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Compact solid state radio frequency amplifiers in kW regime for particle accelerator subsystems

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Abstract. Radio frequency and Microwave (RFM) infrastructure test facility is under development at RRCAT for evaluating and powering, subsystems of particle accelerator. As a part of this facility, design of 20–30 kW UHF solid state power amplifiers is in progress. For this work, design procedure has been formulated for the development of solid state amplifier modules, radial combiner, divider and directional coupler; with specifications suited to RFM power system for particle accelerator. Methodology has been demonstrated by developing two different compact amplifiers with power output of 2 kW each, operating at 352 MHz and 505.8 MHz, respectively. This paper describes underlying design principles and indigenous development of these amplifiers, consisting of 270–300 W amplifier modules, 8-way 2 kW radial combiner/divider and directional couplers. Design methodology for power combiner has been extended by physically realizing higher power (4 kW) 16-way power combiner and 2-way combiner (8 kW) for higher power (8 kW) amplifier configuration planned. Simple design, indigenous technology, high efficiency and ease of fabrication, are the main features of this design.

Keywords. RF amplifier; solid state amplifier; power combiner and divider; directional coupler; radio frequency electronics.

1. Introduction

Recently, many particle accelerator laboratories, around the world, have harnessed the power of solid-state devices, by deploying kW level radio frequency (RF) power source for energizing superconducting structures (Scarpa 2006). Earlier, utility of solid state power amplifier (SSPA), at radio frequency and microwave (RFM), was limited to driver amplifier (Jain *et al* 2006), providing few hundreds of watts, for driving vacuum tube amplifiers. Now, with the advent of superconducting accelerating structures, solid state technology, in parallel, has crossed kW level

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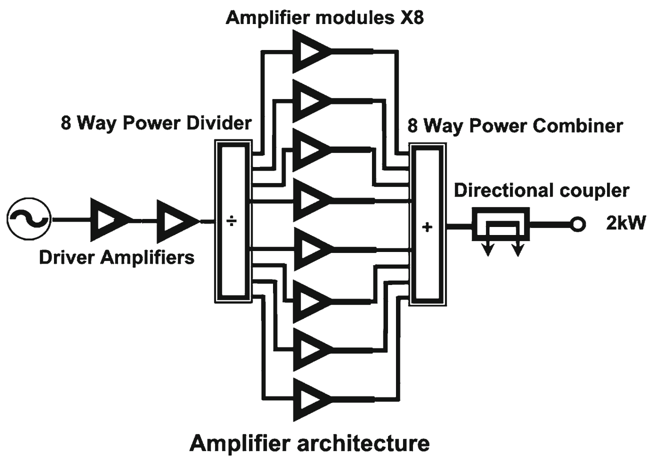

Figure 1. Solid state high power RFM amplifier scheme.

power regime as demonstrated in particle accelerators like Soleil synchrotron (Marchand 2007) in France. Along with getting clean RFM power (free from phase noise and spurious) solid state device failure rate reported from Soleil is 3% per year including infant mortality. Numerous advantages (Gaspar 2008) of SSPA, compared to vacuum tube counterpart, is the main driving force behind rapid development of kW level SSPA.

Output power of individual solid state device is rather modest, being of the order of few hundred of Watts. Hence, kW level RF power is obtained by summing power output of multiple devices (figure 1), developed in the form of amplifier modules. Power summing action is achieved by power divider and combiner (PDC) structures.

Here, unlike communication field, RFM signal is monotonic except pulse modulation in some cases. Hence, for amplifier modules focus is set on suitable, efficient and easily realizable impedance matching network.

In the present work, apart from amplifier design, design of novel PDC, based on simplified method (Jain *et al* 2009), incorporating radial stripline structure; without isolation resistor and external tuning mechanism, has been demonstrated. For directional coupler, method suggested by Teppati (2003) has been modified by removing microstrip line. All these components developed and tested independently, should work as ensemble also. To demonstrate this, two amplifiers with 2 kW output power were developed at 352 MHz and 505.8 MHz, respectively. These SSPA serve as test stand for RF testing of components, needed for achieving final target of 30 kW. For all these RF components, vector and scalar measurements were carried out for validating design procedure. Following this, high power continuous wave (CW) and pulse RF testing was carried out. This exercise provided useful data for life testing, possibility of any arcing at high power, heat dissipation and graceful degradation for upcoming higher power amplifiers.

