# Tunable All-Solid-State Local Oscillators to 1900 GHz


John Ward, Goutam Chattopadhyay, Alain Maestrini [1], Erich Schlecht, John Gill, Hamid Javadi, David Pukala, Frank Maiwald and Imran Mehdi

California Institute of Technology, Jet Propulsion Laboratory, MS 168-314, 4800 Oak Grove Drive, Pasadena, CA 91109

[1] Now at LISIF - Université Paris VI, 4, place Jussieu, 75252 Paris, France



ABSTRACT

We present a status report of an ongoing effort to develop robust tunable all-solid-state sources up to 1900 GHz for the Heterodyne Instrument for the Far Infrared (HIFI) on the Herschel Space Observatory. GaAs based multi-chip power amplifier modules at W-band are used to drive cascaded chains of multipliers. We have demonstrated performance from chains comprised of four doublers up to 1600 GHz as well as from a x2x3x3 chain to 1900 GHz. Measured peak output power of 23 μW at 1782 GHz and 2.6 μW at 1900 GHz has been achieved when the multipliers are cooled to 120K. The 1900 GHz tripler was pumped with a four anode tripler that produces a peak of 4 mW at 630 GHz when cooled to 120 K. We believe that these sources can now be used to pump hot electron bolometer (HEB) heterodyne mixers.


## I. INTRODUCTION

The Herschel Space Observatory is a 3.5 meter diameter passively-cooled telescope that will focus light onto three science instruments (PACS, SPIRE, and HIFI) to observe the cosmos from 450 to 5000 GHz (60 – 670 μm) [1]. Band 6 of the Heterodyne Instrument for the Far-Infrared (HIFI) [2] is a heterodyne spectrometer to cover 1410 to 1910 GHz. Four local oscillator chains operating at 120 K will each pump a pair of orthogonally-polarized HEB mixers. Table 1 provides a brief summary of the four local oscillator chains that will be required to cover this band.

When the development of heterodyne receivers for the Herschel Space Observatory was initiated, state-of-the-art submillimeter sources typically consisted of cascaded whisker-contacted Schottky-diode frequency multipliers driven by phase-locked Gunn oscillators [3,4]. Frequency tuning was achieved with mechanical tuners, and multipliers were mechanically fragile. Above about 900 GHz, the available power was too low to pump a mixer, and so compact solid-state sources gave way to FIR lasers. These lasers are massive, bulky, difficult to operate, require large amounts of power, and only operate at specific discrete frequencies. Thus, the recent development of tunable solid state THz sources represents a major advancement for the THz field.

The results presented here are for planar Schottky diode multipliers electronically tunable with about 10% bandwidth. Power amplifiers driven by commercial synthesizers produce 100 to 150 mW in the 70 to 106 GHz band [5,6]. One to four frequency doublers and/or triplers are cascaded after the W band source. All multipliers are balanced designs implemented with monolithic circuits mounted in split-waveguide blocks. The frequency doublers each have two parallel branches of diodes, while the triplers each have two anti-parallel branches. The low frequency multipliers (below 1 THz) use "substrateless" technology implemented with 1 to $2 \cdot 10^{17}$ $cm^{-3}$ doped GaAs, while the multipliers above 1 THz are fabricated on 3 μm thick GaAs membranes with $5 \cdot 10^{17}$ $cm^{-3}$ doped anodes [7-10]. The first stage multipliers have 3 anodes in series in each branch (for 6 anodes total), and the second stages have 2 series anodes in each branch (for 4 anodes total). All multipliers above 700 GHz have only 1 anode per branch, or 2 anodes per multiplier. Multipliers with output frequencies above 1 THz have diagonal horns integrated into the waveguide split blocks. Further details on the multiplier designs are given in [11]-[15]. A model of a complete chain is shown in Figure 1.

| Band | Chain | Amp Freq. | Multiple | Output Freq. | Required Power |
|---|---|---|---|---|---|
| Band 6 Low | 6a | 88-99.5 GHz | x2x2x2x2 | 1414-1592 GHz | 3 μW |
| | 6b | 92-106 GHz | x2x2x2x2 | 1472-1696 GHz | 2.5 μW |
| *Band 6 High* | 6c | 94.6-106 GHz | x2x3x3 | 1704-1908 GHz | 2.5 μW |
| | 6d | 94.6-106 GHz | x2x3x3 | 1704-1908 GHz | 2.5 μW |

**Table 1.** Frequency and configuration of the four local oscillator chains being developed for Band 6 of the HIFI instrument on the Herschel Space Observatory.

