A Millimeter-Wave Diode-MMIC Chipset for Local Oscillator Generation in the ALMA Telescope

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***Abstract* — A set of MMIC frequency multipliers and balanced mixers have been designed for the local oscillator system of the Atacama Large Millimeter Array (ALMA). These millimeter-wave elements form a critical link in the active multiplier chains between the relatively low frequency microwave oscillators and the very high frequency submillimeter-wave, cooled multipliers of the LO subsystem. A complete chipset for four frequency bands is described, along with preliminary results on prototypes for two additional bands.**

***Index Terms* — Millimeter-wave frequency converters, millimeter-wave mixers, MMICs, phase-locked loops, radio astronomy.**

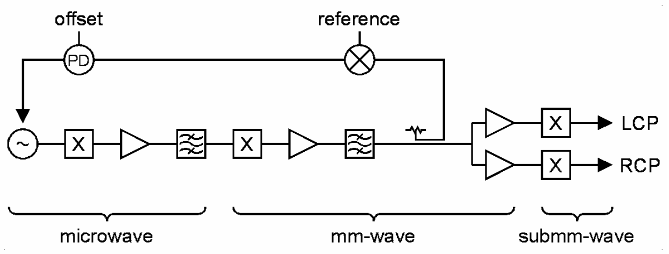

Fig. 1. Block diagram of a typical LO chain for ALMA. The millimeter-wave components, which can be implemented as MMICs but are not available commercially, are described in this paper.

TABLE I
Current ALMA Frequency Bands

Band #	RF Frequency	Final Mult.	IF Range	mm-Wave LO Frequency
Band 1	31.3-45 GHz			
Band 2	67-90 GHz			
Band 3	84-116 GHz	--	8 GHz	92-108 GHz
Band 4	125-163 GHz	x2	8 GHz	66.5-77.5 GHz
Band 5	163-211 GHz			
Band 6	211-275 GHz	x3	12 GHz	74.3-87.7 GHz
Band 7	275-373 GHz	x3	8 GHz	94.3-121.7 GHz
Band 8	385-500 GHz	x5	8 GHz	78.6-98.4 GHz
Band 9 (original)	602-720 GHz	x5	8 GHz	122-142.4 GHz
Band 9 (modified)	602-720 GHz	x6	8 GHz	101.7-118.7 GHz
Band 10	787-950 GHz			

I. INTRODUCTION

The Atacama Large Millimeter Array (ALMA) is a millimeter-wavelength telescope currently under construction in the Chajnantor region of northern Chile. Consisting of an array of antennas, each 12 m in diameter, with an upper frequency limit over 900 GHz, it will be the largest and most sensitive instrument in the world at millimeter and submillimeter wavelengths [1].

Implementing ALMA has presented engineers with numerous technological challenges to overcome, and innovations have been required in almost every subsystem. The local oscillator subsystem, for example, must provide sufficient pump power to SIS mixers up to nearly a THz, tunable over broad ranges, and phase-locked to a reference signal common to the whole array which in some configurations may span up to 10 km.

Fig. 1 is a block diagram for the typical ALMA LO assembly present in each antenna for each frequency band. Specific details, such as the multiplication factors and number of gain stages, may vary depending on the components available and requirements for each band. Generally speaking, however, the LO signal is generated by a phase-locked loop that begins with a microwave YIG-tuned oscillator. This is followed by one or two multipliers that scale the signal frequency up into the millimeter-wave range, where it is mixed with a common reference distributed to the array by optical fiber. Following the PLL is a final stage of amplification and subsequent multiplication which brings the signal frequency up to the submillimeter-wave range required by the receivers.

Because amplifiers are not feasible at the final LO frequency for many of the ALMA bands using present transistor technology, the efficiency of the final stage of multiplication is paramount. Cooled, Schottky-Diode multipliers are being provided for ALMA by Virginia Diodes, Inc. Though some of these are implemented monolithically, the highest frequency band is for now composed of advanced planar Schottky diodes flip-chip mounted on a quartz substrate with integrated matching and idler circuitry. This

