Broadband Fixed-Tuned Subharmonic Receivers to 640 GHz

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Abstract

This paper will describe the design and testing of solid-state subharmonically-pumped mixers from 380 GHz to 640 GHz. The main goal has been to develop robust, compact, solid-state room-temperature receivers with state-of-the-art sensitivity and broad IF bandwidths for applications such as airborne and space-based microwave sounding. Testing of a 380 GHz integrated mixer has yielded state-of-the-art performance, with a double-sideband (DSB) mixer noise temperature of 850 K and a mixer conversion loss of 8.5 dB (DSB) using 7 mW of local oscillator power. The success of this receiver is due to a combination of integrated diode technology and inherently broadband circuit designs achieved with modern high frequency design tools. The recently developed MASTER integrated diode technology allows for precise control of the circuit geometry and for the reduction of parasitic elements, thus allowing greater accuracy of computer simulations and therefore better high frequency performance and bandwidth. The split block geometry used for these mixers is relatively simple to machine, and yet allows for broad fixed-tuned RF and IF bandwidths, and is also compatible with molded and micromachined blocks. Finally, design techniques have been developed for these mixers that give excellent agreement with measurements, thus allowing for rapid prototyping. The major impact of this research is to demonstrate that excellent harmonically pumped mixers using integrated diodes and modern design tools are now a commercial possibility to at least 640 GHz.

Mixer Layout

The mixer block, similar to that described in [1], is split in the E-plane of the RF and LO waveguides, thus simplifying mixer assembly and reducing the losses in the waveguides. The planar diode and mixer circuitry are fabricated on a 35μm thick fused-quartz substrate. The circuits are then placed in a shielded microstrip channel which runs perpendicular to the RF and LO waveguides. A schematic of the mixer block circuit configuration is shown in Fig. 1. The diodes are located in the microstrip channel. Waveguide-to-microstrip transitions are used to couple both the RF and LO into the channel. The microstrip metallization bridges across each guide, necessitating the use of reduced height waveguide to achieve reasonable fixed-tuned bandwidths [2]. For this mixer, half height waveguide was used for the RF, and third height waveguide was used for the LO. A low-pass microstrip filter is used to prevent the RF signal from coupling to the LO guide, and a short-circuited half-wave stub is used to provide the LO termination.

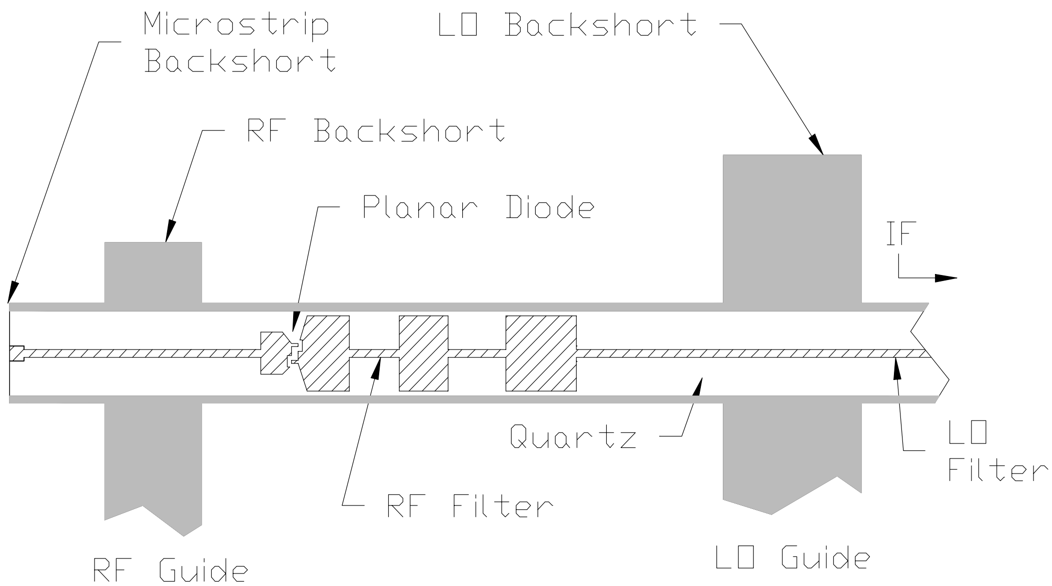

Fig. 1. Schematic of subharmonic mixer configuration.

