Solid-State Terahertz Sources for Space Applications

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1. Abstract

This paper discusses the construction of solid-state frequency multiplier chains [1, 2] utilized for terahertz receiver applications such as the Herschel Space Observatory [3]. Emphasis will be placed on the specific requirements to be met and challenges that were encountered. The availability of high power amplifiers at 100 GHz [4] makes it possible to cascade frequency doublers and triplers with sufficient RF power to pump heterodyne receivers at THz frequencies. The environmental and mechanical constraints will be addressed as well as reliability issues.

2. Introduction

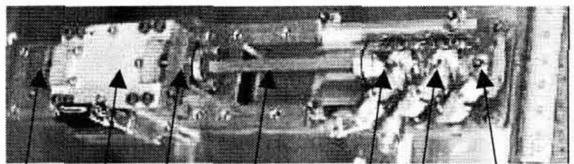
One of the instruments on Herschel is the Heterodyne Instrument for the Far Infrared (HIFI). This instrument will perform high-resolution spectroscopy with sensitive 4 K Super-conductor-Insulator-Superconductor (SIS) or Hot Electron Bolometer (HEB) mixers. HIFI has seven frequency bands covering nearly all frequencies from 480 GHz to 1.9 THz. Six local oscillator chains (LOCs) built at JPL will cover from 1.1 to 1.25 THz and from 1.4 to 1.9 THz. The LOCs described here begin with power amplifiers driven by commercial synthesizers to produce 100 to 200 mW from 75 to 110 GHz [4]. The RF power drives chains of two to four cascaded frequency doublers and triplers to reach the required output frequencies. The chains that cover 1120 to 1250 GHz will be discussed in detail along with some discussion of the differences between these and the higher frequency chains provided at the end of this paper.

The main requirements include: 1) The LOCs will operate in vacuum at 120 K. 2) Precise mechanical alignment of the optical element is required. Specifically, the position of the output horn must be aligned along the propagation axis to within ±100 μm and along the transverse axes to within ±50 μm at 120K. 3) The total LOC mass must not exceed 500 grams and it must fit in a $38x57x245\ mm^3$ volume. 4) No mechanical tuners may be used. 5) The maximum output power must be at least 45 μW for the 1.2 THz chains, and the RF power level must be adjustable to match the mixer power needs. 6) The RF output beam is transmitted via a feed horn and coupled quasi-optically to the mixer.

3. Implementation

For precise alignment, cascaded frequency doublers and triplers were fastened to an adjustable V-bracket. Four vertical alignment screws provide micrometer-precision adjustment of the feed horn position at room temperature. The precise location of the optical axis was adjusted to compensate for thermal contraction of the components when cooled to the 120 K operating temperature. Furthermore, the selected materials must have adequate thermal conductivity to accommodate conductive cooling. The multipliers are separated from the power amplifier module by a waveguide, which allows flexing for optical alignment and relieves thermal stress (see Fig. 1). The waveguide is fabricated from aluminum as is the base plate; thus, minimizing mechanical stresses during cooling. The power amplifier is made of a silicon/aluminum composite. This material matches the thermal expansion coefficient of the GaAs MMIC amplifier chips [4].

The power amplifier dissipates 6 W of DC power, so it is bolted to the base plate with 8 fasteners to aid in heat dissipation. All RF flanges are precisely machined and carefully mated to minimize leakage of RF power, which confuses RF power measurement. RF measurements were performed with absorptive material around the chain to reduce interference. High-yield steel is utilized for the fasteners on all RF flanges to provide sufficient clamping strength at operating temperature.



Isolator, PA, Isolator, Waveguide, Doubler, Doubler, Tripler

Figure 1: 1200 GHz LOC mounted on a supporting plate.

4. Reliability

The mechanical and electrical robustness of the hardware was space qualified in accordance with the ESA interface definition document, IID-A for the Herschel payload. The manufacturing processes for the individual components were individually qualified, and each complete chain was subjected to environmental tests consisting of interleaved vibration and thermal testing. Manufacturing screening started with static acceleration of individual multipliers to 1000 Gs in a centrifuge. This is nearly 10 times the expected maximum random acceleration during launch. To test the reaction to thermal stress, a complete LOC was cycled 60 times between 310 K and 85 K. Then the assembly was vibrated along each of 3 orthogonal axes at qualification levels, which are higher than the vibration levels predicted at launch. Qualification was complete after extensive RF testing at room temperature and at 120 K. Neither mechanical failure nor change in electrical performance was detected during qualification testing.

