Miniature Low-Power Submillimeter-Wave Spectrometer for Remote Sensing in the Solar System

Olga Boric-Lubecke, *Member, IEEE*, Richard F. Denning, Michael A. Janssen, and Margaret A. Frerking, *Member, IEEE*

***Abstract*—Mass and power for the next generation of NASA's heterodyne spectrometers must be greatly reduced to satisfy the constraints of future small-spacecraft missions. In this paper, we present a new receiver concept for remote sensing in the solar system, with greatly reduced mass, power, and size compared to instruments implemented in current missions. This spectrometer was originally proposed for operation in the vicinity of the 557-GHz emission from the H_2O ground–state transition. With the 557-GHz mixer and associated multiplier chain still under development, we prototyped a 220-GHz version of the instrument to verify the receiver concept, and experimentally demonstrated its functionality. The 220-GHz prototype Schottky-diode receiver requires less than 4.8 W, and has a mass of less than 1.1 kg—more than a factor of ten in mass and power reduction compared to current instruments. This significant savings, achieved through minimizing the number of receiver components, does not compromise the functionality necessary, e.g., for a surface-based Mars atmospheric sounding instrument. For the 557-GHz version, we anticipate that the total mass would be about the same as that of the millimeter-wave prototype, while required power would be reduced by about 1.5 W with the use of InP MMIC amplifiers.**

***Index Terms*—Gunn device oscillators, planetary atmospheres, remote sensing, submillimeter-wave frequency conversion, submillimeter-wave mixers, submillimeter-wave oscillators, submillimeter-wave radiometry, submillimeter-wave spectroscopy, temperature, temperature control.**

I. Introduction

THE transformation of water from ice to vapor is one of the most powerful forces for change on planets and small planetary bodies [1], [2]. One of the strongest transitions of the H_2O molecule, the ground–state transition, occurs in the submillimeter-wavelength region, near 557 GHz. A capable spectrometer operating in the vicinity of this spectral line can be used to address many of the needs of future solar-system exploration missions. For example, on Mars, such an instrument can characterize the nature and dynamics of the planetary boundary layer by determining pressure, temperature, and humidity over diurnal and seasonal cycles, with measurements of thermal spectral-line emissions from CO (near 577 GHz) and H_2O. The mass and power consumption typical of current heterodyne spectrometers must be greatly reduced to make them viable as candidates for future small-spacecraft missions of this type [3]. For instance, the microwave limb sounder currently flying on the upper atmospheric research satellite (with three heterodyne radiometers at about 63, 185, and 203 GHz), has a mass of 283 kg and requires 162 W of dc power [4]. The submillimeter-wave astronomical satellite (with two heterodyne receivers at about 490 and 555 GHz), currently waiting to be launched, has a total mass of 92.5 kg, and requires 60.7 W [5]. The microwave instrument for the Rosetta orbiter (with two heterodyne receivers at 236 and 562 GHz, and a full back-end spectrometer) is anticipated to have a mass of 16.2 kg, and require 61 W [6]. The mass and power numbers quoted above are for complete instruments, including the telescope. Such instruments are highly capable, but too large to be implemented in small-spacecraft missions such as those for the Mars surveyor program [7].

In this paper, we present a new instrument concept for remote sensing in the solar system, with greatly reduced mass, power, and size compared to the above mentioned instruments [8]. Initially, the significance of remote sensing in the solar system and the experimental approach are briefly outlined. Next, the proposed miniaturization procedure for a 557-GHz receiver is fully described. The novel local oscillator (LO) frequency-control concept, which eliminates both the active thermal control and phase-lock loop systems, is then addressed in more detail. With the 557-GHz mixer and associated multiplier chain still under development, we prototyped a 220-GHz version of the instrument. Experimental results for this compact 220-GHz prototype, which demonstrate the feasibility of the LO frequency-control approach, are described as well.

