High-performance microstrip directional coupler for radio-astronomical receivers at cryogenic temperature

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A microstrip directional coupler with high directivity is proposed for microwave applications requiring a weak coupling factor. This component has been used in the L-band radio-astronomical receiver of the Sardinia radio telescope. To improve the performance of the receiver, the operating temperature is lowered to 20 K. An in-house cryostat has been manufactured to perform measurements on the directional coupler, and very good agreement with the design specification is achieved.

Introduction: Microstrip directional couplers are employed in many microwave applications, such as circuits for monitoring, source levelling, signal sampling, signal injection or the separation of direct and reflected waves in measurement. Their most popular configuration is the coupled-line directional coupler [1], since it allows one to realise a compact low-cost broadband coupler. Moreover, the coupled port is DC isolated from the through line. However, this configuration suffers from low directivity due to the different phase velocities of the even and odd modes of the coupled microstrip lines, and this is particularly true when a weak coupling factor is required.

On the other hand, high directivity can be achieved by using fully planar capacitive compensated configurations, as in [2], but in some cases more complicate realisations are necessary, such as the addition of non-planar components [3, 4], or the realisation of supplementary capacitive elements by means of multiple ridges in the coupling lines [5].

In this Letter, we present a new configuration of the microstrip directional coupler which is particularly suitable for achieving a low coupling factor with high directivity. The solution presented here is very simple and easy to design since it is based on the reduction of the coupling region by using a V-shaped microstrip line coupled to a short line, as shown in Fig. 1. As a consequence, due to the small coupling region, this configuration does not need to compensate for the different phase velocities of the coupled lines modes, and therefore does not require addition of any capacitive element.

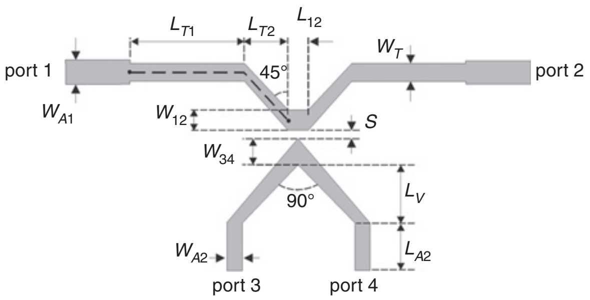

Fig. 1 *Geometry of proposed directional coupler*

Port 1 is input port; port 2 is through port; port 3 is coupled port; and port 4 is isolated port

This coupler has been conceived to be used in the front end of the L-band (1.3–1.8 GHz) receiver of the Sardinia radio telescope (SRT) [6], in order to calibrate the receiver chain by injecting a noise source and a weak coherent comb signal in the RF signal. As a matter of fact, such an application requires a low coupling factor (typically lower than −20 dB), high return loss in the through line and high directivity. Moreover, since the through line is connected in front of the LNA, the lowest insertion loss (IL) as possible is required. To reduce thermal noise, the components of the radio-astronomical receiver, including the directional coupler, will operate at a cryogenic temperature of 20 K. Moreover, as a consequence of the lower temperature, the conductor losses are reduced, thus reducing the ILs.

The proposed configuration can, however, be used in all other applications requiring low coupling and a high directivity, as it is easily scaled to different frequencies and substrates. The coupler has been designed using Ansys HFSS [7] and the realised component (see Fig. 2) shows a very good agreement with the design specifications.

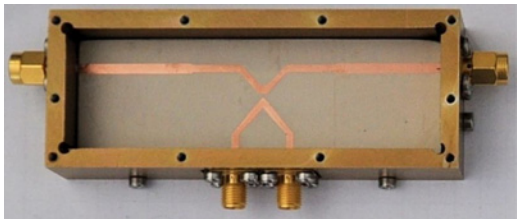

Fig. 2 *Photo of realised prototype*

Coupler design and test: The proposed directional coupler can be used in many different microwave applications. However in order to experimentally assess the proposal, we have designed and manufactured this coupler for the L-band (1.3–1.8 GHz) receiver of the SRT prime focus. The geometry of the directional coupler and its geometrical parameters are shown in Fig. 1. We have used a commercial dielectric substrate (Arlon AD1000) of thickness 3.2258 mm, with a dielectric permittivity of 10.9 at room temperature (300 K). To evaluate the dielectric permittivity at 20 K we have measured, at this cryogenic temperature, the scattering parameters of a through microstrip line of fixed width and length, deriving a dielectric permittivity of 12.5.

