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Cryogenic operation of GaAs based multiplier chains to 400 GHz

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Abstract – The FIRST/HIFI mission allows for the local oscillator frequency multiplier chains to be cooled to 120-150 K in order to increase available output power. This paper will discuss the implication of cooling on GaAs based planar Schottky diode varactors for flight applications. A robust testbed that has been built to measure output power over a wide range of frequencies will be described. Preliminary measurements at cryogenic temperatures done on individual multipliers at 200 GHz along with multiplier chains to 400 GHz will be presented. In a 182-212 GHz designed balanced doubler the peak efficiency at 201 GHz improves from 17% to 30% upon cooling from 300 K to 50 K. When this stage is used to pump a 362-424 GHz designed balanced doubler the efficiency of the two-stage chain increases from less than 0.8% to 3%. This represents an increase in efficiency of 6 dB.

I. INTRODUCTION

GaAs based planar Schottky diode varactor frequency multipliers are being developed at the Jet propulsion Laboratory for the Heterodyne Instrument of the far Infrared and Submillimeter Space Telescope (FIRST-HIFI). The planned FIRST mission will be the only space facility covering the largely unexplored but scientifically significant spectrum from 80 μm to 670 μm [1]. The multiplier technology that is being developed for this mission has been outlined previously [2,3]. A better understanding of multiplier circuits coupled with recent advances in the fabrication of the circuits and planar devices has resulted in tremendous progress towards building planar Schottky diode varactors. Planar Schottky diode multipliers have now been demonstrated up to 400 GHz with excellent performance [4,5,6]. A number of advantages of utilizing planar diode technology for space applications have been described [7]. One advantage that is perhaps not so apparent is the ability of well-designed planar technology to withstand cooling and thermal cycling. In principal whisker contacted circuits can be cooled but the inherently mechanically sensitive approach to the building of whisker contacted circuits does not readily lend itself to thermal cycling.

It has been established that cooling of multiplier circuits can have considerable influence on the output power and efficiency of GaAs multipliers [8,9]. However, what has not been fully explored is the intricate tradeoff between the various diode parameters when one is designing for low-temperature high input-power applications. Only minor temperature dependence is expected in the circuit

losses and embedding impedances. However, the electron mobility in GaAs is strongly temperature dependent. There is a peak in the electron mobility near 100 K for an epitaxial doping of $1.10^{17} \text{ cm}^{-3}$ [10]. Because series resistance is inversely proportional to electron mobility, an increase in multiplier efficiency is expected at cryogenic temperatures. However, a better understanding of electron transport in doped GaAs as a function of temperature is required to take full advantage of the cooling. Moreover, in high input power applications the anode area is substantially hotter than the ambient temperature and accurate thermal models of the chips are required to optimize the anode characteristics for a given frequency, input power and temperature. Work is still under way to obtain a realistic diode model that includes all of these effects and will be reported in the future. This paper will present measured power and efficiency data for a high input-power 200 GHz multiplier circuit. Cryogenic data on a 400 GHz multiplier chain will be also presented. Finally, a robust setup that utilizes a quasi-optical approach for the measurement of output power has been designed and tested to 400 GHz and will be described.

II. DESCRIPTION OF THE TEST SETUP

The test setup consists of an 87-108 GHz continuously tunable source, a cryostat in which the multipliers under test are installed and a Thomas Keating power meter as shown in Figure 1. The source is composed of a 75-115 GHz BWO followed by an 87-108 GHz power amplifier chain that can deliver up to 280 mW at 92 GHz [11]. Power is adjusted by an attenuator and/or a ferrite modulator that also isolates the BWO from the amplifier chain. Frequency is monitored by a microwave counter via a harmonic mixer. A cross-waveguide coupler and a low-offset, low drift power meter are used to monitor the power delivered by the source.

A low loss wide-band isolator is located inside the cryostat, between the coupler and the multiplier chain, to avoid any load pulling effects that can affect the accuracy of the monitoring of the input power. The temperature of the multipliers is adjustable to within $\pm 1 \text{ K}$ in the 35-325 K range using a controller, two temperature sensors, a 25 W resistor and a bracket that mechanically connects the chain to the 15 K cold plate of the cryostat. The vacuum window on the output side is made of a one-mil thick by two-inch diameter Mylar shield. IR radiation going through the window is partly blocked by two 25 μm -thick layers of Zitex 135 material.

