Development of Local Oscillators for CASIMIR

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Abstract— **We present the development of three local oscillator chains to be used on the CASIMIR (Caltech Airborne Submillimeter Interstellar Medium Investigations Receiver) instrument onboard the SOFIA (Stratospheric Observatory for Infrared Astronomy) aircraft. All three chains use all solid-state GaAs-based components to amplify and multiply a ~1-3 mW input signal at W band. At room temperature, the 900 GHz source produces 50-100 μW of power from 800 to 930 GHz. The 1 THz source produces 50-120 μW of power from 960 to 1045 GHz. The 1.4 THz source produces 10-70 μW of power from 1320 to 1470 GHz. When cooled to 120 K, the 1.4 THz chain's output power increases by approximately 3 dB with a peak power of 129 μW at 1395 GHz.**

Index Terms – **CASIMIR, local oscillator, terahertz source, frequency multiplier, cascaded multipliers, GaAs Schottky diode, submillimeter wavelengths.**

I. INTRODUCTION

The Caltech Airborne Submillimeter Interstellar Medium Investigations Receiver (CASIMIR) is a multi-band, far infrared and submillimeter, high resolution, heterodyne spectrometer designed for high sensitivity observations of warm interstellar gas [1]. Multiple bands are being developed to study the transition lines of various molecular species. Of special interest are lines from $H_2{}^{18}O$, H_2D+, and N+ around 1 THz and 1.4 THz. The detectors for the receivers use advanced Superconductor-Insulator-Superconductor (SIS) mixers, pumped by solid-state local oscillator (LO) sources.

We present here the development and characterization of three LO sources which cover 800-930 GHz, 970-1040 GHz, and 1320-1470 GHz, respectively. The first two sources will serve as local oscillators for the spectroscopic lines in the 800-1040 GHz range [2], while the 1.4 THz source will enable the study of the H_2D+ line at 1.37 THz and the N+ line at 1.46 THz [3]. Each chain is composed of cascaded frequency multipliers driven by WR10 or WR8 power amplifiers. The multipliers are based on GaAs substrateless and membrane device technologies, which have been successfully demonstrated on the Herschel HIFI instrument [4],[5]. Measurements of SIS and HEB heterodyne mixers pumped by these LO chains prove that they are low noise and produce power at the correct frequency [6],[7].

II. 900 GHZ LO CHAIN

The 900 GHz LO is driven by a few milliwatts of power in the 88-105 GHz range. Three cascaded power amplifiers amplify the input signal to ~100 mW. This is then followed by a wideband isolator, built by Millitech, and two stages of frequency triplers as shown in Fig 1.

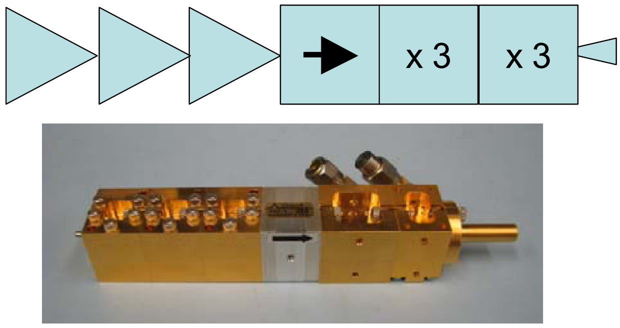

Fig.1: Schematic block diagram and photo of the 900 GHz LO chain, including power amplifiers, an isolator, two stages of frequency triplers, and a corrugated output horn.

The first stage tripler provides output power in the 265-325 GHz range. Its circuit is based on a GaAs Monolithic Membrane Device (MoMeD) with beamleads for electrical connections and handling [8]. The tripler, previously described in [9], has an efficiency of about 7-9% across the band, with average output power ~7-9mW. The second stage tripler (M2) uses a 3 μm GaAs MoMeD with 4 anodes in a balanced configuration. Its design and characterization were previously reported in [10].

The output power of the complete chain was measured using an Erickson PM2 calorimeter by removing the corrugated output horn and attaching a custom-made 300x150 μm to WR10 waveguide transition. At fixed bias voltages for both tripler stages, there is a strong standing wave due to the lack of isolation between the two triplers. By tuning the bias voltages of the frequency multiplier diodes, we were able to obtain a smooth frequency *vs.* power sweep that still meets the required minimum 50 μW of output power across the full 800-930 GHz band. Figure 2 shows the results of the measurements, uncorrected for the loss due to the waveguide transition.

