

THz frequency multiplier chains based on planar Schottky diodes

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1. Abstract

The Herschel Space Observatory (HSO), an ESA cornerstone mission with NASA contribution, will enable a comprehensive study of the galactic and the extra galactic universe. At the heart of this exploration are ultra sensitive coherent detectors for high-resolution spectroscopy. Successful operation of these receivers is predicated on providing a sufficiently powerful local oscillator (LO) source. Historically, a versatile space qualified LO source for frequencies beyond 500 GHz has been difficult if not impossible. This paper will focus on the effort under way to develop, build, characterize and qualify a LO chain to 1200 GHz (Band 5 on HSO) that is based on planar GaAs diodes mounted in waveguide circuits. State-of-the-art performance has been obtained from a three-stage (x2x2x3) multiplier chain that can provide a peak output power of 120 μ W (1178 GHz) at room temperature and a peak output power of 190 μ W at 1183 GHz when cooled to 113 K. Implementation of this LO source for the Heterodyne Instrument for Far Infrared (HIFI) one of three instruments on HSO will be discussed in detail.

Keywords: Planar Schottky diodes, THz, Multiplier, Local Oscillator, Spectroscopy

2. Motivation

The submillimeter-wave spectral bands are one of the least explored, yet information rich, regions of the electromagnetic spectrum with applications in radio astronomy, planetary science and planetary atmospheres. The molecular lines that can be observed at submillimeter wavelengths offer a unique probe of the mechanisms that drive interstellar chemistry including effects on star formation. These molecular lines can also act as tracers for reaction rates in planetary atmospheres. Important applications in Earth's atmosphere range from ozone chemistry to global warming. Because the atmosphere is opaque in the submillimeter wavelength range, observations must be made either from high mountain observatories, aircraft, balloons or space-based platforms, hence the interest on the part of both ESA and NASA.

A number of LO sources have been flown both on spacecraft (e.g. SWAS) and on aircraft such as the Kuiper Airborne Observatory (KAO). However, HSO broke new ground: first by requiring a large number of multiplier circuits to be built and second by requiring solid state sources as high as 2.7 THz [1]. The highest frequency band of the proposed mission was eventually de-scoped but this still left a challenging task requiring broadband coverage from 400 to 1900 GHz. The traditional approach towards meeting these requirements would have been to use Gunn diodes in the 100 GHz range and then utilize whisker-contacted diodes as frequency multipliers. This

approach is extremely difficult to apply over wide bandwidths at the high frequencies needed for HIFI. For the very high frequencies, the alternative approach could have been a FIR laser such as that used in the 2.5 THz source for MLS, but this would entail a number of logistical hurdles. Thus, at the onset of the proposed mission it was obvious that a bold new approach must be adopted to develop robust LO sources that could work well into the THz range.

3. Approach

Given HSO's desire for high frequency, wide bandwidth coverage plus the sheer number of multipliers required made it obvious that a new fabrication approach, which is repeatable, robust, and reliable is necessary. This approach entails several significant innovations. First of all, GaAs based HEMT power amplifiers have been developed and demonstrated that can provide up to a few hundred milliwatts of RF power at 100 GHz. These modules have now been built and tested both at room temperature and at cryogenic temperatures with very impressive performance [2]. While the use of these power amplifier modules provides an opportunity it also poses a challenge: the first stage multiplier circuits must be able to handle these high RF input powers. This also meant that realistic thermal models had to be developed to design the circuits for high power handling.

The second major feature of the new approach is the incorporation of planar Schottky diode integrated circuits in waveguide blocks. Using planar circuit techniques, one can easily incorporate multiple anodes integrated with impedance matching transmission lines, filters, waveguide probes, into a single chip useable to the highest frequency bands. Several variations of the planar processes are used, tailored to the specific frequency bands needed.

Since the HSO is an observational facility great emphasis was placed to getting as much frequency coverage as possible. In ground-based receivers, wide frequency coverage can be attained by use of mechanical tuners in the waveguide blocks to adjust the matching impedances. However, mechanical tuners are undesirable in space applications because of their complexity and reliability concerns. An effort was made to design and build fix-tuned broadband circuits. Emphasis was placed on bandwidth even at the expense of maximum attainable efficiency.

4. A 1200 GHz LO Chain

A typical Band 5 frequency multiplier chain is shown in Figure 1. The RF-input, a K-band tripler from 23.6-37.6 GHz driven by a synthesizer source, is a separate unit and not shown. Low-loss cryogenic isolators are mounted on the input and output of the power amplifier module to provide sufficient RF isolation. These isolators are optimized for high power handling and for operation at cryogenic temperatures. On the output side of the power amplifier a length of waveguide with 45° degree twist rotates the RF fields to facilitate integration with the subsequent LO optics, also not shown in Figure 1.

The first and second frequency multipliers are balanced doublers separated by another isolator. A low loss isolator was not available at the time of chain integration and thus a simple waveguide block with WR-5 waveguide was inserted as a placeholder. The third and final multiplier is a balanced tripler. All of the multiplier housings are an E-plane split block machined from brass and gold-plated. In the last stage tripler, a diagonal horn is directly machined into the block to couple the LO into the mixer via various quasi-optical elements.

