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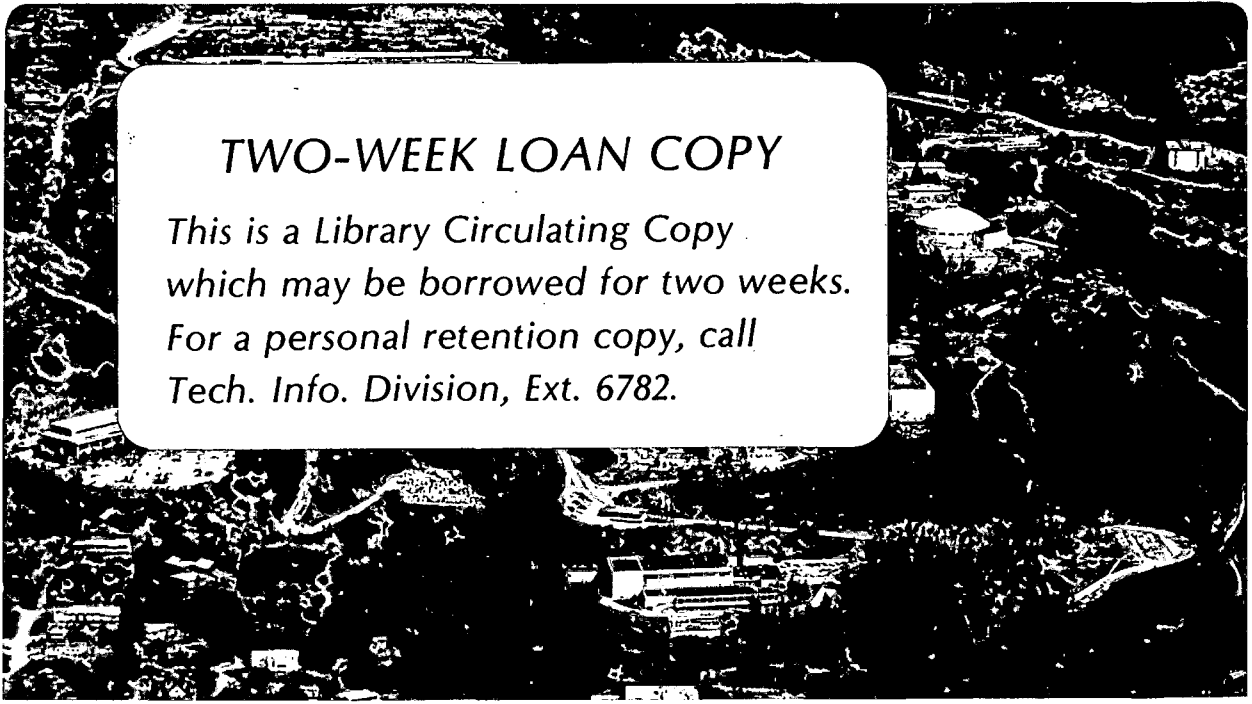
W.F. Kolbe and B. Leskovar

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SENSITIVITY AND RESPONSE TIME IMPROVEMENTS
IN MILLIMETER-WAVE SPECTROMETERS

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Sensitivity and Response Time Improvements
in Millimeter-Wave Spectrometers

W.F. Kolbe and B. Leskovar

Abstract

A new version of a microwave spectrometer for the detection of gaseous pollutants and other atmospheric constituents is described. The spectrometer, which operates in the vicinity of 70 GHz, employs a Fabry-Perot resonator as a sample cell and uses superheterodyne detection for high sensitivity. The spectrometer has been modified to incorporate a frequency doubler modulated at 30 MHz to permit operation with a single Gunn oscillator source. As a result, faster response time and somewhat greater sensitivity is obtained. The spectrometer is capable of detecting a minimum concentration of 1 ppm of SO₂ diluted in air with a 1 second time constant. For OCS diluted in air, the minimum detectable concentration is 800 ppb and with a 10 second time constant 300 ppb.

1. Introduction

In previous reports (1,2,3) we described a microwave spectrometer for the detection of small concentrations of gaseous pollutants. The spectrometer employed a semi-confocal Fabry-Perot cavity (4,5) as a sample cell, and used superheterodyne detection to obtain high sensitivity at low microwave power levels. Two separate microwave sources were used. A Gunn oscillator, operating in the vicinity of 35 GHz, was fed to a frequency doubler to provide sufficient power at 70 GHz to detect the gas resonance. A second source, a klystron operating at 70 GHz, was used as a local oscillator to permit superheterodyne detection. The klystron was phase-locked to the signal source using a 30 MHz IF frequency.

To evaluate the performance of the instrument, measurements were made of the various noise sources present, including the receiver noise and the source noise. The dominant contribution to the source noise was found to be FM noise resulting from phase jitter between the signal oscillator and the local oscillator. This phase jitter was a result of the inability of the

phase-lock loop to maintain perfect tracking between the two oscillators. The same tracking limitations also restricted the ability of the spectrometer to be frequency modulated with sufficient depth and at a sufficiently high modulation frequency to permit efficient detection of the gas absorption signals.

To improve the situation, it was decided to eliminate the klystron and phase-lock loop entirely and to replace it with a modulated frequency doubler. The output of a second unmodulated doubler would then serve as the local oscillator, and one of the sidebands of the modulated doubler would provide sufficient power for efficient detection of the gas resonance. Since both sources would then be derived from a single oscillator, phase jitter between them would be eliminated, resulting in improvements in the areas described above.

