A 2.5 THz Receiver Front-End for Spaceborne Applications

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***Abstract*— The OH radical is an important player in known ozone depletion cycles; however, due to its location in the atmosphere, it must be studied from either a balloon or spaceborne platform. For long-term mapping over large portions of the earth, spaceborne is the most practical. NASA's Earth Observing System Microwave Limb Sounder instrument is slated to house a 2.5 THz Schottky-diode receiver for such measurements. Here we describe the design, fabrication, and testing of the engineering model receiver front end. This is the precursor to the first terahertz heterodyne receiver to be flown in space**

I. INTRODUCTION

The OH radical plays a significant role in a great many of the known ozone destruction cycles, and has become the focus of an important radiometer development effort for NASA's Earth Observing System (EOS) Chem I satellite, which will monitor and study many troposheric and stratospheric gases and is scheduled for launch in 2002 [1]. The Microwave Limb Sounder (MLS) instrument on this satellite is the only near-term opportunity to obtain global measurements of this important radical.

The lowest order OH doublets at 2510 and 2514 GHz fall fortuitously close to a strong methanol laser line at 2522 GHz. A receiver noise of 20,000 K, SSB provides enough sensitivity for daily global stratospheric maps of OH above 35 km and weekly zonal maps above 18 km from a limb-sounding satellite in polar orbit. These requirements are consistent with the performance that can be obtained from state-of-the-art room-temperature Schottky diode mixers. We also plan to monitor the molecular oxygen line at 2502 GHz as a pressure/altitude indicator.

The challenges of producing such sensitive mixers are numerous, but for this application, there is the added challenge of designing a robust receiver which can withstand the environmental extremes of a rocket launch and five years in low earth orbit. In this presentation, we discuss the design and implementation of the first terahertz heterodyne receiver to be flown in space.

II. RECEIVER FRONT END DESIGN

The receiver front-end used to detect the OH radical at 2.5 THz consists of the following components and is schematically outlined in Figure 1:

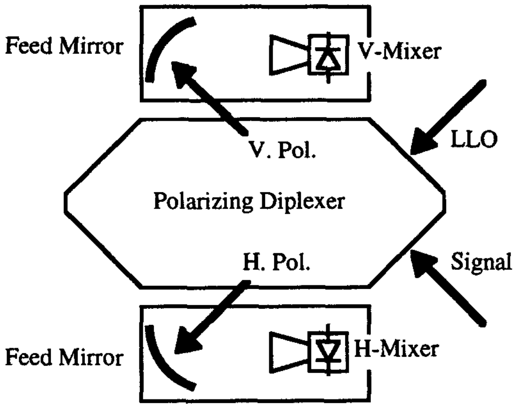

Fig. 1. Schematic diagram of the quasi-optical components in the 2.5 THz receiver front end.

- A diplexer to combine the OH signal and the laser local oscillator (LLO)
- Elliptical feed mirrors to shape the beams of the mixer feedhorns
- Fundamental Schottky-diode mixers for horizontal and vertical polarizations
- Support structures allowing simple, rugged alignment
- Low noise IF amplification chain (not pictured) from 7 to 22 GHz.
- Mixer bias circuitry (not pictured).

Note that the space-qualified LLO is a complex subsystem in itself, and is not included here as part of the front-end. However, it should be mentioned that the LLO technology is quite well developed, and will deliver more than 20 mW of 2.5 THz power for only ≈ 125 W of spacecraft power. The LLO is a mere 75 x 30 x 10 cm in size, and 20 kg in mass.[2]

Shown in Figure 2, the engineering model (EM) diplexer is a dual-polarization Martin-Puplett type. The diplexer's dual-polarization operation serves to lower the system noise and provide the redundancy so important to space flight missions. The design has been optimized for stand-alone use, ruggedness, mass, volume, and thermal stability. It receives 45° linear polarization from the laser local oscillator and the signal, and generates two output beams: one with horizontal and one with vertical polarization. The two 45 mm free-aperture wire grid polarizers incorporate 5 μm diameter gold-coated tungsten wire on 12.5 μm centers.[3] The path difference responsible for constructive interference at both LO and signal frequencies is nominally set at 9.972 mm with invar spacers on one of the rooftop mirror mounts. This path length offers ideally 94% LO coupling, 84% coupling at 8.4 GHz IF, 99% at 12.8 GHz IF, and 46% at the less-important 20.4 GHz IF band. To allow for machining tolerances, a mechanism is used to give ± 200 μm in fine adjustment of this path length. For this, a circular "adjuster wheel" is attached to the diplexer 200 μm