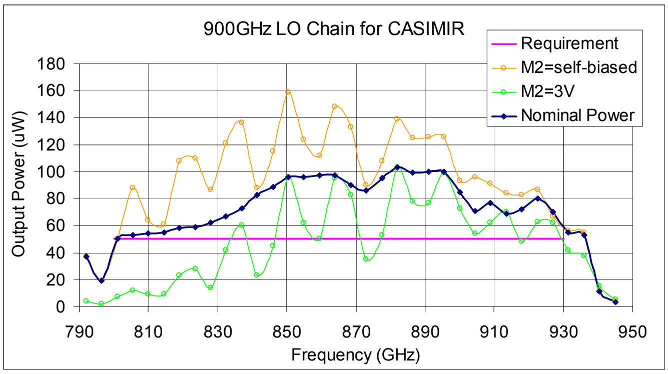

Fig.2: Performance of the 900 GHz LO Chain at room temperature. At fixed bias conditions, a standing wave pattern exists in the frequency sweep. By tuning the bias voltages properly, the nominal output power shown in dark blue is obtained.

III. 1 THz LO Chain

The 1 THz LO is driven by a few milliwatts of power in the 107-117 GHz range. Four cascaded power amplifiers amplify the input signal to ~80-100 mW. This is then followed by two stages of frequency triplers as shown in Fig. 3. Due to the lack of a low-loss wide bandwidth isolator at WR8 frequencies, no isolation exists between the amplifier and the first stage tripler. The final stage tripler has a diagonal horn integrated into the block described in [11]. The CASIMIR horn is scaled such that the dimension of the square on the output flange is 1.86 mm.

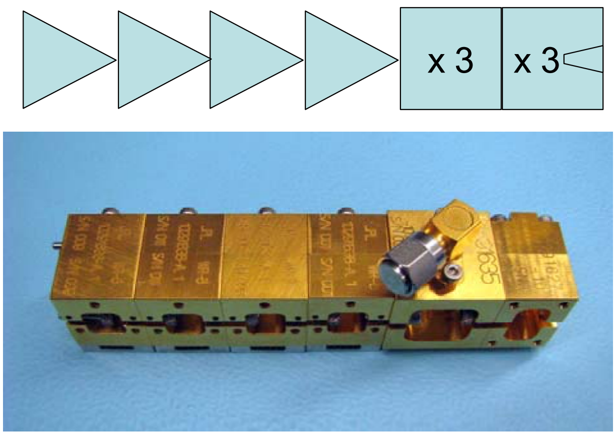

Fig.3: Schematic diagram and photo of the 1 THz LO Chain, including four power amplifier stages and two stages of frequency triplers.

The first stage tripler gives output in the 325-350 GHz range. Its circuit is a scaled version of the 265-325 GHz tripler used in the 900 GHz LO chain. This tripler produces about 6-11 mW of power across the band. The second stage tripler uses a 3 µm thick GaAs MoMeD with 2 anodes in a biasless configuration. The same device has been previously used on the Herschel HIFI instrument for the Band 5 (1.2 THz) receivers [12]. For the CASIMIR chain, the waveguides were redesigned for optimal efficiency in the 970-1040 GHz range.

The output power of the complete chain was measured using an Erickson PM2 calorimeter by attaching a circular to WR10 waveguide transition directly to the output face of the last stage tripler. With fixed bias voltages for both the power amplifier and tripler, the output power of the chain is shown in Figure 4. The required 50 µW of power across 970 to 1040 GHz is met at room temperature even without correcting for the waveguide transition loss. Peak measured power was 120 µW at 980 GHz. The compact nature of this chain, combined with the excellent output power performance without mechanical or electrical tuning, makes this chain very robust and easy to use.

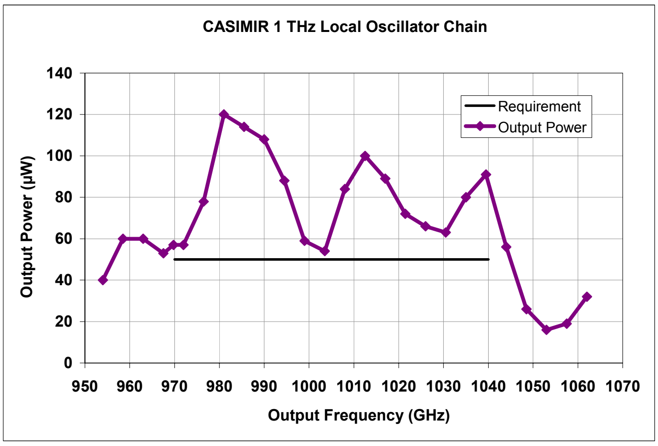

Fig.4: Performance of the 1 THz LO Chain. Measured with Erickson PM2 calorimeter, uncorrected for waveguide transition loss.

