Title: Marki splitter/combiner 4 K Measurements	**Author:** Philip Dindo	**Date:** 07/16/2021
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1.0 Introduction

This report presents measurements of a 4-18 GHz 90° splitter/combiner model MQS-0418AU obtained from Marki Microwave. This SMA connectorized 4-port device and its schematic block diagram are shown in Figure 1-1.

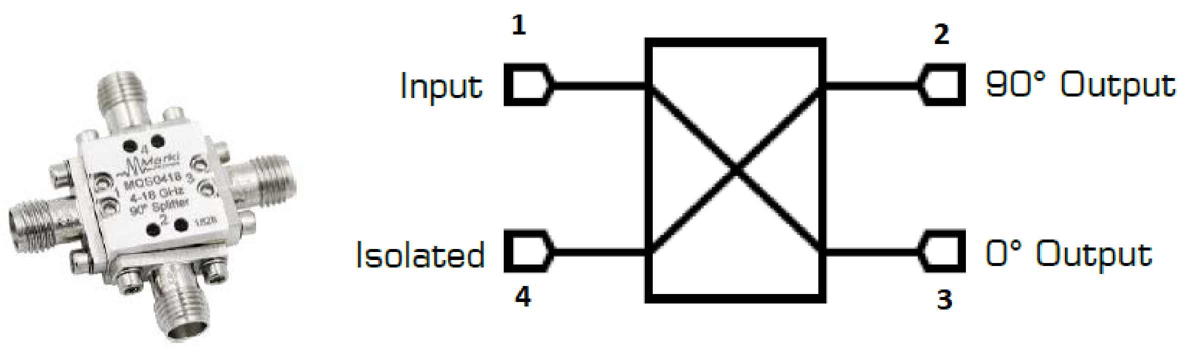

Figure 1-1: MQS-0418AU is a 4-port splitter/combiner with SMA female coaxial connectors. The body measures 14.2x14.2x9.9 mm. The functional block diagram is shown on the right hand side.

This device is realized with gold transmission lines on GaAs substrate. The vendor distinguishes this type of device from a true quadrature hybrid. A quadrature hybrid is symmetrical about all four ports, meaning that in a splitting application any port can be used as an input where the isolated and output ports follow from this selection, and in a combining application any port can be used as an output.

This 90˚ Splitter/Combiner hybrids is not symmetrical. When splitting, ports 1 and 2 can be used as inputs resulting in 3 dB split in output ports with 90° phase difference. If ports 3 and 4 are used as inputs, the output ports would still get 3 dB split but there would be significant phase imbalance between them. As a combiner, only ports 1 and 2 are suitable as output ports. The phase imbalance introduced when using ports 3 or 4 as an input or an output means that reflected signals recombine and cancel poorly inside a 90° Splitter/Combiner.

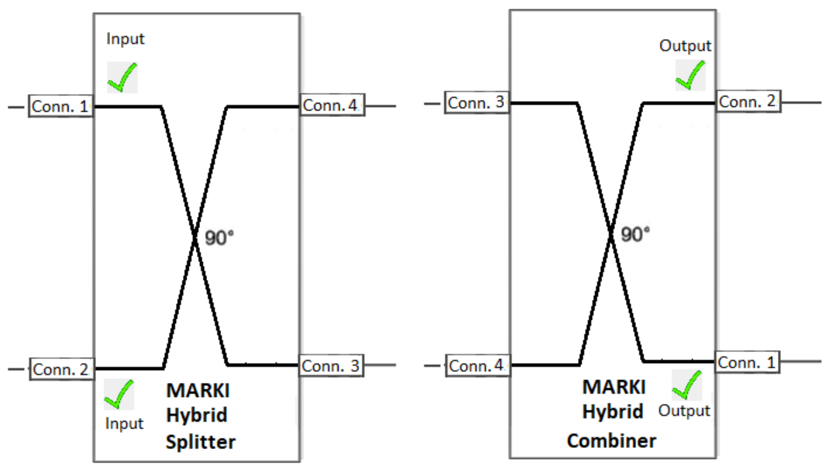

Figure 1-2: This schematic shows valid ports for using MQS-0418AU as a splitter and combiner without resulting in excessive phase imbalance

The phase imbalance is explained with some amount of dispersion in the transmission lines that cannot be compensated, and this forces an asymmetry in the design that results in the isolated port having a "walk-off" in phase response. It is noted in Figure 1-3 which shows a microscope view of the bare die that the two transmission lines originating from the bonding pads on the left hand side are not the same length as the corresponding two transmission lines on the right hand side; this asymmetry may contribute to dispersion.

The electrical specifications of the bare die are shown in Figure 1-4, while the corresponding specifications of the connectorized device are shown in Figure 1-5. The increase in Excess Through Line insertion loss of 0.4 dB from the bare die to the connectorized device is due to the bond wires, transmission lines, and coaxial connectors needed to package the bare die in a connectorized module.

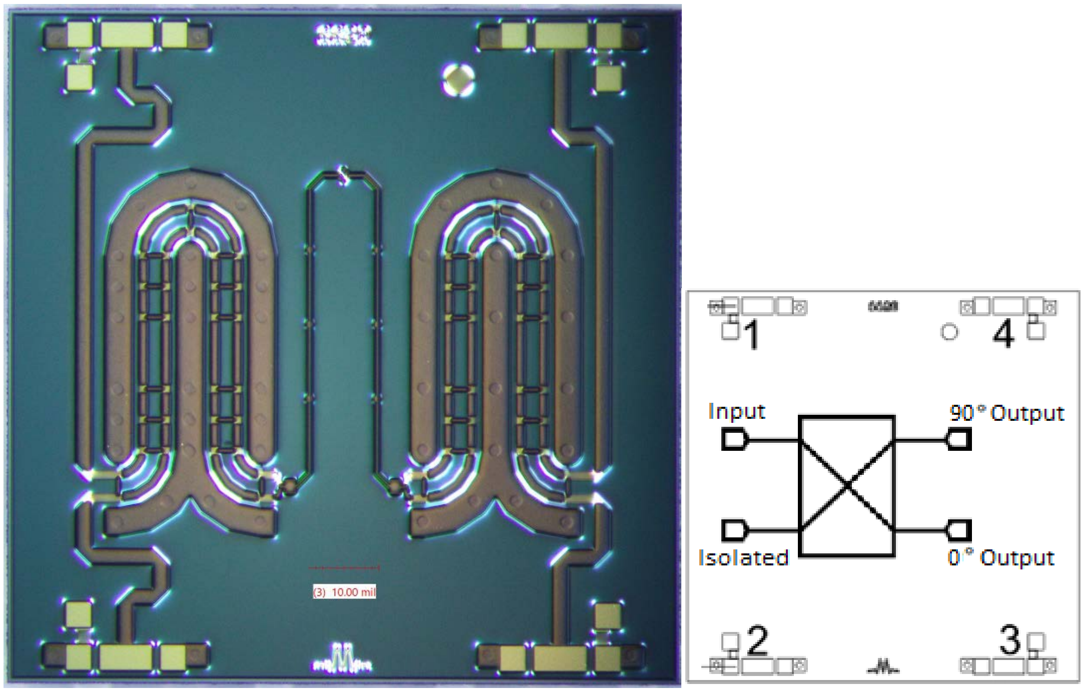

Figure 1-3: Photograph of the MQS-0418CH die and the corresponding outline drawing.

