

ON THE DESIGN AND MEASUREMENT OF A 2.5THz WAVEGUIDE MIXER

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ABSTRACT

The usefulness of waveguide circuits at frequencies as high as 3THz has now been demonstrated culminating in the realisation of a 2.5THz waveguide mixer implementing Schottky diodes.

For waveguide devices to be optimised at these frequencies it has been necessary to modify the design of the waveguide mount paying particular consideration to areas such as ease of assembly, simplification of machining, reliability and fast adjustment of the RF circuit.

This paper discusses the detailed design and associated RF performance of a new 2.5THz waveguide mixer mount that makes use of the following; an ultrasonically bonded RF circuit, a non-contacting backshort and part fabricated waveguide.

All of these features are aimed at determining the optimum impedance required by the Schottky diode used and thus provide a more ideal circuit in which to place it.

INTRODUCTION

There has been much interest in recent years in the potential use of heterodyne receivers for the observation of stratospheric hydroxyl (OH) at frequencies in the terahertz region. Lines can be observed at 1.8, 2.5 and 3.5THz. Various schemes have been considered including receivers employing a Hot Electron Bolometer mixer pumped via an optically derived local oscillator (LO). Such a system has yet to have been demonstrated at terahertz frequencies although the mixer technology can now be considered mature. Schottky diode mixers have demonstrated the necessary performance required to make the measurement and the use of waveguide as the circuit architecture has also been demonstrated. Waveguide has the advantage of providing excellent radiation properties via use of conventional corrugated feedhorns at frequencies as high as 3.1THz [1] and use of a Schottky diode allows operation at ambient temperatures.

Whilst such mixers have the required sensitivity their LO requirement has to date been excessive. Experience at low frequencies indicates that as the conversion loss of the

mixer is reduced, its LO requirement also falls as does its noise. The waveguide mixers built to date at this frequency have made use of the same intrinsic Schottky diodes that have been used in the more common corner cube mixers but appear to require nearly an order of magnitude more LO. Since the waveguide mixer shows comparable RF performance to the corner cube mixer this implies that there is an additional source of loss within the waveguide circuit. Intuitively it might therefore also be expected that the waveguide mixer will overtake the corner cube mixer once the additional circuit losses have been eradicated.

This paper discusses the design rationale, manufacture and testing of a new waveguide mixer that aims to be able to fully optimise the waveguide mount for a given Schottky diode.

DESIGN RATIONALE

At terahertz frequencies the dimensions of the waveguide circuit shrink to human cell proportions. For example, standard waveguide at 2.5THz is $\approx 100 \times 50\mu\text{m}$ in cross section. For comparison a human ovum is $\approx 120\mu\text{m}$ in diameter. The design discussed here has chosen to eradicate unwanted GaAs from the RF circuit therefore the normal lithography techniques that are used to reduce circuit dimensions to such sizes are largely not available. Instead, use is made of ultra high precision machining to form the waveguide cavity and corrugated feedhorn combined with micromachining techniques to produce the RF filter and whisker that is used to contact the Schottky diode and form the RF circuit. Finally, a combination of micromanipulation and ultrasonic bonding is used to assemble the complete mixer.

The main aim of this work therefore has been to ease the constraints made on all of the above whilst allowing the circuit to be realised with sufficient accuracy that it can be adjusted in controlled way. By taking this approach it is hoped and shown that the resulting mixer can produce state of the art performance and at the same time reduce mixer LO requirement.

THE PLANAR WHISKER

The component of the mixer that makes an RF circuit realisable at these frequencies is the planar whisker. This is a lithographically patterned $0.4\mu\text{m}$ thick gold airline RF filter. The tip is sharpened naturally by the fabrication process such that it is able to make reliable contacts onto an $0.25\mu\text{m}$ diameter Schottky diode anode. The resulting arrangement has the minimum parasitic capacitance that can be attained but has sufficient mechanical flexibility built in that can easily pass the environmental tests

required for a mixer intended for space operation. A picture of a planar whisker is shown below in figure 1.

