Novel Designs for Submillimeter Subharmonic and Fundamental Schottky Mixers

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Abstract

To meet requirements for future planetary and astrophysics space missions, new mixers have been designed to take advantage of the frameless GaAs membrane technology developed at JPL. Single-diode fundamental mixers have been designed for 350, 440, 560, 640 and 1200 GHz, with 14% bandwidth. Additionally, subharmonic mixers for 560 GHz have been designed. Two circuit topologies have been used for the subharmonic mixers, one based on previous designs, and the other based on the balanced doubler configuration. These are expected to give single sideband noise temperatures at the diode of about 2500 K, with conversion loss around 13 dB. The fundamental mixers are expected to have SSB noise temperatures near 1300 K at 560 GHz, conversion loss about 8 dB.

I. Introduction

There is a demand for mixers operating in the submillimeter band between 300 and 1200 GHz for observation of various atomic and molecular lines. Near term missions that might use such mixers include a proposal for water detection observations on Mars [1], and measurements of middle atmosphere trace gases and gas dynamics on Venus [2]. Schottky submillimeter and Terahertz sensors would be ideal for future proposed missions to Europa and Titan as well.

The technology used for submillimeter wave Schottky mixers has changed over the years. The basic techniques can be categorized into three types. The earliest — *whisker-diode* mixers — used waveguide mounted diodes with anodes contacted by metal whiskers [3]. This method has been used to produce mixers as high as 4.7 THz [4–6]. Later, *planar diodes* were developed, incorporating integral anode contacts as part of the metallic circuitry fabricated on a semiconductor chip. Mixers are made using this technique for fabrication of the diodes with subsequent etching of the backside of the wafer. This leaves a thin semiconductor slice containing the diode that is then mounted on a quartz substrate containing the remainder of the planar circuit. The substrate with circuit and diode(s) can then be mounted in waveguide.

More recently, complete integrated circuit techniques have been developed at JPL for mixers used at 2.5 THz [7, 8]. In this concept, the mixer and planar circuitry are fabricated together on a portion of GaAs wafer attached to a thick frame used to assist in handling for assembly. The high-frequency section is then etched to a thickness of three µm or so. In the last few years this technique has been extended to lower frequencies for Schottky multiplier applications, and further refined to the extent of eliminating the wide, thick frame when beam-lead processes were established at JPL. Handling by the beamleads proved quite feasible, and the savings in wafer space made the fabrication of more circuits possible. This process is known at JPL as the *MoMed* or *frameless membrane* process.

Demand has grown for Schottky mixers in the 200 to 1200 GHz range for future planetary and Earth science missions. Schottky mixers are ideal for these (especially planetary) missions, because of their longevity and premium placed on weight and size. Schottky mixers have a tremendous advantage over more sensitive cryogenic mixers, since they work with no cooling below room temperature, although their performance does improve at lower temperatures. Cryogenic circuitry requires either a limited lifetime in the case of dewar coolers, or high electrical power, weight, complexity and great expense if cryocoolers are used. Schottky mixers have good performance at room temperature, and performance can be improved with cooling [9–12]. Cooling to 100 K is achievable with simple passive methods.

II. Design of Fundamental Mixers.

Mixers for 350, 440, 560, 640 and 1200 GHz were designed with RF bandwidth around 14 %. These are single-diode fundamental mixers. The advantages of these mixers are: their design is simple and straightforward; it is relatively easy to get good broadband performance; and their small size means that they take up little wafer space. The disadvantages are that they require external LO/RF diplexing outside the mixer block, because the LO and RF signals enter the block through the same waveguide port. Additionally, they use LO power at frequencies near the RF, which requires a longer LO source multiplier chain with consequently more input power. Since the LO is near the RF in frequency, LO phase noise can be mixed down as well, which can be problematic for

