at the center frequency of the divider/combiner. Two transmission-lines, each a quarter-wavelength long and with characteristic impedance of $Z_1 = Z_0\sqrt{2} = 70.7\ \Omega$, lead from the input port to the two output ports. Two transmission-lines, each a quarter-wavelength long and with characteristic impedance Z_0, connect each output port with its associated load port [3]. The two load ports are connected through a transmission-line, a half-wavelength long and with characteristic impedance of $Z_2 = \frac{Z_0}{\sqrt{2}} = 35.4\ \Omega$. Ports 2 and 3 are connected, each through a transmission-line of arbitrary length and characteristic impedance Z_0, with the rest of the circuit. The Gysel resistors $R_0 = Z_0$ can be replaced by a transmission-line of characteristic impedance Z_0, of arbitrary length and terminated in a load of value Z_0 [3]. In this way, each resistor has been substituted with an external load, that is capable of handling high-power. The loads are no longer the power-limiting factor, while breakdown voltage, of the applied dielectric, is the limiting factor [3]. The heat-dissipation capacity of the lines, is the limiting factor for strip-line designs in the continuous wave mode [3]. External loads also provide isolation between output ports. Purpose of the Gysel 3 dB divider is to split an input signal into two equal outputs (equal by phase and amplitude). In reverse direction, Gysel 3 dB divider works as a combiner, meaning it combines two in-phase signals into an output signal. Scattering matrix of an ideal Gysel 3 dB divider/combiner, is

$$S = -\frac{j}{\sqrt{2}}\begin{pmatrix} 0 & 1 & 1 \\ 1 & 0 & 0 \\ 1 & 0 & 0 \end{pmatrix}. \tag{1}$$

The picture of the cross-section of the realized Gysel 3dB divider/combiner, is shown in the Fig. 3.

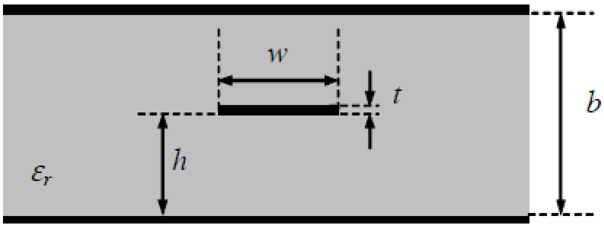

Fig. 3. The cross-section of the realized Gysel 3 dB divider/combiner [5].

The Gysel 3 dB power divider/combiner is realized as a balanced strip-line. The strip made of copper, is placed inside the air-filled casing, made of aluminum. Thickness of the strip is $t = 1$ mm. Distance between the top and the bottom of the casing is $b = 9$ mm. Distance between the bottom of the strip and the bottom of the casing is $h = 4$ mm. Air is chosen as a dielectric, because it has no losses. The width of every input/output line is $w = 10.28$ mm and the length is $l = 10$ mm. The width of every division line, with the impedance Z_1, is $w = 6.277$ mm and the length is $l = 414.3$ mm. The width of every division line, with the impedance Z_0, is $w = 10.55$ mm and the length is $l = 417.4$ mm. The width of the division line, with the impedance Z_2, is $w = 19.97$ mm and the length is $l = 862.48$ mm. The width of every line, that is connected to the external load, is $w = 10.28$ mm and the length is $l = 20.72$ mm. Radius of curvature of centerline is $R = 38.5$ mm. The length of the casing is 500.307 mm and the width is 195.384 mm. The upper and lower plates of the casing, have the same thickness of 15 mm. Five 7/16 connectors are mounted on the casing. The picture of the produced Gysel 3 dB power divider/combiner, is shown in the Fig. 4.

Fig. 4. The picture of the produced Gysel 3dB power divider/combiner.

The port on the farthest left end and the port on the farthest right end, on the Fig. 4, are the input/output ports. The two ports, between them, are the load ports. The port, in the middle of the opposite side, is the input/output port. In the case of an ideal Gysel 3 dB divider, equation (1), the loss for each output port is 3 dB. But, in the case of a real Gysel 3 dB divider, the loss for each output port is slightly higher than 3 dB [6]. The difference, between the real loss and the ideal loss, is known as the insertion loss [6]. Another important parameter, that is used to describe the operation of the Gysel 3 dB divider, is the amplitude balance. The amplitude balance is the difference between power levels at the output ports [7]. Ideally, the amplitude balance should be 0 dB, but in real applications, the amplitude balance is frequency dependent and different from 0 dB [7]. In an ideal situation, the phase difference between the output ports of Gysel 3 dB divider, is 0°, but in the case of a real Gysel 3 dB divider, there is a phase difference, dependent of frequency, equal to a few degrees [7]. The phase difference is called the phase balance.