Parameter	Frequency (GHz)	Min	Typ.	Max	Units
Coupling	4-18		3		dB
Nominal Phase Shift			90		Degrees
Amplitude Balance			±0.4	±2	dB
Phase Balance			±0.5	±8	Degrees
Excess Through Line Insertion Loss			1.5	3.2	dB
Isolation		11	16		dB
VSWR			1.1		
Impedance			50		Ω

Figure 1-4: Electrical specifications of the bare die, part number MQS-0418CH

Parameter	Frequency (GHz)	Min	Typ.	Max	Units
Coupling	4-18		3		dB
Nominal Phase Shift			90		Degrees
Amplitude Balance			±0.4	±2	dB
Phase Balance			±1.5	±9	Degrees
Excess Through Line Insertion Loss			1.9	3.8	dB
Isolation		10	20		dB
VSWR			1.13		
Impedance			50		Ω

Figure 1-5: Electrical specifications of the connectorized device, part number MQS-0418AU

This report presents the measured RF characteristics of a connectorized Marki IF hybrid installed in a cryostat and cooled to 4 K. The following coupler parameters are presented:

- Amplitude characteristics of the 0° and 90° ports
- Excess insertion loss
- Coupler loss
- Return losses of the input port
- Isolation
- Phase balance

2.0 Cryogenic Measurement Setup, Test Method, and Errors

2.1 Measurement Setup

Figure 2-1 shows the cryostat used for measurement of microwave devices at 4 K, along with the coupler and its gold-plated copper mount for heatsinking. The microwave S-Parameter measurements are conducted by Keysight PNA-X Model N2545A with embedded Automatic Fixture Removal (AFR) Software.

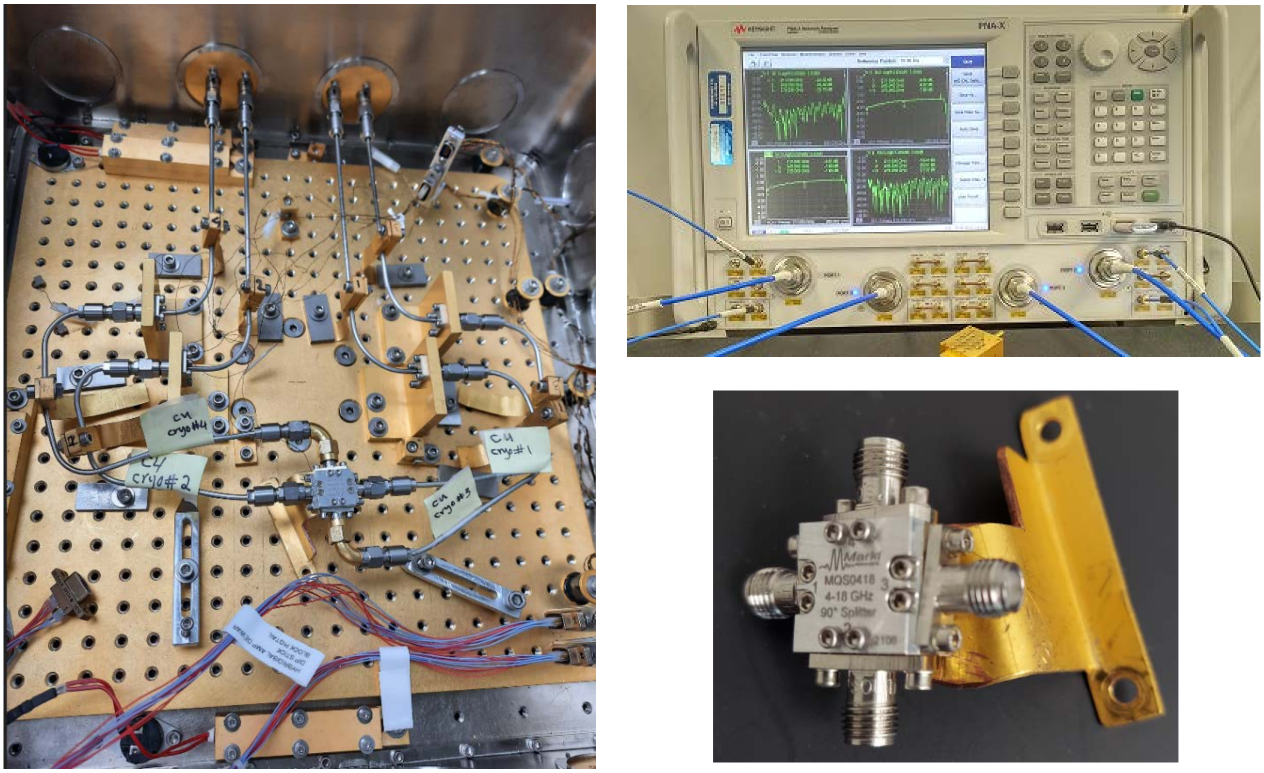

Figure 2-1: Photograph of the cryostat used for microwave measurements at 4 K. The Marki splitter/combiner is fastened to a gold plated copper heatsink and mounted to the 4-K plate. The coupler is shown connected on each side to a 180º bent silver plated copper coaxial cable at 4 K, then to a stainless steel coaxial cable.

2.2 <u>Test Method</u>

The device is measured as a splitter with the Keysight PNA-X input port connected to the port 1 connector of the Marki splitter/combiner as shown in Figure 2-2. The PNA-X cable port numbers correspond directly with the device port connector numbers. With this connection orientation, the isolated and output ports follow from this selection as indicated in the Figure.

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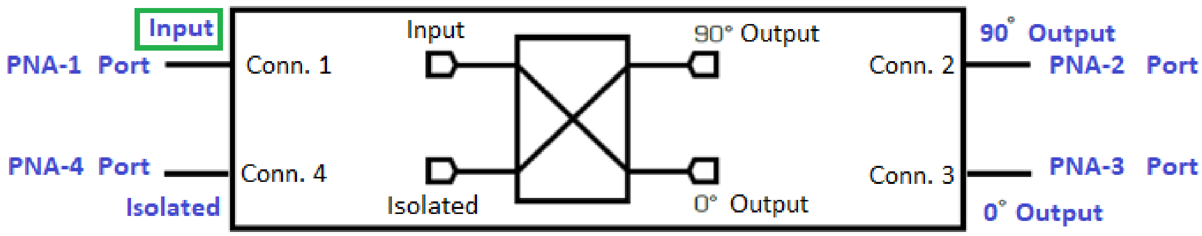

Figure 2-2: Device to Keysight PNA-X connection. The Marki splitter/combiner with coaxial connectors 1 to 4 are shown inside the black rectangle. PNA-X port cables are shown in blue.

