Waveguide cavity 180^0 hybrid coupler with coaxial ports

Alessandro Navarrini, Tonino Pisanu, Renzo Nesti

***Abstract*— We describe the design, construction, and performance of a 180^0 hybrid coupler for the frequency band 1.3-1.8 GHz (L-band). The hybrid utilizes a WR650 rectangular waveguide cavity and has three 50 Ω coaxial ports. The signals are coupled in and out of the waveguide cavity through broadband coaxial probes attached to 7/16-type connectors. The cavity is very compact in terms of the wavelength and has a total length (≈260 mm) of approximately λ_g. The device was optimized using a commercial 3D electromagnetic simulator.**

The performances of this custom hybrid are better than commercial devices: the measured input reflection was below -26 dB, and the maximum deviation from the nominal -3 dB transmissions and 180^0 phase difference were, respectively, ±0.1 dB and ±0.5^0 across 1.3-1.8 GHz, in excellent agreement with simulation.

***Index Terms*—Hybrid coupler, power combiner, waveguide cavity, waveguide to coaxial transition, L-band.**

I. INTRODUCTION

A 180^0 hybrid coupler is a device that splits an input signal into two equal amplitude outputs (-3 dB power coupling) with constant 180^0 differential phase. Most common 180^0 hybrid couplers are reciprocal four-port devices whose fourth port (the sum port Σ) is isolated from the input and is typically terminated with an internal or external matched load (usually 50 Ω.) The 180^0 hybrid coupler is a widespread device in the microwave industry. A variety of designs exist [1] that are based on microstrip/stripline technology (for example the "rat-race" hybrid ring or the "tapered coupled line hybrid,") or on waveguide structures (for example the waveguide magic-T junction.)

In this paper we describe the design, construction, and test results of a three-port 180^0 hybrid coupler based on a waveguide cavity, which is very compact in terms of the wavelength. The device was optimized to be well matched to standard 50 Ω coaxial connectors and to have the lowest possible insertion loss with minimum deviation from the nominal -3 dB coupling and from the nominal 180^0 phase difference. Across the design band, the performances of the hybrid are largely superior to those of commercial devices. The hybrid can operate at low temperatures; because of its compactness, it is suitable for cryogenic use in a low-noise receiver where the encumbrance of the components needs to be reduced as much as possible. The hybrid will be used in a high-performance 1.3-1.8 GHz cryogenic radio astronomy receiver [2] on the Sardinia Radio Telescope [3], a new 64 m diameter radiotelescope which is being built in the Sardinia island, Italy.

II. HYBRID COUPLER DESIGN

The L-band 180^0 hybrid coupler we designed is illustrated in Fig. 1. The device consists of a WR650 rectangular waveguide (165.1×82.55 mm^2) terminated at both ends by reactive loads (short circuits.) The waveguide cavity is very compact in terms of the wavelength and has a total length of approximately $\lambda_g\approx260$ mm. The hybrid has three 50 Ω ports with commercial 7/16-type coaxial connectors attached to metal probes that extend partially inside the waveguide; we named port 1 the coaxial input and ports 2 and 3 the two coaxial outputs. The probe at port 1 couples the input signal inside the cavity and launches the fundamental TE_{10} mode in the WR650 waveguide. After a path length of about $\lambda_g/2$ the signal is extracted out-of-phase from the two identical output probes emerging symmetrically from opposite sides of the wide walls of the rectangular waveguide. All probes are connected to the central pins of the 7/16-type coaxial connectors (Radiall model n. R185 406 080.) and consist of three cascaded coaxial cylinders of different diameters. These cylinders were easily fabricated from a single metal piece using a lathe machine. To improve the matching of the input probe a fix-tuned short-circuit provided by a prism shaped cavity is used as reactive load; this is located on the terminating metal wall of the WR650 waveguide. The cavity has a depth of 25 mm and a width of 50 mm and is centered across the a=165.1 mm wide side of the WR650 waveguide (Fig. 1, bottom panel.) The output probes are located at a distance of 48.5 mm from a short-circuit provided by a simple metal plane. We note that this distance is slightly less than a quarter wavelength in WR650 waveguide,

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λ_g(1.5GHz)/4~62.7 mm.
The external dimensions of the hybrid coupler, excluding the coaxial connectors that stick out from the wide side of the waveguide are 165.1×82.55×259.5 mm^3.

