ngVLA Electronics Memo # 17

Investigation of High Temperature Superconductor (HTS) Directional Couplers for ngVLA Receiver Front-End Applications

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Abstract

We explore the use of High-Temperature Superconductors (HTS) in the Band 1 and Band 2 receiver front-ends for the ngVLA. Electromagnetic simulation is used to design and predict the potential RF performance benefits of directional couplers based on HTS where traditionally copper conductors have been implemented. Other aspects including cost, fabrication, maintenance, and reliability are explored. The device considered in this memo is the directional coupler used to inject a calibrated noise level for receiver gain calibration.

1 Introduction

An ngVLA receiver front-end includes a passive directional coupler in each of the two polarization channels, to inject a pre-calibrated broadband noise power level for gain calibration. Due to its insertion loss and location ahead of the LNA in the cascaded signal chain, this device can degrade the receiver noise temperature and sensitivity of the receiver, especially on the wideband receivers that use coaxial connections. A reduction in the loss of this directional coupler can potentially lead to significant improvement in the overall receiver noise temperature.

A traditional stripline directional coupler uses a copper conductor. An improvement in the noise temperature of the copper device is achieved by operating the device at very low temperatures via cryogenic refrigeration to cool the front-end receivers. Given the availability of low-temperature operation, HTS with critical temperatures greater than the operating temperature can be considered.

In this memo, HTS is studied as an alternative to copper for low-loss receiver front-end passive components. Yttrium-Barium-Copper-Oxide (YBCO) is a popular HTS and will be the material considered in this memo. The two design driving requirements for the front-end are to achieve optimum sensitivity and optimum running cost [1]. The impact of an HTS implementation on these metrics is evaluated.

2 HTS Microwave Devices

Low-loss microwave devices implemented using HTS thin film technology are intriguing due to an extremely low surface resistivity when operated at a physical temperature below its critical temperature. "High temperature" superconductors typically are defined as having a critical temperature above the boiling point of liquid nitrogen at 77 K. The YBCO material considered in this memo has a critical temperature of 92-93 K, a temperature that is well suited for the ngVLA closed-cycle 2-stage cryocooler with stage 1 and 2 temperatures of 80 K and 20 K, respectively.

HTS has been employed previously to realize very low loss, high-Q, highly compact bandpass and notch filters in planar form. It has also been used in other microwave devices to minimize thru loss and maximize sensitivity of cryogenically-cooled receivers [2], [3].

HTS and YBCO are used interchangeably throughout this memo. It is assumed that YBCO is the HTS considered.

3 ngVLA Receiver Front-End Application

The ngVLA receiver front-end block diagram from [4] for Bands 1-2 is shown in Figure 1, with Band 1 (1.2-3.5 GHz), Band 2 (3.4-12.3 GHz). Both receivers have two signal outputs, corresponding to each orthogonal linear polarization. Self-calibration of the receiver is performed by injecting broadband noise at a predetermined level into the signal path. Taking the ratio of measured output power against that without the injected noise allows the system noise temperature to be determined.

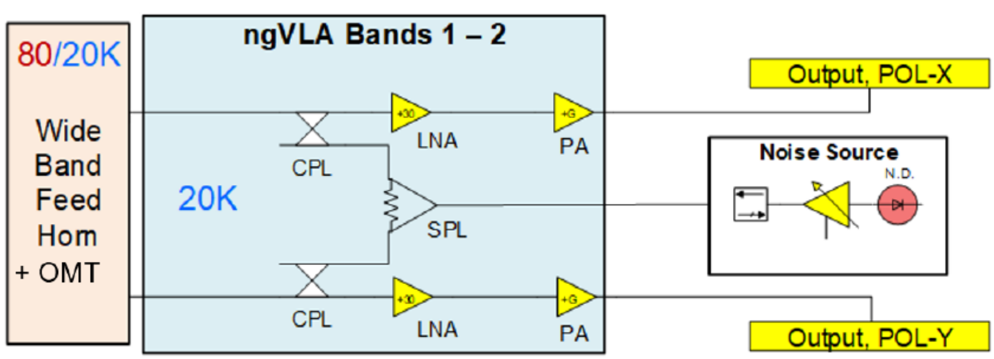

Figure 1. ngVLA Receiver front-end block diagrams [4]

The noise calibration system in the receiver is implemented with a single noise source generator, whose output is split into two nominally equal paths (SPL), and injected into each of the signal paths using a directional coupler (CPL). This calibrator architecture, also implemented on the Jansky Very Large Array (JVLA), is capable of removing gain variations due to electronics between the directional coupler and correlator on 1-second timescales [5]. Any variations prior to the directional coupler in the receiver chain are not accounted for with this calibration technique.

The directional coupler is a 4-port microwave device designed for a particular power division. Two commonly used symbols and power flow conventions are shown in Figure 2 [6]. In general, a small fraction of the RF power is coupled from the Input (Port 1) to the Coupled Port (Port 3), while a majority of the power is passed from the Input to the Thru port (Port 2). The Isolated, or uncoupled port, is the 4th port. The "coupling factor" indicates the fraction of the input power that is coupled to the output port, defined as Coupl=10 log (P_1/P_3). The "insertion loss" is defined as IL=10 log (P_1/P_2), and "transmission" is the algebraic negative of the insertion loss. The "isolation" of the device is defined as Iso=10 log (P_1/P_4). The "directivity" of this device, defined as Dir=10 log (P_3/P_4), is a measure of the coupler's ability to isolate forward and backward waves (or the coupled and uncoupled ports), i.e. the ratio of power at the Coupled port to the Isolated port. S-parameters commonly represent these quantities: S11 for Input Reflection, S21 for Thru transmission, S31 for Coupling, and S41 for Isolation.

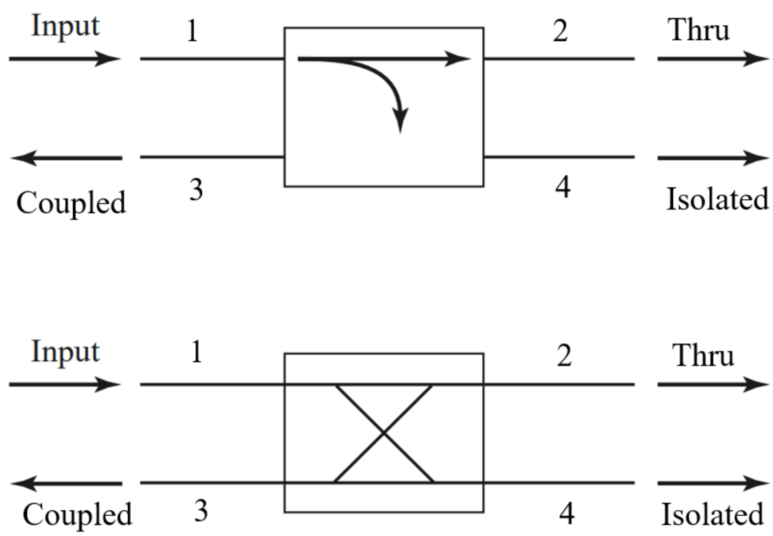

Figure 2. Two commonly used symbols for directional couplers, and power flow conventions [6]

In the radio astronomy receiver, a noise source at the coupled port (Port 3 in Figure 2) injects noise into the Input "main path" towards the LNA (Port 1), while adding minimal loss into the thru path from the feed horn and OMT (Port 2). The directivity is the ratio of injected power propagating toward the LNA relative to power directed back toward the feed. The directivity of the coupler is related to the isolation and should be as high as possible to reduce the fraction of power from the noise source that propagates toward the antenna. In an ideal directional coupler, no power is delivered to Port 4. The insertion loss, the coupling factor, and the isolation are positive numbers if expressed in dB. However, these values are often used as negative. A low coupling factor (0.001 in linear power scale, or -30 dB in algebraic negative dB coupling scale) is typically used in cryogenic receivers: by design, this minimizes the thru loss of the main path, and also the injection of residual thermal noise present in the noise source path when the noise source is switched off. Lower coupling factors could be considered, but are less common in off-the-shelf devices, and would require higher gain in the noise source path or a larger excess noise ratio (ENR) in the noise source.

The impact of the directional coupler on noise temperature can be analyzed using the ngVLA receiver cascade analysis tool [7]. Some of the basic equations relevant to this memo are reviewed herein. The total receiver noise temperature T_{eq} (in Kelvin) is calculated using the Friis equation

$$T_{eq} = T_1 + \frac{T_2}{G_1} + \frac{T_3}{G_1 G_2} + \cdots$$

where each stage in the receiver chain has a noise temperature T_n and available gain G_n, and n is the stage number from 1 to N. The components that precede the LNA, including the directional coupler, are passive devices. Passive devices have a noise temperature of

$$T_e = (A - 1) * T_{phy}$$

where A is the thru loss or attenuation and is equal to 1/G (G is the gain of the device), and T_{phy} is the physical temperature of the device. These passive devices contribute additional noise to the cascade via the LNA noise term, since the LNA noise is divided by the gain that precedes it in the chain. Therefore, it is important to minimize the loss in passive devices ahead of the LNA, in order to achieve the lowest receiver noise temperature possible.

