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Executive summary

The terahertz (THz) spectral region between microwaves and infrared is of crucial importance to current and future space science, Earth observation and astronomy missions. In Earth observation, passive remote sensing of the atmosphere from space at millimetre and sub-millimetre wavelengths will play a key role in the MetOp Second Generation instruments. Terahertz radio measurements will be directed towards processes linking atmospheric composition and climate, notably including the essential climate variables water vapour and ozone. Recently two important astronomy programmes, the ALMA array and Herschel HIFI, have made important astronomical observations in this frequency band.

Despite these, and other potential applications that span the physical, biological, and medical sciences, the terahertz spectrum has yet to be fully exploited. In part this is because it remains difficult to generate conveniently useful amounts of power at THz frequencies. It was to address this problem, by developing generic integrated Schottky diode and amplifier sources using European technology, that the MIDAS project targeted.

The objective of the MIDAS project was to develop solid-state frequency sources based on European technology. To do this, within MIDAS a six fold frequency multiplier was developed to take the output from widely available synthesized sources and generate power covering the W-band, 75-110 GHz. This power was then amplified by power combining European MMIC amplifiers. The output from these amplifiers was further frequency multiplied in newly developed frequency doublers and triplers to generate power spanning the frequency range from 150 to 330 GHz. These final stage frequency multipliers were fabricated on 12 µm thick gallium arsenide membranes that included Schottky diodes with impedance matching networks and integrated capacitor structures. The circuit designs for these final stage multipliers also involved new power combining topologies in order to handle the high levels of power newly available to drive these sources.

In order to design these complicated non-linear structures, a new electro-thermal model was developed and implemented with new design and modelling techniques. In this process, the full electromagnetic model of the frequency multiplier was coupled with the thermal simulation of the structure and the physical modelling of the Schottky region.

1 Summary description of project context and objectives

1.1 Terahertz source requirements

The terahertz (THz) spectral region between microwaves and infrared is of crucial importance to current and future space science, Earth observation and astronomy missions. As well as major international astronomy instruments currently in operation (e.g., the ground based ALMA array, and Herschel HIFI) a number of cosmological and planetary science proposals were submitted to the ESA Cosmic Vision 2015-2025 programme and the JUpiter ICy Moon Explorer (JUICE) has been selected. In Earth observation, passive remote sensing of the atmosphere from space at millimetre and sub-millimetre wavelengths is expected to play a key role in the evolving EU/ESA GMES Sentinel and Eumetsat post-EPS programmes; terahertz radio measurements will be directed towards processes linking atmospheric composition and climate, notably including the GCOS-designated essential climate variables water vapour and ozone.

Despite these, and other potential applications that span the physical, biological, and medical sciences, the terahertz spectrum has yet to be fully exploited. In part this is because it remains difficult to generate conveniently useful amounts of power at THz frequencies. It was to address this problem, by developing generic integrated Schottky diode and amplifier sources using European technology, that this project targeted.

Technology in the terahertz region has largely been driven by the requirements of astronomy and atmospheric remote sensing. This has necessitated the development of heterodyne radio techniques for sensitive high resolution spectral measurements. In this context, Schottky diode technology is uniquely important. Low noise InP front end amplifier technology is generally limited to frequencies below 200 GHz - as frequency rises, gain reduces and amplifier noise deteriorates - and superconducting mixers require cooling. Schottky detector technology, on the other hand, works at all millimetre and sub-millimetre wavelengths and at all temperatures. Most important, Schottky varactor diodes can be used for terahertz power generation through harmonic multiplication from a lower frequency source. With the exception of the 2.5 THz channel on AURA MLS, all space missions involving radio receivers above ~100 GHz have used Schottky diode harmonic multiplication as a source of receiver Local Oscillator (LO) power.

Schottky diodes will continue to underpin terahertz receiver development, since alternative detector techniques and techniques for generating power have disadvantages, especially if power and mass resources are limited.

- Quantum Cascade Laser technology (QCL) shows promise, but requires cooling and has not yet been demonstrated to work at frequencies below about 1.5 THz.

- Photonic down conversion, effected through mixing two optical/near-infrared laser beams in a high speed photodiode, is convenient and can provide power levels at ~100 GHz of several milliwatts. However, the efficiency of photonic mixing decreases rapidly with frequency and for the time being there is little prospect of providing sufficient LO power to drive a Schottky mixer at frequencies above 200 GHz.

- Vacuum tube devices and gas lasers can generate large amounts of terahertz power, but are expensive, inefficient and often (at least with respect to space use) limited in their practicability.

Consequently, Schottky circuits remain the technology of choice for receiver LO power generation at frequencies between ~150 GHz and 2 THz. However, more power is required than is currently available, if the applications in the terahertz spectrum are to be fully exploited. Current Schottky multiplier chains do not readily realise sufficient power to drive Schottky diode mixers at frequencies ~1 THz, or lower frequency focal plane receiver arrays (as required, for example, by meteorological geostationary sounders) or astronomical imagers. Available transmitter power limits radar applications in the field of cloud physics to long millimetre wavelengths. High bandwidth communication applications that might benefit from moving to higher terahertz frequencies are similarly limited by available power, as are sub-millimetre security imaging applications that use active radio systems.

The MIDAS project was aimed at demonstrating and commercialising a new European terahertz power capability, by frequency multiplying (using custom designed diode arrays) high power sources at ~100 GHz derived from MMIC amplifiers, that were in turn driven by a frequency multiplied source. Power combining, in hollow waveguide, was a key feature of both the amplifiers and the high frequency multipliers.

The project was aimed at improving Schottky terahertz sources for future European space instruments. There also remains a strategic need for the technology in Europe. The availability of improved power source technology is critical in a range of emerging markets, from medical and security imaging to non-destructive testing, and a prerequisite for stimulating new applications.

1.2 Terahertz source requirements and European capability

In general, a low noise Schottky mixer radiometer requires of order 1 mW of LO power if a fundamental pump frequency is used, and perhaps two or three times this amount if a sub-harmonic mixing architecture is chosen. It is relatively straightforward to achieve 1-2 mW by harmonic multiplication of a fundamental source at ~100 GHz (derived historically from a Gunn diode oscillator or and more recently a power amplifier) at frequencies up to ~300 GHz using standard components. Producing power at higher frequencies requires higher orders of multiplication, either in a single device or by cascading multipliers, with consequently reduced efficiency and output. In fact, any high order terahertz multiplier requires custom Schottky circuits that are not readily available from commercial houses. A similar problem exists if output power greater than a few milliwatts is required at lower frequencies, since this requires both high power fundamental sources and optimised custom multiplier circuits that are able to handle large amounts of RF power.

For these and other reasons, most terahertz instruments use single radiometers rather than focal plane imaging arrays, and solid state Schottky diode receivers operating above a few hundred GHz are difficult and expensive to deploy.

ESA has long recognised the importance of Schottky technology and the terahertz spectrum to its programmes, and has supported a number of projects aimed at source and detector technology development. Historically, however, the requirement for terahertz components has been based on niche applications in astronomy and remote sensing, and European companies have focussed on the design and manufacture of terahertz components, rather than the underlying device technology. Consequently they have relied on Schottky diodes and circuits developed in the US and supplied by the two world leaders, NASA's Jet Propulsion Laboratory (JPL) and Virginia Diodes Inc. (VDI), an SME spun-out of the University of Virginia. VDI has long been a leading international supplier of Schottky diodes, and together with JPL, has pioneered sub-millimetre integrated diode circuit development. Together VDI and JPL have dominated Schottky circuit development and all ESA and NASA space missions so far have used Schottky diode devices from these two US sources. However, this European reliance is no longer satisfactory.

- There is a real concern that the US export laws may restrict future Schottky circuit availability.
- New applications will demand further integration of the diode with an external circuit (e.g., multi-pixel imaging arrays and 'integrated circuit' receivers), and this demands close co-ordination between the circuit design and circuit fabricator.

The importance of the terahertz region for European space aspirations and the international interest in terahertz security imaging and other applications clearly drives the requirement for the emergence of a reliable commercial European source of THz radiation based on room solid-state techniques operating at room temperature.

1.3 MIDAS Project Concept

The aim of the MIDAS project was to develop and commercialise, using European devices, generic integrated diode and amplifier sources that would allow enhanced power generation in the terahertz band. In order to provide a direction for the work it was intended to demonstrate this new capability by developing a novel integrated diode and power amplifier source, providing powers >100 mW at frequencies around 300 GHz. This is structure is illustrated in Figure 1.

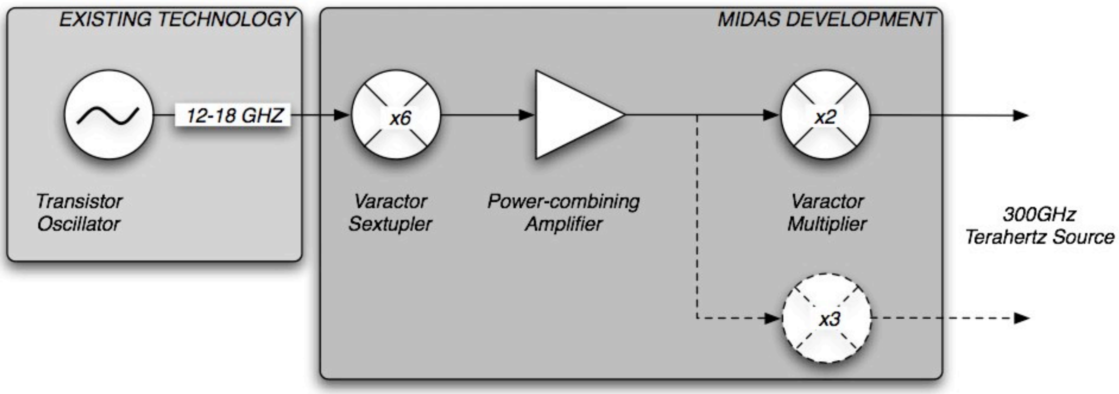

Figure 1:Schematic diagram of ultimate project objectives.

Transistor based oscillators in the 12-18 GHz band are widely available microwave components. The project aimed at multiplying this frequency using a new sextupler to generate power in the 75-110 GHz band. European MMICs power amplifiers, configured in novel power combining schemes, were then intended to amplify this source for a final multiplication stage. The varactor multipliers were custom GaAs Schottky circuits which also involved power combining schemes.

2 A description of the main S&T results/foregrounds

2.1 Overview of the main S&T results from the MIDAS project

The technical goals of MIDAS are challenging and required significant developments in the areas of circuit design, modelling and fabrication. The project required the consortium to develop diode technology that would be capable of handling very high levels of power. In order to test these devices new power combining techniques needed to be developed based on packaging commercial European MMIC technology. Finally, new electro-thermal models were required to accurately predict circuit performance.

The following sections describe in detail:

- **The W-band frequency sextupler**. An innovative frequency tripler design based on discrete Schottky diodes is presented with its measured performance (W band power, bandwidth and efficiency) when pumped with an active doubler circuit.

- **W-band power combined amplifiers**. Prototyped amplifiers include examples using European MMIC chips sourced from IAF (a maximum of 4 MMIC chips were tested) as well as commercial samples. The performance of a complete power combined W-band sextupler chain including driver amplifier and power combined amplifiers is shown.

- **The design, manufacture and testing of frequency multiplier circuits using new integrated Schottky diode circuits** manufactured in the UK. In these circuit examples, physical modelling of GaAs Schottky structures has been taken into account, including the introduction of electro-thermal models within circuit design tools, in order to improve design procedures.

