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Experimental investigation of local oscillator chains with GaAs planar diodes at cryogenic temperatures

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Abstract – **This paper will describe a robust test-bed that has been built to measure multiplier performance over a wide range of temperatures and frequencies. In a 182-212 GHz designed balanced doubler the peak efficiency at 201 GHz improves from 22% to 28% upon cooling from 300 K to 120 K. This stage is then used to pump a 362-424 GHz balanced planar doubler. The peak chain efficiency increases from 3.4% to 6% when the two cascaded doublers are cooled from 300 K to 120 K. This enables the production of 10 mW of peak output power at 377 GHz, which ought to be sufficient for driving the next stage multiplier.**

I. INTRODUCTION

GaAs Schottky diode frequency multipliers are being developed at a number of facilities for the Heterodyne Instrument of Herschel Space Observatory (formerly known as FIRST). The planned mission will cover the 80 μm to 670 μm range with a 14-channel instrument that is based on state-of-the-art sensor technologies [1,2,3]. Cooling of multiplier circuits to enhance performance has been demonstrated [4,5] and thus the mission has base lined cooled operation of the local oscillator (LO) unit. In principal, whisker contacted circuits can be used but the inherently mechanically sensitive approach to the building of whisker contacted circuits does not readily lend itself to thermal cycling. Well-designed and appropriately implemented planar technology is better suited for cooled operation and can be designed to handle thermal cycling and heat dissipation.

Cooling of multiplier circuits can have considerable influence on the output power and efficiency of GaAs multipliers as has been demonstrated [4,5]. However, the intricate tradeoff between various diode parameters for optimum cryogenic applications is still under investigation [6]. Electron mobility in GaAs is strongly temperature dependent while circuit losses also improve upon cooling. However, a better understanding of electron transport in doped GaAs as a function of temperature along with an accurate thermal model of the diode chip is required to take full advantage of the cooling. 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. While work is still under way to obtain a better understanding of temperature related effects in multipliers it is also equally important to experientially characterize multiplier stages and multiplier chains as a function of ambient temperature. The latter objective is being addressed in this paper. A robust test-bed that has been constructed from mostly commercially available items will be described that simplifies the testing of multipliers as a function of ambient temperature. This setup has been used to measure a planar balanced doubler at 200 GHz and a planar chain of two cascaded doublers to 400 GHz. The results obtained will be discussed.

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 [7]. 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 ±1 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 refrigerator, the BWO, the chopper and the vacuum pumps. The RF output beam is focused on the membrane of the Thomas Keating sensor by an over-sized 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 lock-in amplifier greatly improves the sensitivity of the Thomas Keating power meter. 10 μW could be confidently detected with a measurement uncertainty of ±1 μW, whereas the standard configuration results in a 10 μW noise floor.

A commercial power meter is used to monitor 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 however this was not used to correct the data reported.

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 the emission of a cold black body. As the Keating sensor is 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.

