

Wilkinson Type Lumped Element Combiner-Splitter for Indigenous Amplifier Development

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Abstract. Development of wideband solid state power amplifier in ITER [1] ICH&CD frequency range is ongoing. A 12 kW/CW Solid State Power Amplifier (SSPA) is being developed in house. 1×16 wideband splitter/combiner will be used at input/output side. Study has been carried out on two options i.e. coaxial type & lumped element based Wilkinson splitter/combiner. Tentative power level of both input N-Type ports of combiner is ~ 1 kW. Design and simulation for coaxial type Wilkinson combiner is done. Quarter wave length for centre frequency is ~ 1500 mm. To reduce mechanical dimension of combiner, PTFE dielectric is used with sophisticated arrangement. Coaxial combiner required unique fabrication process. Alternate option is proposed as a lumped element based Wilkinson combiner with reduced size, cost & development time. Design and simulation was carried out. Required PCB design & fabrication was done accordingly. Same design will be implemented for splitter as well. Design scheme for the splitter/combiner will be finalized depending on the achieved performance of both the designs. In this paper, detailed design, simulation and test results are presented for both types of combiners. A detailed comparison of combiners is provided.

1. Introduction

The Ion Cyclotron Heating and Current Drive (ICH &CD) system has to couple 20 MW Radio Frequency power to ITER [1] plasma for heating and driving plasma current, in the frequency range of 35-65 MHz [2]. There will be 8 RF sources to generate total 20 MW of RF power at VSWR 2:1[3]. Each RF source is made up of two RF amplifier chains combined at end stage through high power combiner. Each amplifier chain has three cascaded amplifiers, where final stage (~ 1.7 MW) is driven by driver stage (~ 150 kW) which is further driven by a pre-driver stage (~ 10 kW). The driver and final stages are tube based (Diode/Tetrode) amplifiers and pre-driver is a solid state power amplifier (SSPA). SSPA is a wideband solid state amplifier using MOSFET as an active device. There are total 16 pallet modules each having maximum output power of ~ 1 kW. Each pallet module contains one MOSFET and input/output matching circuit. The goal is to achieve power level of ~ 12 kW/CW. 16 pallet amplifier modules will be combined using 16×1 wideband combiners. 16 RF signals, with equal phase, will be required to drive each pallet module. 1×16 wideband splitter will be used at input side. Figure 1 shows the overall scheme of SSPA.



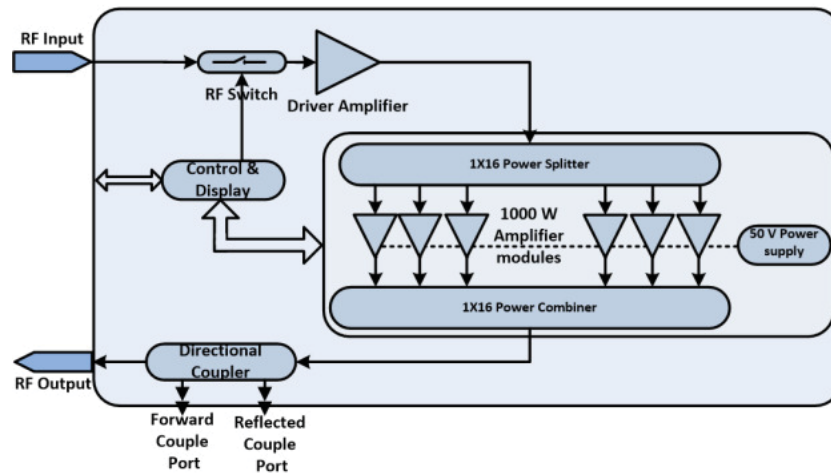


Figure 1. Solid State Power Amplifier (SSPA) block diagram

Wilkinson type combiner/splitter [4] is found as a good choice for development of the input splitter and output combiner for SSPA.

