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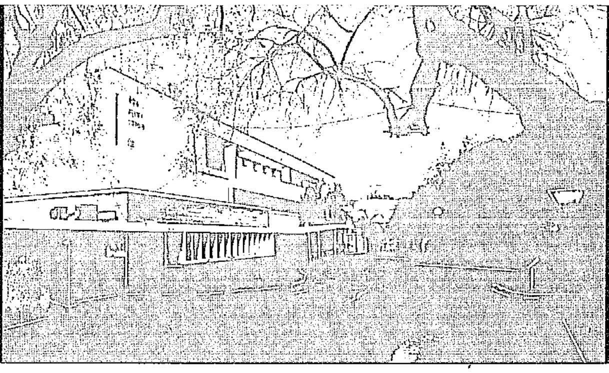
Technical Note



Backend Electronics and Quasi-Optics for Submillimeter Heterodyne Spectroscopy of NO_2

by

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Abstract: *The Submillimeter heterodyne spectroscopy can be carried out in laboratory environment using metal-semiconductor Schottky diode acting as a mixer, which combines two input signals and gives signal of difference frequency as its output. This mixer output is further processed by back end electronics in the receiver before being analyzed. The purpose of this note is to show the characterization of the backend electronics and hence making ready for heterodyne spectroscopy of nitrogen dioxide as a sample gas. Some quasi-optics, whose design and development have also been reported in the note, are used in experimental set up to modify the Submillimeter beam in a desired way. The testing carried out is necessary to calculate the actual, overall performance of the receiver.*

Experimental set-up for SMM spectrosocpy of NO_2

High-resolution heterodyne spectroscopy in Submillimeter (SMM) domain is valuable for understanding molecular vibrational and rotational transitions of atmospherically important gases. Spectral information of such transition can be obtained by down converting the SMM source signal in a Schottky mixer and analyzing its output. The heterodyne technique provides high spectral resolution and possibility of amplification of mixer output. However, due to limited spectrum bandwidth, it is not well suited for detection of broadband continuum radiation. The block diagram of experimental set up is shown in Figure 1 below, for Submillimeter rotational spectroscopy of nitrogen dioxide (NO_2) gas.

In general, three SMM mixers can be used for mixing, i.e., Superconductor-Insulator-Superconductor (SIS) tunnel junction, Hot Electron Bolometer (HEB) and Corner Cube Schottky diode. The Schottky diode is basically a metal-semiconductor diode made from Gallium Arsenide (GaAs) semiconductor and a whisker antenna (metal), which makes contact with the chip. The diode is a majority charge carrier device and exhibits no charge storage. The Schottky diode can be used at room temperature (though it can be cooled to reduce its noise) and therefore it is preferred as a mixer for laboratory spectroscopy of molecules exhibiting comparatively stronger lines. The nitrogen dioxide (NO_2) is filled in a 50 cm long cylindrical gas cell having 5 cm diameter and it is excited by a black body source as shown in Figure 1. The output signal from the cell is combined with output signal of Optically Pumped Molecular Laser (OPML) in a quasi-optical diplexer. The diplexer is basically a Martin-Puplett interferometer producing a composite signal. This composite signal is focused on whisker antenna of Schottky mixer by means of lens. The details of Schottky mixer is given by Pabari [2007]. The Intermediate Frequency (IF) signal available from the mixer is expected to be in the range of 4 to 8 GHz, in general. For the current experiment, this signal is at a frequency of 5.527 GHz and it is passed through a microwave isolator and Low Noise Amplifier (LNA) in the chain before being analyzed into the spectrum analyser.

The purpose of the isolator is to isolate its input and output ports, thus eliminating any possibility of damage to the Schottky mixer by reflected signal from LNA (due to any mismatch) while LNA is used to amplify the IF to a desired level when it is very low in strength. It can reduce overall noise of the system due to high gain (> 50 dB) and very low noise figure (1.6 dB).

It is necessary to characterize the back end electronics sub-systems before using in the experiment. Microwave devices are characterized by Scattering (S) parameters and hence, some basic idea of S-parameters is given in initial part of the note. Latter part of the note discusses about characterization of the devices. Related information of spectrum analyser and data transfer facility is also described for the sake of completeness. Details of few quasi-optics developed for the experiment are given at the end.