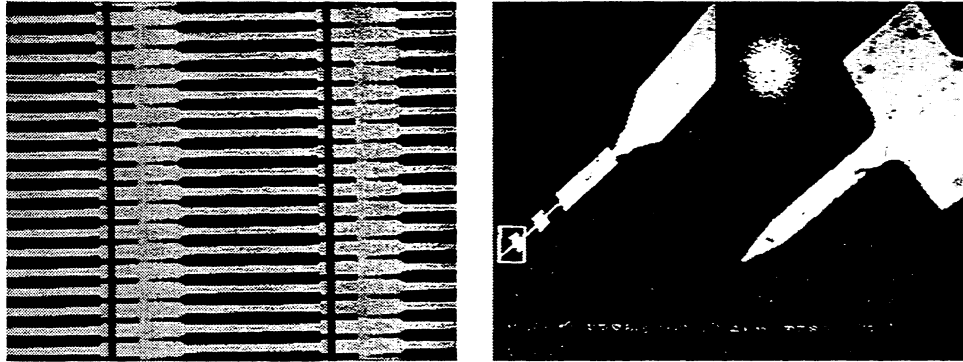


Figure 1: *Pictures of the chrome lithographic mask and a planar whisker*

The RF filter/waveguide probe is adjoined to a bond pad. Directly behind the bond pad there is a weak link to the main carrier which is used to manipulate the whisker. After the whisker has been bonded the main carrier is simply withdrawn leaving the whisker in place.

Sixteen designs of whisker are included on the mask. These have been designed using the approach described in [2] and should allow a full range of embedding impedances to be provided to the diode. It is hoped that each design will be fully characterised so that an understanding can be made as to the true behaviour of the sub micron Schottky diodes used.

A schematic of the mechanical arrangement is shown below in figure 3 alongside a diagram showing the contacting procedure.

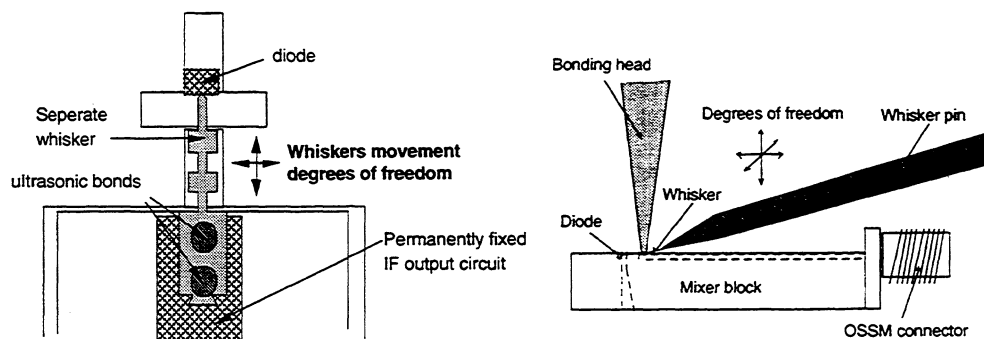


Figure 3: *The mechanical arrangement and contacting technique*

THE MIXER BLOCK DESIGN

Use is made of ultra high precision machining using state of the art mechanical mills and lathes fitted with precision microscopes and measurement slides. Dimensions on drawings are set to the $\pm 0.5\mu\text{m}$ wherever the circuit requires it. Such precision is necessary in order for this potential area of error to be eliminated. However, to ease the machining constraints careful attention has been paid to ensure that overtight tolerances are not specified unnecessarily. Likewise the waveguide mount has been designed so that the machining operations that are most easily carried out are used predominantly. Therefore, the use of electroforming was restricted to the feedhorn only and a novel scheme was devised that enabled the rest of the waveguide cavity to be part assembled. A drawing of the mixer block is shown below in figure 4.

