A 110 GHz Ozone Radiometer with a Cryogenic Planar Schottky Mixer

Olli P. Koistinen, Heikki T. Valmu, Antti Räisänen, *Senior Member, IEEE,* Vjacheslav F. Vdovin, Y. A. Dryagin, and Igor V. Lapkin

***Abstract*—A total power radiometer is presented for monitoring of the stratospheric ozone spectral line at 110 GHz. Special features such as a cooled planar Schottky mixer as the front end and efficient reduction of standing waves in the quasi-optics, are discussed in detail. The noise temperature of the receiver is 530 K (SSB), and the total bandwidth of the receiver is 1 GHz. A dual acousto-optical spectrometer is used for the signal detection.**

I. Introduction

Ozone has many strong spectral lines in the millimeter-wave region, of which the line at 110.836 GHz has been selected to be monitored with the radiometer at Helsinki University of Technology. This spectral line is strong, which makes it rather easy to detect. The receiver technology at *W*-band is also well established. On the other hand, the spectral line lies on the side wing of a very strong oxygen absorption line at 118 GHz that causes both attenuation and a strong tropospheric baseline to the measurement. The main component in tropospheric attenuation, however, is atmospheric water, which dominates at low altitudes. Water absorption increases with frequency, making the spectral lines at high frequencies impossible to be measured at low altitude measurement sites, such as Helsinki University of Technology.

The receiver is a total power radiometer using internal calibration sources. The drifts in the receiver, detected with Allan-variance measurements, restrict the measurement cycle to a maximum of 6–7 s.

The calibration is made for each channel separately, which means that the noise temperatures of the loads have to be accurately known as a function of frequency. Therefore the suppression of the standing waves is of utmost importance in order to get valid results as will be seen below. The first mixer determines the noise temperature of the receiver and the total integration time required. A cooled planar Schottky mixer is used in the receiver. The mixer is very reliable, showing no degradation of noise temperature after several cooling periods. With the present noise temperature of the receiver the integration times are of the order of 40 min at clear weather. Fig. 1 shows the block diagram of the receiver.

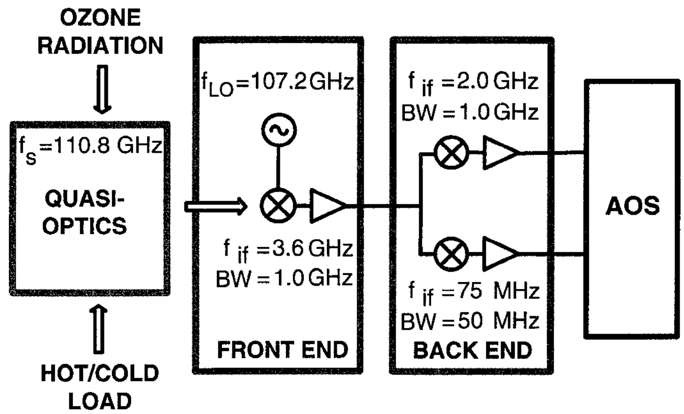

Fig. 1. Block diagram of the receiver.

II. Receiver

A. Quasi-optics

The quasi-optical unit does SSB filtering as well as directing the beam to calibration loads and to the sky. The mirrors are offset ellipsoids and a Mach–Zehnder interferometer is used as the SSB filter to filter out the unwanted lower sideband. A quarter-wave matched teflon lens focuses the beam to the feed horn. The measured losses along the path between the feed horn and cold calibration source are less than 0.1 dB. The elevation angle of the main mirror is adjustable and can be set by the operator to achieve the optimum measurement angle.

B. Front End

The front end of the receiver consists of a dual mode horn antenna, a ring filter for LO power injection, a planar Schottky mixer, and a LNA. All of these components are cooled to 20 K with a closed cycle helium cooler. The measured cross-polarization level of the feed horn is -23 dB, which is sufficient for the application. The local oscillator is a phase-locked Gunn oscillator emitting $+8$ dBm at 107.636 GHz. One of the advantages of choosing the 110 GHz spectral line is that sufficiently high LO power is available from a solid-state source without multipliers. The LNA is a three-stage HEMT-amplifier, which has 10 K noise temperature at 3.0–4.2 GHz and at 20 K physical temperature.

