Multiplier Development for the Upper ALMA Local Oscillator Bands

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***Abstract*— A series of broadband tunerless frequency multipliers applicable for use as local oscillators on the Atacama Large Millimeter Array (ALMA) have been successfully developed. These multipliers are based on GaAs Schottky barrier planar diodes, which are mechanically rugged and repeatable, and thus well suited for use on an array like ALMA. For ALMA Band 9, a cascaded pair of broadband triplers to 600-720 GHz has been successfully demonstrated, and with a drive power of 100 mW over the input range 66.7-80 GHz an output power of 30-40 uW has been achieved at ambient temperature. Preliminary cooled measurements of the cascaded triplers indicate an improvement of more than a factor of 2 upon cooling to 80K, and so these results are a very successful demonstration. The ultimate goal of this research is to create a technology base that expands the use of the terahertz spectrum to more routine but equally important scientific and military measurements, and in the longer term to enable a wide range of commercial applications.**

***Index Terms*—Submillimeter-wave sources. Frequency Multiplier. Frequency Tripler. Spectral Measurements.**

I. INTRODUCTION

THE Atacama Large Millimeter Wave Array (ALMA) requires electronically tunable sources covering the range from 100 GHz to 1000 GHz with individual bandwidths of up to 25%. These sources must be compact, rugged and reproducible in large (> 100) quantities in order to successfully meet the scientific needs of the ALMA project. This paper discusses the successful development of local oscillator sources applicable to the ALMA project.

The ALMA local oscillator sources rely on a combination of MMIC amplifiers (up to roughly 110 GHz) combined with frequency multipliers used to extend the frequency range up to 1000 GHz. The development of the MMIC amplifiers has been carried out by the National Radio Astronomy Observatory Central Development Laboratory (NRAO-CDL), located in Charlottesville, VA, USA. The development of the millimeter- and submillimeter-wave multipliers is being carried out at Virginia Diodes Inc. (VDI), also located in Charlottesville, VA, USA.

Previous research at VDI has resulted in the successful development of triplers for both ALMA Band 6 (211-275 GHz) and Band 7 (275-370 GHz). These multipliers are based on GaAs Schottky barrier planar diodes, which are mechanically rugged and repeatable, and thus well suited for a large array like ALMA. These triplers exhibited an efficiency of approximately 3% at drive powers ranging from 10-20 mW, thus providing more than sufficient LO power for the SIS receivers. A quantity of over 120 Band 6 and 120 Band 7 multipliers were produced and fully characterized in a period of roughly 4 months. These multipliers are now being successfully integrated with the amplifiers at the NRAO-CDL for use in the ALMA receiver cartridges.

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This paper will discuss the development of broadband local oscillators for use on the higher frequency ALMA bands, in particular ALMA Band 9, covering the frequency range from 600 GHz to 720 GHz. The development and characterization of both a cascaded doubler-tripler and tripler-tripler will be presented. Such issues as harmonic content and cryogenic performance will be discussed.

II. CASCADED DOUBLER-TRIPLER

A. Review Stage

One multiplier combination that has been considered for use with ALMA Band 9 is a cascaded doubler-tripler combination. Both the WR-4.3X2 doubler and the WR-1.5X3 tripler are standard VDI components, with typical efficiencies of 10% and 2%, respectively. With an input drive power of 30-40 mW over the band 100-120 GHz the expected output powers are 3-4 mW out of the doubler and 60-80 uW out of the tripler. Figure 1 shows the actual measured performance for several sextupler designs. The power level over most of the band matches the expected power level, but there are ripples in the power, and drop-

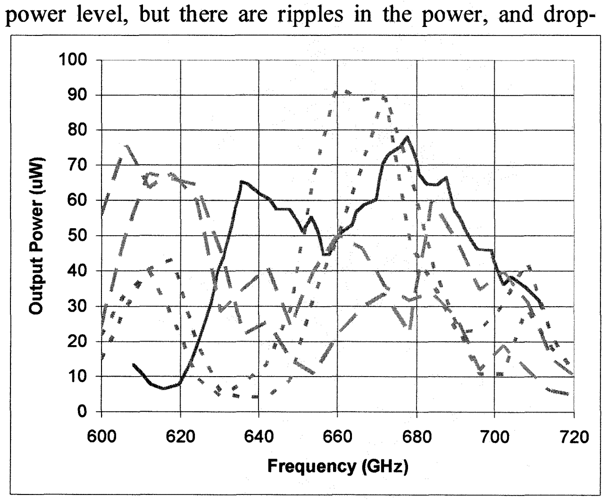


Fig. 1. Performance of cascaded WR-4.3X2 + WR-1.5X3 multipliers for three separate lengths of intervening waveguide. The spacings between the doubler and tripler are approximately 4.6 wavelengths for the solid curve, 3.5 wavelengths for the dashed curves, and 2.8 wavelengths for the dotted curves.