The design of the multipliers is based on an iterative process that optimizes performance based on chip topography, machining tolerances and operating conditions such as input power and temperature. Full three-dimensional electromagnetic solvers along with advanced harmonic balance tools are used to design the multiplier. Moreover, since no mechanical tuners are to be used special effort has to be made to make the circuits broadband even at the expense of reduced efficiency. Therefore the planar GaAs device and the embedding waveguide structure was designed and optimized together. For the doublers as well as for the tripler we pursued a three-step design strategy [3, 4]. In the first step the non-linear component, the diode, was optimized in its anode size at a given doping of the GaAs. The embedding impedance was analyzed by using a harmonic balance simulator equipped with a high frequency diode model developed at JPL [3]. The second step was to design the linear components of the multiplier circuit. Input and output waveguides as well as the bias filter were separately analyzed. The characteristic embedding impedances were calculated using the HFSS finite element electromagnetic simulator. All impedances of the non-linear and the linear simulations were integrated in a complete simulation. In this third step the performance of the complete design was analyzed and optimized.

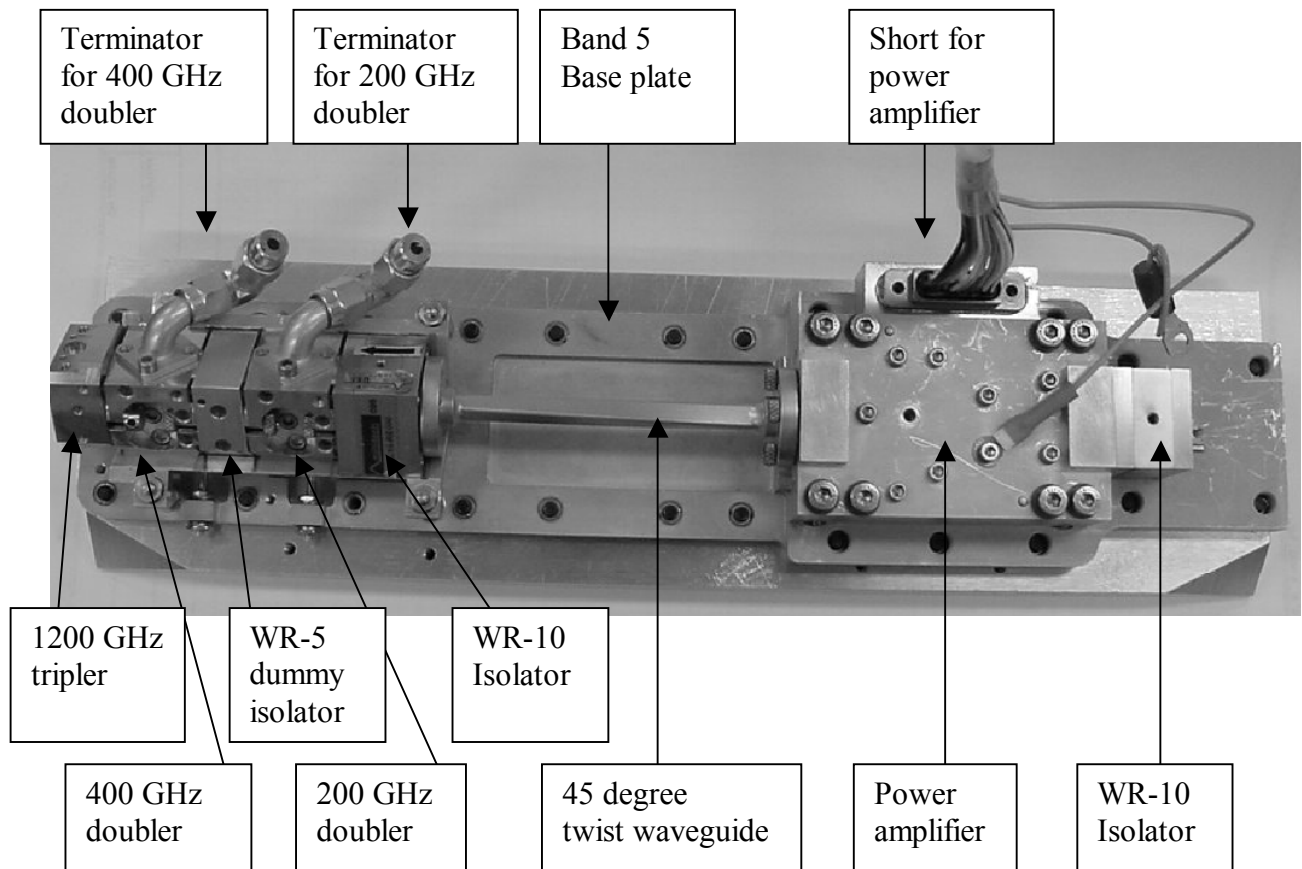


Figure 1: Band 5 frequency multiplier chain bolted with the base plate on a mounting plate. The k-band tripler at the input side of the power amplifier is not displayed.

