# TeraHertz Schottky-Diode Balanced Mixers

Neal R. Erickson[1] and Thomas M. Goyette[2]
[1] Astronomy Department, University of Massachusetts, Amherst, MA, USA
[2] Submillimeter-wave Technology Laboratory, University of Massachusetts, Lowell, MA, USA
Contact: neal@astro.umass.edu

***Abstract*— We report on a very high performance THz balanced mixer/upconverter using a Schottky diode MMIC chip. Using an optically pumped laser at 1561 GHz as an LO source with a coupled power of about 1.5 mW, and 1.5 mW input at an IF frequency of 10 GHz, we obtained a sideband output power of 45 μW (sum of two sidebands). As a mixer, at an LO of 1561 GHz, we measured a mixer noise temperature of ~3000 K DSB. At the same frequency, used as a 16$^{th}$ harmonic mixer the conversion loss is ~55 dB. The design bandwidth is 1250-1650 GHz, and scaled devices have been fabricated for all frequencies through 3.5 THz, but the higher frequency designs have not been tested.**

## I. Introduction

In the THz range there is a need for room temperature mixers to act as both downconverters and upconverters using laser local oscillators. In these applications the relatively high LO power required by Schottky diodes is not a problem. This paper reports on a high performance THz balanced waveguide mixer built using a planar diode MMIC. This development was motivated by a need for a frequency agile sideband generator at 1.5 THz which would use a laser as one input and a 5-40 GHz microwave synthesizer as the other.

## II. Mixer and MMIC Design

The mixer developed in this work is similar to one used for proof of concept testing [1], and is based on crossbar waveguide mixers [2] that have been made for many years in the mm-wave bands. Fig 1 shows the basic circuit, with two diodes in series in the signal waveguide driven at their center point by the LO. This LO port is also the IF output which must be split off from the LO. With separate LO and signal ports, no diplexer is required at the mixer input, and there is high isolation between these ports. A particular advantage of this geometry is that the two diodes are in parallel to the IF port, halving the IF impedance. Given that single diode mixers typically have 100-150 Ω IF impedances, this reduction eliminates the need for an IF matching circuit. The off-chip IF circuit is simply a 50 ohm line.

The MMIC chip designed for the mixer is shown in Fig 2, and its placement in the mixer in Fig 3. The device is built on 3 μm thick GaAs with beam lead contacts for ground, IF and bias. The fragile substrate is completely suspended by the beam leads. At the end of the LO waveguide probe a high impedance line continues along the axis of the waveguide through the backshort, forming the IF port. This creates little disturbance to the THz input circuit and there is little loss of power into the IF port. A thin SiN layer is used between metal layers to produce a bypass capacitor on the bias port, and to add a low impedance section of line to the IF port to improve the LO rejection.

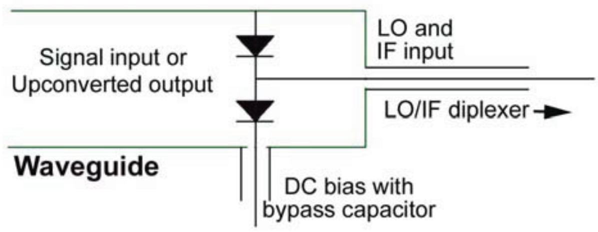


Fig. 1 Schematic diagram of a balanced mixer with LO/IF input on the right and signal input waveguide on the left.

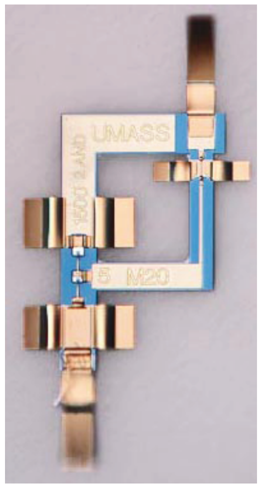


Fig. 2 Photograph of the diode used in the mixer. Overall height of the 1.5 THz device (with leads) for is 570 um.

