Power combining scheme of solid-state RF amplifier

T V Bondarenko, S Y Ilynski, S A Polikhov, G B Sharkov
Scientific Research Institute of Technical Physics and Automation (NIITFA), Varshavskoe shosse 46, Moscow, 115230, Russia
E-mail: tvbondarenko@niitfa.ru, sapolihov@niitfa.ru, gbsharkov@niitfa.ru

Abstract. Solid state amplification technology had developed a lot in recent years. This article is focused on a power combining system of a new power amplifier stage for ISIS neutron source (Rutherford Appleton Lab., STFC, UK). The amplifier is based on a modular block-built architecture that intends using of amplifier modules and combination of their output power (of >kW levels) using high power RF combiners. The power combining system for high power RF amplifier is discussed in this article. The system scheme together with results of modeling, low power measurements of key electrodynamic characteristics and high power operation test are presented.

1. Introduction
RF high power combining system is a part of solid-state RF power amplifier [1] (fig. 1) that is being produced in NIITFA to replace the high power feeding system of ISIS neutron source in Rutherford-Appleton Laboratory (STFC, UK) [2]. Nominal output power level of the system is 250 kW (4 % duty cycle) at frequency of 202.5 MHz. Amplifier is based on a modular system that incorporates 64 amplifying modules with up to 4.3 kW output power each that are connected to the first stage of power combining (PC) system [3].

2. General system design
The high power combining system is based on a two stage architecture with four 16:1 power combiners (PC) as a first stage, and one 4:1 power combiner as a second stage.

Both types of power combiners are box shaped coaxial structures. Power combiners has built-in Teflon tuning elements that allow to change the PC operation frequency ±5 MHz and to tune it's impedance to compensate possible manufacturing intolerances. 16:1 PC (fig. 2) has RF switch on each input port that can operate as a through or short on our operating frequency independently for each port. RF switches has built-in control system that controls its state (through/short) and gives command to change state in order to turn on and off the input port. Power combiner together with RF switches can provide effective power combination of incoming power with up to 3 (of 16) simultaneously turned off channels.

The power combining system is extremely flexible: the number of input ports for both combining cascades is limited only by the case size. This feature opens the potential to build the amplifier with megawatt power range without strong design changes.
Figure 1. General view of two 19” solid state amplifier racks for ISIS neutron source (left), highlighted power combining system of the amplifier (middle) and rack with installed 16 power amplifier modules and one 16:1 power combiner during high power tests (right).

RF switches are manufactured in a housing that incorporates 4 RF switches. RF switch housing has a quick-disconnect design that together with control systems allow using of the RF amplifier modules hot-swap principle in the amplifier. The 16:1 combiner sizes are 560x447x177 mm (LxWxH) without fixation flanges.

Figure 2. 16:1 PC assembled and ready for low level tests (7/8”-N and N-SMA adapters are on output port and N-SMA adapters are on input ports).

Second stage of RF combining system is one 4:1 power combiner that has much simpler design without RF switches or other operational elements (fig. 3). Four 16:1 power combiners are connected to 4:1 power combiner using the 7/8” coaxial waveguide. Output of 4:1 power combiner is connected
to the next amplification cascade of RF power feeding system of ISIS facility through the gas barrier and bidirectional coupler. The overall dimensions of the 4:1 Power Combiner are 446x140x149 mm (LxWxH) without supporting frame and 446x210x153 mm with supporting frame. Bullets of the flanges are not taken into account.

![Image](image1.png)

**Figure 3.** 16:1 PC inner guide and outer view during assembling process

### 3. Measurement

Low level RF tests were performed using the Agilent E5072A vector network analyzer. All input ports were terminated with 50 Ohm loads except for the one under test at the moment (fig. 4-7).