2.2 W-band frequency sextupler

The innovative design proposed by RPG in the framework of MIDAS was to use a multi-anode balanced tripler with a novel biasing scheme based on coupled lines. The use of a split transmission line enables the use of discrete chip in a balanced configuration, without the need to develop a more complex on-chip or on-circuit MIM capacitor. This novel approach is illustrated in Figure 2. As shown in Figure 3, a narrow gap in the central microstrip line allows for independent biasing of each separate transmission line. At RF frequencies, these lines are coupled to each other, and the main propagating mode is the microstrip mode, as it would be if there was only one central microstrip line. By introducing a gap on the GaAs tripler central pad as shown in Figure 4, each branch of the chip, featuring 3 anodes, can be reverse biased independently, making all the 6 anodes operating in Varactor mode, as it would be with a more traditional multi-anode tripler. This architecture also allows for slightly different bias voltages to be applied on each branch of the chip, in order to compensate for any slight imbalances in the chip electrical characteristics.

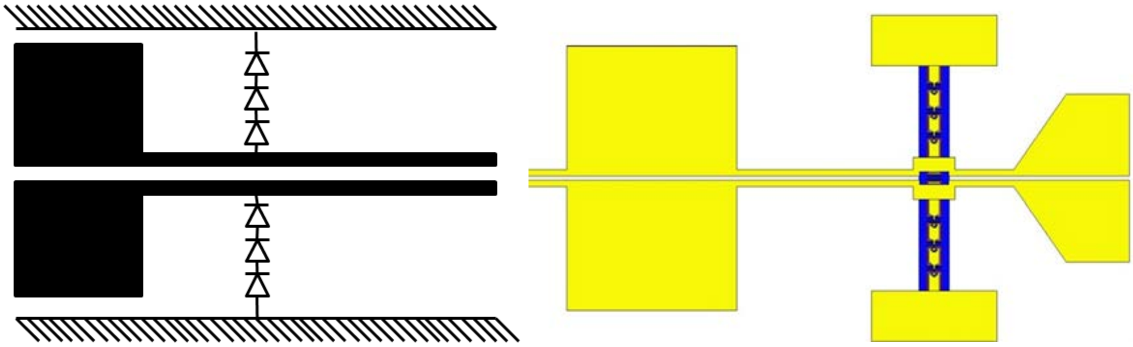

Figure 2: W-band balanced tripler using discrete Schottky diode chip using novel coupled lines biasing scheme.

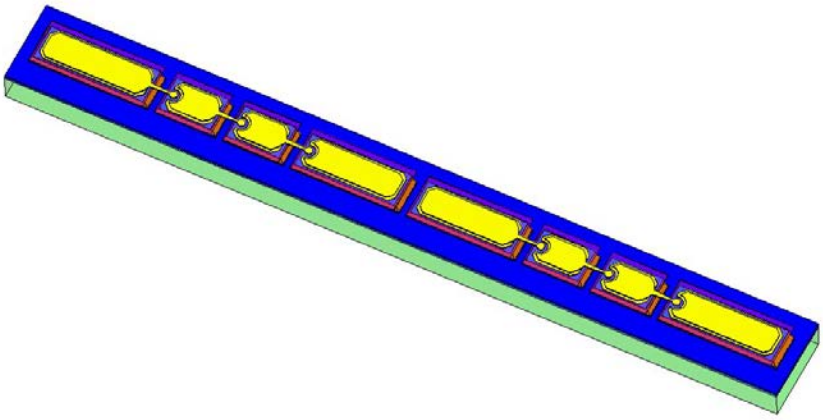

Figure 3: Discrete 6-anodes tripler chip transferred onto AlN designed by RPG and fabricated by STFC. Chip size is approx. 700 µm x 50 µm.

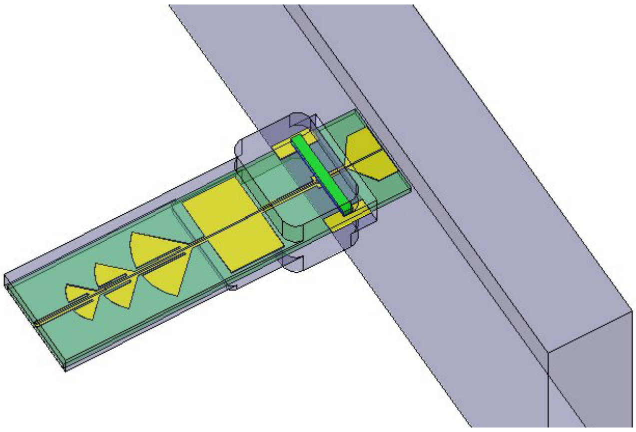

Figure 4: Schematic of W-band bias-able tripler designed by RPG based on a discrete multi-anodes GaAs Schottky Varactor device from STFC.

The W-band tripler block and AlN based circuit have been fabricated and assembled by RPG, and are shown in Figure 5 and Figure 6. Two SMA connectors are used for the biasing lines. One K-type glass bead connector is used for input RF signal at Ka-band. The circuit is based on a 50 µm thick AlN substrate. This choice is motivated by the high thermal conductivity of AlN (typically 180 W/m.K), allowing for efficient heat dissipation of the tripler chip.

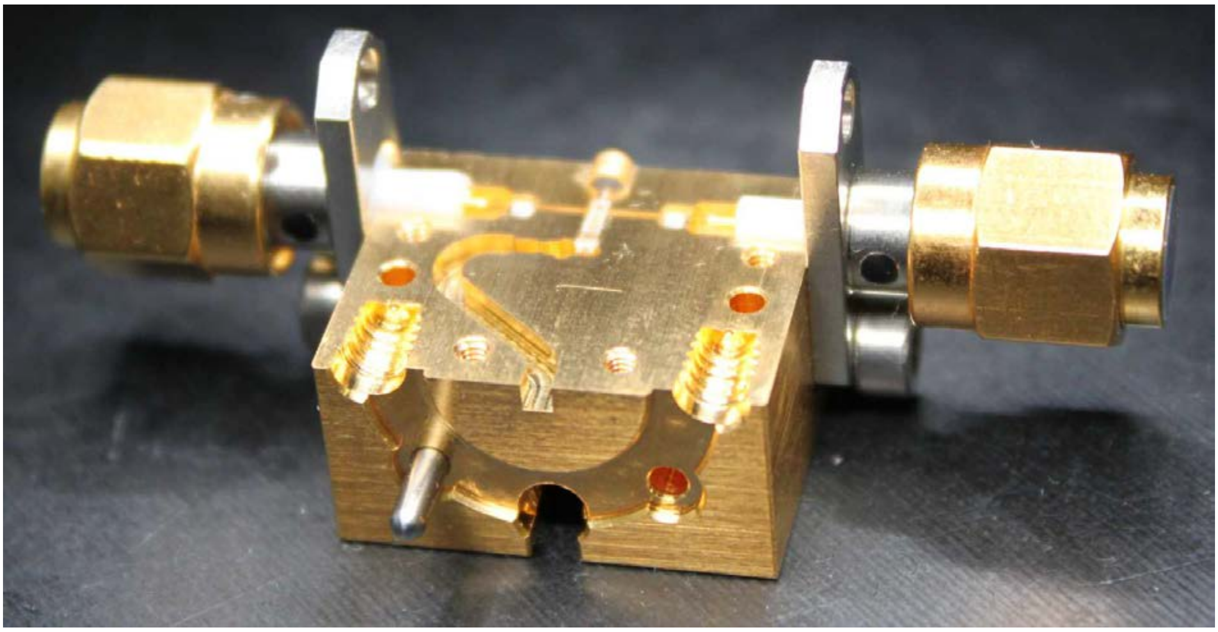

Figure 5: View of the RPG W-band tripler block (lower half), with the AlN circuit mounted inside and connected to two SMA connectors for biasing and a K-type glass bead for RF input signal.

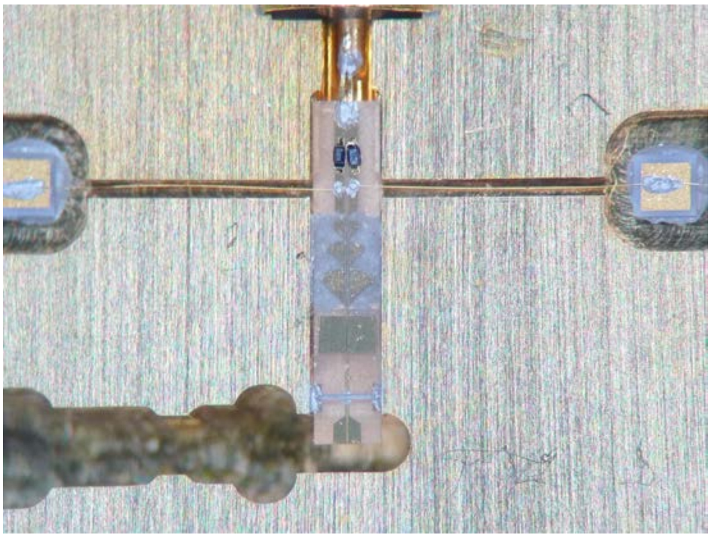

Figure 6: Detailed view of the W-band tripler circuit, with the 6-anodes varactor tripler chip flip-chip mounted onto the 50 µm AlN circuit. The circuit is approx. 2.6 mm long.

The complete sextupler uses an active MMIC doubler and an active MMIC amplifier as a driver stage to pump the W-band tripler described above. In order to conveniently test several active 28-35 GHz driver stages, it was decided to keep the active part and the passive tripler in two separate housings, with a K-type connector as interface. Integrating the active and passive stages into a single housing, however, would be straightforward in the future.

The active driver stage uses an Avago active doubler chip (ref. AMMC-6140) followed by a UMS 20-40 GHz medium power amplifier chip (ref. CHA3093c), packaged in a single housing with input/output K-connectors. These devices have been chosen because of their broad frequency coverage. The active doubler from Avago could be replaced by a European equivalent active doubler chip from UMS, with slightly reduced frequency coverage (for example, 25-33 GHz quadrupler, 28-30 GHz doubler, or 33-43 GHz tripler). The saturated output power of the last stage 20-40 GHz medium power amplifier from UMS is between +20 dBm and +22 dBm, which is suitable for the W-band passive tripler. A photograph of the complete W-band sextupler is shown in Figure 7.

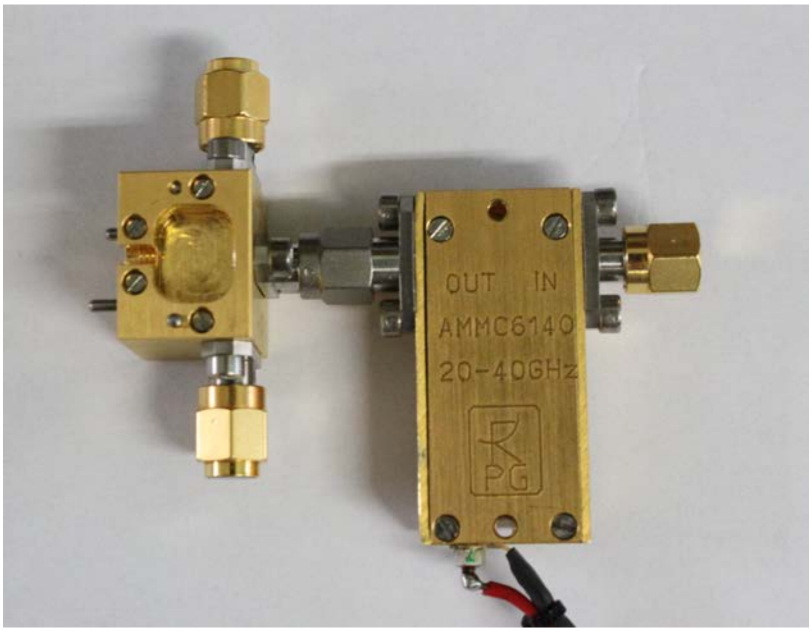

Figure 7: Photo of the complete W-band sextupler, including the active doubler driver stage and the passive W-band tripler stage.

