Electronically Tuned Local Oscillators for the NOEMA Interferometer

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Abstract— **We present an overview of the electronically tuned Local Oscillator (LO) system developed at IRAM for the Superconductor-Insulator-Superconductor (SIS) receivers of the NOrthern Extended Millimeter Array interferometer (NOEMA). We have modified and extended the LO designs developed by the National Radio Astronomy Observatory (NRAO) for the Atacama Large Millimeter Array (ALMA) project to the four NOEMA LO frequency ranges 82-108.3 GHz (Band 1), 138.6-171.3 GHz (Band 2), 207.7-264.4 GHz (Band 3), 283-365 GHz (Band 4). The NOEMA LO system employs commercially available MMICs and GaAs millimeter MMICs from NRAO which are micro-assembled into Active Multiplied Chain (AMC) and Power Amplifier (PA) modules.**

We discuss the problem of LO spurious harmonics and LO signal directly multiplied by the SIS mixers which add extra noise and result into detection of unwanted spectral lines. A waveguide filter is used in the LO path to suppress the higher order harmonics of the LO at the output of the final frequency multiplier, thus mitigating the undesired effect and improving the system noise temperature.

I. INTRODUCTION

For many years, the wide-band millimetre-wave heterodyne SIS receivers installed on the six 15-m diameter antennas of the IRAM Plateau de Bure interferometer have employed local oscillator systems based on commercial solid-state Gunn oscillator [1] cascaded with frequency multipliers [2]. The Gunn oscillator systems have proved to perform reliably on-site. However, the tuning of the oscillators by two motorized mechanical backshorts was time consuming and not perfectly reproducible. Thus, with the advent of NOEMA, we have decided to replace the Gunn LO systems with new electronically tuned LO systems. The NOEMA project aims at upgrading the PdBI interferometer from six to 12 antennas equipped with new dual-polarization quadri-band sideband separating (2SB) SIS receivers delivering four ~3.8-11.6 GHz IF bands. As part of this project we have extended, with some modifications, the LO design developed by NRAO [3] for the ALMA project to the four NOEMA frequency bands: the Band 4 (283-365 GHz) electronically tuned LO has been in use in the first six PdBI antennas since 2010, while a prototype of electronically tuned LO system for Band 1 (82-108.3 GHz) has been installed very recently in the new NOEMA antenna, Ant. #7. Following the successful development of the LO Band 1 prototype, a series of four Band 1 LO systems is currently being fabricated. The Gunn oscillators systems which have been in use on Bands 2&3 are going to be maintained on the seven antennas already available, while an electronically tuned LO prototype has been designed to cover simultaneously the NOEMA Bands 2&3 using a mm-wave switch associated with a doubler (Band 2) and a tripler (Band 3).

We present some of the design features of the NOEMA LO systems by pointing out their main differences with respect to the NRAO LO systems developed for ALMA. The performances in the different NOEMA LO bands will be discussed. Also, we will discuss our measurement results of the spurious harmonics content of the LO system and the adopted solution to reject such harmonics using a wide-band waveguide filter.

II. NOEMA LO SYSTEM

A synoptic diagram for the four bands of the future NOEMA LO system is shown in Fig. 1. Three independent commercial YIG oscillators (MLXS-1783, MLXS-1795 and MLOS-1604) [5] will be used: *a)* one covering 12.86-19.53 GHz for Band 1 (82-108 GHz); *b)* one covering 11-15