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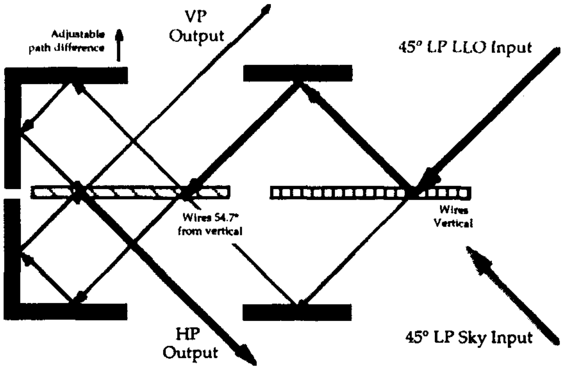

Fig. 2. Diplexer principle of operation. The rightmost grid splits the two input signals into two components (each). The heavy line follows the reflected half of the LLO input. The leftmost grid splits this into two components, and interferometrically combines them after these two components are subjected to slightly different path lengths. The path length difference is adjusted such that the vertical portion of the LLO appears horizontal at the "HP Output" port. The horizontal portion of the LLO travels through the rightmost grid, and appears as vertical at the "VP Output" port. The inverse is true for the sky input.

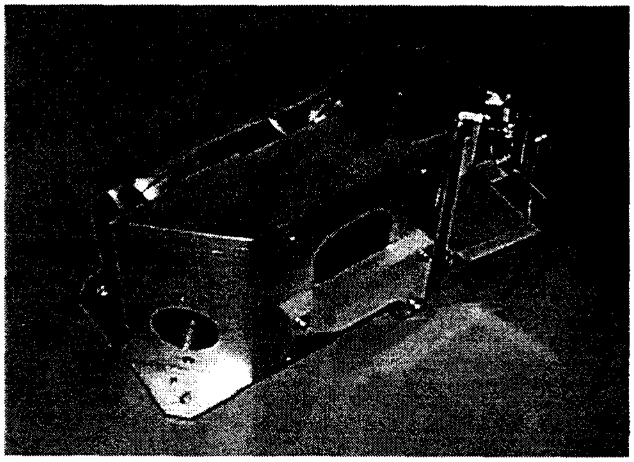

Fig. 3. 2.5 THz diplexer. One can see the LO input port at bottom left, the vertical-polarization output in the center, and the adjuster wheel with tilting roof mirror at the top right. For volume and shape concerns, the diplexer has been fashioned into a "3-D" version of that diagrammed in Figure 2.

off-center. It contacts an invar spacer, and can be rotated to tilt the rooftop mirror mount, causing a change in path length with a negligible effect on beam location. This mechanism is secured with epoxy before flight, and the rooftop mirror mount is spring-loaded to withstand vibration. Figure 3 shows the engineering-model diplexer and its adjustment mechanism.

The feed mirrors are diamond-turned off-axis ellipsoids which convert the rapidly diverging feedhorn beam to a well-collimated beam suited for best diplexer performance. All mirrors are optically accurate, allowing the difficult receiver alignment to include the use of a HeNe laser and an optical autocollimating alignment telescope.

We use a dual-mode Pickett-Potter conical feedhorn [4] to collect the radiation into a single-mode 2.5 THz rectangular waveguide which in turn feeds a mixer. The mixers we are presently implementing are GaAs Schottky monolithic membrane diodes (MOMEDs), designed and fabricated at the Jet Propulsion Laboratory [5]. The mixers utilize a new fabrication technique which offers more robust construction than existing whisker-contact corner-cube designs, while maintaining state-of-the-art noise performance.

The LO power requirements of these mixers (< 5 mW) is modest enough to permit use of a low-power laser LO. Fluctuations of laser power will be minimized through the use of three feedback loops, one of which uses the mixer DC signal to eliminate standing wave variations created by thermal changes as the spacecraft orbits the earth. Future work will also implement novel planar-whisker contacted waveguide mixers from the Rutherford Appleton Laboratory [6].

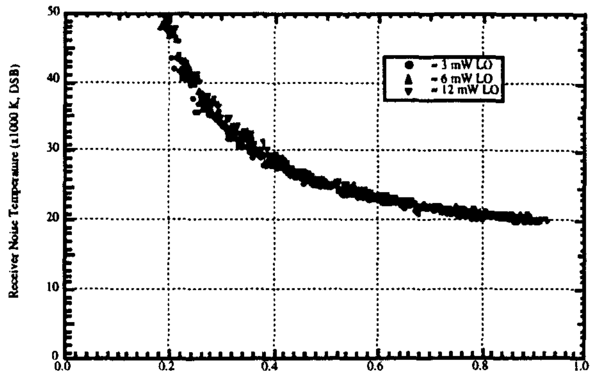

Fig. 4. Receiver noise vs. current at an IF of 8.4 GHz, demonstrating the use of current bias to reduce sensitivity to LO fluctuations. A factor of ≈ 4 in LO power results in virtually no input noise temperature change.

