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Sub-harmonically pumped up-conversion mixers based quantum barrier devices

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Abstract— **This work investigates the prospective performance of single quantum barrier junctions based on sub-harmonically driven mixers. Both ADS and HFSS are employed to evaluate the performance of quantum barrier devices and optimize prior to fabrication. The output powers and conversion efficiencies are explored for two different designs. The first design aimed at 180 GHz showing an output power of -7dBm, while the second design operates at 110GHz demonstrating -0.5dBm of output power. The objective was to develop and evaluate high power up-converters and to explore the conversion efficiencies for direct output upconverters where a power amplifier may not be economically desirable or available. Comparisons with optimized designs based on main-stream Schottky based approaches are used for benchmarking output powers and efficiencies.**

Keywords—Quantum barrier junctions; resonant tunneling diodes (RTDs); sub-harmonically pumped mixers; millimeter-wave power sources, internet of things.

I. INTRODUCTION

Schottky based devices have been frequently employed in heterodyne receivers for numerous applications such as radio astronomy, security and medical imaging and spectroscopy. These devices require fundamental or harmonic frequency generators (local oscillator or LO in short), with candidates such as Avalanche-Transit-Time (i.e., IMPATT diodes) and Transferred-Electron (i.e., Gunn diodes) [1], Tunnel-Injection-Transit-Time (i.e., TUNNETT diodes) [2], as well as a range of amplifiers and multiplied lower frequency sources [3-4]. Even at W-band (75-110GHz) these amplifiers are rare and expensive so for high data rate shorter transmission ranges subharmonic up-conversion offers a potentially attractive low-cost solution for spectrum occupation. Above 100GHz radar and communications sub-systems rely heavily on Schottky mixers and multipliers [5].

In the relatively distant past Esaki tunnel diodes were the preferred device for direct low-power signal detection up to millimetre wave frequencies (30GHz). However due to the constraints of the narrow tunnel junction the Esaki diodes suffer from a high specific capacitance (F/m^2), limiting their usefulness above the millimetre wave frequency range. Unlike Esaki tunnel diodes other antisymmetric heterojunction and quantum barrier junctions such as resonant tunnelling diodes (i.e., RTDs) [6] have fewer constraints on the barrier height and depletion width and can offer a much lower specific capacitance. The heterojunction based nature of these devices leads to a relatively easily and independently optimized current-voltage and capacitance-voltage characteristic, favoring either very low barrier heights, thus low local oscillator drive levels of between -10 and 0 dBm (0.1-1mW), or alternatively the capability of being driven with comparatively high LO drive levels. Alongside the Gunn and TUNNETT diodes, a signal at 0.5THz and beyond can be generated by using RTDs as fundamental oscillators, which are compact, reliable devices and can be operated at the room temperature. More recently, the fundamental oscillation frequency of a RTD has been demonstrated 1.42 THz [7]. The present reported work explores Resonant Tunnelling Diodes for sub-harmonically pumped up-converters (heterodyne signal modulators driven using a lower sub-harmonic of the usual local oscillator signal or pump). These single junction RTDs, *fabricated at University of Leeds* [8], in terms of their design and possible applications favour these sub-harmonic applications over multiple junction Schottky diodes. The RTDs have favourable nonlinear current-voltage characteristics and this property, very high current tolerance, is exploited in high drive level up-conversion mixing applications at millimetre and sub-millimetre wave frequencies using a sub-harmonic LO signal.

In the first two sections of the current paper, ADS and HFSS software are employed to compare and evaluate two up-converter mixers (modulators) and optimize the embedding networks based on Microstrip (MS) and Grounded Coplanar Waveguide (GCPW) technologies. The mixer performance is compared to similarly optimised Schottky based mixers. For consistency, and to support the later physical validation, rectangular waveguide (RWG) to MS transitions and planar to planar transitions are designed and evaluated in HFSS, and their S-parameter blocks extracted and used in evaluation of the mixers. This is presented in the final section of this presentation.

The objective was to evaluate the performance when these single ended up-converter mixers are driven at high power levels, and to estimate the conversion efficiencies (i.e. at maximum power handling of these existing hetero-structures, and which have potential to be further optimised in terms of maximum current density and power handling), it is anticipated that such structures will serve as a useable candidates for highly compact and efficient complex-signal modulators and demodulators (down-converters)for millimetre and sub-millimetre wave frequency sub-systems, and even possibly internet of things wireless front-ends where cost, simplicity and efficiency will be key product drivers.