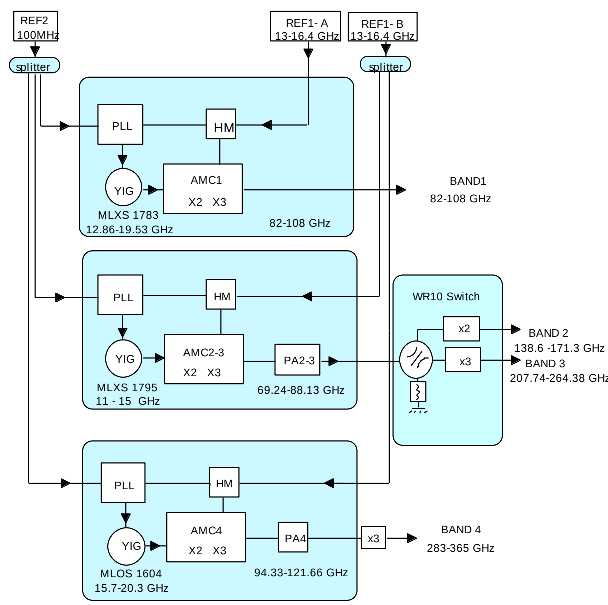

Fig.1 Synoptic diagram of future all electronic LO system for the NOEMA interferometer.

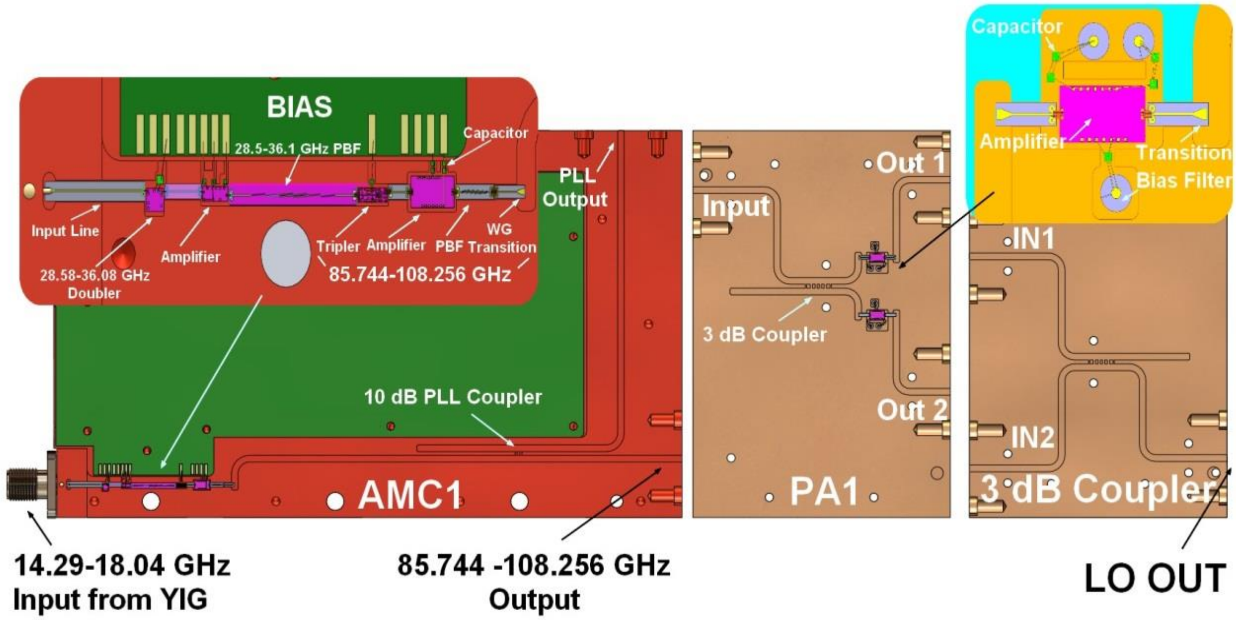

Fig. 2 Active Multiplier Chain (AMC), Power Amplifier (PA) and 3 dB coupler which are parts of the NOEMA Local Oscillator system. Design details of the multiplication chain microassembly of the AMC1, used in the NOEMA Band 1 LO, are shown on the inset on the top left. Details of the 3 mm band MMIC microassembly of the PA1, to be used in a future 3 mm multibeam receiver LO, is shown on the inset on the top right.