II. Remote Sensing in the Solar System

Millimeter- and submillimeter-wave spectral lines are valuable probes of the upper atmospheres of planets and of the cometary comas. Such lines can be completely resolved with a heterodyne receiver, yielding unique information on the velocity and abundance of the observed molecules. For example, close-up observations of the coma of a comet, such as from a spacecraft traveling with the comet, allow the

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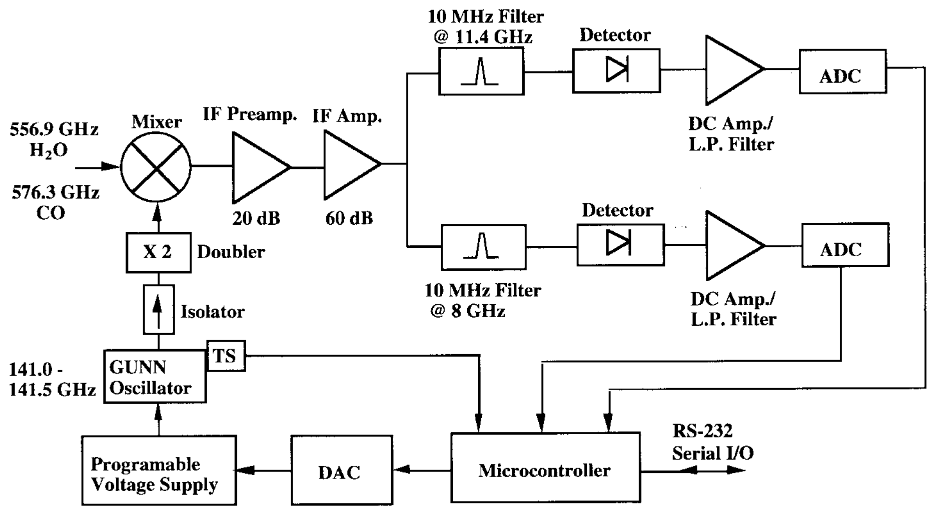


Fig. 1. 156-GHz-receiver block diagram. Miniaturization was achieved through the use of a tunable LO, single downconversion, and power-efficient LO frequency control.

coma's parent molecules to be monitored as they are generated from spots on the surface and accelerate outwards. Detailed observations of the dynamics and evolution of the coma from the neutral molecules which generate it are of paramount importance in understanding the nature and origin of cometary bodies. The microwave instrument for the Rosetta orbiter will include a heterodyne receiver in the vicinity of a 557-GHz water line to address the nature of the cometary nucleus, outgassing, and development of the coma.

In the remote sensing of planets from, e.g., an orbiter, we learn about the dynamics and chemistry of the atmosphere. The Martian atmosphere provides a special case for remote sensing since, in addition to downlooking observations from an orbiter, there is an opportunity for sounding the atmosphere from a surface-based platform provided by a lander [7]. The instrument we propose would be capable of performing unique investigations of the Martian planetary boundary layer from a Mars surveyor lander. In this case, a simple frequency-scanned radiometer looking upwards from the lander is used to obtain simultaneous temperature and humidity profiles. The basis for this determination is the optical thickness of both the 557-GHz ground–state water line and the 6–5 rotational transition of CO near 576 GHz. At any given frequency in the wings of either line, the radiometer observes a signal which is approximately proportional to the average temperature of the molecule along the radiometer line of sight (the instrument observes in the Rayleigh–Jeans region of the Planck thermal emission spectrum of the emitting gas). This temperature average is strictly determined as a weighting by an approximately exponential function of the distance along the line of sight, the characteristic distance of which is controlled by the frequency separation from the line center. The CO 576-GHz transition is optically thick at the line center, and CO is approximately uniformly mixed in the lower atmosphere. Hence, a spectrum measured through the line maps roughly into the atmospheric temperature profile or the physical temperature of the altitude. Inversion techniques can be used to determine this profile from the spectral data and have been thoroughly developed for the strictly analogous case of surface-based sounding of the Earth's atmosphere using the optically thick oxygen band around 60 GHz [9]. At the same time, the spectrum through the H_2O line can be combined with the temperature profile determination to infer the vertical distribution of water vapor or the humidity profile. The vertical distribution of temperature and water vapor in the atmosphere and their variations with time of day and season will be extremely useful for models of horizontal as well as vertical water transport. Such parameters are fundamental to understanding the nature of the Martian climate and the seasonal cycle of water that partly characterizes it.