Extensive ESD precautions must be taken with this kind of hardware, since the ESD sensitivity levels were determined to be less than 10 V [5]. DC bias and RF power limits were determined as a function of input power and frequency, then the operational conditions were determined by derating the maximum voltages, currents, and RF power to more conservative values [5]. Since, the final 1.2 THz stage has by far the smallest anode area, about $0.5\ \mu m^2$, this stage was equipped with a biasless circuit, to eliminate the ESD risk of an external bias connection. After the RF performance of each chain was characterized, long-term RF operation and on-off cycling were performed to verify long-term reliability.

5. RF Performance

The power amplifier has nearly 50 dB gain and is operated in saturation in order to reduce noise. Isolators were placed at the input and output of the amplifier. By varying the output stage drain bias voltage of the saturated power amplifier, the RF output of the LOC can be controlled by greater than 20dB. Additionally this control allows the RF power driving the multipliers to be limited to far less than the maximum of over 200 mW. Use of the amplifier bias to adjust the RF power is preferable to power adjustment with the multiplier bias because of safety and stability issues related to increased reflection of power between multiplier stages and potential oscillations due to biasing the multipliers far from their optimum operating points [5].

The multipliers are electronically tunable for about 10% bandwidth. Mechanical tuners would provide additional freedom for improving the bandwidth; but would increase the mass and complexity. Moving parts would reduce reliability, especially at the 120K operating temperature. Bandwidth is reduced by the non-linear interactions between stages. RF isolators between the frequency multipliers can help reduce these interactions, but these components are only available up to 200 GHz. Further, the 200 GHz isolators have more than 1dB of loss and reduce power peaks without improving power minima. Instead, multipliers were carefully matched to achieve the maximum possible bandwidth. The initial plan was to cover this frequency band with two LOCs because it was feared that a single chain would not have enough bandwidth to cover the entire 1120 to 1250 GHz range. However, the performance of the components is better than expected, so all of the band can be covered with a single chain. The RF performance of a typical 1200 GHz LOC is shown in Fig. 2. The required output power is 45 µW from 1120 to 1250 GHz.

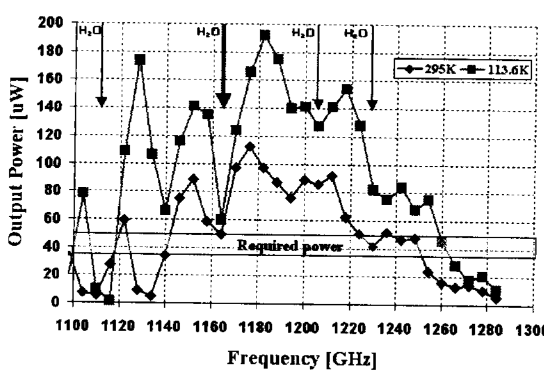


Figure 2: RF output power of a 1.2 THz LOC at 295 K and 114 K. The structure is mainly caused by the waveguide transition to the power meter and by water absorption at 1113, 1163, 1207, and 1228 GHz. Efficiency improves with cooling due to increased mobility of electrons.

To verify the optical interface performance, the beam pattern amplitude was measured with a signal-to-noise ratio better than 10 dB and the main polarization axis was determined. The cross polarization of the diagonal horn was higher than what would be expected from a corrugated horn. The diagonal horn was used because it could be machined with a short waveguide directly into the multiplier split block. By doing this, the RF losses at THz frequencies were minimized.

An important aspect of characterizing an LOC is measurement of any undesirable harmonics that are generated [8], since unwanted harmonics may interfere with mixer performance. With the circuit designs used in [9], harmonics are predicted to be suppressed by more than 20 dB. Furthermore, the output waveguides are cut off for the sub-harmonics. The strength of the harmonics is strongly dependent on the circuits, manufacturing tolerances, and bias conditions. Accurate measurement was difficult; but FTS measurements that have been performed indicate that parasitic output signals were 15 dB or more below the carrier.

LOCs for HIFI are also being constructed to cover 1.4 to 1.9 THz. These are similar to the 1.2 THz chain; but the higher frequency range requires higher multiplication factors. Since the HEB mixers for this band are optimized for low LO power, the LOC power requirement is 2 to 3 µW. Significantly higher powers have been demonstrated with a chain of four cascaded doublers up to 1.5 THz [2] and by a doubler-tripler-tripler chain to 1.8 THz [10].

6. Conclusions

Reliable, compact, tuner-less solid-state LOCs producing over 45 µW from 1.1 to 1.25 THz and chains producing over 2 µW from 1.4 to 1.9 THz have been built or are under construction. Environmental tests revealed no weakness in the workmanship and assembly. No degradation in mechanical structure, RF performance, or DC characteristics was detected after extensive tests. A large RF bandwidth is achievable by carefully selecting and matching individual multiplier stages for optimal performance and minimal interaction.

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