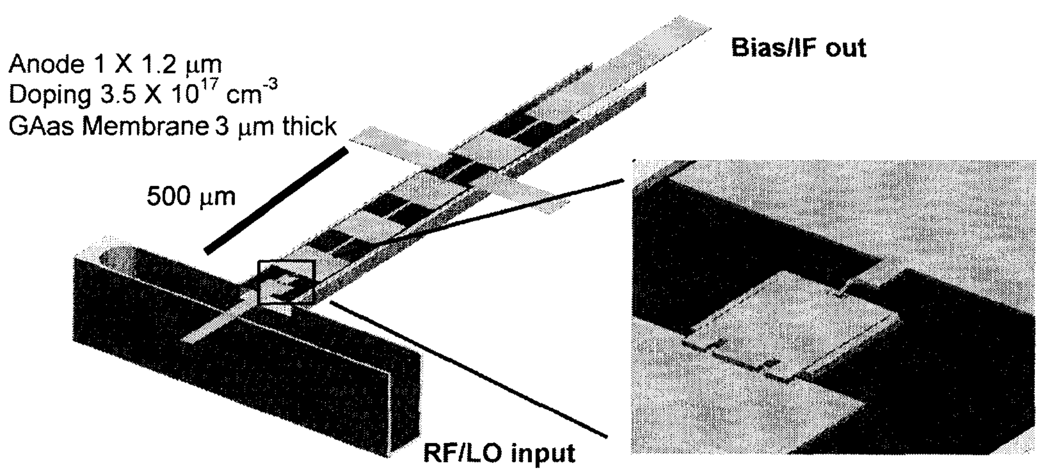

Figure 1. Layout of fundamental single-diode mixer. Technology is frameless membrane with integrated planar diode and suspended stripline circuits.

low IF frequency operation.

Figure 1 shows how the fundamental mixers are laid out. The diode is closely coupled to the waveguide by a shorted probe that also provides DC bias and IF return. The diode is in a series configuration, followed by a high-low style IF/bias filter. The filter presents a short circuit to the RF and LO signals. Since the RF/LO path is so short and the circuit Q so low (typically around 1) achieving wide bandwidth is straightforward. The impedance matching consists primarily of transformation of the waveguide impedance to the mixer resistance, and use of the lines close to the diode to tune out the capacitance of the diode. Using the mounted diode/whisker contact technology, the diode is usually mounted in the input waveguide, and the tuning inductance provided at least partly by the whisker. Since the whisker is extremely thin and is suspended in free space, a reasonably high inductance per unit length. In contrast, the membrane planar circuits have the tuning lines mounted on GaAs. This increases the parasitic capacitance, reducing the effective inductance. In the waveguide, the radiation resistance of the probe is too close to the diode to tune out the capacitance with its reduced effective inductance. Mounting the diode in the IF filter channel removes this problem, and the diode capacitance is completely neutralized by the line. The waveguide probe only needs to provide a resistive match to the diode.

The embedding impedances were calculated using a modified form of the program previously developed for Schottky multiplier design [13, 14]. However, for mixer use the diodes are not operated near their limits of input power and voltage swing, as in the case of high-power/high-efficiency multipliers. A commercial harmonic balance simulator using a basic series-resistance/Schottky-junction model is quite adequate, as

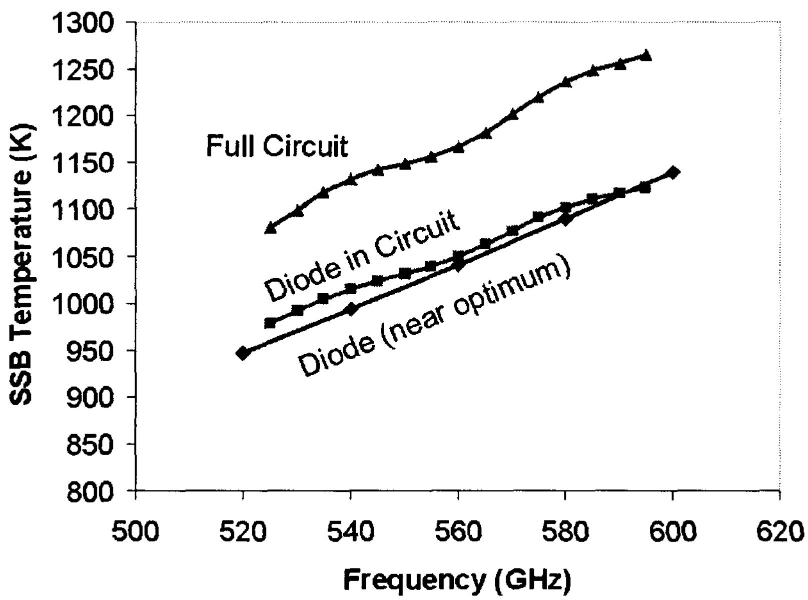

Figure 2. SSB noise temperature of 560 GHz mixer, showing optimized diode, circuit diode and full circuit LO power is 0.5 mW at the diode.

will be discussed later.