In the next section, off-the-shelf directional couplers appropriate for ngVLA Bands 1 and 2 will be measured, and their noise contributions evaluated in the receiver using the cascade analysis tool.

4 Conventional Directional Coupler Test Results

"Conventional" directional couplers in the frequency range for Bands 1 and 2 (1.2 – 12.3 GHz) are typically implemented in stripline (a type of planar microwave transmission line), as a cascade of edge-coupled, quarter-wavelength (λ/4) sections. These are usually fabricated by etching the transmission line pattern on a copper-clad dielectric substrate and stacking another bare dielectric layer over it, with the ground plane facing outward. PTFE-based substrates are often used due to their low cost and ease of fabrication, combined with low RF loss. Couplers of this type can achieve 15-20 dB directivity, better than 25 dB input/output return loss, and very low insertion loss. Bands 1 and 2 have ratio bandwidths of 3.6:1 and 2.9:1, respectively, which would generally require a longer and lossier 3-section design to achieve a reasonably flat coupling factor over their bandwidths.

Special "cold temperature rated" directional couplers were provided by a commercial vendor (Krytar) for evaluation and testing. These units have a nominal coupling factor of -30 dB, and include design modifications that allow them to operate at cryogenic temperatures and survive repeated temperature cycling up to room ambient. The Krytar coupler part numbers for ngVLA Bands 1 and 2 are 101004030-810 and 120430-810, respectively. Pictures of Krytar coupler models 101004030-810 operating in Band 1 and 120430-810 operating in Band 2 are shown in Figure 3.

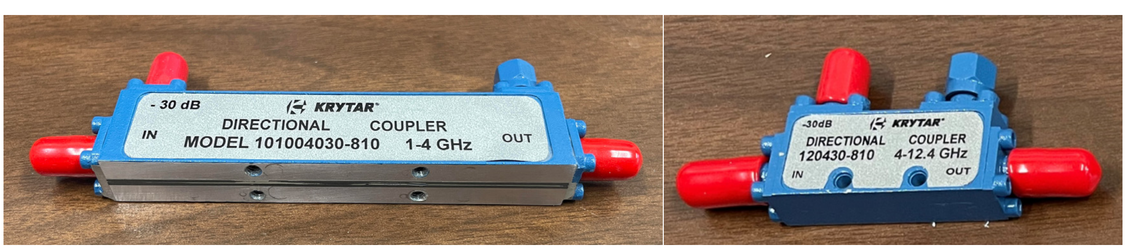

Figure 3. Krytar directional couplers Left) 101004030-810 and Right) 120430-810

4.1 Ambient temperature (295 K) test results

The ambient temperature (≈295 K) transmission (S21) and input match (S11) of the Band 1 and Band 2 couplers were measured by the vendor, and also by NRAO using a calibrated Vector Network Analyzer (Rohde & Schwarz ZNA50), with good agreement in results. The NRAO measurements are shown versus frequency in Figure 4.

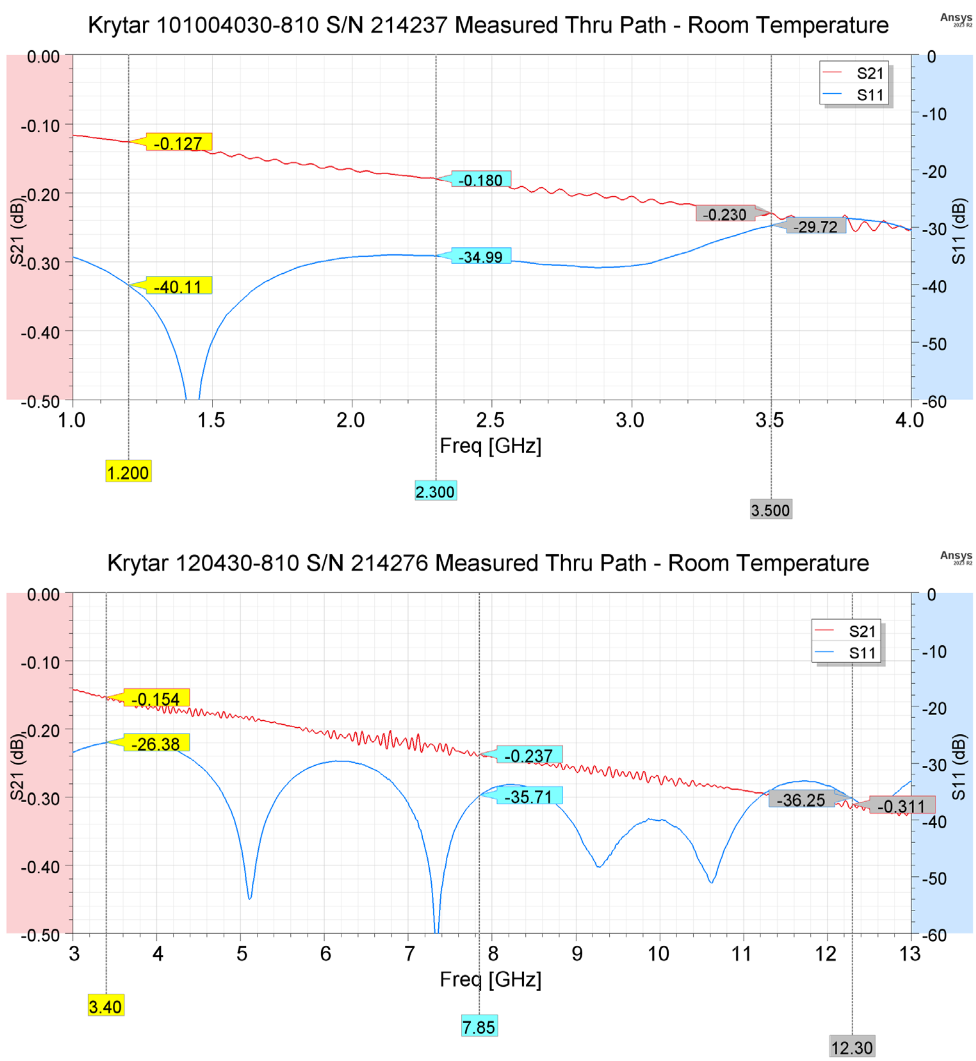

Figure 4. Krytar coupler thru path measurements at room temperature (295 K), for ngVLA Bands 1 (top) & 2 (bottom)

4.2 Cryogenic temperature setup and test results

The transmission (S21) and input match (S11) of both Krytar devices depicted in Figure 3 were also measured by NRAO at ≈20 K cryogenic temperature. A test cryostat and the calibrated Vector Network Analyzer were used for the test. The diagram of the device under test (DUT) measurement setup in the test cryostat is shown in Figure 5, while Figure 6 shows pictures of the DUT mounted in thermal contact with the second stage of the cryostat, where the device is cryogenically cooled at the physical temperature of ≈20 K.

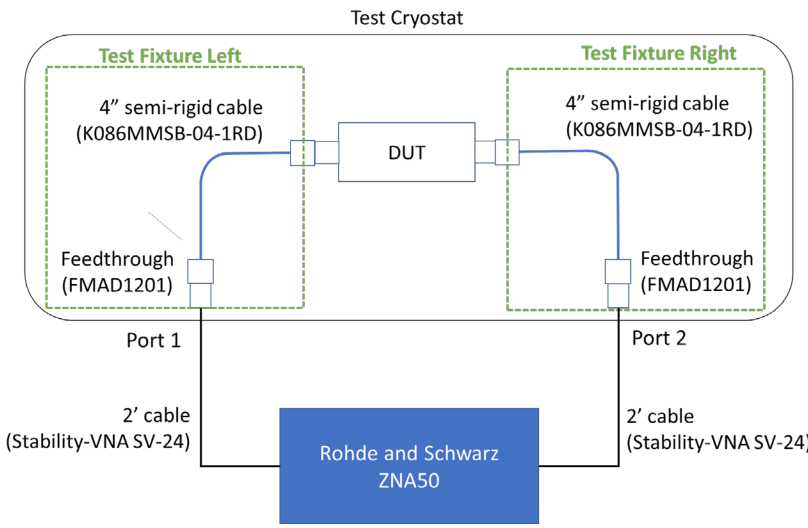

Figure 5. Test setup diagram of the Band 1 Krytar coupler (DUT) inside the test cryostat