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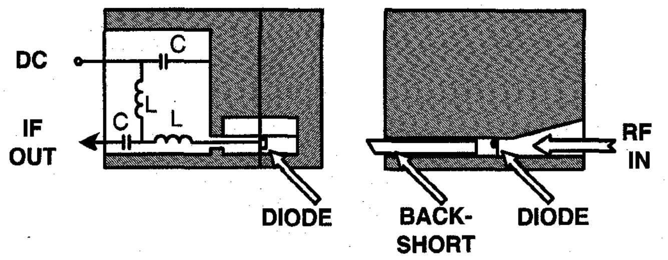

Fig. 2. Schottky mixer.

C. Schottky Mixer

The mixer block, shown in Fig. 2, is based on WR-10 waveguide and has total dimensions of 20 × 20 × 65 mm^3. The block is divided into two parts through the center of the wide waveguide wall. The input waveguide is tapered to 1/4 height to match the diode pair. The taper is 20 mm long providing a VSWR less than 1.2; its losses are estimated to be less than 0.1 dB. The diodes are mounted between the parts of the mixer block. The IF output of the diodes is matched to 50 Ω with a hybrid circuit by properly chosen reactive elements. The IF bandwidth of the mixer is 1 GHz, the center frequency being 3.6 GHz. The output VSWR of a pumped mixer is less than 1.5 over the IF band. A noncontacting backshort that consists of two pairs of high- and low-impedance sections isolated by thin (20 μm) mylar tape is used in this mixer. The single sliding backshort provides possibility of tuning the mixer over the frequency range of 85–115 GHz. A contacting backshort was also tested and provided the same total performance of the mixer.

The characteristics of the commercially available beam-lead planar diodes used in the mixer are given in Table I. The best diodes for cooling were selected through DC *I–V* measurements. When operated at 20 K the mixer diode physical temperature is estimated at an increased temperature of 32 ± 2 K due to LO heating. This estimation is based on the shift of the *I–V* characteristic due to the temperature change. The *I–V* curve was calibrated as a thermometer at liquid nitrogen temperature and at room temperature. Thermal gradient analysis of the mixer structure with a 2 mW internal heat source in the vacuum dewar conditions agrees well with the experimental estimation.

D. Back End

The first IF is split and mixed into two channels for the acousto-optical spectrometer, as shown in Fig. 1. The center frequencies of the channels are 2.0 GHz and 75 MHz.

The signal is detected by a dual acousto-optical spectrometer [1]. The broad-band unit measures 128 channels over the total 1 GHz bandwidth, while the narrow-band unit measures 1024 channels over a 50 MHz band around the center frequency. The broad-band unit is asymmetrical extending 400 MHz below and 600 MHz above the center frequency. Because of the calibration method, nonlinearity of the detectors decreases the measurement accuracy. A maximum of 1 percent nonlinearity has been measured due to the detectors. The error is corrected with experimentally determined correction terms in the measurement software.

TABLE I
CHARACTERISTICS OF THE PLANAR SCHOTTKY DIODES AT ROOM TEMPERATURE

f_c (THz)	R_S (Ω)	C_{tot} (fF)	C_j (fF)	η	N_{epi} (cm^{-3})
2.8	6	20	7	1.12	8×10^{16}

E. Noise Temperature

The noise temperature of the receiver was measured with *Y*-factor method using an absorber in ambient temperature and in liquid nitrogen. The measured DSB receiver noise temperature is 230 K including the window of the dewar and the thick focusing lens at room temperature. The SSB noise temperature of the total receiver system including all quasi-optics is 530 K. These two noise temperatures are related to each other through (1) [2]:

$$T_{RSSB} = \frac{L_s}{L_i} T_i + \left(1 + \frac{L_s}{L_i}\right) T_{RDSB} \tag{1}$$

assuming lossless quasi-optics (in front of the focusing lens). Here L_s and L_i are the conversion losses from the signal and image band, respectively, to the IF band, and T_i is the image sideband termination temperature. For a truly double sideband mixer $L_s = L_i$, and (1) reduces to

$$T_{RSSB} = T_i + 2T_{RDSB}. \tag{2}$$

For our receiver $T_i = 70$ K and $L_s = 7.2$ dB at 110 GHz.