Using the same technique as has been employed at JPL and elsewhere for multiplier design [15], the passive waveguide and suspended stripline circuitry is designed starting with the optimized embedding impedances from the harmonic balance optimization. The design tool was a combination of a commercial linear circuit simulator [16] and the commercial finite element electromagnetic simulator HFSS [17]. This combination allows the circuit to be very accurately modeled electromagnetically. Initially, the circuit is divided into sections connected by transmission lines (waveguide and suspended stripline) that can be assembled in the circuit simulator and rapidly optimized by varying the transmission line parameters. These parameters are the electrical lengths and impedances, which are adjusted by changing the physical length and transmission line cross-section. Once the circuit is designed, the whole thing is analyzed and tweeked using HFSS and the harmonic balance simulator.

The mixer optimization process deviates in several significant respects from multiplier optimization. In the case of a multiplier, it is sufficient to use the efficiency of the multiplier as the optimization criterion, and search for the best combination of bias

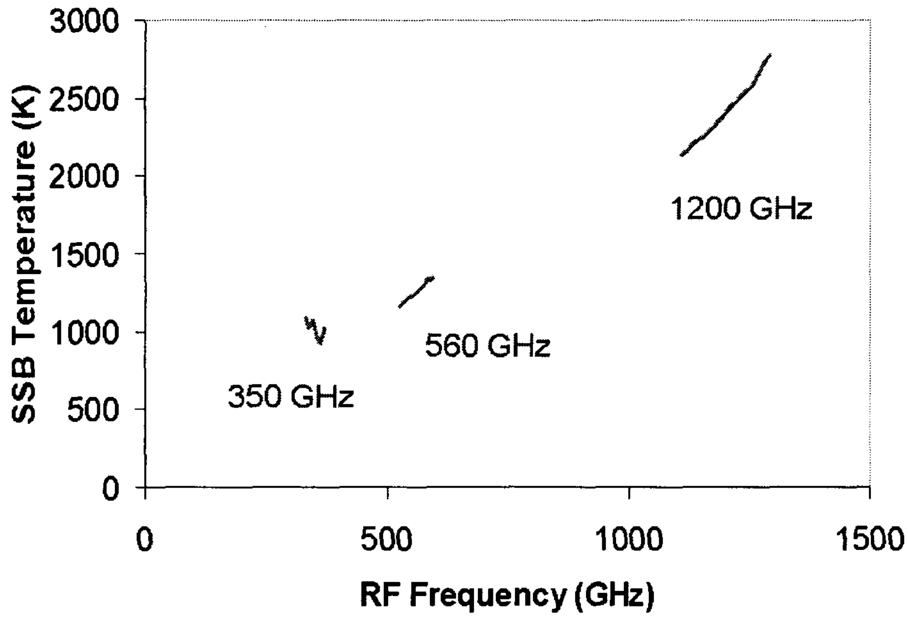

Figure 3. Comparison of calculated noise temperatures of single-ended mixer designs.

voltage, diode size, doping, and embedding impedances to maximize the efficiency (conversion gain). Initially this was tried for the mixer case, but there were two problems. First, optimizing on the actual sideband conversion to be used resulted in a set of unrealistic upper and lower sideband impedances that distorted the upper and lower sideband conversion gains. If the mixer will be operated upper sideband, the lower sideband embedding impedance would be an open circuit, resulting in an unrealistic conversion loss near 3 dB. The reason this is not realistic is that the upper and lower sidebands should both have about the same embedding impedance as that of the LO, unless the IF frequency is a large fraction of the LO frequency (not the case here). In view of this, provision was added to the optimizer to lock the LO, USB and LSB embedding impedances to the same value.

The second problem was that the optimizer often found a type of parametric oscillation mode yielding conversion gains greater than one (zero dB). This would occur at very low RF source resistance of an ohm or so. Something like this type of operation has been observed, but is invariably noisy. Hence, the optimization criterion was changed to the mixer temperature rather than conversion gain.