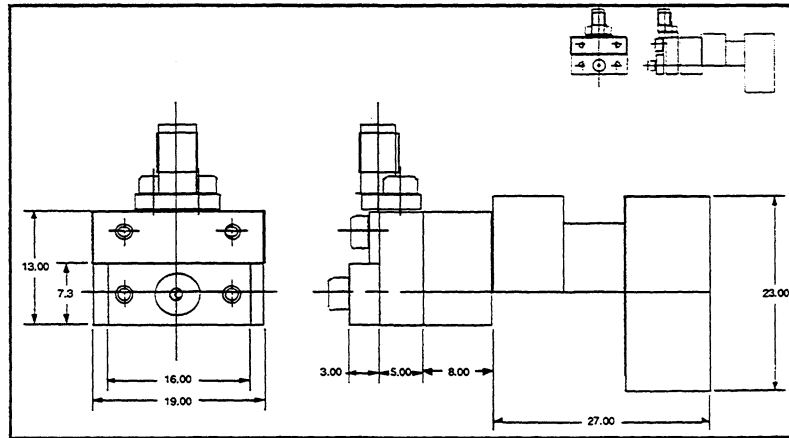


Figure 4: A manufacturing drawing of the 2.5Thz mixer (dimensions in millimetres)

A previous design of mixer [3] had relied on the feedhorn being designated to a particular block. This had the disadvantage that comparisons could not be made between different feedhorns for more than one particular configuration of RF circuit. Thus it was not possible to determine if one mixer performed better than another as a result of its feedhorn having lower loss or because its RF circuit was more optimised. For this design feedhorns are aligned optically by viewing down the throat of the horn rather than the use of accurately placed dowels. Feedhorns can then be interchanged between blocks and performance comparisons are easily made.

The section of waveguide in which the diode and backshort lie is fabricated in two parts. This had also been the case in the previous design but rather than relying on a pressure contact between the side walls and the lid of the waveguide, a small machined diode carrying package is soldered to the main mixer body. This ensures

that a good electrical path exists in the region that is most important for low loss waveguide. A machined diode package is shown below in figure 5 alongside an SEM photograph of the assembled mixer block ready for a diode to be soldered in.