The Schottky devices for the first two doublers are based on the “substrateless” monolithic integrated circuit reported in [4, 5]. Figure 2 shows the 200 GHz balanced doubler chip placed in

the waveguide block. These circuits are distinguished by the fact that most of the GaAs under the chip has been removed. Details of this technology have been presented previously [4,5]. For the 200 GHz chip the thickness of the substrate has been thinned down to about 40 microns. For the 400 GHz circuit the substrate thickness was further reduced to 22 microns. The 400 GHz chip has 4 anodes as compared to 6 for the 200 GHz doubler.

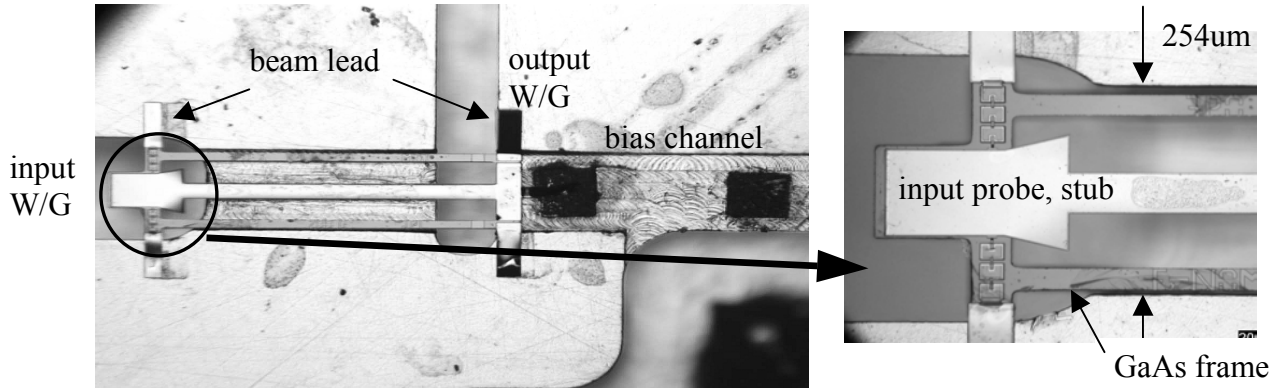


Figure 2: A 200 GHz chip mounted in the block is shown at the left. The magnified anode area is shown on the right. Three anodes per branch are used for impedance matching and power handling. The input and output waveguides have reduced waveguide heights to accommodate impedance matching

For the final stage tripler even with a thinner substrate it was difficult to design the appropriate broadband multiplier [6]. Thus, a different technology, based on GaAs membranes [5] was used to make the chip shown in Figure 3.

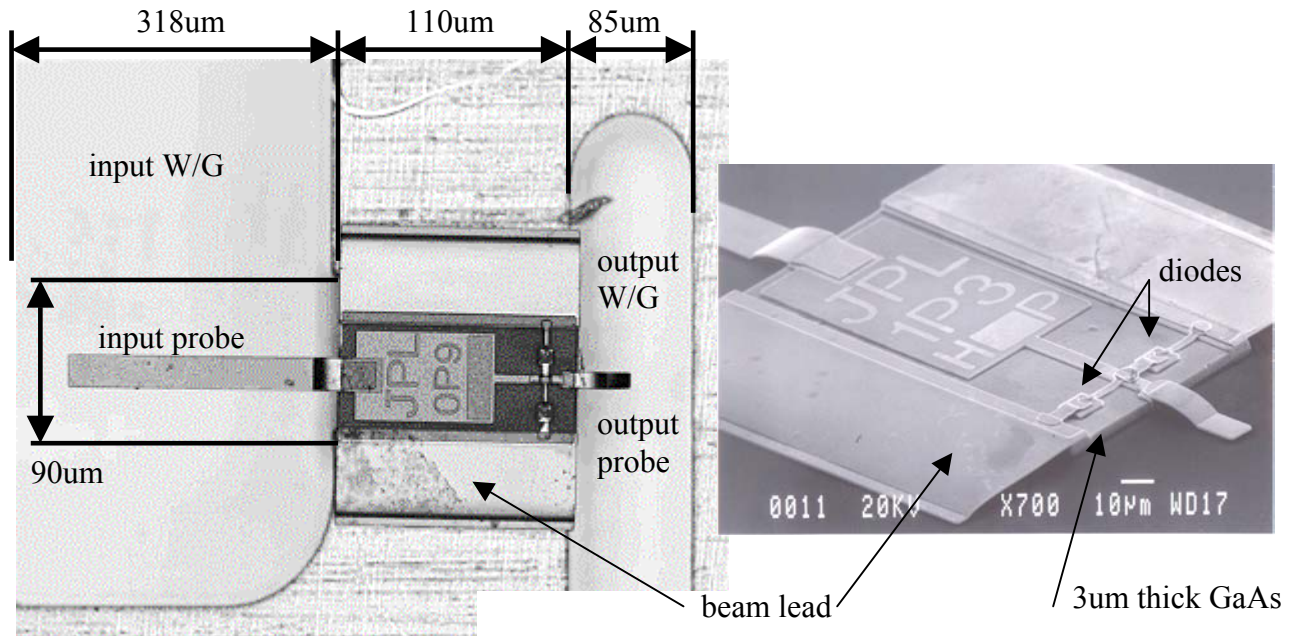


Figure 3: Bias-less GaAs membrane circuit in the last multiplier stage of Band 5. A 3 μ m thick GaAs membrane is suspended across a channel in the split block. Two large beam leads provide the mechanical support and ground contacts to the block and two narrow beam leads act as RF probes in the input and output waveguides.