We measured the power produced by the multiplier chain with a Thomas Keating power meter. A single 25 μm -thick layer of Zitex 135 material is used to protect the membrane of the Thomas Keating sensor from air-borne acoustic vibration, as well as visible and IR radiation. In addition, the Thomas Keating sensor is installed on an anti-vibration-plate with a 0.16 Hz cut-off frequency to eliminate the low frequency vibration produced by the cryogenic generator, the BWO, the chopper and the vacuum pumps. The RF output beam is focused on the membrane of the Thomas Keating sensor by an oversized elliptical mirror that reduces the sensitivity to the optical misalignments. The beam is chopped by a two-blade by ten-inch diameter wheel operating at 20 ± 0.2 Hz. The modulated signal detected by the Thomas Keating sensor is pre-amplified and filtered by a high-rejection, 10-30 Hz band-pass filter. The signal is finally measured by both a high-performance dual-channel digital lock-in amplifier and by the data acquisition card of the Thomas Keating power meter.

We found that the combination of the band-pass filter and the dual-channel lock-in amplifier greatly improves the sensitivity of the Thomas Keating power meter. 10 μW could be confidently detected with a measurement noise of $\pm 1 \mu\text{W}$, whereas the standard configuration results in a $\pm 10 \mu\text{W}$ noise floor.

Calibration procedure: A power meter that does not need to be calibrated monitors the input power. A second power meter, calibrated carefully by the manufacturer, is connected to the last waveguide bend before the multiplier chain, inside the cryostat. Recording at different frequencies the ratio between these two power levels defines a calibration chart. The output power is calibrated automatically by the Thomas Keating control program. RF losses produced by the IR filters and the Mylar film were measured around 200 GHz and 400 GHz. We found a total absorption of less than 7% at 375 GHz. The preliminary data reported in this paper does not correct for these losses. Broadband measurements of these losses are planned and will be used to improve the accuracy of the calibration.

Measurements at cryogenic temperatures: Only modulated signals are taken into account by the Thomas Keating power meter. Therefore, in order to modulate the RF signal produced by the frequency multiplier chain, we decided to use a two-blade chopper wheel. This wheel is located outside the cryostat at room temperature. When the RF beam is cut, the Thomas Keating sensor receives only the IR radiation of the blades that can be considered as a black body at 300 K. When the RF beam is not cut, the Thomas Keating sensor receives the RF signal as well as part of the IR radiation emitted by the metallic components located inside the cryostat. This is because the IR radiation is only partially absorbed by the IR filters at the output window of the cryostat. When operating at cryogenic temperature, this IR radiation is more or less the emission of a cold black body.

As the Thomas Keating sensor is very broadband, it detects a modulated IR signal in addition to the

modulated RF signal produced by the frequency multipliers. This IR signal is 180° out of phase with the RF signal and, therefore, it is subtractive.

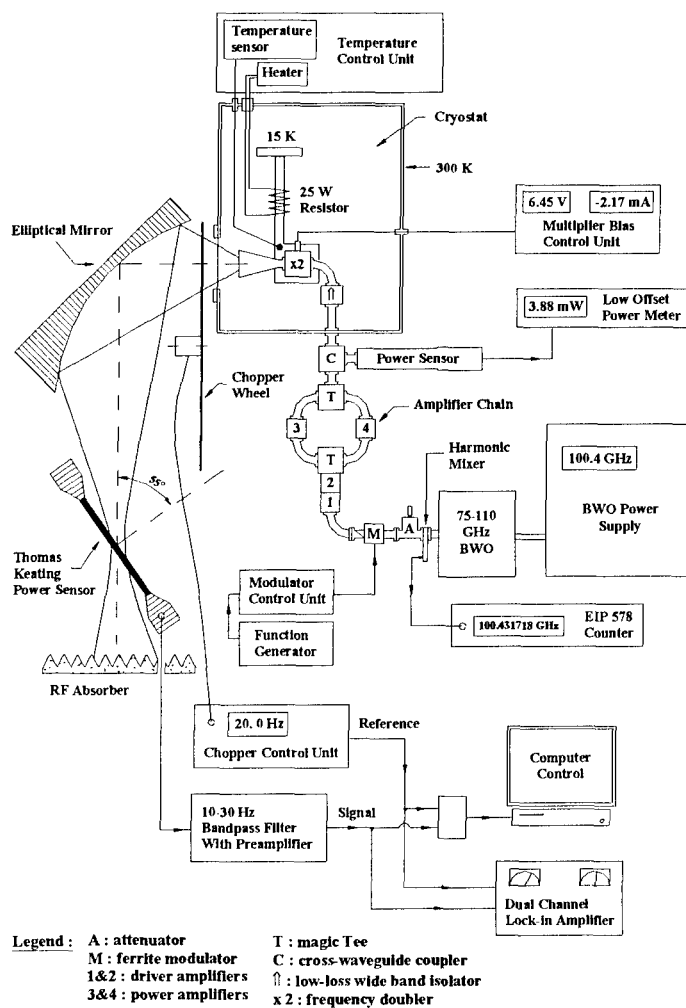


Fig. 1: LO chain power measurement test setup.

