HIGH-POWER, LOW-LOSS, RADIAL RF POWER DIVIDERS/COMBINERS

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Abstract

Development of a 20 kW Solid State Power Amplifier (SSPA), at 352 MHz, is in progress at RRCAT. This design uses radial dividing and combining architecture. As a part of this system, two high power (4 kW) combiners have been designed and developed. First one is 8 way with output ports in opposite but parallel direction to input port. Second one is 16 way with radial output ports. This paper describes design and measured performance of these two structures. Predicted results are in good agreement with those measured results.

INTRODUCTION

With growing interest in high power solid state RF source for particle accelerator [1] [2], design of high Power Divider/Combiner (PDC) structures has received enormous attention. Among different combining approaches, radial combiners proved to be efficient for summing N (>2) amplifiers. The tree structures have simpler design, but they have disadvantage of using multitude of transmission line segments, which add losses. This significantly degrades overall performance, especially for higher N. Radial combiners on other hand, can lead to power combining efficiency over 90% and insertion loss less than 0.5dB. Being in phase structures, their phase and amplitude stability depends upon symmetry, which in turn can be achieved easily with good mechanical design. In this paper, using simplified design methodology, two type of PDCs (8 way and 16 way) have been designed with central feed (1-5/8” rigid line) and peripheral collecting ports (N type connector) structure. With these structures, combined RF power of the order of up to 4 kW can be achieved. Necessary vector and scalar measurements were carried out for testing these designs.

DESIGN

Radial power combiner offers low loss, excellent amplitude and phase balance, with high power handling capability [3]. Unlike corporate combining structures, radial structure permits placement of a large number of ports very close to central feed port, thus minimising combining path and losses. A careful optimisation of physical structure is essential to obtain low insertion loss and good isolation over desired bandwidth. Project design specifications, include 8 way and 16 way PDC with combining efficiency > 90%, 1 dB bandwidth of ± 5 MHz, at center frequency of 352 MHz. As total output power is within 5kW, 1-5/8” EIA flange at output port, has been selected. Similarly at combining port expecting maximum power of 300-400W, N type connectors were selected for these design. Overall design should have insertion loss (other than coupling) less than 0.5 dB between desired coupled ports.

Combiner/Divider model

Proposed combiner/divider structure consists of three parts: the launcher, combining path and N way peripheral ports (Fig. 1). The launcher is coaxial line, feeding radial transmission line. The combining path (the radial line) is a low loss parallel plate stripline type transmission structure, with a central point excitation. From central excitation, energy spreads uniformly outward in the dominant E mode with an axial electric field component. It is important to maintain mechanical stability in feeding power symmetrical in order to prevent propagation of higher order modes. Feed symmetry governs insertion loss and phase imbalance. Last part is N way peripheral port (usually 50 ohm) section, connected to circular combing path. Design methodology of complete structure is stated step by step in terms of these three parts.

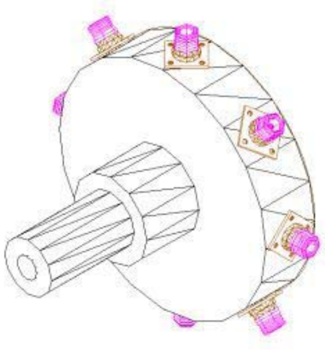

Figure 1: Radial combiner/divider structure

Designing Feed section

A 50 ohm input coaxial feed line is connected to radial line. In between these two lines, comes impedance matching section, realised in the form of coaxial lines having different characteristic impedance. Characteristic impedance of radial line is similar in nature to that of a TEM transmission line [4]. Hence, at feed point each dividing port can be thought as parallel connection of transformed impedance of port termination values. Transformation ratio can be deduced from formula for characteristic impedance of radial line. Problem is significantly complicated by the existence of complex characteristic impedance with spatial dependence, as well Bessel function arguments associated with radial line parameters. However, to simplify design, impedance of radial line at feed point can be assumed that of equivalent resistance of N port connected in parallel.

Using this formula we get approximate real value of radial line impedance, terminated by matched boundary at discrete ports. Coaxial impedance matching sections can be designed with this value for matching it to 50 ohms feed port. This initial step gives us idea for the design of coaxial sections. To improve this approximation and to determine radial line and coaxial line junction dimensions, we need to account for the effect of coaxial/radial line junction discontinuity. This effect can be incorporated in the design using Williamson's [5] equivalent circuit. This calculation gives value of imaginary part at junction in the form of Bessel's and Neumann functions.

Designing combining path and peripheral ports

Design of combining path and peripheral ports was carried out by treating circular geometry as uniformly spaced circular array of coupled non uniform transmission line. [6] [7]. Each line impedance function is expanded in terms of Taylor's series. In this method, all distributed primary parameters of the line and also the voltage and current distribution along the line are considered as Taylor's series. Once V and I matrices are known, S matrix can be derived. For present design, we formulated the problem as circular array of 8 and 16 numbers of coupled linearly tapered transmission line, for 8 and 16 way PDCs respectively. This analysis gives us idea about return loss and isolation.