Then, the coupler has been optimised by using Ansys HFSS in order to comply with the specifications of the L-band (1.3–1.8 GHz) receiver of the SRT. The performance required by this application is:

- nominal coupling (at the centre frequency) $C = -26$ dB;
- input port matching ≤−25 dB over the operating bandwidth;
- highest directivity;
- lowest IL.

The above requirements have been met with the following design steps:

Step 1: The spacing S between the lines and the length L_{12} has been selected in order to obtain the required coupling coefficient.
Step 2: The widths W_{12} and W_{34} have been selected in order to maximise the directivity.
Step 3: Quarter-wave transformers (see the dashed line in Fig. 1) have been designed for impedance matching at ports 1 and 2 ($W_{A1} =$ 2.35 mm is the width of a 50 Ω microstrip line), since this solution is compatible with the maximum longitudinal size allowed for the coupler within the L-band receiver. On the other hand, there is no room inside the receiver for quarter-wave transformers at ports 3 and 4; therefore, we have decided to directly connect these ports to the SMA connectors by using a short line of length L_{A2} and width W_{A2}. Then, L_{A2} (= 6 mm) is selected as short as possible, whereas W_{A2} is chosen to achieve input matching at ports 3 and 4.

These steps are virtually independent, at least for coupling factors less than about −15 dB, provided that they are performed in the order indicated above. Therefore, each one of them requires just a simple trial and error procedure on the parameters pertaining to it. The geometrical parameters of the optimised configuration are reported in Table 1.

Table 1: Geometrical parameters of optimised coupler

S (mm)	L_{12} (mm)	W_{12} (mm)	W_{34} (mm)	W_T (mm)	L_{T1} (mm)	L_{T2} (mm)	W_{A2} (mm)	L_{A2} (mm)	L_V (mm)
0.95	2	2	2.6	1.7	11.5	4.7	1.6	6	5.7

A prototype of the optimised coupler has been realised and tested in the laboratories of the INAF (Italian National Institute for Astrophysics). To perform the measurement at a cryogenic temperature of 20 K, the directional coupler has been arranged inside a square cryostat (see Fig. 3) at a temperature of 20 K, and then tested using a HP8720C vector network analyser (VNA). As is apparent from Fig. 3, the adduction lines are composed of a semi-rigid stainless-steel coaxial cable followed by a hand formable copper coaxial cable. The reference planes for the calibration of the VNA have been set inside the cryostat. Therefore, several refrigeration cycles have been required during the calibration, performed with the two-port SOLT (short, open, load and thru calibration kit. As a consequence, since each refrigeration cycle takes about 6 hours, both the error correction and the measurement of the scattering parameters took many days. Then, in order to reduce the instrumental drift along the days, which could become similar or dominant to the expected $S21$ of the main line, particular care has been adopted: the room temperature was maintained constant throughout the measurement session, and the calibration was checked at the end of the session.

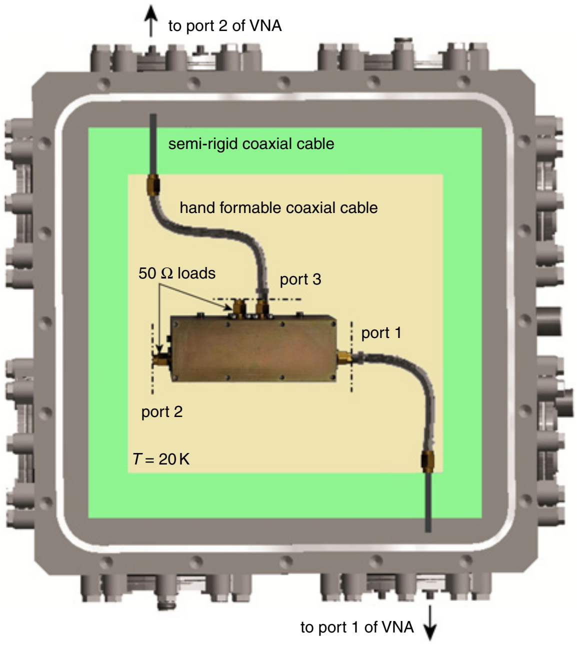

Fig. 3 *Drawing of directional coupler inside cryostat, showing configuration adopted for measuring coupling factor*