Integrated Diode Fabrication

Diode integration has many benefits. First the circuit geometry near the Schottky anodes is nearly planar and defined photolithographically. This simplifies the analysis of the circuit and allows more precise control of the embedding impedances. Second, the elimination of the high dielectric GaAs substrate reduces capacitance. This improves coupling to the Schottky diodes and increases receiver bandwidth. Finally, the assembly of the mixer is much simpler and a higher level of repeatability is achieved. The fabrication process for the integrated diodes is described in [3], and a view of one of the circuits is shown in Fig. 2.

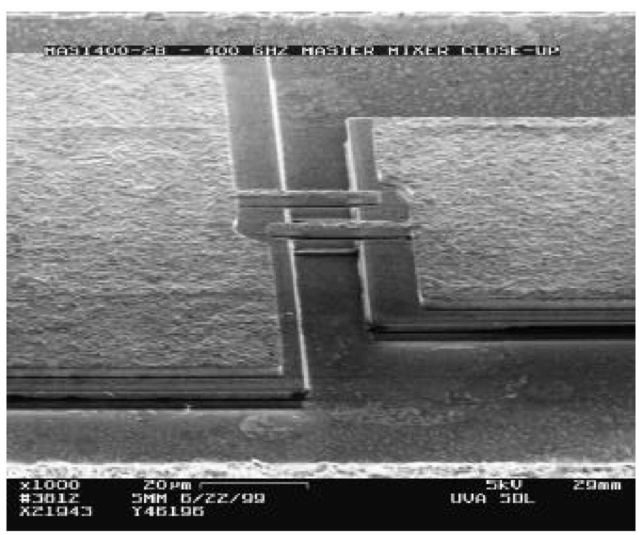

Fig. 2. SEM of an integrated anti-parallel mixer circuit.

400 GHz Mixer Design and Testing

The mixer was designed using Ansoft's High Frequency Structure Simulator [4] to model the waveguide transitions, integrated-planar-diode and the quartz circuit. Coaxial probes were artificially introduced at the two diode junctions during the finite element modeling to allow the direct prediction of the diode embedding impedance [5,6]. The loop parasitics predicted for a planar diode with 20 μm fingers was a finger-to-pad capacitance (C_{FP}) of 2.5 fF and a finger inductance (L_F) of 10 pH. Harmonic balance simulations were performed for the Scottky diode, which had an epitaxial layer doping of 4×10^{17} cm^{-3} and an anode diameter of 0.8 μm. The measured DC parameters for this diode were an ideality factor η=1.32, a saturation current I_{SAT}=3×10^{-13} A, and a series resistance R_s=10 Ω. The zero bias junction capacitance was calculated to be 1.5 fF per anode based on the anode diameter and the epitaxial layer doping. The simulations predict a mixer conversion loss of 4.0 dB (DSB) and noise temperature of 300 K (DSB) using 1.5 mW of LO power. The total conductor and dielectric loss for the horn, waveguide, microstrip, and diode was estimated to be about 2 dB. Using this estimate the predicted performance is a mixer conversion loss of 6 dB (DSB) and mixer noise temperature of 650 K (DSB). The simulations predict a usable RF bandwidth of better than 20% fixed tuned. The LO bandwidth is difficult to estimate since it is closely linked to the amount of power available from the LO source.

The local oscillator power for this mixer was provided by a Gunn oscillator near 100 GHz with 75 mW output power driving a planar balanced doubler with output power greater than 15 mW at 200 GHz [7]. The sensitivity of the mixer was measured at room temperature using broadband IF amplifiers covering the range from 2-12 GHz. An attenuator was used to vary the IF noise temperature, thus allowing the measurement of the mixer parameters.