II. DESIGN METHODELGY

There are no RTD built-in device models in currrent commerical software. Fortunately the RTD current-voltage and capacitance-voltage characteristics can be evaluated using the symbolically defined device capability in ADS (SDD). The SDD model is a polynomial-based nonlinear component and we only use this to represent the nonlinear junction resistor. Other aspects of the device model such as of the sometimes included series inductor (representing delays in filling and emptying the states in the well) [9], and series resistor (representing the low doped undepleted material next to the junction) and parallel capacitor (emitter-collector depletion capacitance), often referred to as parasitics. Consequently adding such elements to complement the SDD aspect is prerequisite to accurate behavioural modelling. To verify the consistency, this SSD capability together with the other paracitics is compared to the in-built model for the Schottky diodes and showed a modest difference of 1.5dB between these two Schottky approaches; hence using the SDD model approach for the RTD representation is justified and helpful in sub-system design.

Considering the well-known matching technique presented in [10], the first optimisation step was to divide the mixer circuit into two parts, entitled the LO/RF and the IF side matching networks, and then each side's elements were individually optimised in HFSS. Together with these matching networks, a grounded stub at IF frequency with a half-length of wavelength (λ) is located at the LO side to facilitate a signal return path of the IF to ensure a maximum in the standing wave of the IF at the RTD, which will not affect the signal at LO frequency. Similarly, non-grounded stub (open-ended stub) at LO frequency with a quarter-length of λ is located at the IF side to facilitate a signal return path of the LO to ensure a maximum in the standing wave of the LO at the RTD, which will not affect the signal at IF frequency. In the same way, at the RF side, locating shunt and series stubs with a quarter-length of λ at IF frequency to extract the RF signal.

Furthermore, the HFSS results of the matching networks and transitions (presented in the 3^{rd} section) were transferred to ADS software in the form of their scattering parameters to accurately represent the discontinuity effects and to evaluate the overall result of the two up-converter mixers.

III. 2X UPCONVERTER MIXERS PERFORMANCES

An up-converter based on a single RTD junction operating at 180GHz and pumped with a sub-harmonic LO signal at 85GHz, is depicted in Fig.1 and operated using a 10GHz (IF input signal) and 10dBm LO power.

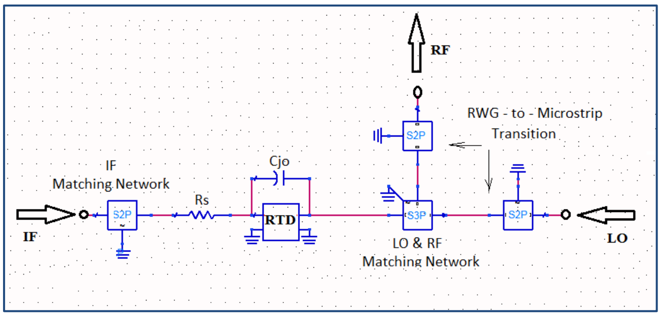

Fig.1. A sub-harmonically upconversion mixer topology.

The simulated performance based on MS-type technolgy is presented in Fig.2 which shows an output power in range of -7dBm at the one-dB compression point (1-dB) input power of 1.5dBm while the two-tone third order intermodulation products (IP3) intercepts at 11.5dBm and 0dBm of IP3-input (IIP3) and IP3-output (OIP3) respectively, and this exhibits a high IP3 suppression of better than 20dBc up-to 5dBm of the input power and such features (i.e., adequate suppression level and power handling capability). This indicates that sub-harmonically up-conversion mixers based on RTDs could be a good candidate for sub-systems at millimetre wave applications and higher, supported by the high power handling capability for a single junction and low overall capacitance.

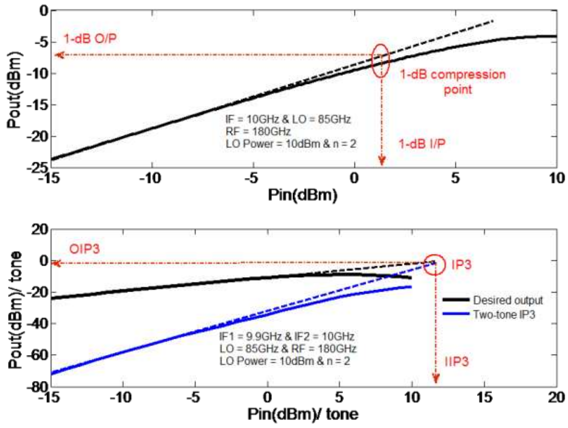

Fig.2. the sub-harmonically upconversion mixer performance at 180GHz.

