International Journal of Microwave and Wireless Technologies, 2012, 4(6), 595–603.
doi:10.1017/S175907871200061X

RESEARCH PAPER

Design and characterization of 50 kW solid-state RF amplifier

AKHILESH JAIN, P. R. HANNURKAR, D. K. SHARMA, A. K. GUPTA, A. K. TIWARI, M. LAD, R. KUMAR, P. D. GUPTA AND S. K. PATHAK

Radio frequency (RF) and microwave amplifier research has been largely focused on solid-state technology in recent years. This paper presents design and performance characterization of a 50-kW modular solid-state amplifier, operating at 505.8 MHz. It includes architecture selection and design procedures based on circuit and EM simulations for its building blocks like solid-state amplifier modules, combiners, dividers, and directional couplers. Key performance objectives such as efficiency, return loss, and amplitude/phase imbalance are discussed for this amplifier for real-time operation. This amplifier is serving as the state-of-the-art RF source in Indus-2 synchrotron radiation source. Characterization on component level as well as system level of this amplifier serves useful data for RF designers working in communication and particle accelerator fields.

Keywords: RF amplifier, Solid-state amplifier, Power combiner and divider, Directional coupler

Received 12 April 2012; Revised 1 August 2012; first published online 19 September 2012

I. INTRODUCTION

Radio frequency (RF) and microwave power amplifiers (PAs) are key technologies for wireless systems [1] as well as for particle accelerators [2]. Owing to the overlap of the frequency regime of these two fields, research efforts for this technology are equally useful. Nevertheless for the former, it is typically the amplifier's linearity, output power, and efficiency that drive the system's performance, power budget, and thermal design. For RF systems of particle accelerators [3], features like phase noise, system efficiency, minimum trips, and modular/scalable architecture are important for quality, stability, and high lifetime of particle beam. RF and microwave amplifiers based on vacuum-tube technology are widely used in these applications due to their high-power capability and established flight history. However, motivated by benefits such as low supply voltage, slow degradation, low research cost, and a wide commercial technology base, there is considerable interest in developing efficient, solid-state power amplifiers (SSPAs) [4] as an alternative to vacuum tube-based systems. Their price, performance, and reliability are quite likely to improve [5] with the evolution of wideband gap semiconductor-based devices [6] and growing demand in particle accelerators. In fact, many institutes like Soleil [7], European Synchrotron Radiation Facility (ESRF) [8], Raja Ramanna Centre for Advanced Technology (RRCAT) [9], and Advanced Photon Source (APS) [10] have developed such sources or are replacing their vacuum tube-based RF power source. Along with getting clean RF and Microwave (RFM) power (free from phase noise and spurious) solid-state device failure rate reported from Soleil synchrotron is 3% per year including infant mortality.

In this paper, design methodology of 50 kW SSPA at 505.8 MHz is described along with characterization at component level as well as system level. It is designed for the RF system [11] of Indus-2 synchrotron radiation source. The Indus Accelerator complex [12] at RRCAT consists of Indus-1 (a 100 mA, 450 MeV storage ring) and Indus-2 (a 2.5 GeV storage ring), sharing a common injector system, comprising of 20 MeV microtron and 700 MeV booster synchrotron.

As the power output of Laterally Diffused Metal Oxide Semiconductor (LDMOS) devices is limited, a large number of PA modules are paralleled for making this kW-level amplifier [13] with the help of power dividers and power combiners. Amplifier architecture relies upon signal splitting, amplification and summing strategy. In order to make modular, scalable, and reliable systems, a combination of multi-way and corporate scheme is used for power summing or combining. Combiner topology is influenced by efficiency, low phase noise, reliability together with economic issues, and size constraints. PAs, which are main gain blocks, need to be designed with least variation in their output signals from a mean value, for maximum possible combining efficiency. In practice, for circuit-level combining there is some variation due to fabrication tolerances, cable connection, and impedance tuning of PAs. Among amplitude and phase variations, the latter is the dominant factor for efficiency degradation as long as variations in amplitude have zero mean [14]. SSPA designers have tried different methods like phase-delay line [15] and forced

Raja Ramanna Centre for Advanced Technology, RRCAT, Indore -452013, India, phone: +91 731 2442725
Corresponding author:
Akhilesh Jain
Email: ajain@rrcat.gov.in

compression of drain characteristics [16] to minimize variation in amplitude and phase of PAs. In the present endeavor a tight control was maintained for this variation by selecting a suitable combiner structure and a PA impedance matching circuit. In combiners, the absence of isolation resistor or moving/planer parts adds toward signal symmetry and reduced system trips. A multi-way unit radial slab-line topology with electrical symmetric structure gives nearly no variation in phase/amplitude with combining efficiency approaching 98%. PA modules with semi-rigid coaxial line transformers and minimum tuning elements give repeatable performance. Experimental characterization verifies the suitability of this design for addressing phase and amplitude errors' problem.