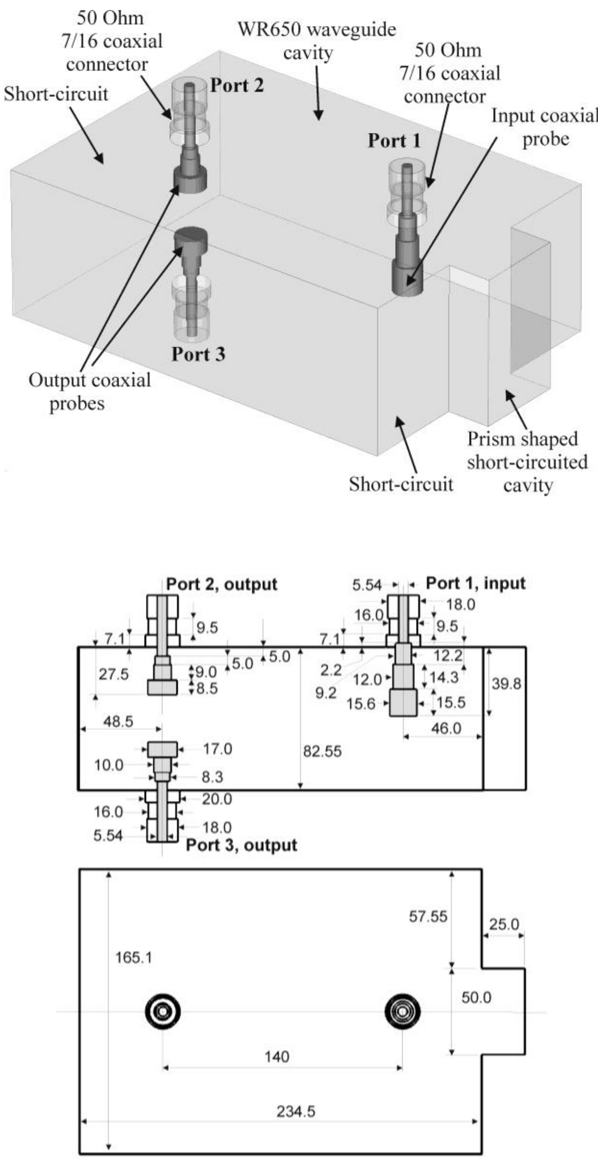

Fig. 1. *Top):* Internal 3D view of the waveguide cavity 180^0 hybrid coupler with 50 Ω 7/16 coaxial connectors. The length of the hybrid (~260 mm) is approximately $\approx\lambda_g$ in WR650 waveguide. *Bottom):* Cut-out views of the hybrid. Units are in mm.

The electrical performances of the structure of Fig. 1 were optimized using the commercial electromagnetic simulator CST Microwave Studio[1] based on the finite integration technique. The parameters that were varied in the optimization were the geometry and location of the reactive loads, the number and size of the cylinders of the coaxial probes, and the distance between the probes. Different shapes were attempted for both input and output backshorts. Optimum performance with lowest wave reflection was found with the prism shaped short-circuited cavity at the single-probe input and the simple metal plane short-circuit at the two symmetrical probe outputs, as illustrated in Fig. 1. The optimum number of cylindrical sections of each coaxial probe was found to be three.

We anticipate (see section IV) that the transmission parameters S21 and S31 are expected to have neither identical amplitudes nor exact 180^0 phase difference; indeed small deviations from this ideal case are due to higher order modes excited by the H-plane asymmetry of the single coaxial probe at port 1 (the output probes are, instead, symmetric.) The effects of this asymmetry could be strongly reduced by increasing the separation between input and outputs. Indeed, a larger input/outputs separation allows to decrease the coupling of the reactive non-propagating higher order modes generated at the two coaxial transitions. The higher order modes are in cut-off in the WR650 waveguide across 1.3-1.8 GHz; therefore, these modes are attenuated, each with its attenuation constant, over a scale distance of order $\approx\lambda_g$. As a consequence, for a separation between the axis of the probes much larger than λ_g, we expect the higher order modes at the two coaxial transitions to be fully decoupled and the effects of the asymmetry to be practically cancelled. The results of the numerical simulations of hybrid couplers where the WR650 cavities have different lengths, confirm that the deviation from the nominal -3 dB coupling and from the 180^0 phase difference between S21 and S31 becomes smaller as the distance between the input and output coaxial probes is increased. The adopted length of only $\approx\lambda_g/2$ (140 mm) between the axis of such probes is a compromise between compactness and acceptable balancing in amplitude and phase.