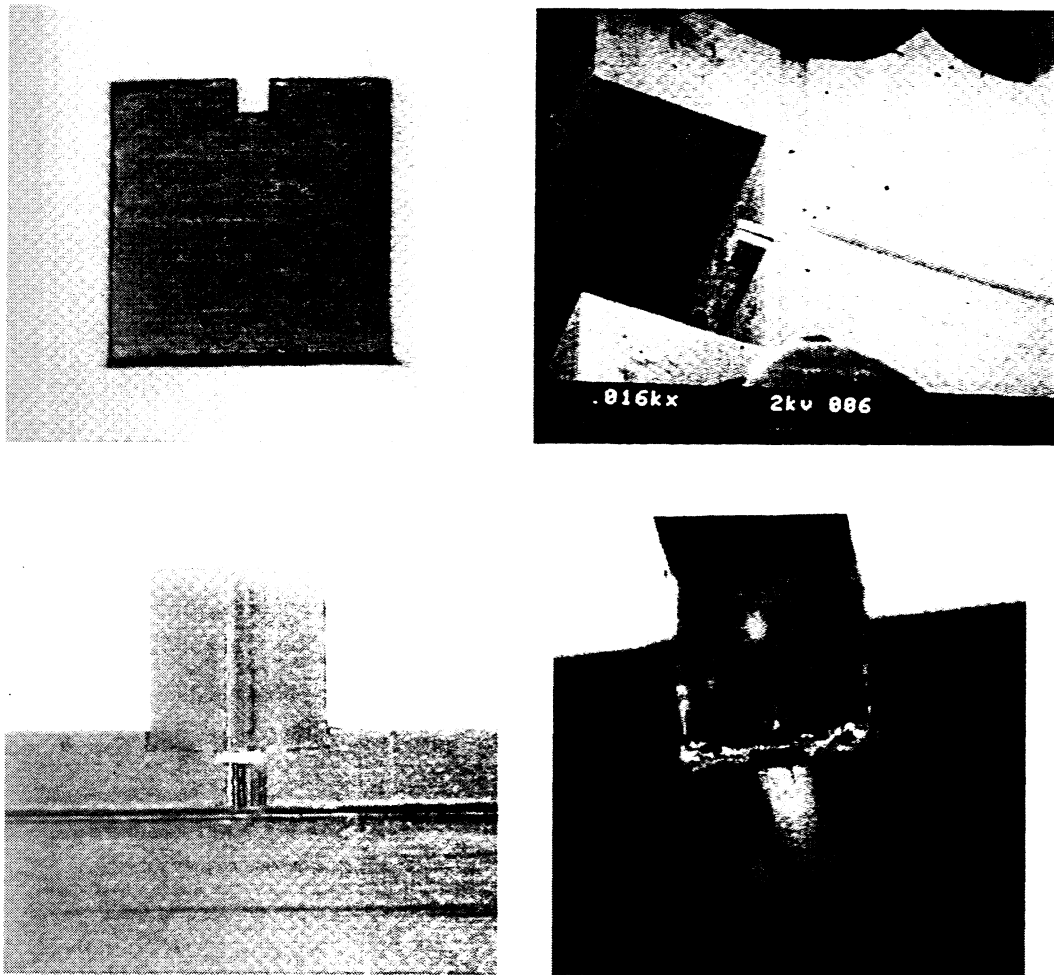


Figure 5: *The machined diode carrier and the mixer block part assembled*

The final stages of assembly required the diode chips to be soldered in followed by the IF substrate and finally the whisker. The two diodes tested so far in this configuration are the X107 and the NF 1T2 both notch front diodes, from the National Microelectronics Research Centre, Cork, Eire and the University of Virginia, Charlottesville, USA, respectively.

Needless to say the process of positioning of the whisker, contacting a diode and eventually ultrasonically bonding it in place took some development but now the process is very repeatable and has the advantage that it is completely 'dry' and 'cold'. Therefore it can be carried out many times with no degradation to the diode chip or

waveguide. A completed circuit is shown below in figure 6 alongside the mixer having just had an NMRC X107 notch front varactor diode soldered in.

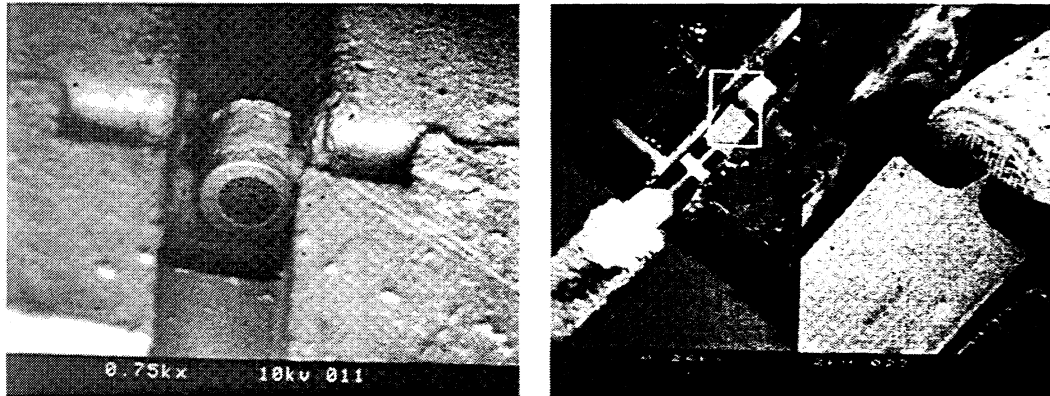


Figure 6: An X107 diode soldered into the mixer and the completed circuit

The final task necessary before RF testing could begin was to insert a tuneable backshort. Initially this consisted of a simple gold ribbon 'shim' that could be etched to the approximate size of the waveguide. Later a technique of painting on protective stripes of Crystalbond wax allowed a structured 'non-contacting' backshort to be realised. The relative performance of these two types has been determined and the non-contacting backshort is by far better, the results are shown later.

Very recently a lithographically micromachined backshort has been developed [4] that has not yet been testing at RF but looks very promising and should result in a further improvement. Pictures of the fabricated and micromachined backshorts are shown below in figure 7. The cross-section of the signal waveguide is 27 X 105 μ m.