II. 50 KW AMPLIFIER DESIGN DESCRIPTION

In order to meet RF power demand and specific requirements encountered in Indus-2 particle accelerator, an architecture based on combination of circuit-level corporate and radial power dividing–combining approach was selected for the 50 kW SSPA. As scalability, modularity, and reliability were the key metrics of this architecture, a generic template in the form of a 13-kW amplifier unit was designed to achieve target power by its repetition and corporate power combining. For 50 kW power, four such units were incorporated in a two stages binary tree with two-port combiners, capable of handling power up to 45 and 65 kW, respectively. This scheme is shown in a simplified manner in Fig. 1 along with estimated gain and power calculation at each junction of the chain.

In this scheme an eight-port divider feeds the RF signal to each of the four 13 kW units. Half of the branch ports of this divider, presently terminated in matched load, are for future expansion. Phase shifters inserted in used branch ports adjust real-time operational phase difference for each unit. Different directional couplers (not shown in the figure) are used to sample RF power at various junctions of this SSPA. Such system allows easy serviceability and expandability with similar mechanical footprint and peripheral connections even for different frequency selection.

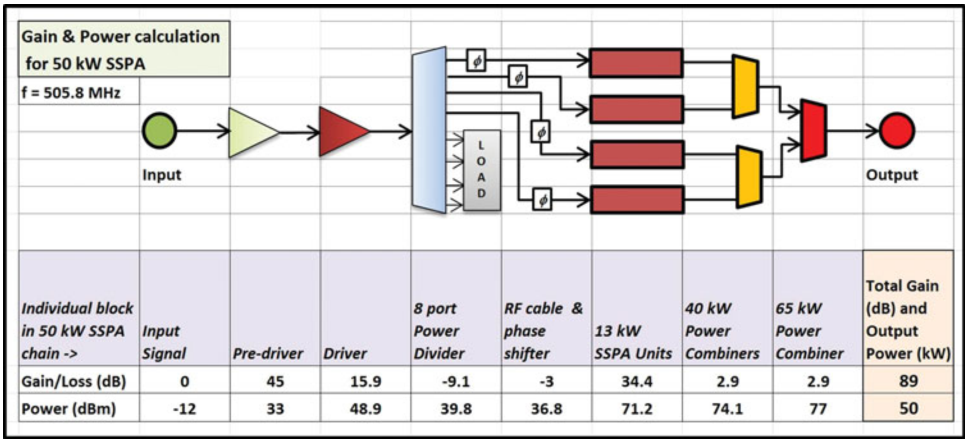
Each of the 13 kW units, designed for this scheme, includes water cooling, Field Programmable Gate Array (FPGA)-based protection and monitoring system apart from PA modules, dividers, combiners, and directional couplers, all housed in a standardized Euro chassis. As seen in Fig. 2, showing simplified RF hardware of this unit, 32 PAs (each one at 500 W) are power combined in two stages. In the first stage there are two similar groups each one consisting of a 16-port radial divider, 16 PAs, and a 16-port radial combiner. In the second stage, outputs from two such groups are combined with the help of a two-port combiner to get the required 13 kW power. A low-power directional coupler is inserted between the output of each PA and the input of 16-port combiner monitor forward and reflected RF component. Every 500 W PA module is individually powered by a compact switched-mode power supply (SMPS) capable of delivering 20 A at 50 V DC with a three-phase AC input.

For data acquisition, each unit together with its interlocks forms an independent system with its own supervisory system performed by a graphical code developed in-house [17] using LabView^{TM} RT. All of the PAs, with the help of the 1 kW coupler connected externally at output, provide a rectified sample of forward and reflected power to FPGA-based CRio analogue modules from National Instruments^{TM}. The whole system works as a distributed system over a TCP/IP network where all 13 kW units function independently and are centrally coordinated by a master PC. The system can be easily expanded by adding new members to this network. A 20 kW directional coupler is used to sample RF power of this 13 kW unit. Each unit occupies 1×1.2 m^2 floor space and has 2 m height. Design description of different building blocks of this SSPA is presented below.

A) The RF amplifier module

For PA design BLF 573 LDMOS was selected as the workhorse on the basis of circuit simulation studies, carried out in Microwave Office^{TM}. Important design specifications of this PA are listed in Table 1.

Target power of 500 W was obtained by two such devices, each one designed for class AB with similar impedance matching and bias circuits, all on the same board. Using power match condition and impedance matching theory [18] gate and drain side impedances (both are having real part less than 2 Ω) were matched to system impedance of 50 Ω with the help of coaxial transformers and *L* section of lumped capacitors and microstrip line as seen in Fig. 3. Parallel RF operation of these two amplifying circuits was achieved with



Individual block in 50 kW SSPA chain ->	Input Signal	Pre-driver	Driver	8 port Power Divider	RF cable & phase shifter	13 kW SSPA Units	40 kW Power Combiners	65 kW Power Combiner	Total Gain (dB) and Output Power (kW)
Gain/Loss (dB)	0	45	15.9	-9.1	-3	34.4	2.9	2.9	89
Power (dBm)	-12	33	48.9	39.8	36.8	71.2	74.1	77	50

Fig. 1. RF architecture and gain/power calculation for 50 kW SSPA.