The second proposed 110GHz up-conversion mixer circuit is based on a GCPW realisation, with a similar configuration to the 180GHz mixer. The 110GHz circuit uses an IF frequency of 20GHz and an LO frequency of 45GHz, with a 16dBm LO power level pumping a single RTD junction.

The performance was evaluated and shown in Fig.3. An output power of -0.5dBm resulting from a6dBm pump power to the 1dB compression point, however, an output power of $\geq$ 0dBm is accessible at 10dBm input power where the suppression of the IP3 is around 20dBc below the desired output signal. Additionally the port-to-port isolation is greater than 20dB for both mixer designs.

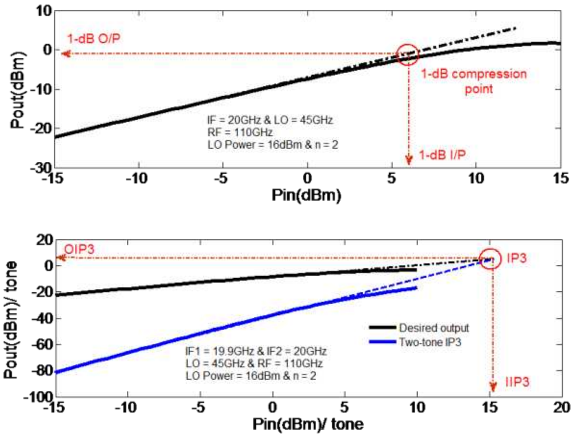

Fig.3. the sub-harmonically upconversion mixer performance at 110GHz.

Table 1 summarises the important results of this work, where a single antisymmetric quantum barrier junction is compared with a pair of Schottkies with back-to-back configuration. At higher frequencies, Table 1 reveals that single quantum barrier junctions (RTDs) are clearly capable of delivering ample output powers. This means that the handling power capability of the single junction is adequate compared to that of the two Schottky diodes, and this reflects the flexibility in terms of the RTD I-V characteristics against the Schottky diodes, thus exploiting a single quantum barrier junction instead of a pair of Schottky diodes can be a potential candidate since the RTD has flexible structure, in other words, controllable single junction surrounded by a pair of adaptable barriers.

TABLE 1: CURRENT WORK VS. PBUPLISHED WORKS.

Frequency	Topology	Element	Output Power	Reference
110GHz	2^{nd} Sub-harmonic	Schottkies/2 diodes	-6dBm	[11]
110GHz	doubler	Schottkies/4 diodes	0dBm	[12]
110GHz	2^{nd} Sub-harmonic	1/ RTD	-0.5dBm	this paper
110GHz	2^{nd} Sub-harmonic	Schottkies/2 diodes	-6dBm	this paper
180GHz	2^{nd} Sub-harmonic	1/ RTD	-7dBm	this paper
180GHz	2^{nd} Sub-harmonic	Schottkies/2 diodes	-11dBm	this paper
273GHz	2^{nd} Sub-harmonic	Schottkies/2 diodes	-17dBm	[13]

IV. TRANSITION DESIGN

To exploit such a sub-harmonically pumped up-converter in an application like a point-to-point communications link, then various electrical transitions are necessary to couple the energy from the diode junction to the rectangular waveguide (RWG) feed to the parabolic antenna. Coupling the mixer output to a high gain parabolic antenna ideally requires a high performance horn antenna and TE_{10} waveguide feed, which implies an efficient waveguide to microstrip (MS) transition to the microscopic mixer circuit. Although this planar transition does not have to be broadband in the case of a single mixer, using such a broadband transition as shown in Fig.4 supports shared antenna use by other offset in-band carriers and diplexers. Fig.4 shows such a broadband antipodal finline to microstrip transition ideally suited to the 180GHz mixer, in that, the pumped 85GHz LO frequency can be applied and the output 180GHz RF frequency can be extracted. Using HFSS software broadband antipodal finline transitions are designed and functioned at two different frequency bands. The designed antipodal finline being inserted into the RWG as shown in Fig.4 on which the designed parameters are illustrated. The transition length, L, is the vital parameter which plays a crucial function to attain the optimum performance at the favoured frequency.

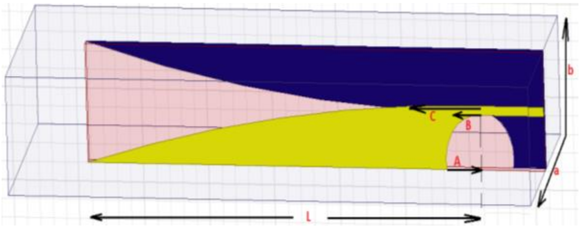

Fig.4. Tapered antipodal finline layout inside RGW.