2. Wilkinson combiner/splitter:

Major technical specification for the 2×1 Wilkinson combiner /splitter is as given in table 1.

Table 1: Major technical specifications

Parameters	Values
Operating frequency	-65 MHz
Flatness (at edge frequency w.r.t centre)	Within 0.5 dB
Return loss (at input port)	Better than - 20 dB
Power handling	~ 2 kW
Connector type	N female (50 ohm)

Wilkinson combiner/splitter is a 3 port (in 2×1 scheme) lossy, matched and reciprocal network. Figure 2a shows the scheme of a 2×1 Wilkinson combiner/splitter. Port 3 of characteristic impedance Z_o is split in two arms with each arm having a quarter wave ($\lambda/4$) impedance transformer of characteristic impedance $\sqrt{2}Z_o$. Port 1 and 2 are connected at the other end of transformer. Isolation between the port 1 and 2 is achieved by connecting a resistor of impedance $2Z_o$ between the two ports.

For characteristic impedance $Z_o = 50 \Omega$ and design frequency $f_o = 50$ MHz

Quarter wave transformer characteristic impedance is [4]

$$Z_{trans} = \sqrt{2} \times 50 = 70.7 \Omega \quad (1)$$

The length of transformer is [4]

$$L_{trans} = \frac{\lambda_o}{4 \times \sqrt{\epsilon_r}} = \frac{6}{4 \times \sqrt{2.1}} = 1.035 m \quad (2)$$

where wavelength (λ_o) = 6 m, PTFE dielectric constant (ϵ_r) = 2.1

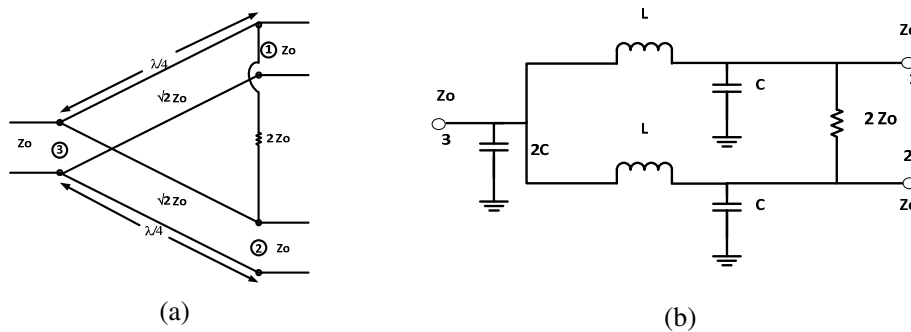


Figure 2. 2×1 Wilkinson combiner/splitter (a) layout (b) corresponding lumped equivalent

The lumped circuit equivalent of 2×1 Wilkinson combiner/splitter is shown in figure 2b. The quarter wave transformer is replaced by an equivalent pi (C-L-C) circuit.

Inductive reactance [4] $\omega_o L = Z_{trans}$

$$L_{trans} = \frac{Z_{trans}}{2\pi f_o} \quad (3)$$

From equation (1) and (3) at design frequency 60MHz; calculated inductance $L = 187$ nH

The resonance frequency is defined as [4] $f_o = \frac{1}{2\pi\sqrt{LC}}$ (4)

From equation (4) at design frequency 60 MHz; calculated capacitance $C = 37.6$ pF. Value of resistance connected between port 1 and port 2 is 100Ω .