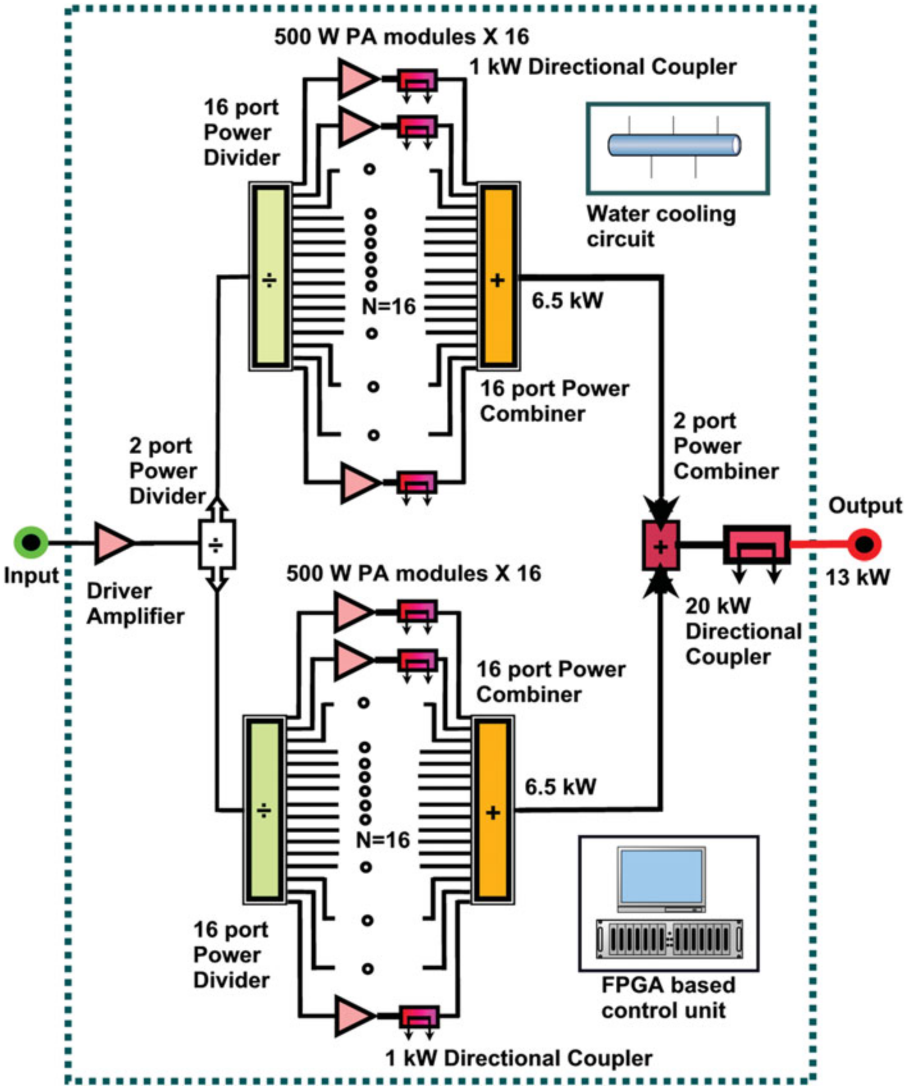


Fig. 2. RF hardware scheme for 13 kW solid-state RF amplifier unit.

the help of on-board Wilkinson divider and combiner. The harmonic balance power analysis [19] and simulation were performed under desired source/load impedances to fine tune the PA circuit. A 500-W circulator, placed before the final output, protected the RF devices from reflected power.

Five such PAs were mounted directly on a water-cooled copper plate. For improved heat transfer, LDMOS devices were bolted directly to this plate by applying a thin layer of silicone oil-based thermal compound. Fig. 4 shows a sketch of this cold plate and inner view of one of the PA modules. The data logging parameters acquired from each module are output forward and reflect power and cold plate temperature.

Fig. 5 summarizes RF performance for a typically designed PA. Power transfer characteristic is linear. Efficiency is lower than the calculated value by nearly 2%. Phase spread or AM–PM conversion factor is quite low. 1 dB bandwidth measured for this PA was 10 MHz. Harmonics and spurious components were −35 dBc.

Table 1. Specification of 500 W RF power modules.

Sr.	Parameter	Value
1	Rated RF power output/power gain	500 W/18 dB
2	Operating frequency and 1 dB bandwidth	505.8 MHz, ±5 MHz
3	Operating mode/class of operation/ efficiency	CW/AB/60%
4	Protection	VSWR, over temperature, overdrive
5	Harmonic distortion/spurious Output	−30 dBc/ − 35 dBc
6	Cooling	Water cooled at 30°C

B) Rigid coaxial passive components

Owing to divide and sum strategy used in SSPA configuration, power dividers, combiners, and directional couplers directly affect final output power and efficiency. Different passive components, as detailed below, have been designed for the 50 kW SSPA. Realized with good mechanical and thermal design, these structures provide an excellent electrical symmetry for power combiners thus improving their amplitude and phase stability. Absence of isolation resistor and planer circuit (microstrip/strip line) in these components makes them attractive for high power and reliable performance,