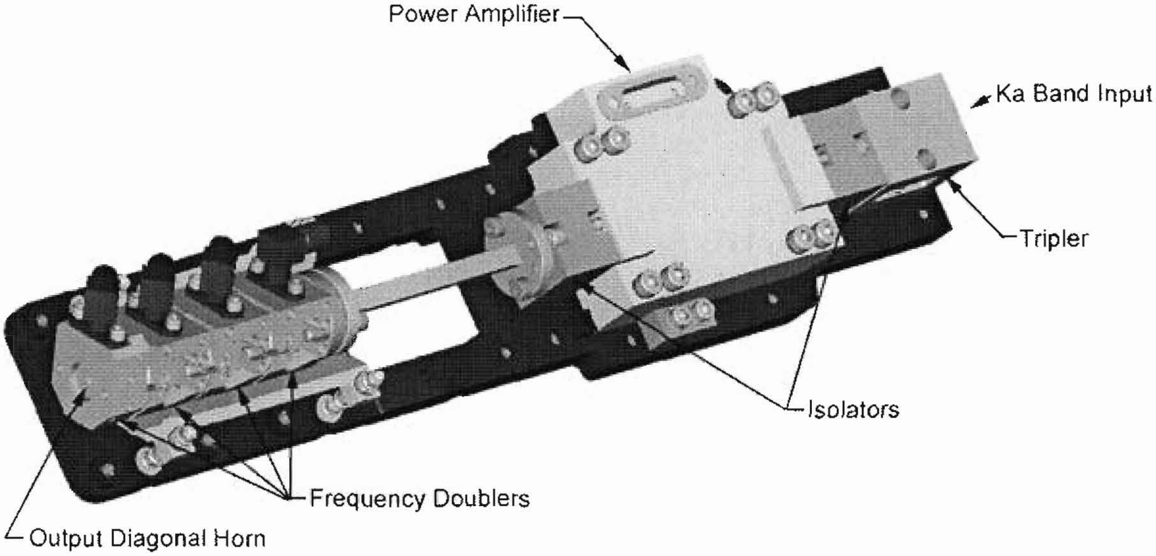


**Figure 1.** Model of a x2x2x2x2 local oscillator chain. The maximum envelope is smaller than 250x60x40 mm. The signal flows from right to left, with the output at the 48th harmonic of the Ka band input. The four frequency doublers are biased through SMA connectors.

## II. MEASURED RESULTS

The measurements were performed at room temperature and at 120 K. The output power of the W band power amplifier was monitored with a directional coupler and power meter. An Erickson calorimeter [16] with waveguide input was calibrated with a DC load and used for all room temperature power measurements below 1.4 THz. A Keating meter was calibrated with a DC square wave and lock-in amplifier, and used for cryogenic power measurements below 1.4 THz. Above 1.4 THz, measurements were made optically with a Golay cell calibrated against the Keating meter. All optical measurements were corrected for the losses in Mylar windows, where applicable, but were not corrected for other optical losses including non-ideal mirror reflectivity and air. Waveguide measurements were not corrected for loss in the connecting waveguides between the device under test and the meter. A summary of typical measured efficiencies and output powers is given in Table 2.

Figure 2 shows preliminary 295 K results of a new 300 GHz chain consisting of two cascaded frequency doublers. This chain produced high power levels suitable for driving further stages of multiplication, such as a doubler to 600 GHz or a tripler to 900 GHz. The first stage doubler to 150 GHz has six planar anodes divided into two parallel branches and produced a peak of over 45 mW from 150 mW in. The second stage doubler to 300 GHz has four planar anodes divided into two parallel branches and produced a peak output power of nearly 10 mW at 292 GHz. Both devices are implemented with $1\cdot10^{17}$ $cm^{-3}$ doped GaAs. We expect the output power of this chain to increase significantly when the multipliers are cooled.

Figure 3 shows recent 295 K measurements of a chain to 375 GHz. Like the 300 GHz chain shown in Figure 2, both doublers are implemented with $1\cdot10^{17}$ $cm^{-3}$ doped GaAs, with six anodes in the first stage to 190 GHz and four anodes in the second stage to 375 GHz. The drive power in the 88 to 99 GHz band was 100 mW. The efficiency of the first stage is flat to better than ±0.6 dB.