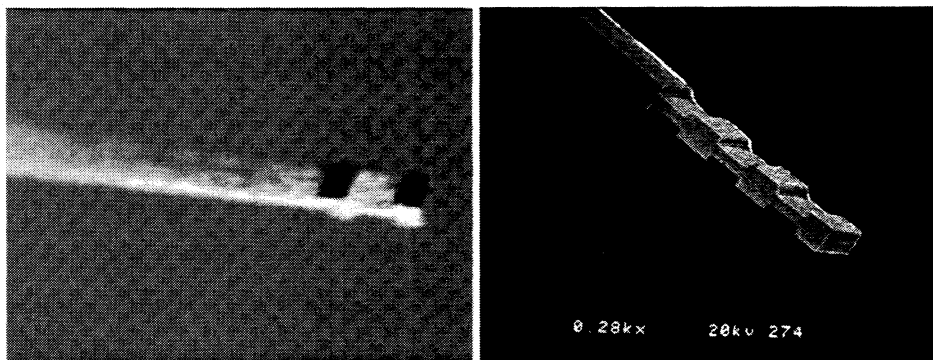


Figure 7: Fabricated and micromachined backshort shims approximated dimensions are 25x100 μ m in cross section

RF MEASUREMENT SET-UP

The mixer has been measured in three ways. Firstly a 3dB beamsplitter formed by projecting a 45 degree wire grid has been used. In order to obtain the corrected mixer performance it is necessary to divide the total receiver noise temperature by two and then correct for the IF contribution again making sure that the conversion loss is also halved. This technique is useful as it gives the intrinsic mixer performance (although Ohmic losses in the grid are still included) and can therefore give insight into the relative performance of an optical coupling circuit such as a diplexer. The correction factor was verified by using a 200GHz subharmonic mixer and rotating the beamsplitter in the signal path to obtain its effective insertion loss as a function of angle. A subharmonic mixer was used as there is no need to inject LO via the polarising grid as is the case for a fundamental mixer. In addition, a 10dB beamsplitter was fabricated using Kapton film membrane and replacing the wire grid. This only became possible when the mixer performance was sufficiently good that the LO requirement was suitably low. Extrapolated values of mixer performance between beamsplitters showed good agreement. This measurement set-up is shown in figure 8. Finally, a Martin Puplett interferometer was used for LO injection, however, this gave only marginally better performance than the 3dB beamsplitter. The reasons for this are not yet clear but poorly aligned optical components appear to be the most likely cause.

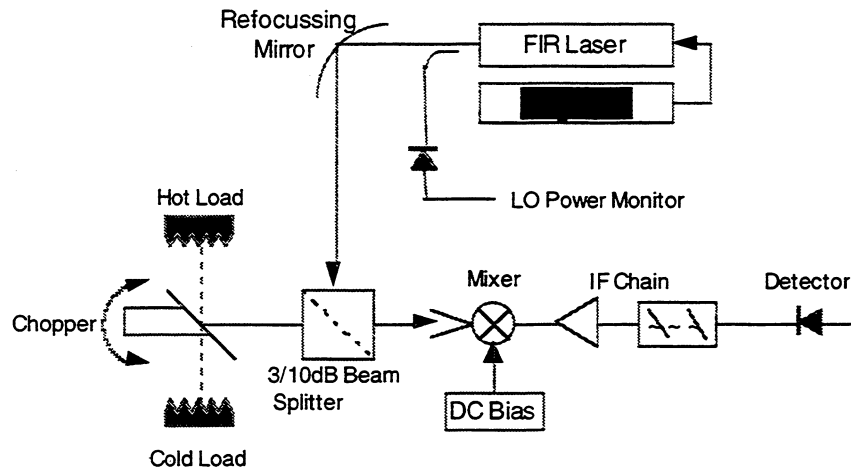


Figure 8: *The measurement set-up*

The chopper was used to remove the instability of the far infrared laser which whilst good, could provide sufficient LO amplitude variations that the total IF noise power was modulated thereby degrading Y-factor measurement accuracy. Therefore, with the

chopper rotating the output from the detector could be displayed on an oscilloscope. The average peak to peak modulated level could then be determined to provide the difference in IF signal power obtained for the hot and cold positions.

RF PERFORMANCE

Of the two diodes tested so far in this configuration the best results have been obtained with the UVA NF 1T2 diodes. These are $\approx 0.5\mu\text{m}$ in diameter and have very good diode IV characteristics.