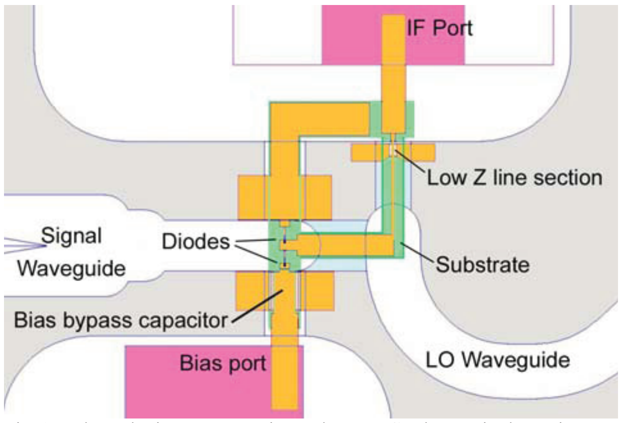


Fig. 3 Balanced mixer cross section. The MMIC substrate is shown in green, metal in gold. Both waveguides transition to diagonal horns on opposite sides of the block.

Two diode-MMIC wafers were fabricated at JPL using the very successful membrane process developed for Hershel HIFI [3]. The wafers had epi-layer doping of $5 \times 10^{17}/cm^3$ and $2 \times 10^{17}$ with identical circuit layouts. Variations of the design were scaled to as high as 3.5 THz, but tests reported here are of only the 1.5 THz design. Simulations of the performance of these designs indicate a relatively flat RF fractional bandwidth of 25%. Upconverted power is limited by the input power which is very constrained in a circuit with just two anodes, since the anodes must be very small for proper impedance matching. The required capacitance Cj(0) is 1 fF at 1.5 THz yielding an anode diameter of 0.5 μm (scaling downward with increasing frequency). However, it is practical to add anodes in series, as has been done with multiplier circuits [4] In principle, using two anodes in series increases the maximum input power by a factor of four, assuming that the failure mechanism is related to power density within the device. This scaling comes about because for the same impedance level, each device can have twice the area if two devices are in series. In the case of failure due to heating, the scaling is much less obvious, since it depends on thermal pathways within the complete circuit, not just local device properties, but there is still some significant advantage. Four-anode devices were fabricated but the anode size was only 1.5 times larger so the maximum power in this case should only increase a factor of three.

The best results were obtained with the $5 \times 10^{17}$ doping devices, but this wafer yield is quite low, ~35% for 2-anode devices, and the yield seems to be near zero for 4-anode devices. The wafer with $2 \times 10^{17}$ doping works acceptably at 1.5 THz, but it is clear that the doping is too low. This wafer has a high yield of 2-anode devices and 30% yield of 4-anode devices.

As is apparent from Fig 2, these are very small devices. While the GaAs membrane can not be touched, the beam leads can be handled safely, and installation in the block is done by positioning the device with a micro-manipulator. Once positioned, conductive epoxy is applied to the IF and bias port leads. Because of the small contact area this can result in a high contact resistance, and a solder contact would be preferred, but is much more difficult to produce.

The block was machined in brass as an E-plane split-block using conventional tools with a CNC micro-milling machine [5] and the block was then gold plated. Both waveguides are 80 x 160 um, stepping up to square cross section before transitioning to diagonal feedhorns on both input and output ports. The diagonal aperture sizes of each were 1.5 mm. Details of the block are shown in Figs 3 and 5. The diode was installed with the beamleads clamped between the halves of the block. The IF port used a K type connector to allow tests up to 40 GHz, but in fact no dimension or circuit capacitance inherent to the design limits the bandwidth below ~150 GHz. For practical reasons of testing and machining, the input waveguide was bent to align with the axis of the output guide. This adds LO loss but this is not a concern with laser sources.