The complete sextupler was measured using a laboratory amplifier module with coaxial input/output interface connection, and a ZVA-40 VNA from Rohde & Schwarz for signal generation. The output power of the tripler was measured using a PM4 Erickson Power Meter.

Measurement results of the W-band tripler are presented in Figure 8. This shows the input power, output power and efficiency versus output frequency. The input power was varied from 80 mW to 150 mW between 82 and 111 GHz. The measured output power ranged from 3 to 10 mW in the frequency range 82 to 110 GHz. The efficiency is over 4 % between 85.5 GHz and 105 GHz, with a peak efficiency of approximately 7.5 % around 96 GHz.

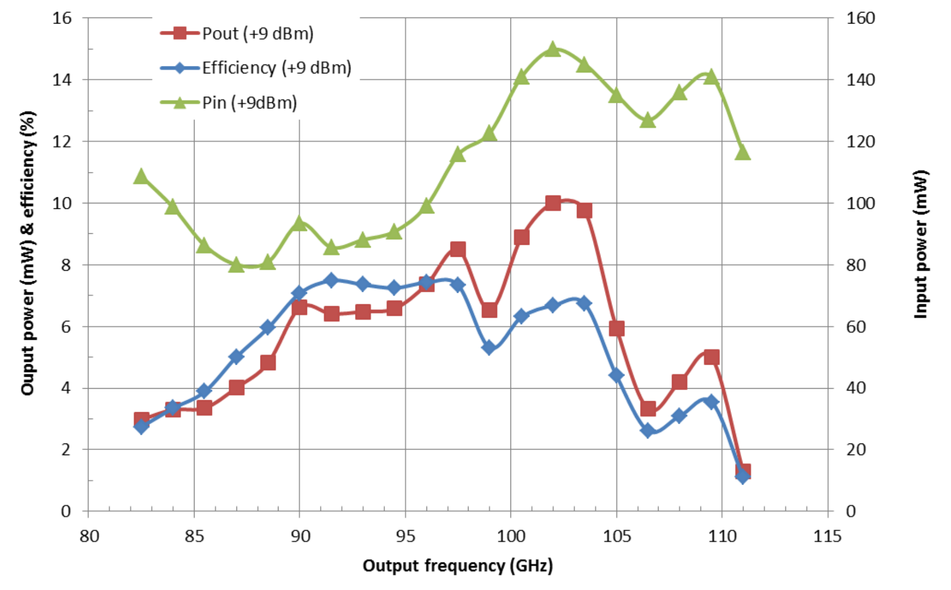

Figure 8: Performances of the W-band tripler versus output frequency. The input power of the sextupler was constant at +9 dBm.

The performances of the W-band tripler versus input power is shown in Figure 9 at two input frequencies. The efficiency of this device remains relatively flat from 60 mW up to at least 160 mW at an output frequency of 97.5 GHz. This circuit can handle an input power of 210 mW with an outpur frequency of 102 GHz. During these measurements, the biasing of the tripler was adjusted for each power point in order to maximize the output power. The bias voltage ranged from 1.7 V/branch in the low power range (approximately 50 mW), up to 6.5 V/branch in the high power range (approximately 160-200 mW), demonstrating the wide range of usable input powers for this tripler.

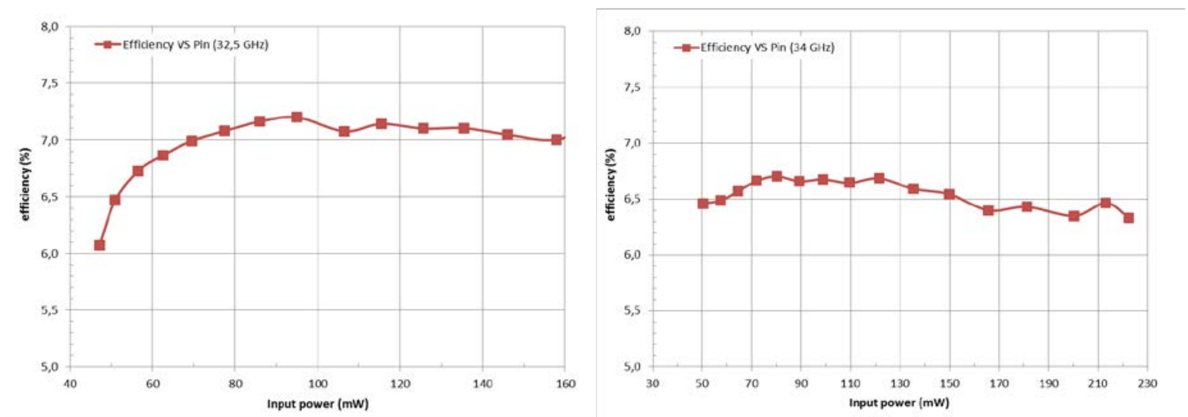

Figure 9: Efficiency versus input power of the W-band tripler at 97.5 GHz (left hand side) and 102 GHz (right hand side) output frequency.

2.3 W-band power combined amplifiers

In order to generate a high power W-band source, a hybrid power combiner has been developed that includes input and output waveguide twists to combine two MMICs in a single module. This includes input and output waveguide flanges that are suitable for further power combining; the module is shown in Figure 10. The measured results of two similar modules, each including two MMIC amplifiers from IAF (CMPA-110 P8) are shown in Figure 11. The maximum saturated output power obtained is close to +23 dBm. These modules use WR-8 waveguide sizes in order to match the operating bandwidth of the amplifiers. These amplifiers can be operated up to 117 GHz, with a consistent drop in power around 114 GHz. Measured output power is over 100 mW in the frequency range 96-112 GHz, as shown in Figure 11.

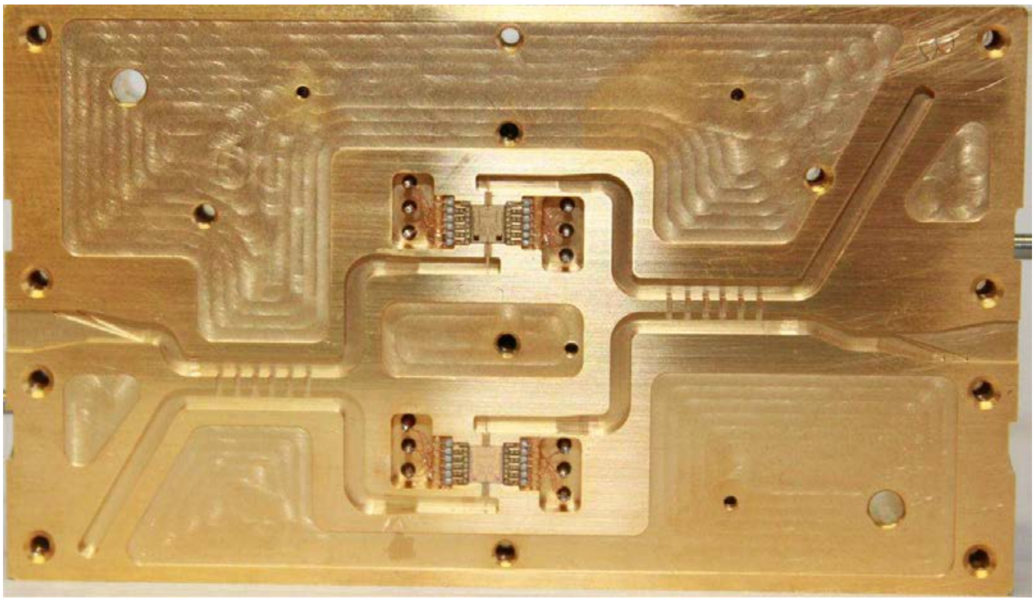

Figure 10: Photograph of the two amplifier MMICs from IAF mounted inside the lower half of a split-waveguide block that includes two waveguide hybrid couplers for power splitting/combining, and two waveguide twists, inside a single housing

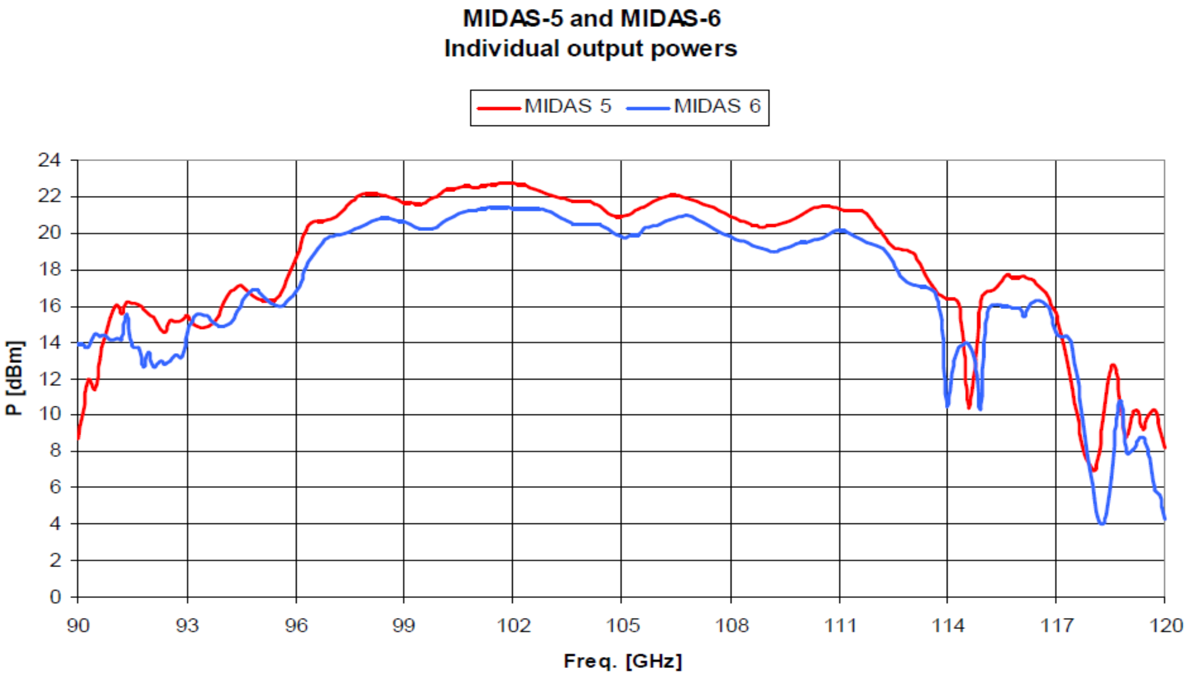

Figure 11: Measured performance of the dual-MMIC internally power combined module using a hybrid power splitter/combiner and waveguide twists. Both curves show the saturated output power in dBm.

In order to further increase the output power from these amplifiers, external power combining of two dual-MMIC hybrid power combined modules was implemented (4 MMIC amplifiers in total). The two external 2-way hybrid waveguide splitter/combiner modules were developed and tested separately before integration. The complete power combined W-band sextupler including driver amplifier and power combined amplifiers is shown in Figure 12 with the final results shown in Figure 13. The measurement results show a maximum output power of 320 mW is obtained around 102 GHz, and a saturated output power over 200 mW is measured between 97.5 GHz and 112 GHz.