III. Instrument Concept

The block diagram of the proposed submillimeter wave receiver is shown in Fig. 1. The heterodyning is performed by a subharmonically pumped waveguide mixer using a planar Schottky barrier diode. The 280-GHz LO signal is provided by a 140-GHz InP Gunn oscillator driving a multiplier. Two RF bands centered at 556.9 GHz (H_2O line) and 576.3 GHz (CO line) are received and downconverted to intermediate frequencies (IF's) of 8 and 11.4 GHz respectively, and subsequently detected through 10-MHz bandpass filters. The Gunn oscillator frequency is variable within the range of 140.975–141.475 GHz, which when multiplied by four gives a sufficient RF bandwidth (of about 2 GHz) for each spectral line. By tuning the LO frequency within this range, the 10-MHz IF filters can be positioned at any desired frequency within the H_2O and CO lines. With the use of a modern dielectric resonator filter, IF frequency resolution could be improved to about $1:10^4$ [10]. The same LO chain, mixer, and IF amplifier chain are used for both RF bands. However, two separate detection channels are required since currently available 140-GHz Gunn oscillators cannot be bias tuned over a wide enough frequency range to detect both the H_2O and CO lines at the same IF frequency. The microprocessor controls the Gunn bias voltage to step the signals through narrow 10-MHz filters, and also to compensate its frequency for temperature changes. With the 557-GHz mixer and associated multiplier chain still under development, we prototyped a 220-GHz version of the instrument with one detection channel to verify the receiver concept (see Fig. 5). In this case, a 110-GHz LO oscillator drives the subharmonic mixer directly.

The goal of this design is to minimize the number of receiver components, and thus reduce mass, required power, and size of the instrument. The tunable IF frequency narrow-band filters eliminate the need for filter banks or a complicated spectrometer backend, and the instrument functions as an extremely simple, but effective spectrometer. The price paid is a significant increase in the time required to obtain a spectrum of atmospheric emission, which is entirely acceptable for Mars sounding applications. Subharmonic pumping simplifies the LO chain by cutting its frequency in half and eliminating the need for an additional solid-state multiplier and RF diplexing elements. The downconverted signal from the mixer is detected at the first IF so that no further downconversion is necessary, which eliminates the need for additional low frequency LO sources and amplifiers. A power-efficient frequency-control technique is also implemented here, which uses bias-tuning of the Gunn oscillator to produce the desired LO frequency over a wide range of temperature, thus eliminating the need for both phase-locked loop and active thermal control systems.

IV. LO Frequency Control

The expected temperature variation on the surface of Mars is more than 50 °C. To ensure that the receiver would function properly in such an environment, some kind of thermal regulation would usually be required. Here, we propose using knowledge of the temperature-dependent behavior of the Gunn oscillator to adjust its frequency, instead of keeping its temperature within a small range with an active thermal control system and controlling its frequency with a phase-locked-loop system. Frequency-temperature curves have been used for Gunn oscillator frequency stabilization in the past, with an accuracy of 25 MHz reported for a Ka-band oscillator [11]. Another low-power technique, using a voltage compensation circuit to produce a constant frequency over a wide range of temperatures, has been recently reported for a Ka-band Gunn oscillator as well, with similar accuracy (15 MHz) [12]. In our receiver, the 140-GHz LO frequency accuracy requirement is about an order of magnitude higher than those quoted in [11] and [12] since it must produce an IF signal which is always within the 10-MHz bandwidth of the IF filter.

Frequency adjustment for the LO is accomplished through a control loop, which consists of a temperature sensor mounted on the Gunn oscillator, a microcontroller, and a programmable voltage supply (see Fig. 1). The microcontroller calculates the Gunn bias voltage required to produce the desired frequency based on the temperature-dependent bias tuning curves of the Gunn oscillator and the measured temperature. The feasibility of this scheme was tested with a 110-GHz temperature com-