A resistive bias-tee arrangement has been chosen to offer protection to the mixers, while providing a DC bias path for the Schottky diode with minimal impact on the IF throughput. We have designed and implemented a differential feedback circuit to provide a stiff current bias with good immunity to noise pickup. The current bias also serves to reduce sensitivity of the device to LLO power fluctuations. As shown in Figure 4, a factor of 4 in LO power results in virtually no change of input noise temperature. Conversion gain behaves similarly. Other devices we have tested exhibit slightly more sensitivity to LO power. Our thinking at present is that the IF transformer match is not as good for these other devices, and the LO power fluctuations result in device impedance changes which have non-negligible effect on the receiver characteristics. The IF transformer is a 7 - 22 GHz quartz suspended-substrate stripline step transformer, typically 250 Ω at the mixer end, and 50 Ω at the amplifier. Recent measurements suggest a lower impedance transformer may improve the match on these devices. Low-noise (150 K) IF amplifiers with AC-coupled inputs [7] handle the downconverted mixer output before sending the signal to the spacecraft's second amplification stage and spectrometer modules. Figure 5 shows the assembled front end components.

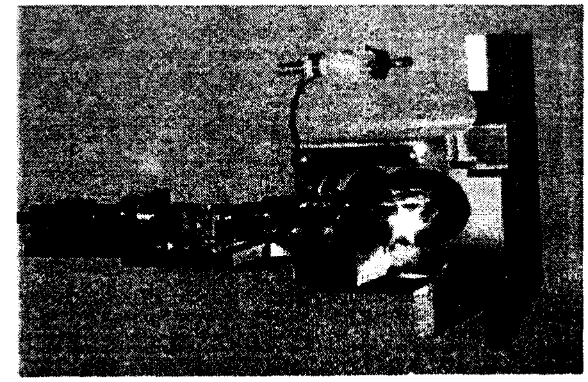

Fig. 5. Closeup of receiver front end components. The chain includes an off-axis elliptical feed mirror, the mixer, a 7 to 22 GHz IF amplifier, a clamped attenuator, and a clamped semi-rigid coax. DC bias for the mixer is presently fed through the connector at top. The face to the right bolts to a long edge of the hexagonal diplexer.

III. 2.5 THZ MIXER TEST SYSTEM

Accurate RF noise measurements at 2.5 THz are complicated by several factors: high mixer noise temperatures, variable atmospheric attenuation, poorly calibrated "absolute power" detectors, unavailability of matched attenuators, "gray" body loads, and imperfect Gaussian beams. The measurement test system used here to overcome these difficulties is schematically shown in Figure 6. At this time, relatively few measurements have been made in demonstrating the successful operation of the flight-type diplexer, as a more flexible Martin-Puplett type diplexer [8] was used for earlier receiver measurements.

The noise temperatures are measured using the standard Y-factor technique on the full receiver only (that is, including the diplexer and atmospheric losses, and the addition of noise by the bias tee and the IF amplifier). A chopper switches the signal beam between a hot and a cold load during the measurement. A lock-in detector at the ≈ 100 Hz chopper frequency extracts a hot/cold load power output variation from a crystal diode detector. A filter is placed in front of the crystal diode detector to select the IF band of interest: 8.4 GHz, 12.8 GHz, or 20.4 GHz. The filter bandwidth is ≈ 700 MHz.

After converting the lock-in signals from RMS to peak-to-peak values, we combine with the average DC output power to give the hot and cold powers needed for an accurate Y-factor calculation. This technique can be used to evaluate receivers with noise in excess of 500,000 K, DSB. It has been demonstrated that the noise temperature measured with the test system is consistent with that measured on the actual EM diplexer.

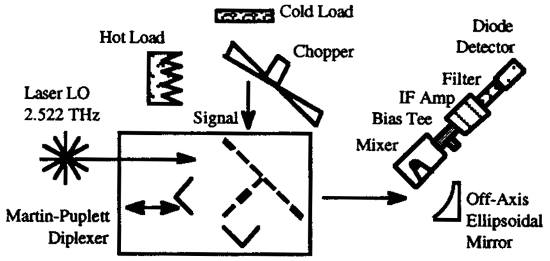

Fig. 6. Schematic of the 2.5 THz mixer test system. It is designed for sensitive measurement of high-noise devices, flexibility, and rapid computer-controlled measurements.