The noise performance of the 560 GHz version of the mixer is indicated in Figure 2. The figure compares the optimized diode noise temperature with that of the diode in the actual circuit. The plot includes the estimate of the total circuit noise temperature. A slight anomaly can be seen: the in-circuit temperature drops slightly below the "optimum" near the top of the band. This is due to the LSB embedding impedance being equal to the USB impedance in the "optimized" calculation. In the actual circuit those impedances are not equal, and the circuit presents a slightly more optimum set of impedances. The circuit's positive reactance decreases with frequency, matching the decreasing capacitive reactance of the diode to improve the tuning slightly.

The fundamental circuit was scaled in frequency to higher and lower frequencies. The calculated circuit noise temperatures are plotted in Figure 3.

III. Subharmonic Mixers.

A. Conventional configuration

The fundamental mixers presented previously have two drawbacks. One is that they have both LO and RF signals entering the mixer through the same port. This requires external diplexing of the frequencies using a beamsplitter or Martin-Puplett interferometer. The former wastes LO power (a scarce resource) and the latter is narrow band and bulky. Operation of the mixer over substantial RF bandwidth requires mechanical tuning. These requirements are highly undesirable, especially for space applications.

A second objection to use of fundamental mixers operation above about 100 GHz using current technology requires LO multiplication from W-band fundamental sources

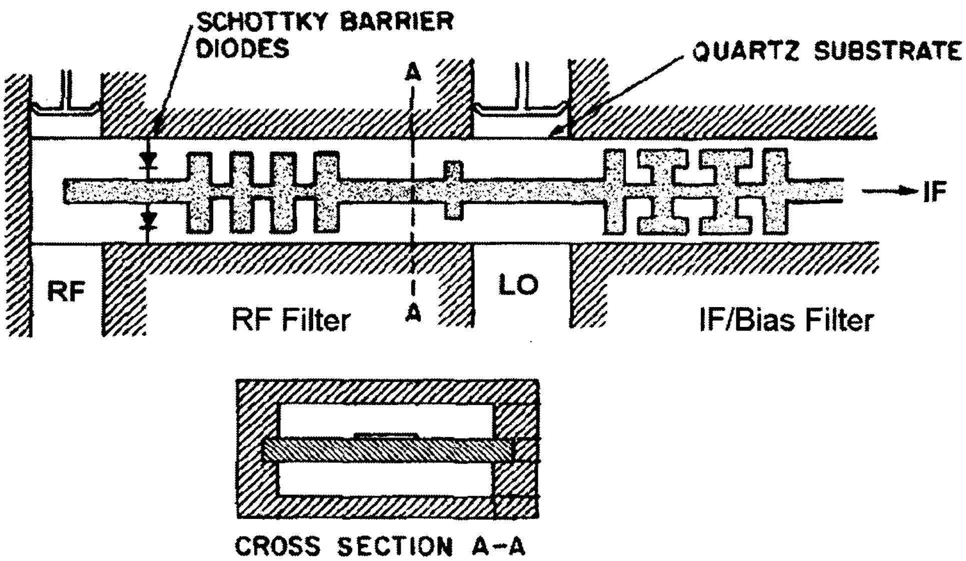

Figure 4. Subharmonic mixer using anti-parallel diode pair. Based on reference [18].

such as Gunn oscillators or amplified multipliers. Half-frequency subharmonic mixers ameliorate both of these problems some. While a balanced mixer will answer the first objection by separating the RF and LO, it requires twice the LO power of the single-diode fundamental mixer. The subharmonic mixer also requires more LO power, but at half the frequency, this requirement is not nearly as onerous.

Submillimeter mixers have been used in the millimeter and submillimeter range for more than two decades [18–20]. While any mixer topology can be designed for harmonic mixing, there is a great advantage to using pair of diodes in anti-parallel configuration [21]. Figure 4 shows the basics, and is excerpted from [18]. The LO is conveyed to the diodes through the central lowpass filter that prevents RF from leaking out the LO path. Likewise, the LO is prevented from leaking through the RF path by the RF waveguide that is cut off at the LO frequency.

The fundamental principle of operation of the mixer is explained fairly simply. On alternate half-cycles of the LO signal alternate diodes in the pair are turned on. When the central line is positive the lower diode is turned on. Conversely, when the central line is negative the upper diode is turned on. Thus, the diode pair has a single conduction peak for each half cycle of the LO or one peak at a specific phase angle of the second harmonic of the LO, near the RF.