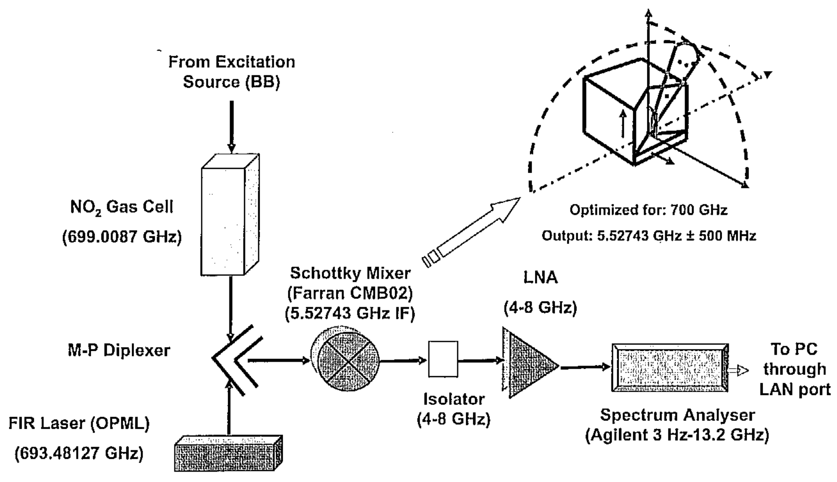

Fig. 1: Experimental set up for molecular rotational spectroscopy of NO_2

S-parameters

S-parameters by Sucher et al [1963], Anonymous [2000] and Anonymous a, [2002], also called Scattering parameters belong to general group of two port network parameters and are similar to Z parameters. They describe performance of a two port network completely. In contrast to Z-parameters, they relate to the traveling waves that are scattered or reflected when a network is inserted into a transmission line of certain characteristic impedance Zo. These parameters are important in microwave design because they are easier to measure and to work with at high frequencies than other kinds of two port network parameters. S-parameters represent linear behavior of a two port network. One such two port network is shown in Figure 2 below along with its S-parameters, transmitted voltages signals (denoted as 'a') and reflected voltage signals (denoted as 'b').

Due to some mismatch at the input and output ports, there can be some reflected signal from the ports and some part of the signal is transmitted; when any two port network is fed by a signal source. In general, a particular S-parameter is defined as ratio of the reflected wave to the transmitted wave at a particular port. There are four S-parameters, i.e., S_{11}, S_{21}, S_{12} and S_{22}, for the two port network shown in Figure 2. The 'b' signals are related to 'a' signals through these S-parameters as following:

$$b_1 = S_{11}a_1 + S_{12}a_2 \qquad (1)$$

$$b_2 = S_{21}a_1 + S_{22}a_2 \qquad (2)$$

From above two equations, one can define all S-parameters of the network as

$$S_{11} = b_1/a_1 = V_{\text{reflected at port 1}}/V_{\text{transmitted at port 1}} \text{ when } a_2 = 0 \qquad (3)$$

$$S_{21} = b_2/a_1 = V_{\text{received at port 2}}/V_{\text{transmitted at port 1}} \text{ when } a_2 = 0 \qquad (4)$$

$$S_{12} = b_1/a_2 = V_{\text{received at port 1}}/V_{\text{transmitted at port 2}} \text{ when } a_1 = 0 \qquad (5)$$

$$S_{22} = b_2/a_2 = V_{\text{reflected at port 2}}/V_{\text{transmitted at port 2}} \text{ when } a_1 = 0 \qquad (6)$$

S_{11} and S_{21} are calculated by measuring incident, reflected and transmitted signals at port 1 and terminating port 2 in matched load (Zo) to make a_2 equal to zero. S_{12} and S_{22} are calculated by measuring incident, reflected and transmitted signals at port 2 and terminating port 1 in matched load (Zo) to make a_1 equal to zero. S_{11} and S_{22} represent reflections from port 1 and port 2 when signal is applied at port 1 and port 2 respectively. Their value of 0 indicates a perfect match (50) at the port while value other than 0 and less than unity indicates reflections. Their value cannot be more than 1 otherwise they represent negative ohmic value.

