TeraHertz Schottky-Diode Balanced Mixers

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ABSTRACT

We report on the first THz balanced mixer/upconverter using a Schottky diode MMIC chip. Using an optically pumped laser at 1562 GHz as an LO source with a coupled power of about 1 mW, and 1 mW input at an IF frequency of 10 GHz, we obtained a sideband output power of 23 µW (sum of two sidebands). As a mixer, at an LO of 1621 GHz, we obtain a conversion loss of 12.4 dB DSB and a noise temperature of 5600 K DSB. Response is believed to be similar over a band 1250-1650 GHz. New diodes have been designed for easier application as mixers up through 3 THz, and a new wafer run is in process.

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. Such mixers primarily use whisker contacted Schottky diodes in cube-corner mixers, originally reported 30 years ago\(^1\). While the cube-corner mixer is very simple, it has a very poor beam pattern and is compatible only with whiskered diodes. This paper reports on the first THz balanced mixer built using a planar diode MMIC in waveguide. This development was motivated by a need for a frequency agile sideband generator at 1.5 THz with >10 µW output power which would use a laser as one input and a 5-40 GHz microwave synthesizer as the other. The typical cube corner in this application can produce only 1 µW and impedance matching is difficult with high offset frequencies.

MIXER DESIGN

The application was a proof of concept, so it had to use existing devices. The MMIC used in this work was designed as a frequency doubler for 1.5 THz, developed at JPL for the Herschel HIFI program\(^2\). THz varactor diodes are essentially the same as mixer diodes since high doping (5x10\(^{15}\)/cm\(^3\)) is needed to minimize carrier velocity saturation losses, and breakdown voltage is low (~4V) since large drive voltage amplitude is not practical. The device is built on 3 µm thick GaAs with beam lead contacts for ground and bias. The doubler circuit geometry is the same as that for a balanced mixer as shown in Figure 1, except that there is no external terminal for the IF port. The IF port was added by contacting the input waveguide probe with a wire which then is brought to an external coaxial port. A balanced mixer has the advantage of separate LO and signal ports, meaning that no diplexer is required at the mixer input. With good symmetry there is high isolation between these ports. The doubler chip as used in the mixer is shown in Figure 2. In this mixer circuit, the coaxial input line of Fig 1 transitions into a waveguide probe in the LO waveguide.

![Schematic diagram of a balanced mixer with coaxial input on the right and waveguide output on the left. The doubler circuit is identical except that the input frequency is half of the output.](image-url)
The block was machined as an E-plane split-block using conventional tools in brass with a CNC micro-milling machine, and the block was then gold plated. Both waveguides are 80 x 160 μm, stepping up to square cross section before transitioning to diagonal feedhorns on both input and output ports. The final aperture sizes of each were 1.5 mm (diagonal). Details of the block are shown in Figure 3. The diode was installed with the beamleads clamped between the halves of the block. A 6 μm diameter gold wire was used to contact the input waveguide probe in order to create an IF port aligned along the axis of the waveguide. This method of contacting the input probe creates little disturbance to the 1.5 THz input circuit and there is little loss of power into the IF port. However it is quite difficult to make the contact with the MMIC and this technique is not suitable for production. The IF port used a K type connector to allow tests up to 40 GHz, but no care was used to maximize the IF bandwidth by design of the IF circuit. For practical reasons of layout 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.

UPCONVERSION RESULTS

Tests were done using an optically pumped laser at 1562 GHz, with a power level of ~10 mW which was attenuated to 1 mW at the mixer input (as measured by a coupling aperture comparable to that of the feed horn). The IF frequency
was 10 GHz with 1 mW power level. The diodes are forward biased in operation, with the conversion efficiency rising with bias up to a maximum of 0.5 mA. The sum of these inputs totals about 2.5 mW which is all dissipated in two diodes on a poor heat sink, so there is some concern about increasing the power and bias levels beyond this point. Bias voltage of the series pair at 0.5 mA with 1 mW each of LO and IF applied is 0.715 V (forward), compared to 1.606 V with just DC applied. At this drive the output power in the two sidebands is 23 µW with only 4.5 µW of LO feedthrough (∼23 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 so 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 was measured with a waveguide calorimeter (Erickson Instruments PM4)\textsuperscript{4} 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.

Figure 4 shows the power output vs drive power. Output power is increasing with each of the inputs, up to the maximum applied, so there is the potential for significantly higher output power if the diodes do not burn out. These diodes are known to fail at ~5 mW DC input, serving as an absolute limit for failure due to heating, but the RF limits are not known. RF dissipation within the diodes is difficult to estimate. The diode bias voltage and current provide an indication, but most of the THz input power is lost in parasitic resistances. The prediction from Agilent ADS is that with 1 mA bias and two times the LO and IF power, the output power will double.