| Output Frequency | Multiple | Intended Use | Typical Efficiency | Typical Power |
|---|---|---|---|---|
| 176 – 199 GHz | 2 | Chain 6a, stage 1 | 30% | 30 mW |
| 352 – 398 GHz | 2 | Chain 6a, stage 2 | *15% | *4.5 mW |
| 704 – 796 GHz | 2 | Chain 6a, stage 3 | *8% | *400 μW |
| 1408 – 1592 GHz | 2 | Chain 6a, stage 4 | 4% | 30 μW |
| 184 – 212 GHz | 2 | Chain 6b, stage 1<br>Band 6 high, stage 1 | 30% | 30 mW |
| 368 – 424 GHz | 2 | Chain 6b, stage 2 | 20% | 6 mW |
| 736 – 848 GHz | 2 | Chain 6b, stage 3 | 10% | 1 mW |
| 1472 – 1696 GHz | 2 | Chain 6b, stage 4 | Not demonstrated | |
| 552 – 636 GHz | 3 | Band 6 high, stage 2 | 9% | 3 mW |
| 1704 – 1908 GHz | 3 | Band 6 high, stage 3 | 0.3% | 10 μW |
| 152 – 159 GHz | 2 | Not used | *27% | *40 mW |
| 304 – 318 GHz | 2 | Not used | *20% | *8 mW |

**Table 2.** Typical measured efficiencies and output powers demonstrated with moderate bandwidth. The temperature was 120 K unless noted with an asterisk, in which case the measurements were performed at 295 K. W band input power ranged from 100 to 150 mW. In all cases the best measured peak efficiencies and powers were significantly higher than the values listed here.

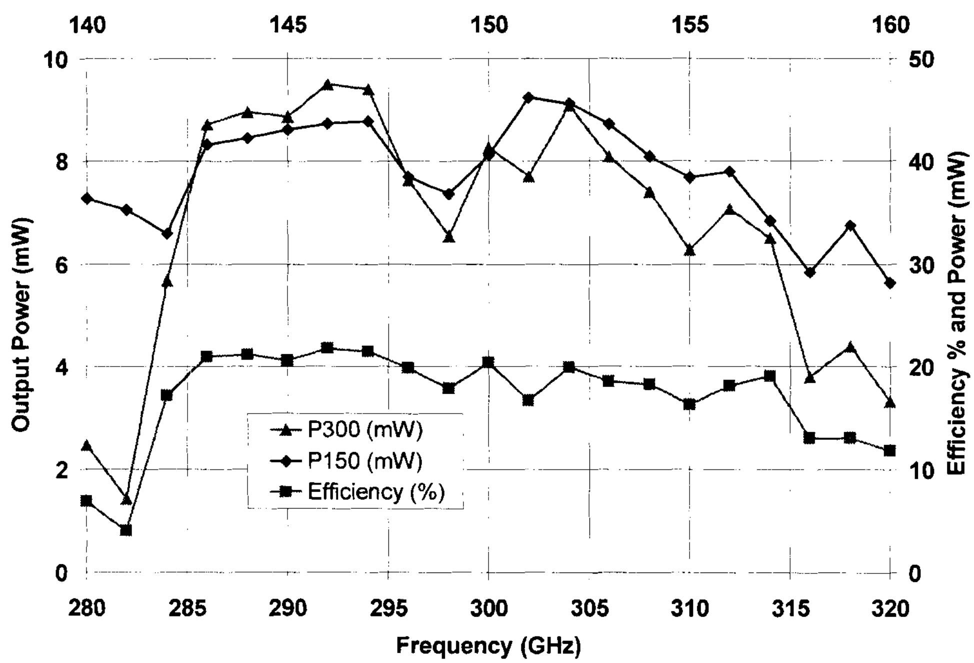


**Figure 2.** Measured room temperature performance of 150 and 300 GHz balanced doublers. The power of the 70-80 GHz input was 150 mW.