2. Amplifier architecture

For energizing superconducting RF cavities, bandwidth of the order of 1–2% is sufficient (Jacob 2006; Zavadtsev 2009). Hence, high power amplifier modules, required in multiple, were designed with matching network (Abrie 1985) using planer microstrip transmission line and coaxial transmission line baluns. Use of microstrip line provides ease of tuning at high power, required even after circuit simulation, under real operating conditions. Efforts were made to keep minimum number of lumped variable matching component. To obtain a better overall efficiency, minimum deviation in the output signal amplitude and phase, of all modules, is required.

To power combine solid state amplifier modules with good efficiency, a combining circuit is required with minimum power loss and adequate port to port isolation. In view of this, theoretical study and prototype testing of various combiner structures (Russell 1979; Abouzahra 1987; Wu 1998), suitable for 300 to 800 MHz frequency range, was carried out (Jain *et al* 2004). Initially, for kW power level, Gysel combiner (Gysel 1975) was developed and tested; however later on due to fabrication difficulties, it was dropped. Among different combining choices, radial combiners (Swift 1988), where power combining or dividing action is achieved in a single step, was found as an efficient candidate for combining n (>2) amplifiers. The tree-structures, for large n, have the disadvantage of utilizing a multitude of connecting transmission line segments, which add losses. Radial combiners on the other hand can lead to power combining efficiency nearly 90% and insertion loss less than 0.5 dB.

In both of these developed amplifiers, necessary controlling and monitoring signals like, enable signal to RF-switch, power supply OK, heat sink temperature of amplifier modules, input and output power signal from RF detector, etc. were interfaced with a compact field point controller, for data acquisition (Sharma 2009). TCP/IP interface was used in this real-time controller to monitor the amplifiers' performance remotely. In order to extract heat dissipated by solid state devices, air cooled and water cooled heat-sinks were used in 352 MHz and 505.8 MHz SSPA, respectively. All of the RFM-related design issues of amplifier modules, power divider/combiner and directional coupler are discussed in the following sections.

2.1 *Solid state amplifier modules*

In order to match very low Input/output impedance of the solid state devices, performing in 20 to 350 W regime, to 50 Ohm, combination of microstrip line and coaxial transmission line is more suitable, especially at UHF. For this design, initial parameters were calculated by simple approximation of Steve Cripps law (Cripps 1999), as outlined in development of 1.5 kW amplifier (Jain *et al* 2008). These parameter provided input for linear simulator, used to design final circuit using microstrip and semi rigid coaxial line transformers. This was followed by optimization of semi-rigid coaxial transformers using EM structure simulator of HFSS^{TM} and experimental optimization.

Using this procedure, high power amplifier modules, providing output power in 200–300 W range and 12–13 dB power gain and operating at 28 V DC, were designed using MOSFET as workhorse. These high power amplifier (HPA) modules are required in large numbers as final output power is sum of output power of all of HPAs. Matching network for all of the modules was designed using planar and coaxial transmission line baluns with minimum lumped variable components.

At 352 MHz, using LR301 MOSFET, ten numbers of 270 W air cooled HPA were designed (figure 2) with forced air cooling. Each module measures 160 mm and 200 mm in length and width. At 505.8 MHz, similarly, 8 water cooled modules, providing 300 W of RF power from MRF 9130 device, were developed. In later case, four such HPA modules were mounted on a single copper water cooled heat sink, measuring 600 mm and 250 mm (figure 2).

Apart from this work, driver amplifier unit at 30 W was designed for boosting signal received from RF generator to a level, required at HPA input. This consists of three cascaded stages (figure 3), each one using MRF9030 device. For each stage, impedance matching network was

Figure 2. 270 W HPA at 352 MHz (left), 300 W HPA at 505.8 MHz (middle) and one heatsink block, cooling four HPA modules at 505.8 MHz.

