The Integration of LNA Based Receivers for Millimeter and Sub-millimeter Wavelength Radio Astronomy

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***Abstract*— Due to improvements in pHEMT technology it is now possible to realize Low Noise Amplifiers (LNAs) at millimeter and sub-millimeter wavelengths. This permits the design and manufacture of cryogenic, LNA-based, sideband separating heterodyne receivers for radioastronomy at frequencies above 100 GHz. There are, however, a variety of design challenges to overcome to enable multi-pixel array receiver topologies. We present the lessons learnt from the recently completed, sixteen-pixel, W-band (70 - 116 GHz) CARUSO receiver and show how we are further miniaturizing these components as we work towards a future integrated receiver technology.**

***Keywords*— Millimeter-wave, submillimeter-wave, radio astronomy, Atacama Large Millimeter submillimeter Array, Low Noise Amplifier, Subharmonic Image Rejection Mixer, Integration.**

I. Introduction

RECENT developments in sub-100 nm gate length Indium Phosphide (InP) pseudomorphic High Electron Mobility Transistor (pHEMT) technology has pushed the boundaries of Low Noise Amplifiers (LNAs) to operating frequencies approaching the terahertz region [1][2][3]. These developments permit the design and fabrication of LNA based heterodyne receivers for the millimeter and sub-millimeter wavelength frequency bands.

Typically, millimeter and sub-millimeter radio telescope receivers are constructed from individual waveguide components that are packaged in separate mechanical housings, as is the case for the European Southern Observatory's (ESO's) recent state-of-the-art receiver for the Atacama Large Millimetre/sub-millimeter Array (ALMA) Band 2 frequency range (67 – 116 GHz) [4]. This allows each of the receiver components to be developed by specialist groups and suppliers, and also allows the best performing / best matched components to be selected for each receiver. However, this discrete component approach does not result in the most space efficient receiver format. For instance, each of the sub-components needs to contain all of the associated circuity within its housing and to have predefined mechanical interfaces. Whilst this discrete approach is viable at lower frequencies, for prototyping, or for a single receiver 'pixel', as operating frequencies increase and complex multi-pixel receiver topologies, such as focal plane arrays (FPA) and phased array feeds (PAF), are required for enhanced observation speed, a more space efficient and integrated approach to receiver design is needed.

The Millimetre-wave Technology Group and the Technology Department, both at the STFC Rutherford Appleton Laboratory, and the University of Manchester Advanced Radio Instrumentation Group (ARIG) have recently completed the sixteen-pixel, 70 – 116 GHz, Cryogenic Array Receiver for Users of the Sardinia Observatory (CARUSO) [5][6].

The sixteen receiving elements of CARUSO are located within the focal plane of the Sardinian 64 m diameter Gregorian telescope. To meet necessary spatial sampling requirements, individual pixel feedhorns that form the array are positioned in close proximity to each other. The randomly polarized signal entering a feedhorn is then divided by an orthomode transducer (OMT) into two linear components of polarization. Each polarization signal is then amplified by two cascaded millimeter-wave LNAs [1] and frequency down-converted by a Subharmonic Image Rejection Mixer (SHIRM) [5][7]. A single receiver dual polarization pixel chain therefore comprises a feedhorn, OMT, four LNAs and two SHIRMs with four intermediate frequency outputs corresponding to upper and lower sidebands for each polarization component. Furthermore, local oscillator power is delivered to each SHIRM via coaxial cables and all 16 pixels are enclosed within a cryogenic system that allows low temperature operation to approximately < 20 K.

Due to a highly demanding development timescale, using individual and previously proven, millimeter-wave component technology greatly lessened the project risk. However, close pixel spacing and telescope quasi-optical interface requirements imposed a volume constraint on the receiver architecture. For instance, each pixel was required to fit within the footprint of the feedhorn with a diameter of 25 mm and a feedhorn center-to-center separation of 31 mm. Moreover, all feedhorn entrance apertures needed to be positioned in close proximity to the cryostat's millimeter-wave signal input window. Complying with these dimensional constraints therefore required bespoke packaging design and miniaturization, but with compactness limited by the need to adopt a standard waveguide flange (WR10) interface format for the majority of the discrete components. Overall integration of

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the receiver pixel chain was therefore limited by the use of separate components. Nevertheless, the approach established a first step towards a future more closely integrated approach and based on the success of the CARUSO receiver, we are now exploring methods of realizing new fully integrated millimeter-wave receivers.