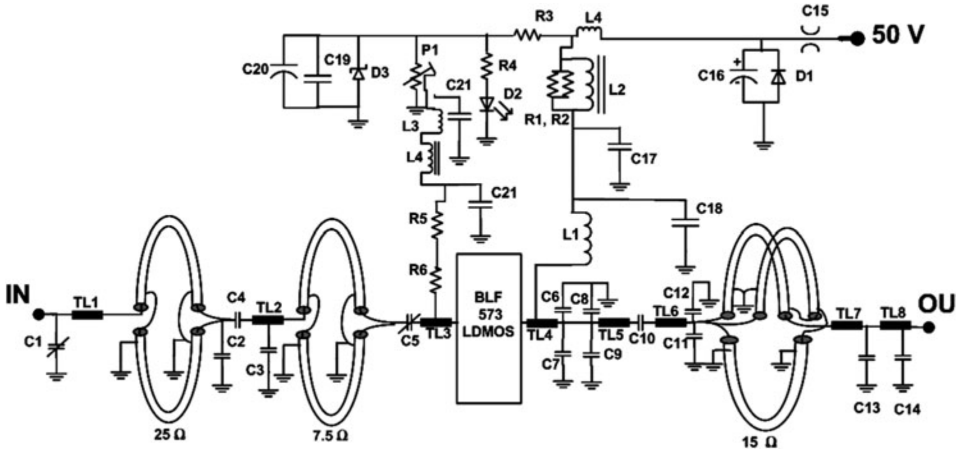


Fig. 3. Impedance matching circuit for one half of the 500 W power module.

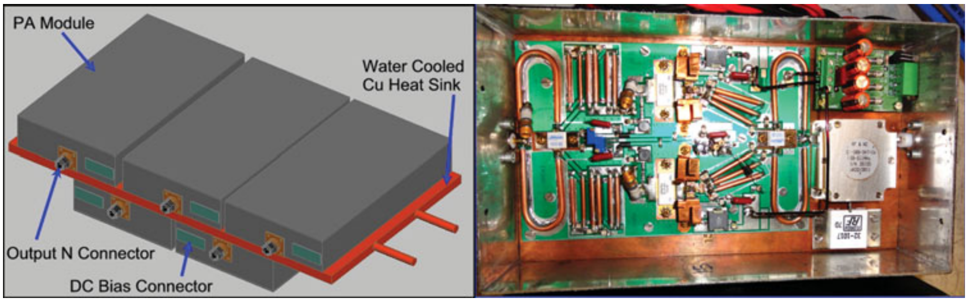


Fig. 4. PA module cold plate with inner view of PA module.

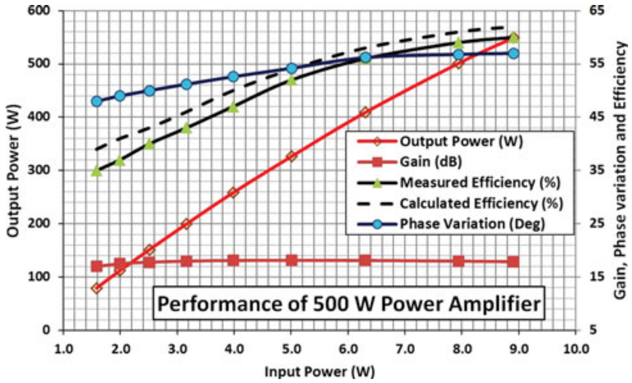


Fig. 5. Measured gain and efficiency of 500 W PA module.

which otherwise may deteriorate due to heat dissipation, aging, and mechanical difficulty in placing the resistor inside the structure.

1) POWER DIVIDERS AND COMBINERS

Two-port in-phase combiners required at different stages are junction of rigid coaxial lines suitably matched at combined port. Instead of Wilkinson-type quarter-wave sections, they make use of cascaded coaxial lines for impedance matching, resulting in overall compact structure. On the other hand, the 16-port divider/combiner has *N* input coaxial ports symmetrically spaced along the circumference of a parallel rigid-slab type radial line with output power extracted from the center, suitably matched to system impedance. A similar

(a) (b)

Fig. 6. Two-port combiners (a) and 16-port radial combiner (b).

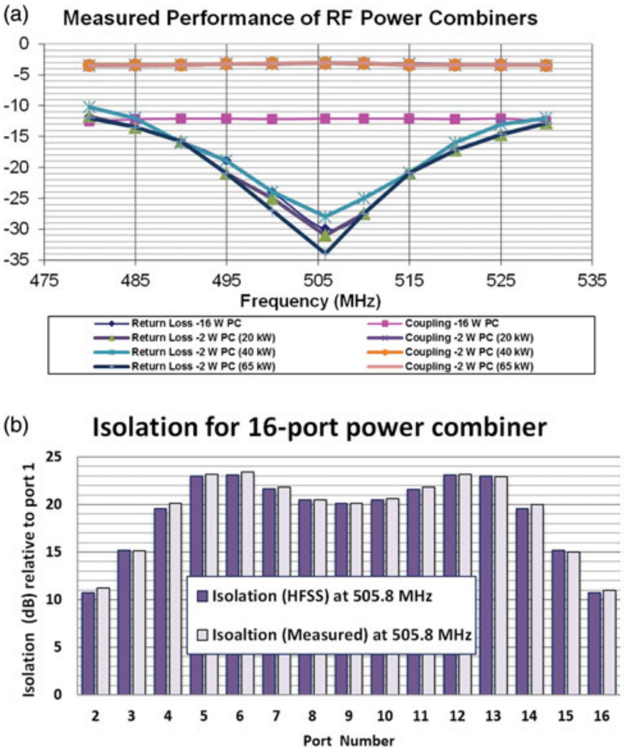


Fig. 7. (a) Measured return loss and coupling for power combiners and (b) computed and measured isolation of 16-port combiner.