The next section describes the components and operation of the modified spectrometer. Because of its importance to the system, the operating characteristics of the modulated doubler are described in detail in section 4. In section 5 we examine the noise measurements that were made to evaluate the performance of the improved spectrometer, and in section 6 we demonstrate its ability to detect small concentrations of the pollutant species, SO_2 and OCS . Finally, in the last section, the conclusions drawn from these measurements are summarized.

2. Spectrometer System Description

The microwave spectrometer used in these measurements is a modification of the system previously described (3). A block diagram of the spectrometer is shown in Fig. 1. It consists of the following major components: solid-state source of microwave radiation, low-noise superhetrodyne receiver, and a tunable Fabry-Perot cavity mounted in a vacuum enclosure.

Microwave power for both the local oscillator and signal oscillator is obtained, in the present system, from a single varactor-tuned Gunn diode generator operating at one half of the spectrometer frequency. The output of the Gunn diode is divided into two equal parts by a 3dB directional coupler. One half of the power is fed to a Spacekom model DV-1 frequency doubler to provide approximately 4 mW of local oscillator power at 70 GHz.

The remaining power is fed to a Baytron model 1 Ka-80/V frequency doubler which is simultaneously modulated at 30 MHz via a bias port. The resulting signal, which is further described below, consists of the doubled carrier, plus sidebands 30 MHz above and below the carrier.

The carrier frequency and both sidebands are fed to a Fabry-Perot cavity. The cavity, which is described elsewhere (4,5) in greater detail, consists of two opposing mirrors, one flat and the other spherical, mounted in a vacuum chamber. Two coupling waveguides are attached to the flat mirror through coupling holes which lead to a transmission loss at resonance of 24 dB. The loaded Q of the cavity is 67000. Because of the high quality factor of the cavity, only one sideband passes through the cavity and reaches the receiver. Either sideband can be detected by appropriately tuning the cavity to the desired value.

After passing through the cavity the microwave signal is converted to an IF frequency of 30 MHz by the receiver. This unit, a TRG model V9125 balanced mixer/preamplifier, has a SSB noise figure of about 12 dB and a conversion gain of 23 dB. The receiver output is further amplified and fed to a pair of 30 MHz phase detectors driven by the same source used in the modulated frequency doubler. The reference phase of one of these phase detectors is shifted by 90° to permit detection of both the in-phase and quadrature components of the cavity response function.

The in-phase component is used to detect changes in transmitted power through the cavity resulting from the sample gas absorption. The quadrature output signal is proportional to the frequency difference between the microwave source and the resonant frequency of the cavity. After appropriate amplification and filtering, it is fed back to the varactor tuning input of the Gunn oscillator, thereby maintaining the microwave frequency exactly at the peak of the cavity response curve.

The actual microwave frequency is determined by a frequency synthesizer controlled by a PDP 11/34 computer. The output of the synthesizer, which operates in the vicinity of 450 MHz, is multiplied by a factor of 76 in a harmonic mixer and compared to the frequency of the signal oscillator. A discriminator operating at 30 MHz provides an output voltage proportional to the difference. After amplification, this signal is fed to a piezoelectric

transducer mounted on the end of the movable mirror of the Fabry-Perot cavity. The cavity is thereby tuned to the appropriate frequency. If the tuning range (6MHz) of the piezoelectric transducer is exceeded, a stepping motor, under control of the computer, is used to reposition the cavity mirror.

The signal-to-noise ratio of the gas absorption signal is further improved by means of a lock-in amplifier connected to the direct output phase detector. Frequency modulation of the microwave source is achieved by adding a modulation signal to the output of the frequency discriminator as shown in the system block diagram, Fig. 1. The same signal is used as a reference for the lock-in amplifier. For the measurements described below a modulation frequency of 205 Hz was used.

The output of the lock-in amplifier is digitized and then processed by the computer where it can be stored, displayed or further analyzed.

3. Modulated Frequency Doubler

As described above, the signal oscillator power was provided by a Baytron, Inc. frequency doubler modulated at 30 MHz. Because this component is a critical part of the system, its performance will be described in some detail.

The doubler consists of a GaAs mixer diode matched to waveguide ports for the two frequency bands. One end of the diode is terminated in an SMA connector permitting the introduction of the 30 MHz modulation signal. A d.c. return path for the mixer diode is provided by a 5K ohm resistor connected to ground. The 30 MHz signal was applied directly to the diode through a 560 pf coupling capacitor. Frequency multiplication and modulation capabilities result from non-linear characteristics of the GaAs mixer diode.

In order to examine the performance of the frequency doubler, the microwave spectrometer shown in Fig. 1 was modified. An independent Klystron source operating near 70 GHz in the vicinity of the doubler output frequency was substituted for the local oscillator. The Fabry-Perot cavity was replaced by an attenuator having the same attenuation but frequency independent transmission characteristics. By adjusting the Klystron frequency, the doubler output could be centered in the 100 MHz passband of the receiver output preamplifier.

The receiver output was displayed on an HP spectrum analyzer. Fig. 2a shows the spectrum produced by modulating the doubler at a frequency of 5 MHz. A frequency lower than the normal 30 MHz was chosen so that all of the sidebands could be displayed within the 100 MHz bandwidth available. To produce the spectrum shown, a microwave power of + 8 dBm at the input of the doubler was used. The 5 MHz modulation power was + 7 dBm. At this power level the first sideband power output is within 6 dB of the doubled carrier power.

Using the known receiver characteristics and measured input power, the conversion loss of the doubler was measured and found to be approximately 23 dB over a wide range of input powers. The first sideband power was also directly proportional to the modulation power over a wide range.