S_{21} and S_{12} can attain value more than 1 in case of active devices. If they are less than unity as in case of passive devices, the signal is attenuated. They can be positive or negative and when they attain negative values, they represent phase shift.

Vector Network Analyser (VNA) is used to measure S-parameters of a microwave device. This instrument is first calibrated using different standards. Normally 'TOSM' (Through-Open-Short-Match) given by Anonymous [2008] type of calibration is used for two port calibration, in which 'Open', 'Short' and 'Match' loads are first connected to port 1 and then to port 2. Each time, after connecting a particular load, calibration is run and instrument takes care of any error for that setting of power and frequency. VNA considers it as a correcting factor for the measurement set up. Then 'through' load is connected between port 1 and port 2 and again calibration is run. The instrument considers correction factor for this case, also. When calibration is over, a 'Device Under Test' (DUT) is connected between two ports of VNA for testing, after removing the 'Through' load. The VNA then measures parameters correctly.

When a matched load is connected to the network, all power is absorbed in the load, but when load is not matched, some power is reflected from the load. The amount of power reflected depends on the mismatch between load impedance and network's impedance. Hence, it needs to define a reflection coefficient (Γ) as given below:

$$\Gamma = V_{\text{reflected}}/V_{\text{incident}} = \rho \angle\Phi = (Z_L - Z_O)/(Z_L + Z_O) \qquad (7)$$

$$\rho = |\Gamma|$$

$$\text{Return Loss} = -20 \log(\rho) \qquad (8)$$

When the transmission line is terminated in a SHORT circuit, a reflected wave is launched back along the line

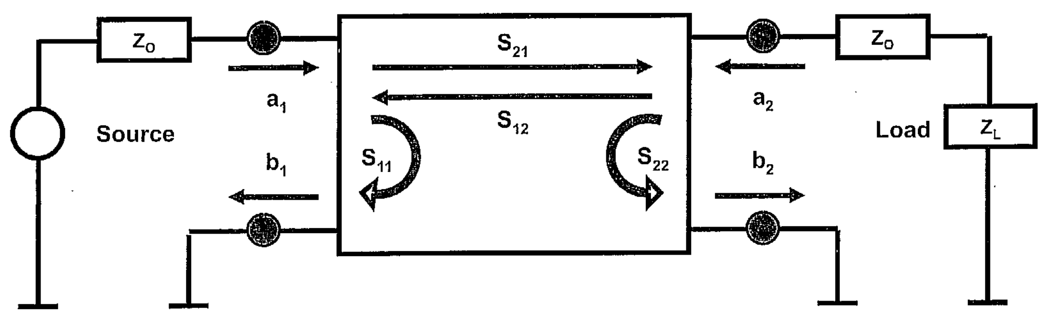

Fig. 2: A two port network and its S-parameters

toward the source. The reflected voltage wave must be equal in magnitude to the incident voltage wave and 180 degrees out of phase with it, at the plane of the load. The reflected and incident waves are equal in magnitude but traveling in the opposite directions. Similarly, when the transmission line is terminated in an OPEN circuit, the reflected current wave will be 180 degrees out of phase with the incident current wave, while the reflected voltage wave will be in phase with the incident voltage wave, at the plane of the load. This guarantees that the current at the open will be zero. The reflected and incident current waves are equal in magnitude, but traveling in the opposite directions. For both, short and open cases, a standing wave pattern is set up on transmission line. The voltage valleys will be zero and the voltage peaks will be twice the incident voltage level. It is therefore necessary to define another quantity known as Voltage Standing Wave Ratio (VSWR) for such standing wave existing on the line. Sometimes, it is also known simply as Standing Wave Ration (SWR).

$$\begin{aligned} \text{VSWR} &= V_{max}/V_{min} \\ &= (1+\rho)/(1-\rho) \qquad (9) \end{aligned}$$

VSWR ranges from 1 (no reflection) to ∞ (full reflection) depending on the load impedance.