IV. MOMED SCHOTTKY DIODE MIXERS

The Schottky-diode mixers and the mixerblock housings have been previously described.[5] To date, we have extensively RF tested 13 different devices of varying designs. Seven of these devices have given receiver noise temperatures of better than 22,500 K, DSB at 8.4 GHz IF. This group has nominal anode sizes of 0.2 μm by 1 μm. Three of the poorer performers had 0.1 by 1 μm anodes, and the others suffered design or mounting problems. Figures 5, 7, and 8 show data from three different devices of the low-noise group.

Figure 7 plots receiver noise versus DC diode bias voltage, for LO power levels between ≈2 and 5 mW. The receiver performance measured here is competitive with that of the best reported in the literature [9], particularly when one considers the fine quality of the beam from the Pickett-Potter horn. Another device (that of Figure 5) showed the same noise temperature vs. current curve for LO power levels of ≈3 mW and ≈ 22 mW. It appears the IF match is responsible for variations in noise with LO power, and we are actively testing this theory at the present time.

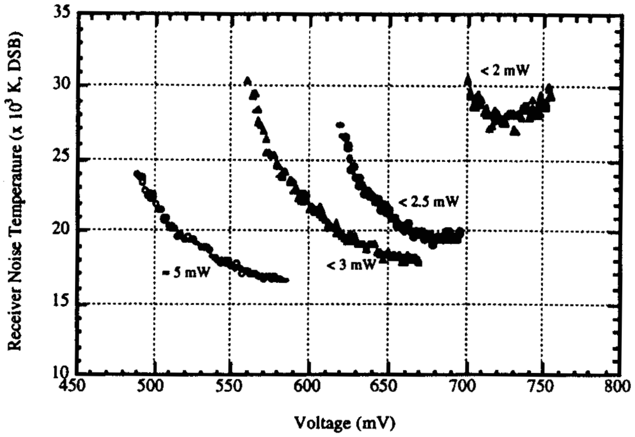

Fig. 7. Measured receiver noise temperature for a JPL MOMED device, with LO power levels between 5 mW and < 2 mW. The best receiver (system) noise temperature obtained was 16,500 K, DSB, with the maximum available LO power of ≈ 6 mW.

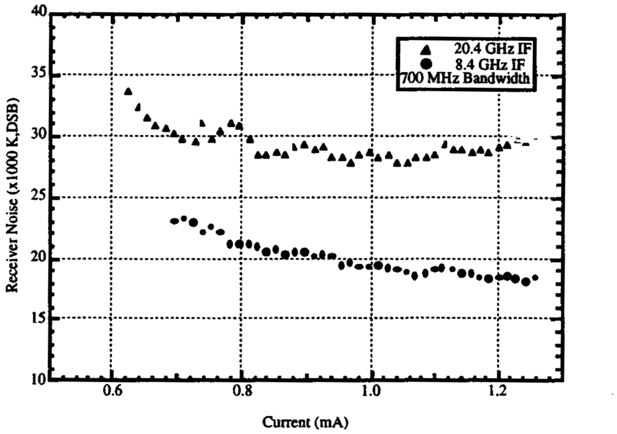

Fig. 8. Receiver noise vs. current at intermediate frequencies of 8.4 GHz and 20.4 GHz. Note the minimum in the 20.4 GHz curve, presumably due to better IF match at moderate currents.

In support of this idea, Figure 8 compares receiver performance at 8.4 and 20.4 GHz. The 8.4 GHz curve suggests that the combined RF and IF match is best at high current (low dynamic resistance). However, the 20.4 GHz curve exhibits a minimum in noise temperature at an intermediate current. Because the 20.4 GHz IF is such a small fraction of the 2.5 THz LO frequency, it is unlikely that the difference in noise temperature and in the shape of the curves is due to an RF effect. Rather, higher loss and sensitivity to structures with mixerblock dimensions make the 20.4 GHz channel more difficult to treat at IF. Network analyzer return loss measurements on this mixer indicate that at 20.4 GHz, the IF transformer is indeed best matched for intermediate DC bias current. Straightforward modifications in the transformer and the mixerblock housing are expected to improve the IF match for all three frequency bands.

Also interesting to note is the return loss measurements for 8.4 GHz predict a best IF match at a relatively low current (≈ 0.5 mA). The behavior in Figure 8 would then suggest that the RF match would improve if the diode impedance were lower (e.g., at higher bias). In addition, the poor performance of the smaller 0.1 x 1 μm anode devices (typically ≈ 50,000 K rather than 20,000 K) provides support for lower impedance diodes. We are in the process now of testing 0.4 x 1 μm anode devices and expect to have results in the very near future.