At input powers in excess of + 10 dBm the doubler saturates, and further increases in output power are not obtained. The output signal also becomes noisier above this value due to shot noise resulting from the d.c. current flow through the diode. At + 8 dBm input power, the d.c. current through the 5K bypass resistor is about 360 μ A.

In Fig. 2b the modulation frequency was increased to 30 MHz with all other parameters remaining the same. The doubled carrier is displayed at an offset of 50 MHz with the sidebands occurring at 20 and 80 MHz, respectively. The weaker lines are due to other modulation sidebands folded into the receiver passband.

Fig. 2c shows the effect of replacing the attenuator input to the receiver with the microwave cavity. The cavity is tuned to the upper sideband frequency at 80 MHz. As can be seen, the carrier and lower sidebands are attenuated by at least 30 dB by the cavity transmission characteristics. It is this rejection of the unwanted sidebands by the cavity which makes the single oscillator system workable in its present form. The sideband attenuation is limited to 30 dB due to a small, non-resonant leakage of microwave power directly between the cavity coupling holes.

4. System Noise Characterization

As described previously (7,8), the sensitivity of the spectrometer is determined by noise contributions from the signal source, the sample cavity and the receiver. Under normal circumstances the thermal noise from the cavity can be neglected.

At sufficiently low microwave source powers, the noise from the receiver will dominate the overall system noise. If this is the case, then the performance of the spectrometer can be improved by increasing the source power, provided that nonlinear processes such as saturation of the gas absorption signal do not occur. Eventually, a point will be reached in which the source noise contribution becomes dominant. Further increases in signal power will not lead to any improvement since the signal and noise will increase proportionally.

Because of the potential importance of the source noise in limiting system performance, it is useful to examine this contribution in more detail. As discussed previously by Strandberg (7) and by Leskovar et al. (8), the source noise is made up of two components. One is AM noise which passes directly through the cavity and is detected by the receiver; the other is FM noise which is converted to AM noise by the slope of the cavity response curve before being detected by the receiver.

In the previous spectrometer, described in Ref. 3, the signal oscillator and local oscillator consisted of two separate sources which were phase-locked together. With this system it was established that the dominant source noise contribution came from FM noise. With the signal oscillator locked to the cavity this FM noise was reduced significantly. However, the maximum reduction which could be achieved was limited by the residual phase jitter between the phase-locked local and signal oscillators.

In the present system, phase jitter between the local and signal oscillators is virtually non-existent because the two sources are derived from a single Gunn oscillator. Thus, it is possible to achieve a greater reduction in FM noise than before.

The conversion to AM noise of a microwave source contaminated by FM noise and passing through a transmission cavity has been given by Strandberg (7). We can adapt his results to the present situation in which the signal oscillator and local oscillator are derived from a single source. We find (3) for the ratio of transformed FM noise power to carrier power at the quadrature output of the receiver,

$$\frac{P_n(f)}{P_s} = \frac{16BQ_L^2 f^2}{v_o^2} L(f) \quad (1)$$

where B is the bandwidth in which the noise is measured, Q_L is the loaded Q of the cavity, and ν_0 is the microwave frequency. $L(f)$ is the SSB FM noise power density in a 1 Hz bandwidth centered at an offset frequency, f . Equation 1 gives the noise expected at the quadrature output when the signal oscillator is free running but is tuned to a frequency close to the resonant frequency of the cavity. When the signal oscillator is locked to the cavity, this noise is further reduced by the loop gain of the cavity stabilization system.

In order to obtain quantitative information, the noise-to-carrier power ratio at the quadrature output was measured as a function of the offset frequency from the carrier. As described in Ref. 3, the measurements were made using an HP model 302A wave analyzer for frequencies less than 50 kHz and an HP model 310 wave analyzer for higher frequencies. The carrier power was established by offsetting the modulation frequency by 1 kHz and by measuring the power at that frequency.

The results, after normalization to a 1 Hz bandwidth, are shown in Fig. 3. Curve (a) shows the noise spectrum of the free running source oscillator after passing through the cavity. The increase in noise power for frequencies close to the carrier reflects the increasing noise density, $L(f)$, of the Gunn oscillator. In fact, from eq. 1 and the known values of cavity Q (67000) and microwave frequency (70 GHz) the noise density can be computed. We find $L(100 \text{ Hz}) = -10 \text{ dBc/Hz}$, $L(1000 \text{ Hz}) = -40 \text{ dBc/Hz}$, $L(10\text{kHz}) = -69 \text{ dBc/Hz}$ and $L(100 \text{ kHz}) = -96 \text{ dBc/Hz}$ in agreement with similar values determined in Ref. 3.

Curve (b) shows the reduction in noise which occurs when the cavity stabilization loop is closed. At low frequencies, the loop gain is large and the noise is reduced essentially to a value equal to the receiver noise shown in curve (d). At higher frequencies, the loop gain decreases and the noise rises to a value comparable to the free running case. At low frequencies the noise observed when the source oscillator is locked to the cavity is actually lower than the receiver noise measured with the source turned off. This is not completely understood, although it might be caused by small amounts of signal oscillator power leaking into the local oscillator port of the receiver.

The dashed line plotted in curve (c) shows, for comparison, the noise spectrum obtained with the previous spectrometer reported in Ref. 3 in which separate phase-locked signal and local oscillators were used. As can be seen, the present configuration results in a noise spectrum which is more than 30 dB lower for frequencies below 5 KHz, a significant improvement, and a direct result of the elimination of signal oscillator-local oscillator phase jitter. The above measurements were performed using a signal oscillator power of -9 dBm applied to the input of the cavity.