III. SIMULATION AND MEASUREMENT RESULTS

A. Simulation

Knowing the criteria that our Gysel 3 dB divider/combiner has to fulfill in the frequency band of interest (return loss S_{xx}, $x = 1, 2, 3$, better than -20 dB, and isolation S_{23}, better than -20 dB), we were able to obtain the final dimensions of the Gysel 3 dB divider/coupler, through the process of computer simulation. First, through the process of optimization in Microwave Office, basic dimensions, like widths and lengths of the strip-lines, thickness of the strip, radius of curvature of centerline and the distance between the top and the bottom of the casing, were obtained. Second, through the process of simulation in HFSS, remaining dimensions were obtained, and those obtained before, through MWO optimization, were adjusted. The lateral view of the model of the Gysel 3 dB divider/combiner in HFSS, is given in the Fig. 5.

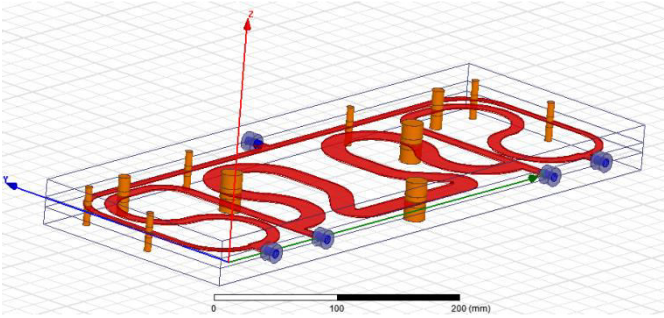

Fig. 5. The lateral view of the model of the Gysel divider/combiner in HFSS.

As can be seen from Fig. 5, the Gysel 3 dB divider/combiner consists of a strip, 1 mm thick, made of copper, that is placed inside the air-filled casing, made of aluminum. The top surface of the strip, is separated from the top of the casing by an air layer 4 mm thick, and the bottom surface of the strip, is separated from the bottom of the casing by an air layer 4 mm thick. The horizontal distance, between the left wall of the casing and the left end of the strip, and the horizontal distance, between the right wall of the casing and the right end of the strip, are both 10 mm equal. There are twenty two cylinders, eleven for each side of a strip, depicted in orange color, made of Teflon, that are used for the support of the strip. Twelve of them are 6 mm in diameter, four of them are 10 mm in diameter and six of them are 18 mm in diameter. The length of each cylinder, is 16 mm. Four millimeters of a cylinder's length passes thru air and twelve millimeters passes thru aluminum. The upper side of the model of the strip, in HFSS, is shown in the Fig 6.

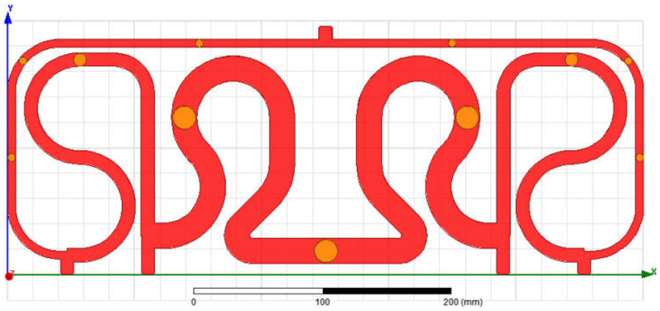

Fig. 6. The top view of the model of the strip in HFSS.

B. *Simulated and measured results*

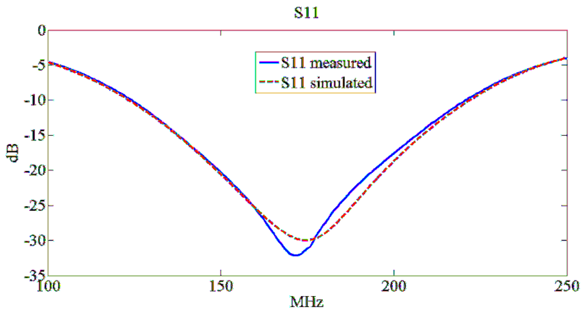

Fig. 7. Comparison of simulated and measured $\boldsymbol{S}_{11}$.

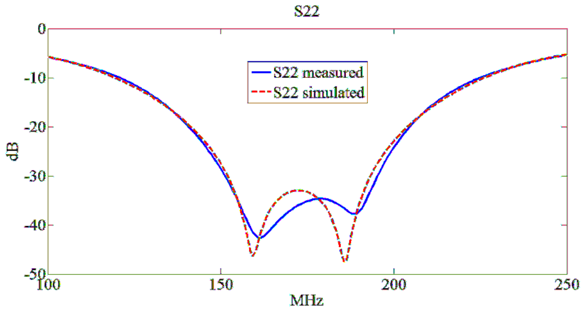

Fig. 8. Comparison of simulated and measured $\boldsymbol{S}_{22}$.