In this process all of the substrate is removed and only a three micron thick membrane is used to hold the chip together. These chips have proven to be very robust. Two large beam leads provide the mechanical support and ground contacts to the block. Input and output coupling is accomplished via on-chip E-plane probes.

5. Multiplier chain performance

Several different blocks and diode variations of the three multiplier stages were investigated with the goal of building a frequency chain for the entire Band 5 frequency range (1119-1250 GHz). Figure 4 shows the performance of the 200 GHz multiplier at room temperature. When the doubler is pumped with 150 mW the measured output power is more than 35 mW over most of the desired output frequency range. The efficiency is between 22 to 28 % across the band. On the 400 GHz doubler (Figure 5) the measured efficiency is about 20 % and the output power is 7 mW with a peak power of 9 mW. The performance of the complete chain both at room temperature and at approximately 113 K is shown in Figure 6. For all of the above measurements the bias on the first two stages is adjusted at each frequency to maximize the output power. The final stage tripler utilizes a self-biased chip and thus does not require any bias tuning. Results from a cryogenic chain at 400 GHz have been previously reported in [7].

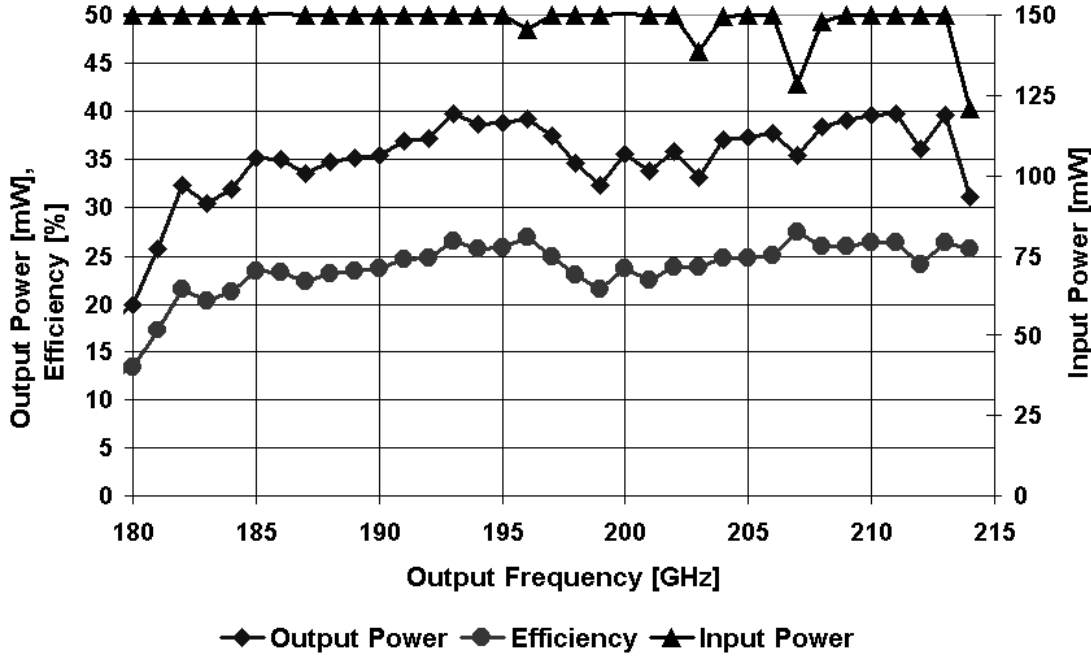


Figure 4: Output power and efficiency of the 200 GHz balanced doubler at room temperature.