## III. UPCONVERSION RESULTS

Upconversion tests were done using an optically pumped laser at 1561 GHz, with an available power level of >10 mW and a variable attenuator before the mixer input. The IF was 10 GHz from a synthesizer. For the tests with the $5 \times 10^{17}$ doping devices, only 2-anode devices were available. Four mixers were assembled with these devices. These were driven with a laser power of ~1.5 mW (as measured by a coupling aperture comparable to that of the feed horn). Diodes were forward biased in operation, with the conversion efficiency rising with bias up to 1 mA (which was the maximum used). With an IF power of 1.5 mW, the output power from the best device in the two sidebands is 45 μW with only 5 μW of LO feedthrough (~25 dB LO-RF isolation). The feedthrough power was measured with the IF signal off, but there is the possibility that the feedthrough may increase with IF applied. In previous tests with a similar mixer a very narrow band FPI etalon was used to separate the LO from the sideband signals. Use of this filter showed that there was no change in LO feedthrough with the IF applied. The THz input and output power were measured with a waveguide calorimeter (Erickson Instruments PM4) [6] built in WR10 waveguide with no transition between the horn and the waveguide in the sensor. The size of the horns and WR10 waveguide are fairly similar so coupling was expected to be good. For two other devices taken from very nearby on the wafer, output power was within 10%, while the fourth device from another region produced only 18 μW.

Fig 4 shows the power output vs IF drive power at the maximum laser power used of ~1.5 mW. Output power is compressed by ~1dB at 1 mW IF level, but is still increasing up to the maximum applied. There is the potential for higher output power, particularly with increased laser power, but diode failure due to heating is likely within a factor of 1.5 higher input. RF dissipation within the diodes is difficult to estimate from diode bias since most of the THz input power is lost in parasitic resistances. Simply summing all the input power is the only way to estimate dissipation, which is ~4 mW at the maximum output.

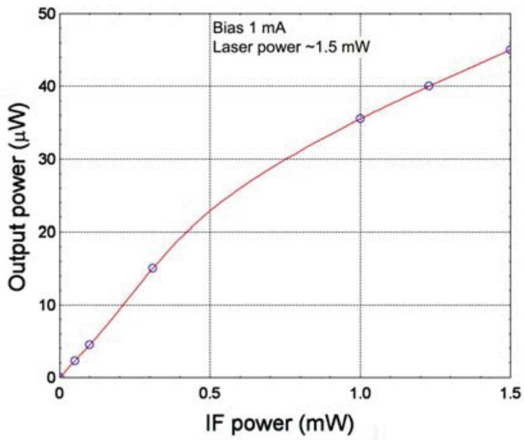


Fig. 4 Output power vs 10 GHz IF drive with laser power of 1.5 mW. The solid line is a spline fit, with no physical model.

Tests at other offset frequencies show the same power output for an IF range of 2 to 40 GHz, with IF coupling nearly flat across this band.. The RF bandwidth is predicted to be 1250-1650 GHz, but no other frequencies have been tested.

The devices with $2\times10^{17}$ doping showed significantly poorer performance. A 2-anode device showed significant saturation effects at 1 mA bias, and best output power was at 0.5 mA. The power output saturated at 13 μW, with an LO power of 1 mW and an IF power of 1 mW . The 4-anode devices worked better, but still required a bias of 0.5 mA although optimum LO and IF power increased to 2 mW and 4 mW respectively. At this drive level the output peaked at 37 μW, and began to decrease with increasing drive. LO-RF isolation with 4-anodes is excellent, just 2 μW feedthrough, or ~30 dB LO-RF isolation.

Perfect LO to RF isolation can never be obtained with this type of mixer because of the essential mechanical asymmetry between the anode and cathode of a planar diode. Isolation should be better at lower frequencies because the asymmetry couples to evanescent modes which become more important with increasing frequency. The 4-anode version of the design has much better isolation because the individual devices are smaller, and thus couple to even higher modes.

A comparison between the 2-anode and 4-anode mixers with $2\times10^{17}$ doping shows that the output increases a factor of 3 with twice the anode number, as is expected for the anode sizes used With similar scaling, 4-anode mixers with $5\times10^{17}$ doping should produce an output power ~150 μW.