outs over part of the band. The standing wave is caused by interactions between the doubler and tripler, and so measurements were made using different spacings between these multipliers. The different curves in Figure 1 correspond to different physical lengths of waveguide between the doubler and tripler. In all of the cases there are significant nulls in the output power caused by standing waves between the multipliers. Also, the performance in the nulls was not found to improve significantly upon cooling, and thus it was necessary to determine a means to overcome this difficulty.

In order to better understand the source of the problem, measurements were performed on the return loss of the broadband triplers. Figure 2 shows the measured return loss for a standard WR-3.4X3 broadband tripler. The performance of the WR-1.5X3 used to produce the results in Figure 1 is expected to be very similar. As can be seen in the graph, as the input drive power becomes low (below approximately 5 mW) the return loss worsens dramatically for this tripler design. For the sextupler to 600-720 GHz described above the return loss of the tripler is expected to be as poor as 3-4 dB, and so the measured ripples in Figure 1 are consistent with this behavior.

In order to overcome this problem of poor return loss for low drive powers a new series of multipliers was developed for operation at ultra-low input drive. Fig. 2 shows the measured return loss for a prototype WR-9.3X3 low-drive broadband tripler. As shown in the graph, the return loss is still very good even for a drive power below ¼ mW. A batch of low-drive triplers was fabricated to cover the WR-1.5 band, and the test results for these devices are shown in Figure 3. Even for very low drive powers the sextupler is still performing well, and gives flat performance over the band, demonstrating the dramatically reduced standing-waves between the components. Subsequent cooled measurements performed at NRAO-CDL indicated an improvement of nearly a factor of 2 upon cooling to 80 K, and the output power was well above the required 20 uW over the entire band. However, because of concerns about the lifetime of the InP MMIC amplifiers required to produce the drive power (30-40 mW from 100-120 GHz), it was decided best to look into an alternate path, a cascaded tripler-tripler.

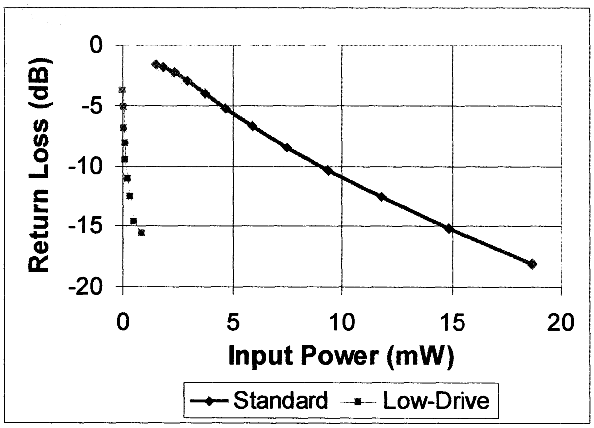


Fig. 2. Measured return loss for typical standard tripler and also for a low-drive tripler.

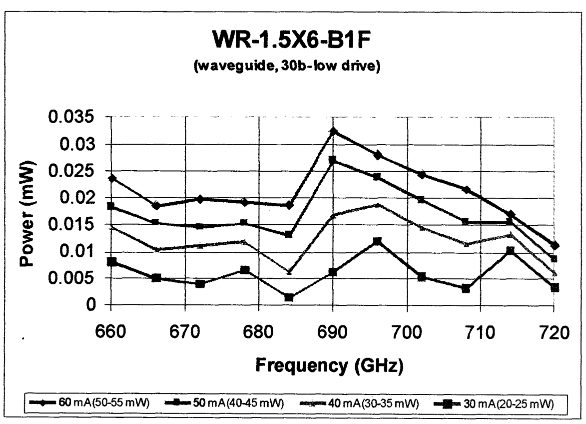


Fig. 3. Measurements of a broadband sextupler using a low-drive tripler.