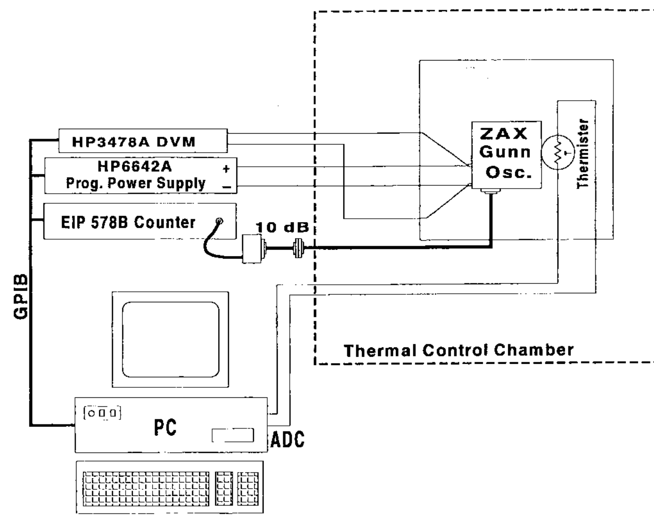


Fig. 2. Test setup for the 110-GHz Gunn oscillator. The Gunn oscillator was placed in a thermal control chamber and its temperature was continuously monitored to ensure that data was taken at thermal equilibrium for each temperature.

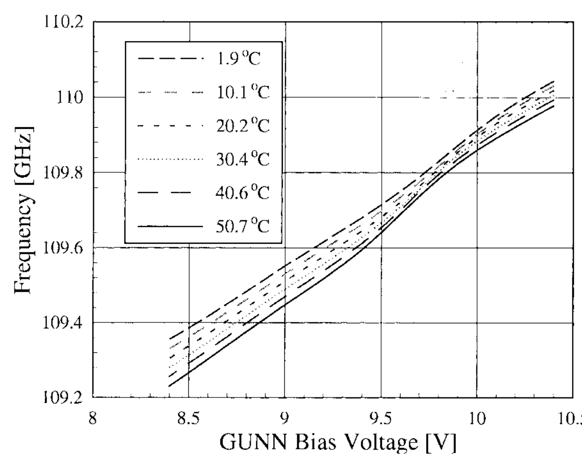
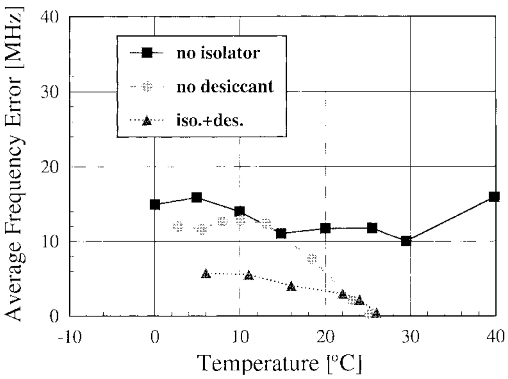
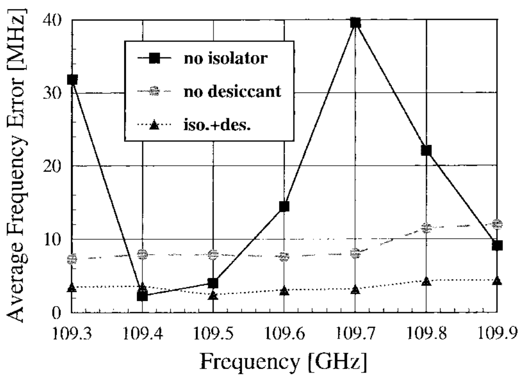


Fig. 3. Measured 110-GHz Gunn oscillator bias-tuning curves for temperatures from 0 °C to 50 °C. A tuning range of 500 MHz was available at all test temperatures.

pensated Gunn oscillator (ZAX ZFFm8/20/109.8/0.3), which was later used for the 220-GHz prototype receiver. Initially, this Gunn oscillator was tested in a temperature range of 0 °C–50 °C, with about a 2 °C step, and frequency versus voltage behavior was recorded at each temperature. The test setup for the Gunn oscillator is shown in Fig. 2. An EIP 578B frequency counter was used to measure the Gunn frequency as bias voltage was swept with an HP6642A programmable power supply. The Gunn bias voltage was checked with an HP 3478A volt meter, and frequency-voltage pairs were recorded with a PC. The Gunn oscillator was placed in a thermal control chamber, and its temperature was continuously monitored to ensure that data was taken only after equilibrium was reached at each temperature. The measured Gunn oscillator bias-tuning curves (see Fig. 3) show that a tuning range of about 500 MHz is available in the temperature range from 0 °C to 50 °C.