In the configuration shown in Figure 1, at around 100 K, this IR radiation has a signal strength of about 150 μW . Consequently, at low RF power levels it can have a significant effect on the measurement. Accurate measurement of this IR signal must be taken and the data must be systematically corrected. One possible solution is to use a better IR filter but this might produce additional RF losses and standing waves. Another solution is to modulate the input power of the multiplier chain. The chopper wheel is removed and the modulation of the IR radiation is eliminated. The validity of this approach was ascertained by making a number of pulsed measurements with the amplifiers and the multipliers. We found that the amplifiers give slightly more power (+4% maximum) when driven with a 50% duty ratio square wave than when driven in CW. This increase of power is taken into account since the input power is monitored with a coupler and a power meter. The measurements show also that the frequency multiplier diodes reach their thermal equilibrium in less than 100 μs . Hence, modulating the

input power of the doubler at 20 Hz does not produce any change in the behavior of the multiplier chain.

III. RESULTS AND DISCUSSION

The 184-212 GHz balanced planar doubler has been described in more detail in [12,13]. It is a 6-anode array with each anode being 1.5x14 μm. The doping in this chip was 1.10¹⁷ cm⁻³. The performance of this doubler as a function of temperature and output frequency is shown in Figure 2. Significant improvement in the efficiency of the multiplier is obtained by cooling from 300K to 50K. However, it can be noted that the basic shape of the efficiency curve remains consistent. The measured output power at 201 GHz was 32 mW and 44 mW respectively at 300 K and 50 K. It is interesting to note that the efficiency for all frequencies is still improving at 50 K even though the theoretical mobility versus temperature data for GaAs indicates a peak around 100 K. This can be explained by the fact that the anode area is much hotter than the ambient temperature and thus the efficiency is still improving.

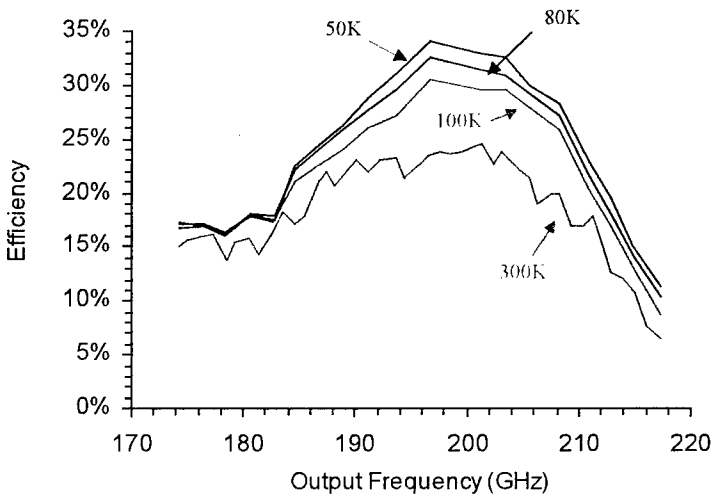


Fig. 2: Multiplication efficiency of a planar diode doubler as a function of output frequency for different block temperatures.

Figure 3 shows the performance of this multiplier as a function of input power. Though this multiplier was designed for high input power, the saturation occurs around 50-75 mW of total input power. However, upon cooling no significant change in the saturation is observed.

The 368-424 GHz balanced planar doubler has been described in some detail in [5]. This is a 4-anode array with each anode 1.5x5.4 μm. The doping used for this chip is 2.10¹⁷ cm⁻³. This doubler utilizes a novel technology that greatly simplifies the assembly and design of multiplier stages. Cryogenic measurements done on the cascaded multiplier stages are shown in Figures 4 and 5. No isolator was used between the two-multiplier stages. The performance of the chain as a

function of input power to the first stage multiplier is shown in Figure4 for the case of 382 GHz. It is interesting to note the strong dependence of the output power on the input power