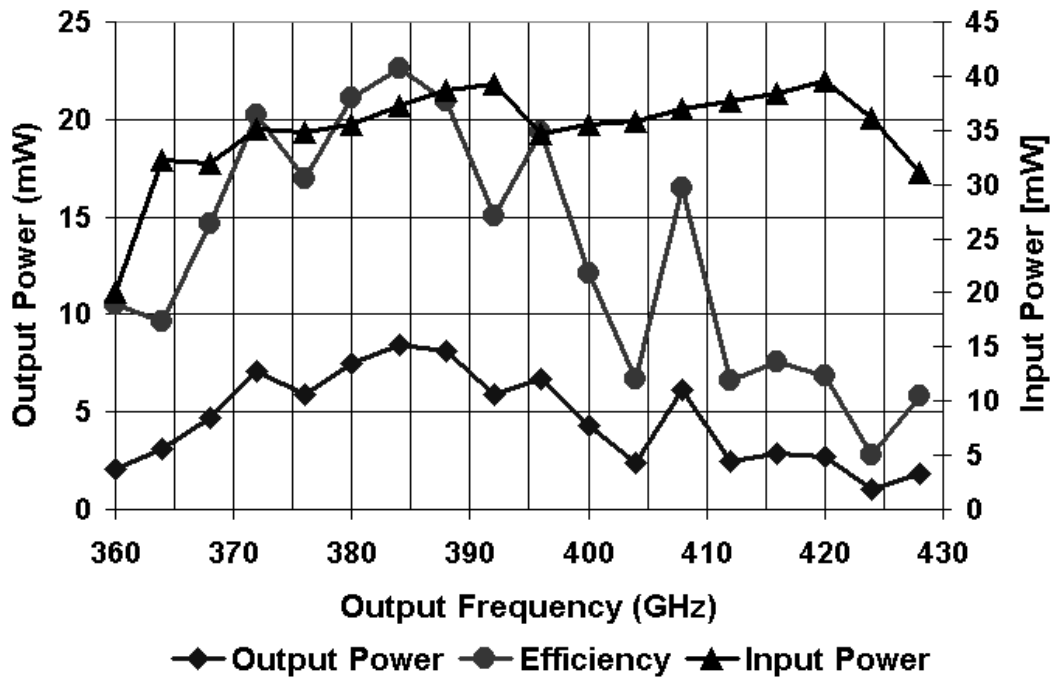


Figure 5: Output power and efficiency of the 400 GHz balanced doubler at room temperature.

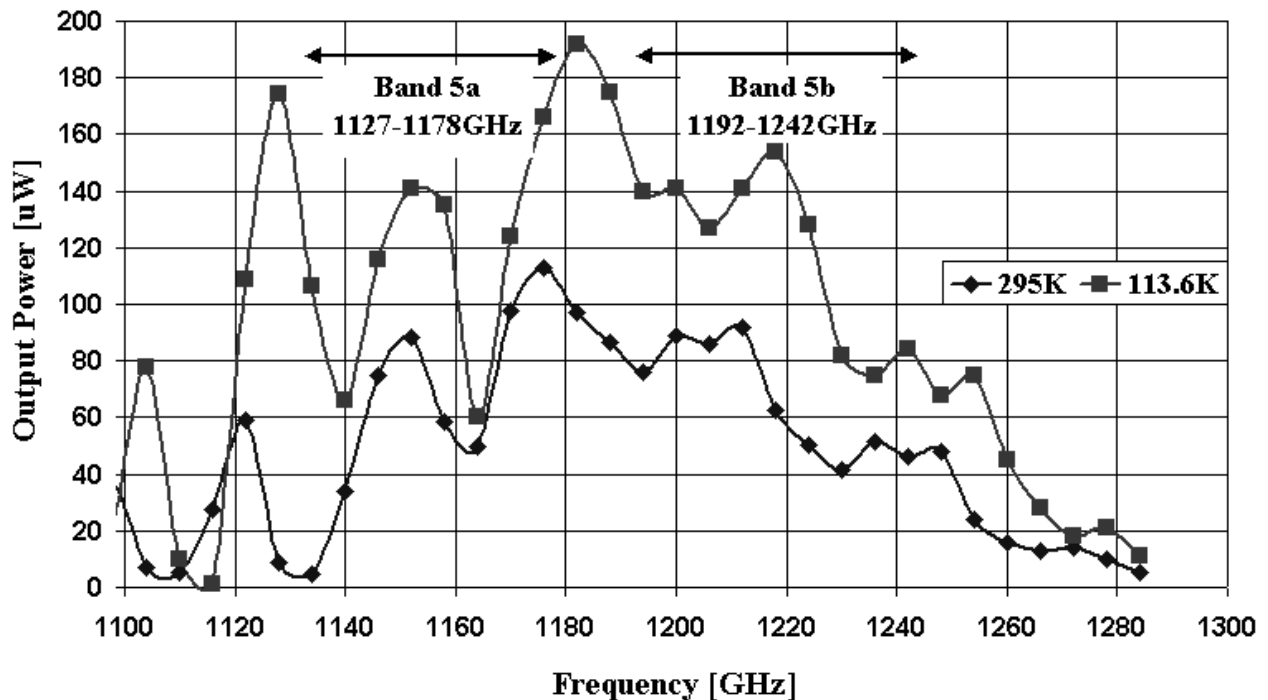


Figure 6: Output power of the 1200 GHz frequency chain (x2x2x3) at room temperature and at 113 K. When the chain is cooled to 113K the full frequency range of Band 5 is covered. The required output power range at operating temperature (120K) is between 35 and 50 μ W.

6. System level constraints

6.1. Mechanical interface

Mounting of the complete chain in the local oscillator sub-assembly presented a challenge. A mounting scheme was desired that would allow for some flexibility in moving the position of the output horn with respect to a 'mounting plate'. It was also desirable to be able to test the chain both at room temperature and at cryogenic operating temperature. Moreover, the total volume available for the chain mounting was rather limited. A flexure design has been constructed to meet these requirements. The chain and flexure are shown in Figure 1. The subsystem specifications on the position of the RF beam are ± 100 microns in the propagation axis and ± 50 microns in the two axes perpendicular to the propagation axes. With 22 M3 fasteners the interface plate is bolted onto the next higher assembly level. The holes for these bolts are over sized by 500 microns to allow for coarse orientation. More precise alignment of the RF beam generated by a diagonal feed horn is possible with four vertical screws and two horizontal alignment screws on the flexure as indicated in Figure 7. The 70.9mm long twisted waveguide section provides the flexibility needed for the adjustments. All components used in the chain have different thermal expansion coefficients and this has been taken into consideration with the design.