![Fig 4. Output power vs input drive at 1562 GHz.](image)

Tests at higher offset frequencies show the same power output up to an IF of 40 GHz, using the same drive level at the mixer diodes as derived from the bias voltage. IF coupling is not flat across this band, so the IF power varied with frequency. The RF bandwidth is predicted to be 1250-1650 GHz, and two other laser frequencies (1272 and 1621 GHz) have been tested. At both the input power was poorly calibrated because the laser mode was very poorly matched to the feed horn, but the DC bias conditions were the same as at 1562 GHz, so the power reaching the diodes is the same. Output power was 17 µW at 1272 GHz with 2.5 µW of LO feedthrough power, while at 1621 GHz the output was 21 µW with 5.5 µW of feedthrough. Thus the output circuit coupling is fairly flat over the band, but there is no data about the input circuit tuning. 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 is better at lower frequencies because the asymmetry couples to evanescent modes which become more important with increasing frequency.

**DOWNCONVERTER RESULTS**

Measurements have been made as a conventional mixer downconverter only at 1621 GHz. For this work the IF source was replaced by a 3 GHz IF amplifier with an isolator on the input, and an IF noise temperature of 214 K. With an estimated LO power of 1 mW (the same as for upconversion testing) and a bias current of 1 mA, the Y factor of the receiver was measured with room temperature and liquid nitrogen cooled loads. This yields a complete receiver noise temperature of 9300K DSB. Conversion loss is 12.4 dB DSB and the derived mixer noise temperature is 5600 K DSB. This noise is substantially lower than cube-corner mixers at similar frequencies and the beam pattern should be much better.\textsuperscript{5} No effort was made to optimize the noise vs LO power, and better results could certainly be obtained with a lower noise IF amplifier.
Other mixers built for this frequency range all require cooling. THz Schottky mixers show noise reduction by only a factor of two when cooled due to the high doping of the diodes, with no benefit to the noise below ~50K. Therefore the best achievable receiver noise with this mixer might be ~3000 K DSB. The state-of-the-art at these frequencies is the HEB mixer operated at 4K. A balanced HEB mixer-receiver (made using waveguide hybrids) at 1.3 THz has a receiver noise temperature of 1100-1200 K, but has a much more restricted IF bandwidth of ~2 GHz.

FUTURE WORK

To follow up this work, a new wafer run is now in process to make devices specifically as upconverters. The same basic design will be used but with an added planar IF terminal, having a bandwidth of at least 100 GHz. As before the circuits will be fabricated on 3µm thick GaAs. Figure 5 shows one layout, where it can be seen that the new IF port is simply a planar version of the previous design. A short section of a low impedance line is added by the ground leads on the IF port, and this serves to reduce RF leakage. Variations of the design will be scaled to as high as 3.5 THz. Simulations of the performance of these designs indicate an RF fractional bandwidth of 25% with relatively flat output power. There is no way to significantly increase the power available from a similar 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 giving 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. 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. We will test circuits using four anodes (2 series pairs) to determine the power scaling.

As is noted from the scale bar in Figure 5, these are very small devices, and they become extremely small at 3 THz. The greatest problem in working with them is picking them up without damage, since the membrane GaAs can not be touched. Beam leads can be handled safely, and installation in the block just requires positioning the device properly, best done with a micro-manipulator. Once positioned, conductive epoxy is applied to the IF and bias port leads.

Figure 5. Layout of all-planar mixer diode for 1.5 THz. This new device uses membrane GaAs in an open square with beamleads for support and grounding, as well as IF and bias ports. In some devices a single diode anode is replaced by two in series.
At these higher frequencies a quantum cascade laser could be the LO, leading to a simple all solid state LO with wide tunability. The IF offset frequency can exceed 100 GHz. For use as an LO, image rejection is required, and while this may be done with filters, it also may be enhanced using an SSB upconverter design, which may be fabricated using a pair of these chips plus waveguide hybrid couplers.

A challenge with QCL lasers is a means of locking their frequency since their free running stability is poor. Frequencies are typically measured by comparison to a microwave reference via harmonic mixing but signal to noise is poor unless the mixer uses a relatively low harmonic. This mixer can serve as a very efficient harmonic mixer (leaving one input unused) so that the laser frequency can be compared to a microwave reference in the 50-100 GHz range.

CONCLUSIONS

Planar Schottky diode MMIC’s can serve as efficient upconverters and low noise mixers well into the THz range, offering room temperature operation. This new balanced mixer also separates the LO and IF ports, making an extremely simple, compact receiver requiring no LO/signal diplexer. With the fabrication of new diodes, construction of these mixers may become relatively straightforward.

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