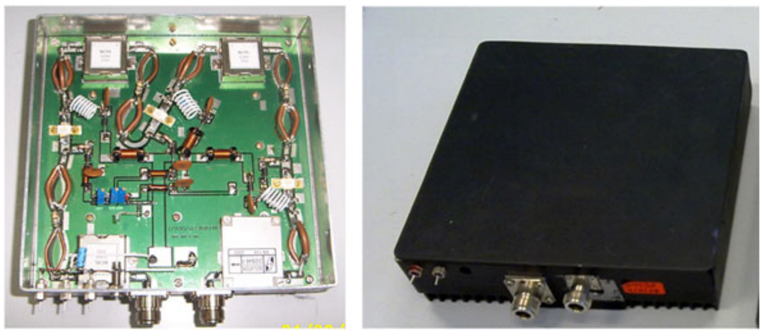

Figure 3. Low power (30 W) solid state driver.

realized using 4:1 and 9:1 semi-rigid coaxial transformer. Using tuning elements, same driver circuit was used at 352 MHz as well 505.8 MHz.

2.2 *Power divider and combiner*

For high power, efficient and scalable PDC structures, combining methods (Russell 1979) include circuit-level power combining approach and spatial or quasi-optical power combining methods. While the former suffers from poor combining efficiency due to multiple of transmission lines used, the latter is useful for millimeter wave applications. Radial combiners (figure 4), a subcategory of circuit level approach, can lead to power combining efficiency nearly 90% and

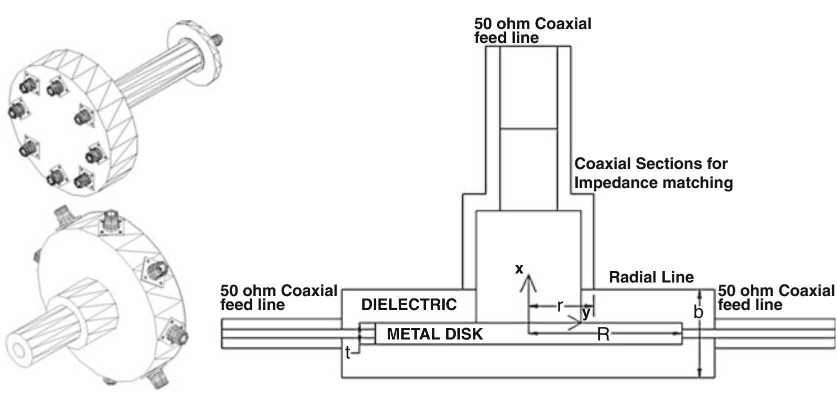

Figure 4. High power radial divider and combiner with its scheme (right).

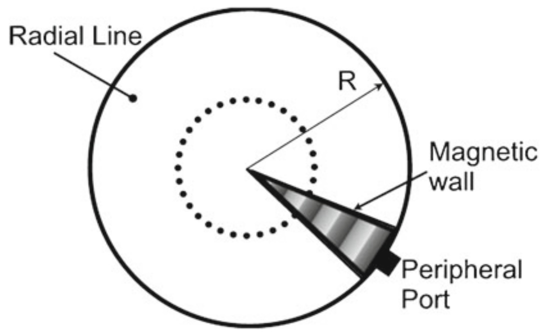

Figure 5. Radial line approximation.

insertion loss less than 0.5 dB. Being in-phase structures, their phase and amplitude imbalance, among different peripheral ports, depends upon structural symmetry. Fathy (2006) has outlined simplified approach for radial combiner, incorporating isolation resistor with quarter wave resonators in microstrip configuration, followed by physical verification at 12.5 GHz for 30 W final output power. For RFM system of particle accelerators, much higher power radial PDC at comparatively lower frequency band (VHF to S band) is required. To fulfill these requisites, design approach needs to be modified appropriately so as to make use of slab line or stripline like rigid transmission structures, without quarter wave matching section and isolation resistor. At high power, isolation resistor may lead to heat dissipation, ageing and mechanical difficulty in placing resistor inside kW level power handling PDC structure. Depending upon design frequency, appropriate translation of design parameters in mechanical friendly transmission media, is necessary for preventing higher order modes, and thus, for obtaining near ideal performance.

