A NOVEL PLANAR BALUN STRUCTURE FOR CONTINUOUS WAVE 1KW, 500 MHZ SOLID-STATE AMPLIFIER DESIGN*

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Abstract

In general, the coaxial type baluns (balance-unbalance converter) play key role in push-pull amplifier circuit in the increasing high power solid-state technique transmitter design for accelerator application. However, the coaxial type baluns not only increase the complexity in manufacturing procedure but also introduce additional tolerance variation between modules. The variation between parallel power modules would decreases combining efficiency and thus increase the operation cost. Here, a novel planar balun has been proposed and successfully implemented on 1kW solid-state amplifier design for continuous wave operation with the new fin-added water cooling plates. The results can demonstrate that the feasibility of the newly designed planar balun is quite suitable for CW operation with its excellent low loss, balance property and also handmade free mass production and less variation in between.

INTRODUCTION

In recent years, solid-state technical RF power source have been demonstrated to have great opportunity to replace tube type RF power source, like klystron and IOT in accelerator fields. Especially, SOLEIL has successfully built up and operation 1 x 35 kW and 4 x 180 kW solid-state transmitters for synchrotron operation for more than six years [1] with the claimed high reliability and redundancy. For those solid-state power amplifier modules used in SOLEIL, the saturation power per module adopting VDMOS can reach 330W at the beginning of 21st century [2]. After almost ten years of advancement in semiconductor industry, the latest 6th generation LDMOS has come up with higher voltage, power and ruggedness capability [3]. For the amplifier constructed by ELTA Company for ESRF, the technology transferred from SOLEIL has built up 75kW per tower by 128 650W RF modules with NXP BLF578 power chips. Similarly, APS in US also developed their in house solid-state amplifier by adopting Freescale^{TM} MRF6VP41H chips and its demo circuit design for 1kW output power in a single module [4]. The above modules using NXP or Freescale chips both use coaxial type baluns to achieve push-pull operation. In the mean while, NSRRC also develops in house PA modules using traditional semi-rigid coaxial cable balun for up to 900W output power [5]. Besides the tolerance between chips, the manufacturing process of semi-rigid coaxial type balun contains much human hand participation which, of course, not only introduces more variation than expectation but also is a time consuming process. Thun, ESRF also tried to develop their home-made PA adopting NXP planar balun structure [3] [6] which had encountered the overheating problem on the capacitors soldered on the balun. That square shape balun uses transformer topology (see Fig. 1) to construct the planar balun with 180 degree phase difference and equivalent amplitude at two output ports as well as impedance transformation. However, such multi-turn transformer still brings some additional complexity in layout and calculation. In this article, the proposed novel round planar balun based on Marchand balun structure [7] brings the advantages of much more compact size, simple layout, excellent balance performance, impedance transformation and low loss at 500MHz. Besides the property of the balun itself, it has also been applied successfully on actual solid-state amplifier design for CW 1kW, 500MHz operation. The long-term reliability tests of the newly developed solid-state amplifier using BLF578 chip and the novel balun are under progress with the new cooling plate design with the high thermal conductivity diamond thermal grease.

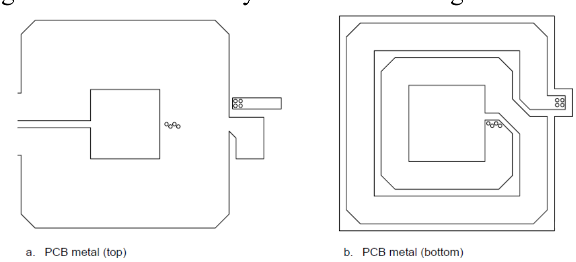

Figure 1: The planar balun structure from NXP design example [6]

PLANAR BALUN DESIGN AND ITS PROPERTY

The operation theory of Marchand balun is mainly resulted from the building standing wave and strong coupling between input and output structure. In the beginning, the Marchand balun is also built by coaxial type transmission line with additional coupling metals. Since the population of planar microstrip line, the Marchand balun is also adopted in planar design like Fig. 2 [8]. The difference between the proposed balun in this article and the traditional Marchand balun is the end of the input line. For the traditional Marchand baluns, the opposite end of the input port is kept in open circuit and has total length of half wavelength. However, in this new circular deign, that end is shorted to ground and has quarter wavelength in total.

