A 600GHz tripler with >5mW and 6% efficiency

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***Abstract*— We present test measurements for a 600GHz tripler with an output power in excess of 5mW and efficiency close to 6%. Simulations were presented at the ISSTT 2015 "A 600GHz high power tripler for space applications". The design uses a new method of diamond-film attachment, which allows very effective heat-sinking of the Schottky varactor diodes to create a high power tripler which could be used to drive a super-THz multiplier, or a sub-harmonic mixer for space use. Thermal management was a primary concern as we believe this is the major limiting factor for the high efficiency of the device at this frequency and power. The RF and thermal aspects of the design will be reviewed and compared with the measured results. As far as we are aware, this is the highest power single multiplier device (with no power combination) yet made at this frequency. We believe output powers of nearly 8mW from a single device may be possible, given sufficient input power.**

INTRODUCTION

Schottky varactor multipliers have a very long history yet they remain the only way to produce power at the THz range that is reliable, monochromatic, compact, efficient and not reliant upon cooling. Producing useable amounts of power at THz frequencies requires very high power driver stages in the sub-THz range. This is often just as challenging as the final, highest frequency stage and is the subject of this paper.

Our novel design allows relatively high powers to be reached in the frequency ranges from 200GHz – 700GHz. This frequency range and power remains out of reach of high power GaAs or GaN MMIC amplifier technology, or indeed of conventional multipliers, due to the very high input power required. Using such a high powered driver multiplier, one can easily provide in excess of 1mW at frequencies over 1THz with a suitable final multiplier. Power combination using multiple devices remains possible, further boosting output power. The same technology can be used to create a wider band design at the expense of some efficiency.

The main activity of this work was to analyse the limits of high power, high frequency varactor sources. We wanted to test assumptions made during the simulations that multipliers are essentially thermal limited (given adequate breakdown voltage) and to verify the role of velocity saturation in combination with overheating in our simulations. Support was from ESA AO/1-6649.

TRIPLER RECAP

The tripler design has already been discussed in ISSTT 2015 "A 600GHz High Power Tripler for Space Applications". The design is quite standard balanced, 4-anode design, with DC bias. The three unusual aspects of this design are using a thin diamond membrane to dissipate heat away from the anodes, a thin low-dielectric support membrane and large (but thin) heat-dissipative mesas with a direct heat-path to the diamond. Each of these modifications is less effective in isolation, but in combination allows very effective thermal management.

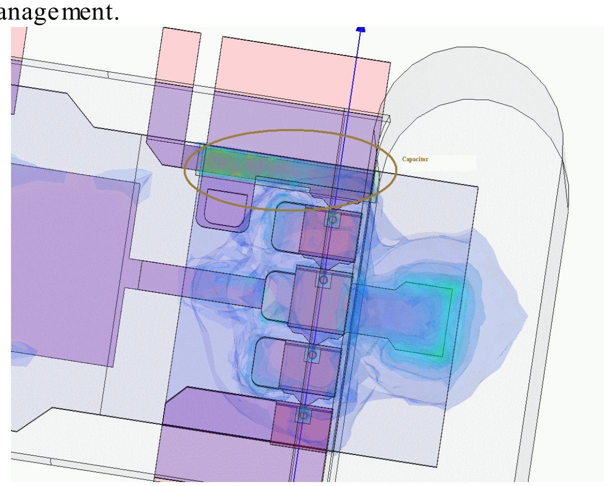

Fig. 1 The tripler shown with gold straps to the CVD diamond. The area circled is a single-layer capacitor for DC bias. Contours are 600GHz E-field

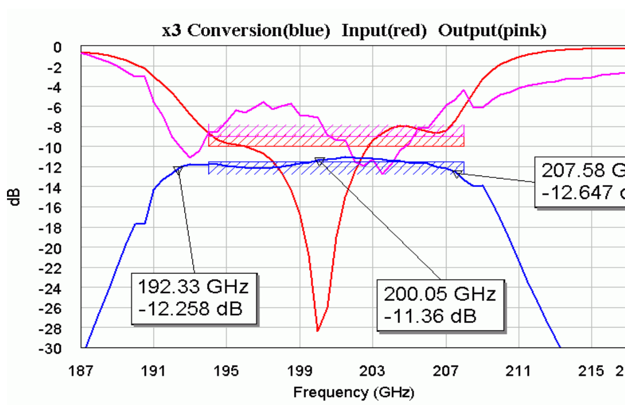

Fig. 2 Simulated conversion efficiency and input and output match (dB scale) for an input power of 100mW and 10V bias

MEASUREMENT RESULTS

Manufacture of the THz-MIC was done by ACST GmbH, using their modified FD-processTechnology details will be covered in other papers by Ion Oprea (ACST).The main goal of this project was to demonstrate that very high output power was possible at these high frequencies using standard varactor technology if one had a good design and one could maintain low anode temperatures.