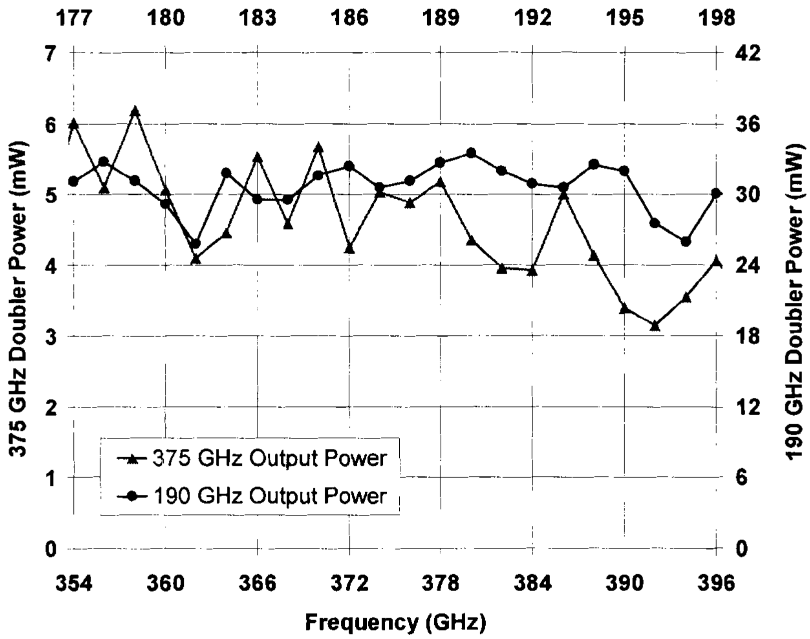


**Figure 3.** Measured room temperature performance of 190 and 375 GHz balanced doublers. The power of the 88.5-99 GHz input was 100 mW.

Early in this project, it was recognized that for a local oscillator chain to produce adequate power at 1.9 THz to pump a pair of orthogonally-polarized mixers, the power produced by the lower frequency driver multipliers must be as high as possible. With this requirement in mind, a novel four-anode tripler to 600 GHz was designed to be used to drive a final tripler covering the 1.7-1.9 THz band. Dividing the drive power across four anodes effectively doubles the power that can be safely handled by the multiplier as compared to previously-existing two-anode balanced triplers. See [17] for an overview of the failure mechanisms of Schottky varactor multipliers and what limits the maximum safe power. Figure 4 shows the device mounted in the waveguide block with a close-up of the anode region. It can be seen from Figure 5 that the performance of these triplers is very consistent. The 295 K measurements were made with about 23 mW of drive power in the 200 GHz band. The efficiency is in the 4 to 8% range. The performance improves dramatically with cooling, with 120 K peak output power of 4 mW at 630 GHz and efficiency ranging from 7 to 13%. Detailed information about this design will be given in [18].

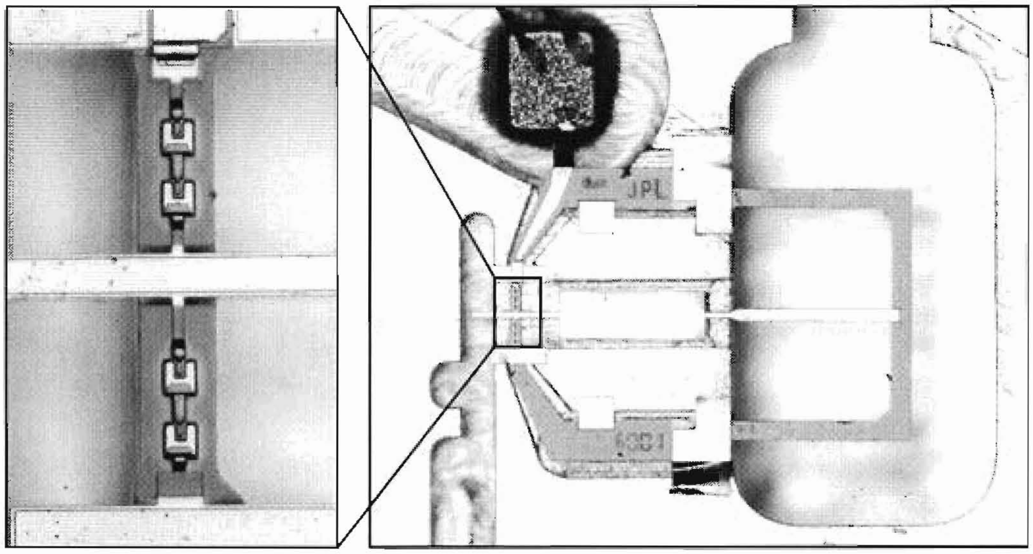


**Figure 4.** A four anode balanced 600 GHz tripler. The device is about 1 mm long. The 200 GHz input signal enters from the upper right. Four diodes lie near the output waveguide to the lower left. A frame minimizes the amount of GaAs in the channel between the input and output waveguides. The four anodes are biased in series from the discrete capacitor to the upper left.