GHz for Band 2 (138.6-171.3 GHz) & Band 3 (207.74 264.38 GHz), which will share this common drive oscillator, and *c)* one covering 15-21 GHz for Band 4 (283-365 GHz). Single AMC and PA modules, named AMC2-3 and PA2-3, will also be used for both Band 2 and Band 3. The Band 1 LO will operate continuously by means of a dedicated YIG oscillator and a dedicated reference in order to always be available for calibration purposes. Two first PLL reference signals (REF1, 13-16.4 GHz) from two independent modules employing four output connectors are available in the system. One module provides the first reference for Band 1, while the second module provides the reference for Band 2&3 and for Band 4. The second PLL reference (REF2, 100 MHz) is distributed between all PLLs through a splitter. All LOs are locked with the REF2 signal using an harmonic mixer (HM) which is coupled with the AMC module and pumped by REF1. The 100 MHz IF from the HM is filtered and amplified before entering the 100 MHz PLL box. A CAN interface controls the YIG PLL as well as the AMC and PA bias allowing to change the magnitude of the LO power available at the LO system output. The output of the common Band 2 and Band 3 module is connected to a mechanical switch which diverts the LO signal to either a frequency doubler for Band 2 or a frequency tripler for Band 3. The non-switched positions of the switch are terminated by a waveguide load in order to absorb the LO power of the unselected band. The Band 1 LO employs only an AMC while the Band 2&3, and the Band 4 LO use an AMC followed by a PA and a 3dB recombination hybrid coupler.

III. LO DESIGN

The architecture of the AMC and PA MMIC micro-assembly is very similar for all four NOEMA bands and only the Band 1 modules are presented here. The Band 1 PA and 3 dB coupler find application in a LO system for a future 3 mm multibeam receiver but they are not used in the NOEMA Band 1 LO system.

A. AMC and PA

Here, we present the details of the AMC, the PA and the 3 dB coupler with base specifications which were taken for the initial LO Band 1 design (~85.7-108.2 GHz, see Fig. 2). Measurement results proved that the LO Band 1 system work very well and that even the more extended goal bandwidth, ~82-108.2 GHz, could be achieved (see Fig.1). In Fig. 2, the PA and the 3 dB coupler are presented in reverse orientation compared to the AMC to show the details of the MMICs packaging.

In the AMC1, the 14.29-18.04 GHz input signal coming from the YIG oscillator goes through a 28.58-36.08 GHz MMIC frequency doubler, an MMIC amplifier, a band pass filter, and a MMIC frequency tripler. At the tripler output, the 85.744-108.256 GHz signal is amplified by a medium power MMIC amplifier [4] and filtered by a pass-band filter. Then, the LO signal is coupled, through a waveguide-to-microstrip line transition, into a long WR10 waveguide that carries the signal at the output of the AMC. Inside the AMC module, a fraction of the mm-wave output signal is injected into -10 dB waveguide coupler and is sent to the PLL output, which is connected outside the AMC module to the PLL harmonic mixer.

The AMC waveguide output is connected to the waveguide input of the PA, inside which the main LO output signal is split in two arms by a 3 dB hybrid coupler. The signal in each arm is amplified by a medium power MMIC amplifier. The two PA waveguide outputs are then recombined by a second 3 dB hybrid coupler situated inside a different module. This hybrid arrangement optimizes the saturated power level and the output return loss.

B. Micro-assembly

1) *MMIC*: Table 1 summarizes, for each band, the types, names and frequency ranges of the MMICs which are integrated into the modules of AMCs and PAs. Table 2 shows, for each band, the name and the frequency ranges of the YIG oscillators.

