High-power low-loss air-dielectric stripline Gysel divider/combiner for particle accelerator applications at 352 MHz

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Abstract: This study presents a new two-way Gysel combiner based on an air-dielectric stripline which allows to handle very high radio-frequency power levels with low-loss suitable for power combination in accelerator applications. The insertion loss of the combiner is 0.1 dB (2%). A thick stripline implementation allows improving the power capability in both continuous wave (CW) and pulsed operation. In addition, a mechanical tuner allows compensating for assembly and fabrication discrepancies. A methodology of designing the Gysel combiner as well as high-power measurements up to 22 kW in pulsed mode are presented. Simulations and measurements are in very good agreement.

1 Introduction

Particle accelerators require efficient, high-power and reliable radio-frequency (RF) sources, with RF peak power from dozens of kilowatts up to the megawatt level operating both in continuous wave (CW) and pulsed modes. Solid-state power amplifiers (SSPAs) generate a growing interest for particle accelerators applications thanks to modularity, reliability and prolonged lifetime of the SSPA solutions. Scalability, easy maintenance and a reduction of cost are highly impacting adoption of SSPA solutions [1]. Therefore, SSPAs are foreseen to represent a promising replacement of traditional RF sources, essentially tetrodes in the frequency range from few MHz up to 2 GHz [2].

Due to a limited output power per SSPA, it is required to combine a certain number of amplifiers at different power levels e.g. 10 kW [3], one to few hundreds of kW [4], in order to produce the RF power for driving the accelerating cavities. The Gysel combiner [5] offers an attractive alternative to combine multiple high-power inputs, with the requirement of efficiency and especially it does not use circulators. In comparison with the Wilkinson combiner [6], its high-power capability is achieved by using external loads with high power-handling capabilities. In addition, the Gysel architecture enables to choose the characteristic impedance of its transmission lines (TLs), instead of using conventional 50 Ω. Then the impedances seen from input and output ports of the Gysel combiner are able to design much lower than 50 Ω, meaning that wider TLs can be adopted for enhancing power handling capability. For power amplifier (PA) design, it means that the PAs can deliver more output power by using wider microstrip lines and are easier to do high-power matching to low transistors' output impedance.

This paper presents a compact Gysel combiner using thick air-dielectric stripline well suited for power combining from a 10 kW level to a few dozens of kW. A demonstration of high-power capability up to a nominal pulsed power level of 22 kW is performed, more than twice the nominal power. Simulations and measurements are in very good agreement.

2 Theory and design

2.1 Analysis of the air-dielectric Gysel combiner

The structure of the Gysel combiner consists of three different TLs of characteristic impedance Z_1, Z_2, Z_3 connected at each branch and two external loads, as in Fig. 1. The even–odd mode analysis is used to determine the values of characteristic impedances in the Gysel combiner. As can be seen in Fig. 2, we can derive the admittance looking towards the ports, as follows:

$$Y^o_{\text{in}} = \frac{1}{jZ_1\tan\theta} + \frac{1}{Z_2}\frac{RZ_2 + jZ_2Z_3\tan\theta - RZ_3\tan^2\theta}{jRZ_3\tan\theta + jRZ_2\tan\theta - Z_2Z_3\tan^2\theta} \quad (1)$$

$$Y^e_{\text{in}} = \frac{1}{Z_1}\frac{Z_1Z_o + jZ_1Z_2\tan\theta - Z_oZ_2\tan^2\theta}{jZ_oZ_2\tan\theta + jZ_1Z_o\tan\theta - Z_1Z_2\tan^2\theta} \quad (2)$$

