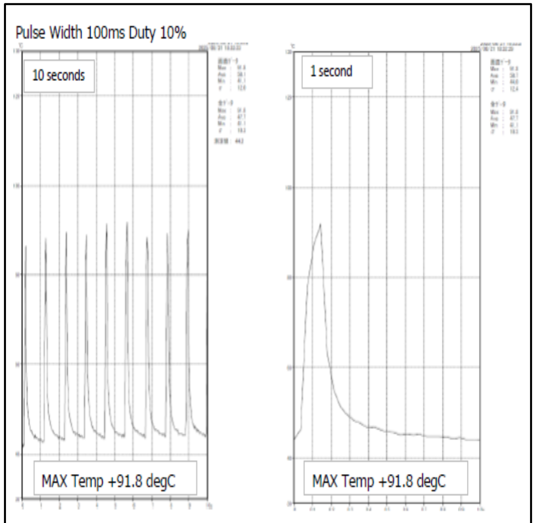
Conditions Frequency 352MHz
Output Power 1,050W
Water temperature +32degC
Transistor BLF9782P (AMPLEON)

○ Temperature measurement point

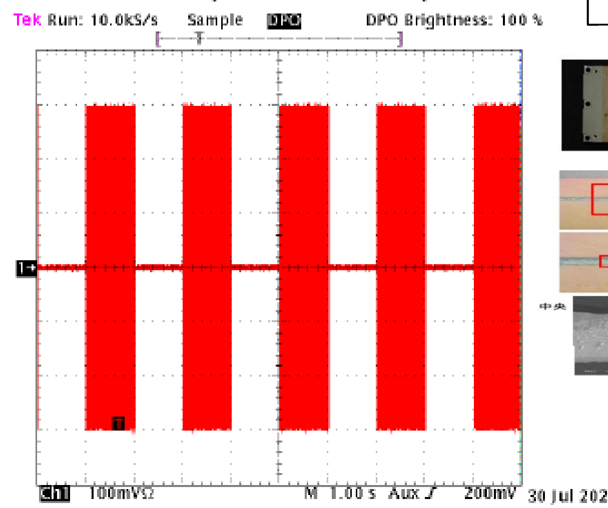




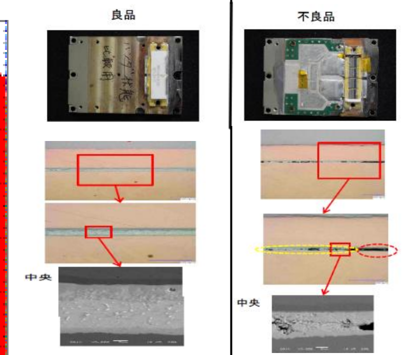
Measurement Condition

- Frequency: 1,300MHz
- Pallet (Device + Circulator + Directional Coupler) Output (ON): 630W@ 50ohm
- Output (OFF): 0W@ 50ohm
- Environmental Temperature: +25decC to 28degC
- Water Temperature: +30degC
- ON/OFF Ratio: 1sec / 1sec (duty=50%)
- ON/OFF Count: 2 million times
- Test Period: 2-July 2025, 14:59 to 18-August, 2025, 9:31

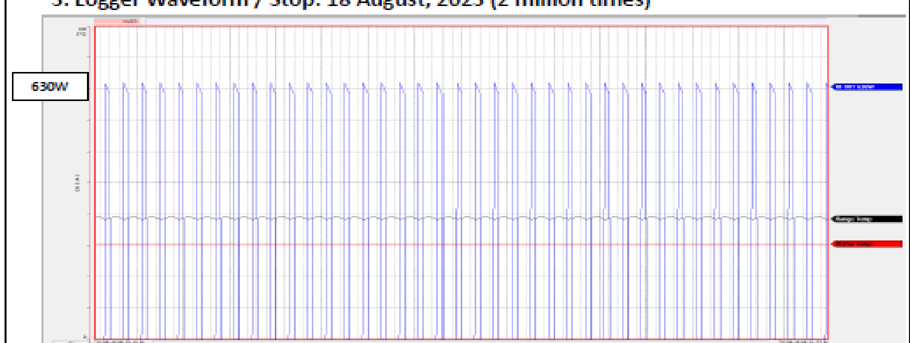
1. Pulse waveform (ON: 1sec/ OFF: 1sec)



Soldering Fatigue



5. Logger Waveform / Stop: 18 August, 2025 (2 million times)



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