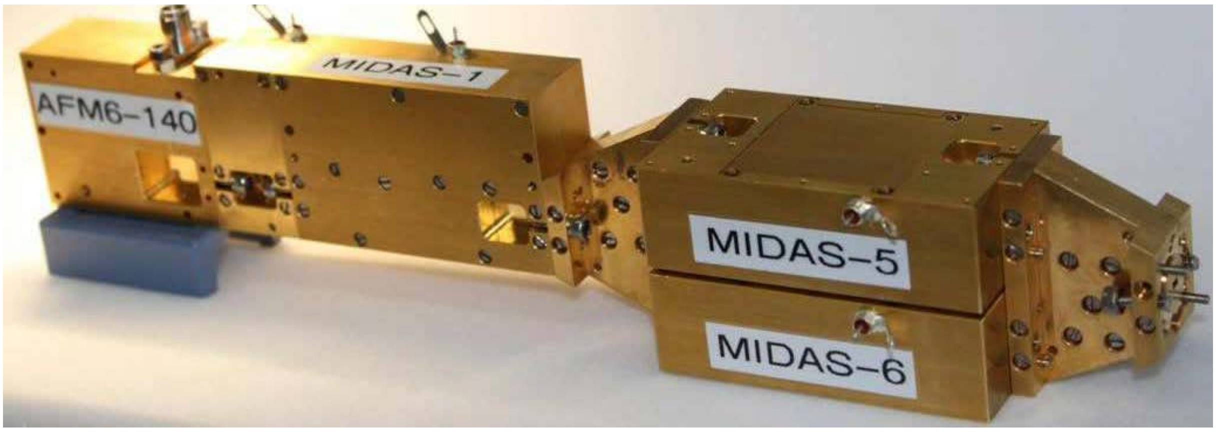

Figure 12: Photograph of the complete power combined sextupler chain including driver amplifier and power combined amplifiers.

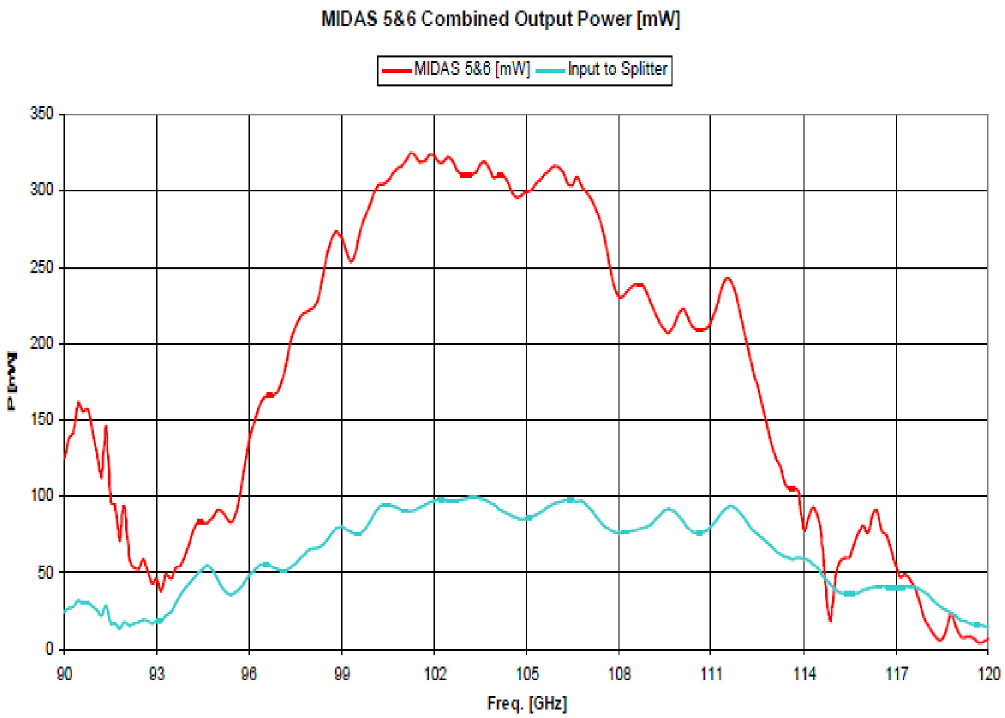

Figure 13: Measured performance of complete power combined sextupler chain including driver amplifier and power combined amplifiers (4 MMICs combined in the final stage). The graph shows the saturated output power in mW (top curve), and input power (bottom curve).

Commercially available MMIC amplifiers from Hittite in the US have been packaged in individual housings, and externally power combined using a 2-way external hybrid splitter/combiner. Each of these MMIC amplifiers has a saturated output power of +22 dBm in the frequency range 81-86 GHz, and over +20 dBm in the frequency range 79-90 GHz. The measured output power of the 2-way externally combined single chips amplifier modules is shown in Figure 14. A maximum output power close to 400 mW has been measured around 83 GHz, and a saturated output power over 200 mW has been measured between 79 GHz and 89 GHz. It is expected that an output power over 400 mW can be achieved in the frequency range 80-89 GHz by power combining 4 similar MMIC amplifiers.

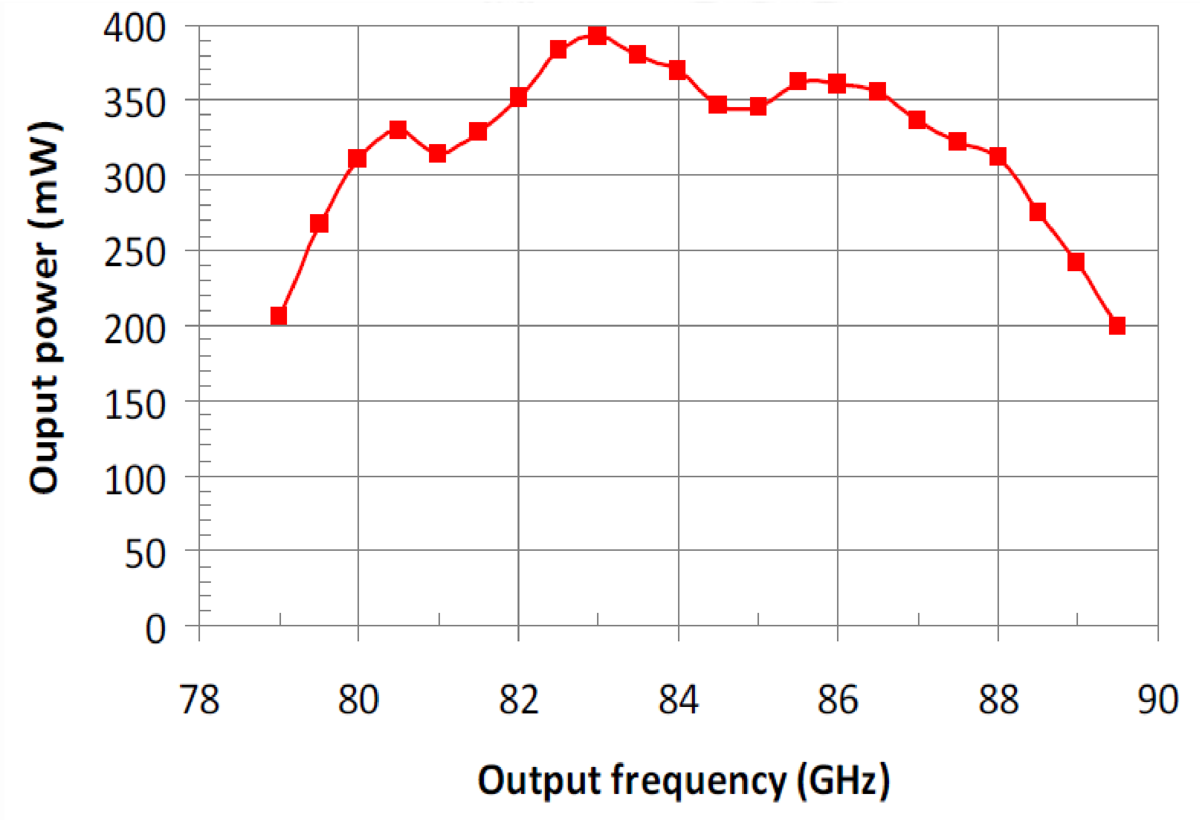

Figure 14:Measured performance of an external 2-ways hybrid power combination of Hittite single-MMIC amplifier modules (2 chips in total), showing the saturated output power in mW.

2.4 The design of frequency multipliers

In this project, the circuit topology was chosen carefully as a balance between the needs of the device to operate at high frequencies and the demands set by thermal and electrical power management. The overall approach was to design the circuits on a 12 µm membrane of GaAs which was calculated to handle the designate input power. The plan, if time was available, was to subsequently reduce the thickness of this GaAs membrane and replace it with an equivalent dielectric loading of CVD diamond. This approach would allow direct comparison of the improved thermal management by supplanting some of the native GaAs with the considerably higher thermal conductivity of the transferred substrate. Unfortunately technical issues incurred during this project did not allow the consortium to reach this second demonstrator stage.

The frequency tripler circuit was designed in an open-loop configuration to allow more than two diodes to be easily implanted on chip, this dramatically increases the power handling capabilities of the multiplier by allowing a varactor mode operation and increasing the number of series connected diodes.

During MIDAS project, two solutions were considered to meet the power handling and output power specification goals of the project. The first solution was to use an 18 diode chip. This configuration would consist of three parallel diodes put in series with 6 other similar stages. This option naturally favours high power handling with minimum parasitic elements in the area surrounding the anode. Following a set of fabrication and design reviews, it was ultimately decided to implement a 6 anode frequency tripler with series connected diodes. This configuration is more adapted to the diode fabrication process at STFC, featuring fewer, but wider anode areas, in order to handle the appropriate input power.

The final circuit demonstrator included six Schottky planar varactor diodes monolithically integrated on a 12 µm thick GaAs substrate and connected in series at DC. The bias is provided through an on-chip capacitor made with a 1 µm dielectric layer sandwiched between two metallic plates. This capacitor permitted the biasing of the varactor diodes to improve the efficiency and power handling of the multiplier. This capacitor structure can introduce an imbalance in the diode cell, so special care was required to understand the tolerance specification of the fabrication process in order that the final circuit design was intolerant to these natural errors.

The design methodology consisted of optimizing the tripler cell dimension in conjunction with the circuit matching network. This process is iterated as necessary to optimise the tripler cell dimensions and the impedance step lengths. This is done in order to match the input and output ports to the diode and thereby obtain a maximum coupling efficiency. A second optimization step was implemented to widen the bandwidth using matching elements in the input waveguide. The final circuit design is presented in Figure 15 and Figure 16. These images also show the modifications required in the capacitor region to reduce the effects of asymmetry in the diode cell, since these might severely alter the ultimate circuit performance. The final simulated performance of this circuit is presented in Figure 17 and also shows the effect of the final waveguide tuning used to broaden the bandwidth.