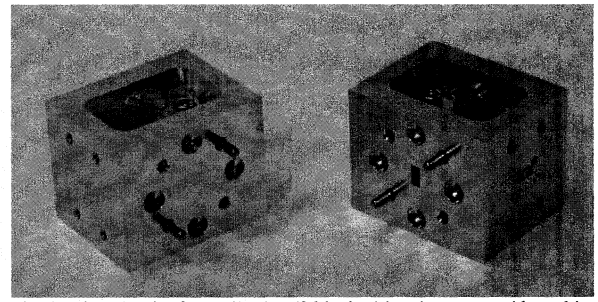


Fig. 4. Photograph of two WR-1.5X9 blocks (showing output side and input side). The WR-1.5X9 consists of a WR-4.3X3 tripler (170-265 GHz) integrated with a WR-1.5X3 tripler (500-750 GHz) into the same block housing.

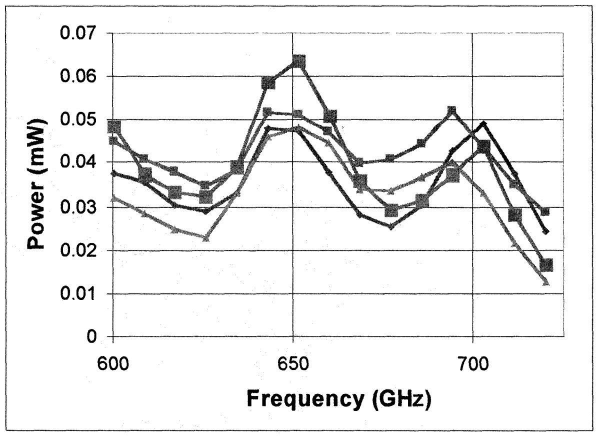


Fig. 5. Measured data for four identical-builds of WR-1.5X9 blocks.

III. Cascaded Tripler-Tripler

Figure 4 shows a picture of a WR-1.5X9 multiplier, which consists of a WR-4.3X3 tripler integrated into the same housing with a WR-1.5X3 tripler. The input drive band to the multiplier is from 67-80 GHz, and it is assumed that an input drive power of 100 mW will be available at the multiplier input. The WR-4.3X3 has an efficiency of 3-4%, and so the power delivered to the WR-1.5X3 will be 3-4 mW. A low-drive tripler was used in the WR-1.5X3 tripler to avoid standing waves. The efficiency of the low-drive WR-1.5X3 tripler is in the range 1%, yielding an expected output power at room temperature of 30-40 uW. The measured output power for several identical WR-1.5X9 blocks are shown in Figure 5, and indicate that the multipliers are working as expected.

One important consideration for the overall multiplier design is the analysis and minimization of unwanted harmonics. A graph of the frequency bands for the various harmonics for a tripler-tripler to ALMA Band 9 is shown in Figure 6, where the base harmonic N=1 covers 67-80 GHz, and the desired harmonic is N=9 covering 600-720 GHz. There are three waveguides to consider: 1) the input to the first tripler, 2) the waveguide between the triplers, and 3) the output waveguide. In the graph two different output waveguide sizes, WR-1.5 (500-750 GHz) and WR-1.2 (600-900 GHz) are shown to allow comparison between them, as discussed below.

In looking at the graph, it can be seen that any fifth harmonic output from the first tripler (N=5) will be blocked by the output waveguide over nearly the entire band, even with the larger WR-1.5 waveguide (TE10 cutoff 393 GHz), so this harmonic is not an issue. Another harmonic to consider is the second harmonic content from the second tripler (i.e. the multiplication path X3-X2, N=6). For the WR-1.5 waveguide it is possible for this N=6 harmonic to propagate out the output waveguide. By switching to WR-1.2 waveguide (TE10 cutoff 492 GHz) it is possible to block this N=6 harmonic output. Other harmonics, for example the 7th, 8th and 10th, would be impossible to filter out if they are found to be present in the output, and so the suppression of these harmonics must rely on circuit balance.