2.3 Measurement Errors

One of the difficult measurement tasks is to de-embed the effects of the multiple coaxial cables and adapters leading from the room temperature calibration planes of the VNA to the 4-port device under test at 4 K. Each of the four measurement channels consists of the following cables and adapters:

- At room temperature: female to male K-connector adaptor (Fairview, Part # SM-3240)
- At room temperature: female to female K-connector Vacuum feedthrough (Fairview, Part # SM-3224)
- Room temperature to 77 K: stainless steel looped coaxial cable with male and female K-connector ends (UT-85-SS-SS)
- 77 K to 4 K: stainless steel coaxial cable with male and female K-connector ends (Model: UT-85-SS-SS)
- 4 K heatsink to DUT: copper/silver plated copper-weld coaxial cable with two male K-connector ends (Model: UT-85-TP).

Figure 2-3 shows schematically the use of the AFR software. The cable chains leading to the ports of the device under test are designated as 2-port fixtures SA, SB, SC, and SD. AFR software uses time domain measurements with short-circuit calibration standards to identify the location of the discontinuities and frequency domain measurements to compute the S-parameters of fixtures SA, SB, SC, and SD.

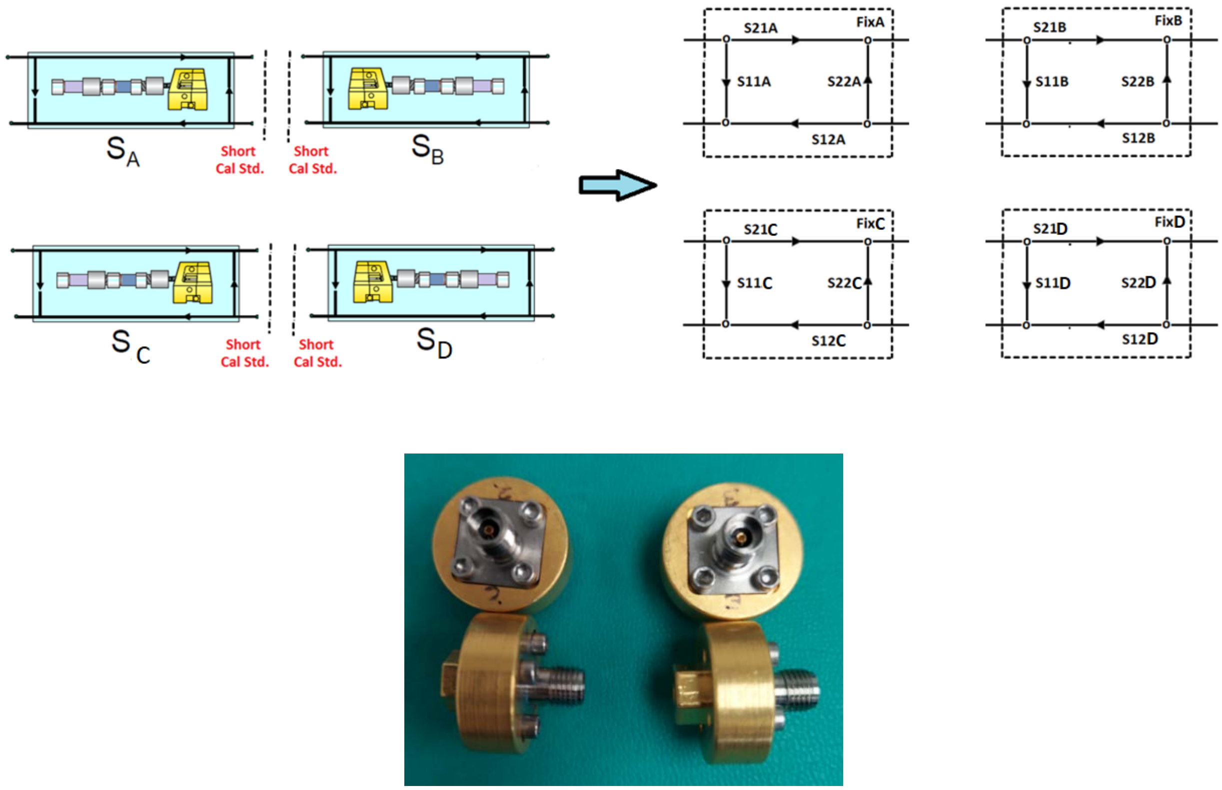

Figure 2-3: Keysight Automatic Fixture Removal software computes the S-Parameters of the four fixture sets SA, SB, SC, and SD. Each fixture is a set of coaxial cables interconnected with adapters leading to the device under test. AFR uses short-circuit calibration standards (bottom figure) connected to the ends of the 4-K cables with the DUT removed.

The AFR measurement is a three-step procedure:

1. Four-port calibration of the PNA-X from 10 MHz to 40 GHz using an electronic calibration module (ECAL model Keysight N4692D). The reference planes are located at the ends of the PNA-X test cables.
2. Measurement of four cable chains connected to the short-circuit calibration standards at 4 K. The AFR software in the PNA-X utilizes this measurement to de-embed the DUT from the long coaxial cable runs between the VNA reference planes and the calibration short-circuits.
3. Measurement of the DUT at 4 K when connected with the same four cable runs as in the previous step. The AFR software de-embeds the Marki device from the cable runs back to the VNA reference planes.

Microwave Office software is used to display the measured S-Parameters and the coupler characteristics.

De-embedding errors due to Keysight AFR software are evaluated as described in the following procedure:

- With the coupler (at room temperature) directly connected to the PNA-X the S-parameters are obtained.
- Calibrate the cable chains using the calibration shorts with AFR software at room temperature.
- Then the coupler is installed in the cryostat at room temperature with the same cables that would be used for the 4 K measurements and the S-parameters are obtained at room temperature and de-embedded by Keysight AFR software.

These two sets of S-Parameters should be identical if there are no de-embedding errors. However, there are errors in the process, and a comparison of S-Parameter amplitudes and return losses gives an indication of the accuracy to be expected at 4 K. Figure 2-4 shows the expected errors in coupler amplitude output measurements of +/- 0.3 dB. Figure 2-5 shows the de-embedded return loss and isolation is worse than the actual directly measured profile by 2 to 5 dB.