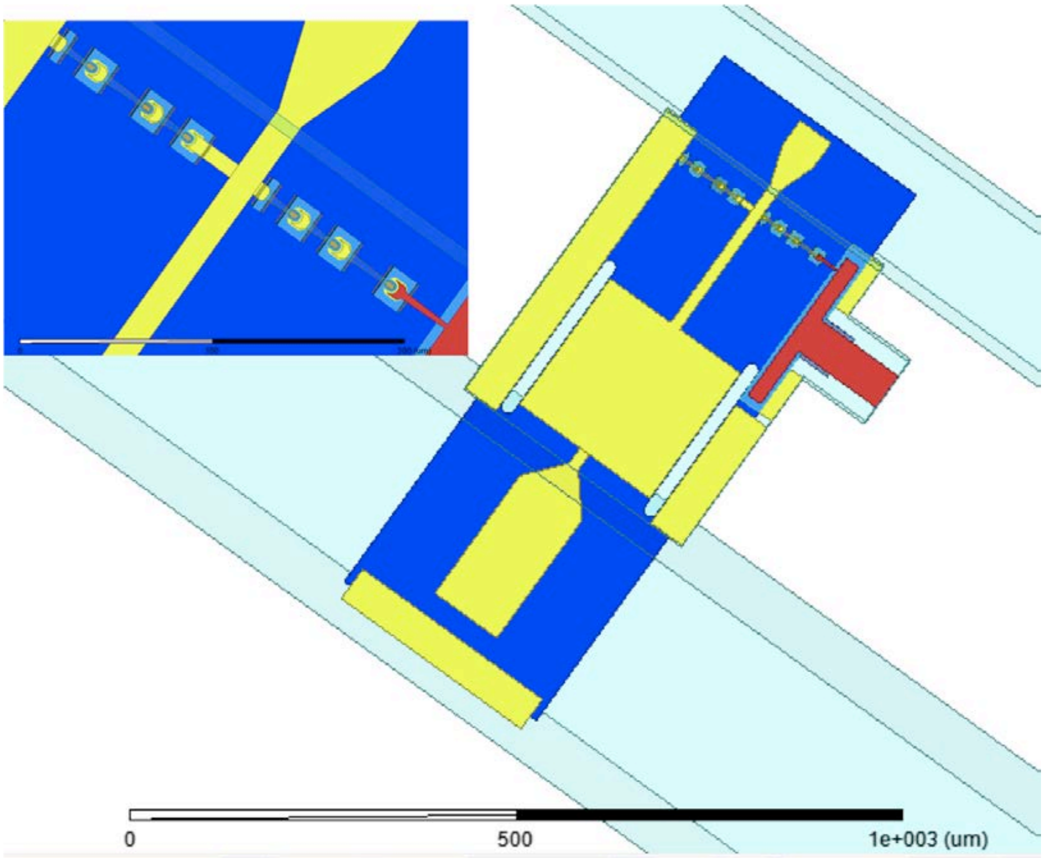

Figure 15: Final 3D circuit model implemented in HFSS with its on-chip capacitor according to STFC process. Top left : close up on tripler cell and its 6 anodes.

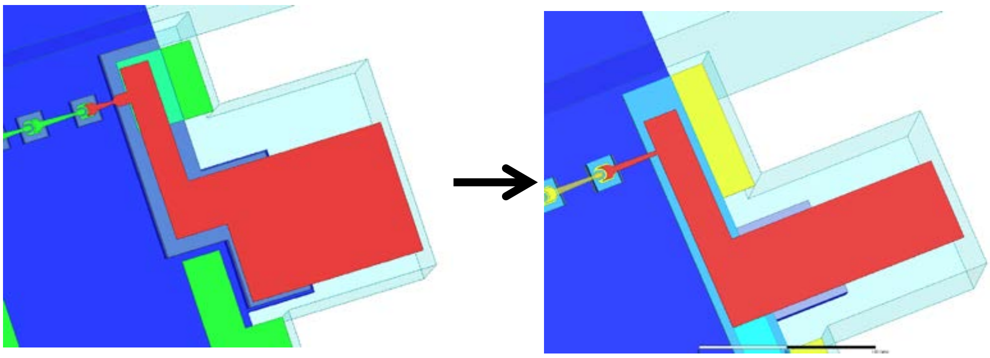

Figure 16: Updated version of the bias port: an asymmetry creates an imbalance of the diode cell and has a great impact on the circuit performance.

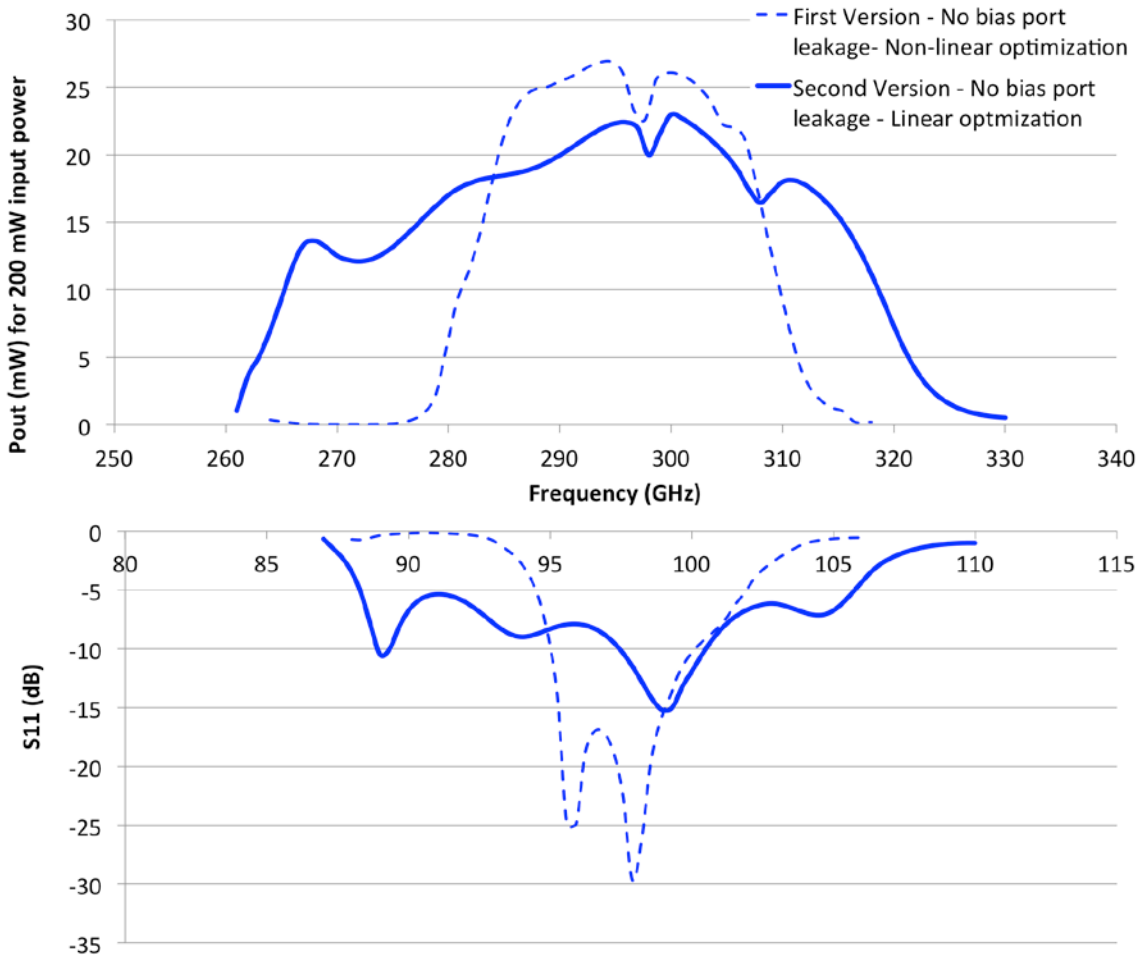

Figure 17: Performance results of 300 GHz single chip. The dot and plain lines correspond respectively to the first and second version of the design. Top: output power with 200 mW of input power, bottom: return losses at input port in dB.

2.5 Physical modelling of GaAs Schottky structures

Self-heating has become in one of the most important issues in the design of circuits with the emergence of new high power THz applications. However, there is a lack of temperature dependent models in commercial circuit design software. Therefore, the introduction of electro-thermal models in circuit design tools is required in order to improve the design procedures.

The methodology carried out by UPM within MIDAS regarding electro-thermal modelling of Schottky devices is summarized below:

- Development of a physics-based numerical electro-thermal model. This model was coupled to an in-house circuit simulator based on the harmonic-balance technique [MODEL 1].
- Extraction of thermal impedances by specific thermal simulation software in order to take into account the regions of the device where electrical effects do not take place.
- Development of an analytical electro-thermal model which is implemented in ADS [MODEL

2].

A schematic of UPM methodology for modelling Schottky devices is presented in Figure 18.

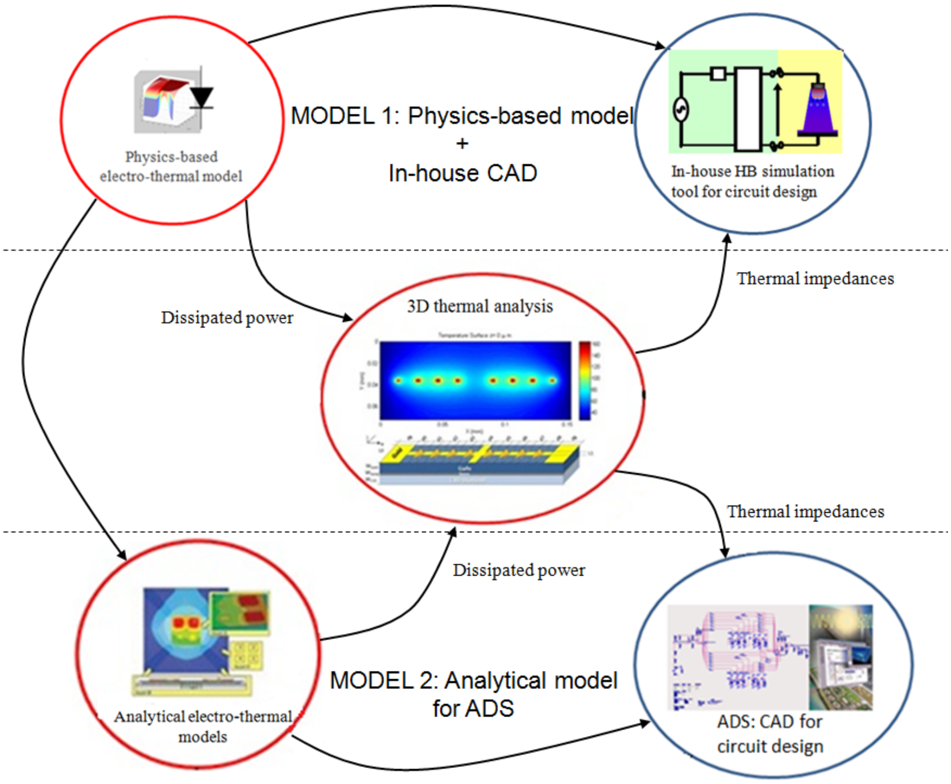

Figure 18: UPM methodology for modelling Schottky devices.

2.5.1 Physics-based electro-thermal model

A physics-based numerical electro-thermal model for Schottky diodes has been developed which couples to a circuit simulator based on the harmonic balance technique, with the aim to design high performance Schottky-based circuits working at millimeter and submillimeter wavelengths. This model takes into account both electrical limiting transport mechanisms and self-heating. The thermal characteristics are accounted for by adding the heat conduction equation to existing physics-based electrical models based on the drift-diffusion theory or Monte Carlo technique. The integration of electro-thermal models into circuit simulators provides a tool which can be used to design and analyse Schottky diode based circuits.

Thermal phenomena are strongly affected by 3D propagation effects and are relevant on volumes much larger than what are needed for an accurate electrical description. These characteristics make a direct numerical solution of the coupled electro-thermal problem inefficient. An accurate and efficient approach is, thus, required, based on the full numerical solution of the transport equations coupled to the heat transfer equation in a reduced volume. This reduced volume includes all zones of the device where electrical effects take place. Thermal effects from the excluded device volume are accounted for by thermal impedances, which are extracted via 3D thermal simulation of the corresponding zones.

2.5.2 Extraction of thermal impedances

The thermal part of a single anode can be defined as a parallel RC circuit as shown in Figure 19. R_{th} is the thermal resistance in K/W. C_{th} is the thermal capacitance in $W \cdot s/K$ and defines the cut-off frequency of this low-pass filter ($f_c = \frac{1}{2\pi \cdot R_{th} \cdot C_{th}}$). For excitation frequencies higher than this cut-off frequency, the thermal behaviour is defined by the averaged dissipated power and not by the instantaneous dissipated power. In other words, $\tau_{th} = C_{th} \cdot R_{th}$ is the thermal time constant, which is in the range $[10^{-6}, 10^{-3}]\, s$.