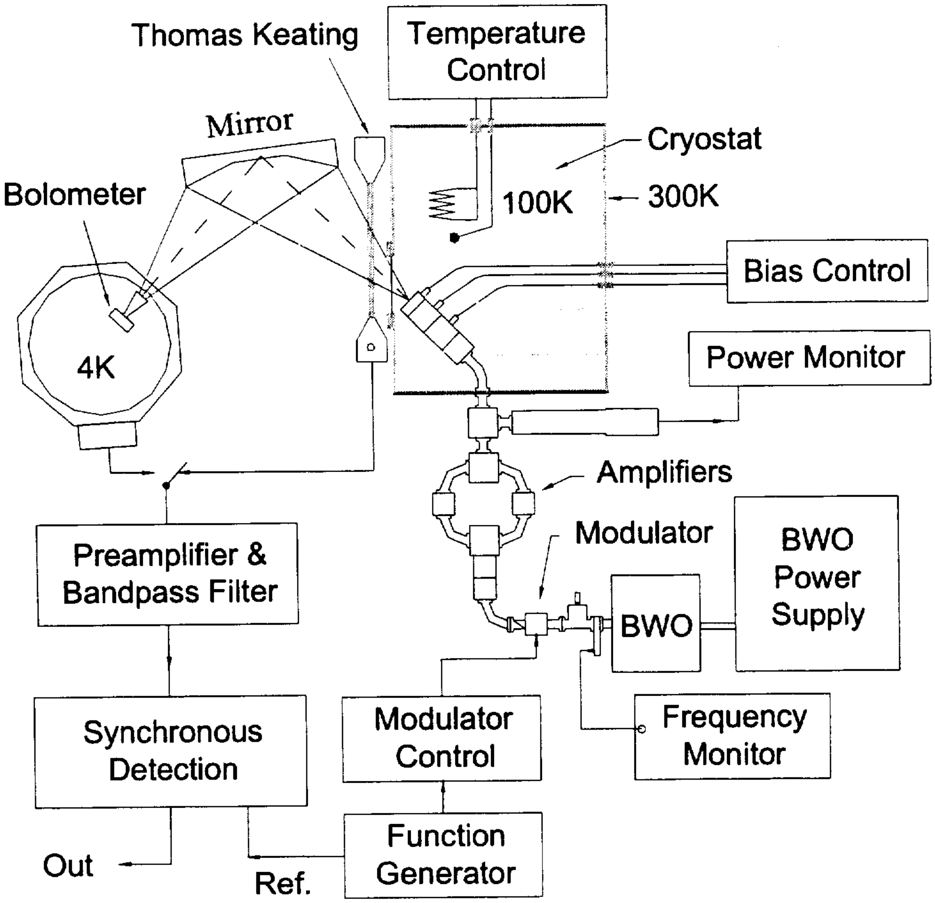

Figure 1: Test-bed for the measurement of output power from multipliers at cryogenic temperatures.

In the configuration shown (Fig. 1) at 100 K this IR radiation is about 150 μW. Consequently, at low output power levels it can have a significant effect on the measurement. 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. MULTIPLIER MEASUREMENTS

The 184-212 GHz balanced planar doubler with preliminary measurements has been described previously [8]. It is a 6-anode array with each anode being 1.5x14 μm. The doping in this chip was $1\times10^{17}\,cm^{-3}$. The discrete chip is mounted directly onto the waveguide block and a 1-mil wire is used to connect the chip to the bias capacitor. The close-up of the chip and the chip mounted up-side-down in the waveguide block is shown in Figure 2.

Room temperature performance of the 200 GHz doubler stage is shown in Figure 3. This particular multiplier exhibits a peak efficiency of about 21% at 188 GHz with a peak output power of 36 mW. The 3-dB bandwidth is approximately 20 GHz or 10%. The input and output backshorts are fixed and in obtaining the performance shown in Figure 3 only the device bias is optimized. The optimum bias range is between 11 and 13 volts. Under these pump conditions we have used this device extensively (both at room temperatures and at cryogenic temperatures) and have noticed no degradation in performance.

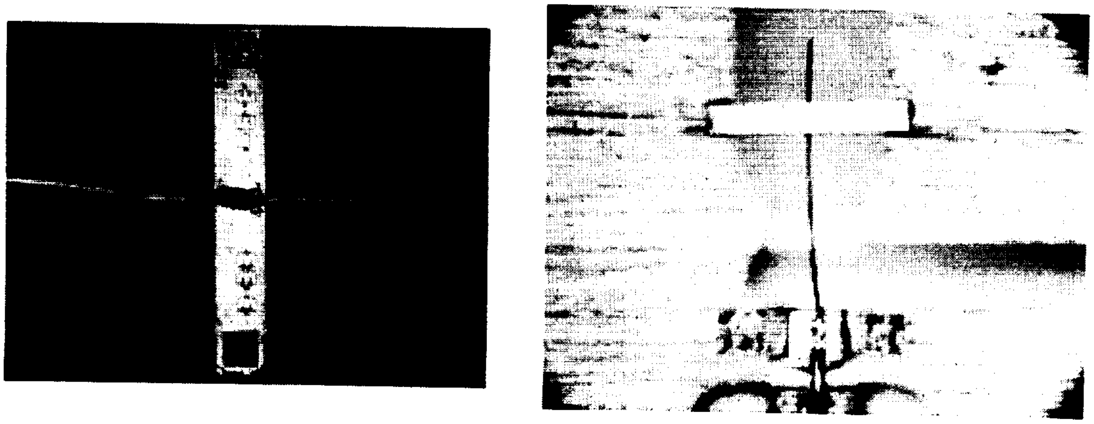

Figure 2: Discrete 6-anode chip (left) mounted up side down in the 200 GHz waveguide multiplier block (right).