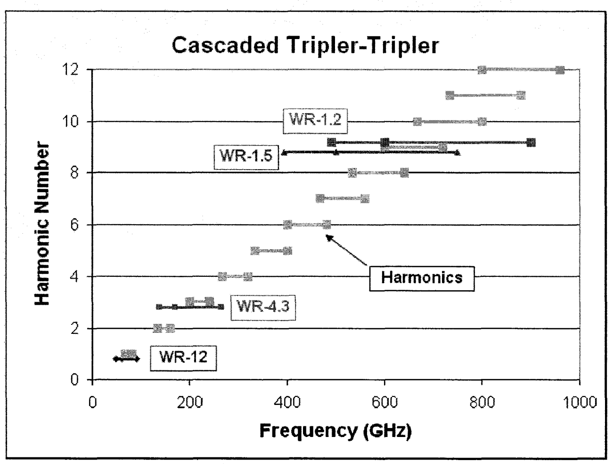


Fig. 6. Harmonic Design for a cascaded Tripler-Tripler to ALMA Band 9 (600-720 GHz). The light blue lines show the frequency ranges for the various harmonics of the input drive (100-120 GHz). The other lines show the range for the various waveguides in the cascade (the TE10 cutoff frequency, then recommended lower and upper band edges).

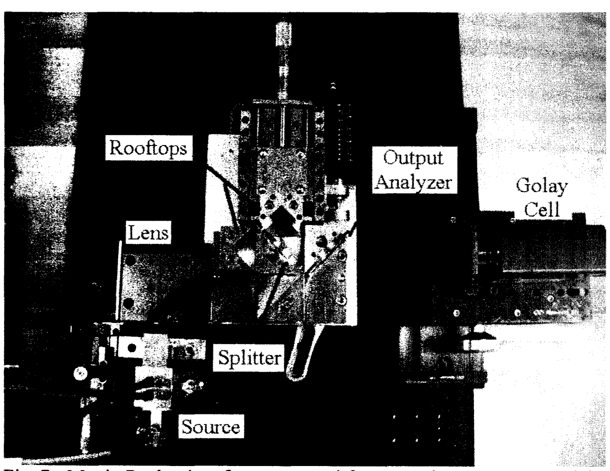
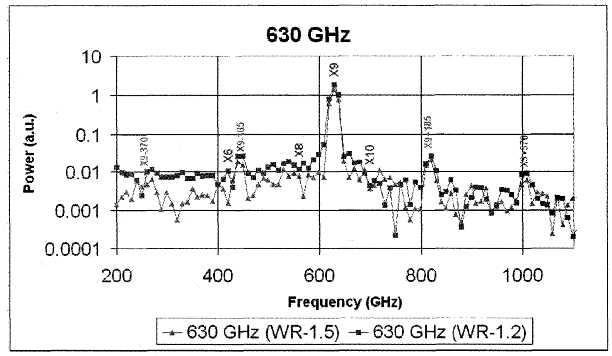
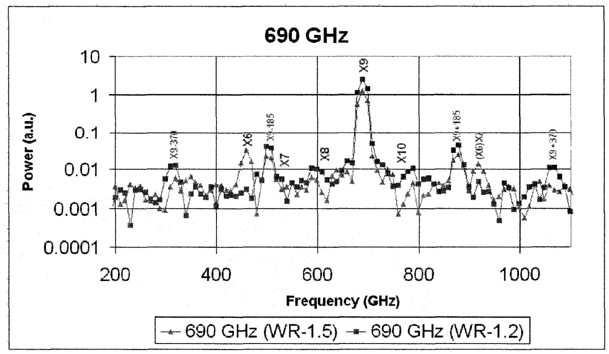


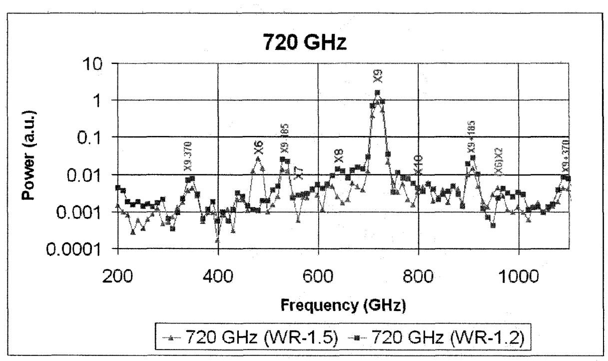
Fig. 7. Martin-Puplett interferometer used for spectral measurements of the WR-1.5X9. The micrometer has a stage wobble at 0.4 mm periodicity, which adds artifacts to the spectra at integer offsets of +/- 185 GHz from any strong tone.