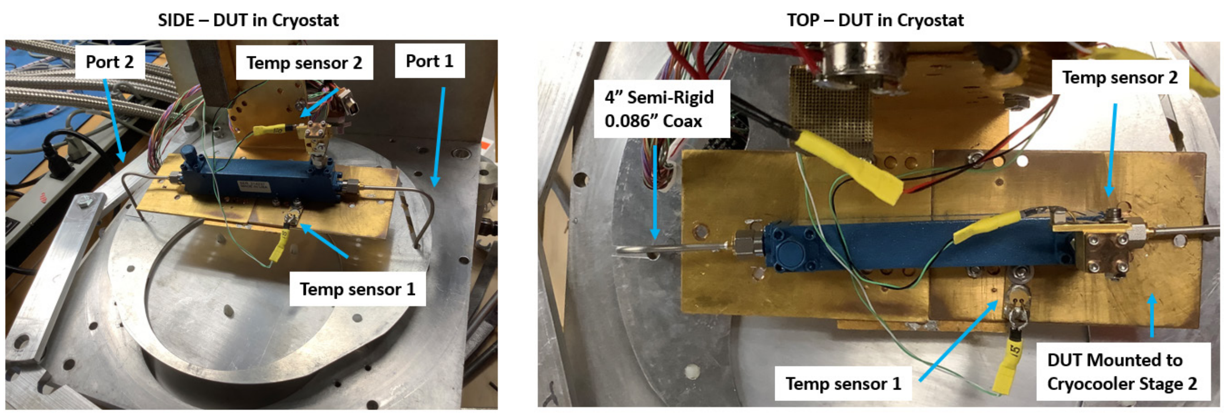

Figure 6. Band 1 Krytar coupler (DUT) mounted in test cryostat

The test fixture is de-embedded from the measurement to get the DUT response using AtaiTec In-Situ De-embedding™ (ISD) software which requires the measurement of a cooled 1X-short test coupon in place of the DUT. Comparative test results at 20 K and 295 K of the Band 1 101004030-810 and Band 2

120430-810 Krytar couplers are shown in Figure 7. There is a reduction in loss when the devices are cooled to 20 K.

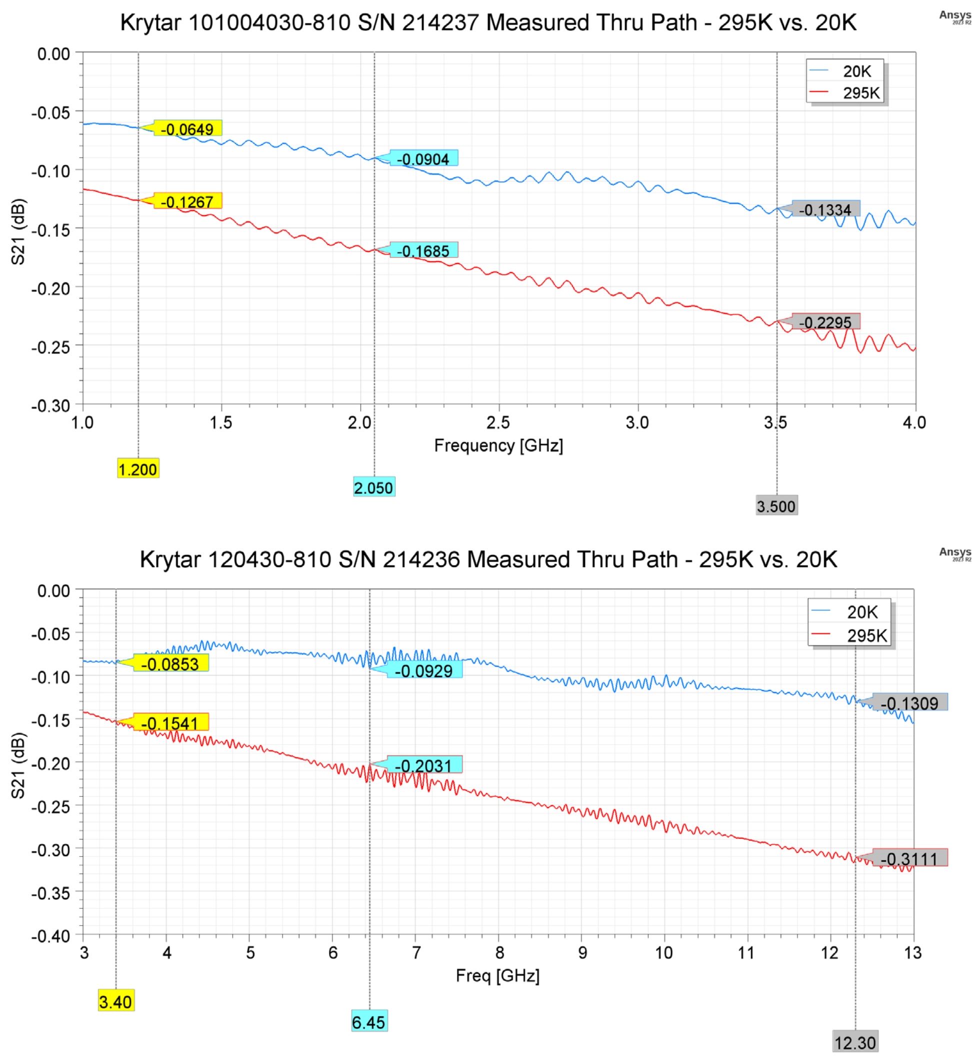

Figure 7. Measured transmissions of Band 1 and 2 Krytar couplers at 295 K (red trace) and 20 K (blue trace)

4.3 Directional Coupler Receiver Noise Contributions

These measured losses at cryogenic temperature were input into the ngVLA cascaded receiver analysis tool, to determine the specific and overall noise temperature contributions in each band, for the receiver alone (T_{rx}) and for the total system (T_{sys}). Nominal atmospheric observing conditions at the VLA site are assumed to derive the system temperature T_{sys} [4]. Table 1 below contains a summary of these results, at the band edges and (geometric) center frequency. The coupler port is assumed to be looking into an RF termination at a physical temperature midway between Stage 1 (80 K) and room ambient (300 K), or 190 K.

Table 1. Commerical directional coupler noise contributions

		Band 1			Band 2		
	Freq (GHz)	1.2	2.05	3.5	3.4	6.45	12.3
Coupler	Loss (dB), at 20 K physical temperature	0.065	0.090	0.133	0.085	0.093	0.131
	T_{phy} (K)	20	20	20	20	20	20
	Noise Temp, Thru (K)	0.61	0.80	1.09	0.70	0.94	1.48
	Noise Temp, Coupled (K)	0.19	0.19	0.19	0.19	0.19	0.19
LNA	Noise Temp (K)	2.83	2.26	1.46	4.83	2.72	3.97
	Noise Temp (K) (adj. with coupler loss)	2.87	2.31	1.51	4.83	2.72	3.97
Coupler + LNA	Cascaded Noise Temp (K)	3.36	2.92	2.32	5.51	3.40	4.89
	Δ Noise Temp, due to coupler (K)	0.53	0.66	0.86	0.68	0.68	0.92
Entire Receiver Chain	Entire receiver chain Cascaded T_{rx} from [7] (K)	9.9	9.8	10.1	10.9	10.5	14.5
	Coupler fraction of Cascaded T_{rx} (%)	5.4%	6.7%	8.5%	6.2%	6.5%	6.4%
	Entire receiver chain Cascaded T_{sys} from [7] (K)	22.6	16.9	15.6	19.1	17.1	21.0
	Coupler fraction of Cascaded T_{sys} (%) (6mm PWV, 60° antenna elev.)	2.4%	3.9%	5.5%	3.6%	4.0%	4.4%

The directional coupler degrades receiver sensitivity by contributing 5.4 – 8.5% of the noise to the front-end T_{rx} and to a lesser degree the system T_{sys} (2.4 – 5.5%). The majority of this noise (65 - 80%) is due to the insertion loss of the device in the thru path and a smaller portion (20 - 35%) is due to the coupling path contribution. In the thru path, lower loss would further reduce noise. This is the primary reason that HTS is considered as an alternative to these conventional couplers.

5 Modeling and Simulation

In this section, the electrical performances of conventional and HTS devices are analyzed. First, material properties are researched for 295 K (room) and 20 K temperature operation. Next, directional couplers are synthesized using Keysight Pathwave Genesys™ software. Finally, electromagnetic simulation is performed in order to compare the loss contributions of conventional and HTS devices.

5.1 Material properties

The material properties in conventional and HTS directional couplers need to be modeled accurately in order to obtain valid simulation results. For the purposes of this study, it is assumed that conventional couplers use copper conductors on low dielectric constant PTFE-composite substrates, while HTS couplers use YBCO films on MgO, a low-loss crystalline substrate material with a high dielectric constant. Each conductor and dielectric are researched below.

Copper

- *Conductivity*. The International Annealed Copper Standard (IACS) established the electrical conductivity of copper at 5.8×10^7 S/m at 20°C. A residual resistivity ratio (RRR) has been used to compare the conductivity of copper at room temperature to 0 K. The performance of coppers with a range of RRR was collected by NIST in [8]. This data shows that below 20 K, there is not much improvement in resistivity down to 0 K. In [9], C101 copper was measured at 4 K and it was found that DC conductivity increased by a factor of 106. However, at RF frequencies, the apparent effect of the extreme anomalous skin effect regime [9] leads to much lower RRR values. RRR at 5 - 7 GHz was measured at 8.3 and calculated at 7.9 using the effective conductivity in the non-anomalous regime equation. For the purposes of this memo, RRR values of 8 and 1 (i.e., no improvement at cryogenic temperatures) will be simulated. In reality, this RRR will likely be better at the lower frequency Band 1 according to the equation in [9].