The first designed finline ttransition is intended to work at 85GHz at which the standard RWG interior dimension (a and b) are 2.54mm and 1.27mm respectively. Keeping the values of A, B and C in respective with 0.5mm, 0.05mm and 0.1mm, the founded optimum L is 3mm. Likewise the second designed finline is planned to operate at 180GHz at which the standard RWG interior dimension (a and b) are 1.3mm and 0.65mm correspondingly. In this case the values of A, B and C are corresponded to 0.15mm, 0.051mm and 0.35mm, giving an optimum L of 2mm. The prospective simulated return losses of the 85GHz and 180GHz transitions are presented in Fig.5 and Fig.6 respectively. It is obvious that the performances in respective are better than 15dB and 10dB over the two different frequency bands.

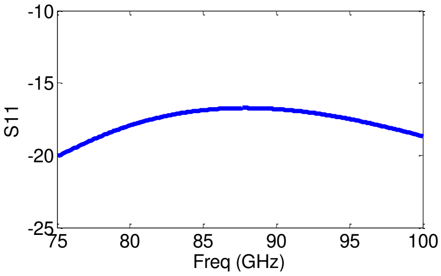

Fig.5. The transition performance at W-band.

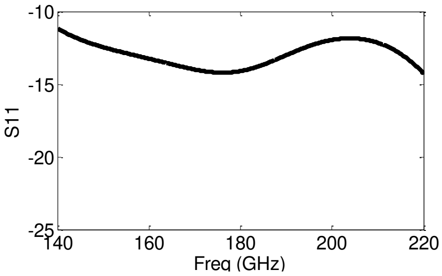

Fig.6. The transition performance at G-band.

To validate the aforementioned transition performance, two transitions in a back-to-back configuration are evaluated. The simulated results of the 85GHz and 180GHz transitions are demonstrated in Fig.7 and Fig.8 respectively. It is evident that the performance is sensible and better than 10dB at both the W-band and G-band.

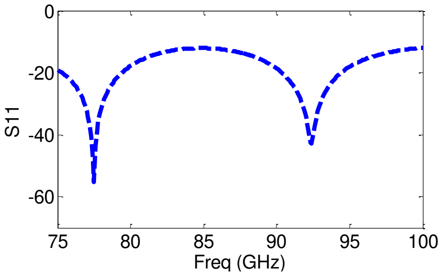

Fig.7. The back-to-back transition performance at W-band.

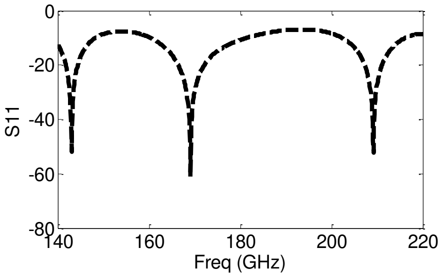

Fig.8. The back-to-back transition performance at G-band.

For measurement purposes, 3D E-plane split blocks are designed to mount the back-to-back transitions. Using SolidWorks CAD design software the designed split block is shown in Fig.9.

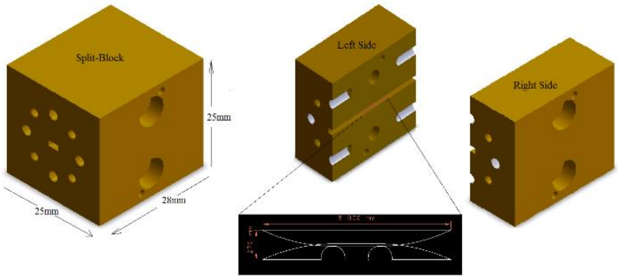

Fig.9. The back to back transition mounted in a 3D split-block.

Where the sub-harmonic mixer circuit is based on a microstrip design then a transition to a grounded co-planar waveguide (GCPW) is helpful, as depicted in Fig.10, in allowing a co-planar waveguide (CPW) on-wafer probe to assess the design early in the fabrication cycle and independently of the Microstrip-to-finline-to-rectangular waveguide assembly. The designed GCPW-to-MS transition provides a good match of 19dB return loss at the desired frequency (i.e., 85GHz) and better than 16dB over whole frequency band as shown in Fig.11.