3. Modelling and Simulation:

3.1. Coaxial 2x1combiner/splitter:

Modeling and simulation of coaxial type combiner/splitter was performed using CST MWS software. Inner conductor diameter was constrained on the available copper wire diameter ($a = 2.85$ mm) while corresponding outer conductor diameter (for transformer $b = 15.74$ mm and for ports $b = 6.56$ mm) is found from equation (5) [4].

$$Z_{trans} = \frac{138}{\sqrt{\epsilon_r}} \log_{10} \frac{b}{a} \quad (5)$$

Where $\epsilon_r = 2.1$ (PTFE)

The outer conductor is simulated by cylindrical grooving on two aluminum plates placed back to back as shown in figure 3a. Copper inner wire is supported coaxially inside the grooves using PTFE rods. The effective length of quarter wave transformer is reduced to 1.035m. Overall size of the coaxial combiner is reduced by providing unique shape to the transformer section. Coaxial combiner/splitter shows transmission S11 or S22 value -3.04 dB at band center (50 MHz) and - 3.15 dB at band edged (35 and 65 MHz). Return loss S11 and S22 are better than - 30 dB for the whole band and isolation between port 1 and 2, S12 or S21 is better than -15 dB for whole band.

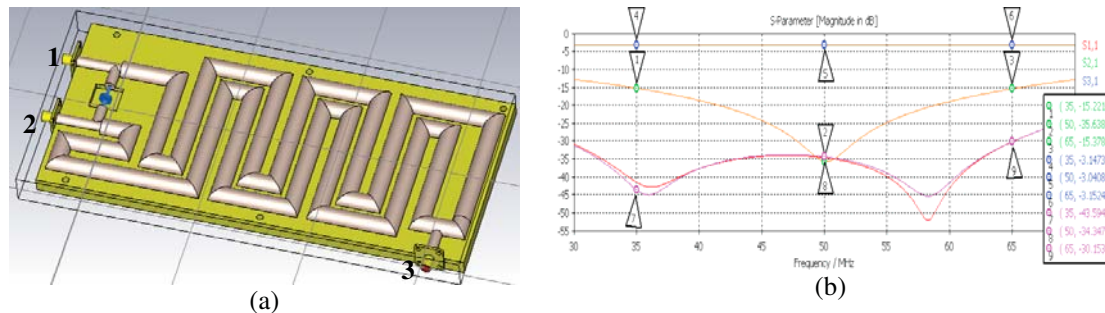


Figure 3. (a) CST model of 2×1 coaxial Wilkinson combiner (b) S-parameter results of the model

3.2. Lumped 2×1 combiner/splitter

Lumped type combiner designed for 50 MHz shows a very quick fall in the transmission response ~ 1.0 dB when we go above 60 MHz (up to 65 MHz); to make the response more flat at higher frequency the design frequency was shifted to 60 MHz. The value of inductor and capacitor were calculated as given in equation (3) and (4). The closest value found practically for the inductor and capacitor were 192 nH and 37.5 pF and they were taken for simulation. Figure 4a shows the simulated circuit of lumped combiner/splitter. The transmission S31 or S32 are - 3.01 dB at 60 MHz. The transmission reduces to - 3.37 dB and - 3.09 dB at band edges 35 and 65 MHz respectively. Return loss S11 or S22 is better than - 23 dB for the whole band. Isolation is better than -10 dB for the whole band.

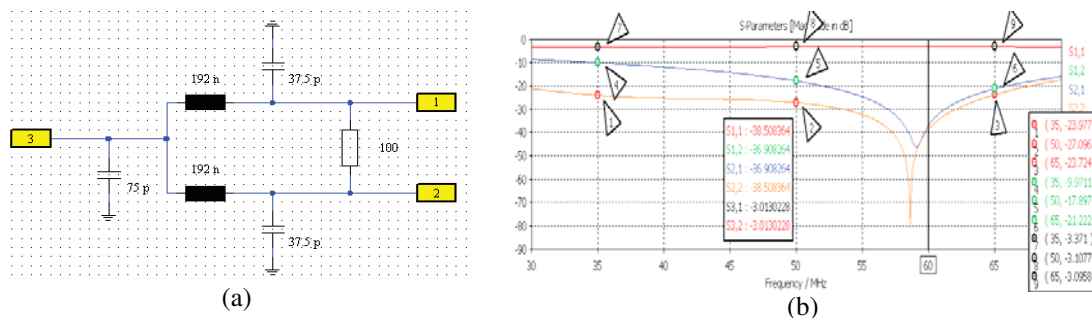


Figure 4. (a) Simulated circuit for 2×1 Wilkinson combiner/splitter (b) S parameter responses