- *Roughness*. Roughness for copper-clad material depends on manufacturing, with electrodeposited (ED) being somewhat rougher than rolled copper. The RMS surface roughness values for ½ oz. rolled copper are 0.4 µm on the dielectric side and 0.3 µm on the top side, while for the same weight of ED copper they are 2.0 µm and 0.4 µm, respectively [10]. Rolled copper roughness is used in the simulations.

- *Thickness*. ½ oz. and 1 oz. copper are most commonly available. For the simulations, ½ oz. (18 µm thickness) is used. At room ambient, this is over 9 times the nominal skin depth at the lowest frequency.

- *Plating*. The copper is assumed to be un-plated.

PTFE-composite substrate

- *Dielectric constant*. Dielectric constants of around 2.05 - 2.3 are typical for these substrates. For the purposes of evaluation, this range is not considered to have a significant impact on the conclusions of this study. A value of 2.1 is chosen for simulation. It is reported in [11] and [12] that the dielectric constant of Teflon changes very little at cryogenic temperatures.

- *Dielectric loss*. Dielectric loss at room temperature is very low. For instance, Rogers 5880 at 10 GHz has a dissipation factor (loss tangent) of 0.0009, and this value will be used for room temperature simulation. At cryogenic temperatures, PTFE loss is reported to improve significantly. In [11], the dielectric loss of Teflon is reported as 8×10^{-6} at 77 K, and in [12] it is reported as 2.3×10^{-6} at 28 K and 5.6×10^{-6} at 84 K. A value of 2.3×10^{-6} was used for a 20 K cryogenic simulation.

- *Thickness*. Dielectric thicknesses are usually available in 127, 252, 508, 787, and 1575 µm. 787 µm is chosen for this study. The stripline total substrate thickness will be 1575 µm, composed of a 787um section above and below the signal trace. The chosen thickness is typically used in commercial devices in this frequency range because the substrate thickness is large enough to result in a relatively wide, low-loss 50 Ω trace, but not so thick as to create low cutoff frequencies for higher-order modes.

YBCO

- *Surface resistance*. Rather than conductivity, surface resistance is the parameter measured for HTS materials. This value changes over frequency and temperature, with lower resistance achieved at lower frequencies and temperatures. Traditional conductors have a $f^{1/2}$ relationship to conductivity, but HTS has a f^2 relationship. Therefore, as the frequency goes up, the benefit of YBCO decreases and there is a "cross-over" point. Some research groups [2] have used a fixed surface resistance such as 5×10^{-5} Ω at C-band and 2×10^{-5} Ω at L-band in simulation. For this memo, the surface resistance is modeled at 20 K over frequency as a dataset according to [13], as shown in Figure 8. The reactance of the surface resistance was set to zero for simulation in HFSS, but included for Sonnet, according to [14]. The thickness of the YBCO film, assumed to be 1 μm, is much greater than the London penetration depth at 20 K, assumed to be 150 nm, and the impact on the simulation result is minimal.
- *Roughness/Thickness*: Roughness and thickness are not characterized for YBCO, but the effect on the surface is accounted for in the surface resistance of the impedance model.
- *Plating*. No plating is assumed.

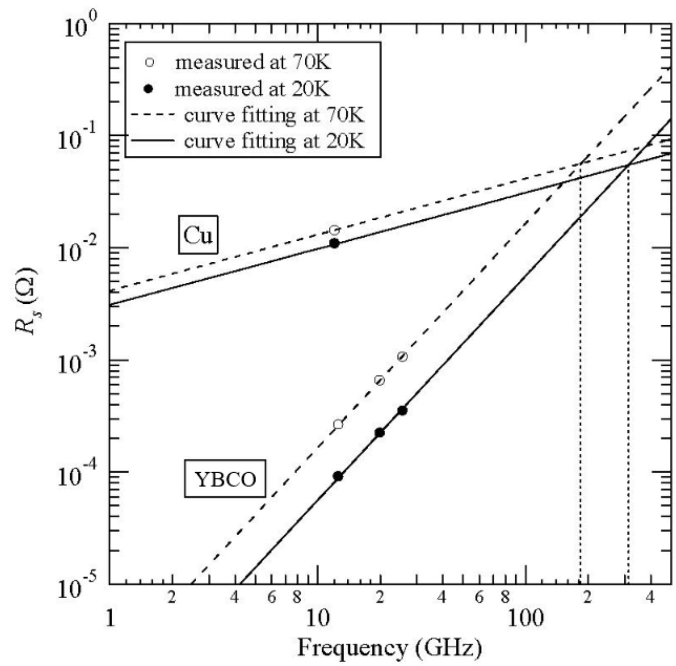

Figure 8. Measured YBCO surface resistance over frequency at 20K and 70K and curve fit lines [13]

MgO substrate

- *Dielectric constant*. A dielectric constant of 9.63 was measured in [15]. A dielectric constant of 9.68 was used by [2]. A value of 9.63 is chosen for our simulation.
- *Dielectric loss*. A dissipation factor of 5×10^{-6} was used in [15] and is used in our simulation.

- *Thickness*. Substrate thickness is set at 508 µm. This is the standard wafer thickness available. Note that a "top substrate" of the same thickness is assumed to be added for a total ground-to-ground stripline thickness of 1016 µm.

5.2 Directional Coupler Design Synthesis

Genesys was used to synthesize the stripline geometry for the ngVLA Band 1 and Band 2 directional couplers. A width-symmetric 3-section backward-wave coupler was chosen with input goals of -30 dB coupling factor, 20 dB return loss, and 20 dB directivity. Two substrates were defined, for the conventional and HTS designs. Some parameters such as loss tangent, resistivity, and roughness do not impact the synthesized design. Dielectric constant, metal thickness, and substrate height are the key parameters, defined in Table 2.

Table 2. Substrate parameters for Genesys synthesis

Substrate	Dielectric constant	Metal Thickness (µm)	Substrate Height (µm)
Copper / PTFE-composite	2.1	18	1575
YBCO / MgO	9.63	1.0	1016

The synthesized coupler dimensions for the conventional and HTS versions are summarized in Table 3 and Table 4, respectively, for both bands. A 50 Ω line impedance for both geometries was also extracted for use as input/output lines, with the copper-based design having a trace width of 1.252 mm and the YBCO-based design with a width of 0.194 mm.

Table 3. Conventional Copper / PTFE-composite synthesized dimensions (in mm). See Fig. 9 for the definition of TL1/TL2/TL3

Section	Width	Spacing	Length (Band 1)	Length (Band 2)
TL1 / TL3	1.302	1.663	22.48	6.59
TL2	1.297	0.873		

Table 4. HTS YBCO / MgO synthesized dimensions (in mm)

Section	Width	Spacing	Length (Band 1)	Length (Band 2)
TL1 / TL3	0.167	1.304	10.517	3.081
TL2	0.166	0.792		

Note: Genesys did not appear to synthesize geometry according to the return loss and isolation goals. The simulation in this tool with these models predicts a perfect return loss and an isolation > 25 dB.

5.3 Directional Coupler Electromagnetic Simulation

Two electromagnetic software suites are used in an attempt to get consistent results across tools and simulation methods: HFSS™, a finite element method (FEM) solver, and Sonnet™, a method of moments (MoM) solver.

HFSS is set up as follows:

- Driven-modal solution with waveport excitations.
- Adaptive mesh at 15 GHz for Band 1 and 5 GHz for Band 2. Max delta S of 0.001.
- Sweep in 100 MHz steps to 15 GHz for Band 2 and to 4 GHz for Band 1.

Sonnet is set up follows:

- Cell size is set to 0.02x0.02 mm^2 for conventional metal and 0.005x0.005 mm^2 for HTS.

Copper is modeled as a trace with its thickness, finite conductivity boundaries, and surface roughness. YBCO is modeled as an impedance boundary with a real surface resistance that changes over frequency [15] in HFSS. In Sonnet, a reactive impedance was modeled.

5.3.1 Band 1

The geometry for the Band 1 3-section backward wave couplers synthesized by Genesys is modeled in HFSS and Sonnet. In each case, a section of stripline was added to each port of the coupler, for coaxial connector termination. The lengths of each section for both couplers were unmodified from the Genesys synthesized values. Width and spacing of the conventional coupler also used the Genesys dimensions directly. The HTS coupler dimensions were modified somewhat as shown in Table 5 from synthesis in order to achieve similar performance for return loss and coupling factor as the conventional design model.

Table 5. HTS YBCO / MgO Genesys synthesized and HFSS dimensions (in mm)

Section	Genesys Synthesized Width	HFSS Width	Genesys Synthesized Spacing	HFSS Spacing
TL1 / TL3	0.167	0.200	1.304	1.22
TL2	0.166	0.195	0.792	0.72

The HFSS geometry for the conventional and HTS designs, along with the simulated E-field mid-band with 50 dB scale is shown in Figure 9 and Figure 10 respectively.