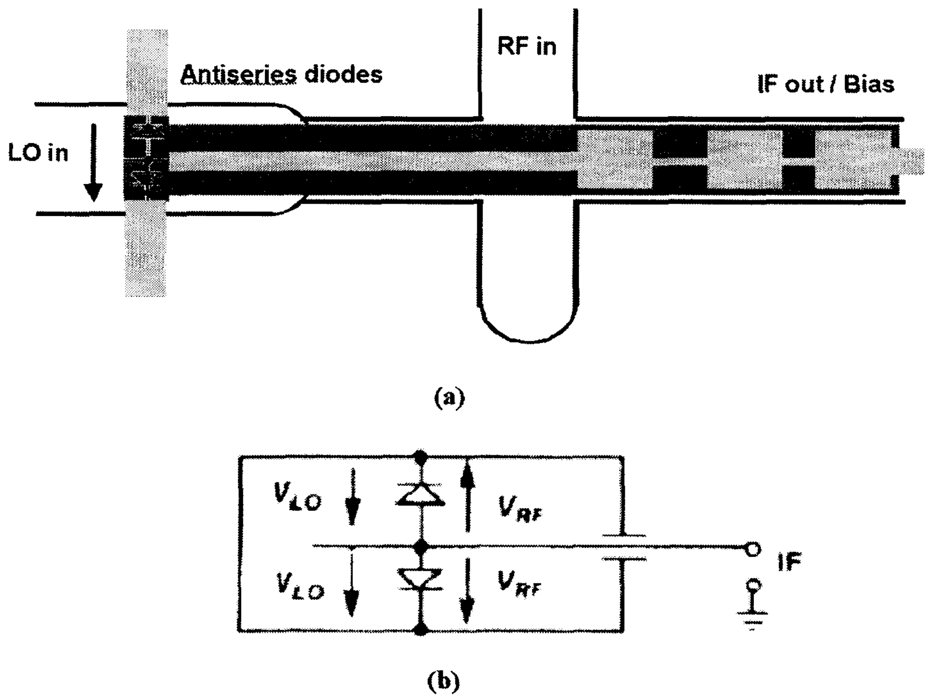

Figure 5. New "doubler-style" subharmonic mixer. (a) Schematic of layout. (b) Signal phasing.

This configuration does have a couple of design-related drawbacks compared to the single-diode mixer. The high-low RF filter requires a long path between the LO input and the diodes, compared to the fundamental design. This makes it much harder to achieve the same bandwidth for the LO pump. In the design described here, the LO bandwidth achieved was closer to 10 percent than the 15 percent of the fundamental designs, and the quality of the match was not as good. The penalty of the LO mismatch is an increase in required LO power, around a factor of two.

A more serious problem is in the length of line connecting the RF probe to the diodes. Achieving optimum LO match dictates that this line be of a length to present close to an open circuit to the diodes. Since the probe is approximately an open circuit with a phase shift around 90°, the length of this line giving the best LO match is around a quarter wavelength. The best RF bandwidth match, however, requires that the diodes be as close to the RF guide as possible, and the nearly half wavelength probe to diode line greatly reduces the achievable bandwidth. It is hoped that future improvements in circuit design (possibly including use of stubs near the diodes) will improve the situation.

B. "Doubler-style" configuration.

In order to address some of the difficulties with the conventional configuration, an alternate design is being fabricated. This design is based on the balanced doublers that have been used at submillimeter and terahertz frequencies for more than a decade [22–24]. The great advantage of this morphology is that the LO and RF signals are separated by the circuit symmetry, rather than by separate filtering structures. This means that the impedance matching and probes can be very close to the diodes, greatly increasing the achievable bandwidth.