Calibration planes of VNA are indicated by dashed lines. The VNA and cables connecting the VNA to cryostat are not shown

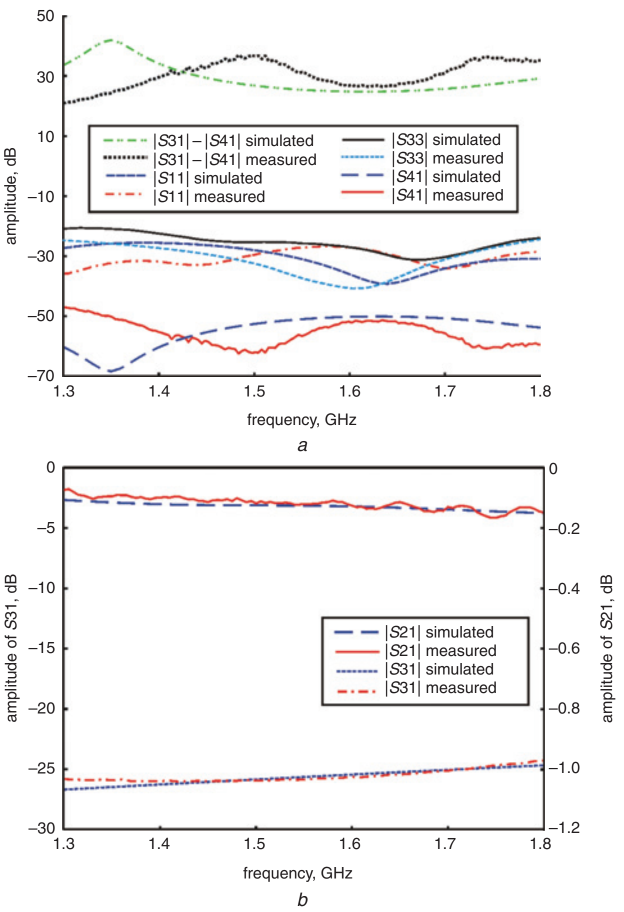

Fig. 4 *Scattering parameters of proposed directional coupler*

a Simulated and cryogenic measured $S11$, $S41$, $S33$ and directivity
b Simulated and cryogenic measured $S21$ (IL) and $S31$ (coupling)

Fig. 4 shows the scattering parameters of the designed directional coupler. The agreement between the simulation and measurement results is very good and the manufactured prototype fully complies with the design requirements. As a matter of fact, the measured coupling coefficient at the centre frequency (1.55 GHz) is −25.9 dB, the return loss of the through line is greater than 25 dB and the directivity is greater than 20 dB over the operating bandwidth. Finally, the measured IL of the through line varies between −0.08 and −0.16 dB.

It is worth noting that the IL of an ideal directional coupler (with infinite isolation, and impedance matched at all ports) [1] can be computed as $\mathrm{IL}\ [\mathrm{dB}] = -20 \log \sqrt{1 - C^2}$, which, in our case ($C = 0.05$ at 1.55 GHz), gives IL = − 0.011 dB. On the other hand, the cryogenic measured $S21$ at 1.55 GHz is −0.121 dB (see Fig. 4*b*), with a very low net loss of just 0.1 dB, which is compatible with the losses of microstrip lines, connectors, trough walls and solderings.

Conclusion: We have presented a new configuration of a microstrip directional coupler for weak coupling factors with high directivity. This component is simple, fully planar and easy to design. The proposed coupler has been manufactured and mounted in the L-band receiver of the SRT prime focus, operating at a cryogenic temperature of 20 K, showing an extremely low IL.

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One or more of the Figures in this Letter are available in colour online.

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