For matching between common feed port and peripheral port, instead of quarter wave transformer, coupled non-uniform (linearly tapered) transmission lines, arranged in radial fashion, were used. This arrangement provides some betterment in bandwidth, as compared to use of narrowband quarter wave sections. Initially, design of feed port and sector components of radial PDC was based on radial transmission line approach (Marcuvitz 1951; Jain *et al* 2007). It was realized in stripline-like structures and designed using Taylor's series expansion of radial line impedance (Khalaj-Amirhosseini 2006) for each peripheral port bounded by magnetic wall (figure 5). This method was time-consuming. Also 16-way PDC, designed earlier, was bulky and RF contact of branch port with radial transmission line was mechanically poor.

Later on, improved power combiners were reported (Jain *et al* 2009) using this simplified approach. However, during repeatable development, it was noticed that RF contact of branch port

Figure 6. Eight-way radial power divider at 505.8 and 352 MHz.

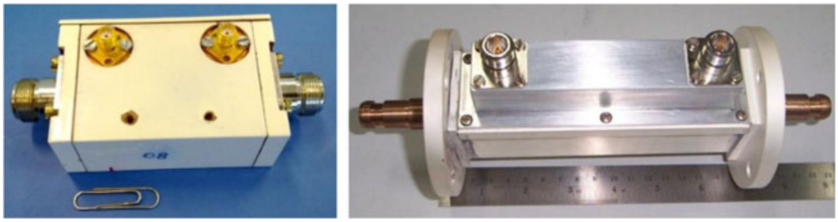

Figure 7. Directional couplers of 1 kW (left) and 4 kW (right).

is again creating problem in mechanical assembly. In the present development, this problem was removed by making structure simulation of more rugged and repeatable PDC structure. Contact of branch with periphery of radial line was realized by bullet-shaped pins, similar one was used in rigid coaxial lines. Also length of feed line was shortened with change and a coaxial matching sections. After design optimization using structure simulator, two types of 8-way PDC, operating at 352 and 505.8 MHz, respectively (figure 6), were designed with 1–5/8″ EIA central coaxial feed port and standard N connector, at peripheral collecting ports. Choice of frequency and RF power was selected so as to fulfill project requirements of the institute.

Placement of peripheral ports and radius of combining path (disk size) in PDC is dictated by N connector footprint, so as to accommodate all N connectors with some space for movement, while making cable connection. During EM simulation, performed afterwards, care was taken to remove high electric field spots away from restricted regions, where possibility may exist for dielectric failure at full power.

In the present design, radius of circular outer disk is 200 mm for both 8-way as well as 16-way PDC at both of the frequencies. Impedance matching from radial line to 50 Ω environment was carried out by different impedances' coaxial line sections having same outer conductor diameter of 65 mm. This matching section length, at 352 MHz, is 90 mm in 8-way PDC and 110 mm in 16-way PDC. At 505.8 MHz, length is less by 20 mm for 8-way PDC. Provision has been made for frequency tuning by placing internal Teflon rings. No additional external tuning screw or isolation resistors were used in this design.

2.3 *High power directional coupler*

For measuring output forward power, two types of wideband (300–800 MHz) directional coupler were designed based on procedure outlined by Teppati (2003). In this design, a rectangular coaxial transmission (main) line with 1–5/8″ EIA flange as terminal ports, was coupled to another rectangular coaxial (auxiliary) line (figure 7). A thin metal diaphragm with properly shaped aperture was inserted between centre conductors of main line and auxiliary line. Compared to Teppati design, computation of coupling profile for aperture of diaphragm was carried out using linear approximation. For low power (1 kW) design, a small rectangular line section (length 60 mm) was used. For coupling purpose, a small air suspended strip line was used. For high power (4 kW) coupler, design calculation gives final length nearly 250 mm (between EIA flanges), which was reduced to 170 mm using HFSS™, achieved by optimization of aperture shape.