On the other hand, in order to get a full thermal characterization of a multi-anode structure, the thermal interactions among anodes have to be taken into account. Therefore, an analysis based on a thermal resistance matrix scheme was implemented. This matrix is extracted through 3D thermal simulations carried out by specific simulation software.

The self-heating effects and thermal interactions among anodes can be modelled as shown in Figure 19. The thermal capacitance is not included in the equivalent circuit because it is assumed that the current sources represent the averaged dissipated power.

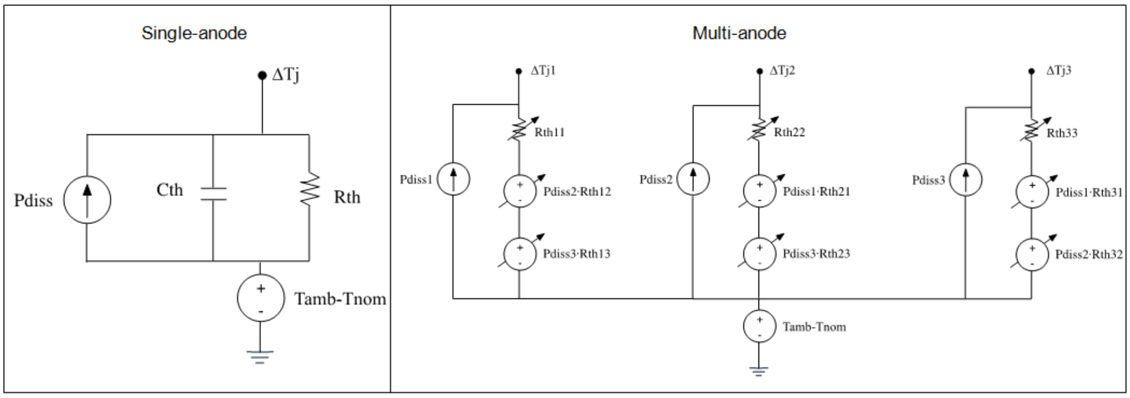

Figure 19: Equivalent circuit for the thermal resistance model.

Following the multi-anode topology of Figure 19, the temperature increments in each anode due to self-heating and thermal interactions among anodes are related to the dissipated power, P_{diss_i}, in all the anodes by a thermal resistance matrix:

$$\begin{pmatrix} \Delta T_{sh_1} \\ \Delta T_{sh_2} \\ \Delta T_{sh_3} \\ \vdots \\ \Delta T_{sh_N} \end{pmatrix} = \begin{pmatrix} R_{th_{11}}(T_{j_1}) & R_{th_{12}}(T_{j_1}) & R_{th_{13}}(T_{j_1}) & \cdots & R_{th_{1N}}(T_{j_1}) \\ R_{th_{21}}(T_{j_2}) & R_{th_{22}}(T_{j_2}) & R_{th_{23}}(T_{j_2}) & \cdots & R_{th_{2N}}(T_{j_2}) \\ R_{th_{31}}(T_{j_3}) & R_{th_{32}}(T_{j_3}) & R_{th_{33}}(T_{j_3}) & \cdots & R_{th_{3N}}(T_{j_3}) \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ R_{th_{N1}}(T_{j_N}) & R_{th_{N2}}(T_{j_N}) & R_{th_{N3}}(T_{j_N}) & \cdots & R_{th_{NN}}(T_{j_N}) \end{pmatrix} \cdot \begin{pmatrix} P_{diss_1} \\ P_{diss_2} \\ P_{diss_3} \\ \vdots \\ P_{diss_N} \end{pmatrix} \quad (1)$$

where N is the number of anodes and ΔT_{sh_i} is the temperature increment in anode i due to self-heating and thermal interactions among anodes. The elements $R_{th_{ip}}(T_{ji})$ account for the temperature increment in anode i produced by the dissipated power in anode p when no power is dissipated in the rest of anodes.

The elements $R_{th_{ii}}(T_{ji})$ can be interpreted as the self-induced thermal resistance in each anode, whereas the elements $R_{th_{ip}}(T_{ji}),_{i \neq p}$ model the thermal interactions among anodes.

An in-house thermal simulation tool and a commercial software called FloTHERMTM are currently used for extracting the thermal resistance matrix. Our simulation tool must only be considered as a fast design tool which provides a first approach to the final solution. It is not as accurate and versatile as the commercial software. An example of temperature distribution obtained with our in-house simulation tool is shown in Figure 20.

Figure 20:Temperature distribution obtained with our simulation tool.

2.5.3 Analytical electro-thermal model implemented in ADS

An analytical electro-thermal model has been implemented in ADS from Agilent as a 3-terminal device using the Symbolically Defined Device capability. The three terminals correspond to anode, cathode, and temperature increment ΔT_j.

A comparison between ADS and UPM diode models was carried out on a 6-anode balanced tripler at 260-340 GHz from OBSPARIS. Figure 21 shows the efficiency comparison for 70 mW of input power varying the thermal resistance and ambient temperature without considering coupling effects among anodes. Figure 22 shows the efficiency obtained with coupling effects (blue colour) and without coupling effects (red colour) at ambient temperatures of $27\ °C$ (dashed lines) and $70\ °C$ (solid lines). These new electro-thermal models compare well with published data but work towards a full experimental validation will continue beyond the lifetime for the MIDAS project.

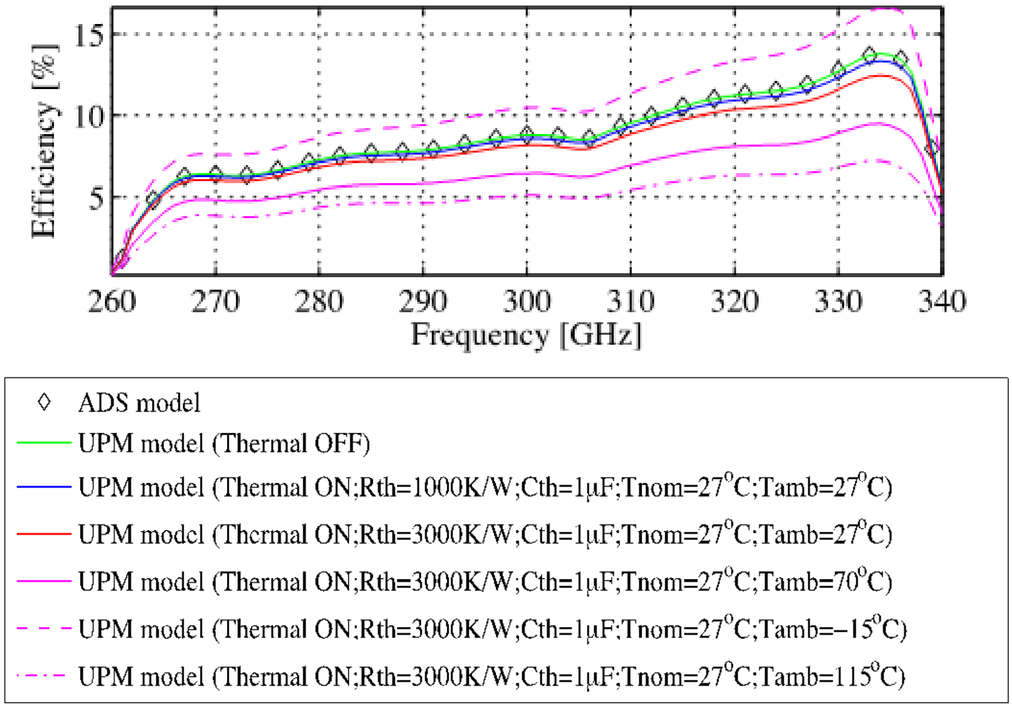

Figure 21:Efficiency results with 70 mW of input power and Vbias = -13 V

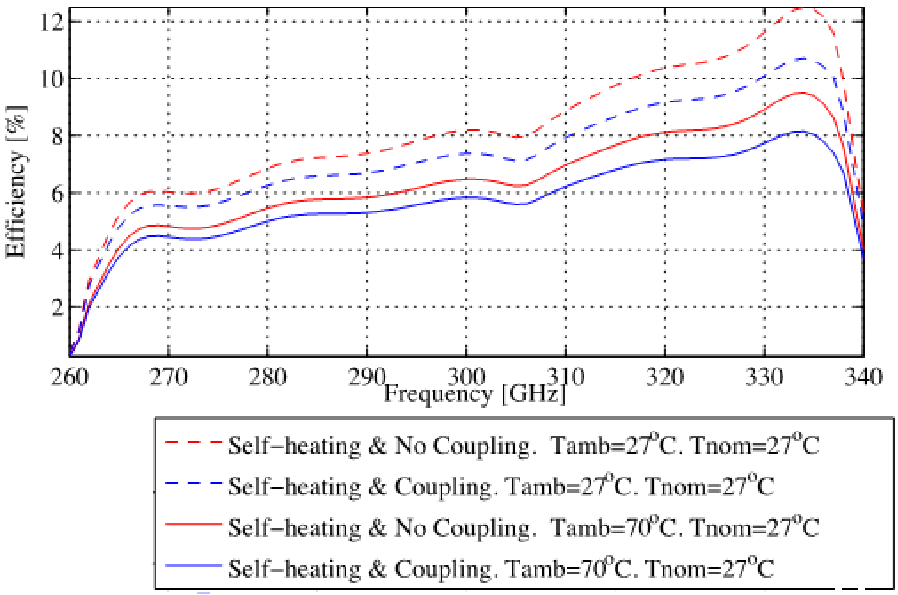

Figure 22:Efficiency results with 70 mW of input power and Vbias = -13 V

2.6 Integrated Schottky diode circuits

A schematic of a 300 GHz frequency tripler is shown in Figure 23 together with the mask layout drawing. The complete circuit prior to backside processing and separation from the substrate is shown in Figure 24 together with a detailed view of the anode and air-birdge region. The final GaAs membrane circuits is shown in Figure 25. The image shows a 12 µm membrane of GaAs with beam-leads from three of the edges. Towards the lower right hand side of the image an integrated capacitor provides an RF ground whilst allowing a DC bias to be applied to the diodes. The region between the low impedance filter section and the grounding beam-leads is fully removed as required by the circuit design.