The DSB mixer noise temperature can be calculated from T_{RDSB} using (3)

$$\begin{aligned} T_{RDSB} = {} & (L_{lens} - 1) T_{room} + L_{lens}(L_{feed} - 1) T_{feed} \\ & + L_{lens} L_{feed} T_{MDSB} + L_{lens} L_{feed} L_{DSB} T_{IF} \end{aligned} \tag{3}$$

where $L_{lens} = 0.35$ dB due to absorptive and reflective losses of the lens, $T_{room} = 297$ K, $L_{feed} = 0.5$ dB due to the dewar window, feed horn, and ring filter at an estimated average temperature of $T_{feed} \approx 30$ K, and $L_{DSB} = L_s/2 = 4.2$ dB. Equation (3) gives $T_{MDSB} = 140$ K for the cooled mixer. At room temperature the mixer noise temperature has been measured to be $T_{MDSB} = 485$ K, which is about 3.5 times the noise temperature of the cryogenic mixer.

The best reported Schottky mixer DSB noise temperatures at the frequency of 110 GHz are 35 and 155 K for a cryogenic mixer and a room temperature mixer, respectively, with a whisker contacted Schottky diode [3], and 350 K for a room temperature planar Schottky mixer [4]. The authors are not aware of any previous reported results with cryogenic planar Schottky mixers. The above noise temperatures reported in [3], [4] have been obtained with a 1.4 or 1.5 GHz IF while in our mixer the IF is centered at 3.6 GHz. A higher IF results in a higher noise temperature [3].

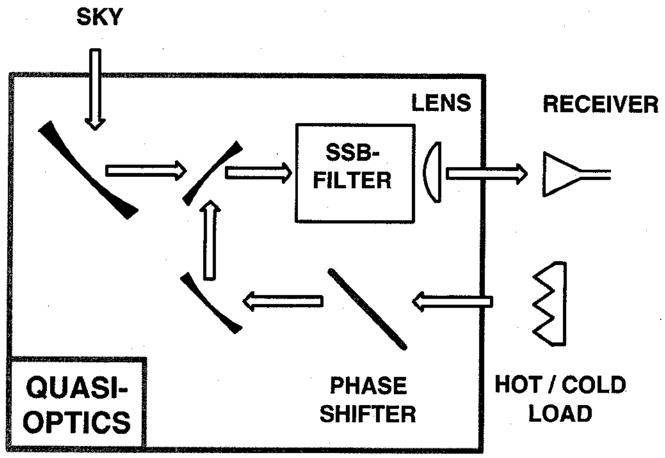

Fig. 3. Quasi-optical unit of the receiver.

III. Calibration

The quasi-optical unit of the receiver is presented in Fig. 3. The radiometer uses internal hot and cold loads for calibration. The hot load is a room temperature Eccosorb WG-4 foam absorber. To detect the standing waves caused by the hot load, a comparison measurement was made using the ozone radiometer with a randomly moving absorber as the hot calibration source and the radiometer's hot load as the measurement target. The random movement eliminates the standing wave caused by the calibration source at long integration times, and because the temperatures of the calibration source and the measurement target are equal, the measured standing wave is primarily due to the radiometer's hot load. The measured ± 0.6 K standing wave is too high and has to be reduced with methods described below.