Our new development is working Towards ALMA System-on-chip European Receivers (TASER) and is supported by ESO and additionally through the Horizon Europe RADIOBLOCKS project. A key objective is the creation of a highly integrated hybrid receiver configuration that unifies LNA and SHIRM devices within a single integrated waveguide block. This work will utilize the proven LNA and SHIRM technologies developed for CARUSO, with a view to future translation of the developed technologies to higher frequencies. The performance of the CARUSO LNA and SHIRM components will be used in this study as a baseline for assessing and quantifying the performance of the integrated LNA+SHIRM devices. In this paper we will present and analyze several alternative routes towards achieving this goal that can be used as a basis for future highly integrated receiver components.

II. LNA AND SHIRM TECHNOLOGIES

The LNAs used for this work are based on those developed in the ARIG for ESO's ALMA Band 2 project [1][4]. The LNAs each incorporate 2-stage MMICs fabricated using the Northrup Grumman 35 nm gate length InP HEMT process [3]. The gate and drain of both transistor stages on the MMICs can be independently biased. The input and output ports of the miniaturized LNA package use a modified version of the standard UG-387/m waveguide flange with two of the screw holes removed. The LNAs use WR10 waveguide and custom waveguide-to-microstrip transitions are used to couple waveguide signals to and from the MMIC.

The SHIRM [5][7] comprises a pair of InGaAs Schottky barrier diode subharmonic mixers, bespoke signal splitting and recombination circuitry, and necessary signal, LO, and IF connections. All components and structures that form a SHIRM unit are integrated within a single mechanical package, providing a very compact solution. The RF signal is divided with a 90-degree phase difference between the two mixers, while the LO power is coupled with a 90-degree phase difference to the subharmonic mixers. The IF outputs are combined in an IF quadrature hybrid, at whose output ports the downconverter upper and lower sideband signals appear separately.

III. LNA+SHIRM INTEGRATION

The intention is to develop an integrated LNA+SHIRM using the well proven LNA and SHIRM technologies that have been previous demonstrated during the CARUSO project. This LNA+SHIRM will serve as both a building block for highly integrated receiver technologies in the 67 – 116 GHz frequency band, as well as a steppingstone to translate this integrated technology to higher frequencies in the future.

One potential use for such integrated receiver technologies would be in future upgrades of the receivers in the ALMA observatory, in particular there is desire to upgrade and combine the Band 4 and 5 frequency ranges (125 – 211 GHz) into a single receiver. Recently the ALMA wideband sensitivity upgrade [8] has been published and future receiver upgrades would be expected to be compatible with these specifications. In particular there is a requirement for 16 GHz of IF bandwidth for each sideband of the receiver, typically this would cover a frequency band of 2 – 18 GHz or 4 – 20 GHz. The CAURSO SHIRM currently has an IF bandwidth of 4 – 12 GHz, which is limited by the on-chip IF hybrid coupler, and as such an upgrade of this component would be necessary to make the integrated LNA+SHIRM compatible with the ALMA WSU specifications.

The RF and LO hybrids in the SHIRM are currently implemented using waveguides and are wavelength dependent structures, so the physical size of the coupler is significantly larger for the LO than for the RF. Switching the LO waveguide hybrid to an on-chip hybrid delivers a major benefit because it will greatly reduce the overall length of the integrated LNA+SHIRM and will therefore be a key focus for our projects. Inserting a 40 – 60 GHz LO hybrid is in some ways more straightforward than the RF equivalent, as frequencies and fractional bandwidth are lower and loss requirements less demanding. However, when considering SHIRMs for higher frequencies a higher frequency LO will be required, consequentially reducing the size of a waveguide hybrid and the miniaturization benefit of using an on-chip coupler. As the choice of LO hybrid implementation is independent of choice for the RF hybrid, all three of the integration options studied later in this paper can utilize a waveguide structure or an on-chip component for the LO hybrid.