The NMRC X107 diodes are over five times the area being $\approx 1\mu\text{m}$ square and therefore have five times the parasitic capacitance but also have good IV characteristics. Only two RF filter/waveguide probe configurations have been tried so far for these diodes and so they may yet provide good performance. For the X107 diodes the best corrected mixer noise temperature to date is $\approx 40,000\text{K DSB}$.

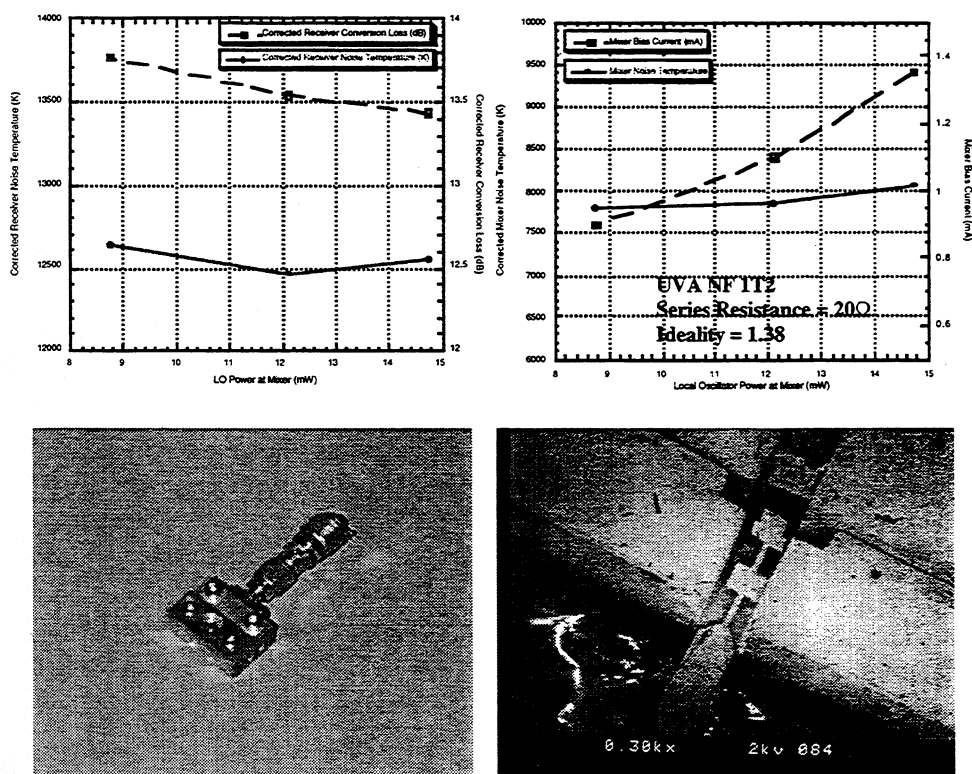


Figure 9: The best RF performance to date and the RF circuit and mixer block.

The UVA NF 1T2 diodes showed very good performance from the first iteration. Figure 9 shows the best performance that has been obtained to date from RAL mixer DW1 measured using the 3dB beamsplitter.

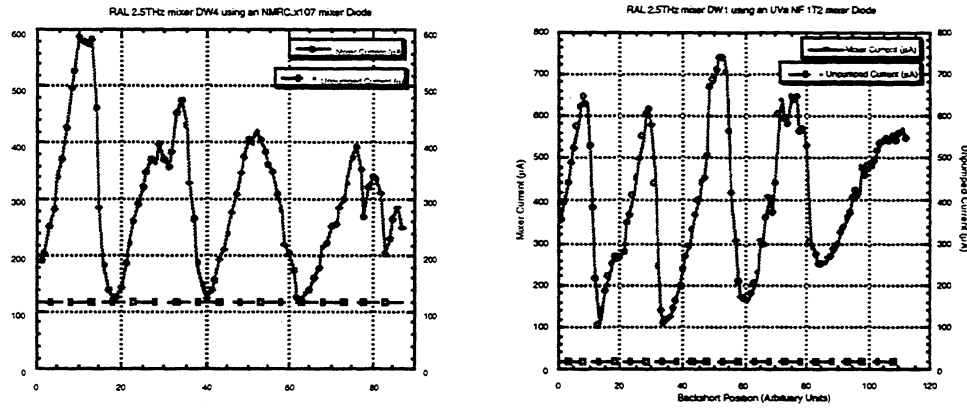
The UVA NF1T2 diode had a series resistance of 20Ω and an ideality factor of 1.38 . The whisker has a waveguide probe width of $19\mu\text{m}$ and first filter section length of $26\mu\text{m}$. An SEM photograph of this structure is shown beneath the plots alongside a photograph of the completed mixer with the backshort drive removed.