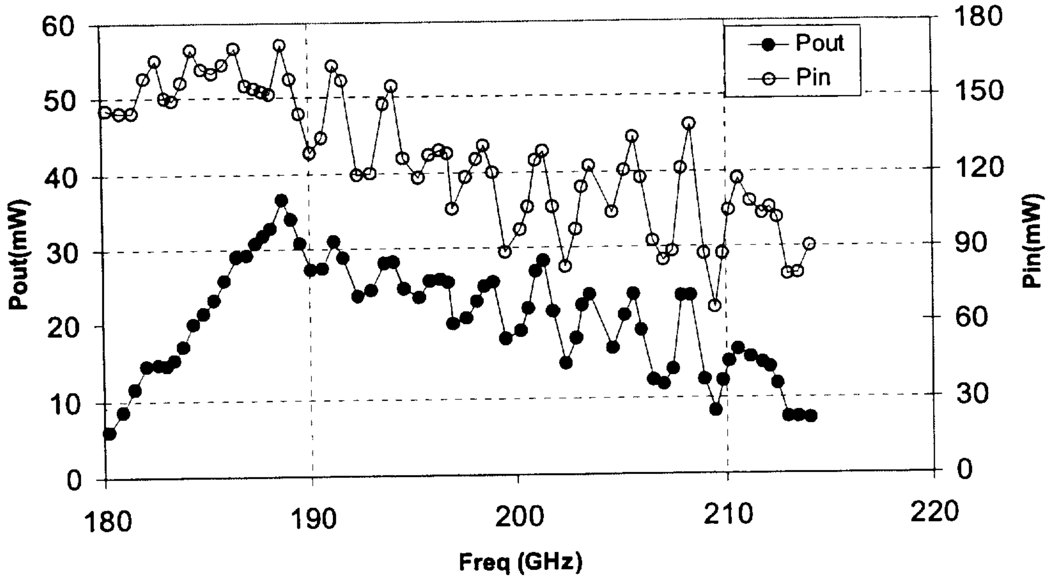

Figure 3: Room temperature performance of the 200 GHz stage doubler. Power-combined power amplifiers are used to increase the input power.

Since the room temperature measurements were made with the Keating meter the only setup change required for low temperature operation was to close the cryostat lid and activate the cryostat. The multiplier was tested at 120 K. This particular temperature is significant only because the multipliers operating on the Herschel Space Observatory are being baselined for this temperature range. The performance of the stage at 120 K is shown in Figure 4 (input power is similar to the curve shown in Figure 3 since the power amplifiers are not cooled). For comparison the output power and efficiency at room temperature have also been plotted on the same graph. For all frequencies a clear enhancement in output power can be observed with cooling. The peak efficiency of the multiplier stage increases from 21% at room temperature to about 28% at 120 K. This represents an increase of 30%. The basis for this increase is the improvement of the mobility of the free carriers in GaAs as the ambient temperature is decreased from room temperature. The enhanced mobility results in reduced series resistance thus improving the multiplier efficiency. The peak output power of the multiplier increases from 36 mW to 42 mW.

The 400 GHz doubler is constructed using the substrateless device technology that has been previously described in detail [9]. Essential features of this technology are that the anodes and the matching circuit are formed together with most of the metallalic circuit suspended in air. A 30 micron thick GaAs frame holds the chip together. Extensive use of beamleads is made both for handling and mounting purposes. A picture of the substrateless 400 GHz doubler inside the waveguide block is shown in Figure 5. This is a 4-anode array (anodes are at the far left of the chip) with each anode 1.5x5.4 μm. The doping used for this chip is $2x10^{17}$ cm^{-3}.

The 200 GHz stage described earlier is used to pump the 400 GHz balanced doubler. The two blocks are cascaded with no isolators in between. An external dual mode horn centered at 400 GHz was mounted on the output guide of the second stage doubler and the output power was measured using the Keating meter as described earlier. Output power and the efficiency of the second stage at 120 K are shown in Figure 6. Also, shown is the available input power to the second stage multiplier. A peak in the efficiency of the second stage is observed around 368 GHz approaching 28%. The maximum output power from the cascaded chain is about 10 mW at a frequency of 378 GHz. At this particular point the efficiency of the second stage is 25%. Note that a maximum combined efficiency of 6% is measured and the 3dB bandwidth of output power is about 18 GHz or about 5%. The ripple present in the output power is due to the mismatch between the multiplier stages.