IV. 1.4 THz LO Chain

The 1.4 THz LO features three amplifier blocks, an isolator, and three stages of frequency multiplication. It is driven by a few milliwatts of power in the 72-82 GHz range. First, three cascaded power amplifiers amplify the input signal to ~130 mW. This is then followed by a wide-band isolator, a frequency doubler, and two additional stages of frequency triplers as shown in Fig 5.

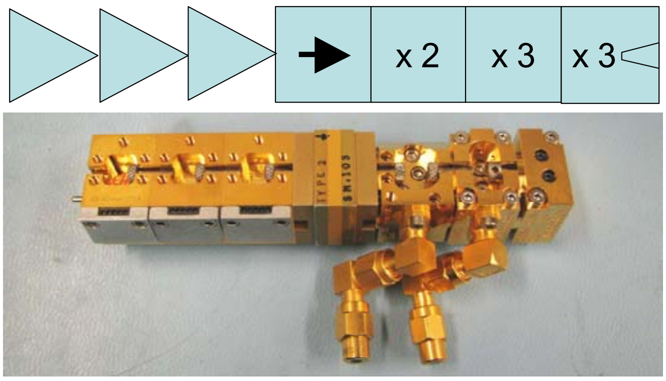

Fig.5: Schematic diagram and photo of the 1.4 THz LO Chain, including three power amplifier stages, one doubler stage and two tripler stages.

The first stage multiplier is a frequency doubler that gives output in the 144-164 GHz range. The circuit is based on the substrate-less device technology used on Herschel / HIFI [12], scaled to ~150 GHz. This doubler produces about 40 mW of power across the band with a fixed bias voltage of –6V.

The second stage multiplier is a frequency tripler operating from 430 to 495 GHz, with ~4 mW of power across 445 to 490 GHz. The bias voltage is mostly fixed at +12V except at output frequencies below 445 GHz, where it prefers to be biased closer to 0V. The circuit uses a 5 µm GaAs MoMeD which is a scaled version of the 265-325 GHz tripler discussed earlier in this paper.

The final stage frequency tripler features a 2-anode bias-less MoMeD device on a 3 µm thick GaAs membrane, shown in Figure 6. It operates from 1320 to 1470 GHz, and has an integrated diagonal horn [11]. The horn dimensions are scaled such that the output square dimension is 1.35 mm.

Fig.6: Photo of the 1.4 THz tripler device mounted in its waveguide block, featuring 2 anodes on 3 µm GaAs membrane in a biasless configuration.

A. Investigation and Management of Signal Purity

The photo in Figure 5 shows the presence of an extra waveguide shim between the second and third multiplier stages. This is inserted to suppress a spurious signal that was found after an investigation into the spectral purity of the chain, as described below.

The spectral purity of the 1.4 THz chain output signal was analysed with a Fourier Transform Spectrometer (FTS) based on a simple Michelson interferometer. With an input signal at f_0=80 GHz, the chain is expected to produce f_0x2x3x3 = $18f_0$, the 18th harmonic, at 1440 GHz. However, when the output spectrum is analysed with the FTS system, we find an additional signal at 1280 GHz that is stronger than that at 1440 GHz.

To investigate this spurious signal, the output of the first stage doubler was analysed with the FTS. It was found that a strong 4th harmonic ($4f_0$ = 320 GHz) was present in addition to the nominal 2nd harmonic ($2f_0$ = 160 GHz). When this 4th harmonic enters the second stage multiplier, it gets tripled to the 12th harmonic ($12f_0$ = 960 GHz), and at the same time, some of the 4th harmonic leaks through to the third stage multiplier. The last stage tripler takes these two additional inputs, the 12th harmonic and the 4th harmonic, and *mixes* them to produce the 16th harmonic at 1280 GHz. Additional signals at $12f_0$ and at $10f_0$, from mixing the $6f_0$ and $4f_0$ signals, are also present. The signal flow diagram and frequency spectrum are shown in Figure 7.