TABLE I
MMIC PROPERTIES

MMIC name	f_{min} [GHz]	f_{max} [GHz]	NOEMA Band
Ampli EBPA 75	60	87	2, 3
Ampli EBPA 96B	81	110	1
Ampli EBPA107C	92	122	4
Tripler 110TRP1	90	124	1, 4
Tripler 81TRP1	70	92	2, 3
Doubler HMC 578	24	33	1, 2, 3
Doubler CHX2091	32	40	4
Ampli AMMC5040	23	40	1, 2, 3, 4

TABLE II
YIG PROPERTIES

YIG Name	f_{min} [GHz]	f_{max} [GHz]	NOEMA Band
MLXS1783	12.86	19.53	1
MLXS1795	11	15	2, 3
MLOS 1604	15	21	4

2) *Filter design*: The band-pass filters employed in the AMC modules (shown in Fig. 2), were designed with the commercial software ADS (Keysight Technologies). They consist of six pairs of microstrip coupled lines interfaced with coplanar lines at the filter input and output as shown in Fig. 3. The lines are deposited on 80 µm thick alumina substrate.

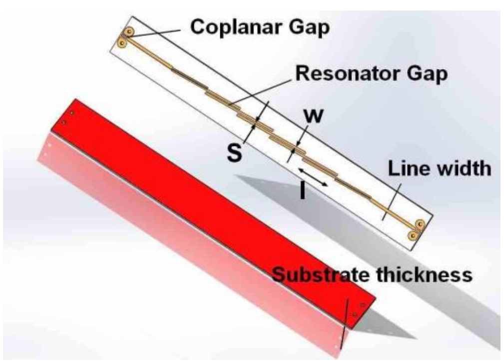

Fig. 3 A typical band-pass filter on alumina substrate showing the microstrip coupled lines and the nomenclature of the lines length (l), width (w) and gap (s). The filter backside (ground plane) is metallized.

3) *Coupler design*: The waveguide hybrid couplers (10 dB coupling, 90° phase difference) for the PLLs, which are part of the AMCs, consist of two $\lambda_g/4$ sections of branch-line waveguides. The waveguide hybrid couplers (3dB coupling, 90° phase difference) of the PAs and 3 dB recombination modules consist of six sections of $\lambda_g/4$ waveguide branch-lines with variable width, as shown in Fig. 4. The couplers were optimized using the commercial electromagnetic solvers ADS and CST Microwave Studio.

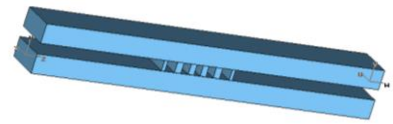

Fig. 4 Typical 3 dB-90° branch-line waveguide hybrid coupler with six $\lambda_g/4$ sections used in the mm-wave LO system. A waveguide load is integrated in the unused waveguide port.

IV. LO FABRICATION

A. LO rack

Fig. 5 shows the local oscillator rack we have built for the NOEMA LO Band 4. DC biasing of the inner LO rack modules is provided by a dedicated rack (not shown).

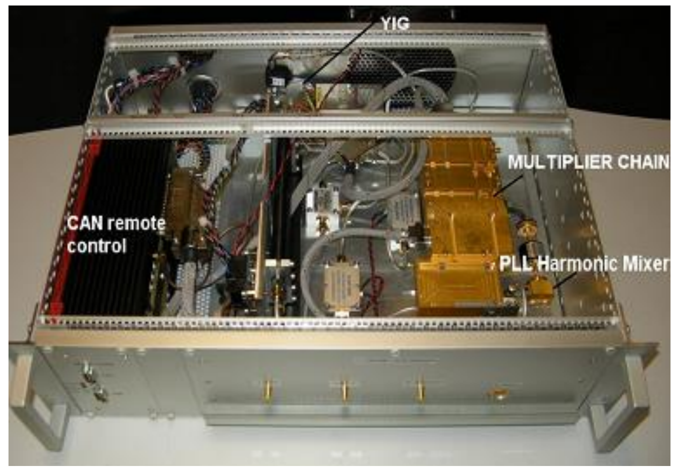

Fig. 5 The NOEMA Band 4 LO rack showing the CAN remote control interfaces, the YIG oscillator, the AMC, PA and 3 dB combination coupler, the PLL HM, the output WR8 waveguide flange as well as the three coaxial accesses for REF1, REF2 and IF monitor on the rack front panel.