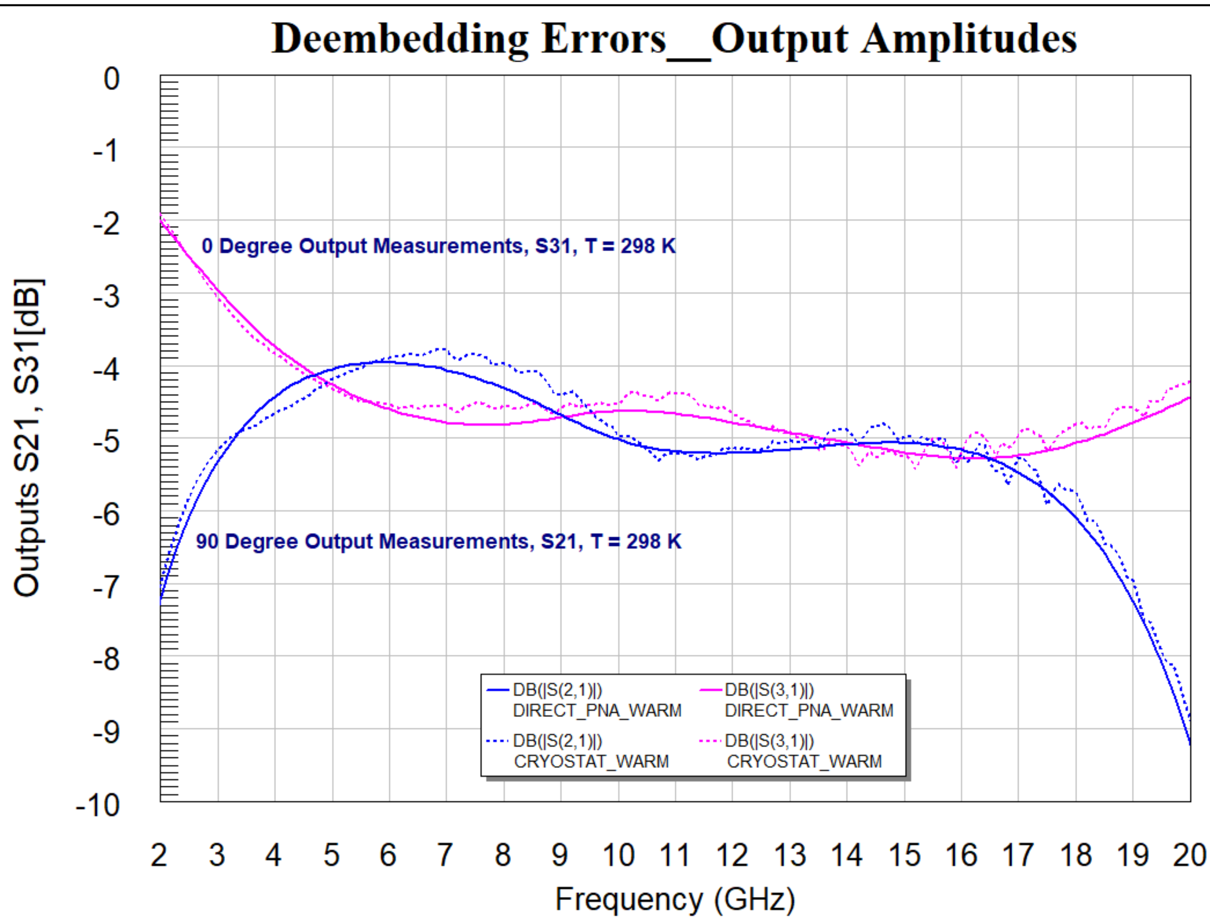

Figure 2-4: 90° output (solid blue) and 0° output (solid magenta) of the Marki splitter/combiner at room temperature measured directly on the PNA-X. 90° output (dotted blue) and 0° output (dotted magenta) of the coupler at room temperature measured inside the cryostat and de-embedded with Keysight AFR software. The maximum error is +/- 0.3 dB.

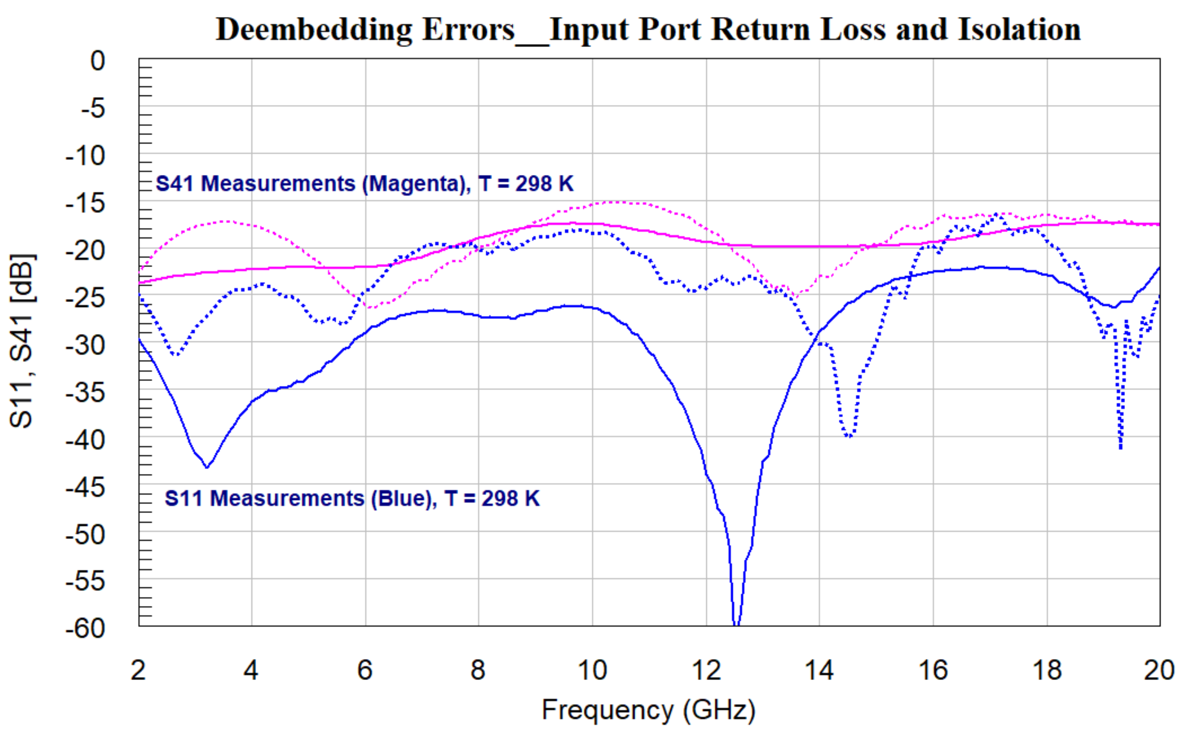

Figure 2-5: Return loss (solid blue) and isolation (solid magenta) of the Marki splitter/combiner at room temperature measured directly on the PNA-X. Return loss (dotted blue) and isolation (dotted magenta) of the coupler at room temperature measured inside the cryostat and de-embedded with Keysight AFR software. The return loss due to de-embedding is 5 dB worse than the actual result. Similarly, the isolation is worse than the actual result by 2 to 5 dB.

3.0 Measurements at 4 K

We cooled the Marki splitter/combiner to 4 K and warmed to room temperature it a total of seven times, and it did not change on successive thermal cycles. It appears that thermal cycling did not affect the GaAs substrate and its mounting inside the connectorized module. This device appears to be usable in a cryogenic environment.

3.1 Amplitude Characteristics

Figure 3-1 shows the amplitudes of the 0° output and 90° output and the amplitude balance corresponding to the four device orientations with respect to the PNA-X at 4 K measured from 2 to 20 GHz. The amplitude balance remains within -1 to 0.5 dB window.