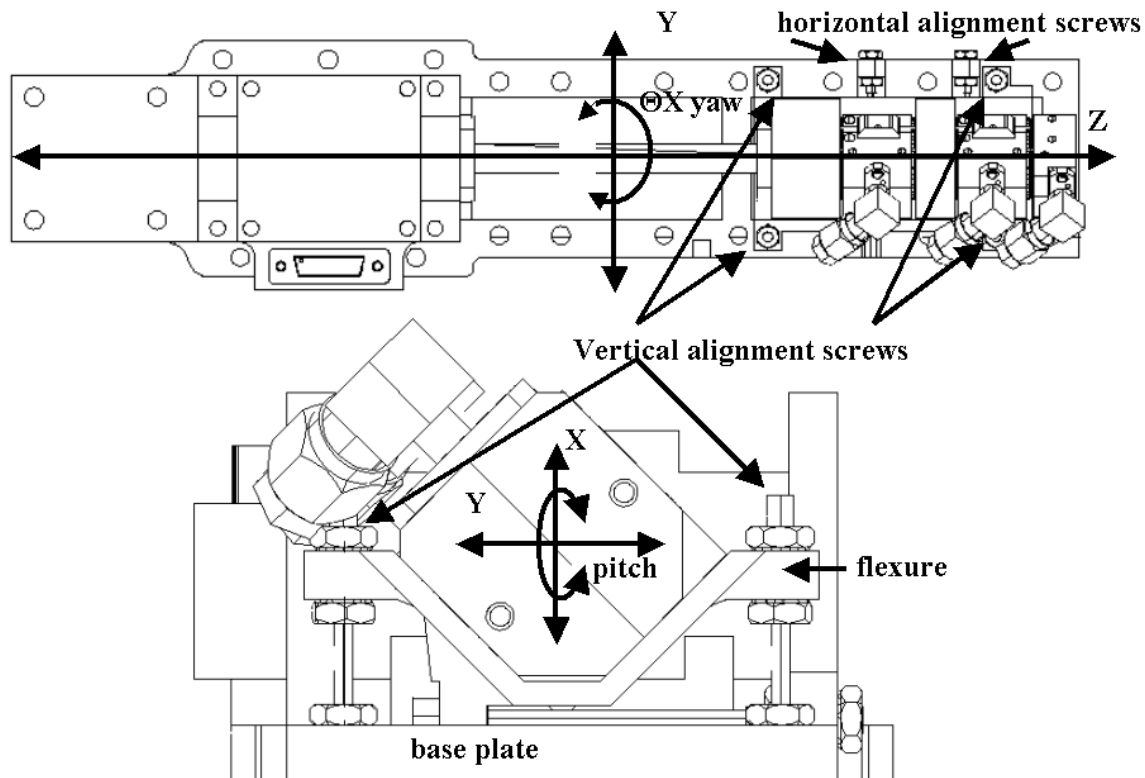


Figure 7: Top and front views of the chain mounted on the flexure are shown in this figure. Two vertical alignment screws are shown and one of the horizontal alignment screws.

6.2. Optical interface

A diagonal horn integrated in the frequency tripler is used as the antenna [8]. Compared with the Pickett-Potter or the corrugated horn this horn is relatively simpler to fabricate in a split block. It also provides the desired beam pattern for interface to the optical sub-system. The beam pattern for one of the nominal chains has recently been measured in the far field at MPIfR (Max-Planck-Institut fuer Radioastronomie) and shown in Figure 8 (courtesy of C. Kasemann and T. Klein). An AB Millimetre network analyzer was used to measure the amplitude and phase. A dynamic range of nearly 40dB at an output power level of approximately 50 μ W (room temperature) at 1120 GHz was achievable. The measured beam agrees quite well with the theoretical prediction, however there is a slight asymmetry in the side lobes (-20dB level). This might be attributable to a slight offset between the two block halves. A modified alignment procedure will be used to minimize distortion of the RF beam.