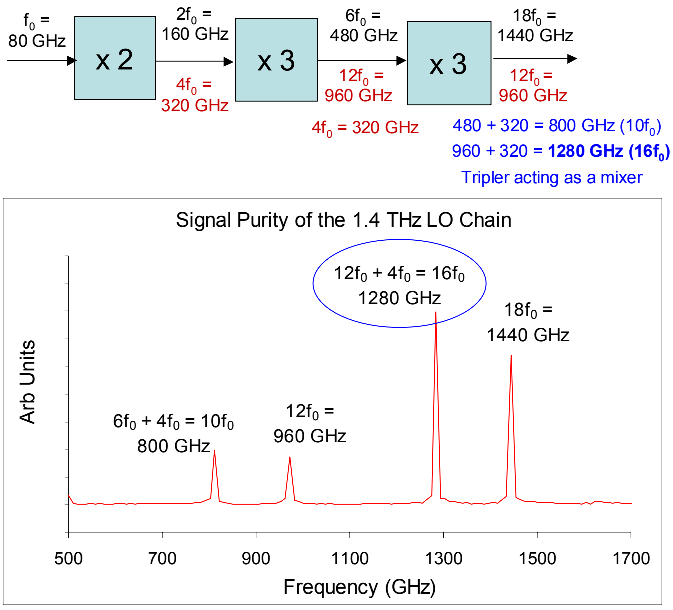

Fig.7: FTS spectrum of the 1.4 THz chain at 1440 GHz. The extra signals can be traced to the presence of a fourth harmonic at the output of the first stage doubler. This fourth harmonic propagates through the second multiplier as well as getting tripled before going into the third multiplier. The final stage tripler then acts as a mixer, producing the 10th and 16th harmonics in addition to the nominal 18th harmonic.

The solution to removing the spurious signal at $16f_0$ is to cutoff the $4f_0$ signal from going into the last stage tripler, thereby eliminating the mixing action. An extra waveguide shim with dimensions 432 µm x 216 µm x 1.5 mm, whose cutoff frequency is at 350 GHz, was machined and inserted between the second and third stage multipliers. FTS measurements of the output spectrum of the second stage multiplier before and after insertion of this waveguide confirm that the $4f_0$ signal is effectively cancelled after the extra waveguide section. With this waveguide shim inserted, the FTS spectrums of the chain at 1.36 THz and at 1.46 THz are shown in Figure 8. It is observed that in addition to the 18th harmonic, the 12th and 24th harmonics are still present due to mixing of the 18th and 6th harmonics. However, their power levels are much lower than the nominal signal, and the frequencies are far enough away from the main signal that they will not affect the LO pump into the SIS mixer.

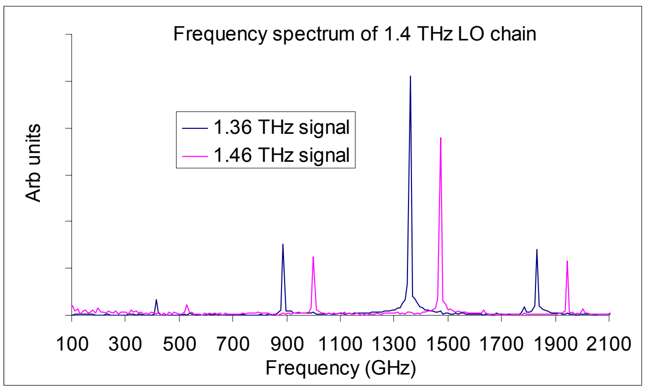

Fig. 8: Frequency spectrum of the 1.4 THz LO chain at 1.36 THz and 1.46 THz. The 16th harmonic has been removed by placing an extra waveguide shim between the second and third stage multipliers.

B. Frequency Sweep at Room Temperature

The output power of the complete 1.4 THz chain, including the extra waveguide shim, is measured by placing a Thomas Keating meter at Brewster's angle of 57 degrees to the axis, located ~10 cm away from the output horn. With nominally fixed bias voltages for the power amplifier and both stage multipliers, the output power of the chain is shown in Figure 9. The chain meets the required 10 µW of power across 1320 to 1470 GHz. A strong atmospheric absorption line due to water vapour is present at 1410 GHz, which could account for the dip seen in the frequency sweep. Peak measured power was 70 µW near 1350 GHz and 1395 GHz.

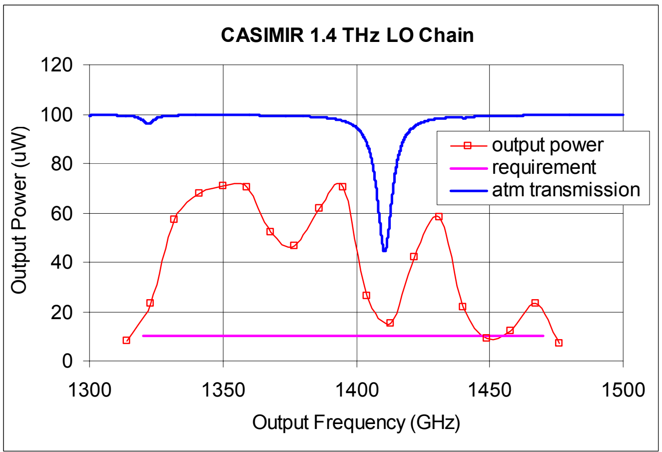

Fig.9: Performance of the 1.4 THz LO chain operated at room temperature, measured with a Thomas Keating meter, uncorrected for atmospheric losses from water vapour absorption. Atmospheric transmission is courtesy of Scott Paine's AM model [13] calculated with 25% relative humidity and 10 cm path length.