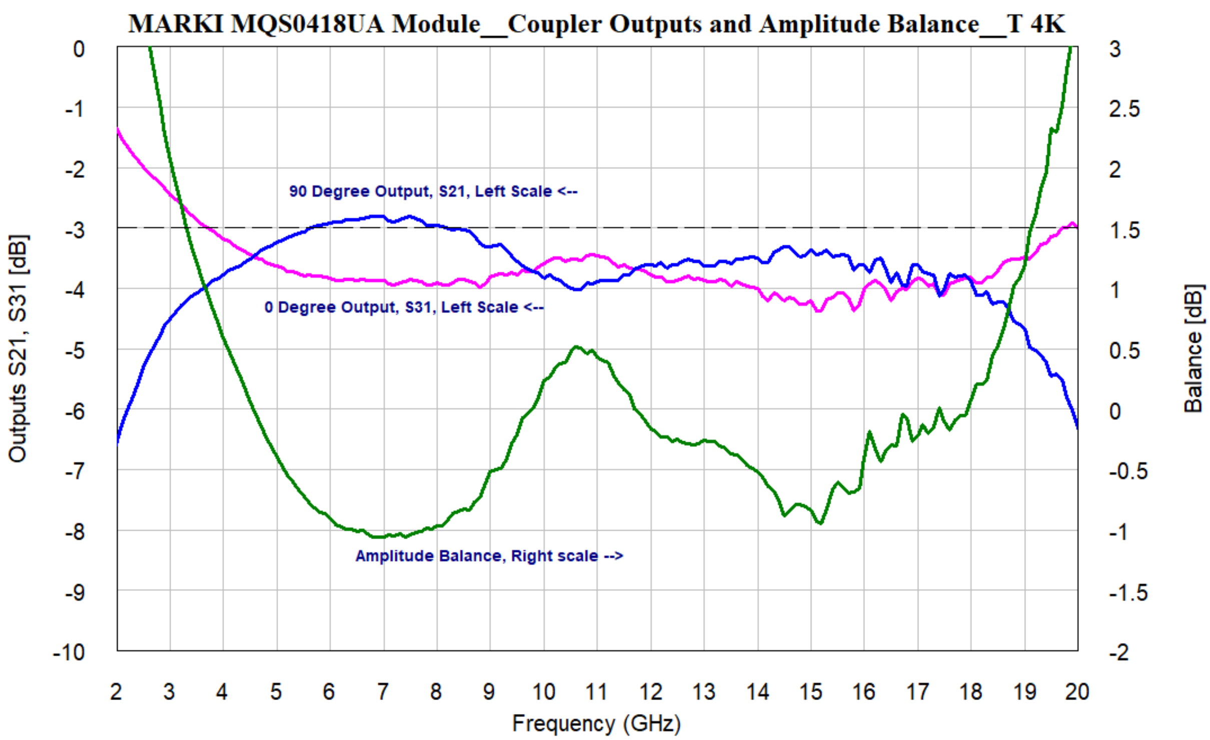

Figure 3-1: 0° output amplitudes (magenta S31, left Y axis), 90° output amplitudes (blue S21, left Y axis), and amplitude balance (green, right Y axis) of the Marki splitter/combiner measured at 4 K.

3.2 Excess Insertion Loss Characteristics

Figure 3-2 shows the excess insertion loss of the coupler both at room temperature and 4 K, which is measured by averaging the 0° output and 90° output amplitudes in dB and calculating the offset from -3 dB. The error in the cold measurement (blue trace) is evaluated by comparing both the warm excess insertion loss measured directly on the PNA-X (solid magenta) and the warm de-embedded measurement (dotted magenta) with the coupler in-cryostat. The curves are within ~0.3 dB. The cold excess insertion loss varies from -0.4 to -0.8 dB. The improvement in excess insertion loss on cooling is possibly due to decrease in the loss of the gold conductors at 4 K.

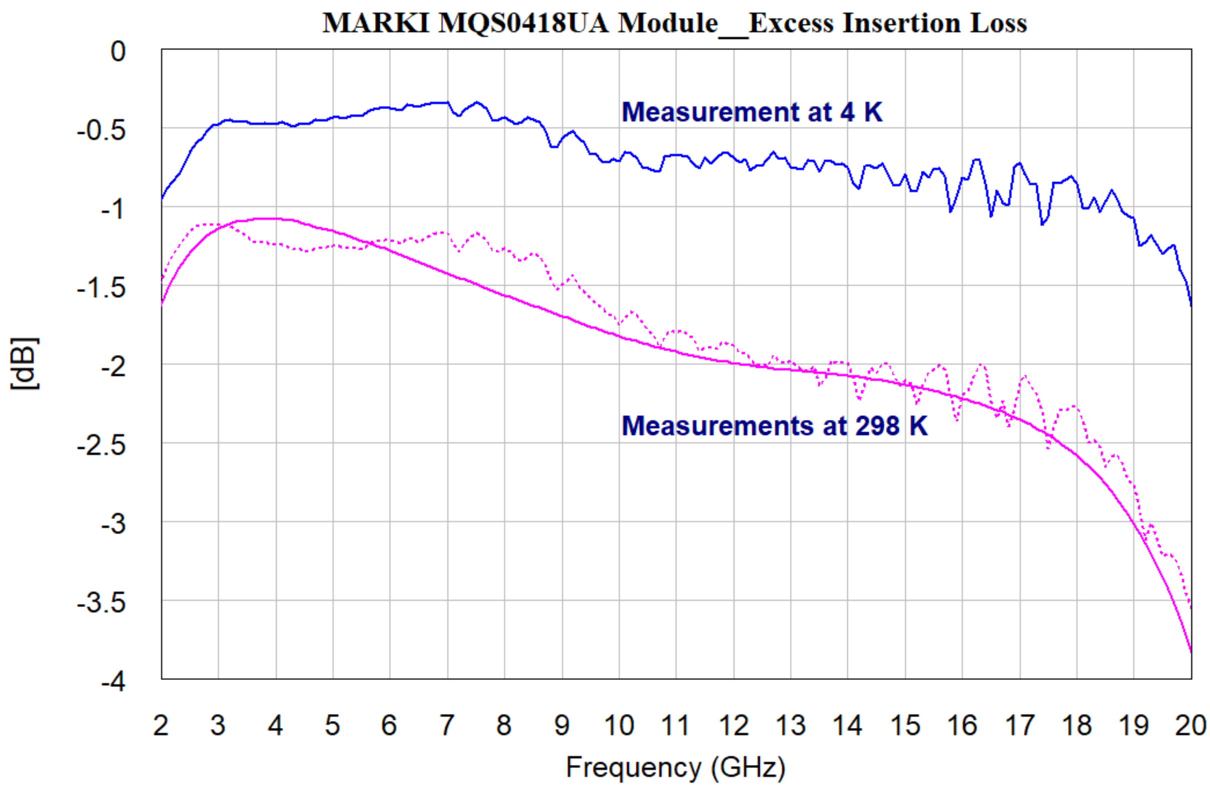

Figure 3-2: Comparison of warm (T = 298 °K, Magenta traces) and cold (T = 4 °K, Blue trace) excess insertion loss of the splitter/combiner. The solid magenta trace corresponds to measurement directly on the PNA-X, and the dotted magenta trace corresponds to the in-cryostat warm measurement de-embedded with the Keysight AFR software. The difference between the warm measurements are an indication of the error in the cold measurements.