*Work supported by National Science Council
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ISBN 978-3-95450-115-1

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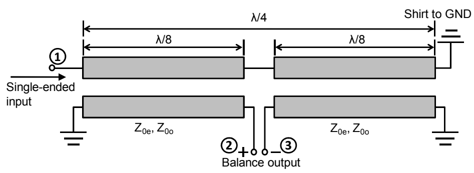
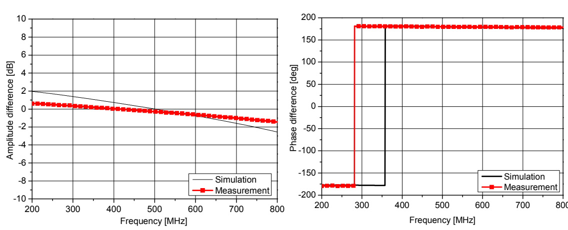


Figure 2: The proposed Marchand type balun with shorted end at input port

The very detail operation principle will not be discussed in this article. The key point is that with the ground-shorted end of input line, the length of the balun can be greatly reduced. Since the created quarter wavelength standing wave resulting from the ground-shorted end have unsymmetrical electrical field, additional length compensation stub is added on the output port at shown in Fig. 4. Before discussing the loss property by the back-to back connection of the proposed planar balun in Fig. 4, the amplitude and phase balance properties are simulated and measured as shown in Fig. 3. The amplitude error is only 0.31dB and phase unbalance is only 0.5deg in measurement. Practically, +/- 0.5 dB amplitude error and +/- 1deg phase unbalance are acceptable. Fortunately, in push-pull amplifier application, the little unbalance can be compensated by proper mirror connection of each other as shown in Fig. 4.



(a) (b)

Figure 3: The simulation and measurement result of (a) amplitude balance and (b) phase difference

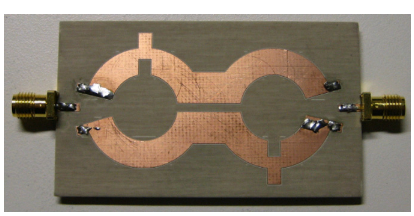
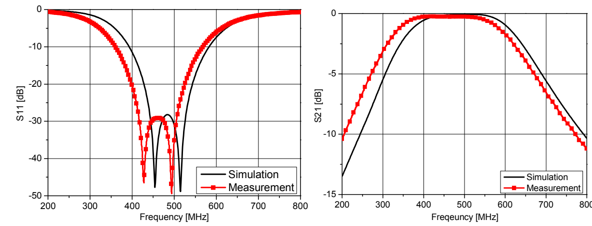


Figure 4: The back-to-back transmission loss setup of the proposed planar balun

Fig. 5 (a) and (b) show the simulation and measurement results of the back-to-back planar balun which has lower than 30dB return loss and about 0.2dB transmission loss at 500MHz. The slight frequency shift between simulation and measurement mainly results from the manufacturing error and dielectric property variation of actual material. 0.2dB transmission loss can be equivalent to about 2.25% power loss on each individual balun. For 1kW operation, there will be about 22.5W heat loss on the balun. The coaxial balun back-to-back setup is also tested to have about -0.24dB transmission loss which has similar loss level with the proposed planar balun.



(a) (b)

Figure 5: (a) Input return loss and (b) transmission loss of the proposed planar balun in back-to-back connection under simulation and measurement

The Newly Designed Water Cooling Plates

Due to the high power continuous operation, the cooling capability for the chip heat dissipation is very important. For the 1kW operation with 60% efficiency, there will be 667W heat needs to be taken away by the water cooling plate under the chip. The typical way to design the water cooling structure is just machine a round water tunnel under the chip. Here, a simple fin structure is applied with only 1.5mm thickness copper under the transistor. Also with the help of nano-diamond thermal conducting grease of N-302 (I-Connoisseur International) with the claimed 2000W/mk thermal conductivity of diamond, the heat can be efficiently brought away by the cooling water.