III. MECHANICAL BLOCK

We fabricated and tested two identical hybrid couplers. The mechanical block of each hybrid consists of several parts. Photographs of a fully assembled hybrid and of its unassembled parts are shown in Fig. 2. The main part of each hybrid is a 298 mm long section of commercial WR650 rectangular waveguide realized with 2.15 mm thick copper. This waveguide section is closed at both ends by two aluminum backshorts (short circuits) indicated as the “Input backshort” and the “Output backshort” (Fig. 2, top panel.) The backshorts are fabricated as mechanical inserts that fit tightly inside the open ends of the waveguide for their entire lengths; they are kept at their nominal position by thin caps that serve as mechanical stops when in touch with the waveguide walls. Probe pass-throughs were made by drilling three circular holes and by welding a copper shim outside the waveguide to ensure proper support for the fixation screws of the 7/16 connectors. A photograph of the assembled probe-connector combinations is shown in Fig. 3. Each three-cylindrical-section probe was fabricated out of a single piece of brass. The smallest cylinder of the probe is attached to the central pin of a 7/16-type connector that has a diameter of 5.54 mm. The probe has a threaded hole in its smallest cylinder to screw in the threaded section of the connector central pin. This allows the two parts

[1] CST Microwave Studio, Darmstadt, Germany.

to be tightly connected together. The probes form a rigid and mechanically robust assembly with the 7/16 connectors.

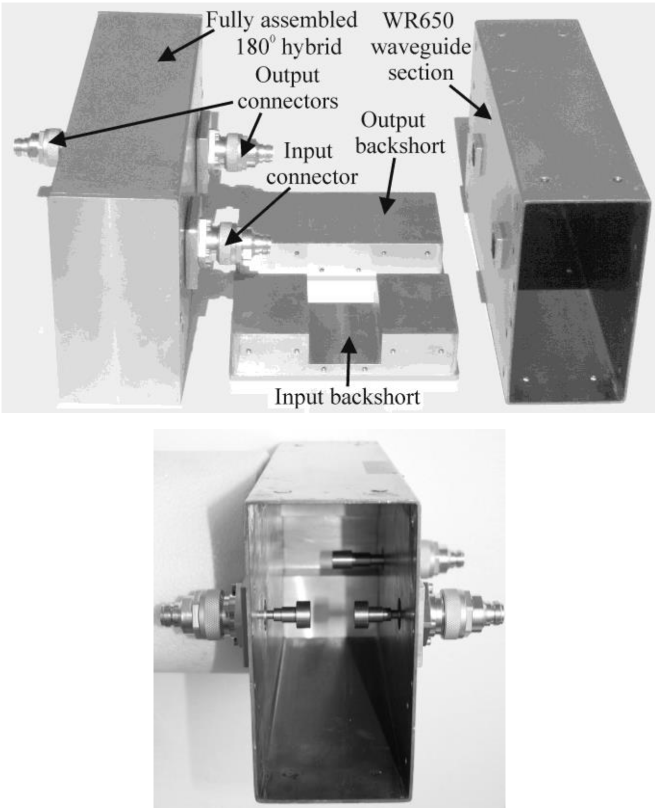

Fig. 2. *Top):* Photograph of the two hybrids. A fully assembled hybrid is shown on the left. The input and output backshorts are shown in the middle. The right side shows the unassembled WR650 waveguide. *Bottom)*: Photograph of one assembled hybrid with input backshort removed.

Fig. 3. Photograph of the probes. The input probe and assembled input probe-connector combination are shown on the left. The two assembled output probe-connector combination (and one unassembled output probe) are shown in the center-right. The 7/16-type to N-type connector transitions attached to the 7/16 connectors were used for test of the devices.

IV. Simulation and Experimental Results

The two hybrid couplers were tested using an HP8720C Vector Network Analyzer (VNA.) The analyzer was calibrated to remove systematic instrumental effects at the N-type connector ports of its extension coaxial cables; we used a full two-port calibration with N-type calibration kit. The two hybrids have very similar electrical performances.

The graphs in Fig. 4-6 show simulation and experimental results of the hybrid coupler illustrated in Fig. 1. A Cartesian mesh was automatically generated from the CST software and the time-domain solver calculated the broad-band response of the device in one simulation run. We set the parameter “lines per wavelength” to 30; this is the minimum number of mesh lines per wavelength in each coordinate direction for the shortest wavelength in the simulation.