structure acts as a power divider with the roles of the feed port and the branch ports reversed. The designed structures are shown in Fig. 6.

For combining *N* sources, radial power combiners [20] offer a superior approach with efficient, reliable, and high-power output in compact housing. Design methodology of radial combiner [21] includes computation of relative input impedance $Z'(r)$ and real value of characteristic impedance of radial line at radius r for dominant *E* mode. This methodology together with full-wave analysis in HFSS$^{\text{TM}}$ results in accurate prediction for the operating parameters and optimization of the electromagnetic structure.

All these designed structures were qualified after rigorous RF measurements. Measured return loss and power combining ratio or coupling for these combiners (Fig. 7(a)) conform to the calculated values. Comparison of HFSS result and measured isolation among branch ports for 16-port combiner is given in Fig. 7(b). Insertion loss for 16-port combiner is less than 0.1 dB corresponding to a combining efficiency of 98%.

Imbalance in forward transmission coefficient from feed port to branch port, as seen in Fig. 8 is less than 0.2 dB in amplitude and nearly 2° in phase.

All these measured data with minimum ripple in amplitude and phase prove the worthiness of the design methodology. It allows repeatable design and minimum loss in the system due to mismatch/reflection at various junctions of the SSPA.

2) DIRECTIONAL COUPLERS

For directional sampling and measurement of high-power RF signal coaxial directional couplers are the reliable high-power solution. Coupler structures at different power, designed for present application, are coaxial type with rectangular cross section. The coupling mechanism is similar to the one suggested by Tepatti *et al.* [22]. Energy from longitudinal symmetric main line to auxiliary coaxial line is coupled using an aperture cut in a thin metal diaphragm. Each line has an outer conductor with a square cross section and a cylindrical inner conductor. The aperture shape corresponds to the desired longitudinal profile of the coupling factor. The necessary analysis, carried out in parts for longitudinal and transversal problems, provide the coupling factor and the

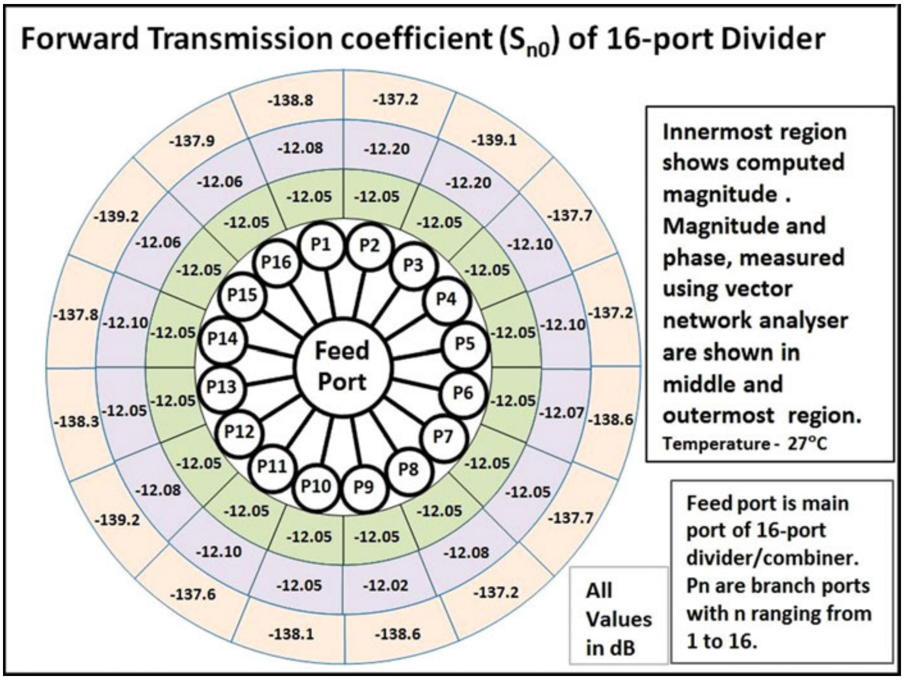


Fig. 8. Forward transmission coefficient of 16-port radial combiner.