C. Frequency Sweep at 120K and Comparison with HIFI

We have also made measurements at the cryogenic temperature of 120K and compared the results with the Herschel / HIFI Band 6A (1.5 THz) LO chain. The multiplier blocks of the 1.4 THz chain were placed in a cryostat at 120K, while the amplifiers and isolator driving the multipliers remained at ambient temperatures outside the cryostat. Measurements were made with the Keating meter under the same bias conditions as at room temperature. Compared with room temperature results, the output power increased by a factor of approximately 3 dB across the band (see Figure 10). Output power was over 50 µW from 1325 GHz to 1445 GHz except around the water line at 1410 GHz. Peak output power was 129 µW at 1395 GHz. To the best of the authors' knowledge, this is the highest reported power by an all-solid state source in this frequency range.

In Figure 11, the performance of the CASIMIR chain at 120K is plotted against data from the Herschel / HIFI chain. The peak power of the CASIMIR chain is higher than the peak power of the HIFI chain by a factor of 6.

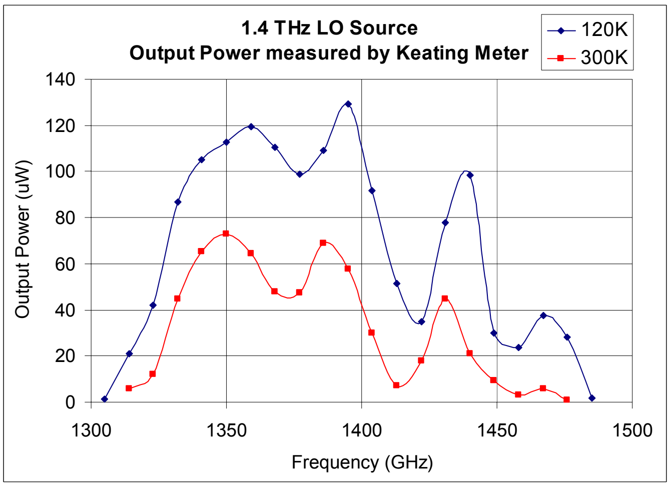

Fig. 10: Performance of the 1.4 THz LO chain at ambient and cryogenic temperatures. The output power at 120K is a factor of 3 dB better than at 300K.

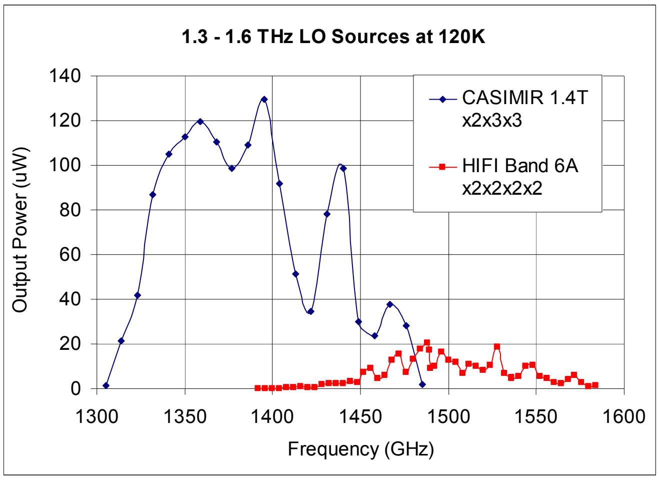

Fig. 11: Performance of the 1.4 THz LO chain compared to the Band 6A LO chain of Herschel HIFI.

V. CONCLUSIONS

The fabrication, development, and characterization of three local oscillator chains for CASIMIR have been presented. The 900 GHz and 1 THz LO chains meet and exceed the required performance in terms of output power and frequency range. The 1.4 THz LO chain exhibits state-of-the-art performance at room temperature and when cooled to 120 K. Compared with Herschel / HIFI, the results are impressive: more than a factor of 10 better at room temperature and a factor of 6 improvement at 120K.

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