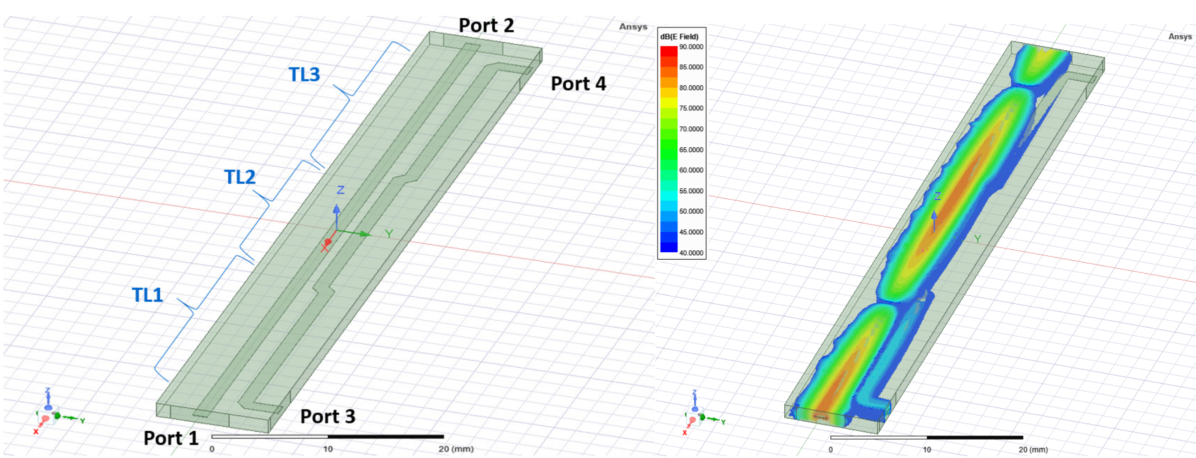

Figure 9. Copper / PTFE-composite Band 1 Directional Coupler HFSS Model and E-field plot

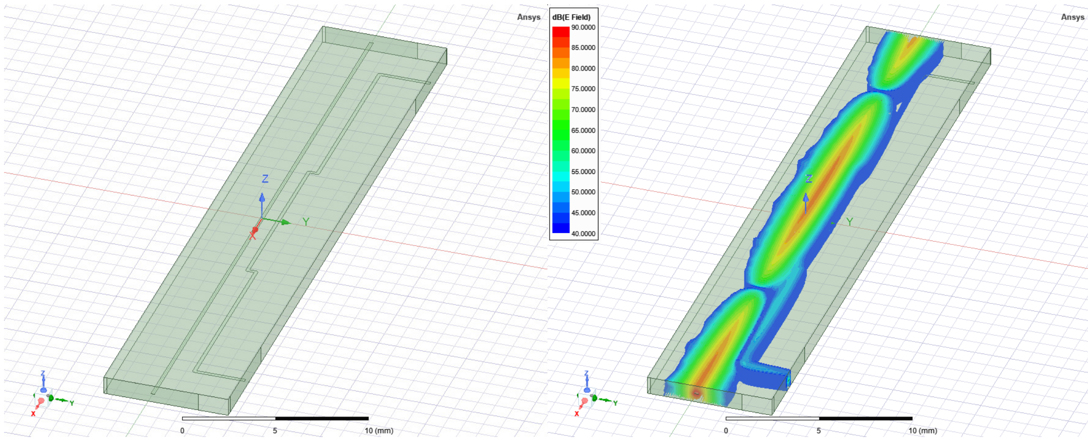

Figure 10. YBCO / MgO Band 1 Directional Coupler HFSS Model and E-field plot

Sonnet simulation subsections are shown in Figure 11.

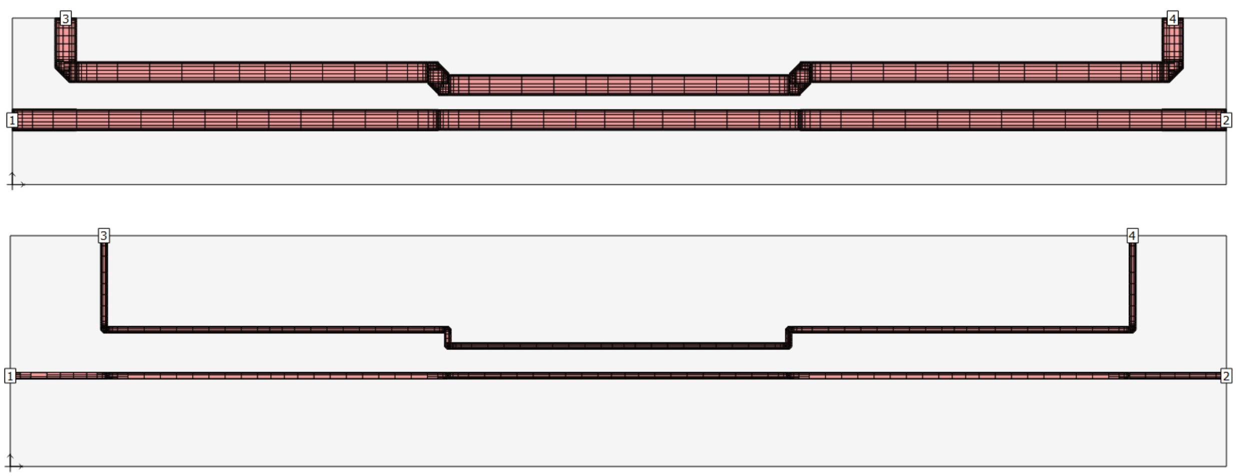

Figure 11. Sonnet subsections for Band 1 coupler simulations. Top) Conventional and Bottom) HTS

Figure 12 and Figure 13 show the 20 K simulated coupling factor (amplitude of S31) and input reflection (amplitude of S11) comparison between the directional couplers (based on conventional Copper/PTFE-composite) and HTS (based on YBCO / MgO), respectively in HFSS and Sonnet simulators. There is a satisfactory match between simulation tools and comparable performance between designs.

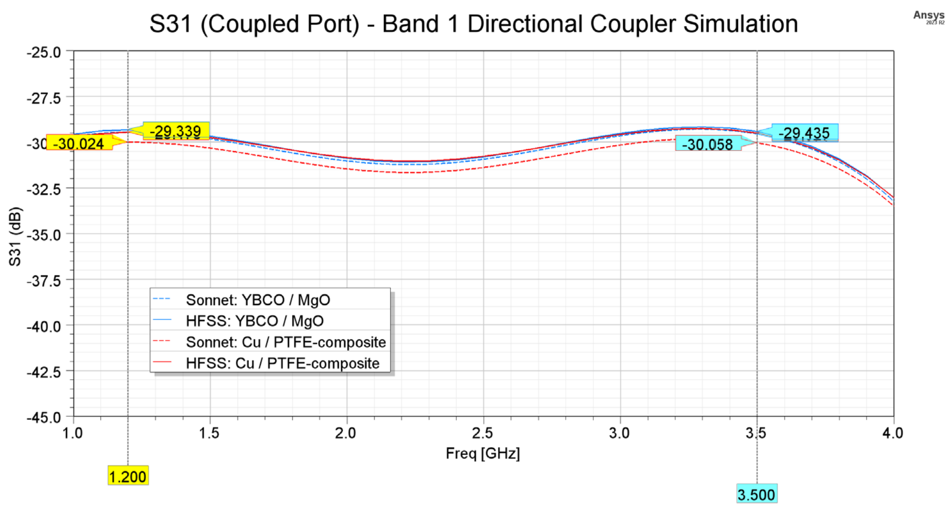

Figure 12. Simulated coupling factor for conventional and HTS directional couplers, Band 1

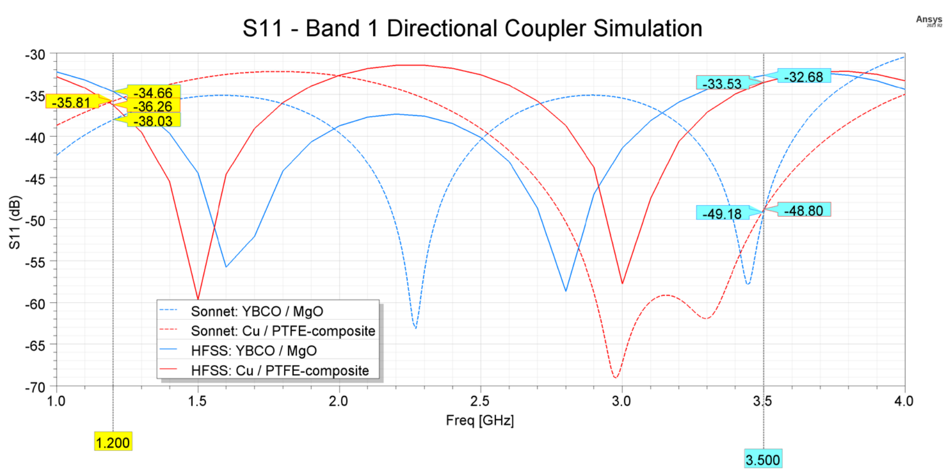

Figure 13. Simulated input match for conventional and HTS directional couplers, Band 1

A comparison between the Thru transmissions (S21) is shown in Figure 14. For the conventional design, room temperature values and cryogenic values of copper conductivity and dielectric losses are each simulated.