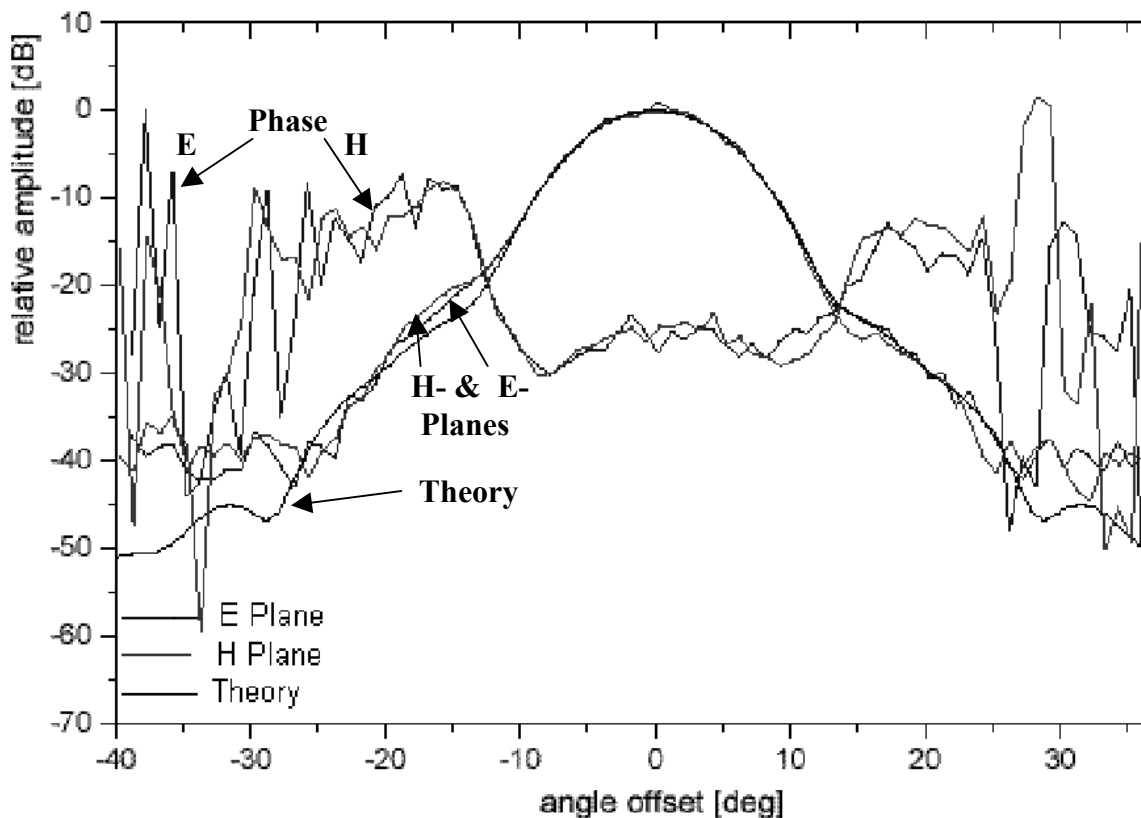


Figure 8: Beam pattern measurement of the 1200GHz diagonal feedhorn. The measurement was performed at the MPIfR (Max-Planck-Institut fuer Radioastronomie) in Bonn/Germany by Christoph Kasemann and Thomas Klein.

6.3. Power Leveling

Power leveling of +3 dB above the optimal and -10 dB below the optimal LO power is desirable from a system point of view. There are a number of possible solutions. The simplest would be to use an electronic variable attenuator in the chain. A component with acceptable loss has not been found, although some concepts have shown good promise [9]. A second approach is to detune the chain by adjusting the bias on the multiplier stages.

Figure 9 shows the effect on output power of a chain when the bias voltage on the first stage multiplier is varied. The 200 GHz doubler is nominally biased at -5 V with 2 mA of rectified current. The 400 GHz doubler is nominally biased at -5.2 V with 15 μ A of current. As the bias on the 200 GHz stage is further increased some power adjustment becomes possible. However, the current through the second stage also varies. With increasing reverse voltage the reliability of the diodes is compromised.

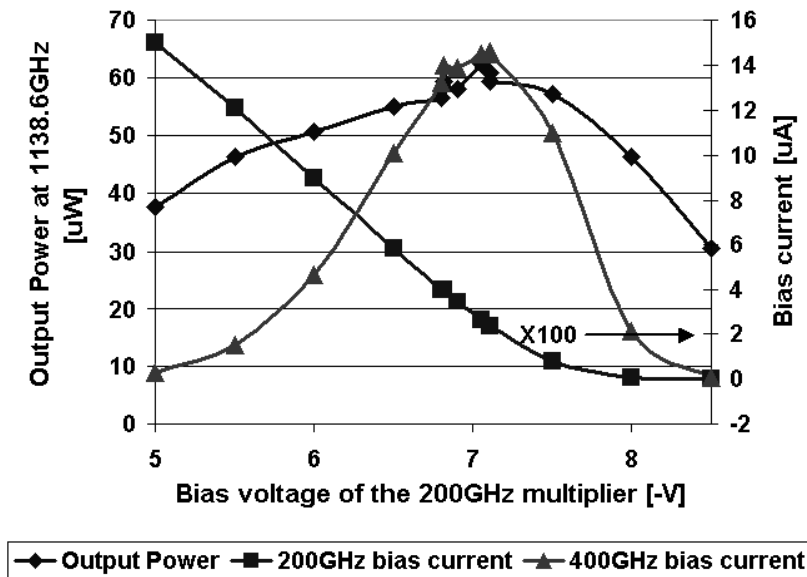


Figure 9: The output power of the chain versus the rectified currents in the first two stages are displayed. Care must be taken to avoid excessive reverse currents during any part of the pump-cycle that can cause device degradation.