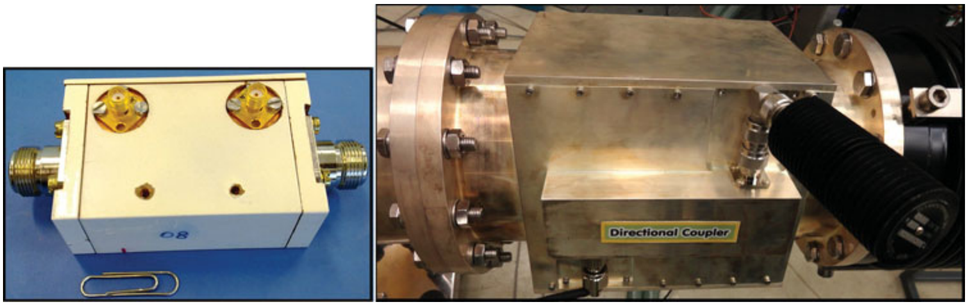


Fig. 9. 1 kW and 65 kW directional couplers.

characteristic impedances as functions of the structure dimensions. For transversal part, use of even and odd mode impedances (Z_{oe} and Z_{oo} [23] was made for such uniformly coupled asymmetric lines.

$$k(z) = \frac{Z_{oe}(z) - Z_{oo}(z)}{Z_{oe}(z) - Z_{oo}(z)} \qquad (1)$$

Here, $k(z)$ is the coupling factor. The longitudinal design procedure adopted was based on the following equations [24]:

$$A_{13} = j2\pi\frac{l}{\lambda}\int_0^l k(z)e^{-4\pi(l/\lambda)z}\,dz \qquad (2)$$

Here, A_{13} is voltage coupling from main port to coupled port, l is the length of the coupler, and λ is the wavelength. With proper choice of various dimensions, final design was carried out using structure simulator. Using this approach, three types of wide band (300–700 MHz) couplers have been built and characterized for maximum forward power of 1, 20, and 65 kW, respectively. Two such couplers are shown in Fig. 9.

Table 2. Coupling and directivity of three types of designed directional couplers.

Directional coupler type, kW	Calculated (HFSS) coupling, dB	Measured coupling, dB	Calculated (HFSS) directivity, dB	Measured directivity, dB
1	40	41	30	29
20	50	49.3	28	23
65	50	49.8	28	22 dB

Measured insertion loss for all of these couplers is less than 0.05 dB whereas return loss is better than 28 dB at center frequency. Measurement results show very good agreement with the design specifications and electromagnetic simulations as compared in Table 2.

III. 50 KW AMPLIFIER: COMPLETE SYSTEM

50 kW SSPA (Fig. 10) completed with RF and ancillary components was commissioned and interfaced with Indus-2 SRS RF cavity resonator after being tested with a matched 80

Fig. 10. 50 kW solid-state amplifier.

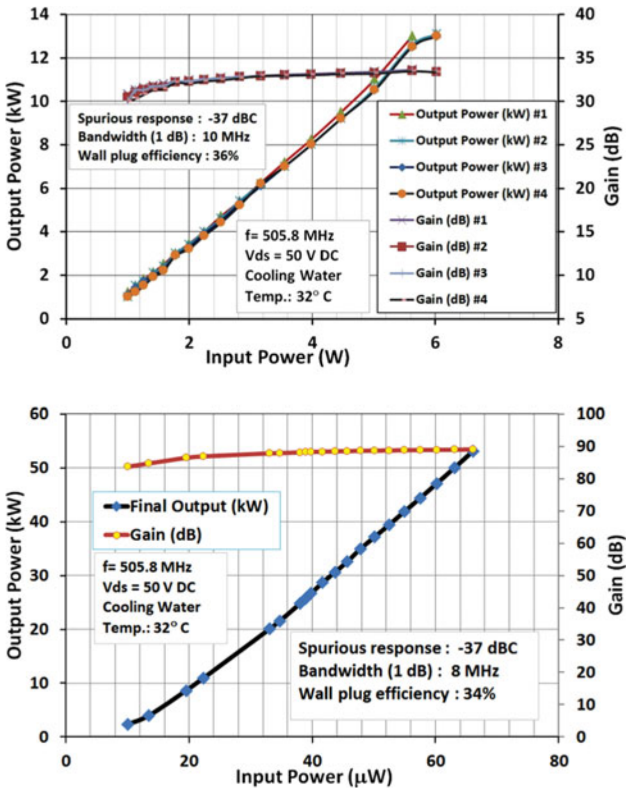


Fig. 11. Measured power transfer characteristics of 13 kW units (#1 to #4) and 50 kW SSPA at 505.8 MHz.

kW RF water-cooled load. Presently, a high-power circulator is placed for the safety of this amplifier from the reflection generated at the RF cavity during beam injection and ramping. This amplifier is complete in all respects of safety interlock, water cooling, and power supply. Panel PC provides a GUI for all user related controls and indicators. An independent low conductivity water (LCW) plant capable of delivering up to 1200 l/m at a maximum pressure of 8 bar was used in the Indus-2 SSPA RF area. The supervisory and the interlock systems were tested in advance. The directional couplers were characterized *in situ* at high power. Measurements of output power, gain, and efficiency were performed for each of the 13 kW units individually followed by same measurement for complete 50 kW SSPA.

