HEAT DISTRIBUTION ANALYSIS OF PLANAR BALUNS FOR 1kW SOLID-STATE AMPLIFIERS AND POWER COMBINING FOR 1.8kW*

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Abstract

Solid-state transmitter for booster and storage ring in synchrotron would be composed of hundreds of amplifier modules. The amplifier module is biased at class AB and constructed in push-pull operation. Recent trend of amplifier module design features higher power up to 800 Watts and equipped planar balun (balance-unbalance converter) for push-pull operation. In NSRRC, the exclusive round planar design has encountered high temperature situation at kW range. Therefore, further study on this thermal condition is carried out in this study. Four types of planar balun design and two laminate materials are used for heat analysis. The typical coaxial balun is also applied on actual amplifier design. The results bring the better design with proper laminate choice and leads to acceptable thermal distribution with 1kW output power at 500MHz. Besides, for a more compact module with higher output power, the combination of two chips on the same circuit reaching 1.8kW is also presented.

INTRODUCTION

Since the usage of solid-state technology for high power transmitter application has become more and more popular in accelerator facilities application [1-2], the study of the basic property of solid-state amplifier module in maximum available power is still required. In UHF band, the common used transistors are Freescale MRF6VP41KH and NXP BLF578 serial chips [3-4]. The above chips can operate reliably with properly water cooling below them. Although these chips claim them to have maximum output power of more than 1200W in pulse operation, for CW operation, due to thermal dissipation limitation with the increasing temperature, the practically available maximum power is still limited within 1000Watt [3].

In 2013, NSRRC has developed an exclusive kind planar balun with low loss that can greatly reduce the generated heat on it [5]. However, the thermal study still lacks systematic experiments to diagnosis what is the key issue affecting the thermal distribution and RF performance. In this article, four versions of planar balun and one coaxial balun on two kinds of microwave laminate are manufactured with BLF578 chip and tuned to have 1kW saturation power. The thermal distribution at output parts of the amplifier circuits are thus discussed in a more detail manner.

PLANAR BALUNS WITH BALANCE TUNING MECHANISM

Several versions of printed planar balun have been designed and applied on the push-pull amplifier circuit design in the past two years in NSRRC. Although the printed balun can successfully deliver 1kW output power continuously without problem, certain power degradation and higher driving power is also observed during tests. Unlike coaxial balun soldered on circuit which has better thermal transmission path through substrate and heat sink, the printed balun is actually floated without touching base heat sink for efficient thermal transmission path. Besides, the proposed planar baluns is modified from Marchand balun [6] and forming circulator shape, some tuning is still necessary for better amplitude and phase balance. In order to have flexibility of tuning, the tuning mechanism is kept in each version as shown in Fig. 1.

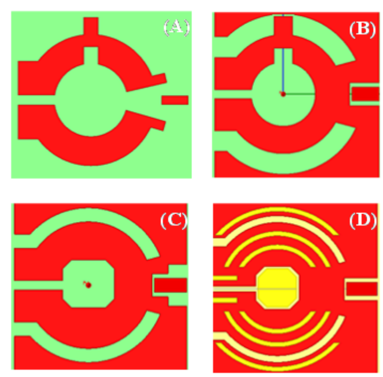

Figure 1: Evolution of four types of planar baluns (A) a simple modified Marchand balun with tuning stub(B) ground surrounding of version (A) (C) planar balun with square centre tuning slot (D) heat sink fin added balun.

EXPERIMENTAL SETUP: LAMINATE AND COAXIAL BALUN

Based upon the above four types of balun, two kinds of laminates are also chosen as their substrate for the circuits to be printed on. These two laminates are Rogers RO4003C and RO6035HTC which have similar permittivity but significant difference in dielectric loss and thermal conductivity. The basic property of the laminate is listed in Table 1.