The choice of waveguide or on-chip implementation for the RF hybrid is complicated by the higher frequency and also by the integration of the LNA with the SHIRM. We will present in this paper on the three integration options that have been studied for the RF, section of the LNA+SHIRM, these are:

1. Waveguide RF Hybrid: Maintain the LNA followed by the RF waveguide hybrid coupler: Fig. 1a.
2. On-chip RF Hybrid: Maintain the LNA and follow it with an on-chip RF hybrid coupler in place of the waveguide structure: Fig. 1b.
3. Balanced Approach: Insert the LNA MMICs inside the SHIRM structure in the RF paths of the Schottky diode mixers: Fig. 1c.

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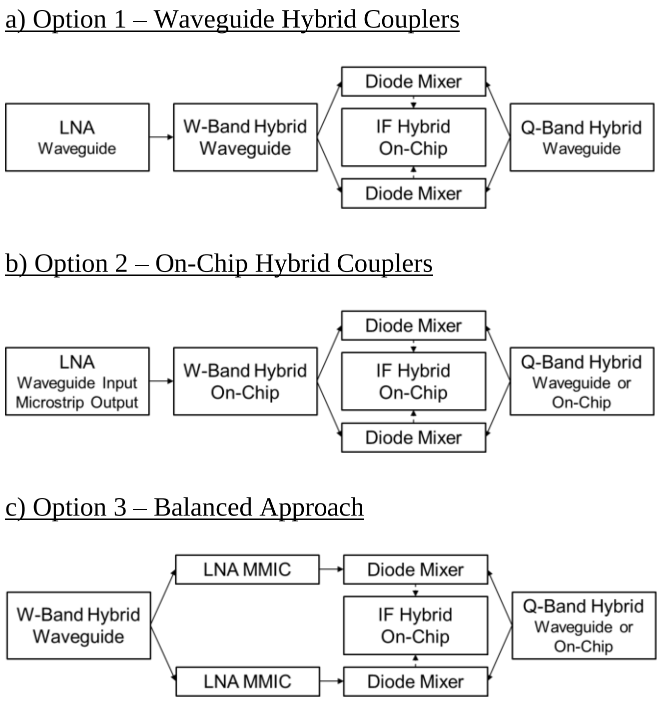

Fig. 1. Block diagrams of the three integration options for an LNA+SHIRM that are being studied.

Each of these options will be described in more detail through the rest of this paper:

Option 1 – RF Waveguide Hybrid Coupler

The first of the integration options will make minimal changes to the existing component designs. All of the components in the LNA and SHIRM offer very high performance and have been extensively modelled in the HFSS 3D EM simulator as well as manufactured in larger numbers as part of the CARUSO project. This includes the RF waveguide hybrid structure which offers excellent low loss performance with good amplitude and phase balance.

The integration of the LNA and SHIRM into a single block allows for the removal of the intervening waveguide flange interface, the space required in the block for two sets of screw and dowel pin holes, and the short length (11.4 mm) of waveguide between the output of the LNA and the input of the hybrid coupler that had been necessary to accommodate these. The overall length of this integrated LNA+SHIRM design is 72.8 mm. The CAD model of this LNA+SHIRM integration utilizing waveguide hybrids for both the RF and LO is shown in Fig. 2.

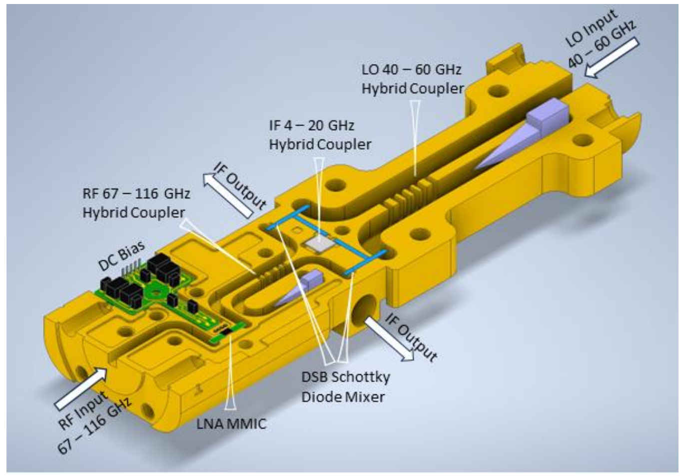

Fig. 2. CAD model of the LNA+SHIRM integration using the first integration option described in this paper, with the RF and LO hybrid couplers implanted with waveguide structures. The overall length of the LNA+SHIRM is 72.8mm.