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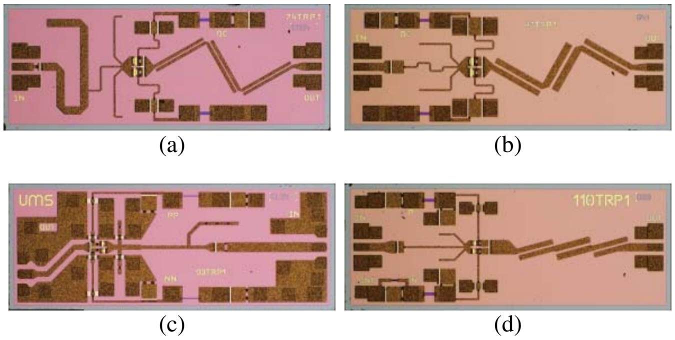


(a) (b)

(c) (d)

Fig. 2. Photographs of the MMIC triplers for (a) Band 4, (b) Band 6, (c) Band 8, (d) Bands 3, 7, and 9-modified. Chip dimensions are 2.0 x 0.73 x 0.1 mm.

high-performance component is more reliable and less expensive than classic whisker-contact diode multipliers, yet is capable of better efficiency and more power at high frequency than that of a fully-monolithic design in the submillimeter-wave range. However, the goal of minimizing the global cost of the array drives us to selecting a MMIC approach for as many of the remaining elements of the LO subsystem as possible, so virtually every active component between the YIG oscillator and the final multiplier is a MMIC chip.

The lower-frequency MMICs, including usually the first stages of amplification and multiplication, are available at low cost from commercial suppliers, but the millimeter-wave multipliers, mixers, and power amplifiers required custom designs. Thus, the MMIC chipset described in this paper closes the gap between the relatively low frequency microwave oscillators, and the very high frequency, submillimeter-wave multipliers.

II. ALMA BANDS

Frequency coverage for the ALMA facility has been divided into 10 bands, as shown in Table I. Bands 3, 6, 7, and 9 are scheduled to be delivered with the first antennas on the construction site, and complete chipsets for those bands have already been developed. Chips for bands 4 and 8 are also under development for deployment in the near future. Table I also shows how the millimeter-wave frequencies for the MMIC portions of the LO subsystem are derived, based on the multiplication factors that follow them and the IF frequency range of the front ends for those bands. Not unexpectedly, the differing multiplication factors lead to a great deal of overlap between the required bands and the potential for chip reuse.

It is worth noting that Band 9 was originally expected to use a quintupler following the last stage of amplification, and that chips were designed for the resulting 122-142.4 GHz frequency range. However, the Band 9 schematic was eventually modified to incorporate a final multiplier of 6 instead of 5, allowing us to take advantage of better power amplifiers that were available at the lower input frequency [2]-[4].

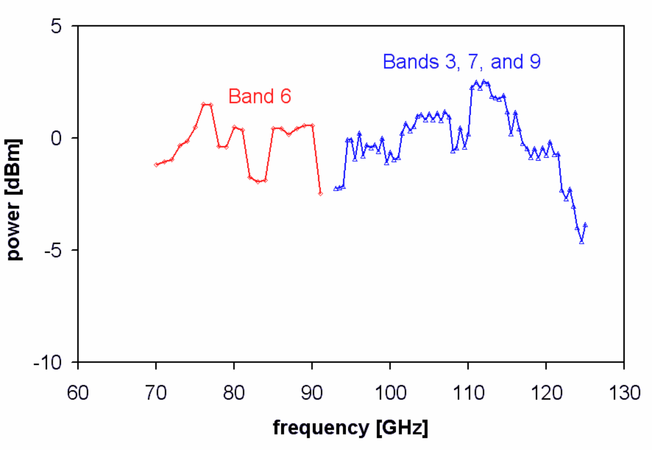


Fig. 3. Output power for the triplers in Bands 3, 6, 7, and 9-modified. Input power was 17.6 ±1.2 dBm.