3. 2 kW solid state amplifiers

Finally, for high power testing and RFM data generation, all these components were assembled as solid state power amplifier with 2 kW output power, initially at 352 MHz and later on at 505.8 MHz. Both of these systems have been tested up to 2 kW.

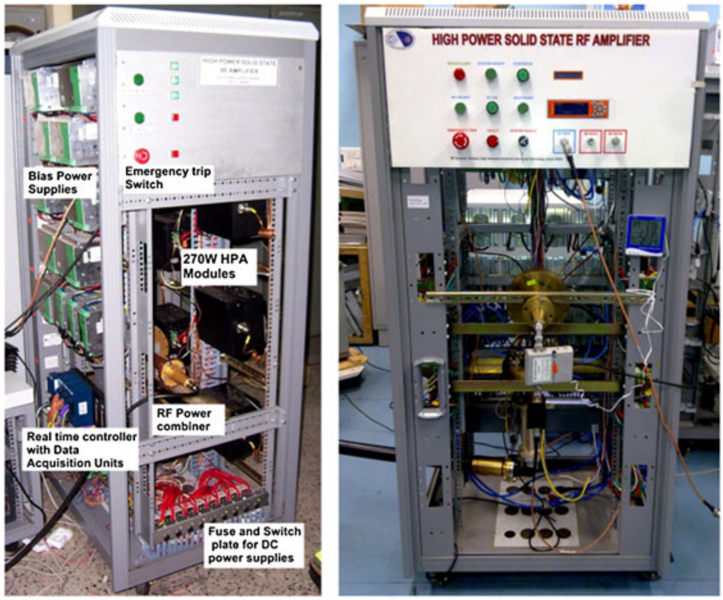

Figure 8. 2 kW amplifiers at 352 MHz (left) and 505.8 MHz - with power combiner/divider, amplifier modules, bias power supplies and real-time controller.

At 352 MHz, initially output power obtained from each module was 220 W, providing around 1.5 kW when assembled as complete system (Jain *et al* 2008). Later on output matching circuit of this design was improved to increase output power of HPA up to 270 W resulting in final output power up to 2 kW. Complete system (figure 8) was housed in a standard 32U Euro cabinet. At the input of power divider, a similar 270 W module was used as preamplifier, driven by 30 W module. Forced air cooling was sufficient as DC to RF power conversion efficiency of modules was more than 60%.

Similarly, 2 kW amplifier at 505.8 MHz was assembled with eight numbers of 300 W amplifier modules, two numbers of eight-way power combiner/divider, high power square coaxial type directional coupler and driver amplifier. Design architecture is similar to amplifier at 352 MHz, except water cooling used in the present study. Four modules were mounted on a copper heat sink. Two heat-sinks are placed opposite to each other with control electronics at the front.

4. 8 kW solid state amplifier

Encouraged by successful measurement results of 2 kW amplifier at 352 MHz and 505.8 MHz, 8 kW amplifier scheme at 352 MHz, as shown in figure 9, was designed. At the core of this scheme, 16 numbers of 270–300 W amplifier modules will be power combined using 16-way radial power combiner. Two such ensemble will be again power combined using a two-way combiner having 3–1/8″ rigid coaxial output. Complete system housed inside 42U euro rack can be considered in two halves, each one similar to other half in terms of RF components.