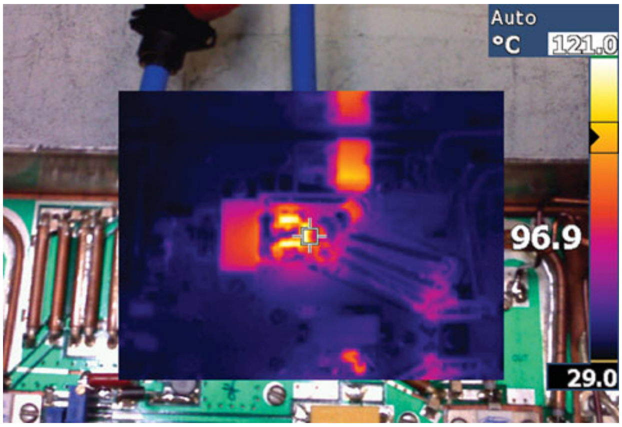


Fig. 12. IR image showing maximum temperature on drain side of one of the devices.

This characterization data of 13 kW units and this amplifier are shown in Fig. 11. There is a minor deviation in power characteristics of all four 13 kW units. This helps in achieving the best possible efficiency at corporate combining stage. For all amplifiers the characteristic is linear in common operation region. For 13 kW SSPA one dB compression point is beyond 12.5 kW. Average gain of 50 kW SSPA is 88 dB whereas 1-dB gain compression point is beyond 52 kW output power.

Thermography check-up of the PA modules showed that at maximum power, temperatures in the modules (near drain of LDMOS) can reach up to 95°C. Fig. 12 shows Infra Red (IR) image with maximum temperature of capacitor near drain side.

IV. CONCLUSION

At 505.8 MHz, a modular and scalable 50 kW solid-state RF amplifier was successfully designed and characterized for use with Indus-2 synchrotron radiation source. This amplifier make use of divide and sum strategy using 50 V LDMOS-based 500 W amplifier module, power combiner, divider, directional coupler, and FPGA-based control and interlock. With proper design of these modules and rigid structure RF components, amplitude and phase imbalance could be managed to a satisfactory level. The measured and predicted results are in good agreement. Successful development and characterization of this amplifier adds confidence for future development for selecting solid-state RF source, among other tube-based sources.

ACKNOWLEDGEMENT

We are thankful to members of the RF systems division for their contribution in the development of high-power solid-state RF amplifiers. Thanks are also due to members of the Indus accelerator team for their participation in Indus-2 operation with deployment of these amplifiers.

REFERENCES

[1] Raab Frederick, H. et al.: Power amplifiers and transmitters for RF and microwave. IEEE Trans. Microw. Theory Tech., **50** (3) (2002), 814–826.

[2] Giacomo Marco, D.: Solid state RF amplifiers for accelerator applications, in Particle Accelerator Conf. PAC09, Vancouver, Canada, 2009.

[3] Valuch, D.: Radio frequency systems of the CERN synchrotron accelerators, in Radioelektronika 2009, Geneva, Switzerland, April 2009, 17–24.

[4] Ulf, S.; Rolf, R.; Se'bastien, C.; Kristina, W.; Martin, O.: GaN devices for communication applications: evolution of amplifier architectures. Int. J. Microw. Wirel. Technol., **2** (1) (2010), 85–93.

[5] Heid, O.; Hughes, T.: Solid state RF power the route to 1 W per Euro cent, in Particle Accelerator Conf.-2011, New York, USA, 2011.

[6] Kuhn, J. et al.: Design and realization of GaN RF-devices and circuits from 1 to 30 GHz. Int. J. Microw. Wirel. Technol., **2** (1) (2010), 115–120.

[7] Marchand, P.; Lopes, R.; Ribeiro, F.; Ruan, T.: Development of high power solid state amplifiers at SOLEIL, in IPAC-2011, San Sebastián, Spain, 2011, 376–378.

[8] Jacob, J.; Mercier, J.M.; Langlois, M.; Gautier, G.: 352.2 MHz – 150 kW Solid State Amplifiers at the ESRF, in IPAC-2011, San Sebastián, Spain, 2011, 71–73.

[9] Hannurkar, P.R. et al.: Development of high power solid state RF amplifiers and their deployment in indus-2 synchrotron radiation source, in 22nd Annual Conf. Indian Nuclear Society INSCA-11, Hyderabad, India, 2011.

[10] Popovic, B.; Waldschmidt, G.: RF solid state driver for argonne light source, in Particle Accelerator Conf.-2011, New York, USA, 2011.

[11] Hannurkar, P.R. et al.: INDUS-2 RF system, in INPAC-2005, VECC, Kolkata, India, 2005.

[12] Singh, G. et al.: Status of INDUS-2 synchrotron radiation source, in INPAC-2011, Delhi India, 2011.

[13] Akhilesh, J.; Sharma, D.K.; Gupta, A.K.; Hannurkar, P.R.: High power solid state RF amplifier for proton accelerator. Rev. Sci. Instrum., **79** (1) (2008), 014702–014707.

[14] York, R.A.: Some considerations for optimal efficiency and low noise in large power combiners. IEEE Trans. Microw. Theory Tech., **49** (8) (2001), 1477–1482.