3.3 Total Power Losses

Figure 3-3 shows the total power loss of the coupler both at room temperature and at 4 K, which is determined from the square root of the sum of the squared absolute values of S11, S21, S31, and S41. This loss is caused by dielectric absorption, radiation effects, and conductor losses.

The error in the cold measurement (blue trace) is evaluated by comparing both the warm total power loss measured directly on the PNA-X (solid magenta) and the warm de-embedded measurement (dotted magenta) with the coupler in-cryostat. The curves are within ~0.3 dB. The cold total power loss varies from -0.3 to -0.75 dB. The improvement in total power loss on cooling is possibly due to decrease in the loss of the gold conductors at 4 K.

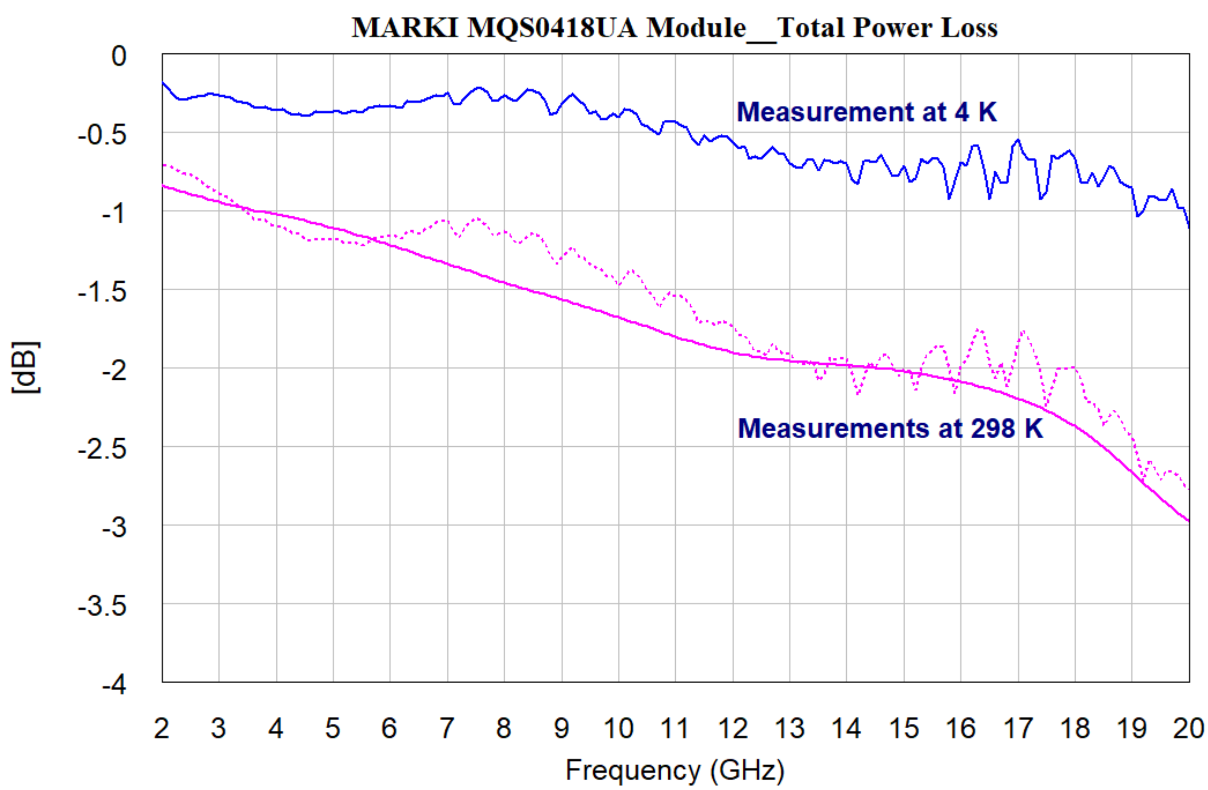

Figure 3-3: Comparison of warm (T = 298 °K , Magenta traces) and cold (T = 4 °K, Blue trace) total power loss of the splitter/combiner. The solid magenta trace corresponds to measurement directly on the PNA-X, and the dotted magenta trace corresponds to the in-cryostat warm measurement de-embedded with the Keysight AFR software. The difference between the warm measurements are an indication of the error in the cold measurements.

3.4 Port Match

Figure 3-4 shows the port return loss at 4 K temperature. Return loss, S11 is -15 dB as a worse case. However, note that this de-embedded characteristic may be worse than the actual S11 by about 5 dB, so the true return loss is expected to be -20 dB or better.

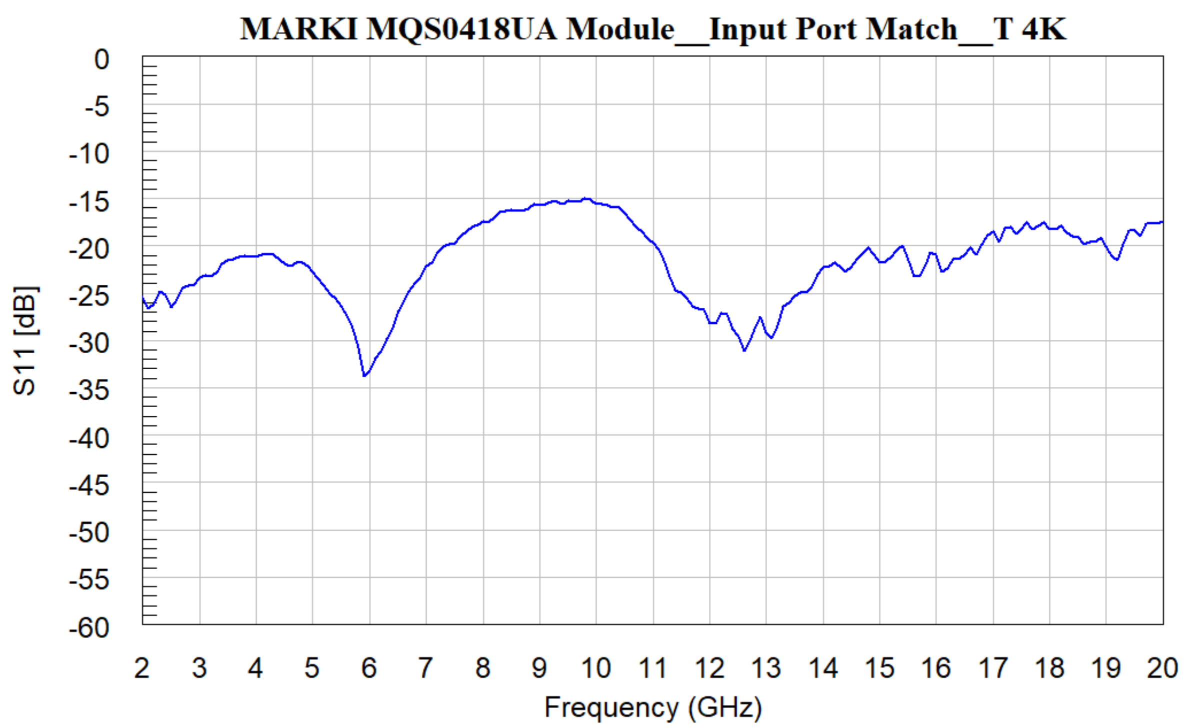

Figure 3-4: Port match S11 of the Marki splitter/combiner measured at 4 K. Note that the return loss at 4 K due to de-embedding of fixture cables tends to be higher than the actual return loss by as much as 5 dB.