V. QUALIFICATION FOR SPACEFLIGHT

Although it is quite difficult to create a low noise terahertz receiver in the laboratory, a serious challenge exists in making it robust enough for practical use. Much effort has gone into the design of the receiver front end so that it will withstand the environmental extremes of vibration during launch. The nature of the device and its mounting fixtures make the other environmental effects less difficult to deal with: thermal, vacuum, and radiation effects are not a serious problem in the EOS-MLS spacecraft. It is yet another chore to ensure the 5 year lifetime of the mission.

The spaceflight qualification of the front end began with a balloon flight of a breadboard model front end. The front end performed without a problem, and some useful OH data was retrieved.

To further establish the reliability of the mixers, the mixerblocks were subjected to thermal testing. Rapid thermal cycling (4 cycles -50 C to +100 C, 20 min dwell times at each extreme) was performed on 6 devices, and found to have no noticeable effect on the DC device characteristics. As thermally-induced damage is potentially the most difficult problem to circumvent, the test results offer a good deal of reassurance that the JPL MOMED mixers will perform well in a flight environment. The predicted flight survival temperature range for the EOS-MLS THz receiver front end is from -20° C to +55° C.

The small size of the MOMED mixers makes them relatively insensitive to the low-frequency vibration experienced during launch. The rest of the front end is quite susceptible to damage. To test the robustness of the design, the assembled front end was subjected to the following random vibration, for 3 minutes each in x, y, and z axes (expected to mimic the launch environment):

20 - 50 Hz	+6 dB/octave
50 - 500 Hz	0.2 g^2/Hz
500 - 2000 Hz	–6 dB/octave
Overall	13.0 g (rms).

Figure 9 shows the assembled front end on the z-axis shake table. The front end survived vibrational testing quite well, with the only defect noted to be the cracking of an epoxy joint used to secure the horizontal mixerblock SMA connector. RF coupling, noise temperature, and DC I-V characteristics were otherwise identical before and after the test. We do not plan to use epoxy is such a manner for the flight receiver.

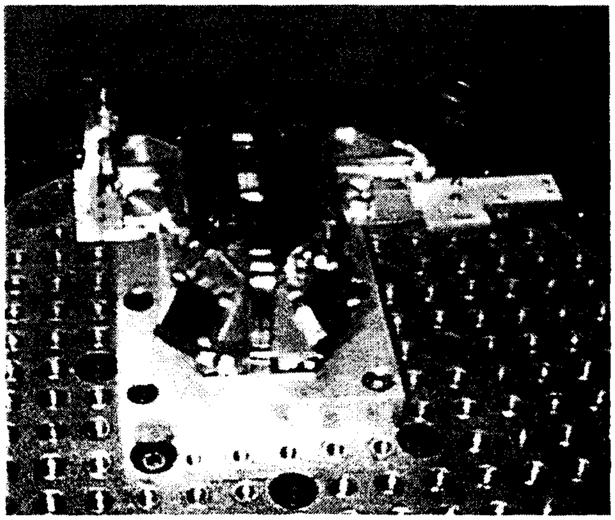

Fig. 9. Assembled receiver front end, mounted on the electrodynamic shake table. Note the "vertical" mixer on the left, and the "horizontal" mixer on the right. The diplexer adjuster wheel is atop the roof mirror on the left.

The burden of operation in a vacuum environment primarily places requirements on the types of epoxies allowed, and on the thermal difficulties due to lack of convection. Simulations have been performed to estimate temperatures around the receiver front end, and predict no problems. The diplexer is designed to be insensitive to temperature, and harmful thermal gradients are minimized.

The predicted total radiation dose over the 5 year mission life is 60 krad (Si). Proton irradiation of the device will not be an issue because it is surrounded by ≈ 5 mm of brass mixerblock. In addition, GaAs diodes are known to be relatively immune to total-dose effects resulting from the deposition of ionizing energy.[10]

To ensure mixer lifetimes in excess of the 5 year mission, accelerated lifetests with fit to an Arrhenius-lognormal degradation are planned to begin in early 1999. Parameters used to define a device failure are expected to include I_{sat}, R_s, η, as well as the low-frequency noise signature of the device. It is hoped that one can use the low frequency noise as a diagnostic as well as a measure of degradation.[11]

VI. SUMMARY

Excellent performance of fixed-tuned Schottky-diode receivers in a robust, standalone receiver configuration has been demonstrated. Such performance is required for monitoring of atmospheric chemistry, as well as several important remote-sensing and in-situ applications. With the concurrent development of low-power, compact THz laser local oscillators, this technology is realizable in a spaceborne platform.

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