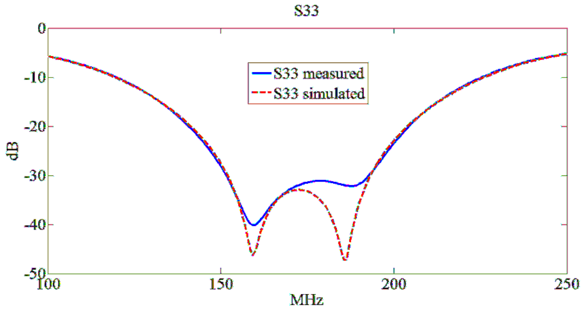

Fig. 9. Comparison of simulated and measured $\boldsymbol{S}_{33}$.

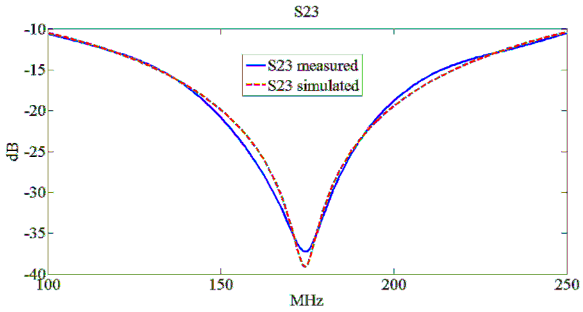

Fig. 10. Comparison of simulated and measured $\boldsymbol{S}_{23}$.

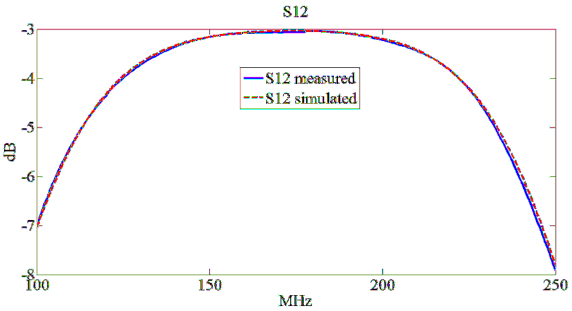

Fig. 11. Comparison of simulated and measured magnitude of S_{12}.

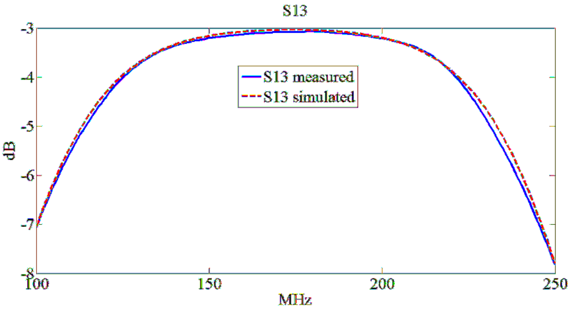

Fig. 12. Comparison of simulated and measured magnitude of S_{13}.

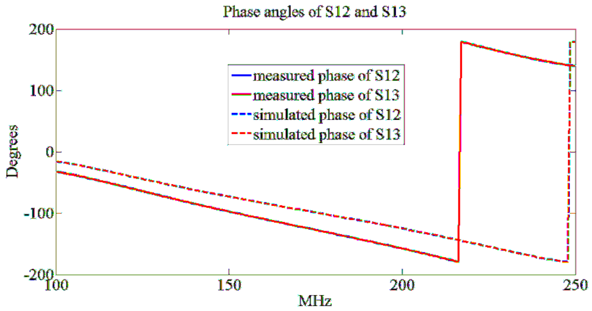

Fig. 13. Comparison of simulated and measured phase angles of S_{12} and S_{13}.

Figure 7 is showing that measured return loss S_{11} is lower than -17 dB, over the frequency band of interest. Measured return loss S_{22} is lower than -24 dB, over the frequency band of interest, as can be seen in Fig. 8. Figure 9 is showing that measured return loss S_{33} is lower than -22 dB, over the frequency band of interest. Measured isolation S_{23} is lower than -18 dB, over the frequency band of interest, as can be seen in Fig. 10. Insertion loss is equal or lower than 0.205 dB and the amplitude balance is ± 0.047 dB, over the frequency band of interest, as can be seen in Fig. 11 and Fig. 12. In Fig. 13 we can see that the phase angles of S_{12} and S_{13} are practically the same, and the phase balance is $\pm 0.1°$, over the frequency band of interest.

IV. CONCLUSION

The process of designing the Gysel 3 dB power divider/combiner, that was presented in this work, proved to be very successful, because there is a great degree of similarity between simulation and measurement results. The simulation, in HFSS, has shown that the Gysel 3 dB combiner can withstand input power levels of 16 kW per port. The main advantages of the Gysel 3dB divider/combiner are external isolation loads (permitting high-power loads), easily realizable geometry and monitoring capability for imbalances at the output ports [3].

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