For matching condition in the odd mode, we have

$$Y^o_{\text{in}} = \frac{1}{Z_o} \quad (3)$$

For matching condition in the even mode, we have

$$Y^e_{\text{in}} = \frac{1}{2Z_o} \quad (4)$$

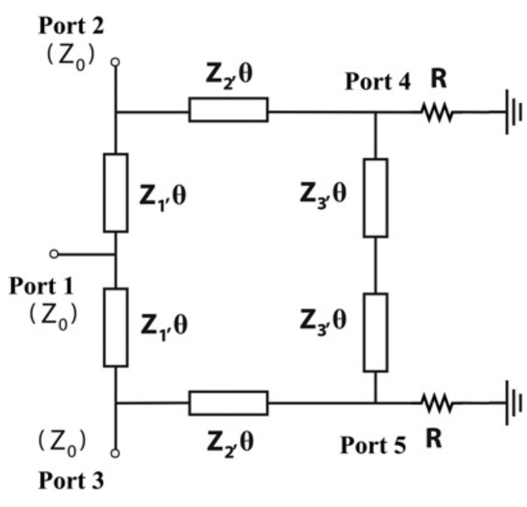

Fig. 1 *Conventional two-way Gysel combiner*

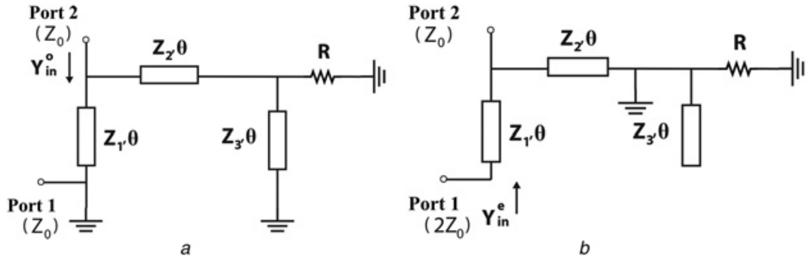

Fig. 2 *Even–odd mode analysis*

In a conventional Gysel structure, all TLs are quarter-wavelength long. Considering quarter-wavelength conditions and solving (1) and (3), (2) and (4) we can derive the relationship amongst the characteristic impedances

$$Z_1^2 = 2Z_o^2 \tag{5}$$

$$Z_2^2 = RZ_o \tag{6}$$

Impedance $Z_3 = Z_o/\sqrt{2}$ is chosen for minimising transmission loss, common port return loss, output ports return loss, isolation among output ports, bandwidth as in [7]. The characteristic impedances are determined as follows: $Z_o = R = 50\ \Omega$, $Z_1 = 70.7\ \Omega$, $Z_2 = 50\ \Omega$, $Z_3 = 35.3\ \Omega$.

2.2 *Design and implementation*

As presented in Fig. 3, the high-power combiner design consists of four parts: air-dielectric TLs, N-type connector ports, matching network from strip-line to coaxial ports and the aluminium housing. The first step is to design the geometric parameters for the air-dielectric TLs, which have the equivalent characteristic impedances determined previously. The balanced air-dielectric strip-line structure used is a thick copper plate of thickness, $t = 1.5$ mm. The position of strip-lines are fixed using Teflon spacers (spacing $H = 17.5$ mm) allowing to implement a predefined space from the ground planes. The width of characteristic impedances are then characterised using Cohn's approximation [8].

$$Z = \frac{94.15}{\sqrt{\epsilon_r}\left(((W/H)/(1 - t/H)) + (C'_f/0.0885\epsilon_r)\right)}\ \Omega \tag{7}$$

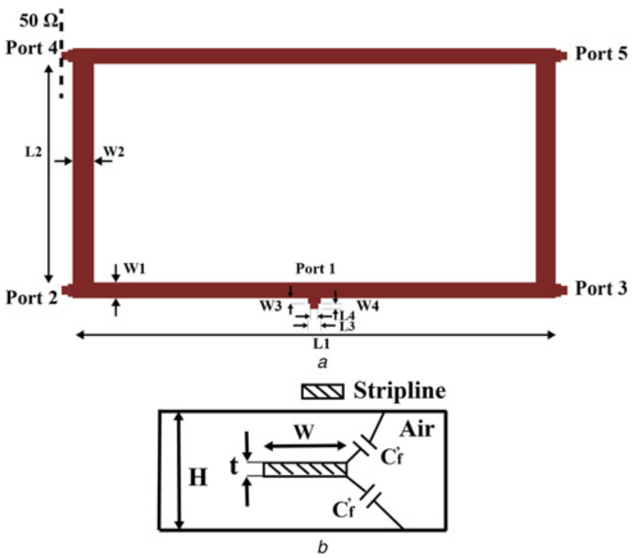

Fig. 3 *Geometry of the two-way Gysel combiner*
a Balanced air-dielectric structure
b Top view