Option 2 – RF On-Chip Hybrid Coupler

The RF waveguide hybrid structure discussed above has a fixed size and shape that limits further miniaturization. Using a waveguide structure also requires a transition from microstrip to waveguide between the output of the LNA and the input of the RF hybrid and then another opposite direction transition at the outputs of the hybrid. Each transition introduces unwanted losses and reflections. The use of a waveguide structure also limits future possibilities for further on-chip integration. It is therefore desirable to investigate other integration techniques that could offer potential further miniaturization and integrations of the LNA+SHIRM.

The second integration option will investigate the potential for using an on-chip RF hybrid coupler. The performance of the on-chip hybrid will be critical to the success of this integration, especially over the wide bandwidth involved.

Option 3 – Balanced Amplifier Approach

The third integration option will take a more holistic approach to the integration of the LNA and SHIRM components. With individually packaged LNA and SHIRM components there is no choice but to have the LNA before the entire SHIRM structure. An integrated design approach allows for the adjustment of the topology of the entire LNA+SHIRM structure to reach the ultimate goals. A pair of LNA MMICs can be inserted after the RF hybrid and in-front of the Schottky diodes within the SHIRM structure. The benefits of this approach will be the introduction of a balanced amplifier structure into the design, potentially offering improvements in the reflection coefficient of the RF input of the LNA+SHIRM. This location of the LNA and mixer also opens up potential for future on-chip integration of these components, that may be

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attractive when translating this LNA+SHIRM technology to higher frequencies.

Although, this study of LNA+SHIRM integration is currently only considering a single LNA gain stage in the design, for a full receiver it is likely that two stages of LNAs will be needed to provide sufficient gain to minimize the noise performance of the receiver. Typically, an isolator would be required between LNA gain stages to prevent gain ripples. However, with the improvements in input reflection coefficient of the LNA+SHIRM offered by the balanced amplifier structure, the isolator may no longer be necessary. The inclusion of an external RF LNA in front of the LNA+SHIRM would also reduce the effect of the RF hybrid losses on the overall system noise, allowing the hybrid to be implemented in either a waveguide structure or on-chip component. This choice of hybrid implementation is essentially the same consideration that is being studied for integration options 1 and 2 described earlier in the paper; the waveguide structure would offer the best performance, but the on-chip component would offer better miniaturization and further integration options. This consideration will be dependent on the RF frequency of the LNA+SHIRM: as the frequency increases the size of the waveguide hybrid will reduce and the difficulty of implementing an on-chip hybrid with acceptable performance will increase.

The main disadvantage of this approach is that twice the number of LNA MMICs are required. At a system level this will have both technical and cost implications, especially for focal plane array systems where multiple individual receiver pixels (and therefore multiple LNA+SHIRM components) are being used. It is typical that all of the transistor stages in the LNAs are biased independently in order to have the most control over the gain and noise performance. However, in receivers with large numbers of LNAs and receiver pixels, this strategy will lead to a very large number of bias cables that need to be assembled in the cryostat and to pass through its vacuum case, increasing the complexity of the system. The increase in the number of MMICs will also result in a corresponding increase in the power, and therefore heat dissipation from the LNAs in the cryostat, something that will be exacerbated as the number of pixels is increased for larger FPA or PAF receivers. Another drawback is that a second MMIC bias circuit must be contained within the LNA+SHIRM, which will require careful design to keep the size of the integrated LNA+SHIRM block within the acceptable envelope for FPA and PAF receivers. However, for the most part, these challenges are well understood or can be quantified during the design of the components and receiver pixel(s). For example, the cost of the required MMICs and heat dissipation can be factored into the design of a receiver, and steps can be taken to bias multiple LNA stages from a single set of bias lines, reducing the number of cables required in the cryostat and also the size of the bias PCBs required for the MMICs.