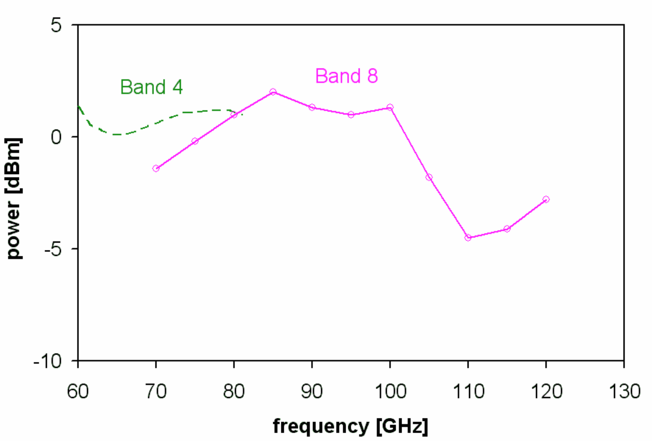


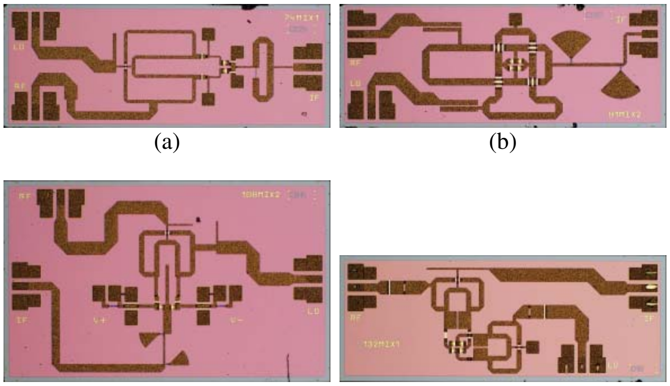
Fig. 4. Output power for the triplers in Band 4 (simulated) and Band 8 (measured). Input power for the Band 8 tripler was 19 dBm.

III. MULTIPLIERS

Broadband, Schottky-Diode MMIC triplers in W-Band have already been demonstrated [5]-[6]. Building upon this earlier work, several new triplers have been designed for the ALMA millimeter-wave LO frequency bands. These generally correspond to the second stage of multiplication in Fig. 1. Photographs of these chips appear in Fig. 2.

These chips were all fabricated by UMS in their BES Schottky-Diode MMIC process. All the diodes in these high frequency designs have a contact area of 3 μm^2. The junction capacitance for these devices is nominally 6fF, with a parasitic series resistance of 7 Ω.

Each of the triplers is composed of three basic sections. First is an input matching network with open-circuited stubs, which also serves to provide a third-harmonic ground-return.


(a) (b)

(c) (d)

Fig. 5. Photographs of the MMIC mixers for (a) Band 4, (b) Band 6, (c) Band 3, 7, and 9-modified, and (d) Band 9-original. Chip dimensions are 2.0 x 0.73-1.2 x 0.1 mm.

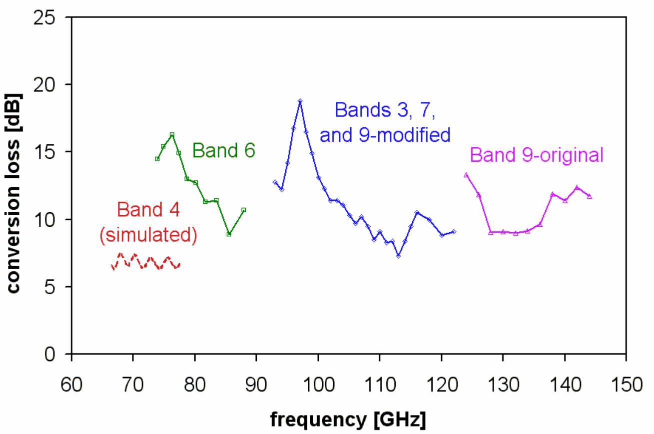


Fig. 6. Measured conversion loss for the mixers used in Bands 3, 6, 7, 9-original, and 9-modified, and simulated conversion loss for the mixer in Band 4. LO power in all cases is 10 dBm.

Following this is an anti-parallel diode pair which efficiently generates the third harmonic while intrinsically suppressing all even-harmonic spurs. Finally, the output matching network includes AC-grounded stubs which provide a ground-return path at the fundamental frequency, as well as a means of injecting DC-bias to the diodes, and a low-order bandpass filter that rejects higher-order spurious tones.

Measurements of the output power versus frequency for the two triplers used in Bands 3, 6, 7, and 9 (the four bands that will be delivered with the first antennas) is shown in Fig. 3. The input power in both cases was approximately 18 dBm, though it varied over almost a 3 dB range due to limitations of the test setup. This fluctuation of the input power can account for much of the ripple seen in Fig. 3, especially since the conversion loss is a relatively strong function of the input power. Generally speaking, the triplers deliver about 1 mW of power over their design range with approximately 18 dB conversion loss.