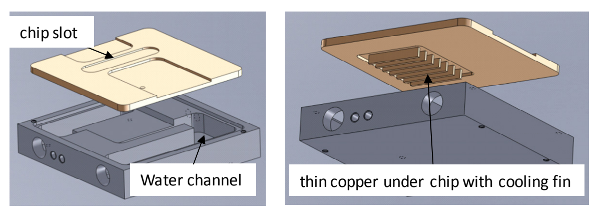


Figure 6: Advanced cooling capability of the fin shape water channel under the RF power chip

1kW Solid-state Power Amplifier with the Novel Planar Balun

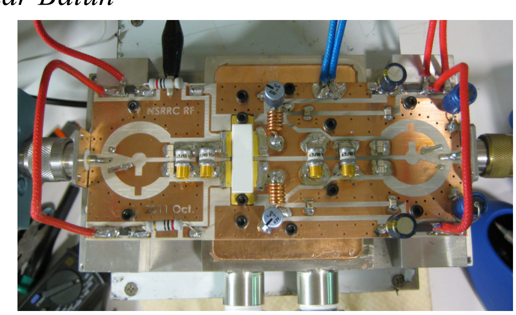


Figure 7: The 1kW planar balun RF power amplifier circuit with new cooling plate for CW power test

After the design and performance verification of the new planar balun, the 1kW solid-state power amplifier design is then applied in the push-pull operation. The chip is BLF578 which is claimed to have 1200W saturation power at 225MHz. In our design, the centre-frequency is

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500MHz (499.65MHz) for synchrotron master clock operation at NSRRC, Taiwan. Due to the higher operation frequency, the BLF 578 chip is expected to have lower gain and efficiency than its specification. The picture of the accomplished amplifier board with the newly developed cooling plate under it is shown in Fig. 7.

Measurement Results

For class-AB operation and maximum output power, the chip is biased at Vds=50V, Vgs=1.298V and quotient current of 200mA. Besides the cost issue, the other advantage of solid-state amplifier is that it can operate at different bias voltage (Vds) with reduced saturation power but still with similar DC-to-RF efficiency. This property is very attractive for synchrotron system operation under varying RF power requirement with high efficiency for reducing electricity cost. As shown in Fig. 8, higher than 1kW output power is available from the amplifier with the proposed planar balun at Vds=50V. In most output power range as shown in Fig. 9, the derived power gain is higher than 16dB at 50V drain-source bias. Also, Fig. 10 also demonstrates the tuneable saturation power and the optimum efficiency at different drain-source bias voltage value. For these various drain bias value, the gate voltage is kept constant. This property also demonstrates that once the gate bias is fine adjusted during manufacturing, it can be kept without sacrificing performance even if the drain voltage is varying with the system power requirement.

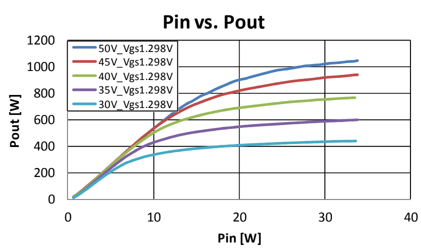

Figure 8: Driving power versus output power of the 1kW PA circuit under various drain voltage with constant gate voltage

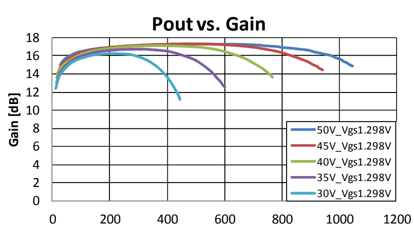

Figure 9: Power gain versus output power of the designed planar balun PA module under various drain voltage with constant gate bias

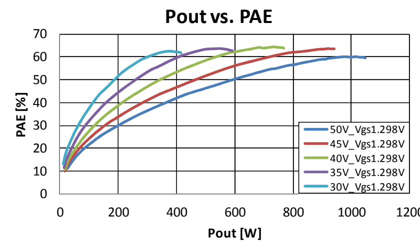

Figure 10: The power added efficiency of the designed planar balun PA circuit under various drain voltage with constant gate potential

CONCLUSION

In this article, a new compact round shape planar balun is proposed with the properties of extreme balance, low loss and less manpower in manufacturing. Such characteristic is quite suitable for push-pull power amplifier application and mass production. Besides, the improved water cooling structure is also designed to have great cooling capability. Hence, the 1kW, 500MHz CW operation power amplifier with above novelties is successfully implemented for future synchrotron application. With the new planar balun, the mass production of the solid-state amplifier circuits would greatly reduce the cost and time of hand-made process than those using typical semi-rigid coaxial cables.

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ISBN 978-3-95450-115-1