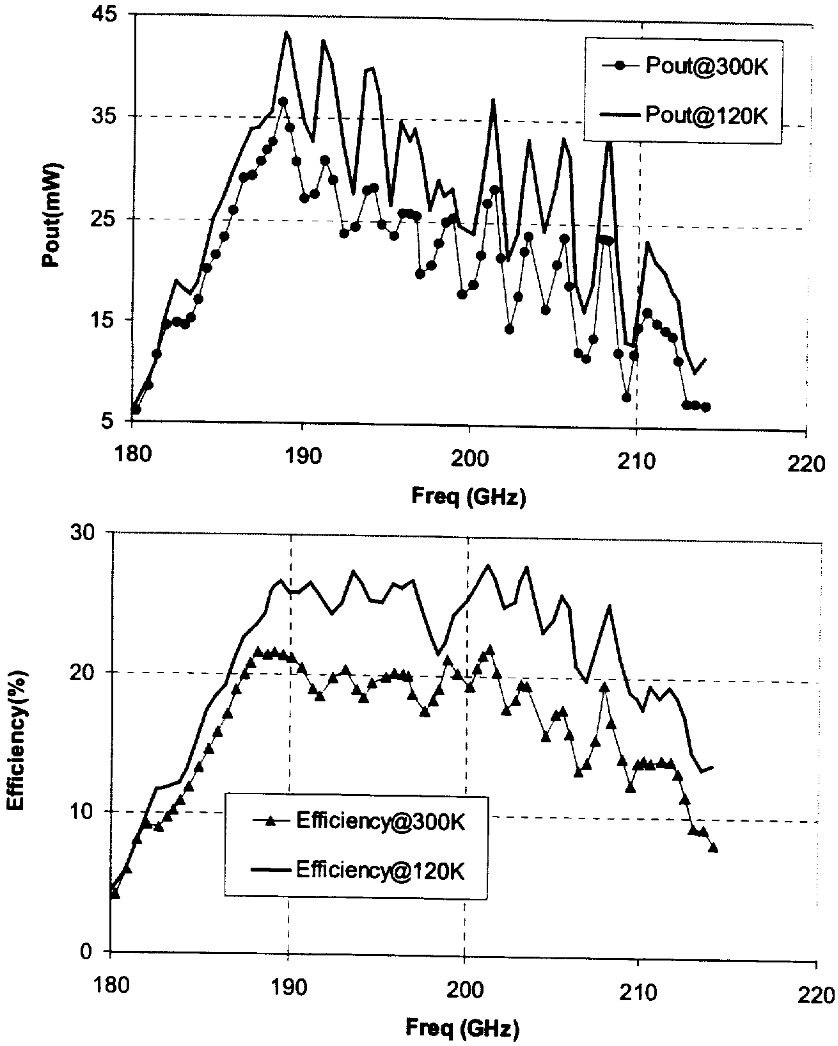

Figure 4: Output power (top) and efficiency (bottom) performance of the 200 GHz stage at 120 K.

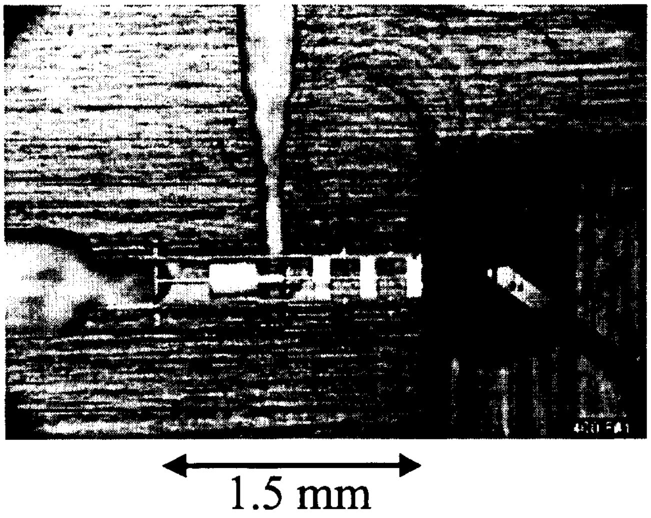

Figure 5: Inside of the 400 GHz balanced doubler with the top half of the split block removed. The output guide is shown in the top half of the photograph. The chips are made with the substrateless technology that requires only a simple assembly process.