Similarly, Figure 10 shows the effect on output power from a nominal chain when the bias of the second stage is varied. The 400 GHz doubler showed a fast change from positive current to negative bias current when its bias voltage was moved to more negative values. This indicates that the input RF power and the DC bias condition applied on the multiplier have to be limited to avoid degradation and/or destruction of the device. Even though this demonstrates that some bias detuning can be used there are certain limitations. The effect of bias detuning on noise and chain stability is also not well understood at this point in time. Moreover, one has to be extremely careful not to detune the bias into an unsafe regime where the diodes might be damaged. This second necessity strongly limits the practicality of this technique.

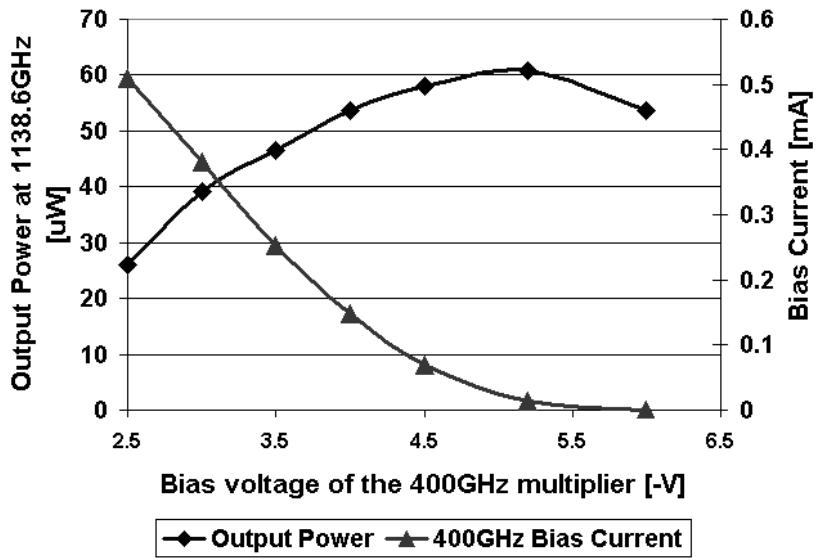


Figure 10: Output power of a nominal 1200 GHz chain versus the bias conditions on the second stage multiplier. More than 3dB of power leveling is not recommended since the required bias conditions can cause excessive reverse current through the diodes.

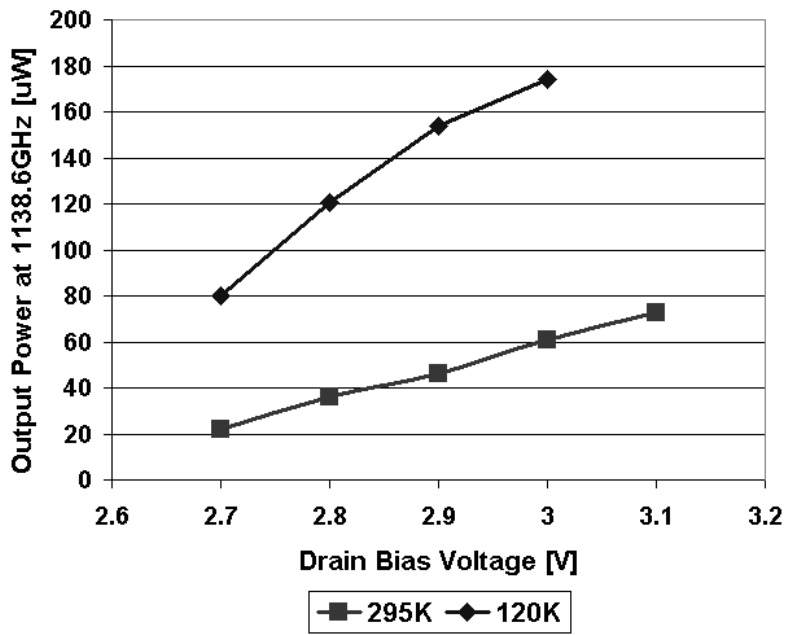


Figure 11: Output power of a nominal 1200 GHz chain as a function of drain bias both at room temperature and at 120 K. More than 3 dB of power leveling can be obtained.

A third approach is to reduce the amplifier bias voltage. This was not possible on the earlier chipsets due to out of band oscillations, but the most recent chips seem to operate well with reduced drain bias. The output power of a nominal chain with drain bias control is shown in Figure 11. The output power of the power amplifier can be adjusted from 10 dBm to 25 dBm at 120K with a 0 dBm input signal [2]. Due to the simplicity of this approach it will be desirable to use this as the primary control while finer adjustments can be made with multiplier bias.

7. Conclusion

A fully solid state LO chain that covers the 1119 to 1250 GHz frequency range (HSO Band 5) has been demonstrated. The output power is above 40 microwatts throughout this frequency band when the chain is operated at cryogenic temperatures. Electronic power leveling based on power amplifier bias and multiplier biases has been demonstrated. The chain is currently being flight qualified and a number of interface concerns between the chain and the subassembly have been addressed. Chain stability and noise properties are currently also under investigation [10].

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