Fig. 4 shows a measurement of the noise-to-carrier power ratio spectrum at the direct output of the spectrometer with the microwave source stabilized on the cavity resonance. Measurements of the total output noise and the receiver noise contribution are shown for two values of source power, -15 dBm and -9 dBm, at the input port of the cavity. At the lower source power level (-15 dBm), for frequencies above 1 KHz, the total noise is equal to the receiver noise. Presumably, at this power level, the receiver noise is dominant. This is confirmed by the fact that at the higher power level of -9 dBm the total noise is reduced. The total noise is now about 1 db above the receiver noise, indicating that the source noise is becoming a dominant contributor. Because the FM noise is so low (Fig. 3) this noise must be due to AM fluctuations.

Below 1 kHz the source noise increases somewhat above the receiver noise at both values of input power. The origin of this noise is not well understood. As in the case of the higher frequency spectral components, it is apparently AM in nature. The published specifications (9) for the Hughes model 4162 Gunn oscillator used show that the AM noise of this device increases at low frequency offsets from the carrier. However, this effect was not observed in noise measurements using the same oscillator in the previous spectrometer.

A more likely explanation is that the noise is generated in the doubler itself. At the microwave power level used to drive the doubler, shot-noise and avalanche processes may be occurring. The former process is not known to produce a 1/f noise contribution, but the latter may (10). In any event, the degradation at the modulation frequency of 205 Hz used in the measurements described below is not more than 3 dB.

5. Measurements of Dilute Gas Mixtures

In order to illustrate the performance of the spectrometer, measurements were made of the absorption lines of two gases, SO_2 (sulfur dioxide) and OCS (carbonyl sulfide) diluted in air. Cylinders of these two gases diluted to a concentration of about 50 ppm (actually, 49 ppm of SO_2 and 59 ppm of OCS) were purchased. These mixtures were further diluted with air in a gas handling system employing calibrated flowmeters.

In the SO_2 measurements, the $6(1,5) - 6(0,6)$ transition at 68972.1 MHz was observed and for OCS, the $J = 6 - 5$ transition at 72976.8 MHz was detected. All measurements were made under the same conditions of pressure, microwave power and modulation depth. These were: 0.082 Torr pressure, -15 dBm microwave power and 300 kHz rms modulation depth at a frequency of 205 Hz. These values were selected to produce an optimum signal-to-noise ratio.

The results for SO_2 are shown in Fig. 5 and the results for OCS are given in Fig. 6. Because of the modulation and lock-in detection, the observed signal is approximately proportional to the derivative of the Lorentzian absorption line.

For SO_2 , concentrations of 49 ppm, 4.7 ppm and 2.5 ppm were used. At the two higher concentrations a time constant of 1.0 sec was used in the lock-in detector. The minimum concentration of SO_2 detectable under these conditions can be estimated from the noise baseline spectrum also shown in Fig. 5b to be about 1.0 ppm. This value is about 20% better than that reported earlier (3) using the previous spectrometer.

In order to demonstrate the improvement in sensitivity possible with somewhat longer time constants, a lower concentration of 2.5 ppm was measured by averaging 10 scans each with a time constant of 1.0 sec. The effective time constant is thus 10 sec. From the signal amplitude and noise shown in Fig. 5c, the minimum detectable concentration was found to be about 450 ppb.

For OCS, concentrations of 59, 5.6 and 3.0 ppm were measured. As in the case of SO_2 above, a time constant of 1.0 sec was used for the two higher concentrations and an effective time constant of 10 sec was used for the lowest concentration. From the signal and noise data in Fig. 6 we find the minimum detectable concentration for OCS to be 800 ppb for a 1 sec time constant and 300 ppb for a 10 sec time constant. The minimum detectable concentration for OCS is somewhat lower than that for SO_2 because the OCS absorption coefficient is larger.

6. Conclusions

A modified version of a microwave spectrometer designed to measure the concentrations of diluted samples of pollutants and other gaseous species has been described. With this modification, a significant reduction in the complexity of the overall system has been achieved by replacing a klystron, high voltage power supply and phase-lock loop by a simple modulated frequency doubler. The sensitivity of the resulting spectrometer was fractionally improved.

The noise performance of the modified system was measured. It was found that the FM source noise contribution was significantly reduced by eliminating the local oscillator phase-lock loop. The noise at the direct output of the spectrometer was measured and for frequencies greater than 1000 Hz found to be no worse than that obtained with the previous instrument. Below 1000 Hz the noise was slightly higher. At 205 Hz, the modulation frequency, the noise was about 3 dB higher. However, this did not degrade the observed signal-to-noise ratio for the gas samples.

The source noise observed is probably AM noise generated by the modulated doubler. This device was an off-the-shelf unit not designed for this purpose. With a properly designed doubler and optimization of its operating conditions, it should be possible to obtain a significantly lower conversion loss and a correspondingly lower noise. Such a modification is presently under consideration.

Finally, it should be noted that the elimination of the phase-locked local oscillator has resulted in better frequency tracking capabilities for the spectrometer. As a result, it has been possible to increase the modulation frequency and modulation depth significantly without deteriorating the system noise performance.