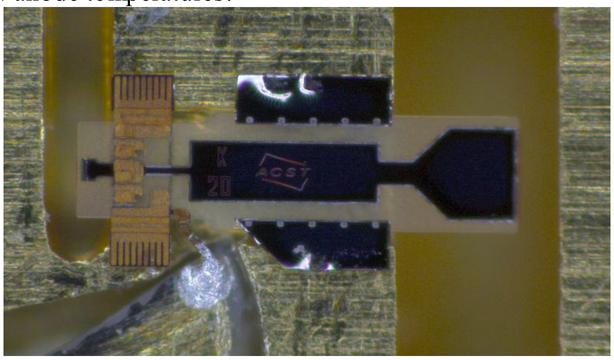

Fig. 3 Device mounted in the split-block, ready for testing

Testing took place at RPG Radiometer Physics, Nov. 2015 using a specially fabricated driver chain, producing close to 100mW at 200GHz [1].

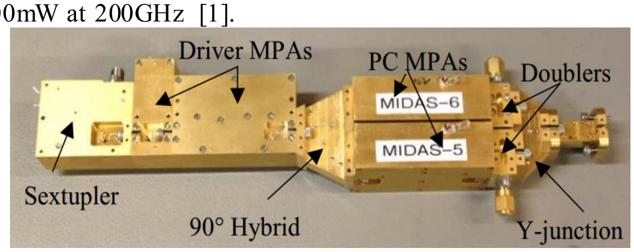

Fig. 4 Power combined amplifier/doublers for the high power 200GHz test source (courtesy of Bertrand Thomas, RPG GmbH)

At 100mW input power, the anode temperatures were expected to rise in temperature by about 60°C from room-temperature. Maximum anode temperature was expected to be 390K. While this may still seem high, it is greatly reduced compared to normal anode temperatures and emphasizes the large thermal problem faced. After using a diamond heatspreader, the thermal conductivity of gold is the new thermal limitation.

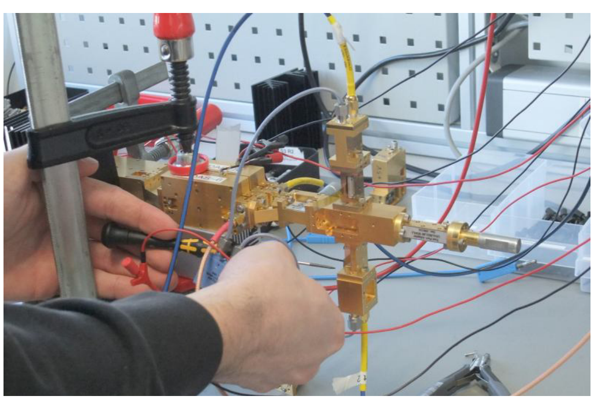

Fig. 6 Double-directional coupler and harmonic mixers, providing full input match characterization (similar to a VNA)

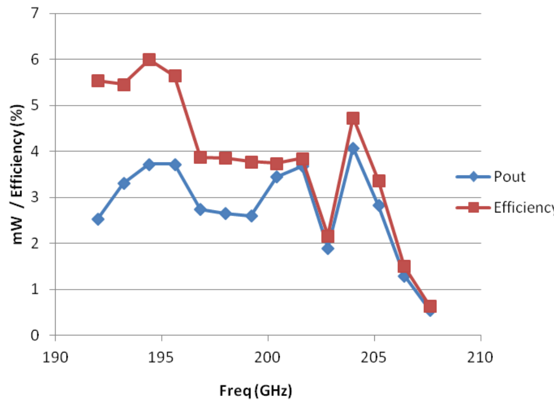

Fig. 7 Plot of measured Output power (blue, mW) and Efficiency (red, %). Frequency scale is for the tripler input.

Output power was measured using an Erickson PM4 power meter with no corrections applied, either for waveguide losses or power-meter calibration. Maximum power was seen at around 610GHz, with 4.96mW measured. After power-meter corrections this corresponds to well over 5mW.