## IV. Downconverter results

This device has been tested as a conventional mixer downconverter only at 1561 GHz. The IF source was replaced by a 3 GHz IF amplifier with a noise temperature of ~150 K. The mixer was the same one giving best results as an upconverter. With an estimated LO power of 1 mW and a bias current of 1 mA, a Y factor of 1.050 was measured with room temperature and liquid nitrogen cooled loads. This yields a complete receiver noise temperature of 4500K DSB. Assuming a typical noise contribution of a mixer diode ~300 K, the estimated mixer noise temperature is 3000 K DSB, and the conversion loss ~10 dB. This is not an optimized result, with DC bias and LO power only roughly adjusted. The DC resistance of the IF contact to the MMIC is ~9 ohms, adding 1.4 dB to the conversion loss if capacitive bypassing of this resistance is not significant at 3 GHz. This noise is substantially lower than any other Schottky mixer results at a similar frequency, and is less than would be expected based on lower frequency results with waveguide mixers.

Other types of mixers built for this frequency range all require cooling. THz Schottky mixers show noise reduction by only a factor of two [7] when cooled due to the high doping of the diodes, with no further reduction in the noise below ~50K. Therefore the best achievable receiver noise with this mixer might be ~1600 K DSB, but since the diode noise dominates, similar noise may be achieved up through a very high IF. A state-of-the-art waveguide HEB mixer at 1350 GHz has a receiver noise temperature ~1200 K [8], but has much more restricted IF bandwidth of ~3 GHz, so this Schottky mixer may be very competitive, particularly in applications requiring wide bandwidth. Its reduced cooling requirements are another advantage, and many years of experience with Schottky diode mixers at lower frequencies has shown them to have the best dynamic range and stability of any type of receiver.

## V. Harmonic Mixing

At these frequencies a quantum cascade laser could be the LO, leading to a simple all solid state receiver with wide frequency coverage through use of the >100 GHz wide IF. QCL's can easily produce >1 mW output power, and can operate at ~50 K. Although output mode control can still be a problem, solutions are emerging that should produce good quality beams, and single frequency operation. A remaining challenge with QCL lasers is a means of locking their frequency since their free running stability is poor. At mm wavelengths, sources are typically measured by comparison to a microwave reference via harmonic mixing. This has not been possible in the THz range due to the need for high harmonics and the resulting very high conversion loss which typically increases as ~3 dB per harmonic. Using one of these mixers, we attempted to measure a 1561 GHz laser mixed with an LO near 39 GHz (N = 40) but no signal was detected implying a conversion loss >120 dB (consistent with Lc~3dB·N). To overcome this limitation complex multiplier chains [9] have been used to produce a reference signal which is mixed with the laser in a fundamental HEB mixer but this complexity is almost too great to justify the use of a laser LO. However, this new mixer can harmonic mix with a very high LO, reducing the harmonic number N to below 20 and the conversion loss to ~60 dB.

To test this application, a WR 10 waveguide was added to one mixer, coupling to the IF microstrip line, but leaving the coaxial IF port functional for low frequencies, as shown in Fig 5. The waveguide port is fairly well matched from 75 to ~100 GHz, although only about half the power couples toward the mixer chip since there is no filter structure in the microstrip line.

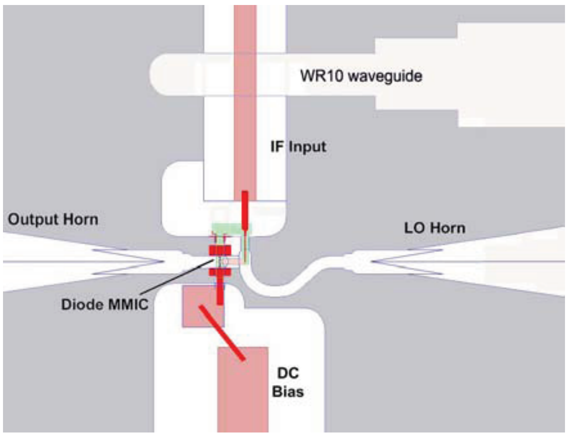


Fig. 5 Layout of the mixer block showing the added WR10 waveguide which allows low frequencies to couple from the mixer to the coaxial IF port at the top of the block. This waveguide is bent to offset it from the LO feedhorn.