7. Acknowledgments

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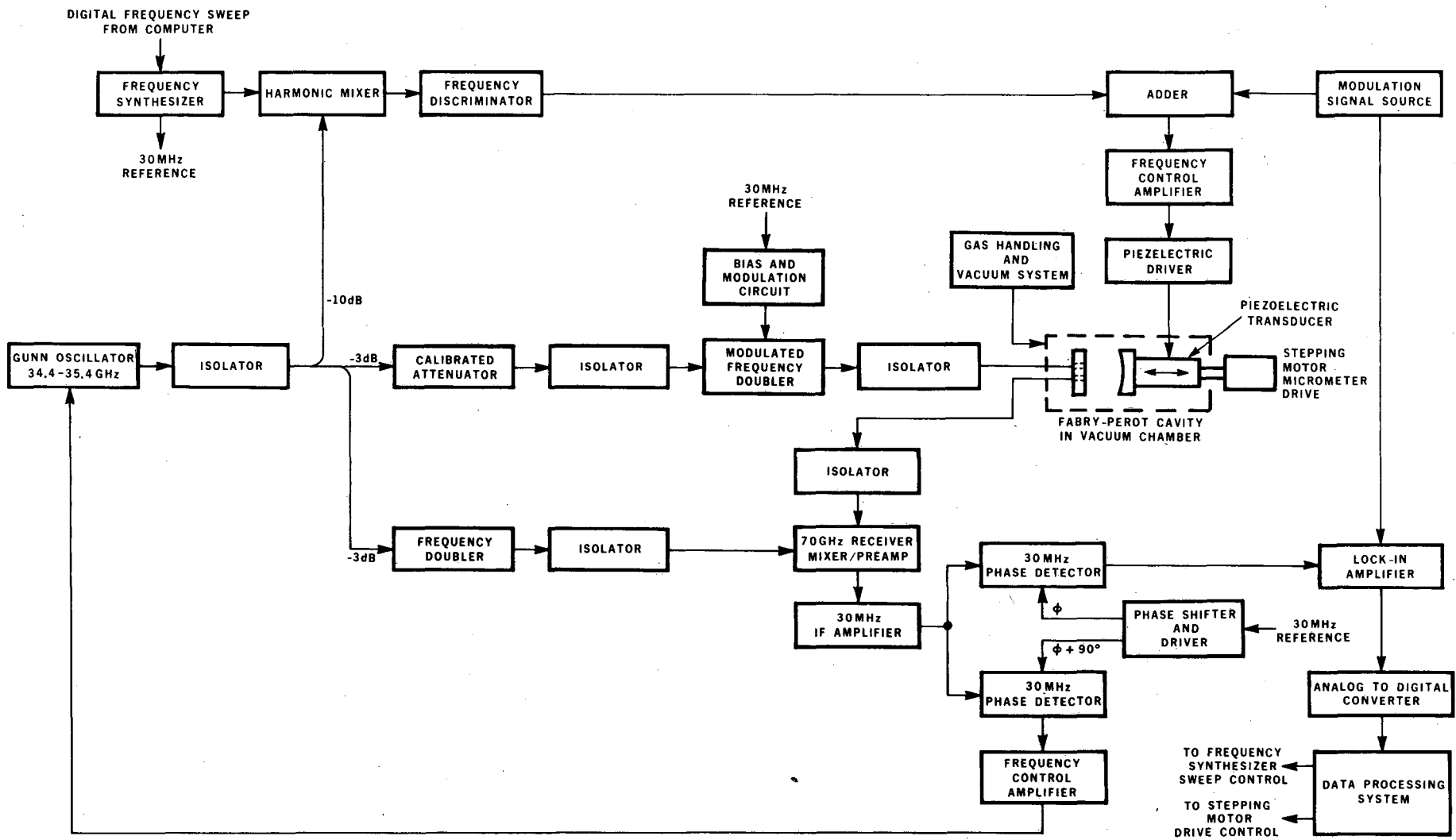
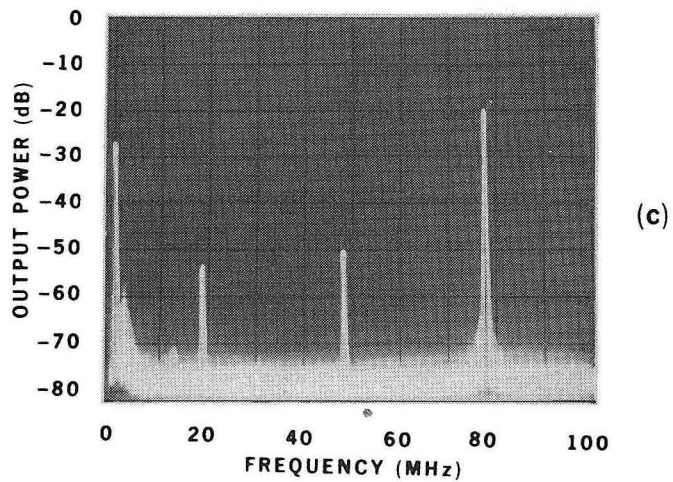