The corrected mixer noise temperature is $\approx 7,800$ DSB. Whilst this mixer showed the best performance it had a particularly poor backshort. A comparison is made in figure 10 between the backshort this mixer used, a simple etched shim, and that used by another mixer incorporating a fabricated ‘non-contacting’ backshort. We have defined a intuitive quality factor which relates to how successfully a backshort can tune out coupled LO power. In principle a perfect backshort can prevent any power being coupled to a diode

We define a quality factor, Q , where:-

$$Q = \frac{(I_{\text{peakLO}} - I_{\text{NOLO}})}{(I_{\text{dipLO}} - I_{\text{NOLO}})}$$

I_{peakLO} = Maximum coupled current
 I_{dipLO} = Minimum coupled current
 I_{LO} = Current no LO



Fabricated non-contacting backshort $Q \approx 250$

Simple close fitting shim $Q \approx 8$

Figure 10: Comparison between the two types of backshort tested so far

Unfortunately this particular mixer suffered ESD damage before it could be tested using the 10dB beam splitter and is presently being re-assembled. The best uncorrected system performance has been obtained for a later mixer, DW2. This mixer has a slightly shorter first section length on the RF filter, $20\mu\text{m}$ versus $26\mu\text{m}$ for DW1. However, it still showed good performance. The best uncorrected system

performance was $\approx 16,800\text{K}$ DSB measured using the 10dB beam splitter. The results are shown in figure 11. The corrected mixer performance $\approx 9,500\text{K}$ DSB.

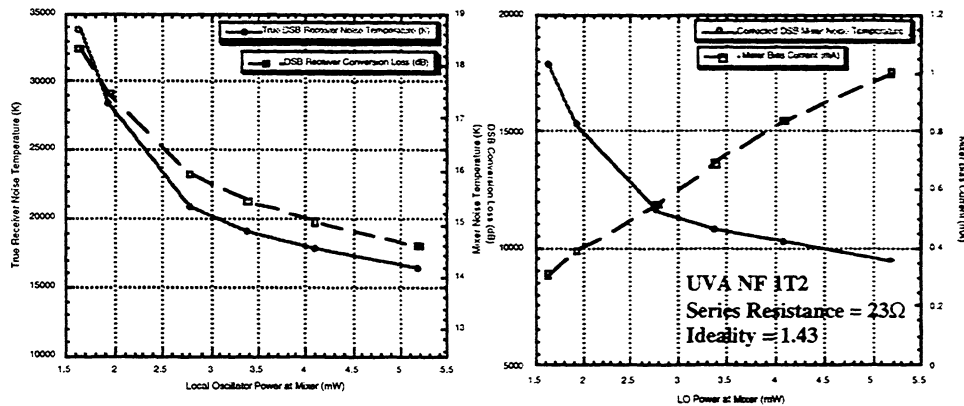


Figure 11: *Best uncorrected system receiver performance*

CONCLUSIONS

State of the art performance has been demonstrated for a 2.5THz waveguide mixer that makes use of a combination of novel design and assembly. First results indicate that the circuit is by no means fully optimised. The best mixer produced to date had a non-optimum backshort. In addition, only two variations of RF circuit design have been tested. The RF performance for this design of mixer is better by a factor of nearly two compared to that of the previous mixer design in terms of both mixer noise, conversion loss and LO requirement. However, this result has been obtained with the same intrinsic diode, the UVA1T2, implying that it has come about purely as a result of improved waveguide circuit design, fabrication and assembly. Further improvement can be expected in the near future.

ACKNOWLEDGEMENTS

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