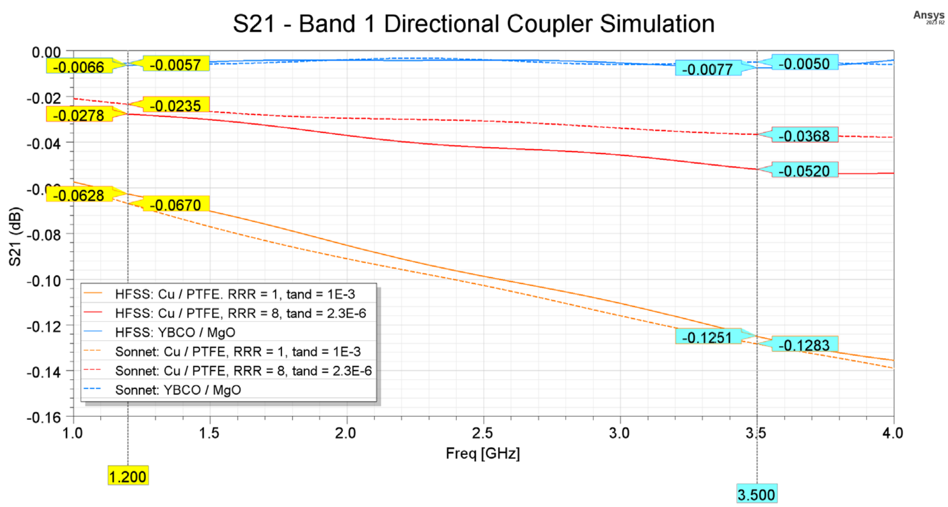

Figure 14. Simulated Thru transmission (S21) for conventional and HTS directional couplers, Band 1

According to the simulation, HTS can provide an improvement in loss of about 0.03 - 0.04 dB at the upper edge of Band 1, if cryogenic properties are assumed for the conventional design.

5.3.2 Band 2

The Band 2 synthesized design has the same widths and spacings as Band 1, but shorter traces due to the higher frequency. Again, the modified widths and spacings for the HTS Band 1 design are used for Band 2. The HFSS geometry for the conventional and HTS designs, along with the simulated E-field mid-band with 50 dB scale is shown in Figure 15 and Figure 16 respectively. Sonnet simulation subsections are shown in Figure 17.

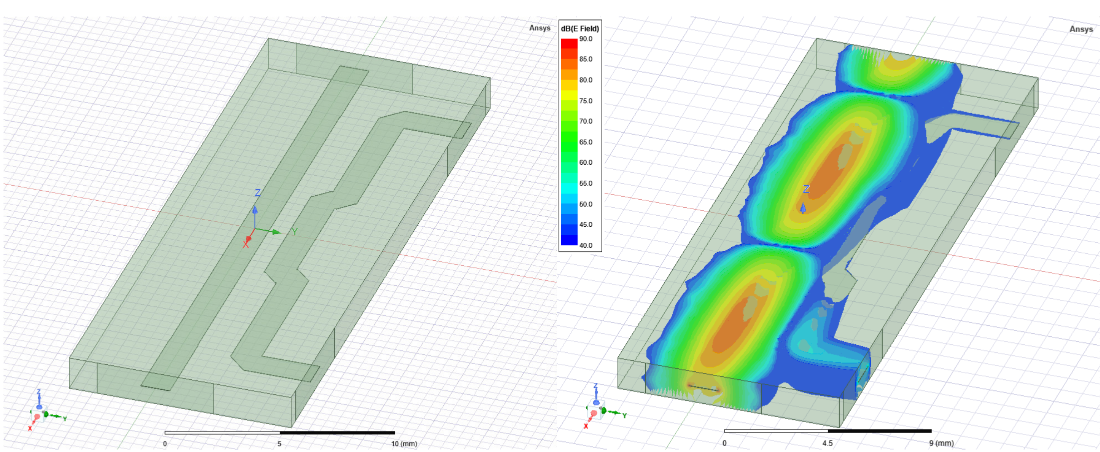

Figure 15. Copper / PTFE-composite Band 2 Directional Coupler HFSS Model and E-field plot

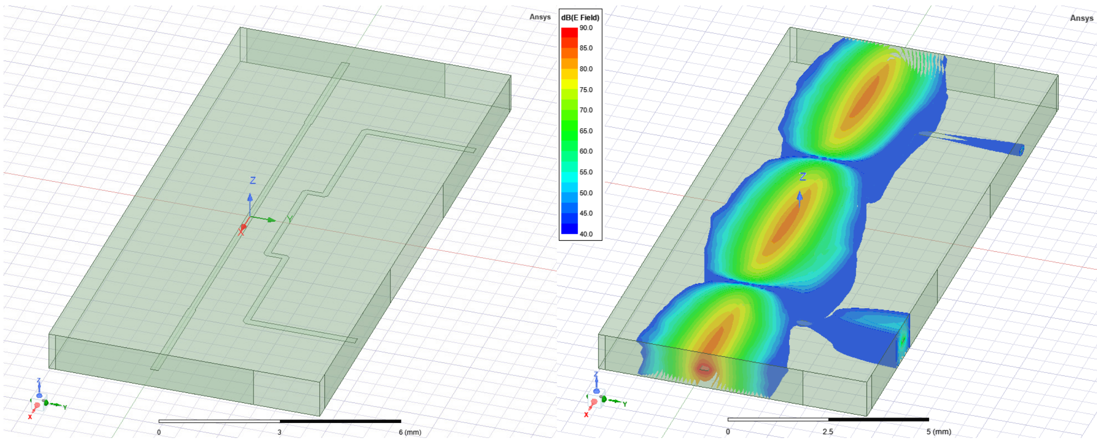

Figure 16. YBCO / MgO Band 2 Directional Coupler HFSS Model and E-field plot

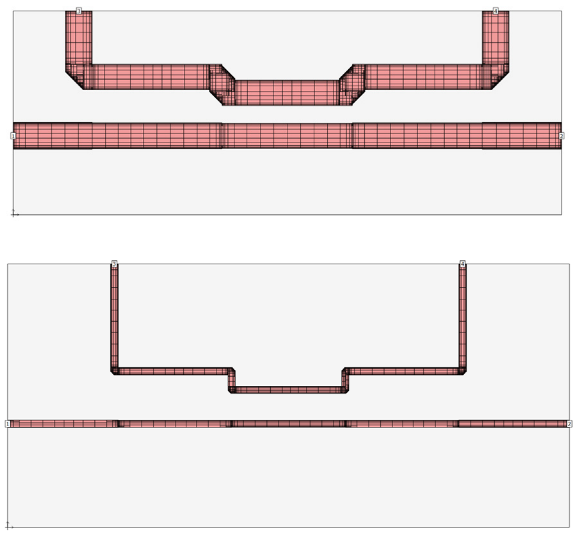

Figure 17. Sonnet subsections for Band 2 coupler simulations. Top) Conventional and Bottom) HTS

Figure 18 shows the simulated coupling factor comparison between the conventional and HTS models. The performance of the designs is comparable.

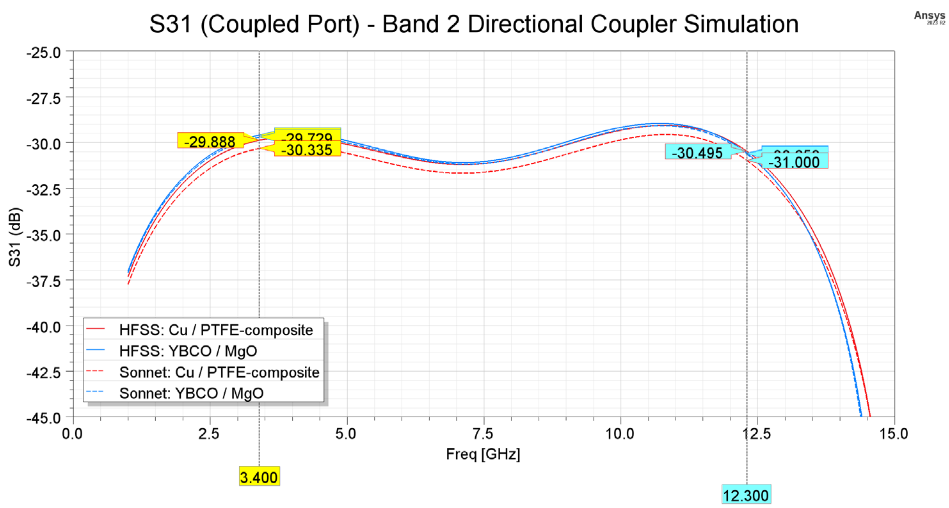

Figure 18. Simulated coupling factor for conventional and HTS directional couplers, Band 2

A comparison of the Thru transmissions (S21) is shown in Figure 19. Like the simulation for Band 1, the room temperature values and cryogenic values of copper conductivity and dielectric losses are each simulated for the conventional design.