Characterization of backend Electronics

Characterization of Isolator

An isolator is a nonreciprocal transmission device that is used to isolate one component from reflections of other components in the transmission line. An ideal isolator completely absorbs the power for propagation in one direction and provides lossless transmission in the opposite direction. It is placed in between two devices, i.e., one which causes the reflections and the other which is to be protected from such reflections. This is an extremely useful device for "isolating" components in a chain, so that bad VSWR don't contribute to gain ripple. Isolators can be made from 100's of MHz to W-band (110 GHz). They can be packaged as planar microstrip components, coaxial components or as waveguide components.

In the current experimental set up, microwave isolator is placed in between Schottky mixer and Low Noise Amplifier (LNA) to protect the mixer from reflected signal, if any due to any mismatch, coming from LNA towards the mixer. It has been characterized by measuring its S-parameters using Vector Network Analyser (VNA) from Rohde and Schwarz

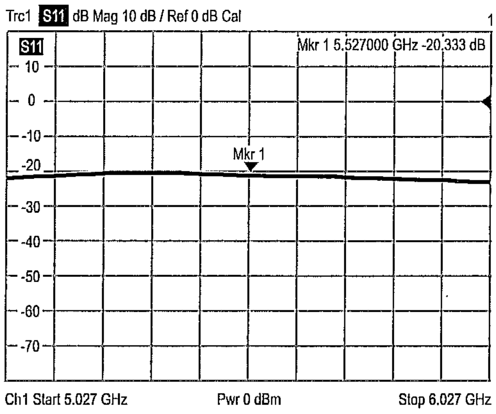

Fig. 3 (a): S_{11} (dB) parameter of isolator

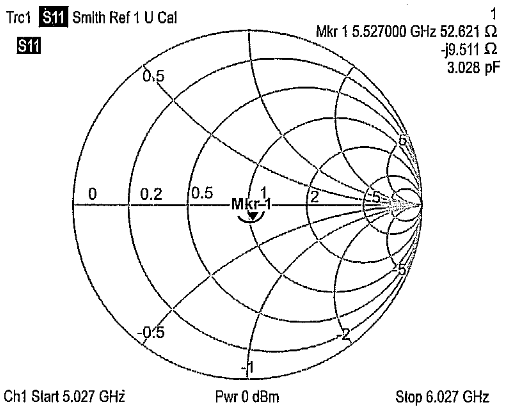

Fig. 3 (b): S_{11} (Smith) parameter of isolator

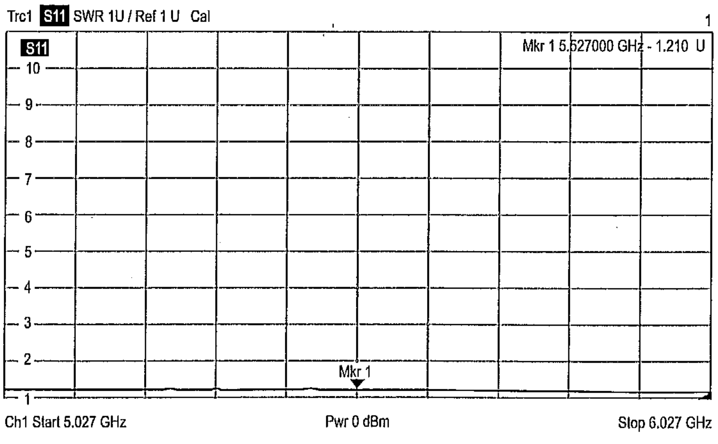

Fig. 3 (c): S_{11} (SWR) parameter of isolator nodel no. ZVB8). Figures 3 to 6 show all important arameters of isolator.

The S_{11} parameter of isolator defines a) the input return ss, b) impedance at input port and, c) Voltage Standing ave Ratio (VSWR) at the input port (Figure 3 (a, b, c)).

The S_{21} parameter (Figure 4) of isolator defines its rward transmittance indicating the desired passage of gnal from its input to output side with minimal signal loss.

The S_{12} parameter (Figure 5) of isolator defines its isolation between its input and output ports in the reverse direction. The higher value guarantees the reflected signal not reaching towards the Schottky mixer and protects the mixer.