(a)



(b)



(c)

Fig. 8 (a-c). Measured output spectra of the WR-1.5X9. The peaks marked in magenta are artifacts caused by stage wobble and quasi-optical system standing waves. The red curves are for blocks with WR-1.5 output, while the blue curves are for modified blocks with output waveguide equivalent to WR-1.2 (i.e. TE10 cutoff frequency of 492 GHz).

The next issue to consider then is which harmonics are expected be present in the output, and in what magnitude. Both of the triplers are balanced designs, and so even harmonics are suppressed by the inherent balance. The question then is what level of suppression is achieved for the present multiplier. A theoretical analysis of the harmonic content is possible, but because the presence of these harmonics depend upon asymmetries, either electrical or in the embedding circuit, it is difficult to accurately predict their level. Previous measurements of the individual triplers have found that the even harmonics (N=2, 4, …) and higher odd harmonics (i.e. N=5, 7, …) are suppressed to a level 15-20 dB below the tripled output (N=3).

In order to gain a better understanding of the harmonic content of cascaded triplers, a polarizing Martin-Puplett diplexer was used to characterize the output spectrum. A picture of the spectrometer is shown in Figure 7. An input lens is use to collimate the power from the source, which then propagates through the interferometer. An output analyzer is then followed by a Golay cell that is used to detect the output signal. The source was electrically modulated using a coaxial SPST switch. There are two main sources of artifacts in this spectrometer. First, the stage translating the rooftop mirror has a wobble with a periodicity of 0.4 mm, effectively AM modulating the interferogram and producing "sidebands" on the output spectrum at integer multiples of 185 GHz above and below any tones present. A second artifact is caused by the presence of standing waves between the source and the detector, which produce artifacts at integer multiples of any tones present. These artifacts can be seen in the spectra shown in Figure 8. That these are artifacts and not true signals has been verified by a series of measurements on a variety of multipliers, as well as correlation of these results with measurements by other groups.

In looking at the measured spectra, the spectrum for an output frequency of 630 GHz (Figure 8(a)) shows that the only measurable signal is the desired 9th harmonic. The noise threshold for the measurement is approximately 25 dB below the desired output. If we look at the spectrum for an output frequency of 690 GHz (Figure 8(b)) with WR-1.5 waveguide (TE10 cutoff 393 GHz) then it is possible to see the appearance of a 6th harmonic at a level approximately 15 dB below the main carrier. However, reducing the output waveguide size to WR-1.2 (TE10 cutoff frequency of 492 GHz) chokes off the 6th harmonic. The measured output power for WR-1.5X9 with and without the WR-1.2 filter was measured to be the same. Figure 8(c) shows that the 6th harmonic has been successfully suppressed all the way to the upper edge of the band, 720 GHz. One final question is whether the 6th harmonic signal is generated by a doubling of the N=3 harmonic, or by a tripling of the N=2 harmonic. To determine this a similar measurement was performed with WR-1.5 output waveguide and WR-3.4 intermediate waveguide. In this case the 6th harmonic was still present in the output indicating that the path is indeed X3-X2, and not X2-X3.

IV. Conclusion

This paper has described the successful development a cascaded pair of broadband triplers, the WR-3.4X3 + WR-1.5X3, for use on ALMA Band 9, covering the frequency range from 600-720 GHz. With a drive power of 100 mW over the input range 66.7-80 GHz an output power of 30-40 uW has been achieved at ambient temperature. Preliminary cooled measurements of the cascaded triplers indicate an improvement of more than a factor of 2 upon cooling to 80K, and so these results are a very successful demonstration for use with ALMA Band 9. In addition, research is now underway on the development of multipliers for ALMA band 10, covering 787-950 GHz. A tripler-tripler has been successfully testing with an output power of 15-20 uW when driven by an input power of 60-75 mW.

These sources are not only applicable to the ALMA project, but to a wide range of scientific and commercial applications. The ultimate goal of this research is to create a technology base that expands the use of the terahertz spectrum to more routine but equally important scientific and military measurements, and in the longer term to enable a wide range of commercial applications.

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