Figure 5 shows the configuration in schematic form. The RF is conveyed to the

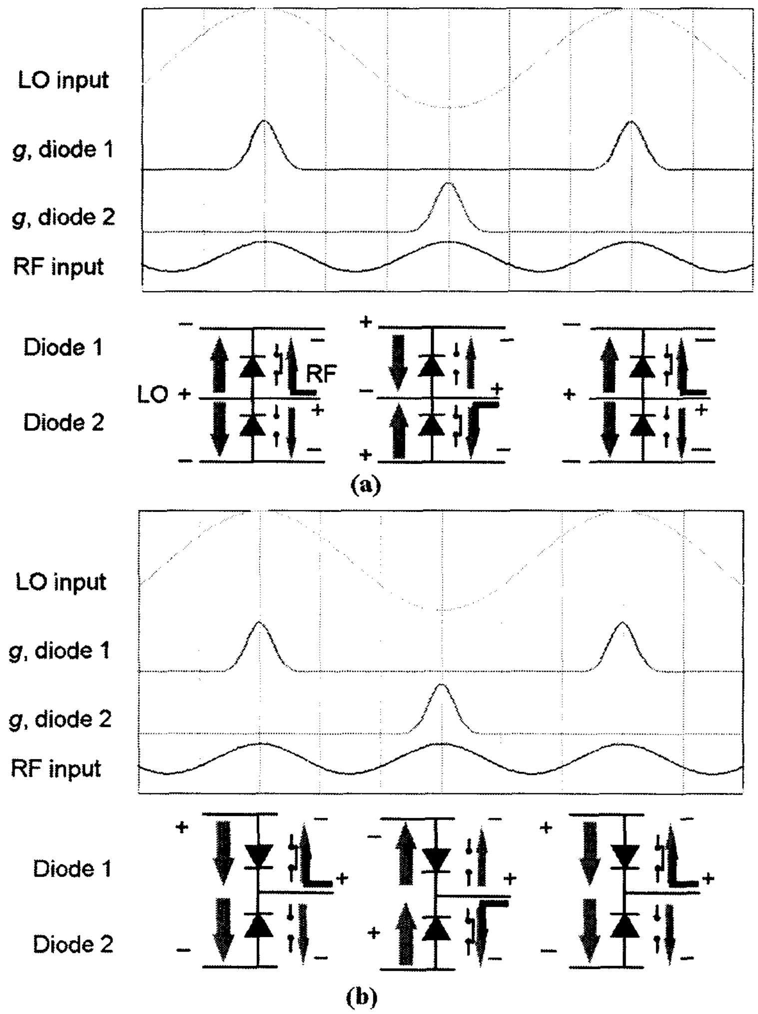

Figure 6. Schematic of subharmonic mixer switching operation. Blue arrows represent the voltage polarity, red the RF/IF current.(a) Conventional arrangement. (b) "doubler type" arrangement. Note the similarity in switching sequence and RF/IF current flow.

diodes in a similar way as for the previous subharmonic mixer circuit, through a quasi-TEM unbalanced transmission line connected to the RF input waveguide using a simple line probe. The LO is injected directly from the waveguide into the diodes connected in anti-series across the guide. The two diodes in the pair are thus excited in-phase at the LO, so one diode is reversed compared to the conventional subharmonic mixer with quasi-TEM line LO excitation.

Figure 6 shows a comparison of the switching waveforms that clarifies the similarities and differences between the two circuit topologies. Figure 6(a) shows the

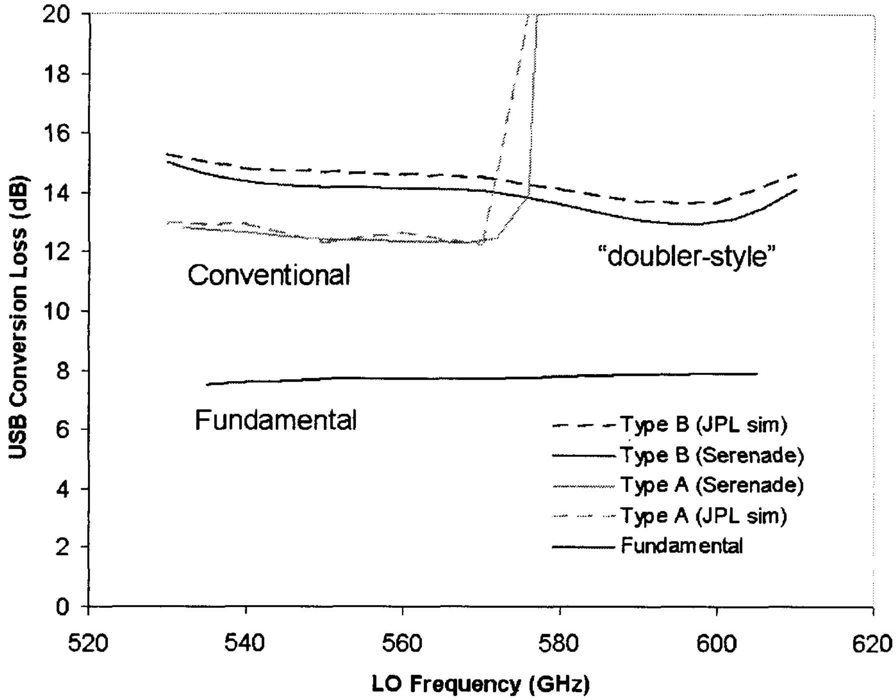

Figure 7. Conversion loss of two subharmonic types compared to fundamental.