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Table 1: Laminate Properties

Material	RO4003C	RO6035HTC
Thickness	30mil	30mil
Dielectric constant, ε_r	3.55	3.5
Dielectric loss	0.0021	0.0013
Thermal conductivity	0.64W/m/K	1.44W/m/K
Thermal coefficient of ε_r	+40ppm/°C	-66ppm/°C
Maximum operation temperature	>288°C	>288°C

In addition, the coaxial type balun for 1kW demonstration was also fabricated as reference by NXP application note [7]. The example 1kW circuits by planar balun and coaxial balun are shown in Fig. 2 and 3. For impedance tuning purpose, the trimming capacitors are also added on coaxial version which is not shown in Fig. 3(a). The coaxial balun circuit would stop increasing RF power due to thermal limitation of trimming capacitor of 125°C as shown in Fig. 3(b).

The infrared image for these circuits will be monitored during power tests by IR camera - FLIR SC325. However, the copper has low emissivity (~0.1-0.2) in Infrared band, it will show low temperature even the metal has gotten hot. Covering black and thin paint with emissivity of 0.95 over the circuit surface would be better for actual temperature reading. The setup is shown in Fig. 2(a). In Fig. 2, the chip has also opened its ceramic cover to see the actual temperature of chip during 1kW operation.

MEASUREMENT PROCEDURE

After the circuits have coverred with black paint, the IR camera will monitor their maximum temperature according to their operating power. Since planar balun (D) has heat sink fin, for better comparison, a 12x12cm AC fan with about 2m/s air speed at the distance 15cm from circuit is used for air cooling during the tests of each circuit. The typical IR image during high power operation is shown in Fig. 2(b). Figure 2(a) shows the chip with its ceramic cover opened and the properly obtained thermal distribution at laminate and copper strip line in (b). The maximum chip temperature is 133°C with 1kW RF power (Let Si emissivity=0.6).

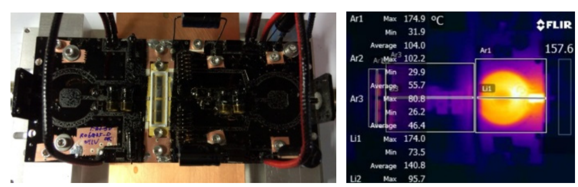
Since each components of the circuit including the laminate has its own maximum allowable operating temperature, the maximum output power will be controlled once any one of the components has reached its safety region. Besides, the solder may start to reflow and cause arc when it reach 200°C, the thermal test will stop when any point of the circuit has reach 200°C. Table 2 shows the temperature limitation during this test according their datasheet.

Table 2: Thermal Limitation of Overall Circuit

Components	Maximum allowable temperature
Laminate	>288°C
Solder	200°C
Trimming capacitor	125°C
Metal cap	200°C
Ceramic cap	125°C

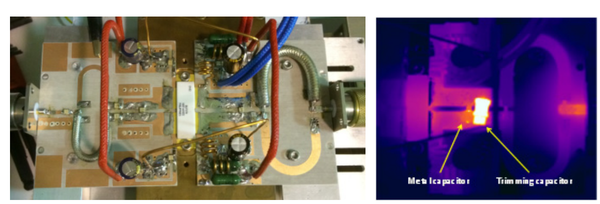
INFRARED RESULTS

There are two kinds of laminate and five kinds of baluns to be tested. However, not all of the baluns are fabricated on both materials. Planar balun types (A)-(C) as shown in Fig. 1 are fabricated on two laminates, while planar balun (D) in Fig. 1 only be put on laminate RO6035 and coaxial balun on RO4003. The interesting phenomenon found during test is that the coaxial balun type amplifier did not have high thermal situation over its coaxial, however, the trimming capacitor and its nearby metal cap has become hot when the output power getting close to 500W as shown in Fig. 3(b). According the NXP's application note AN10967 [7], even using the metal cap, the temperature can still reach 155°C under CW 1000W output power. The high temperature of the trimming capacitor may result from its poor thermal conducting ceramic case.



(a) (b)

Figure 2: (a) The thin black paint with emissivity of 0.95 covering the circuit (b) The IR image of the amplifier circuits during 1kW operation.



(a) (b)

Figure 3: (a) The reference circuit using coaxial balun and its (b) IR image at output parts with 500W output power.