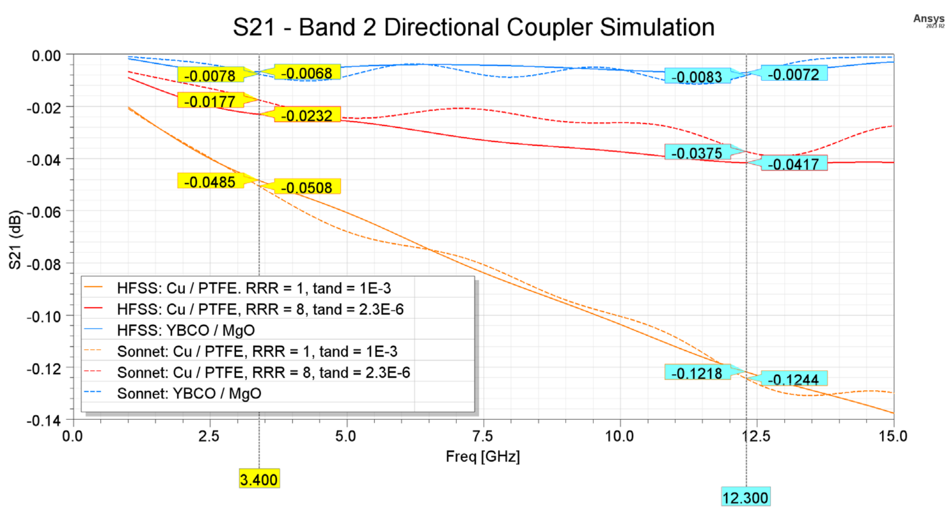

Figure 19. Simulated Thru transmission (S21) for conventional and HTS directional couplers, Band 2

At the higher Band 2 frequencies the trace loss is increased per unit length, but the traces are shorter. The overall net effect is that the loss of the Band 2 coupler is very similar to the Band 1 coupler. HTS can provide an improvement of about 0.03 - 0.04 dB at the upper edge of Band 2 at 12.3 GHz, if cryogenic properties are assumed for the conventional design.

While directivity was not discussed above due its limited impact on the trade between conventional and HTS designs, it was simulated. Good match between HFSS and Sonnet was observed for each design. In all Band 1 designs, >20dB was achieved, but for Band 2 just 13dB directivity was achieved (min). It was noted that in the Genesys synthesis tool, directivity can be specified as an input, but it does not change the synthesized design. Additional investigation into directivity improvement would be recommended for the Band 2 design.

5.4 Summary

The electrical performance of HTS vs. conventional striplines was explored in detail. If an HTS stripline coupler could be manufactured, assuming cryogenic coppers and dielectric losses improve as described in the references, the improvement for HTS relative to conventional couplers is about 0.04 dB. The improvement in the system noise temperature of the full receiver chain is expected to be roughly 1.2% for a 0.04 dB loss reduction. The simulated losses of these couplers are lower than the Krytar couplers presented in section 4, whose design details are not known. This is believed to be primarily due to the added SMA coaxial tab launch connectors that are used in the real Krytar couplers. Note that the use of even thicker substrate materials can further reduce losses somewhat, but do result in other tradeoffs, such as lower cutoff frequencies for higher order modes.

6 Packaging Considerations

The simulations assumed a perfectly realizable stripline. Additionally, the wave port excitations assume that the energy is coupled at the input and output ports with no losses. These packaging considerations are explored in this section.

6.1 Stripline Fabrication

Simulations assumed that an HTS stripline could be readily fabricated somewhat similarly to the conventional devices, but this is not true. The hard substrates, like MgO, used in YBCO fabrication are brittle and fragile. Building a stripline with these substrates is very uncommon due to the potential for cracking. In contrast, commercial couplers use soft PTFE substrates, where the air gap between the top and bottom substrates is eliminated using brute force compression. The resulting deformation of the dielectric around the connector launcher tabs seems to have little effect on performance. HTS is typically fabricated in microstrip, which has its own set of challenges in regard to building a broadband directional coupler with good directivity. Suspended stripline was also explored for HTS, but it was found that it has similar issues in directivity as microstrip. In addition, the cutoff frequencies of its higher-order modes can be very low since the dielectric constant of MgO is high.

6.2 Coaxial Connectors

The simulated thru loss for the coupler designs was much lower than the measured Krytar devices. One of the major contributors to this extra loss is the use of the coaxial connectors on the input and output of the device.

The source of the connector insertion loss is a combination of conductive losses, dielectric losses, contact resistance, and radiative losses. Conductive losses can be significant due to the plating typically used in these connectors which often consist of very thin gold (~4 microinches) on a thicker high-phosphorous nickel underlayer with low electrical conductivity. Some portion of the RF currents will flow on the nickel and experience higher conductive losses.

Insertion loss of connectors is often unspecified. The Krytar couplers use high quality SMA connectors which do have an insertion loss specification [16] equal to

$$Insertion\ Loss\ (dB) = \ 0.03 * \sqrt{frequency(GHz)}$$

At the upper end of Band 2, this is 0.105 dB per connector, or 0.21 dB for the pair of input and output connectors. When this connector loss over frequency is subtracted from the stripline transmission (S21) simulation results shown in Figure 14 and Figure 19 for Band 1 and 2 respectively, there is a very good match to the Krytar Thru transmission (S21) measurements. A comparison between the measured Krytar couplers and the "connectorized" simulation models are shown in Figure 20 and Figure 21 for Band 1 and 2, respectively. While the internal Krytar coupler design details are unknown, this result seems to indicate that the modeling done may represent the Krytar devices fairly well.

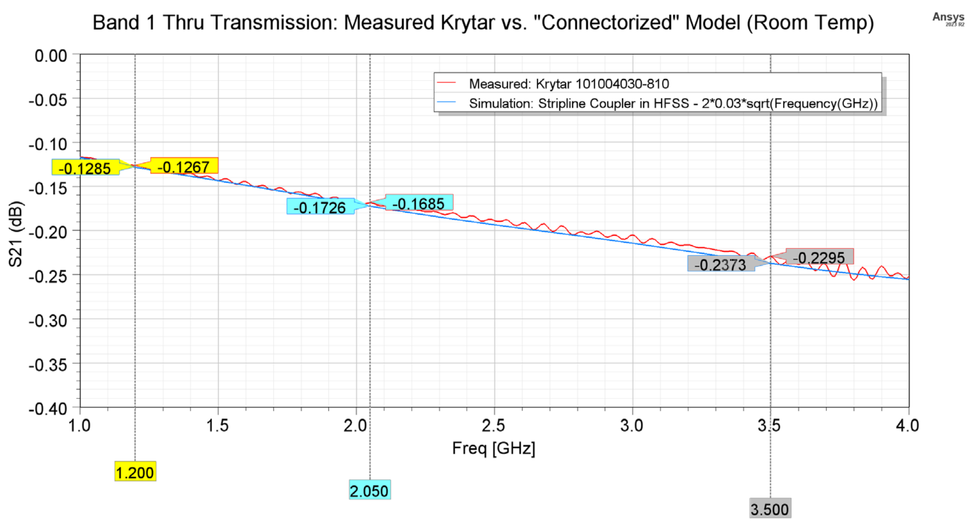

Figure 20. Thru Path Comparison of "Connectorized" Model to Measured Krytar 101004030-810 at Room Temperature

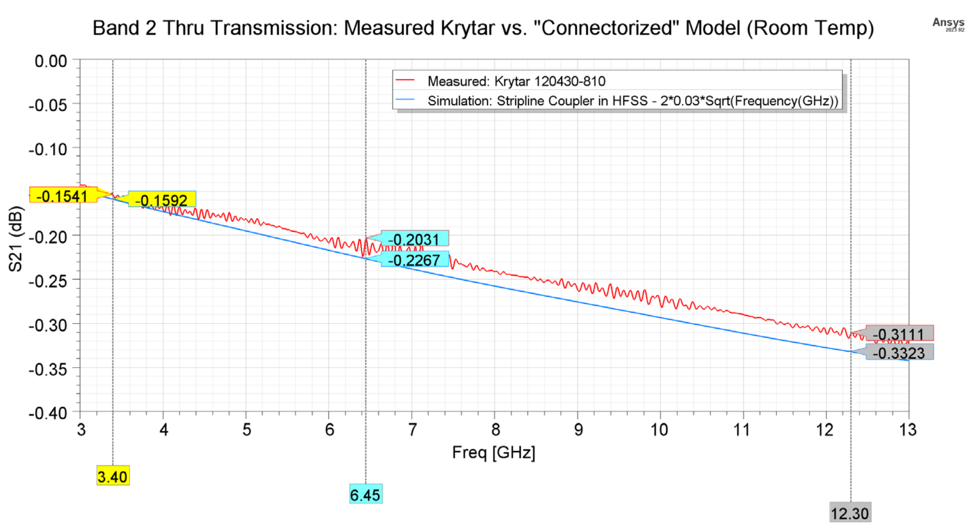

Figure 21. Thru Path Comparison of "Connectorized" Model to Measured Krytar 120430-810 at Room Temperature

Connector losses at cryogenic temperatures are not available from the manufacturer. No attempt was made to independently measure these losses, but they are expected to improve at cryogenic temperatures due to better electrical conductivities and lower dielectric losses. To fit the measured cryogenic Krytar data, a connector loss factor of 0.013*sqrt(freq(GHz)) is subtracted for a pair of connectors from the HFSS Thru transmission (S21) simulation to create a "connectorized" model. The comparison of the model to measured is shown in Figure 22 and Figure 23 for Band 1 and 2, respectively.