The cold calibration source is designed to efficiently block the incoming infrared radiation. If the blocking is not good, the surface of the absorber is heated and the noise temperature is different from the temperature of the cold plate. The cold load designed for the radiometer has been measured to have broad-band noise temperature equal to its physical temperature within the measurement accuracy, which shows that infrared radiation is blocked excellently. A rooftop metal structure painted with Eccosorb 269E absorber coating is used to absorb the incoming wave and to cause multiple reflections between the absorber layers to the reflected fraction of the wave. Fig. 4 shows the structure of the cold load.

The absorbing coating is added as a thin layer on the metal, and due to that a single layer has a rather high reflection level. This causes the overall reflection level to become high enough to cause clearly observable standing wave in the ozone measurement. The reflection level of the cooled cold load has been measured with HP 8510C network analyzer to be -27 dB. A similar measurement as for the hot load was made for the cold load using the atmosphere as a cold reference load and assuming the hot load reflection to be known from the measurement described above. The amplitude of the resulting standing wave is ± 0.8 K, which is slightly higher than that for the hot load and agrees with the network analyzer measurements that give 2 dB higher reflection level for the cooled cold load than for the hot load.

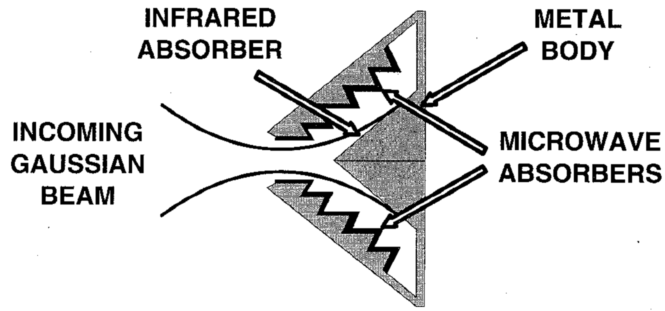

Fig. 4. Cold calibration load.

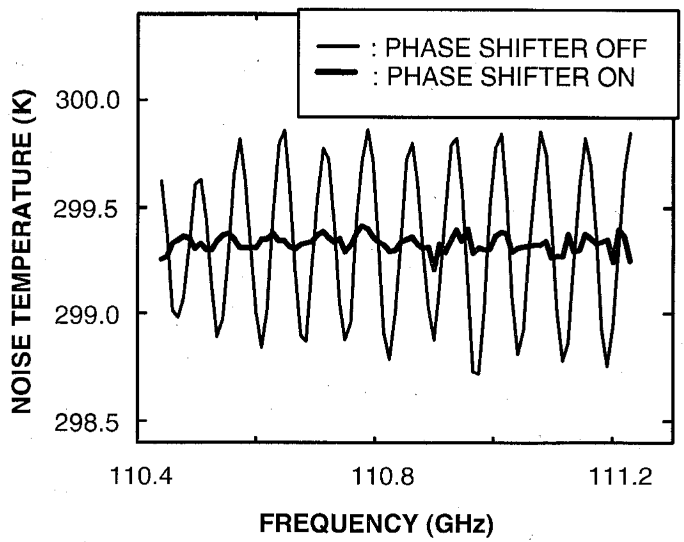

Fig. 5. Measured standing wave of the hot calibration load.

The standing waves seen in the results above are caused by reflections between the calibration loads and the teflon lens. The standing waves can be efficiently reduced by adding a differential phase shift of 180° to the quasi-optical path for half of the measurement time. Adding a rotating dielectric plate to the Gaussian beam causes the desired effect [5]. This is used in the HUT ozone radiometer. The material of the thin plate is teflon, which has low losses and rather low dielectric constant. The plate is in Brewster angle to avoid reflections and it is moved into the beam every second measurement cycle. Rapid rotating of the plate was also tested, but excess reflections caused by the edges of the plate were detected. The plate is made with an accurate milling machine using a special vacuum mount plate. The accuracy of the thickness of the plate is ± 10 μm. The measurement of the hot load was repeated with the phase shifter, which shows that the hot calibration load is accurate within ± 0.1 K compared to ± 0.6 K without the phase shifter. A small standing wave still observable is due to the slight inaccuracy of the phase shifter's angle and in its form. These combined introduce a reflection from the mounting plane of the quasi-optics. The measured standing wave of the hot calibration load with and without the phase shifter is presented in Fig. 5.