3.5 Coupler Isolation

Figure 3-5 shows the coupler isolation at 4 K temperature. Coupler isolation, S41, is -15 dB as a worse case. However, note that this de-embedded characteristic may be worse than the actual S41 by as much as 2.5 to 5 dB, so the expected coupler isolation is expected to be -18 dB or better.

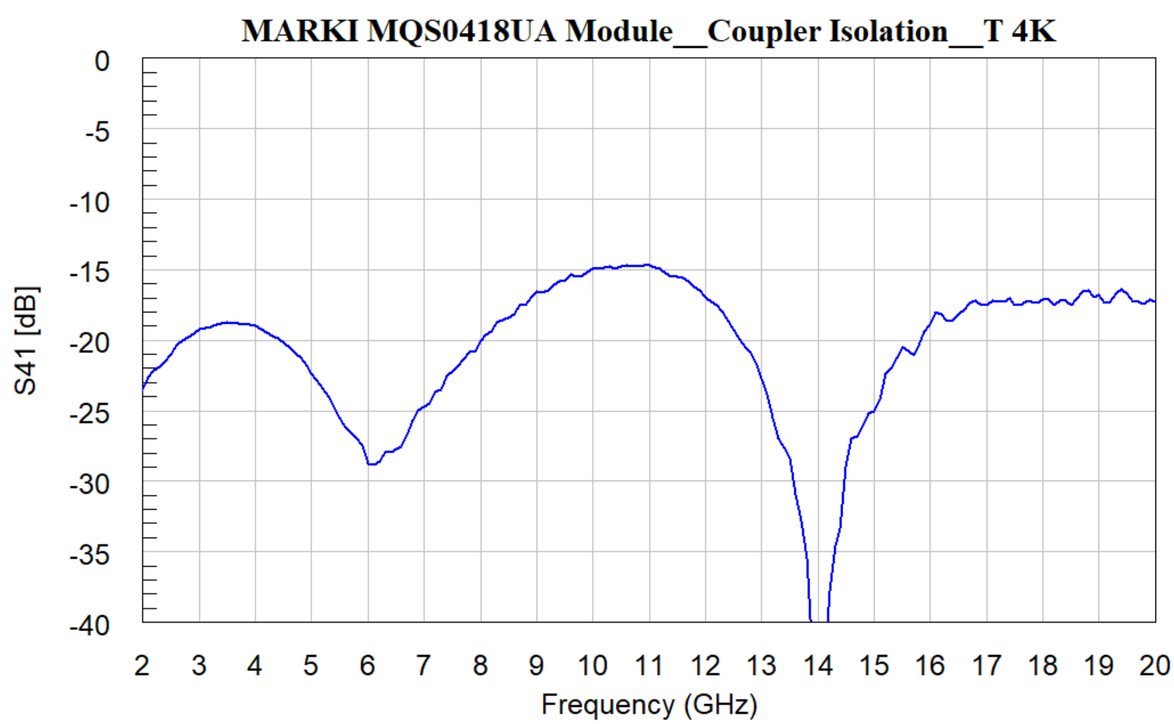

Figure 3-5: Coupler Isolation S41 corresponding to four orientations of the Marki splitter/combiner measured at 4 K. Note that the return loss at 4 K due to de-embedding of fixture cables tends to be higher than the actual return loss by as much as 2.5 to 5 dB.

3.6 Phase Balance

Figure 3-6 shows the phase balance at 4 K temperature. With the input signal applied to connector port 1, the phase balance is within 5 to 8 degrees. However, With the input signal applied to connector port 3, the phase imbalance is 10 to 12 degrees.

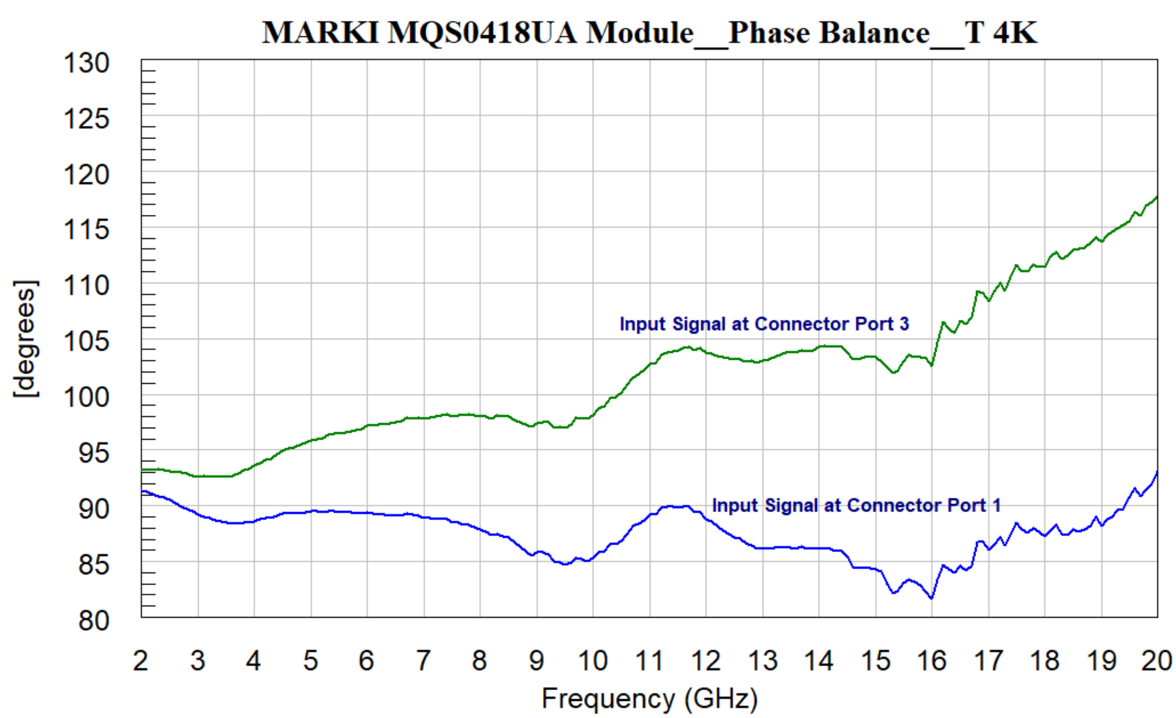

Figure 3-6: Phase balance of the Marki splitter/combiner measured at 4 K. Blue trace corresponds to input signal applied to connector port 1, green trace corresponds to input signal applied to connector port 3.