Fig. 4 shows the simulated and measured reflection coefficient of the fundamental TEM mode at the coaxial input

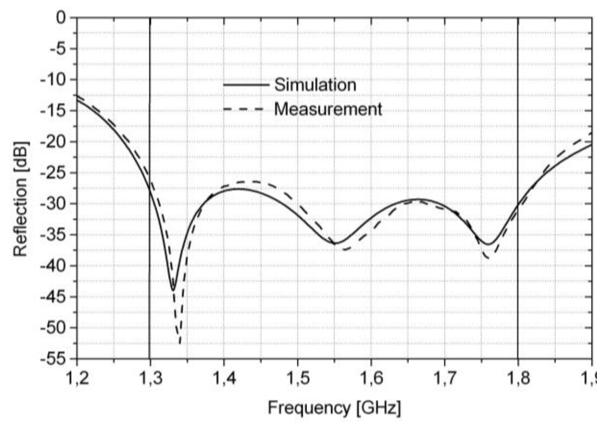

Fig. 4. Simulated (solid line) and measured (dashed line) reflection at the coaxial input (port 1) of the hybrid coupler illustrated in Fig. 1.

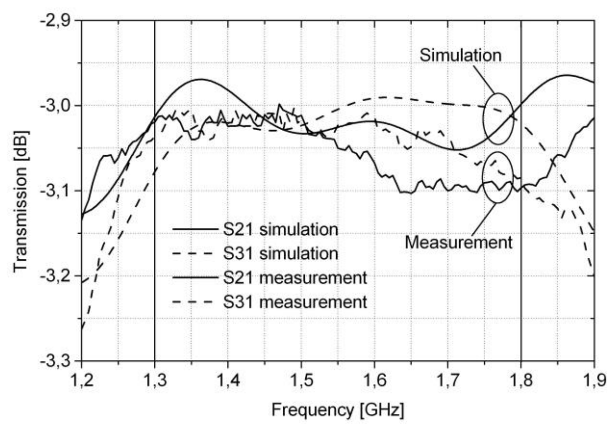

Fig. 5. Simulated and measured transmissions of the hybrid coupler (includes the effects of the coaxial connectors): S21 (solid line) and S31 (dashed line).

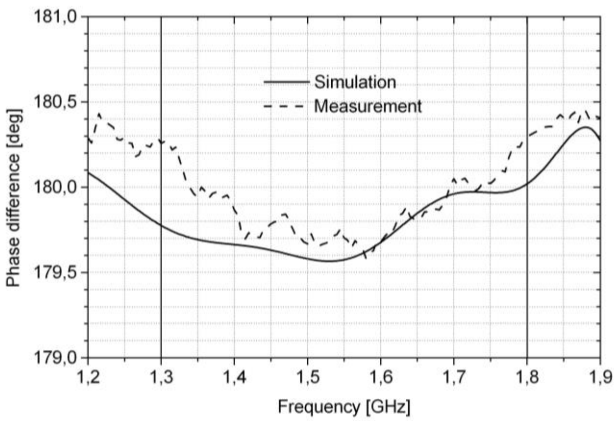

Fig. 6. Simulated (solid line) and measured (dashed line) phase difference between the outputs of the hybrid coupler.

of the hybrid when the two outputs are 50 Ω terminated. In the graph, vertical lines denote the nominal band edges at 1.3 and 1.8 GHz. The measured reflection is below -26 dB over the entire band of interest and is remarkably close to the simulation result.

The attenuation of the hybrid is extremely small and is determined by the contribution of the waveguide section and of the probe-coaxial connector combination. The attenuation of the standard WR650 waveguide falls in the range 0.006-0.009 dB/m, while the one of each 7/16-type connector is estimated of the order of 0.02 dB. Therefore, at room temperature, the attenuation of the hybrid is essentially due to the connectors and is of the order of 0.04 dB.

The |S21| and |S31| transmission parameters of the hybrid, including the effects of the connectors, are shown in Fig. 5. The simulated transmissions have similar, but not identical, values (see Sec II) close to the ideal -3 dB, with variation of less than ±0.07 dB across our band of interest. The measured transmissions are also shown in Fig. 5 and have very similar levels, close to the simulation results. The measured maximum deviation from the nominal -3 dB is only ±0.1 dB across the band.

The simulated and measured phase difference between the transmitted amplitudes are shown in Fig. 6. The measured maximum deviation from the ideal 180^0 is only $\pm 0.4^0$ across the design band, in close agreement with simulations.

The performance of our waveguide hybrid coupler is largely superior to that of commercial devices. For example, the measured performance of the commercial MCLI hybrid[2] that we tested across the band 1.3-1.8 GHz are the following: input reflection, transmission, and phase difference between the outputs, of respectively <-20 dB, -3 dB±0.5 dB, and $180^0 \pm 3.5^0$, to be compared with our waveguide cavity hybrids for which the equivalent quantities are <-26 dB, -3 dB±0.1 dB, and of 180^0 $\pm 0.4^0$.

[2] MCLI (Microwave Communication Laboratories Inc.), , model HJ4.

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