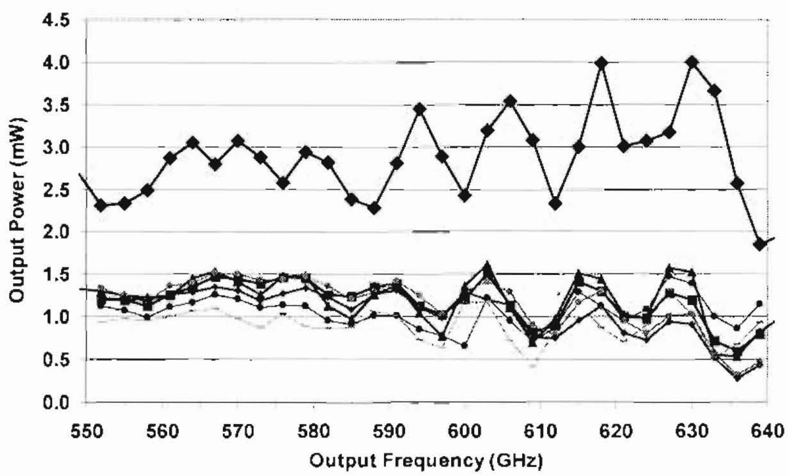


**Figure 5.** Measured performance of a variety of six different 600 GHz triplers. The lower family of curves was measured at room temperature with about 23 mW of input power in the 200 GHz band. The upper curve shows the 120 K performance of one of these units when the chain was driven with 150 mW at W band. The ripple is caused by interaction between the two stages of multiplication.

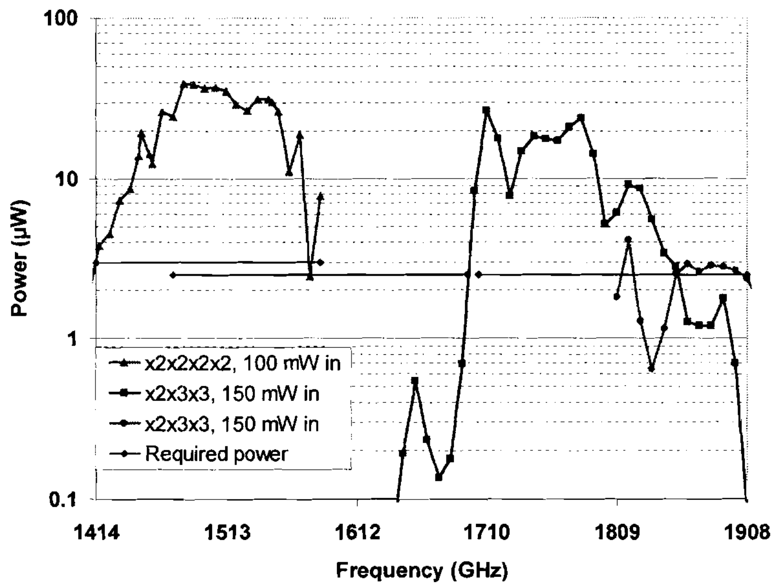


**Figure 6.** Results measured at 120 K. Measured LO power required at the HEB mixer lenses ranges from about 0.2 to 1 μW [20,21]. The required power is expected to be adequate to pump two mixers with orthogonal polarizations with a single LO chain, and to compensate for all optical losses in the system including beam mismatch, diplexer loss, etc.

Figure 6 shows the current performance of the flight multiplier chains for all of Band 6. Although significantly higher peak power has been produced around 1.5 THz, the performance displayed for the 6a chain was optimized for bandwidth and reliability. The curves above 1.7 THz are for x2x3x3 chains including a 600 GHz tripler shown in Figures 4 and 5 and a 1900 GHz tripler described in [19]. Peaks of 24 μW at 1780 GHz and 9 μW at 1820 GHz represent the highest power measured to date for solid state sources. The authors believe that with continued effort the power above 1820 GHz can be substantially increased.

## III. CONCLUSIONS

Solid-state, electronically tunable, broadband sources suitable for use as local oscillators in heterodyne receivers have been demonstrated up to 1908 GHz. These sources are flight qualified, and have been optimized to be low power, low mass, compact, tunerless, and mechanically robust. A novel four-anode frequency tripler has produced 4 mW at 630 GHz, and 24 μW of continuous power was demonstrated at 1.78 THz. Three-quarters of the 1410-1910 GHz band has been demonstrated with output power over 2.5 μW. Remaining challenges include filling in a gap in frequency coverage from 1580 to 1700 GHz.

## ACKNOWLEDGEMENTS

The authors wish to acknowledge the significant contributions of Ray Tsang, Robert Lin, Brad Finamore, William Chun, Luis Amaro, Alex Peralta, Ed Luong, and Jim Velebir. We also thank Peter Bruneau, James Crosby, and Hal Janzen for the superb fabrication of the many high frequency waveguide blocks needed for this project. Technical discussions with Neal Erickson of the University of Massachusetts are gratefully acknowledged. Finally, this work would not have been possible without the continued support of John Pearson and Peter Siegel. The research described in this publication was performed at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

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