Fig. 3 shows a fixed-tuned frequency sweep of a 425 GHz mixer. The upper limit of the

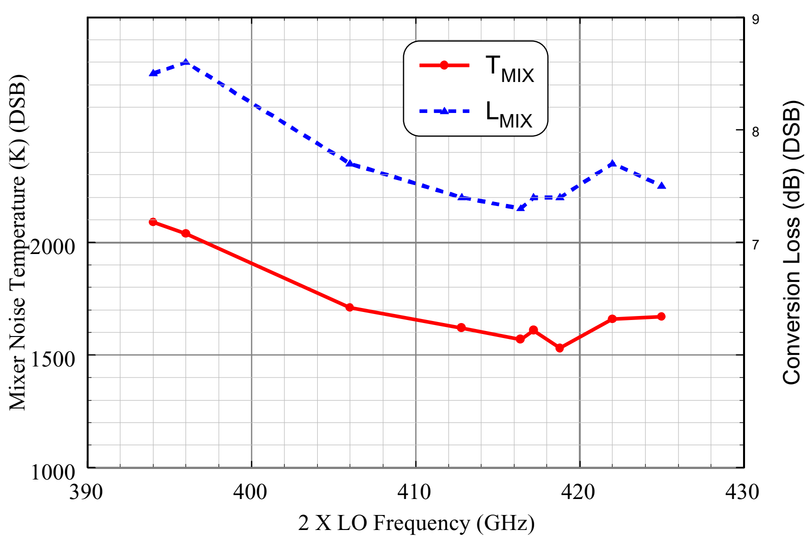

Fig. 3. LO Frequency sweep with fixed backshorts for 425 GHz subharmonic mixer.

frequency range was set by the Gunn oscillator and not the mixer. Fig. 4 shows a typical IF sweep for the same mixer, indicating the broad IF bandwidth of this design. The diode's IF impedance was constant at about 100 Ω up to at least 12 GHz, and a mismatch to the 50 Ω amplifier impedance was accepted. The slight increase in the mixer noise temperature at the highest frequencies is caused by losses in the Duroid IF circuit, which was designed for operation up to 6 GHz, and could be shortened to improve IF bandwidth. An IF sweep for a 380 GHz mixer is shown in Fig. 5. For this case the RF backshort was several wavelengths away from the circuit, thus causing the increase in noise temperature seen at the higher IF frequencies.

The LO power coupling for these mixers was optimized for operation at 425 GHz, and the 425 GHz mixer required less than 2 mW of LO power. The LO coupling for the 380 GHz mixer used the 425 GHz LO coupling circuit, and the LO power required increased to 7 mW. This LO power requirement could be reduced by re-optimization and re-fabrication of the LO and integrated diode circuit. Fig. 6 shows a fixed-tuned sweep of the LO frequency for the 380 GHz mixer.

500 and 640 GHz Mixer Designs

Simulations were performed to evaluate the performance of subharmonic mixers at 500 GHz and 640 GHz. For the first iteration of the design it was assumed that the dimensions of the finger/anode region of the diode were constant, while the rest of the circuit was scaled up to higher frequencies. This compromise would allow the use of previously developed diode fabrication techniques. However, as shown in Fig. 7, the simulations predicted that while the 500 GHz circuit still behaved reasonably well, the mixer's performance was severely degraded at 640 GHz. Further examination revealed that the loop resonance between the finger inductance and the junction and parasitic capacitance was causing this degradation [8]. To overcome this

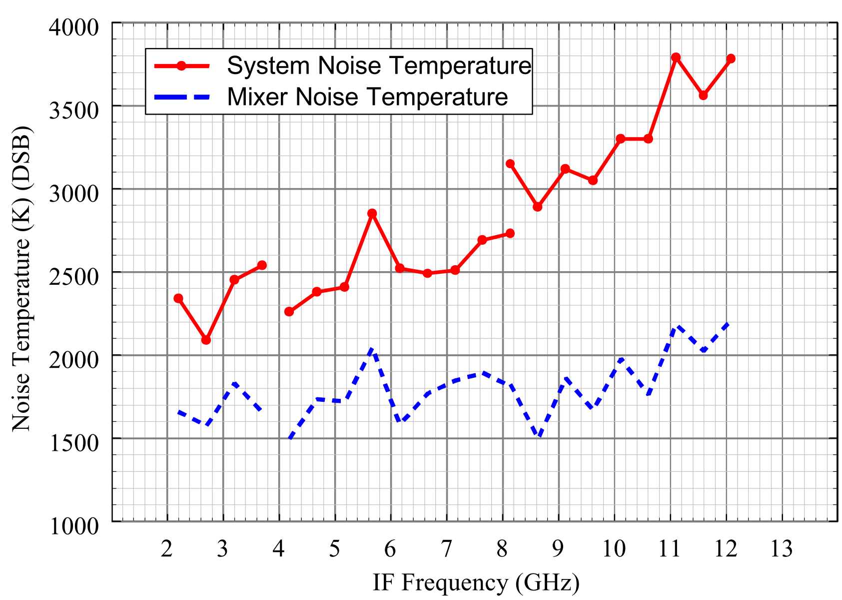

Fig. 4. IF sweep for 425 GHz Receiver.