For this system, 16-way combiners and two-way high power combiner, were designed and successfully tested (figure 9). Impedance matching from radial line to 50 Ω environment was carried out by different impedances' coaxial line sections having same outer conductor diameter

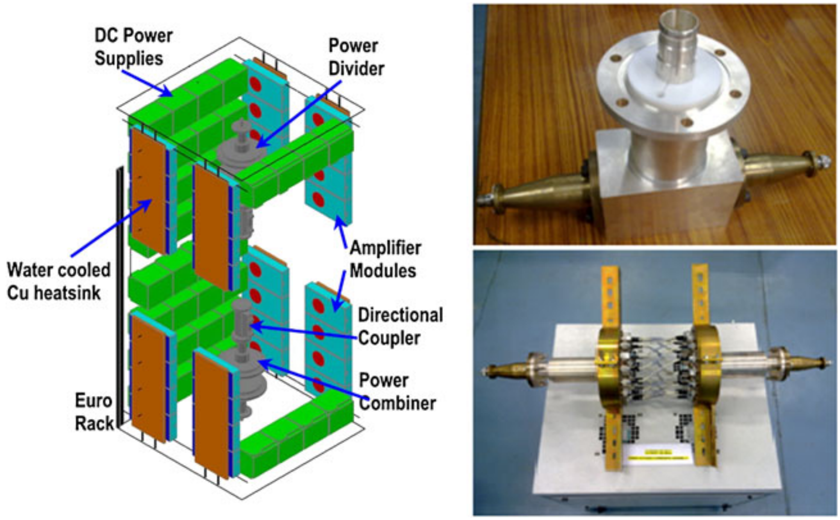

Figure 9. Architecture of 8 kW amplifier with 2-way and 16-way power combiners.

of 38.6 mm. This matching section length is 86 mm. 2-way PDC is with 3–1/8″ EIA output flange to handle power level up to 15–20 kW at 352 MHz.

5. Measured performance

RF measurement of different RF components, described above, was performed at low and high CW and pulse RF power. At low power, measurement was carried out using vector network analyser E5071B for complete scattering parameter matrix measurement. At high power, scalar measurement was performed using Rohde & Schwarz NRT power meter and FSP7 spectrum analyser along with directional coupler. For the sake of briefness, some of the measurement results are discussed here.

At 352 MHz, measured response of ten amplifier modules, measured just after assembly and soldering, is shown in left part of figure 10. For comparison purpose, response of earlier designed eight HPA modules at 220 W is also shown. Later on, modules giving output power less than

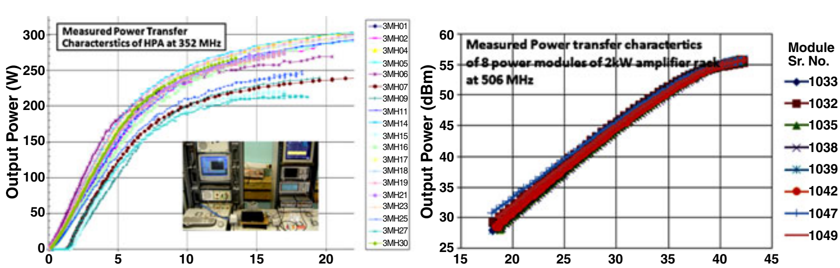

Figure 10. Measured results of amplifier modules at 352 (left) and 505.8 MHz.

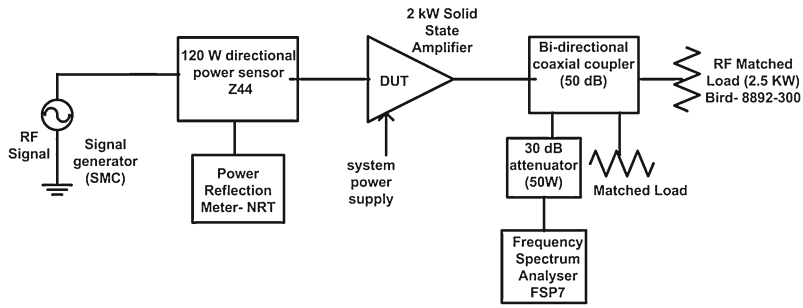

Figure 11. Scalar measurement test set-up for 2 kW amplifiers at 352 and 505.8 MHz.