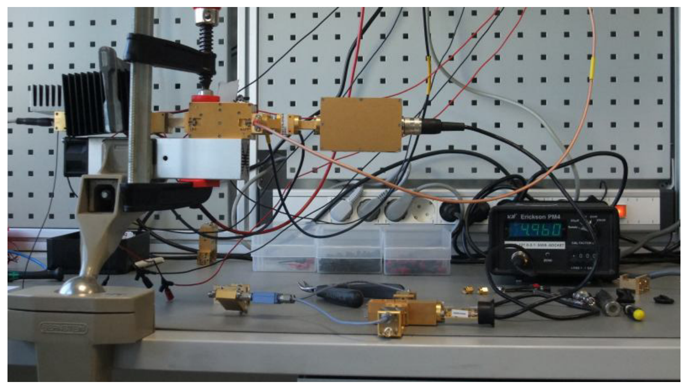

Fig. 7 For output power measurements, the PM4 meter is directly connected to the tripler using a taper-transition to overmoded WR10.

COMPARISON BETWEEN MEASURED AND SIMULATED

The multiplier at first glance provided quite acceptable output power, but detailed comparison between simulation (Fig 2) and measurement (Fig7) shows a major discrepancy in the efficiency which seems to be optimal only at the lowest frequencies. This was especially strange, as the value of Cj0 of the fabricated THz-MIC was smaller than ideal, so we expected a high frequency shift (see later section “block manufacture error”).

Detailed measurements were taken at the highest power point (610GHz), as the principal objective of the project was to confirm simulation and measurement at high powers. A plot was taken of output power, against bias point. This same plot shows the value of DC current.

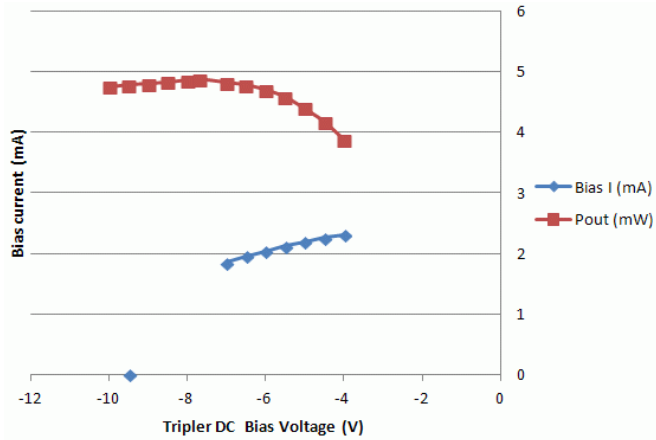

Fig. 8 Measured output power (at 610GHz) vs. DC bias, showing output power (red) and rectified DC bias current (blue)

Maximum efficiency occurs when voltage peaks are just staring to forward bias the varactors and a small rectified DC current is seen (as expected see Fig 8). What was interesting to us was that the efficiency remained quite respectable, even at lower bias voltages. Indeed, we tested the device with even lower voltages (and higher currents) and performance was less impaired than expected. This might be a useful indication that we can use even fewer anodes and live with an abnormally high bias current (to avoid the voltage breakdown limitations). The tripler seems extremely robust. It was tested it with high currents (several mA) and also with DC bias over 12V with no incident. The device remained fully functional throughout and resisted all attempts to destroy it.

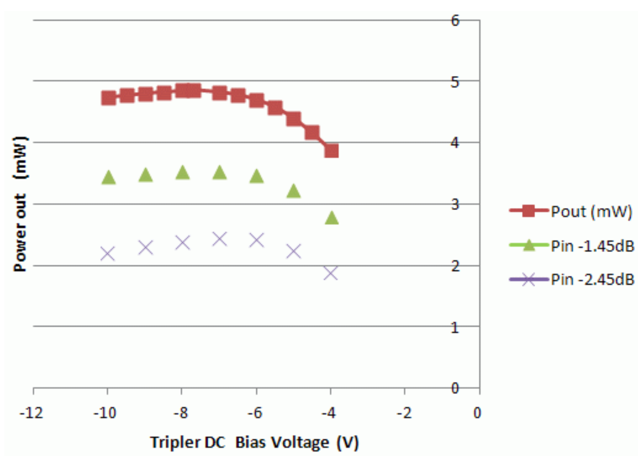

Fig. 9 Power output vs. Bias voltage plotted for different input powers

Another test performed was to reduce the input power and measure output power against DC bias voltage (Fig 9). The data shows the optimal DC bias point reducing with reduced input power (as expected). At full power, -8V bias is optimal, whereas at near ½ power, -6V is better. All these power curves are very similar to predicted and give us confidence in our thermal and RF models. However, the efficiency plots against frequency do not look correct, and indeed an error was subsequently found:-

MACHINING ERROR DISCOVERY AND SIMULATION

On further inspection of assembly photos, a fabrication error was discovered in the block, making the input waveguide backshort too long.