subharmonic mixer discussed previously. The LO alternately excites the top and bottom diodes as the positive and negative halves of the LO waveform bias the diodes on and off. The conductance peaks can be considered as the opening and closing of two diode switches. To the incoming RF signal the mixing occurs as if the RF current were flowing through a single diode being switched on and off at twice the LO frequency, near the RF.

Figure 6(b) shows the "doubler-style" connection. Since the two diodes are in anti-series across the waveguide, a similar situation applies as to the conventional mixer: the top and bottom diodes are turned on and off alternately during opposite phases of the LO cycle. Hence, the diodes again appear as a single diode switched at twice the LO frequency. For the embedding impedances, at RF and IF, each diode sees twice the actual circuit impedance. In the "doubler-style" mixer, each diode sees half the full waveguide impedance at the LO, whereas in the conventional mixer each sees half the actual impedance.

IV. Subharmonic Mixers Compared.

Despite its advantages of bandwidth and circuit simplicity, the "doubler-style" subharmonic mixer suffers from a major drawback. In the conventional subharmonic mixer topology, the anti-parallel connection prevents signals near even LO harmonics from coupling to sidebands of odd LO harmonics and vice-versa [21]. Thus, energy produced from mixing the RF (even) into sidebands of the LO (odd) is prevented from leaking out the LO path. The prevention of this loss will reduce the theoretical conversion loss by around 3 dB, and is the primary motivation to using the anti-parallel configuration over a single-diode subharmonic mixer. Further, signals and noise near the LO (odd) are not mixed down to the IF (even). This removes a noise source that can be significant in

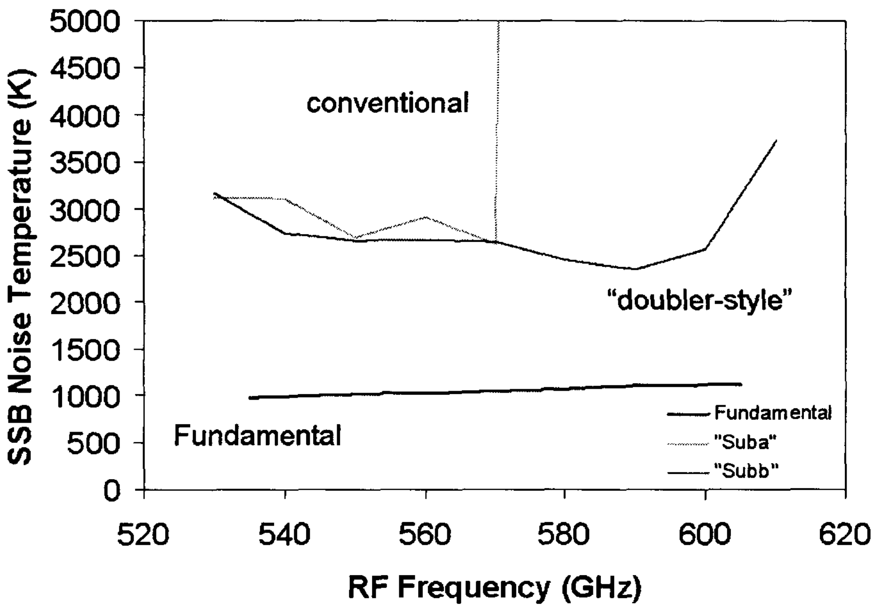

Figure 8. SSB mixer noise temperatures.

receiver performance.

The doubler-style mixer has none of these advantages. Since the mixer (like a doubler) is configured to couple the fundamental and second harmonic, RF signals mixed down to sidebands of the LO can escape into the LO input guide. Furthermore, LO noise near the LO fundamental will be mixed down to the IF frequency. This topology is shared with the single-diode subharmonic mixer [21]. The primary motivation in using this topology over either a single diode design or the conventional design is circuit simplicity and increased bandwidth. The performance calculations presented here indicate that the conventional design must be done exactly right to take advantage of its superior attributes.