With this wideband port we mixed the 1561 GHz laser with an LO at 97.4 GHz. This LO was in turn derived from a commercial x8 active multiplier chain plus synthesizer. (N = 16 for the mixer). The inefficient coupling is not a concern since the WR10 source produced more power (10 mW) than the diodes can survive. While setting up the test with a 2-anode mixer, one of the diodes was burned out but the test was continued with the surviving diode, and the mixer still worked well. The measured conversion loss was ~55 dB and the S/N on a spectrum analyser was ~40 dB in 10 kHz resolution BW (and 300 Hz video BW). With 2 working diodes the conversion process should be more efficient since it favours even or odd harmonics (depending on the input port). With an LO in the 150-200 GHz range, harmonic mixing up to ~3 THz should be practical.

## VI. Conclusions

Planar Schottky diode MMIC's can serve as efficient upconverters and low noise mixers well into the THz range, offering room temperature operation. The balanced mixer design separates the LO and IF ports, making an extremely simple, compact receiver requiring no LO/signal diplexer, and having no restriction on IF bandwidth. With cooling their noise temperature may be competitive with HEB mixers in applications requiring wide IF bandwidth and high stability. These mixers should be feasible throughout the THz range and devices have already been fabricated which may operate up to 3.5 THz. LO requirements are within the power available from QCL's, and the combination should form very simple receivers. Harmonic mixers using the same design have low conversion loss and can serve to provide the frequency comparison needed to lock the QCL.

## Acknowledgment

The authors wish to thank R. Grosslein for machining the blocks and R. Erickson for the assembly. The diodes were fabricated by Imran Mehdi's group at JPL. M. Coulomb of the UMass Lowell Submillimeter Technology Lab assisted in the tests.

## References


[1] N. Erickson, "A Schottky-Diode Balanced Mixer for 1.5 THz," *19th International Symposium on Space Terahertz Technology*, pp. 221-223, Apr 08, Groningen.

[2] S. Maas, *Microwave Mixer 2nd Eds,* pp 291-293, Artech House, 1993.

[3] A. Maestrini, J. Bruston, D. Pukala, S. Martin and I. Mehdi, *"Performance of a 1.2 THz Frequency Tripler Using a GaAs Frameless Membrane Circuit,"* IEEE MTT-S Int'l Microwave Symposium (Phoenix), pp. 1657-1660, May 2001.

[4] B.J. Rizzi, T.W. Crowe and N.R. Erickson, ``A High-Power Millimeter-Wave Frequency Doubler Using a Planar Diode Array," *IEEE Microwave and Guided Wave Lett*. vol 3, pp. 188-190, 1993.

[5] G. Narayanan, N. Erickson, R. Grosslein, "Low Cost Direct Machining of Terahertz waveguide Structures," *Tenth International Symposium on Space Terahertz Technology*, pp. 518-528, Mar. 99.

[6] N. Erickson, "A Fast and Sensitive Submillimeter Waveguide Power Meter," *Tenth International Symposium on Space Terahertz Technology*, pp. 501-507, Mar. 99.

[7] P.F. Goldsmith, H.R. Fetterman, B.J. Clifton, C.D. Parker and N.R. Erickson, *Cryogenic Operation of Submillimeter Quasioptical Mixers*, International Journal of IR and MM Waves, vol 2, pp. 915-924, 1981.

[8] D. Meledin, et al, "A 1.3 THz Balanced Waveguide HEB Mixer for the APEX Telescope," IEEE Trans Microwave Theory Tech., vol MTT 57, pp. 89-98, 2009.

[9] A.M. Baryshev, P. Khosropanah, W. Zhang, W. Jellema, J.N. Hovenier, J.R. Gao, T.M. Klapwijk, D.G. Paveliev,B.S. William, S. Kumar, Q. Hu, J.L. Reno, B. Klein, J.L. Hesler, "Phase-locking of a 2.7-THz quantum cascade laser to a microwave reference," 20*th International Symposium on Space Terahertz Technology*, pp. 49-52, Apr 09, Charlottesville.