4. Fabrication and Testing

4.1. Coaxial 2×1 combiner/splitter

Coaxial type combiner/splitter is machined over an aluminium plate, with PTFE rods as dielectric to support the inner wire. Two aluminium plates were machined to achieve the half circular groove and then bolted back to back to with PTFE rods within the groove. N type connectors were mounted at the ports and inner pin was soldered with the inner conductor wire. Figure 5 shows the fabricated and assembled coaxial type combiner/splitter with VNA setup for testing. The Insertion loss S31 and S32 is - 3.20 dB and - 3.01 dB respectively at band centre (50 MHz). Transmission at band edge (35 and 65 MHz) has better than 0.11 dB flatness. Return loss S22 or S11 is better than - 20 dB for whole band. Figure 6(a) and 6(b) shows the S-parameter response of coaxial combiner/splitter.

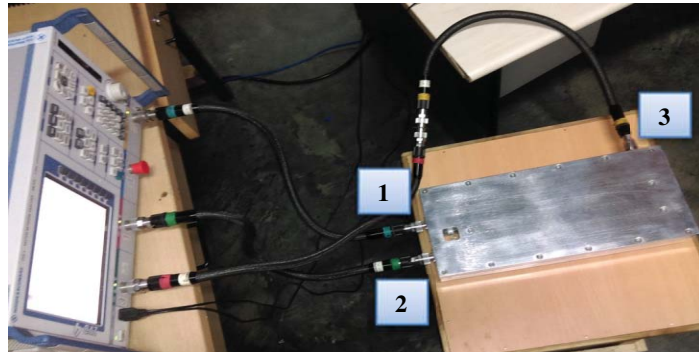


Figure 5. Fabricated coaxial splitter/combiner VNA setup

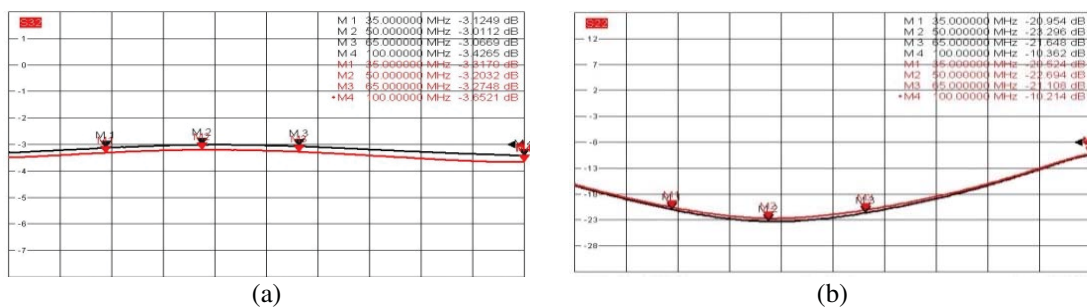


Figure 6. S parameter response (a) Insertion Loss (S31 and S32) (b) Return loss (S11 and S22)

4.2. Lumped 2×1 combiner/splitter

The Lumped type Wilkinson combiner/splitter is built by lumped circuit components (resistor, inductor and capacitor) mounted over a PCB. Figure 7 shows the lumped Wilkinson combiner/splitter with N type connector ports. Transmission S31 and S32 are - 3.0 dB and - 3.2 dB respectively at 50 MHz and a flatness of 0.31 dB is achieved at band edge. Return loss S11 or S22 is better than -17dB for whole frequency range. Isolation S12 or S21 is - 10 dB at 35 MHz and improves up to - 16 dB at 65 MHz. Figure 8(a) and 8(b) shows the S-parameter response of lumped combiner/splitter