[15] Diop, P.; Ruan, T.; Lopes, M.; Polin, R.; Ribeiro, J.; Marchand, F.: High power 352 MHz solid state amplifier for the SOLEIL synchrotron, in Particle Accelerator Conf., PAC-2005, Knoxville, Tennessee, 2005.

[16] Gaspar, M.; Pedrozzi, M.; Ferreira, L.F.R.; Garvey, T.: A compact 500 MHz 4 kW solid-state power amplifier for accelerator applications. Nucl. Instrum. Methods Phys. Res. A, **637** (1) (2011), 18–24.

[17] Sharma, D.K.; Gupta, A.K.; Akhilesh, J.; Hannurkar, P.R.: Embedded control system for high power RF amplifiers, in INPAC-2011, New Delhi India, 2011.

[18] Cripps Steve, C.: RF Power Amplifiers for Wireless Communication, Artech House, Inc. 685 Canton Street, Norwood, MA 02062. 1999.

[19] Vendelin George, D.; Pavio Anthony, M.; Rohde Ulrich, L.: Microwave Circuit Design Using Linear and Nonlinear Techniques, 2nd ed., John Wiley & Sons, Inc., New York, NY, 2005.

[20] Fathy, A.E.: Development of a radial combiner – a tribute to Nathan Marcuvitz, in IEEE MTT- Symp. Digest – 2011, University of Tennessee, Knoxville, USA, 2011, 1–4.

[21] Akhilesh, J.; Sharma, D.K.; Gupta, A.K.; Hannurkar, P.R.: Design of high power radio frequency radial combiner for proton accelerator. Rev. Sci. Instrum., **80** (1) (2009), 016106-1-3.

[22] Valeria, T.; Michele, G.; Andrea, F.; Augusto, O.; Giovanni, G.: Broad-band coaxial directional couplers for high-power applications. IEEE Trans. Microw. Theory Tech., **53** (3) (2003), 994–997.

[23] Cristal, E.G.: Coupled-transmission-line directional couplers with coupled lines of unequal characteristic impedances. IEEE Trans. Microw. Theory Tech., **14** (6) (1966), 337–346.

[24] Arndt, F.: High pass transmission line directional coupler. IEEE Trans. Microw. Theory Tech., **16** (5) (1968), 310–311.

Akhilesh Jain received B.E. in Electronics and Communication engineering from Vikram University in 1991 and M.Tech. in Microwave Engineering from Indian Institute of Technology, Kanpur in 1994. He joined Raja Ramanna Centre for Advanced Technology (RRCAT), Indore in 1994. Since then he is engaged in research and development of high-power solid-state RF amplifier and related components.

P.R. Hannurkar received his B.E. in Electronics and Telecommunication from College of Engineering, Pune. He served as a Scientific Officer at Bhabha Atomic Research Centre (BARC), Mumbai, after graduating from the 20th batch of BARC Training School. Since 1986 he is leading RF and microwave activities for various particle accelerators in RRCAT.

Deepak Kumar Sharma completed his B.E. (Bachelor of Engg.) from RGTU (Rajiv Gandhi Technical University) India. After completing his graduation in Electronics Engineering, joined the orientation course on advanced technologies and was appointed as a scientific officer in RRCAT. Since then he is working in the field of high-power solid-state RF amplifiers for various particle accelerator applications.

Alok Gupta completed his M.Tech from the Department of Electrical Engineering, Indian Institute of Technology, Kanpur in 2005. Since then he is posted as a scientific officer at RRCAT under Department of Atomic Energy, India. His main areas of interest are RF amplifier, power combiners, directional couplers, and high-power rigid line components.

Dr. Ashish Kumar Tiwari received the degrees of M.Tech. in Microwave Electronics from Delhi University, India and Ph.D. from Jadavpur University, Kolkata, India in 2008. Presently, he is a scientific officer in RRCAT. His research interest includes solid-state amplifiers, computational electromagnetic antennas, and vacuum electron devices.

Mahendra Lad completed his B.E. in (Electronics and Telecommunication) from Devi Ahilya University, Indore in 1986. He joined RRCAT in 1987 as a scientific officer. Since then he is involved in RF system development for Synchrotron Radiation Sources at the center.

Ramesh Kumar did B.Sc. (Engineering) in Mechanical from Ranchi University in 1989. He joined Bhabha Atomic Research Centre, Mumbai in 1991 as a scientific officer. Presently, he is involved in the development of coaxial and waveguide-based transmission line systems for RF system of accelerators at RRCAT.

Dr. P.D. Gupta is Director, RRCAT. He is steering R&D programmers in several frontline areas of accelerators and lasers including synchrotron radiation sources and their utilization, development of superconducting radio-frequency cavities for high-energy accelerators, proton linac development for spallation neutron source, high-power RF sources, cryogenics and magnet technology, ultra-intense laser-plasma interaction, and lasers in research and industry.

Dr. S.K. Pathak did Ph.D. in Electronics and Communication Engineering from the Department of Electronics and Communication Engineering, IIT, BHU, Varanasi. His research interest includes applied electromagnetics, bioelectromagnetics, microwave scattering and antennas, microwave engineering, etc. He has one US patent and has published more than 26 papers in reputed journals.