where C'_f is the fringing capacitance in µF per centimetre, which is evaluated from one corner of the strip to the adjacent ground plane; $\epsilon_r = 1$ is used as the relative dielectric constant of air; H is the plate spacing; W and t are the width and thickness dimensions of the TLs. The 50 Ω input/output ports impedances and external load ports are transformed and matched to the impedances Z_{in} of the input strip-lines' impedance seen from the coaxial ports by using a two-section stepped impedance transformer, as shown in Fig. 4. The transformer is designed by adjusting the width and length of the two sections, design procedure developed in (8) and (9). The coaxial port is located at the centre of the two-section matching network and its inner conductor of a diameter of 3 mm is extended as a feeding probe, and is connected to the matching network. The feeding probe is silver plated to minimise loss and soldered to the transformer. The strip-line section close to the feeding probe is adjusted to a thickness of 3 mm. The feeding technique and adapted matching strategy enable to reduce the return loss at the input of the coaxial port

$$Z_{\rm in} = Z_1 \frac{Z'_L + jZ_1 \tan(\beta l_1)}{Z_1 + jZ'_L \tan(\beta l_1)} \tag{8}$$

$$Z'_L = Z_2 \frac{R_L + jZ_2 \tan(\beta l_2)}{Z_1 + jR_L \tan(\beta l_2)} \times -10pt \tag{9}$$

The combiner design is designed and simulated using CST Microwave Studio to fine tune the calculated values at 352 MHz. As seen in Fig. 3, the optimal parameters of the combiner are as follows: $W_1 = 14$ mm, $L_1 = 455$ mm, $W_2 = 19$ mm, $L_2 = 235$ mm, $W_3 = 4.5$ mm, $L_3 = 12$ mm, $W_4 = 8$ mm, $L_4 = 7.5$ mm, and the length of feeding probe is 10.5 mm. It may happen that the strip-line is not perfectly balanced between the two grounds. A mechanical tuner is provided in order to compensate manufacturing and assembly tolerances. The tuner consists of an upper plate and a lower aluminium plate, made movable using few adjustment screws, as shown in Fig. 5. The two plates are electrically connected to the ground planes using adjustment screws. The electric and magnetic field lines patterns for 0.5 W of output power are shown in Figs. 6 and 7. For a 10 kW output signal, it is equivalent to 0.53 MV/m electric field. The maximum simulated power handling capability is 100 kW.

3 Experimental results

3.1 *Low-power measurements*

The Gysel combiner is designed at a centre frequency of 352 MHz, as can be seen in Fig. 8 where the simulated *S*-parameters are

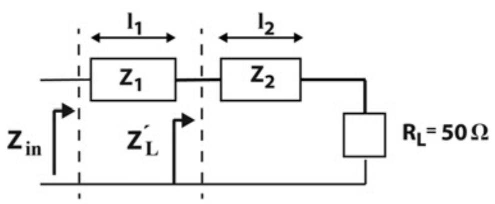

Fig. 4 *Two-section stripline forming a transformer*

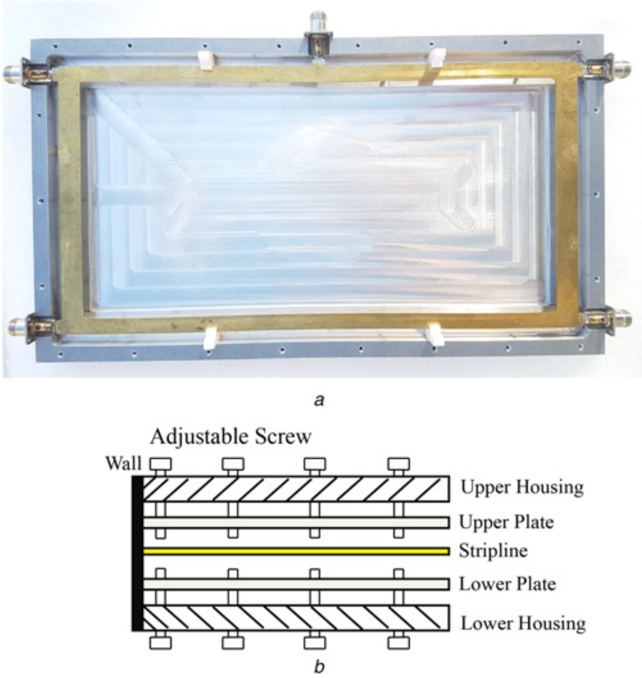

Fig. 5 *The fabricated Gysel combiner*
a Fabricated air-dielectric Gysel combiner
b Cross-sectional mechanical tuner integrated in the Gysel combiner. The tuner is placed under the striplines in Fig. 5*a*