All Power Combiner characteristics meet requirements except for slight mismatch of insertion loss. The insertion loss is 0.5% higher that it was predicted in high power RF combining system design. However this excess of power loss is compensated by lower power losses in 4:1 Power Combiner (0.35% instead of predicted 0.9%) so the total insertion losses of the high power RF combining system are now 3.14% that is within predicted 3.2%.

Results show that 16:1 power combiner is tuned 0.25 MHz down from operation frequency: to 202.25 MHz. This is in very precise agreement with CST calculation. Power transmission deviation for all of the ports lies in +0.34...-0.27% band from mean transmission value that is also in fine agreement with CST.

![Image](image2.png)

**Figure 4.** S11 parameter (reflection from output port) for different amount of shorted RF switches and Sn1 parameters (transmission from output to one of the input ports) of 16:1 PC.
Figure 5. Deviation of power transmission coefficients (output-input transmission) of input ports and -1 dB operational frequency bandwidth of 16:1 PC.

Figure 6. S11 parameter (reflection from output port) and Sn1 parameters (transmission from output to one of the input ports) of 4:1 PC.

Figure 7. Deviation of power transmission coefficients (output-input transition) of input ports and -1 dB operational frequency of 4:1 PC.
Table 1. Measured parameters of 16:1 and 4:1 power combiners and initial requirements

| Parameter                          | 16:1 PC Requirements | 16:1 PC Measurements | 4:1 PC Requirements | 4:1 PC Measurements |
|------------------------------------|-----------------------|-----------------------|---------------------|---------------------|
| S11, dB                            | < -20 dB              | -29.13                | < -25.0 dB          | -41.5               |
| <Sn1>, dB                          | > -12.10              | -12.10                | > -6.04             | -6.03               |
| Power division equality, %         | < 5% span             | +1.72..-1.35          | < 5% span           | +0.34..-0.19        |
| Insertion loss, %                  | < 2.3                 | 2.79                  | < 0.90              | 0.35                |
| 1 dB bandwidth, MHz               | > 10.1                | 12.5                  | > 10.1              | 66.0                |

4. High power level RF tests

After ensuring that both power combiners operate correctly first high power test were held. 16 power amplifier modules were connected to 16:1 power combiner’s inputs, water cooled matched load was connected to combiner’s output. Tests had shown stable operation with nominal output power of 64 kW with up to 2 shorted RF switches for more than one hour. System operation with more than two shorted RF switches on nominal output was not tested.

The operating mode was: 50 Hz pulse repetition rate with 2 % duty cycle. Duty cycle was set lower than nominal value due to limited power throughput of cable connection between power combiner and matched load. Nevertheless duty cycle value doesn’t affect much the power combiner functionality due to exceptionally low power dissipation in power combiner. Now therefore we can conclude that the power combiner is fully functioning.

5. Conclusion

Power combining scheme for a solid-state power amplifier was described in this article. Power combining scheme has two stages with four 16:1 power combiners on the first and one 4:1 power combiner on the second stage. The first power combiner has RF switch on each input port that allow to turn on and off any power amplifying module of the amplifier, up to three of 16 RF switches can be turned off simultaneously without efficiency loss. This feature also allows using the hot-swap to change any power amplifier module on the run.

Both power combiners were manufactured and tested on low RF levels: results shows fine matching between calculations and assembled units. High power tests were held for one 16:1 power combiner. They confirmed correct operation of 16:1 power combiner on nominal output pulse power of 64 kW for more than one hour without any failures with up to two turned off RF inputs.

6. References

[1] Бондаренко Т.В., Краснов А.А., Полихов С.А., Шарков Г.Б. ВАНТ Серия: Техническая физика и автоматизация, выпуск 74, с. 3-13, 2016
[2] D J S Findlay, ISIS — PULSED NEUTRON AND MUON SOURCE, Proceedings of PAC07, p. 695-699, 2007.
[3] G.B. Sharkov, A.A. Krasnov, S.A. Polikhov, et al. Proceedings of NAPAC, p. 873-876, 2016