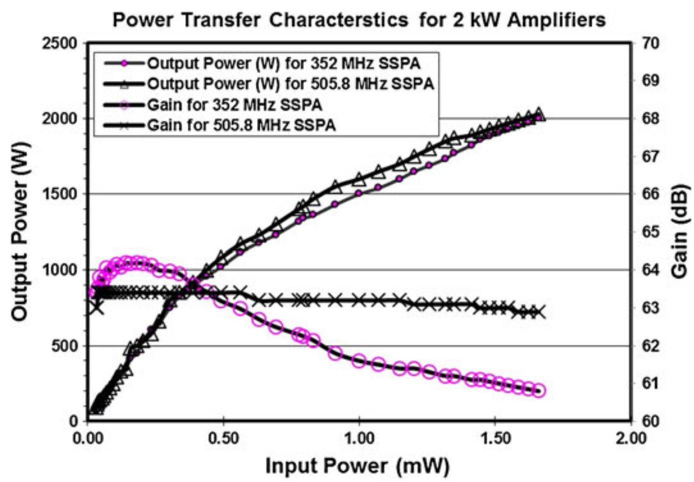

Figure 12. Measured results of 2 kW amplifiers at 352 and 505.8 MHz.

250 W were tuned with chip capacitors to giver rated power of 270 W. DC to RF power conversion efficiency of each module is in excess of 60%. For 2.5 kW (pulse) power testing, duty cycle was varied from 3% to 15% with 0.2 mS pulse width.

At 505.8 MHz, measured response of amplifier modules is shown in right part of figure 10. Maximum saturated power obtained was in excess of 300 W with saturated gain of 13 dB. Assembled system has been tested up to 2 kW CW.

At high power, scalar measurement was performed for each of 2 kW amplifier using Rohde & Schwarz NRT power meter and FSP7 spectrum analyser along with directional coupler (figure 11). RF power transfer characteristics of these amplifiers are shown in figure 12. This characteristic is linear in common operation region (1 kW onwards). For each amplifier, RF testing was performed for more than 110 h, with each test segment stretching for 3–6 hours in time. During this life time testing, no any problem like excess heating or local hot spot formation, was observed. Finally in the series of experiments, for safety purpose, radiation level was measured. This figure measured less than 1 mW/cm^2, which is much below the safe limit prescribed in frequency range of 300–800 MHz.

For graceful degradation study purpose, degradation in output power was measured without amplifier modules. For this case, unused (failed) ports were terminated with system impedance. Figure 13 shows degradation in normalized output power as number of failed ports increase.

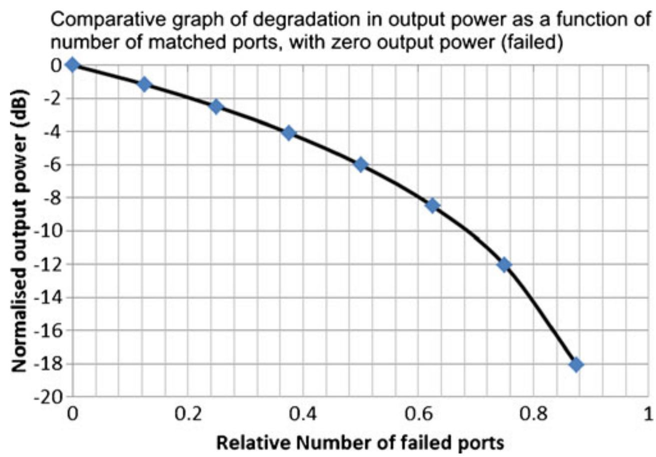

Figure 13. Measured results of graceful degradation experiment.

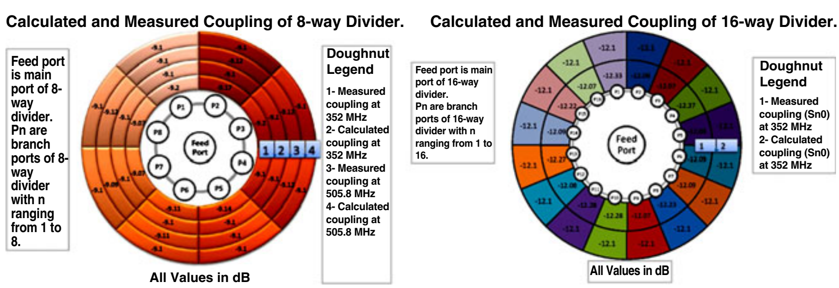

Figure 14. Measured and calculated power coupling - for 8-way PDC at 352 MHz and 505.8 MHz (left) and 16-way PDC at 352 MHz (right).