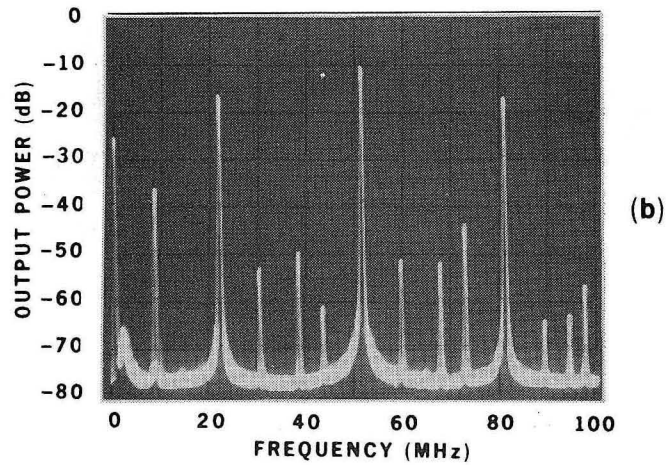
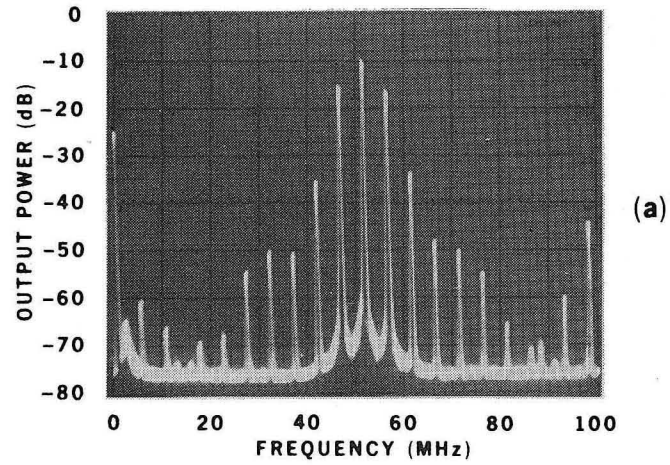
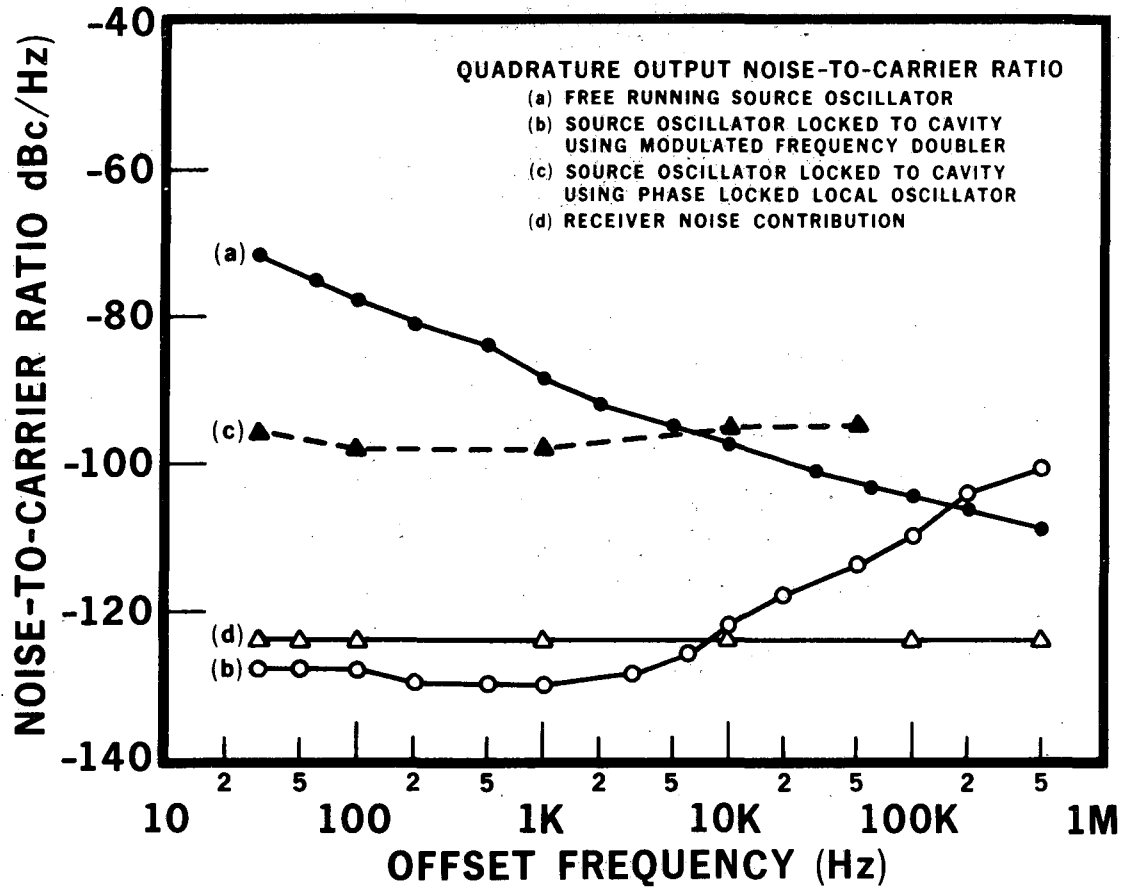