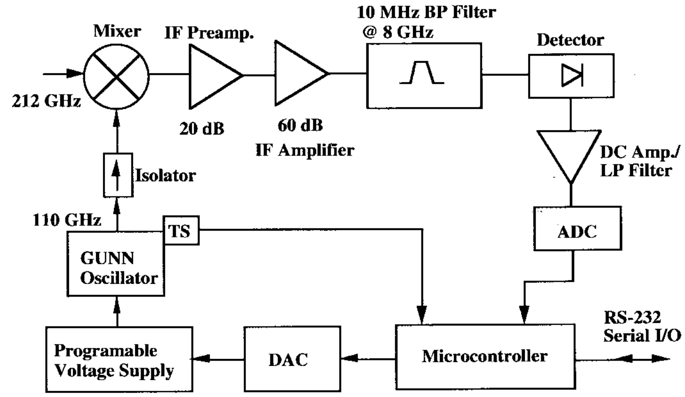
(a)



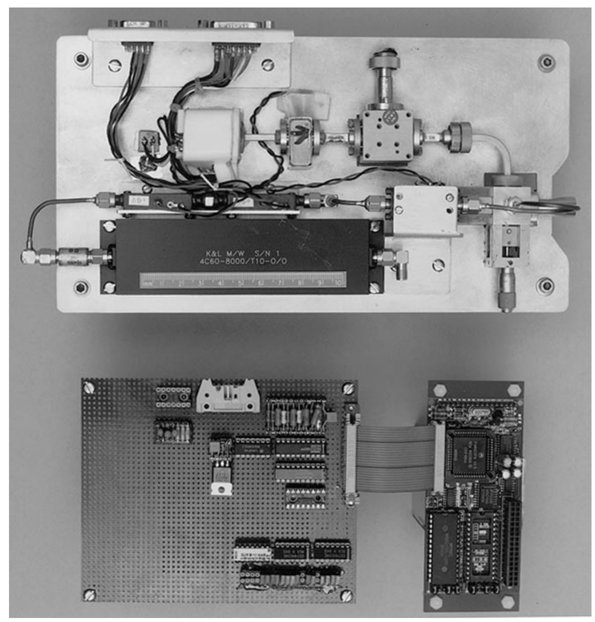
(b)

Fig. 4. (a) Average frequency error versus temperature. (b) Output frequency for three cases: without an isolator, with an isolator but without desiccant, and with both an isolator and desiccant. An accuracy of 5 MHz was achieved with both an isolator and desiccant.

Seventh-order polynomial curve fits of Gunn bias voltage versus frequency were produced at each of 22 measured Gunn temperatures. The coefficients for these curve fits are stored as floating point numbers in an 8 $\times$ 22 (one temperature and seven polynomial coefficients) matrix in memory on the microcontroller board. Since each value requires only 6 bytes, the memory demand for this table is quite reasonable (slightly over 1 Kb in the prototype). In an actual flight system, such a table could easily be produced using mask-programmed read-only memory (ROM) for long-term reliability. In order to calculate the Gunn bias voltage that will produce a desired frequency, the microcontroller first measures the temperature of the Gunn oscillator, then steps through the coefficient matrix comparing the temperature of each fit with that of the oscillator. A linear interpolation is performed, using two estimated bias voltages calculated with the coefficients for the fits above and below the actual Gunn temperature. The result is a bias setting for the current temperature which is then sent to the DAC producing the bias voltage. This operation requires about 100 ms to complete, which allows several adjustments each second when other microcontroller tasks are included. This appears to be adequate to adjust for the normal rate of change of the Gunn oscillator. For the prototype, this program was used on a PC for convenience. The operation of the



(a)



(b)

Fig. 5. (a) Block diagram of the 220-GHz radiometer. (b) Picture of the prototype. The 220-GHz prototype has a mass of 1.05 kg, a power requirement of 4.8 W, and dimensions of 30 cm $\times$ 15 cm $\times$ 10 cm.

program with a Motorola 68HC11 family microcontroller was later verified.