The S_{22} parameter of isolator defines its output return loss (Figure 6 (a)), impedance of output port (Figure 6 (b)) and VSWR at the output port (Figure 6 (c)). Table 1 gives measurement results for isolator.

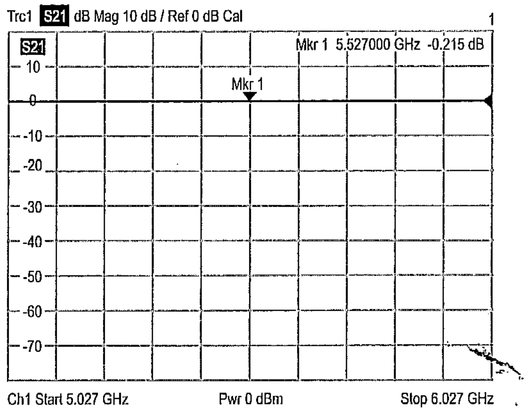

Fig. 4: S_{21} (dB) parameter of isolator

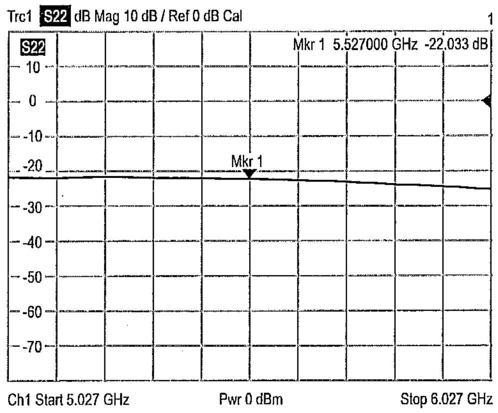

Fig. 6 (a): S_{22} (dB) parameter of isolator

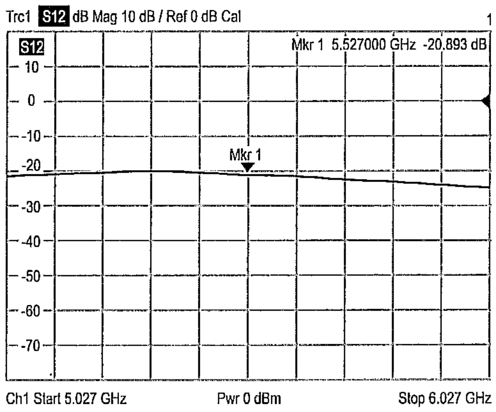

Fig. 5: S_{12} (dB) parameter of isolator

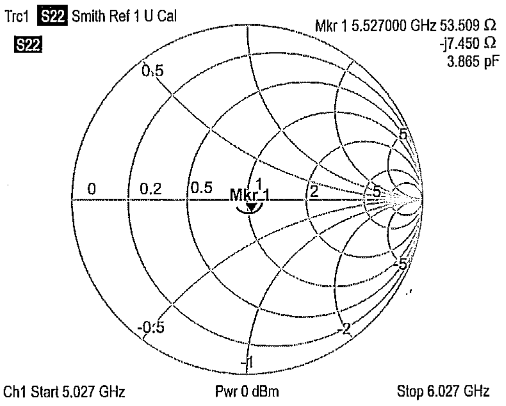

Fig. 6 (b): S_{22} (Smith) parameter of isolator

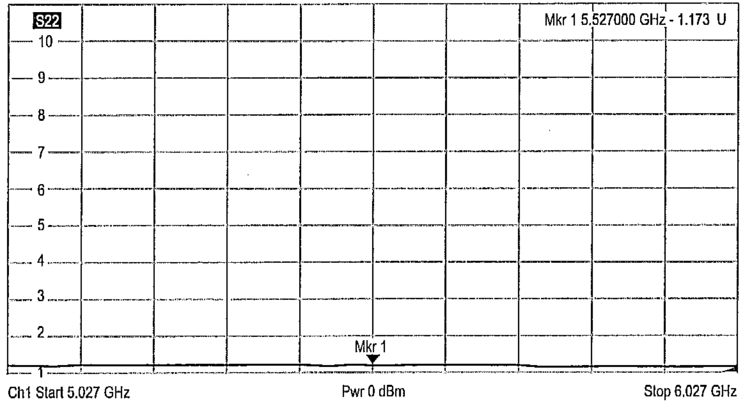

Fig. 6 (c): S_{22} (SWR) parameter of isolator

Table 1: Measurement results for isolator

Sr. No.	Parameter	Specified Value*	Measured Value
1.	Input Return Loss S_{11} (dB)	-	> 20
2.	Input Impedance (Ohm) at IF of 5.527 GHz	-	52.621 - j 9.511
3.	Input VSWR	≤ 1.21	≤ 1.21
4.	Insertion Loss (dB)	< 0.4	< 0.3
5.	Isolation (dB)	> 18	> 20
6.	Output Return Loss S_{22} (dB)	-	> 21.5
7.	Output Impedance (Ohm) at IF of 5.527 GHz	-	53.509 - j 7.450
8.	Output VSWR	≤ 1.17	≤ 1.173

* The specified values are for the isolator from UTE Microwave (model no. CT-4026-OT with serial no. Z6632)

Characterization of Low Noise Amplifier

Field Effect Transistor (FET) or High Electron Mobility Transistor (HEMT) is normally used as a basic design element for Low Noise Amplifier (LNA) in case of microwave applications. HEMT is also called heterostructure FET (HFET) given by Aucoin and Anonymous b [2002]. The low noise amplifier (LNA) is a special type of electronic amplifier to amplify very weak signals. As per Friis' formula, the overall noise figure of the receiver front-end is dominated by the first few stages. Using an LNA, the noise of all the