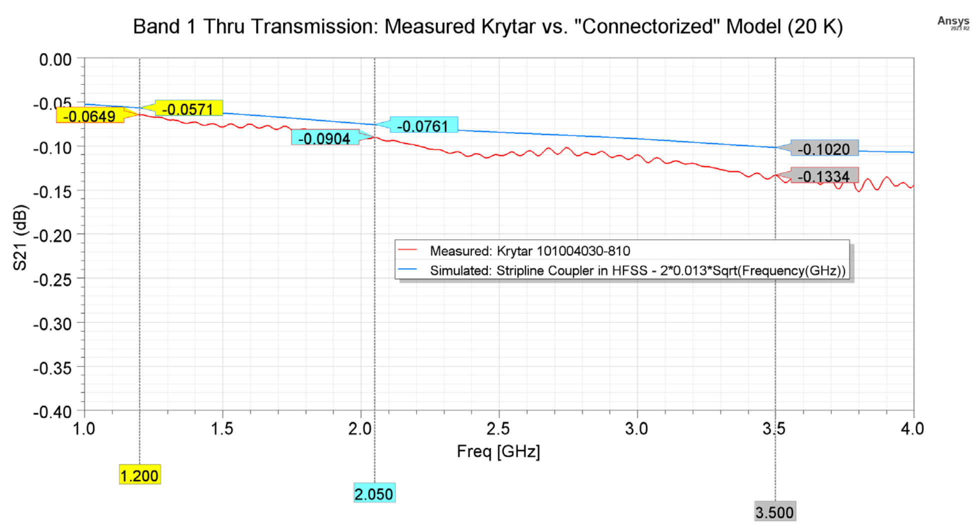

Figure 22. Thru Path Comparison of "Connectorized" Model to Measured Krytar 101004030-810 at 20 K

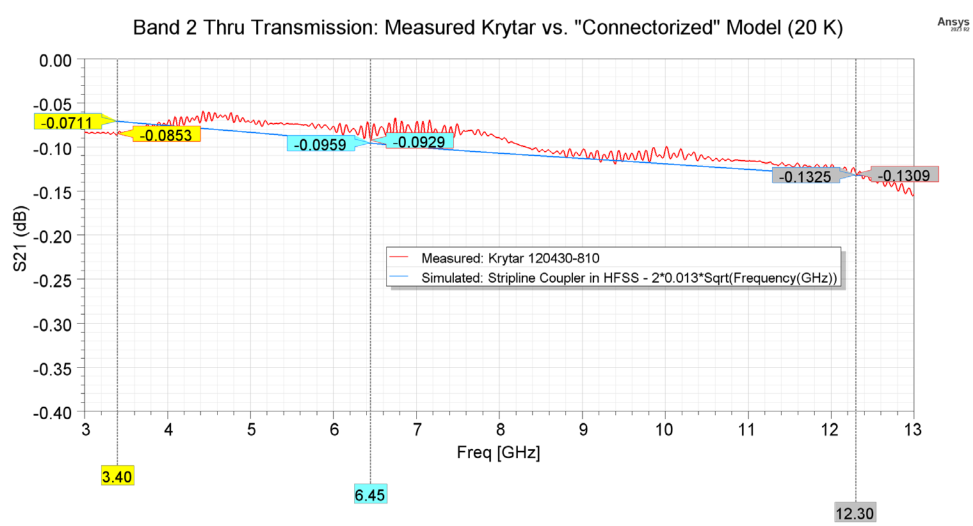

Figure 23. Thru Path Comparison of "Connectorized" Model to Measured Krytar 120430-810 at 20 K

6.3 Wirebonding and Soldering

Unlike conventional couplers, a YBCO film cannot be soldered directly with a coaxial launch tab due to the sensitivity of YBCO to heat. Wirebonds must be used for interconnection, with gold bonding pads patterned on the YBCO.

6.4 Mechanical packaging

The mechanical carrier for the HTS/MgO device must be carefully chosen. Specific materials for the mechanical block, with a coefficient of thermal expansion (CTE) closely matching the HTS MgO substrate are the most suitable to avoid cracking or breaking the device upon cooling. Usually HTS devices are assembled on a plated titanium carrier as the titanium thermal expansion coefficient is similar to that of MgO. The titanium plating (typically done with a thin gold layer) improves the electrical conductivity and allows good soldering of the coaxial connectors. For example, packaging of the MgO device with mechanical carriers made out of aluminum, copper, or brass, with linear thermal contraction from 293 K to 20 K of 41.4, 32.6 and 38.3 × 10^{-4}, respectively, is not suitable as the substrate might break (depending on how the substrate is glued to the mechanical carrier). In comparison, Titanium has a 293-20 K linear thermal contraction of only 15.1 × 10^{-4}, i.e. approximately 2.75 times lower than aluminum, and much closer to the one of MgO.

7 Cost, Reliability, and Maintenance

Cost, reliability, and maintenance are very important considerations for choosing a technology to implement in the ngVLA front-end receivers, given the large number of antennas and receivers spread over a wide geographic region.

1) *Cost*. Rough cost estimates for 2" and 4" wafer production in the USA for high-quality YBCO+MgO printed substrates were provided by a highly-regarded domestic source [17]. A summary of these approximate costs per unit is shown in Table 6. While the wafer costs are quite reasonable, HTS stripline device packaging is not currently technologically advanced, leading to a large increase in cost. A packaged HTS device cost is expected to be $1000 - $2000 each in production (S. Berkowitz, personal communication, 03 August 2022), compared to $425 for a conventional copper coupler [18]. The conventional option is readily available at a fraction of the cost of the custom HTS device.

2) *Reliability*. YBCO is sensitive to heat and humidity. The superconductivity of the film can be destroyed by soldering or by extended exposure to high humidity or frost. This is a concern for a ngVLA cryostat that could experience a rapid vacuum loss while cold, due to a vacuum breach.

3) *Testing and Maintenance*. The superconductors only have good conductivity when operated below the critical temperature. This implies that most production testing and troubleshooting would require cooling to below the critical temperature at the device or receiver level. Specifically, it would not be possible to test the ngVLA receivers at room temperature (for troubleshooting purposes) if these were equipped with HTS couplers. Such a limitation would not exist if the receivers were equipped with conventional copper couplers.

Table 6. HTS substrate fabrication costs, 3-section directional coupler, for Bands 1 & 2

	Band 1		Band 2		Notes
Minimum # of devices needed:	**631**				[1]
Device dimensions (width x length):	**4x37mm**		**2.5x10mm**		
Wafer diameter (in.)	**2**	**4**	**4**	**2**	[2]
Number of wafers processed per run:	**12**	**3**	**12**	**3**	[2]
Number of couplers fitting on the wafer:	10	46	60	270	
Minimum # of single-sided wafers needed:	64	14	11	3	[3]
Minimum # of wafer processing runs req'd:	6	5	1	1	
Actual # of wafers to process (filled):	72	15	12	3	
Maximum # of devices available, all wafers:	720	690	720	810	
Minimum production yield required:	88%	91%	88%	78%	
Patterning cost, per wafer:	$408	$2,500	$408	$2,500	[4]
Processing run cost, per batch:	$1,634	$1,634	$1,634	$1,634	[5]
Bare wafer cost, each:	$60	$250	$60	$250	[6]
Photomask charge, per order:	$2,000	$2,000	$2,000	$2,000	[7]
Total processing & material costs, less dicing and packaging:	**$59,624**	**$63,340**	**$11,604**	**$14,268**	**[8]**
Fabrication cost per device:	**$94.46**	**$100.35**	**$18.38**	**$22.60**	

Notes:

[1] - Includes 20% added spares.
[2] - Wafer diameters and associated batch process capacities are from the vendor.
[3] - Does not include top substrate.
[4] - Vendor estimate; assume applies to only circuit side.
[5] - Vendor estimate, single-sided YBCO/Au.
[6] - Vendor estimate.
[7] - Vendor estimate, depends on wafer size and minimum feature size.
[8] - Includes top & bottom substrates; patterned only on top, bottom w/ground plane only; wafer processing on both.

8 Conclusions

HTS was explored as a possible technology for use in the directional couplers on Bands 1 and 2. Although the YBCO films themselves have very low surface resistance, it was determined through simulation that this technology offers no more than 0.1 dB improvement in insertion loss compared to copper, and the true benefit is roughly on the order of less than 0.04 dB. The improvement in T_{sys} of the full receiver chain is expected to be 1.2% for 0.04 dB loss reduction.

An HTS stripline device is currently not readily fabricated and there is a high level of associated technical risk, due to the development required. HTS results in more expensive devices that require cooled receivers for testing. HTS has some challenges in regards to reliability since the YBCO film is sensitive to heat and moisture and the substrates are brittle.

9 Acknowledgements

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