Using the experimental setup from Fig. 2, and a desktop PC to simulate the microcontroller, the error in predicted frequency was recorded. The average frequency error is shown in Fig. 4 versus (a) temperature and (b) output frequency for three cases: the Gunn oscillator connected directly to the frequency counter (without an isolator) with an isolator, but without desiccant, and with both an isolator and desiccant. Initially, the Gunn oscillator was connected directly to the frequency counter, but it was determined that an isolator was necessary since there was a large (5–40 MHz) frequency-dependent frequency error. After adding an isolator between the Gunn oscillator and the frequency counter, the frequency error decreased (10–16 MHz), and a very strong temperature dependence was observed, with the error getting smaller as the temperature was increased. This was interpreted as an indication that the presence of water might be a problem and,

TABLE I
TOTAL MASS AND POWER MEASURED FOR THE 220-GHz PROTOTYPE, AND PROJECTED FOR A PLANNED 560-GHz RECEIVER. FOR THE 557-GHz FLIGHT VERSION, WE ANTICIPATE THAT THE TOTAL MASS USING DIELECTRIC RESONATOR FILTERS WOULD BE ABOUT THE SAME AS THAT OF THE MILLIMETER-WAVE PROTOTYPE, WHILE REQUIRED POWER WOULD BE REDUCED BY ABOUT 1.5 W WITH THE USE OF MORE EFFICIENT InP MMIC AMPLIFIERS

	MEASURED 220 GHz		**PROJECTED 560 GHz**	
Component	**Mass [g]**	**Power [mW]**	**Mass [g]**	**Power [mW]**
feedhorn	50			
mixer	280		100	
IF amplifier	50	2500	10	1000
filter	220		70	
detector	20		40	
ADC	40	100	80	200
micro-procesor	60	100	60	100
DAC	50	100	50	100
GUNN	40	2000	40	2000
doubler			100	
isolator	40		40	
wiring			100	
structure	200		300	
TOTAL	**1050**	**4800**	**990**	**3400**

consequently, the Gunn oscillator and isolator were placed in a zip-locked bag filled with desiccant pouches, and left to dry overnight. The next set of measurements, in a "dry" environment (which will be the case for space applications), exhibited a much smaller error, less than 5 MHz at most temperatures, and negligible at room temperature and above. This accuracy is completely acceptable for the 220-GHz prototype, where a 110-GHz LO drives the subharmonic mixer and produces an IF signal within the range of a 10-MHz-wide filter. In the case of the 560-GHz receiver, an accuracy of 2.5 MHz will be required since the LO frequency will be doubled before feeding the subharmonic mixer. Such an accuracy is likely to be achieved below-room temperature as well, with further "drying" of the oscillator. However, to further insure the accuracy of the LO frequency, measurements symmetrically offset from the center of a spectral line will be compared as calibration points, and the Gunn frequency adjusted if necessary in actual use. This kind of frequency control results in extremely simple circuitry, and requires very little power, only that which is necessary for the operation of the microcontroller.

V. EXPERIMENTAL RESULTS

A block diagram of the 220-GHz radiometer is shown in Fig. 5(a), and a picture of the prototype appears in Fig. 5(b).

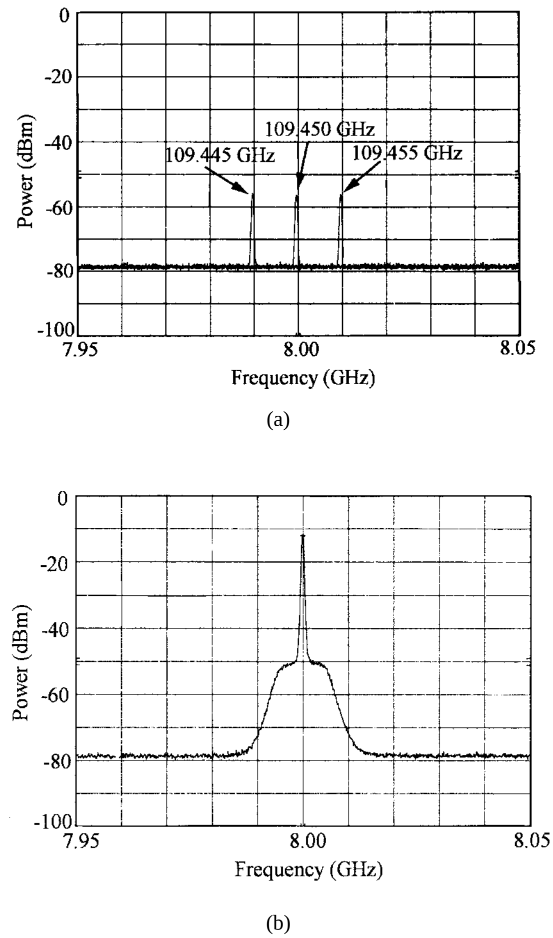


Fig. 6. (a) Spectrum of the downconverted 210.9-GHz signal at the output of the mixer for three LO settings demonstrating LO tunability and (b) at the output of the IF filter for fixed LO. The functionality of the end-to-end receiver was confirmed by varying the signal frequency, and adjusting the LO frequency accordingly, to always produce an IF signal at 8 GHz, as shown in (b).