Figure 7 shows a comparison of the conversion loss of the two configurations. The calculations were done using a simulator developed at JPL for multiplier design that incorporates a sophisticated diode model. They were also done using a commercial simulator [25] having a simple Rs/Schottky junction diode model. The similarity of the results shows that for mixer analysis in this frequency the simple model is quite adequate. The fundamental mixer is included for reference.

Note that the conversion loss of the conventional mixer is somewhat lower than the "doubler-style" mixer, as expected. However, the bandwidth is also much less. It can be expected that more careful circuit design using more sophisticated techniques possible with the membrane technology would improve the performance and bandwidth, allowing them to approach the fundamental mixer. Attention needs to be paid to the LO and RF matching, as well as matching of the sidebands near the LO fundamental. This tuning appears not to be optimized for this design, and there appears to be substantial loss within the diodes. This loss cannot be completely eliminated, which is probably a fundamental limitation on all subharmonic mixers, and may prevent them from ever being as efficient or low-noise as the equivalent fundamental mixer. Nevertheless, the advantages in circuit simplicity over the fundamental single diode design and elimination of loss in the input diplexing makes subharmonic mixers an attractive alternative.

Figure 8 indicates the calculated SSB noise temperature of the three mixer types. Again, the conventional mixer should perform better with circuit improvements. Figure 9 shows the RF to upper sideband conversion loss. The JPL simulator cannot directly calculate the loss of the conventional subharmonic mixer, so only the commercial

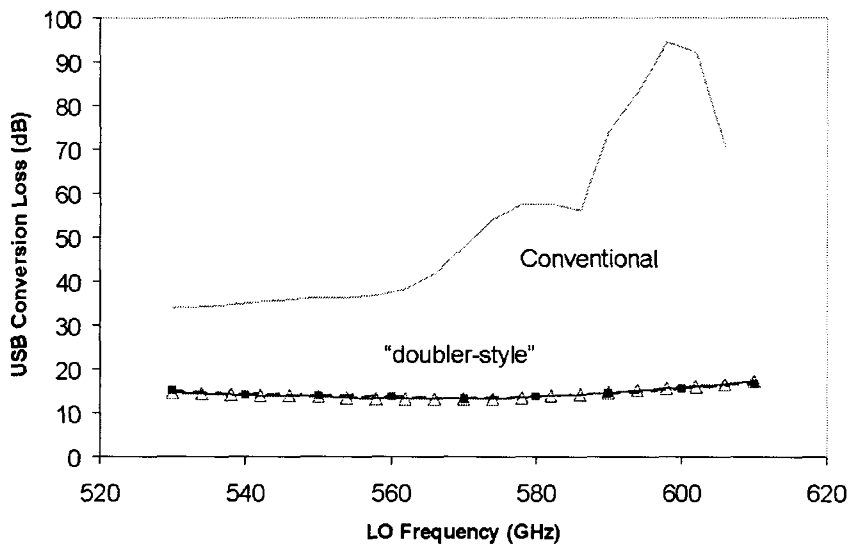

Figure 9. RF to USB of LO fundamental conversion loss. Conventional has much higher loss than "doubler-style".

simulator calculation is given. This is compared to the "doubler-style" RF/fundamental USB loss, indicated by two lines for the JPL and commercial simulators. (These lines appear to coincide at this scale.) It can be seen that the RF to LO-USB conversion loss is about the same as the RF/IF loss for the doubler-style configuration, but is far greater for the conventional mixer.

V. Summary and Conclusions.

Three mixer design types have been presented for the 350 to 1200 GHz frequency range. Simple and high-performance fundamental mixers with wide bandwidth and low mixer temperature are easily scalable over a wide frequency range using the JPL GaAs membrane process. Predicted SSB noise temperatures are around 1100 K over a bandwidth of 15 %.

Two types of subharmonic mixers with RF frequencies centered on 560 GHz were also presented. The conventional type based on an anti-series diode pair should have lower noise the "doubler-style" that uses and anti-series diode connection. Due to the difficulty in matching to the conventional configuration, the two designs presented are predicted to have similar noise performance, with the conventional configuration having a lower bandwidth.

Future designs will incorporate more careful matching circuit configurations, which should allow the conventional mixer topology to surpass the "doubler-style" topology and approach the fundamental mixer in performance.

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