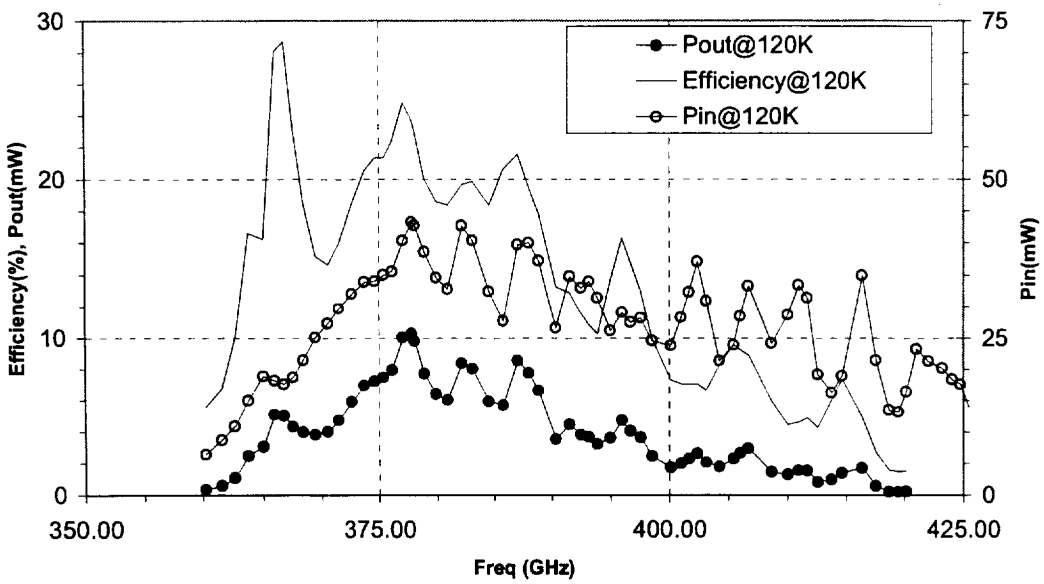

Figure 6: Performance of the cascaded chain at 120 K. The power available to the second stage multiplier is shown as Pin.

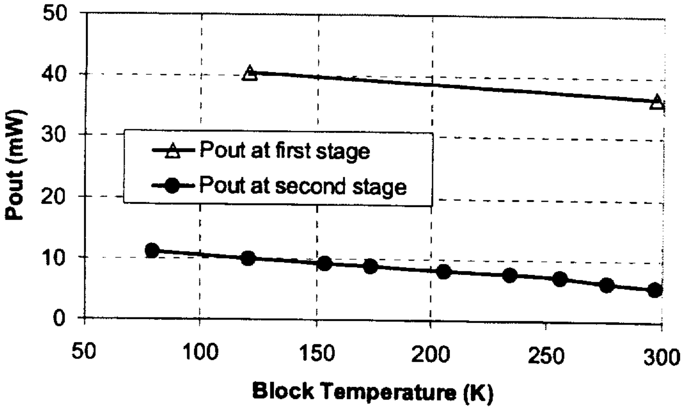

Figure 7: Output power from the two multiplier stages as a function of ambient temperature. The first stage output power is measured at 188.5 GHz while the second stage output power is measured at 377 GHz.

Figure 7 shows the effect of ambient temperature on the power performance of the two stages. We note that in each case the output power is linear with decreasing temperature with the slope for the second stage being sharper than for the first stage. This measurement is made at fixed frequencies of 188.5 and 377 GHz (corresponding to the first and second stages). We note that as the temperature is lowered the efficiency of the second stage approaches the efficiency of the first stage. There can be a number of possible explanations for this effect and further careful analysis is required to draw valid conclusions. It is possible that the anodes on the first stage are considerably hotter than the ambient temperature and thus the mobility improvement in the first stage is not has pronounced as the second stage. Also, one must take into effect current saturation effects, which can dominate the performance of the first stage due to the lower doping and higher input power. The chain efficiency as a function of temperature is also shown in Figure 7. An improvement of about 2.5 dB is observed when cooling from 300 K to 120 K.

IV. CONCLUSION

A test setup built to study performance of cryogenic multiplier stages has been described. Planar balanced doubler stages from 100 to 200 GHz and from 200 to 400 GHz have been measured at cryogenic temperatures. The chain efficiency can be improved by about 2.5 dB when the chain is cooled from 300K to 120 K. This improvement can be attributed to the enhancement of electron mobility and the reduction of current saturation effects in the individual multiplier stages. More work is required to quantitatively understand the interplay between device doping, temperature and input power for each stage.

V. ACKNOWLEDGEMENTS

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