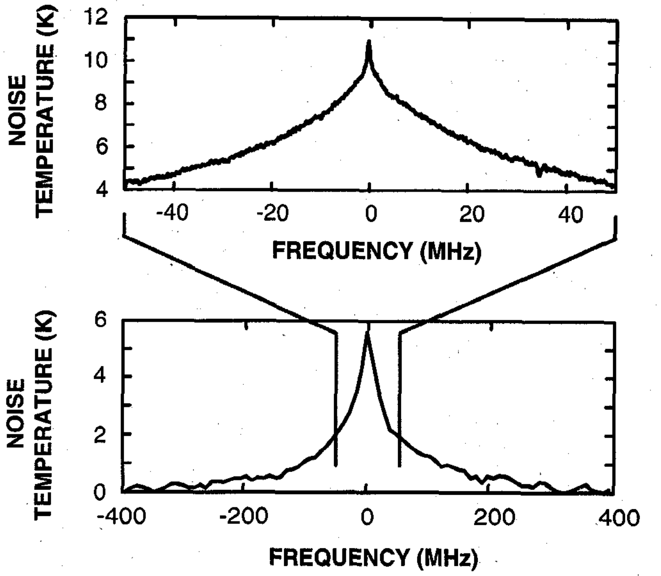

Fig. 6. Measured ozone spectral line. Averaging due to the broad channel width in the broad-band AOS makes the spectral line peak to appear lower.

The measurement error due to the standing waves of the calibration loads is 0.1 K for one channel. The error reduces to less than 0.05 K when the channels are averaged to obtain exponentially broadened channels that are used for the inversion routine that gives the vertical profile of ozone. The error caused by nonlinearity of the receiver is negligible. The resulting total error of 0.05 K allows measurements when the zenith tropospheric noise temperature is less than 170 K (usually heavily cloudy weather). The tropospheric attenuation determines the strength of the ozone spectral line at ground level and thus the maximum level of the systematic errors of the receiver.

IV. Results

Fig. 6 shows a typical daytime measurement in February 1993. An integration time of 40 min was needed at clear and cold weather. The tropospheric baseline has been removed from the result, and for clarity the frequency band is restricted to 800 MHz divided symmetrically from the center frequency. A very fine spectral resolution is achieved around the peak of the ozone line. The bandwidth of the narrow band AOS is approximately one-half of the cycle of the standing wave caused by the quasi-optics. The line wings of the measured ozone line are however very symmetrical, which implies that the level of the standing wave is very low compared to the line strength. A ± 0.1 K standing wave can be detected in the broad-band AOS measurement.

V. Conclusions

A radiometer has been built for continuous ground-based measurements of stratospheric ozone. Semi-operative ozone measurements with the receiver were started at Helsinki University of Technology in March 1993. With the achieved level of systematic errors, measurements can be made most days of the year at the low-altitude measurement site. Typical measurement times of 0.5 to 1.5 h depending on weather are required to get valid data for the inversion of the vertical profile of ozone. The systematic errors of the receiver are expected to be further reduced by improving the accuracy of the standing wave elimination process.

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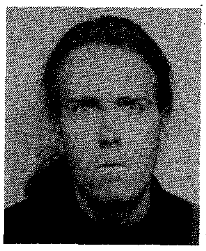

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Dr. Räisänen was the Secretary of the 12th European Microwave Conference (EuMC-82). He was the Counselor of the IEEE Student Branch in Helsinki from 1982 to 1989, and the Chairman of the IEEE MTT/AP Chapter in Finland from 1987 to 1992. In 1992 he served as the Conference Chairman for the 22nd European Microwave Conference (EuMC-92).

Vjacheslav F. Vdovin, photograph and biography not available at the time of publication.

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