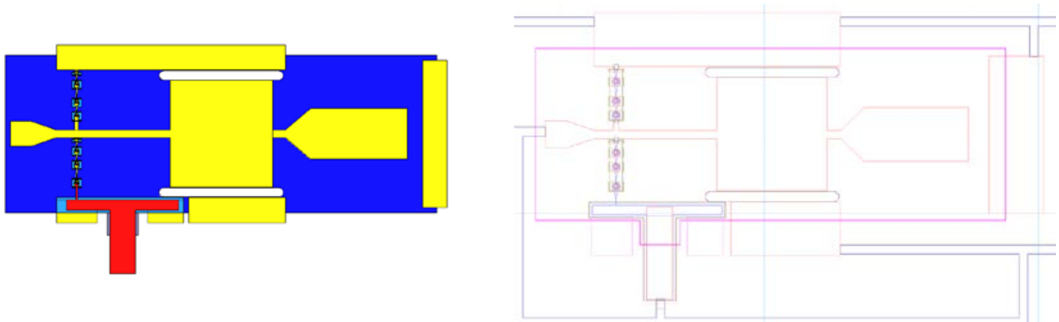

Figure 23:a) Schematic of 270-330 GHz frequency tripler, b) Image of mask layout

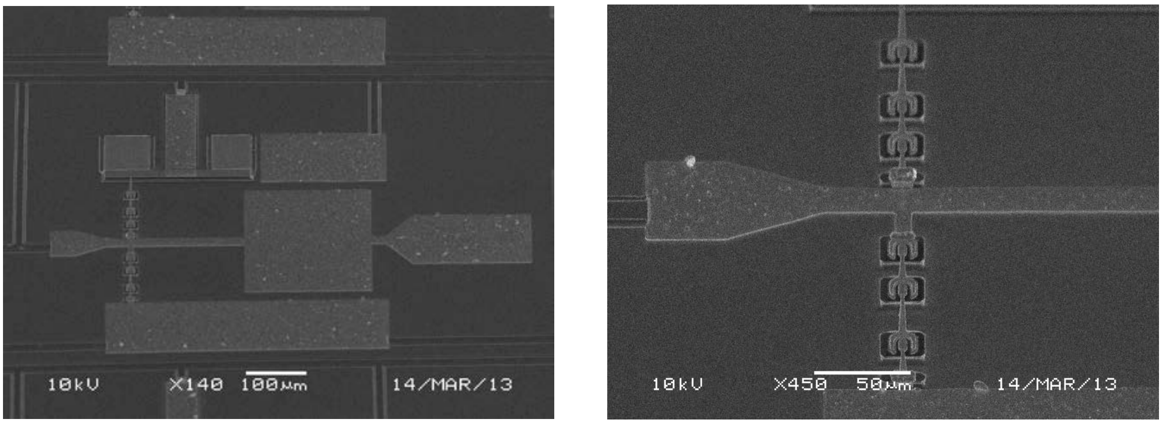

Figure 24: a) Fabricated 270-330 GHz frequency tripler (on wafer), b) diode area

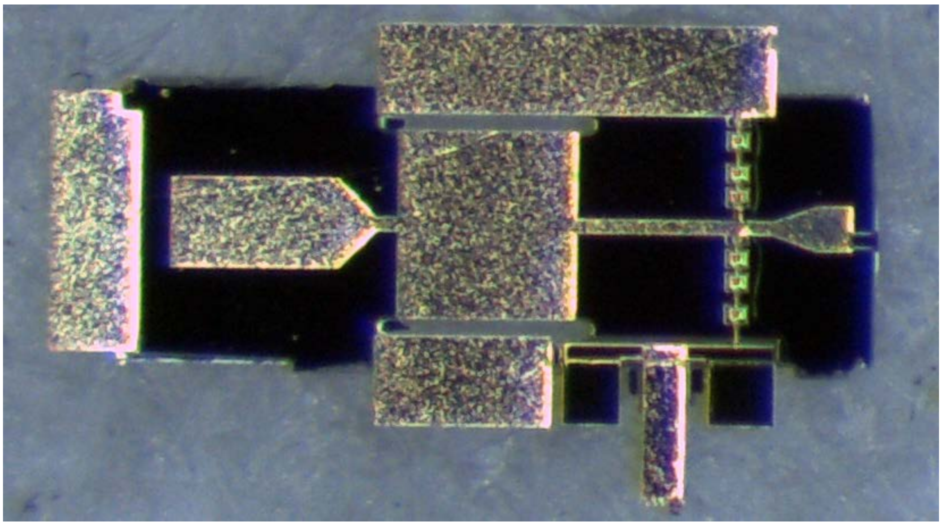

Figure 25: A 330GHz integrated frequency tripler on 12 µm GaAs membrane

The 300 GHz integrated tripler circuits show good current-voltage characteristics with typical data presented in Figure 26.

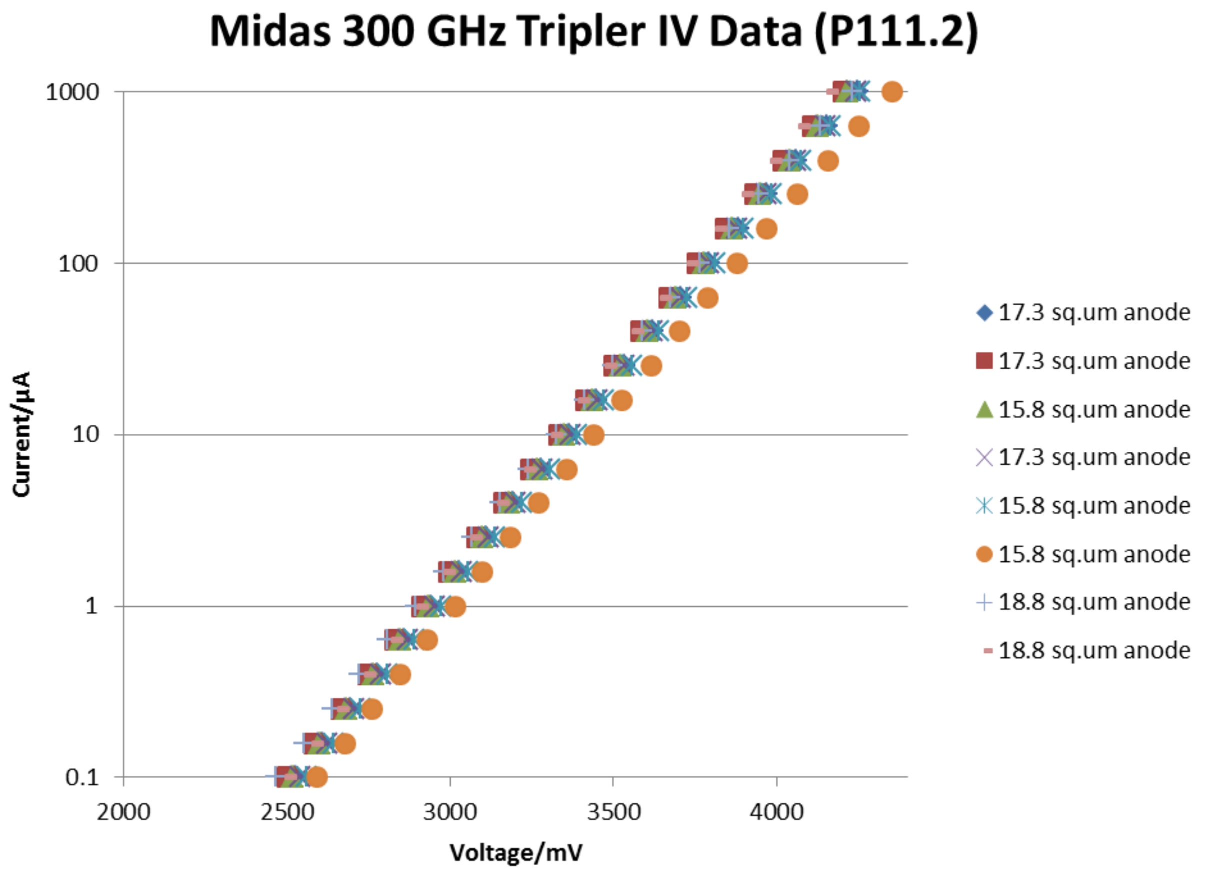

Figure 26: Typical current-voltage characteristics for the 300 GHz integrated triplers

The integrated triplers were mounted in conventional two-way split blocks which include waveguide based impedance matching. An image of the block is shown in Figure 27 and with the membrane circuit mounted in Figure 28 and Figure 29. In this circuit the DC bias is supplied along the plane of the split block.

Figure 27: Machined 300 GHz frequency tripler block

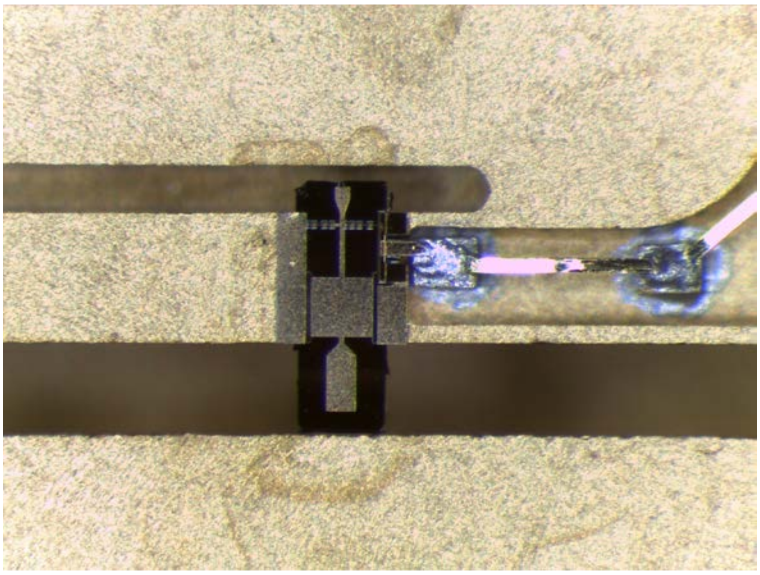

Figure 28: 300 GHz integrated tripler mounted in a waveguide housing

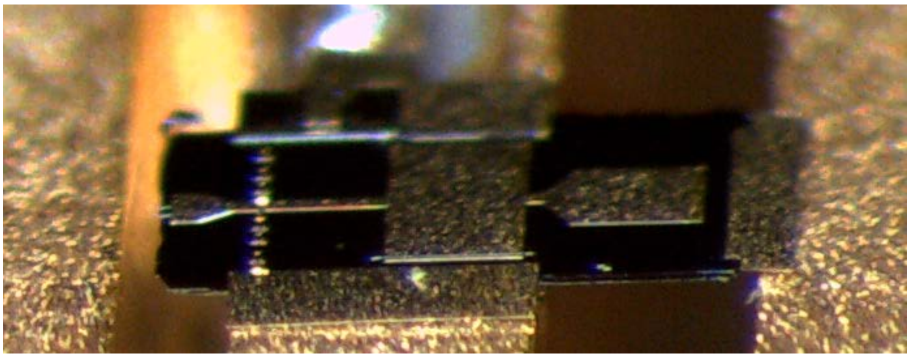

Figure 29: 300 GHz integrated tripler mounted in a waveguide housing (angled view)

The flange-to-flange conversion efficiency of these triplers was measured using a synthesized frequency source that was frequency multiplied by six and amplified using the technology developed by RPG. The circuit was designed for 200 mW input power but less than this was applied in the performance data presented below. The output power from the tripler was measured using an Erickson PM4 power meter.

According to the design, the optimum bias was calculated to be -13V across six diodes in series. A sweep of output power versus bias voltage at 270GHz for a series of diodes with an anode area of 17.8 μm^2, is shown in Figure 30. In the circuit configuration a positive voltage applied to the tripler block presents a reverse bias to the series of diodes.

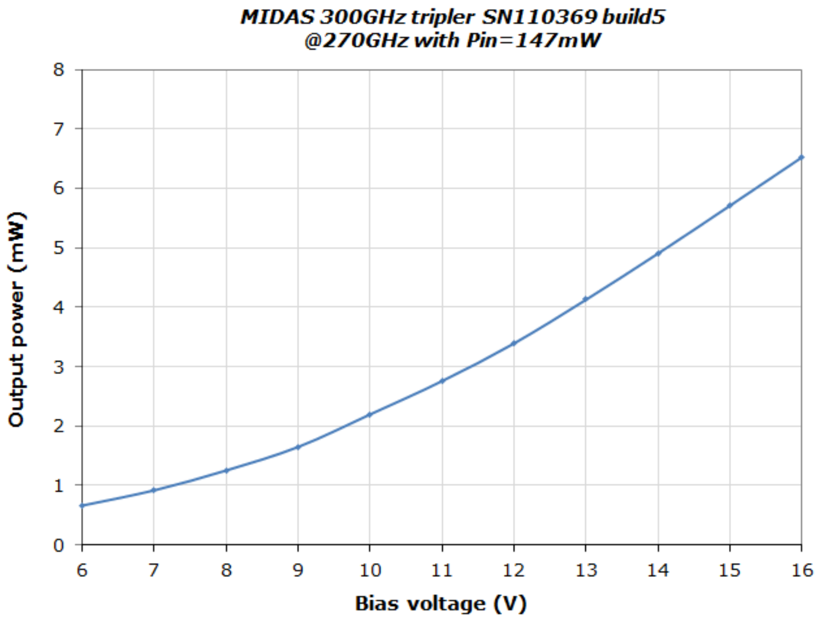

Figure 30: Tripler output power versus DC bias voltage at 270 GHz and 147 mW input power.