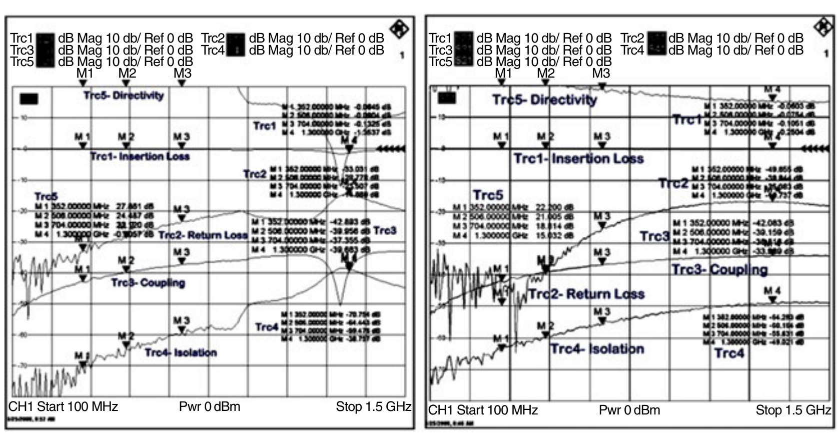

Figure 15. Measured performance (insertion loss, coupling, return loss, isolation and directivity) of low power (1 kW) and high power (4 kW) directional couplers.

For developed PDC structures, return loss of feed port, insertion loss, and coupling from feed port to branch port and phase imbalance were measured. Return loss for feed port (assigned port zero) was −30.8 dB and −27 dB for 8-way and 16-way PDC, respectively against the calculated value of −35 dB and −30 dB for respective cases. Measured power coupling S_{n0}, expressed in dB, is assumed as power ratio between any of the n (n varies from 1 to 8 or 16) branch port and feed port, when all other ports are matched terminated. It can be seen from figure 14 that deviation (loss) in coupling from HFSSTM calculated value (9.1 dB for 8-way and 12.1 dB for 16-way PDC) is much lower in each case.

In practice, some amplitude and phase imbalance is expected due to imperfect mechanical symmetry. Measured phase deviation of all transmission coefficients was less than 0.7 degree. Combining efficiency, calculated by measured data, was better than 96% for this 8-way PDC. For phase imbalance measurement and power combining testing, two similar PDCs were connected back to back (as shown in lower right part of figure 9). Ports connections were randomly changed several times. Worst case insertion loss for this back to back divider–combiner system was 0.43 dB. Almost similar data was obtained from measurement of 505.8 MHz PDC. Measured insertion loss and combining efficiency for 16-way PDC at 352 MHz was 0.1 dB and 93%.

For directional coupler, low power measurement carried out is shown in figure 15. For 1 kW coupler, directivity is in excess of 27 dB and 24 dB at 352 and 505.8 MHz, respectively. Similar figures for 4 kW coupler are 22 and 21 dB. Wideband (300–800 MHz) performance is evident from this measurement. Measured insertion loss, at 2 kW, was less than 0.05 dB for 1 kW coupler and less than 0.1 dB for 4 kW coupler, both at 352 MHz. Afterwards, more than 10 couplers were fabricated and tested to check repeatability. Deviation in most of the measured parameters (coupling, isolation and directivity) was less than 2 dB.

6. Conclusion

At 352 MHz and 505.8 MHz, compact and modular kW level solid state RF amplifiers have been successfully developed and tested. Using approximate design methodology, the multi-way power divider and combiner were designed and tested. The measured and predicted results are in good agreement. Successful development of this first-time attempted 2 kW amplifier adds confidence for future development for selecting solid state RF source in particle accelerator, among other tube-based radio frequency and microwave sources.

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