B. LO micro-assembly

Fig. 6 shows a photo of the microassembly around the final 3 mm band MMIC amplifier located at the end of the LO Band 1 AMC chain.

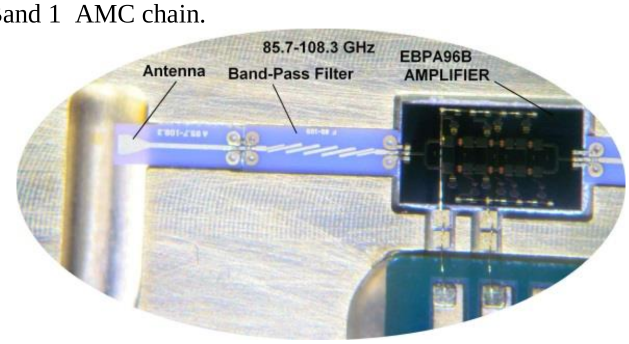

Fig. 6 Photo showing part of the LO Band 1 AMC chain microassembly with transition from WR10 waveguide to microstrip, the 85.7-108.3 GHz band pass filter, the EBPA96B amplifier, the signal coplanar ribbon and the bonding wires for biasing the MMIC.

V. LO MEASUREMENT RESULTS

A. Output Power

The curves on Fig.7 show the output powers measured at the output waveguide flange of the LO Band 1 rack equipped with AMC+PA+3 dB coupler, of order +17 dBm, and equipped with AMC only, of order +13 dBm. The output power largely exceeds the one necessary for optimum pumping of the 3 mm band NOEMA 2SB SIS receiver, thus requiring a 15 dB attenuator to be cascaded with the AMC chain in order to bring the LO Band 1 output power within a suitable range.

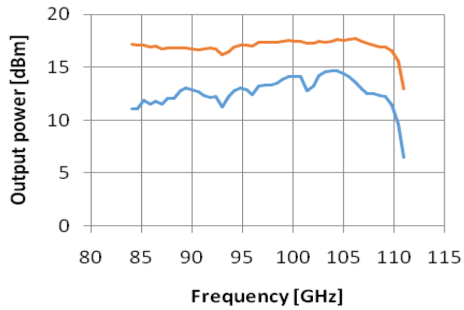

Fig. 7 Output power of the LO Band1 AMC chain (blue curve) and AMC+PA+3dB coupler (red curve).

VI. LO SPURIOUS HARMONICS AND FILTERING

The multiplied chain of the LO system use active and passive multipliers which, in addition to the main (wanted) LO tone, might be source of unwanted harmonics at the SIS mixer LO input. Thus, an unwanted down-conversion might result from a beating of the LO harmonic frequencies and the frequencies of the astronomical sources if their frequency difference falls into the IF band. This can lead to spurious detection of astronomical lines whose frequencies are outside the nominal RF band as long as the SIS mixer is able to respond to those frequencies. Also, the SIS mixer can act as multiplier of the LO frequencies, thus leading to generation of unwanted harmonics. Whatever the harmonic generation mechanism, if the power of these harmonics is high enough (compared to the fundamental tone) to sufficiently pump the SIS mixer, it can increase the SIS receiver noise temperature by adding noise from the sidebands of the harmonics to the IF output. Also, the tones can have enough pumping power to produce a detection of unwanted spectral lines on the sidebands of the LO spurious during astronomy observations.

As an example, we have measured the power of the LO spurious harmonics present in the signal of a Band 2 Gunn LO system consisting of a ~67-90 GHz Gunn (itself working in second harmonic) followed by a VDI frequency doubler. The LO system is expected to deliver a final LO signal with a main tone tunable across ~134-180 GHz. RF signals of frequency near the third harmonic (H3), the fourth harmonic (H4), and the fifth harmonic (H5) of the ~67-90 GHz Gunn oscillator were injected, in turn, through the receiver RF input in order to produce a beat with the spurious harmonics of the doubler; these would result in a line detection in the 2SB receiver IF bands, either LSB, USB or both. The level of the third harmonic of the Band 2 VDI LO doubler was measured across the LO band, using a Band 3 (200-276 GHz) SIS receiver as detector. We measured the variation of the intrinsic power level of H3 of the 130-180 GHz WR6.2x2 doubler [2] as a function of frequency with respect to its value at 136 GHz. We found that the variation of the H3 power level for frequencies above 138 GHz is between 6 and ~30 dB higher than at 136 GHz.