The remaining unknown to this integration approach is whether the inclusion of the LNA MMICs within the SHIRM structure would adversely affect its operation. Specifically, it will be important to understand how the gain and phase difference introduced by the MMICs varies between units of the same design. If the difference between the two MMICs is too great, then this may disrupt the balance of the SHIRM and reduce the performance, affecting the sideband separation rejection ratio and causing an imbalance between the upper and lower sideband outputs. It may therefore be necessary to perform on-wafer pre-screening phase and gain measurements of the MMICs and to select suitable pairs for the LNA+SHIRM.

Summary of RF Hybrid Integration Options

A summary of the three integration options for an LNA+SHIRM are presented in Table 1, which lists a selection of the important design and performance considerations. These considerations are highlighted for each option depending on if they are a positive, negative, or need more investigation during our current projects.

The first integration, using an RF waveguide hybrid structure, requires the least changes to the pre-existing LNA and SHIRM designs, but also offers the least benefits of integrating the components (due to the waveguide coupler) and also the least potential for future developments towards on-chip integration.

The second integration option, replacing the RF waveguide hybrid coupler with an on-chip component, offers more potential benefits from the integration of LNA and SHIRM, and also offers a clear path towards future integration of multiple components onto the same chip. However, the performance of the RF on-chip hybrid coupler needs to be investigated in order to better understand the potential performance trade off that would need to be made in order to allow for this integration.

The third integration option, adopting a balanced approach and placing an LNA MMIC with each of the diode mixers within the SHIRM structure, offers some attractive upsides such as the potential for on-chip integration of LNA MMIC and mixer, and introducing the balanced amplifier topology to the LNA+SHIRM that should provide very good input reflection coefficient on the RF port. The implementation of the RF hybrid coupler in this option will take into account the findings of the first two integration options of this study. A waveguide hybrid will offer the best performance but will be limit the miniaturization potential, however this will be less of a factor at higher frequencies as the size of the hybrid is reduced. An on-chip hybrid will reduce the size of the LNA+SHIRM integration and offer the possibility for future on-chip

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integration, however the performance trade off to enable this may become prohibitive at higher frequencies.

TABLE I. SUMMARY OF THE INTEGRATION OPTIONS

	#1	#2	#3
RF Hybrid	Waveguide	On-Chip^	Waveguide or On-Chip^
LNA MMIC	One MMIC	One MMIC	Two MMICs*
Bias PCB	No Issue	No Issue	Space Constraints&
MMIC Phase	No Issue	No Issue	Phase Difference#
Integration	Least Integration	More Integration	More Integration
Future On-chip Integration	No	Yes	Yes

Positive | Needs Investigation | Negative

^ Performance of on-chip RF hybrids will need to be investigated
* Two MMICs would lead to twice the power dissipation, twice the number of bias PCBs, connectors and cables
& Careful design will be needed to fit the bias PCB for the second MMIC in the layout
# Concern if possible phase and gain differences between MMICs could affect SHIRM performance.

IV. CONCLUSIONS

This paper has presented the outcomes of our initial study on the integration of the LNA and SHIRM components of a cryogenic millimeter-wave receiver for radioastronomy. Currently the RF and LO hybrid couplers of the SHIRM are implemented as waveguide structures, however changing these to on-chip hybrid components will offer miniaturization and integration benefits but the performance trade offs need to be assessed. Three different options for the integration of the LNA MMIC with the RF section of the SHIRM have been presented, each of which offer different benefits and have been assessed with a view towards future highly integrated millimeter and sub-millimeter wave receiver instrumentation. More work will now be carried out to assess the performance tradeoff between using a waveguide or on-chip hybrid components at the RF and LO sections of the SHIRM, and whether the inclusion of the LNA MMICs within the SHIRM topology will affect the down conversion performance.

ACKNOWLEDGEMENTS

The authors of this paper would like to thank Gie Han Tan, Carlos de Breuck, and Tony Mroczkowski from ESO for useful discussions as part of the TASER project. They would also like to acknowledge the contributions of Nart Daghestani, David Cuadrado-Calle and Claudio Jarufe to the design and development of the LNAs and the components for CARUSO.

This work has been carried out as part of the TASER: *Towards ALMA System-on-a-chip European Receivers* project, which is funded by the ESO European ALMA Development Fund; and also as a part of the RADIOBLOCKS project, which has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No 101093934.

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