Fig. 1 Block diagram of microwave spectrometer.



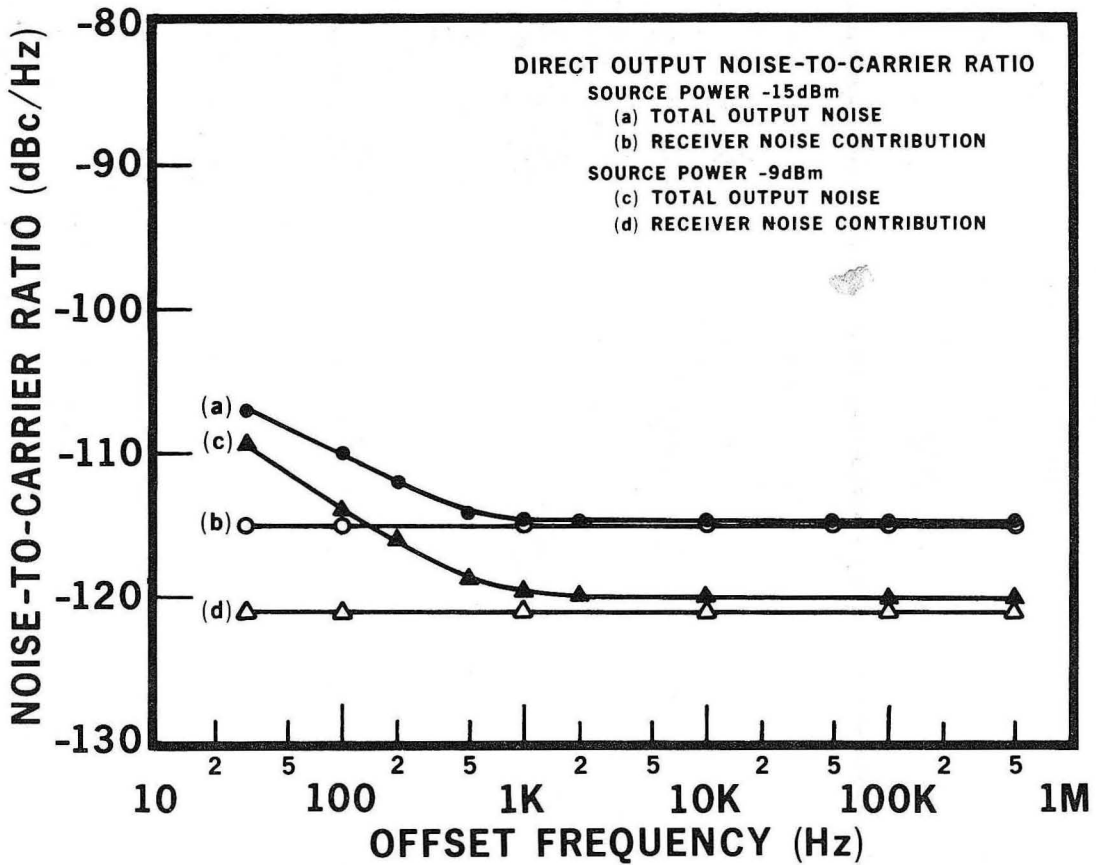
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Fig. 2 Frequency spectrum of modulated doubler. (a) Doubler output spectrum with modulation at 5 MHz., microwave input power +8 dBm and modulation input power +7 dBm. (b) Same as (a) with modulation frequency 30 MHz. (c) Same as (b) showing cavity rejection of unwanted sidebands.



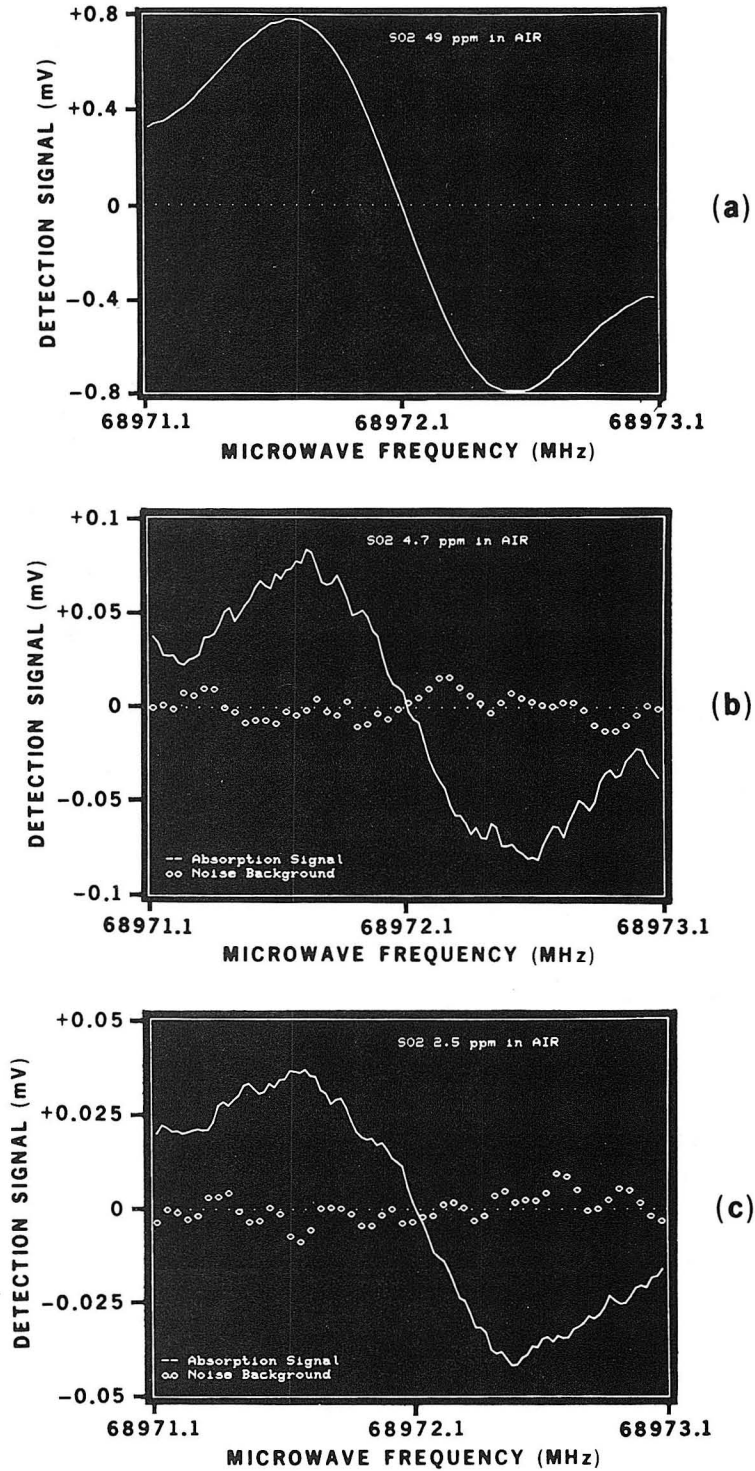
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Fig. 3 Noise-to-carrier power ratio measured at the quadrature output of the spectrometer. (a) Signal oscillator free running, (b) signal oscillator locked to cavity, (c) signal oscillator locked to cavity using two phase-locked microwave sources (Ref. 3), (d) residual noise contribution of receiver. Signal source power was -9 dBm.