In order to mitigate the LO spurious harmonics problem, we have designed, fabricated and characterised a ~134-184 GHz band pass filter that suppresses the harmonics H3, H4, and part of the H5 at the output of the VDI frequency doubler. The filter also rejects H3 from the fundamental frequency of the Harmonic2 Gunn oscillator, which pumps the Band 2 LO doubler. When the doubler H3 of the Band 2 LO is reduced by more than 20 dB with a band pass filter, the receiver noise temperature at 136 GHz LO decreased ~16 K in the LSB and 11 K in the USB (measured receiver noise reduced from ~53 K to ~37 K in LSB). The receiver noise is unaffected by the filter for LO frequencies above 138 GHz because the H3 power level of the doubler is between 8 and ~30 dB lower than at 136 GHz. The problem of the Band 2 LO harmonics rejection using a band pass filter will be discussed in the presentation and in the full paper.

A similar approach is used to mitigate the spurious harmonics in other LO bands: a stainless steel cutoff attenuator suppresses the SIS mixer noise excess given by the H2 from the Band 4 LO output tripler, while a 15 dB attenuator located at the LO output is used to suppress the noise excess added to the Band 1 2SB SIS mixer. The excess noise temperature given by the Band 4 LO output tripler was reduced by 15 K using the cut-off attenuator at the tripler output. With a 15 dB attenuator at the Band 1 LO AMC output, there is no LO excess noise on the SIS mixer compared to a Gunn oscillator.

VII. CONCLUSION

We have presented the LO system being developed for the NOEMA project and given some details of its design. The output power of the Band 4 LO is between +13 and +18 dBm across the 93-121 GHz band using an AMC followed by a PA and 3 dB coupler modules. The NOEMA LO Band 1 employs only an AMC chain delivering between +11 and +15 dBm in the 82-109 GHz band. Across the LO Band 1, the power is between +16 and +18 dBm when adding a PA and 3 dB module in cascade to the AMC chain; such configuration can be used for a multibeam receiver LO.

The generation of spurious harmonics along the local oscillator chain is discussed. Measurement results of the spurious harmonic content are presented; a solution that strongly mitigates the problem by filtering is discussed.

REFERENCES

[1] J. E. Carlstrom, R.L. Plambeck, and D. D. Thornton, "A continuously tunable 65-115 GHz Gunn oscillator," IEEE Trans. Microwave Theory Tech., vol. MTT-33, pp. 610-619, July 1985.

[2] Virginia Diodes, 979 2nd Street SE, Suite 309, Charlottesville, VA 22902, United States.

[3] E. Bryerton, K. Saini, M. Morgan, M. Stogoski, T. Boyd and D. Thacker, "Development of electronically tuned local oscillators for ALMA," Infrared and Millimeter Waves and 13th International Conference on Terahertz Electronics, pp. 72-73 vol1, IRMMW-THz, 19-23 Sep., 2005.

[4] M. Morgan, E. Bryerton, H. Karimy, D. Dugas, L. Gunter, Duh Kuanghann, Yang Xiaoping, P. Smith and Chao Pane-Chane, "Wideband Medium Power Amplifiers Using a Short Gate-Length GaAs MMIC Processs,'' IEEE MTT-S Intl. Microwave Symp. Digest, pp. 541-544, Boston, MA, 2009.

[5] Micro Lambda Wireless, Inc, 46515 Landing Parkway Fremont, CA 94538, United States.