4.0 Wideband IF Hybrid Applications

A wide band IF hybrid can be applied in two ways in a sideband separating mixer receiver:
(1) to separate the upper- and lower- sidebands components of the two outputs from the mixer, and
(2) in a balanced IF amplifier.

These applications and suitability of the Marki splitter/combiner are discussed below.

4.1 Sideband Separating Mixer-Amplifier Assembly

Figure 4-1 shows a sideband separating mixer-amplifier assembly where the incoming RF signal passes through a quadrature 3-dB RF hybrid inside the mixer block which splits it into two components 90° out of phase. Each of the RF components is mixed with in-phase LO signals. The IF outputs from the mixers are sent to the inputs of the IF splitter/combiner which separates them into upper sideband (USB) and lower sideband (LSB) components. The Marki splitter/combiner ports 1 and 2 must be used as inputs so that the phase balance is tightly controlled. In this arrangement, the proposed use of Marki splitter/combiner will split inputs A and B appropriately into LSB and USB outputs.

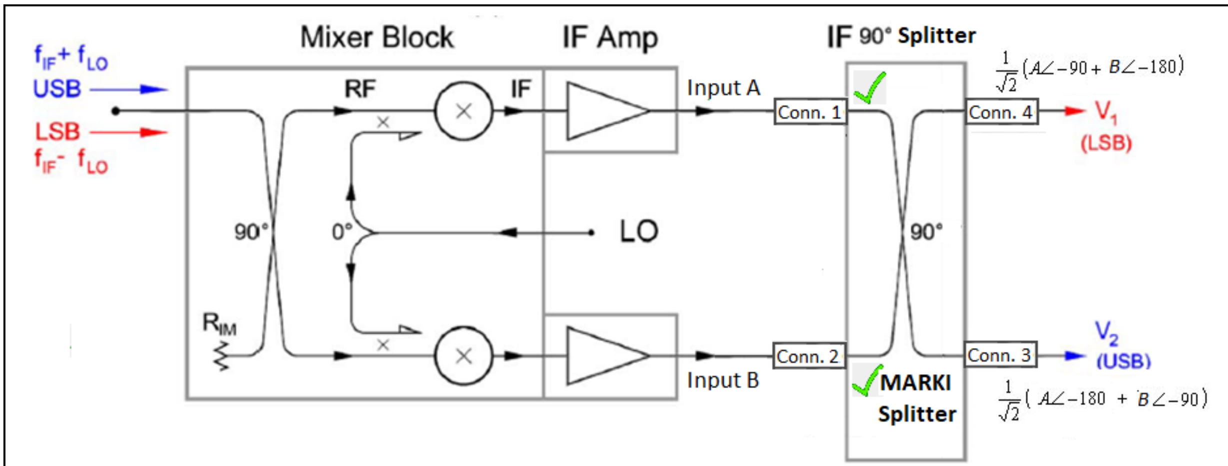

Figure 4-1: This schematic shows an application for the Marki 90° splitter in sideband-separating mixer-amplifier assembly.

4.2 Balanced Amplifier Assembly

In the second application, the balanced amplifier is proposed to minimize the mismatch between the superconducting mixer and amplifier shown in Figure 4-1 above. With a balanced amplifier two identical amplifiers and two IF quadrature hybrids are needed such that the input reflections from the amplifiers are channeled to the isolated port of the first IF quadrature splitter/combiner, and the output reflections are channeled to the isolated port of the second IF quadrature splitter/combiner. Figure 4-2 shows a balanced amplifier assembly which incorporates two identical amplifiers and two Marki splitters/combiners. For this assembly configuration to work both of the Marki splitters/combiners must be fully symmetric as each unit receives signals into the input and output ports; therefore phase balance will be an issue in this application. Hence a Marki splitter/combiner would not be suitable in a balanced amplifier.

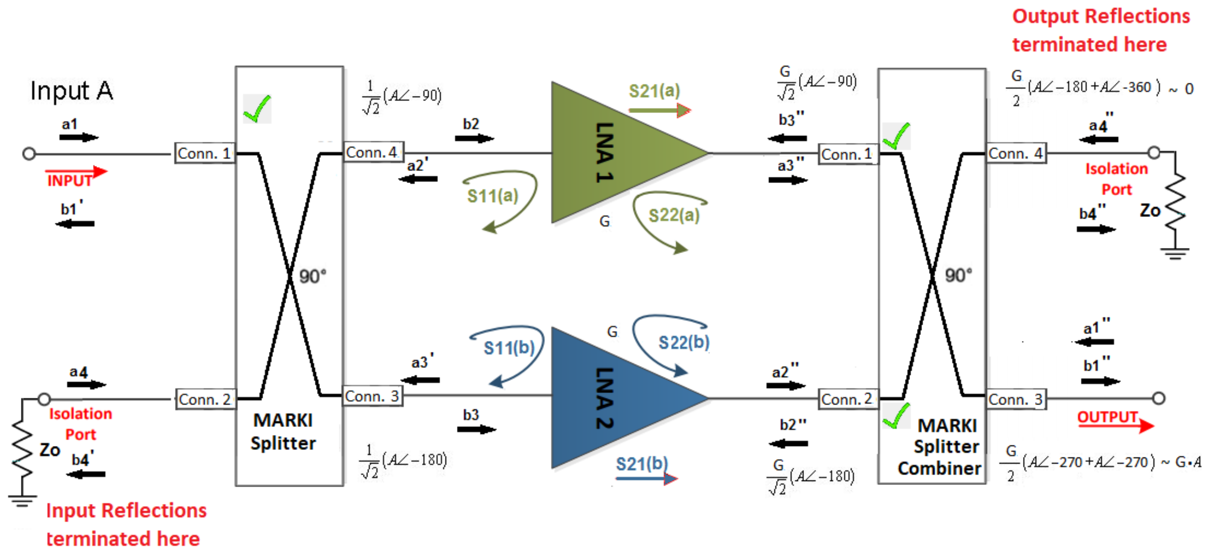

Figure 4-2: This schematic shows a balanced amplifier assembly with two Marki splitters/combiners.

5.0 Conclusions and Acknowledgements

This report described measurements of a Marki MQS-0418AU splitter/combiner at 4 K. The component was installed in a cryostat and cooled to 4 K multiple times. RF characteristics were measured and showed broadband 4 to 18 GHz performance which could be suitable for use in sideband separating mixer-amplifiers.

We would like to thank Carlos Ramirez for preparing the copper heat sink to mount the device on the 4 K plate. We also would like to thank the following personnel from Marki Microwave: Christopher Marki for agreeing to loan the module and bare dies for this work, and Valence Muvunyi for sending us the room temperature S-Parameters of the connectorized version.