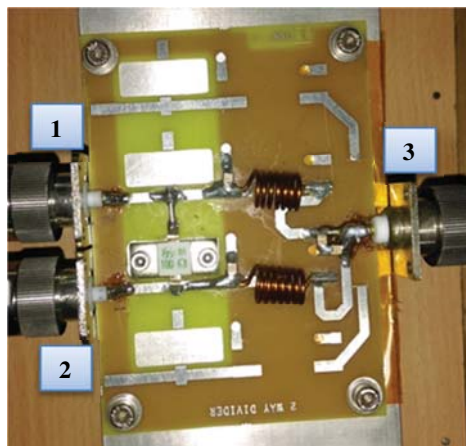


Figure 7. Lumped 2×1 Wilkinson splitter/combiner

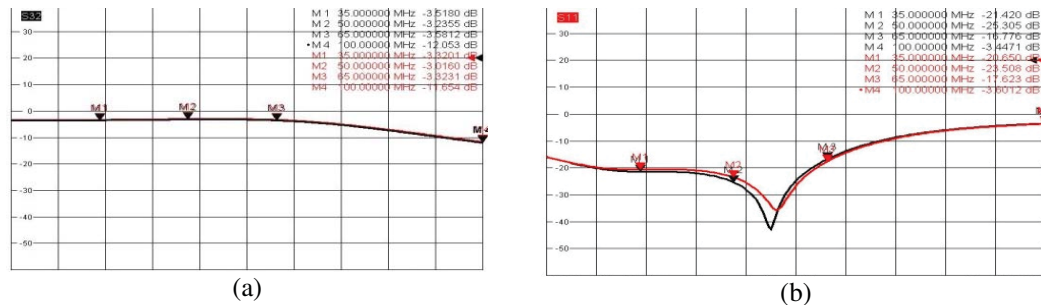


Figure 8. S parameter response (a) Insertion Loss (S31 and S32) (b) Return loss (S11 and S22)

5. Conclusion

Detailed study of Wilkinson type 2×1 splitter/combiner was done. Two options for development of combiner i.e. coaxial and lumped element were chosen. Calculation for coaxial type combiner transformer impedance and corresponding lumped equivalent is provided. Both the options were simulated using CST MWS and fabrication was done and test results were obtained for comparison. A comparison for the two options is provided in table 2.

Table 2. Comparison of lumped and coaxial 2×1 Wilkinson type combiner/splitter

Properties	Lumped type	Coaxial type
Transmission flatness over whole band	~ 0.3 dB	~ 0.11 dB
Return loss over whole band	Better than - 17 dB	Better than - 20 dB
Isolation between input ports	- 10 dB at 35 MHz - 16 dB at 65 MHz	Better then - 20 dB
Power handling	Depends upon lumped element dissipation limit (~ 1.5 kW)	Restricted by the N type connector power handling (~ 3 kW)
Size	Smaller (PCB mount)	$385 \times 170 \times 40$ mm
Fabrication method	PCB development and soldering of lumped elements	Machining of aluminium plate and bolted
Cost	Comparatively less	Machining cost is high

Lumped type combiner/splitter is easier to fabricate and has lower fabrication cost but it has lower isolation, lower return loss and lower transmission flatness between input ports, smaller bandwidth and lower power handling capability (depending on components used) with respect to the coaxial type combiner/splitter. Coaxial type combiner developed here has larger dimension and relatively higher fabrication cost.

References

- [1] ITER-Physics Expert group 1999 *Nuclear Fusion* **39** 2137
- [2] Lamalle P U et al. 2013 *Fusion Eng. Des.* **88** 517
- [3] Mukherjee A et al 2015 *Fusion Engineering and Design* **96–97** 542
- [4] Pozar D M 2012 *Microwave Engineering* fourth edition (John Wiley & Sons, Inc), chapter 7 p 328-329