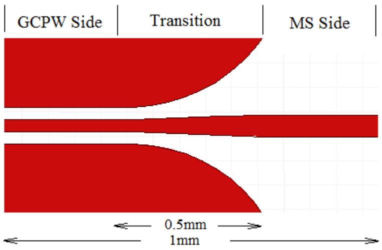

Fig.10. The GCPW-to-MS transition configuration.

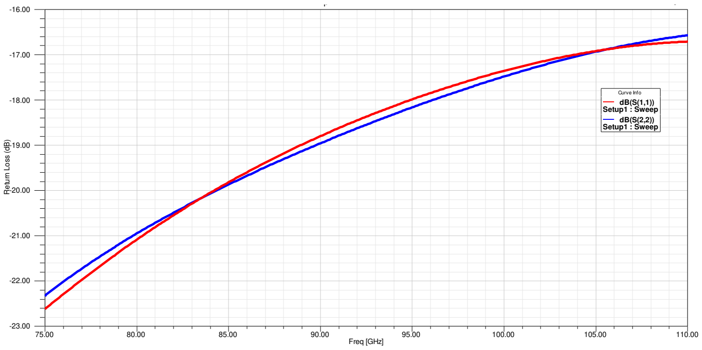

Fig.11. The GCPW-to-MS transition performance at W-band.

The GCPW circuit dimensions for the 110GHz mixer design is not immediately comparable with our current CPW on-wafer probes, so GCPW-to-GCPW transitions are designed to support these measurements. The mixer IF, LO and RF ports are therefore adapted using this transition to suit the CPW wafer probe. Fig.12 shows the constant impedance transition layout while Fig.13 demonstrates the simulated performance providing 15dB return loss over whole frequency band.

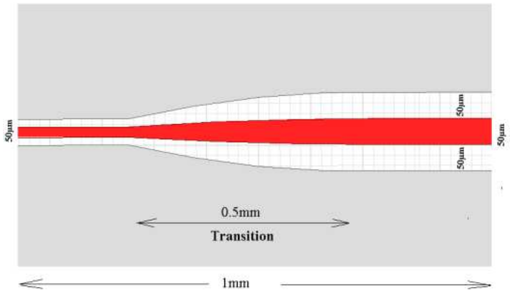

Fig.12. GCPW-to-GCPW transition configuration.

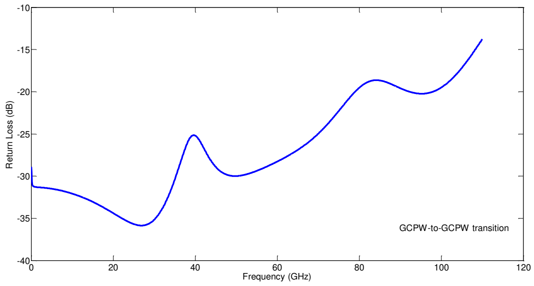

Fig.13. GCPW-to-GCPW transition simulated performance.

Figure 14 shows the typical current-voltage characteristics for 5 alternative sizes of single diode junction. In practice the growth process can be better optimised to give identical anti-symmetric characteristics as have been used in the simulations discussed earlier.

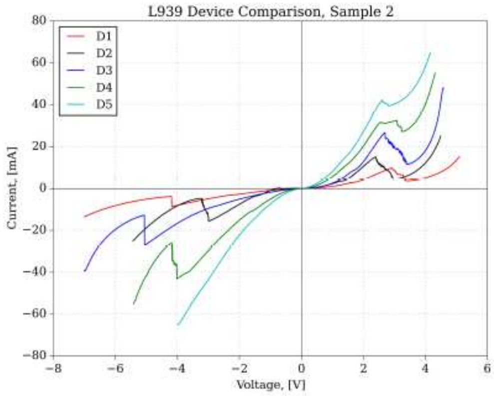

Fig.14 Measured Current-voltage characteristic for our RTD’s,

Device numbers refer to areas of 30, 60, 110, 225 and 450μm^2

V. CONCLUSION

The merits of using single quantum barrier junctions, as modulation elements suited to handling comparatively high local oscillator voltage swings and peak current densities of, +/- 5V, +/- 36KA/cm^2 Fig 14, and thus signal output powers, has been presented. Simulations show that at high millimetre wave frequencies good up-converted output powers and conversion efficiencies are possible when operating with high power sub-harmonic local oscillators, and thus these devices are worthy of further study as stand-alone high power modulators where power amplifiers are not yet available. The fabrication and measurements of the designed mixers circuits and transitions are considered in the next phase.

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