Band 8 will use a pre-existing design [5], the measurements for which are reproduced in Fig. 4. The figure also shows simulated data for a newly developed Band 4 tripler that has not yet been tested. Although historically the conversion loss has been about 2 dB higher than that predicted by our simulations, the agreement in terms of saturated output power and frequency response is usually good. Harmonic rejection for these triplers is typically in excess of 20 dB.

IV. MIXERS

A number of custom millimeter-wave balanced mixers were also required to complete the phase-locked loops in the ALMA LO subsystem, and were made using the UMS BES Schottky diode MMIC process. These circuits are shown in Fig. 5. The RF and LO frequency ranges are those shown in the last column of Table I, with a common IF frequency range of DC-200 MHz. There were two basic topologies used for the design of these mixers. Those mixers shown in Fig. 5a and Fig. 5c are single-balanced mixers that are loosely based on earlier broadband, millimeter-wave mixer designs [7]. This topology consists of a single balun, implemented here by a folded ring hybrid, which drives a pair of diodes in series. Short-circuited stubs provide RF matching and a ground-return for the IF. The IF signal is the extracted from between the two diodes through a low-pass non-reflective filter.

The chips shown in Figs. 5b and 5d, however, are double-balanced ring-mixers. Ring hybrids are used in both cases to couple the LO and RF signals into the diode ring. For the band 6 mixer, shown in Figure 5c, the hybrids are arranged in a convenient interlocking layout that encloses the diode ring and allows easy access to the differential ports for RF/LO injection, and to the common-mode ports for IF extraction and ground-return. The same could not be done with the original Band 9 (122-142.4 GHz) mixer, because the resulting ring hybrids were too small to fit around the diodes. Instead, the hybrids were folded adjacent to the diodes and connected to them with a differential matching network. Both layouts were successful, and we believe these represent the first fully-monolithic double-balanced mixers in this frequency range.

Tests on early versions of these mixers revealed that the performance can be very sensitive to the impedance present on the IF port at the RF/LO frequency. The IF port is connected to a PC-Board where the low-frequency PLL circuitry is implemented, so the exact impedance seen on this port at the much higher millimeter-wave frequencies is not easily predicted or controlled, but generally it is reactive and changes very rapidly as a function of frequency. This was not originally considered important because the on-chip hybrids were meant to isolate the millimeter-wave frequencies from the IF port by placing a virtual short between the diodes where the output line is connected. However, like the off-chip components, these hybrids *also* present a reactive impedance to the IF port at frequencies above and below the resonant center-frequency of the structure. It is possible, then, for an off-chip component in the IF path to resonate with the on-chip hybrid in the millimeter-wave band, which has the effect of decoupling the diodes from one of the input signals. This is particularly problematic for the LO, since a small drop in the absorbed LO power can have a relatively large effect on the conversion loss of the mixer. For this reason, some of our early mixers exhibited suckouts near the center of their intended band of operation when integrated with the rest of the system.

We were able to solve this problem by placing a structure on the IF output line that was very lossy in the RF/LO band, but lossless in the low IF band. Effectively, we put single-order, non-reflective, bandstop filters on the chip after the mixer to prevent any possible resonance with off-chip components. This effectively removed or at least greatly reduced the dip in the conversion loss at the center of the band without affecting the overall conversion loss everywhere else.

The measured conversion loss for each of these mixers is shown in Fig. 6. Although the original Band 9 mixer for 122 - 142.4 GHz is no longer needed for ALMA due to the new frequency plan, the initial design turned out very well and is worth reporting here.

V. POWER AMPLIFIERS

The final custom MMIC components required for many of the ALMA LO bands are power amplifiers. Typically, at least 20 mW is needed in the millimeter-wave bands to drive the final stage of multiplication in order to get enough LO power for the SIS mixers. Some custom MMIC designs that were suitable for this application had already been developed for other projects [2]-[3], but additional circuits needed to be developed and the results are described in another publication [4].

VI. CONCLUSION

We have described the development of a set of millimeter-wave MMIC multipliers and balanced mixers for the ALMA radio telescope array. These chips have been integrated with other commercial MMICs and components to form a compact, cost-effective local-oscillator system for driving submillimeter-wave SIS receivers. Early tests on an integrated receiver system have shown that the noise contributed to the front-end by the LO assembly built with these chips is less than that of a Gunn Oscillator.

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