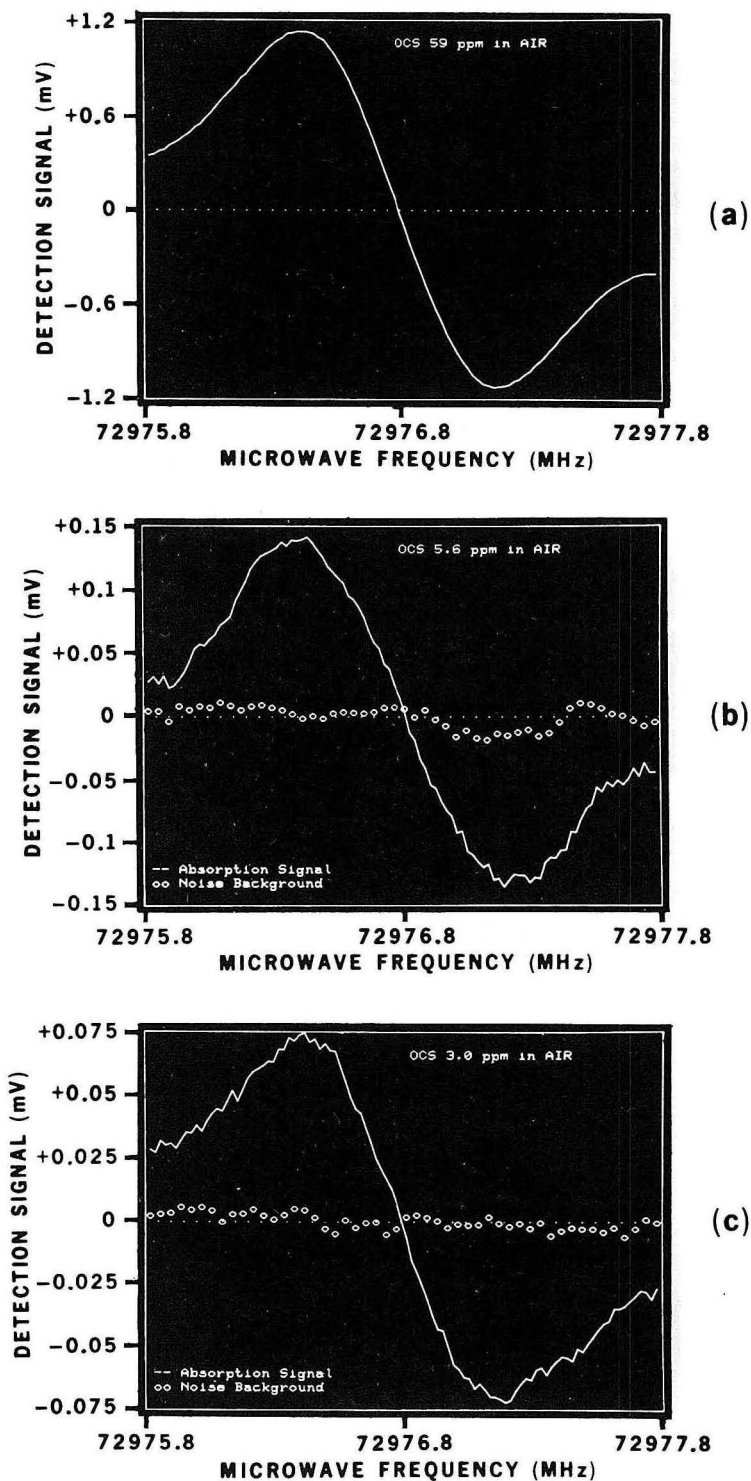
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Fig. 4 Noise-to-carrier power ratio measured at the direct output of the spectrometer showing total output noise ratio and receiver noise contribution for microwave source power levels of -15 dBm and -9 dBm.



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Fig. 5 Derivative absorption signal for SO₂ gas diluted in air. Pressure is 0.082 Torr, modulation 0.33 MHz rms at 205 Hz. Concentration: (a) 49 ppm, (b) 4.7 ppm and (c) 2.5 ppm. In (a) and (b) the time constant was 1.0 sec; in (c) it was increased to 10 sec. Also shown in (b) and (c) is the noise baseline.



XBB 8012-14409

Fig. 6 Derivative absorption signal for OCS gas diluted in air under same conditions as Fig. 5. Concentration: (a) 59 ppm, (b) 6.5 ppm and (c) 3.0 ppm.

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