Placement of peripheral ports and radius of combining path is dictated by placement and dimension of N connector footprint, to accommodate all N connectors with some space for movement, while making cable connection. Due to this reason, N type connectors in 16 way PDC, were placed on periphery, unlike 8 way PDC, where combining ports are in line and opposite to Central feed.

Design Optimisation

During this simplified design approach, many real time discontinuities were ignored. These discontinuities include radial line to coaxial line discontinuity and discontinuities involved in step changes of inner conductor of different coaxial lines in impedance matching section and finite thickness of substrate and strip line. Hence for final optimisation, complete design was simulated using full wave EM simulator of HFSS. During this simulation, we computed first, impedance at feed port. This value was used for improving impedance matching section at central feed (1-5/8" rigid coaxial port) using circuit simulator. During this simulation care was taken to remove high electric field spots away from restricted regions, where possibility may exist for dielectric failure at full power. Fig. 2 and 3 shows completely assembled 8 way and 16 way PDCs.

Circular section radius is kept 80mm for both 8 way as well as 16 way PDC. Impedance matching from radial line to 50 ohm environment was carried out by different impedances' coaxial line sections having same outer conductor diameter. This matching section length is 95 mm in 8way PDC and 86 mm in 16 way PDC. Provision has been made for frequency tuning by placing Teflon rings.

Figure 2: 8 way power combiner/divider structures

Figure 3: 16 way power combiner/divider structure

MEASURED PERFORMANCE

Both of fabricated PDCs were measured at low and high power. At low power, measurement was carried out using vector network analyser E5071B. At high power scalar measurement was performed using R&S NRT power meter and FSP7 spectrum analyser. Insertion loss was measured as 0.2 dB and 0.4 dB for 8 way and 16 way PDC respectively. VSWR at the input port was measured as 1.05 and 1.15, while return loss measured at input feed was less than -35 dB and -22dB, for 8 way and 16 way PDC respectively. 90% bandwidth for 8 way and 16 way PDC was found to be in excess of 50 MHz. Figure 4 and 5 shows variation of return loss (S00) and feed port to dividing port coupling (S10) with frequency, for both of the structures. Measured performance of 8 way and 16 way PDC was satisfactory.

For phase imbalance measurement and power combining testing, two similar 8 way PDCs were connected back to back. Thus one PDC performs dividing action, while second one combines divided power. Ports connections were randomly changed several times. Total worst case insertion loss for this divider-combiner system was 0.43 dB. As each 8 way PDC has insertion loss of 0.2 dB hence loss due to phase mismatch is 0.03 dB which is very low. This measured value directly reflects control over phase stability in radial PDC. Combining efficiency calculated by measured data was better than 93% and 89% for 8 way and 16 way PDC.

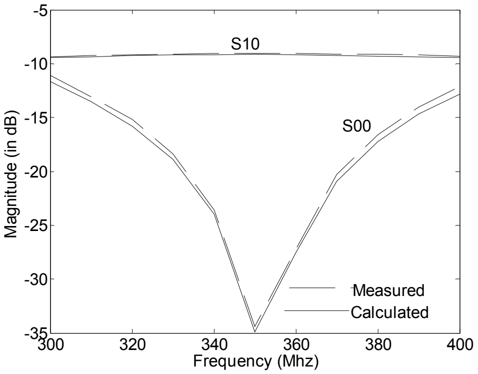

Figure 4: Comparison of measured and calculated results for 8 way Power Divider/Combiner

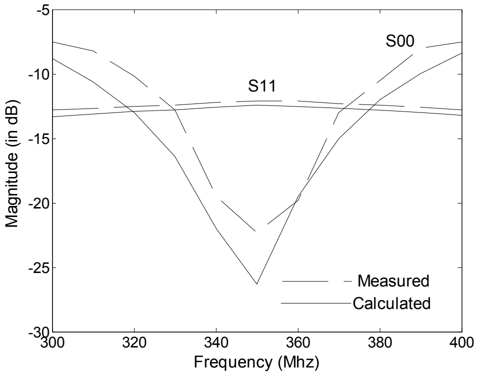

Figure 5: Comparison of measured and calculated results for 16 way Power Divider/Combiner

CONCLUSION

Using approximate design methodology, two different types of PDC at 352 MHz, were designed and tested. Zero Order structure design was further optimised using HFSS, full wave EM simulator. Measured and predicted results are in good agreement. Inspired by successful operation of Soleil 200 kW Solid state source and successful development of these PDC, another 8 way and 20kW power PDC design has been started. This successful development adds confidence for selecting solid state RF source in particle accelerator, among other tube based sources for few hundred kW of RF power regime.

ACKNOWLEDGEMENT

We are thankful to Mr. Ramesh Kumar and Mr. R K Arya for carefully preparing and assembling all of the combiner/ divider parts, with a special care from RF design point of view. For testing and measurement work, we are grateful to Ms Vasanti Sekhar. Mr D K Verma has carefully assembled all lines and testing rack with necessary electronics. We are also thankful to S. K. Jain for providing useful suggestions for mechanical assembly at various occasions during the course of this development. We are thankful to M/s Vistech Information system (P) Ltd. Banglore for providing us evaluation version of HFSS.

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