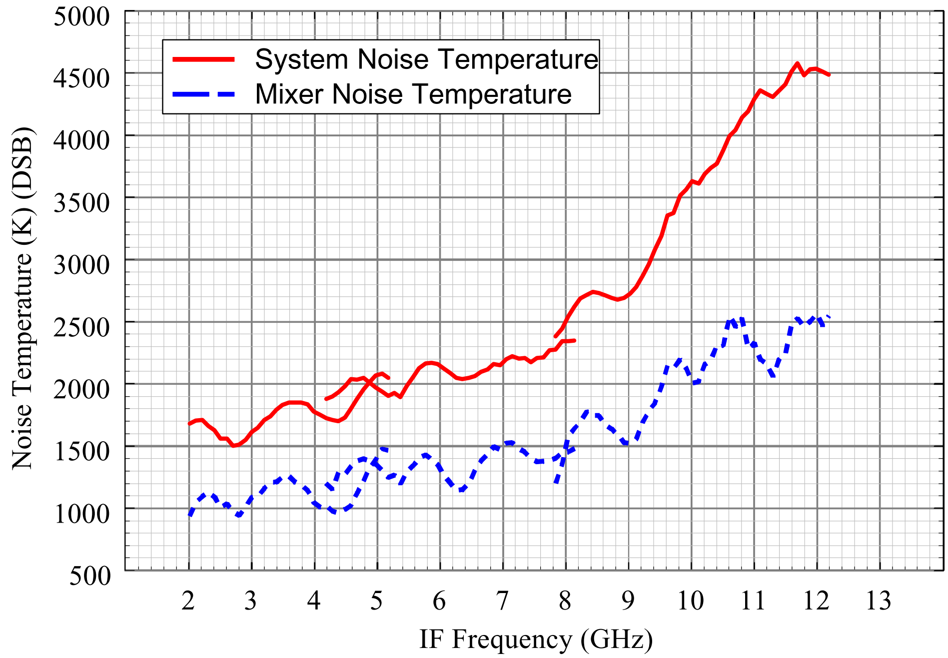

Fig. 5. IF sweep for 380 GHz Receiver. The RF backshort was several wavelengths away from the circuit, thus causing the increase in noise temperature at the high IF frequencies.

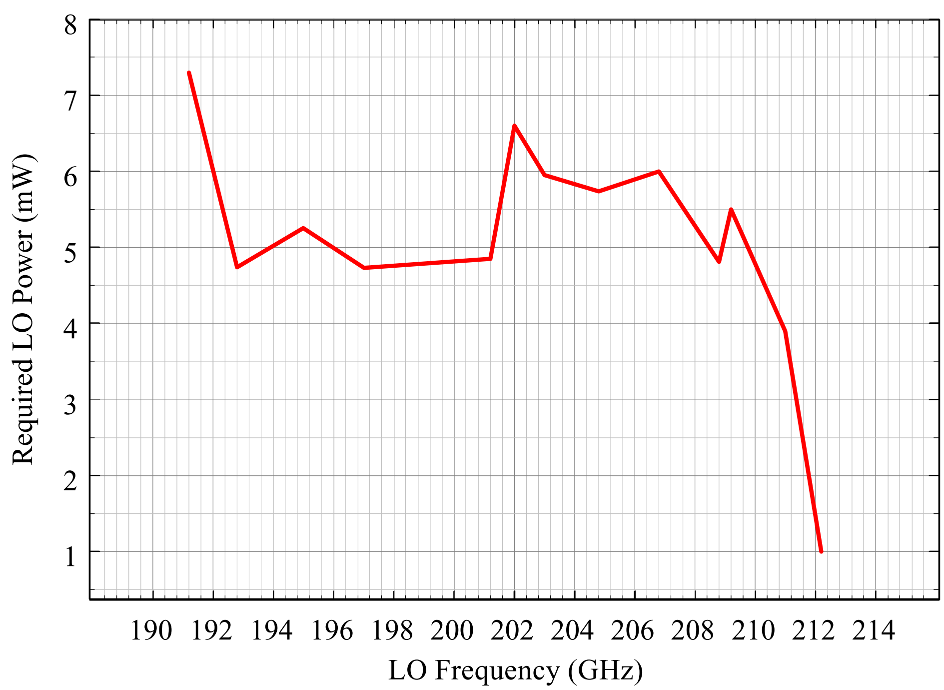

Fig. 6. Required LO power for 380 GHz Receiver.