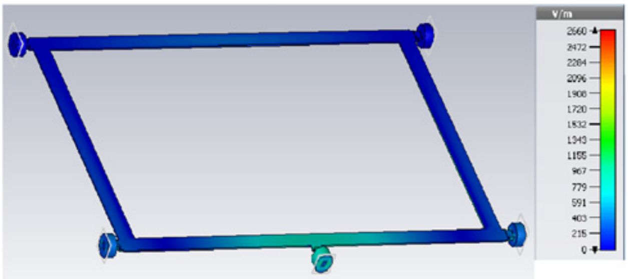

Fig. 6 *Electric field distribution in the presented combiner at 352 MHz. The simulation is done for 0.5 W of output power*

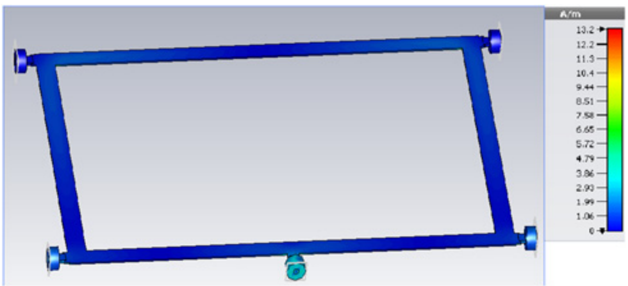

Fig. 7 *Magnetic field distribution in the presented combiner at 352 MHz. The magnitude of the magnetic field is shown for 0.5 W of power fed to the output port*