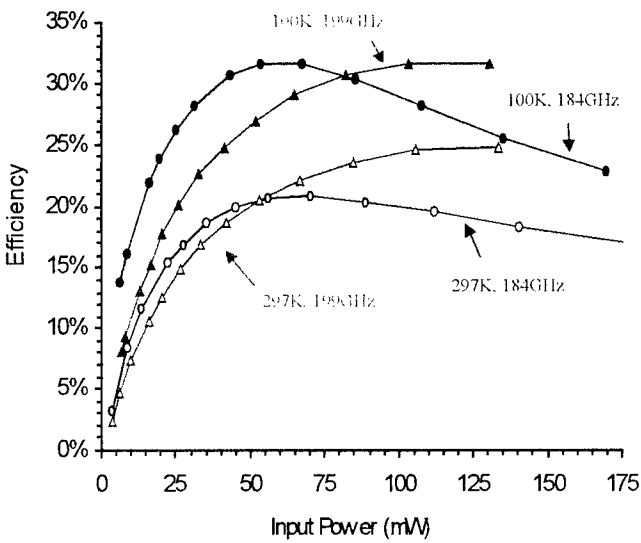


Fig. 3: Conversion efficiency of a planar diode doubler versus input power at different frequencies & different temperatures

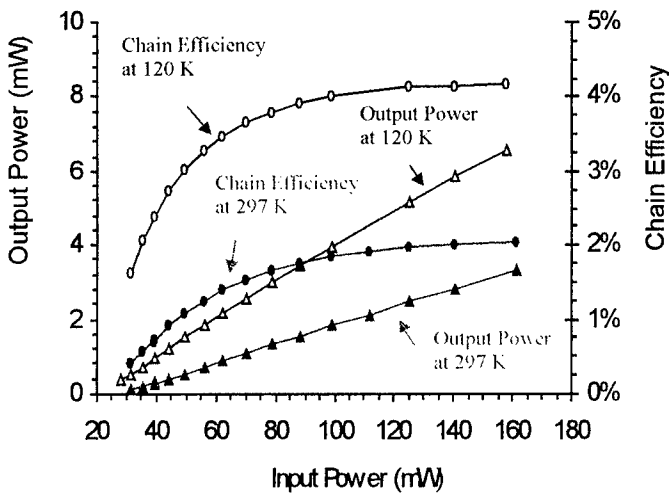


Fig. 4: Output power and chain efficiency at 382 GHz versus input power at 120K & 297K.

Figure 5 shows the output power and efficiency of the chain as a function of block temperature for two different frequencies. An improvement of 3 dB at 382 GHz and an improvement of 6 dB at 402 GHz is achieved in the efficiency of the chain, when cooling from 300 K to 50 K. It should be pointed out that at room temperature the first stage multiplier is under-pumping the second stage multiplier. Thus, cooling the multiplier chain improves significantly its performances since the first stage

multiplier is putting out more power and the second stage is getting more efficient with increased input power.

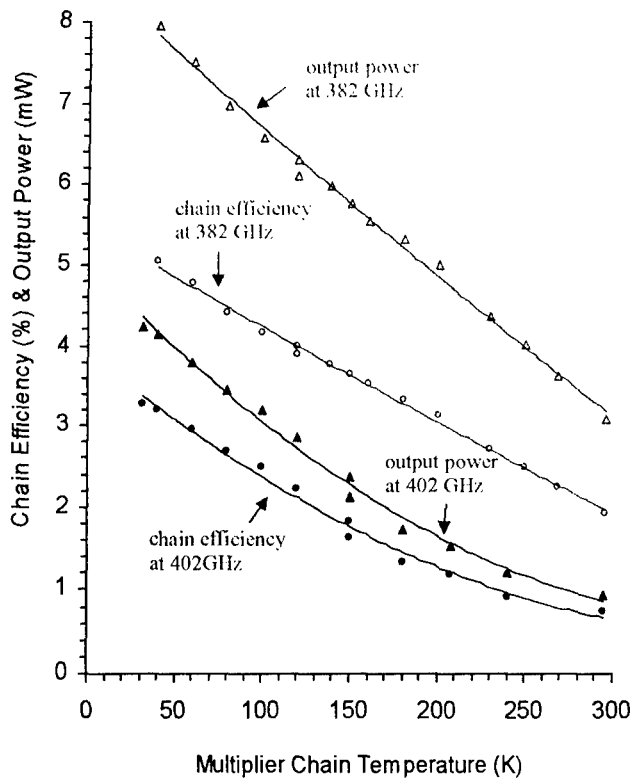


Fig. 5: Output power and chain efficiency at 382GHz & 402GHz versus temperature.

IV. CONCLUSION

A robust cryostat testbed that allows accurate calibrated measurements of power and frequency for a considerable frequency range has been described. Results presented have shown that the multiplier efficiency continues to improve beyond 100 K due to the possible heating of the anode chip in high input-power multipliers. A fix tuned multiplier chain to 400 GHz (x2x2) cooled to 50 K shows an improvement of over 3 dB.

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