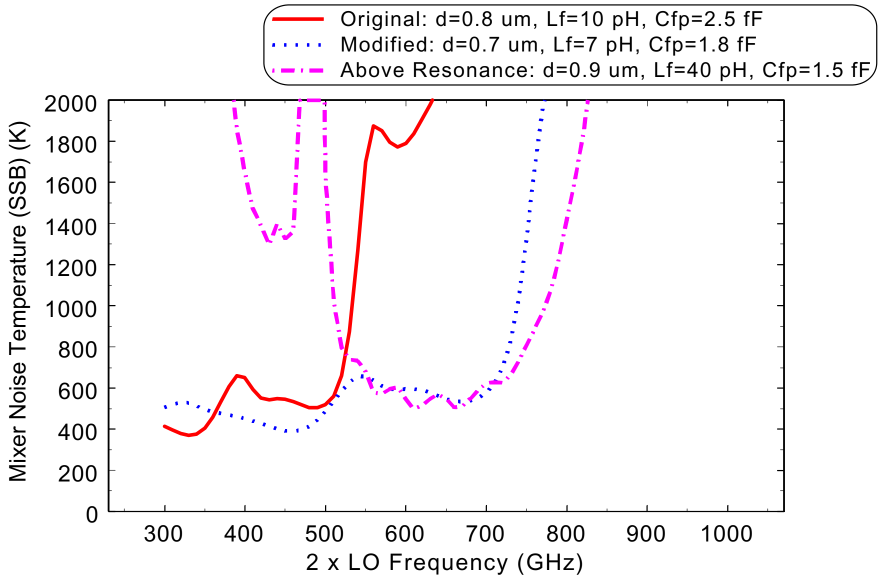

Fig. 7. Predicted performance for various 600 GHz diode configurations.

problem, it was necessary to reduce the finger length and the spacing between the fingers, thus pushing the loop resonance to higher frequencies. The predicted performance for the modified design is shown in Fig. 7.

Another design possibility for the 640 GHz mixer is to operate above loop resonance [8]. For this configuration, the finger length and the spacing between the fingers is increased, thus pushing the loop resonance down in frequency. The predicted performance for a 640 GHz design with L_F=40 pH and C_{FP}=1.5 fF is also shown in Fig. 7. The bandwidth for the mixer above resonance is predicted to be determined by external circuit consideration, and not by the loop characteristics. The above-resonance mixer was also predicted to require a similar amount of LO power and to have a similar sensitivity to fabrication and assembly variations as a below-resonance mixer. Using this configuration, the diode fabrication can be simplified, and the basic circuit configuration used at much higher frequencies with little sacrifice in performance.

Conclusions

We have demonstrated a subharmonically pumped 380 GHz integrated-diode mixer with broad fixed-tuned LO, RF and IF bandwidths and excellent sensitivity. The mixer was pumped by an all-solid-state LO source. The mixer block was fabricated by standard split-block machining techniques, but was specifically designed to be compatible with micromachining [9] and molding technologies that have recently been demonstrated. The mixer design is also readily scalable to higher frequencies.

This research has enabled us to efficiently design and build submillimeter wavelength mixers that are not only highly sensitive, but also have enhanced mechanical robustness and large fixed tuned bandwidth. The coupling of these new analysis techniques and the new integrated diode technology can be easily extended to other circuit designs such as balanced and subharmonic mixers and frequency multipliers, and will allow the development of a new generation of SubMillimeter-wave Integrated Circuits (SMICs) for a wide range of scientific, military and commercial applications.

Acknowledgments

The author would like to thank Steve Marazita, Bill Bishop and Thomas Crowe for fabricating the integrated Schottky diode circuits used for this research. This work was supported by NASA-GSFC Grant No. NAG5-6507 and by the U.S. Army National Ground Intelligence Center under contract DAHC90-96-C-0010.

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