Upon the arrangement of the laminate and baluns described above, the maximum temperature over the circuit versus output power of these 1kW circuits are shown in Fig. 4. These curves tell that the higher thermal conductivity can obviously decrease the maximum operating temperature during high power operation. The

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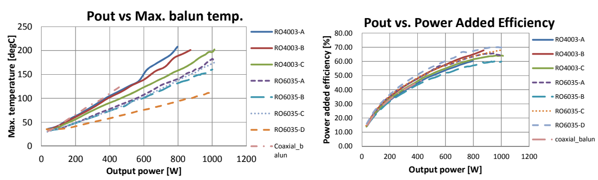
planar balun (C) can also decrease its loss by eliminating the discontinuity of phase/amplitude control stub over the planar balun on substrate RO4003C. On RO6035HTC, the performance of these three types of baluns does have significant improvement even though there is no heat sink fin over it. The excellent low temperature one is the balun (D) which reaches only 120°C when it runs at 1000W/500MHz comparing to the demo board by NXP (155°C at metal cap). The balun (D) circuit also has the best power added efficiency ((Pout-Pd)/(Vd*Id) of 70%). However, the RF performance of the two laminates has no significant difference, since the efficiency of the chip also has close relationship with proper impedance matching, the balance of the chips within and the bias condition. In summary, keeping output circuit temperature as low as possible shall be a safer condition for efficient continuous 1kW amplifier module operation

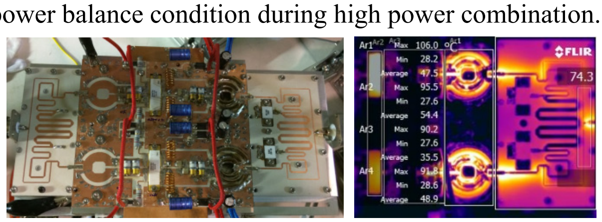


(a) (b)

Figure 4: (a) The maximum temperature and (b) its power added efficiency of various baluns on two ROGERS laminates by sweeping output power.

DUAL CHIP POWER COMBINATION

Since the compact planar balun is quite attractive to combine them within single module, the dual chip combination for higher output power per module is demonstrated here. Figure 5(a) shows the dual chip combination by Gysel power combiner/divider, while its IR image is also shown in Fig. 5(b). The temperature distribution between these two chips can provide actual power balance condition during high power combination.

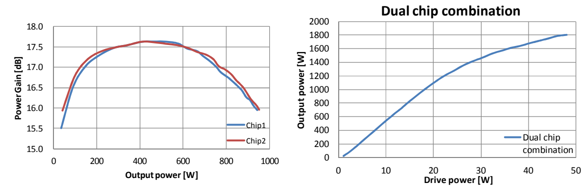


(a) (b)

Figure 5: (a) Dual-chip combination circuit for higher output power in single module (b) Dual chip circuit IR image during operation.

POWER COMBINATION RESULTS

Since the BLF578 transistors are not identical between chips, the fine tune of separate circuits for phase/amplitude equivalent is quite important for efficient power combination. The measured power gain of these two chips is shown in Fig. 6(a). The VNA measured phase and amplitude error between chips are 1.8° and 0.21dB which are acceptable by Gysel power combiner. Figure 6(b) shows the 1800 Watt output power with the available 48W drive power in laboratory.



(a) (b)

Figure 6: (a) The power gain versus output power of two chips before power combination (b) Dual chip power combination results in 1800W RF power.

CONCLUSION

Four types of NSRRC developed planar balun are analysed by 1kW, 500MHz amplifier circuits on two kinds of laminate. The coaxial balun type circuit is also added as reference. The planar balun without perturbing stub can greatly reduce its surface temperature under high RF power. The heat sink fin added one can greatly reduce the thermal situation as well as improve the efficiency of the amplifier at saturation power. In addition to the chip temperature, the heat distribution at any component of high power amplifier circuit shall be as low as possible for reliable system operation. Two chips power combination for 1.8kW at 500MHz is also obtained by Gysel combiner/divider within a single module.

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