The heterodyne receiver uses a subharmonic planar Schottky-diode mixer [13], a Gunn oscillator described in the previous section for the LO, and an IF at 8 GHz with a 10-MHz bandpass filter. Measured mass and power for this receiver are shown in Table I. The prototype receiver has a total mass of less than 1.1 kg (exclusive of telescope) and a dc power requirement of less than 4.8 W, which is more than a factor of ten reduction in mass and power compared to current instruments. Off-the-shelf GaAs amplifiers, with internal voltage regulators that use a significant amount of power, were used in this prototype, since monolithic-microwave integrated-circuit (MMIC) amplifiers were not readily available. The total power is about evenly divided between the IF amplifier chain and the Gunn oscillator. Though the 10-MHz filter takes considerable space [black box in Fig. 5(b)], its mass is relatively small (220 g) and it does not require any power. All components chosen for this receiver were designed to withstand large temperature variations according to the manufacturers specifications. Projected mass and power for a 560-GHz receiver, with dielectric resonator filters [14] and MMIC amplifiers are also shown in Table I. The submillimeter-wave multiplier and second detection channel (see Fig. 1) would introduce additional components, but total mass would not necessarily increase if dielectric resonator filters are used. The use of more efficient InP MMIC amplifiers is also expected to somewhat reduce the mass and volume of the receiver, and more importantly reduce the required power by about 1.5 W over the millimeter-wave prototype.

The prototype receiver was tested using a laboratory signal source and a spectrum analyzer as a detector. The signal source consisted of a frequency synthesizer (HP 83 623A), source module (HP 83 557A, X4 multiplier), and frequency tripler [15]. To demonstrate LO tunability, a fixed signal was observed at 210.9 GHz with three different LO settings (109.445, 109.450, and 109.455 GHz) and monitored at the output of the mixer. This is shown in Fig. 6(a), where we can see that the detected signal is identical at all three LO frequencies. Since the laboratory source produced a very narrow signal, less than 1 MHz wide [see Fig. 6(a)], it was not possible to observe different parts of the spectral line by sweeping the LO. The functionality of the end-to-end receiver was, therefore, demonstrated by varying the signal frequency, and adjusting the LO frequency accordingly, to always produce an IF signal at 8 GHz. The output of the IF filter for a signal at 210.9 GHz and an LO frequency of 109.450 GHz, is shown in Fig. 6(b).

VI. Conclusions

We have demonstrated the reduction in mass and power for a functional heterodyne receiver system by more than a factor of ten over existing systems, thus creating a powerful tool for future space missions. Such a compact instrument could be used, e.g., for remote sensing of the Martian atmosphere from a lander to provide atmospheric data fundamental to understanding the nature of the Martian climate. A 220-GHz prototype radiometer with a total mass of less than 1.1 kg, which uses less than 4.8 W of dc power, was designed, assembled, and tested. Miniaturization and power efficiency were achieved through the elimination of several system components, partly through the use of an unconventional LO frequency-control technique which enables the operation of the instrument for a wide range of temperature. Functionality of this receiver was demonstrated using a laboratory signal source. In the 557-GHz flight version, we anticipate that the total mass would be about the same as that of the millimeter-wave prototype, while required power would be reduced by about 1.5 W with the use of more efficient InP MMIC amplifiers.

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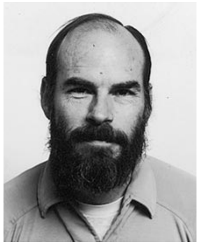

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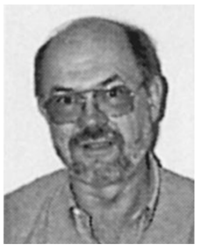

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