A performance plot of the tripler, with an anode area 17.3 µm2 per diode, as a function of output frequency is shown in Figure 31. In this measurement a peak output power of 7.77 mW was measured at 269 GHz, the efficiency was calculated to be 5.7% at this frequency. A strong standing wave was observed during this measurement, in order to improve the input matching, a waveguide isolator was inserted between the drive source and the tripler. In this case the input power to the tripler was reduced, these results are presented in Figure 32; the reduced efficiency is likely to be a consequence of the lower available input power.

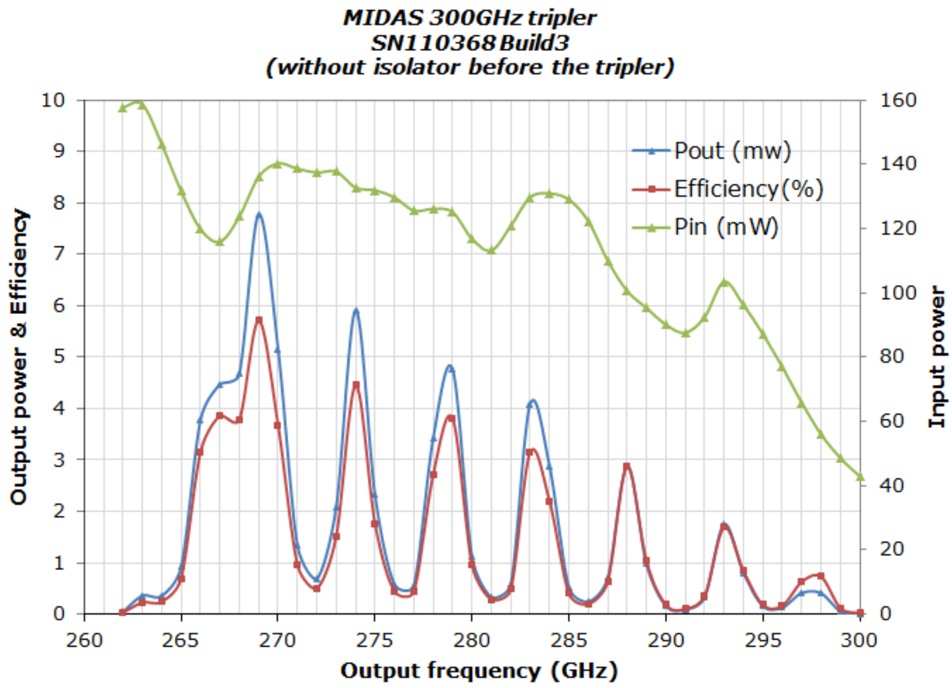

Figure 31: The red curve and the blue curve show respectively the measured efficiency and the output power with -15V DC bias, the green curve with filled triangle markers shows the input power injected into the tripler.

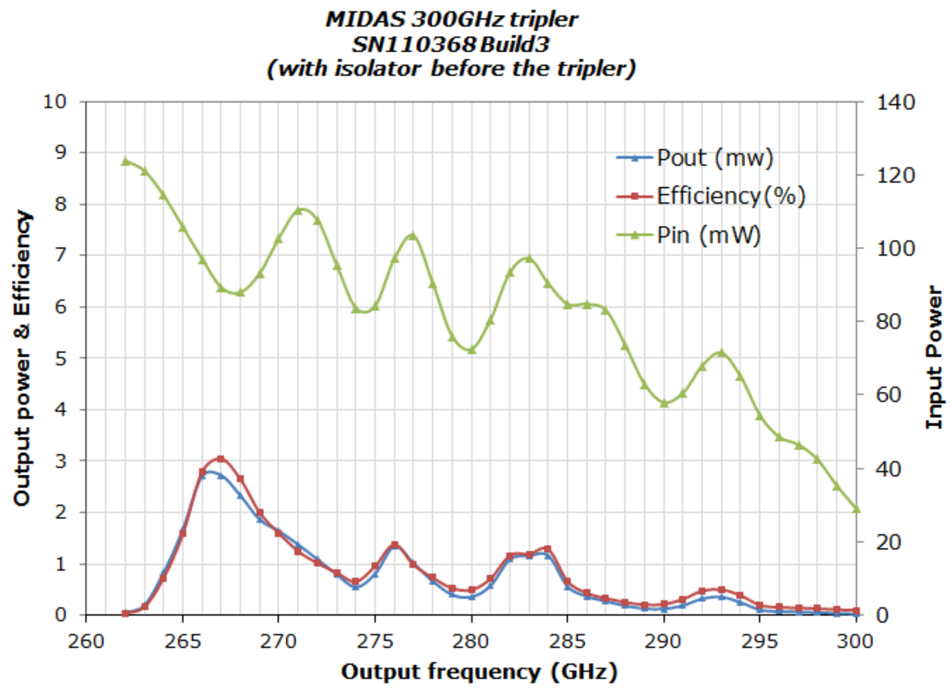

Figure 32: 300 GHz tripler measured with an isolator between the source and multiplier.

In comparing the simulated and final measurement results it appears that the final circuit exhibits a standing wave in the output power. This standing wave is attributed to matching issues at the input of the tripler, possibly related to fabrication problems with the integrated capacitor. A simulation of the tripler performance with the input powers presented during measurement is presented in Figure 33. In this simulation, the junction capacitance has also be modified to match the final fabricated and tested structure. The retro simulations indicate a measured output power reduced by a factor of two from the simulated results. A proportion of this discrepancy will be from natural variation in the series resistance of the diodes, further re-builds and measurements would clarify this. Simulations also indicate that the efficiency would increase with available input power. Again, further measurements are required to confirm this.

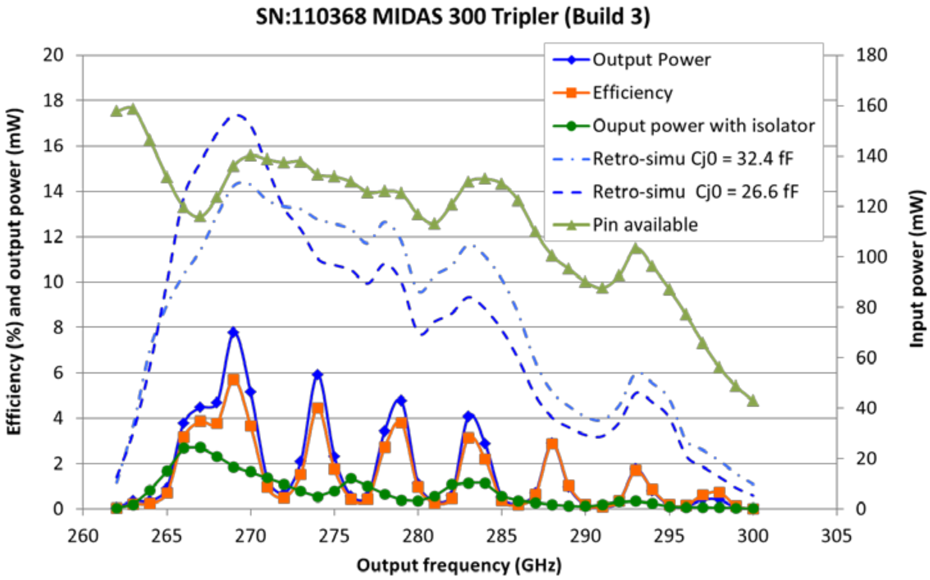

Figure 33: Retrospective simulation of the complete tripler

3 The potential impact

3.1 Impact

The MIDAS project was firmly aimed at Area 9.2.2: “Research to support space transportation and key technologies” of the FP7 Cooperation Work Programme: Space. In this context, the primary impact of the proposed work was to reduce European dependence on critical technologies required for space by developing Schottky diodes and demonstrating their application in the field of terahertz power generation. “Schottky diodes for high frequency applications” was specifically noted in the work programme as a critical technology for which Europe has been historically dependent upon imports. In line with the intentions of the EC, the MIDAS programme has:

- Developed essential millimetre wave Schottky technology required for current and future ESA missions specifically including EPS-SG Polar System that would otherwise be entirely reliant on US device technology.

- Demonstrated a method of generating RF power in a part of the spectrum that has significant commercial benefit and is of clear strategic importance for European industry. This will allow EU companies to take maximum advantage of emerging world markets, without any restrictions caused by possible US export restrictions, and without limitations from incumbent US diode suppliers.

- Developed new models that can be used to simulate Schottky based structures with the ultimate aim of producing better results and higher reliability structures for future space instruments.

- Developed a set of technologies that offer significant clear strategic opportunities for European industry.

The MIDAS project has made an important contribution towards consolidating the development of world-class solid-state THz source technology within Europe. Whilst the highly ambitious goals of the demonstrators have not been realised, Europe stands in a significantly stronger position at the end of the MIDAS project than was the case in 2008 when the proposal was submitted. Further work is clearly required within the EU to match world-state-of-the-art technology in this important area but it is undeniably the case that European research organisations and industry now competes directly with longer standing and better funded groups based in the US. Furthermore, as a result of MIDAS, as well as other programmes funded by the EU, ESA and national funding bodies throughout Europe, European groups have a new set of design and fabrication tools that are enabling application and supporting a growing commercial market.

The impact of this MIDAS programme can be considered on three separate timescales.

Short term

In the short term, Schottky diodes fabricated within MIDAS are being further studied by ESA in the framework of a diode pre-space qualification reliability activity focused on implementing European diode technology in EPS-SG Polar System. European MMIC amplifier technology is available from RPG with significantly higher levels of output power than has previously been commercially available. This packaged amplifier technology based on both EU and US MMICs is enabling new meteorological instruments to be developed by RPG. For example, the high power GaN amplifiers are a critical component in a new 94GHz cloud radar that will be tested in summer 2013. It is expected that these will become another important product in the line of meteorological measurement equipment offered by RPG.

Medium term

In the medium term, new device models developed at UPM will influence future designs and the ability for European groups to compete at the highest level. The new fabrication technologies developed within MIDAS will influence new circuit designs by allowing higher levels of circuit integration. The increased power at W-band developed within MIDAS will also allow new circuit designs that are optimised to handle this level of input power and therefore generate higher output powers than have been previously demonstrated in Europe.

Long term

Our long term expectation is that results from MIDAS will firstly directly benefit astronomy, space science and Earth observation programmes by allowing novel European technical solutions to on-going receiver development. Specifically, the integrated amplifier/varactor technology developed by MIDAS will make it possible for ESA TRP and GSTP projects to advance the state-of-the-art using entirely European devices. Secondly, by removing customers' concerns about possible export restrictions, Europe will be well placed to take full advantage of the emerging markets in China, India, Japan and eventually Russia.

3.2 Dissemination activities

The main dissemination activities for MIDAS have been through conference presentations. The technology developed for power combining, device modelling and circuit fabrication will further allow follow on publication after the conclusion of this project.

3.3 Exploitation of results

The MIDAS project placed a strong emphasis on the commercial exploitation of the results, as evidenced by including RPG as one of the core partners. RPG is the largest supplier of millimetre wave components in Europe and has an expanding range of active components based on European diode technology. The rapidly expanding market for test and measurement equipment is also dominated in Europe by Rohde and Schwarz, which is the majority share owner of RPG.

4 The address of the project public website and contact details

4.1 Public website

http://www.stfc.ac.uk/RALSpace/Areas+of+expertise/Technology/Millimetre+and+terahertz+instrumentation/Projects/26678.aspx

4.1 Contact details

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