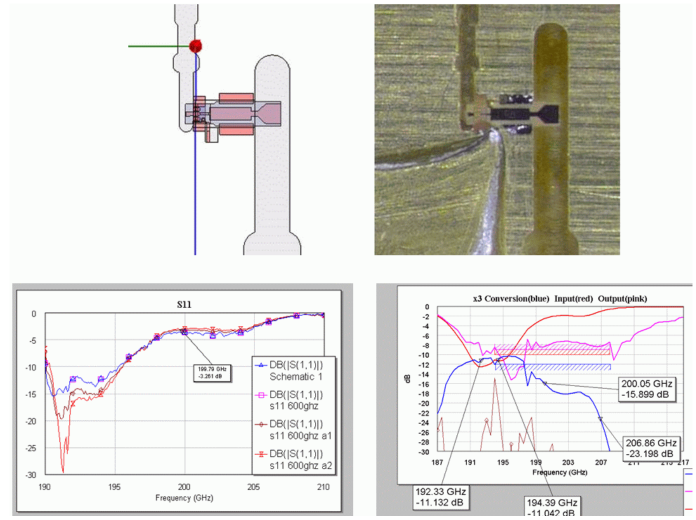

Fig. 10 machining error discovered, and updated simulation including error

The bottom left plot of Fig10 shows the measured S11 for the tripler, using the measurement setup from Fig 6. Below 197GHz, the input mach is good and efficiency is high (using the VNA measurement in Fig 6). After simulating this machining error (and also the lower Cj0 of the MMIC), we saw an almost exact duplication of this input match (red curve, bottom right of Fig 10).

We then plotted the complex impedance of the input match on a Smith chart (de-embedding the correct amount to set the reference phase to the same position as the simulation). The correlation between simulation (left) and measured (right) in Fig 11 was very close. The marker point is the same frequency.

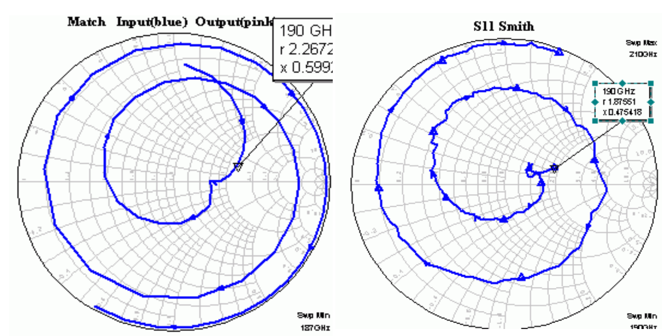

Fig. 11 S11 (input of tripler) simulated (left) and measured (right)

We will build a corrected block and measure again, as we expect still better performance with all parameters correct. Unfortunately, this was not possible in the time available before the ISSTT conference. As the main point of the project was to verify the simulation models and to test the output power at 600GHz, all goals were reached, even with a machining error, and also with an MMIC with less Cj0 than optimal.

FOLLOW-UP

We saw in the measurement data that biasing the device at quite low voltages and accepting quite high DC rectified current was less detrimental than we expected. A high power tripler, using just 2 anodes, well heat-sunk using the grounded beam-leads would seem a logical follow-up, as one can achieve this without requiring diamond heat-sinking for the central diodes. The ACST varactors have extremely high break-down voltages, exceeding -10V per anode. This is a key feature in allowing relatively few diodes to be used, which reduces losses even further and simplifies the structure considerably. The use of very thin mesas, with thickness of approximately 1 skin-depth (in GaAs) would also seem to be very helpful. The correct choice of doping concentration is also obviously very important. A design which is optimised for as large an anode diameter as possible is also beneficial, as this helps reduce the current density in the GaAs, and keep the critical series resistance value low

Observed efficiency reduction in similar devices, which have traditionally been attributed to purely velocity saturation effects may be a mixture of effects, including overheating. Carrier mobility and velocity saturation is strongly temperature dependent, and partly explains why Schottky multipliers and mixers perform substantially better when cooled. We therefore believe there is every advantage in keeping anodes as cool as possible. This aspect seems often overlooked in current designs.

CONCLUSIONS

A single (no power combining) 600GHz tripler has been constructed with over 5mW of output power. As far as the author's knowledge, this is the highest power device yet made at this frequency. Efficiency of near 6% is seen and is completely in agreement with the simulations of the device (when taking into account machining errors) and also in-line with other similar reported devices for narrow-band use from other groups (440GHz x3 with 8% efficiency [2]). We expect still higher output powers with a correctly machined block and when the tripler can be driven by a higher powered 200GHz source (when available). A maximum output power of nearly 8mW is expected before the device is thermally or breakdown-voltage limited.

ACKNOWLEDGMENT

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