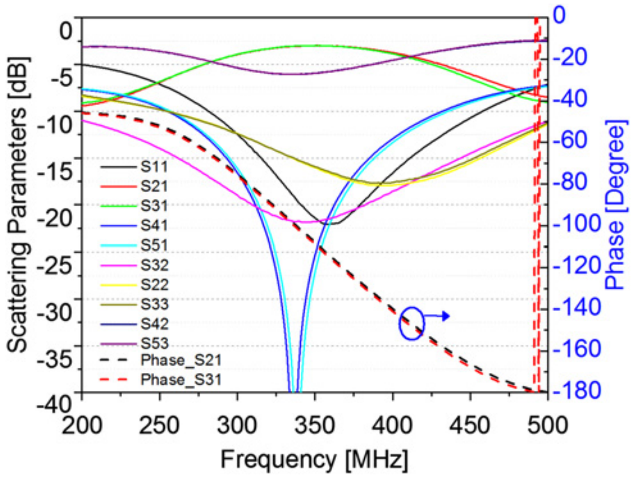

Fig. 8 *Simulated scattering parameters of the Gysel combiner*

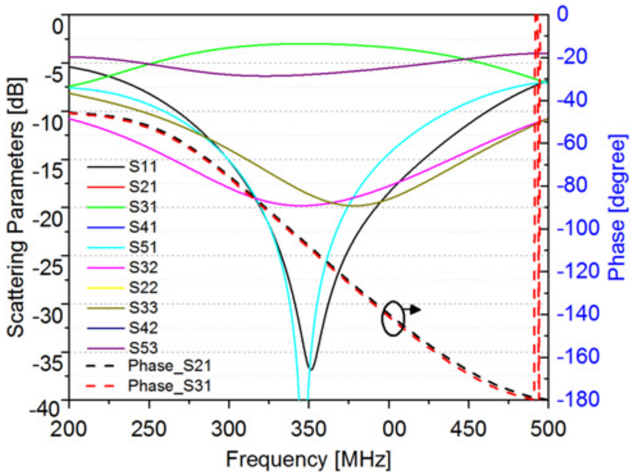

Fig. 9 *Measured scattering parameters of the fabricated Gysel combiner*

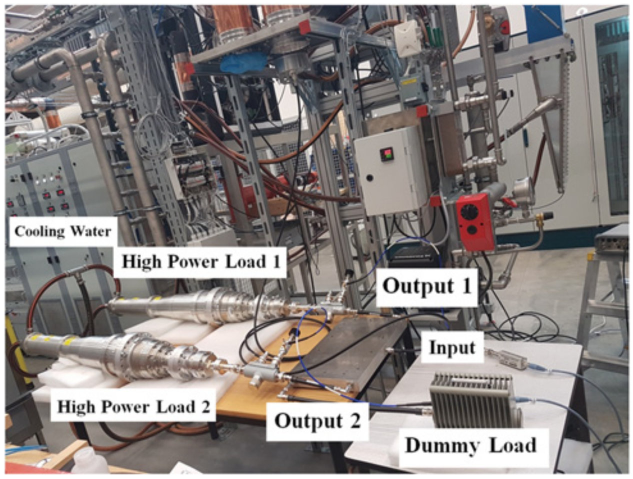

Fig. 10 *High-power measurement setup of the presented Gysel combiner*

presented. The measured results are presented in Fig. 9. The return loss at port 1 is measured 22 dB at 352 MHz, as presented in Fig. 9, while the simulated return loss is 30 dB. The simulated return loss at ports 2 and 3 is about 20 dB. As seen in Fig. 9, there is a relatively small imbalance in the measured return loss at ports 2 and 3. Values of the return loss are measured roughly at 17 dB level at 352 MHz. The isolation between ports 2 and 3 is measured to be 22 dB and is similar to the simulated isolation of 20 dB, presented in Fig. 8. The Gysel combiner is characterised by an extremely low insertion loss of only 0.1 dB (2% power loss),

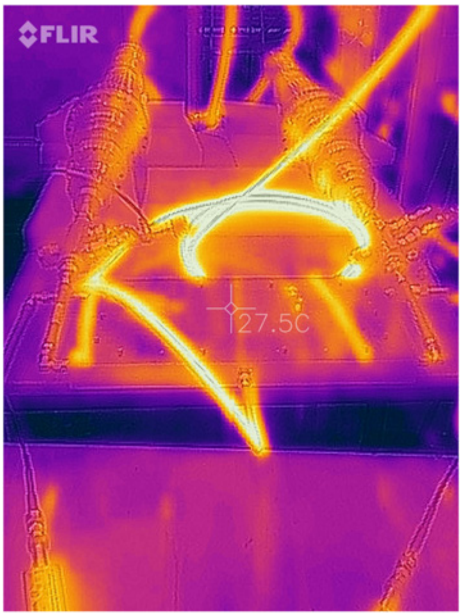

Fig. 11 *Thermal image during high-power RF measurement. The Gysel combiner temperature is at 27.5°C. The maximum temperature is 45°C (yellow) and the minimum temperature is 25°C (purple)*

considering the ideal combining factor of a two ways combiner of 3.03 dB and the measured splitting loss of 3.13 dB. In addition, the combiner features a good isolation, well above 30 dB between port 1 and the external load at ports 4 and 5. The measured phase imbalance between ports 2 and 3 is 0.09°. The isolation of ports 4 and 5 is strongly correlated to the amount of reflected power from ports 2 and 3. The measured coupling *S*-parameter coefficients S_{24} and S_{53} between output ports and isolation load ports agree well with the simulated results, equivalent to roughly 6 dB. The directional coupler *S*-parameter coefficients S_{24} and S_{53} can also be used to monitor effectively imbalances in power delivered to the output ports. Thanks to the fine-tuning procedure, variations in the TLs' impedance due to the tolerances of the fabricating and assembly process can be effectively compensated, and the presented Gysel combiner performs very well with very small discrepancy between simulations and measurements.

3.2 High-power measurements

High power-handling capability of the presented combiner is characterised up to 22 kW, shown in Fig. 10. The measurement uncertainty is 0.05 dB that corresponds to around 1%. In a long test run at 22 kW with 5% duty cycle, the combiner temperature stabilises at 27.5°C, the thermal image shown in Fig. 11. The high-power insertion loss is comparable to the low-power measurements.

4 Conclusion

A new two-way Gysel combiner is successfully designed, fabricated and characterised at 352 MHz. The combiner performs well under a high-power measurements, where the combining power reached 22 kW. The air-dielectric-based Gysel combiner avoids dielectric loss using air as dielectric. The low insertion loss of 0.1 dB (2%) of the air-dielectric combiner is extremely low in comparison with dielectric-substrate combiners [9]. The thick stripline used in the combiner results in a significant enhancement of the thermal conductivity, improving the behaviour of the combiner for high-power applications in the order of dozens of kW power levels. The efficiency and power handling capability of the combiner are greatly improved by choosing appropriate thickness of striplines and using air as a dielectric. Simulated and measured results are in very good agreement.

5 References

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