subsequent stages is reduced by the gain of the LNA and the noise of the LNA is injected directly into the received signal. Thus, it is necessary for an LNA to boost the desired signal power, while adding as little noise and distortion as possible, so that the retrieval of this signal is possible in the later stages. For achieving lower noise, the amplifier needs to have high amplification in its first stage. Therefore, JFETs and HEMT in the form of distributed amplifiers could be used. They are driven in a high current regime, though not energy efficient, but it reduces the relative amount of shot noise. Input and output matching circuits do not use resistors and hence, they enhance the gain but do not contribute to noise. Biasing is normally done by large resistors, because energy efficiency is not needed and also a large resistor prevents leakage of the weak signal out of the signal path (or noise into the signal path).

It is necessary to calibrate the VNA in a 'One Path Two Port' given by Anonymous [2008] manner to precisely measure test parameters due to few reasons, i.e., very high gain (50 dB) of LNA, limited range of VNA and uni-direction operation of LNA. However, in this mode, only S_{11} and S_{21} can be measured with full calibration. These are shown in Figures 7 and 8 below. The S_{11} parameter of LNA defines its input return loss, input impedance and input VSWR. The S_{21} parameter of LNA defines desired amplification of signal when signal is applied to its input. In the current experiment, the isolator output is connected to input of LNA.

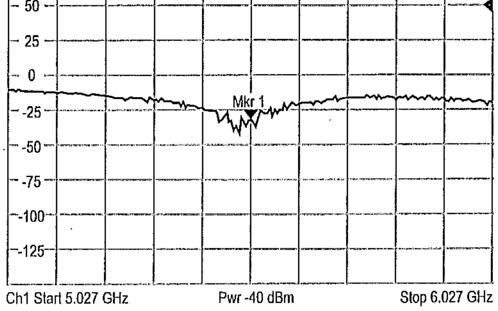

Fig. 7 (a): S_{11} (dB) parameter of LNA

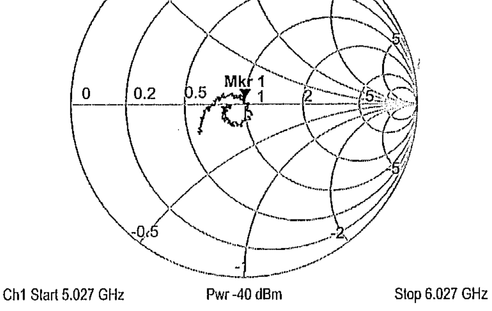

Fig. 7 (b): S_{11} (Smith) parameter of LNA

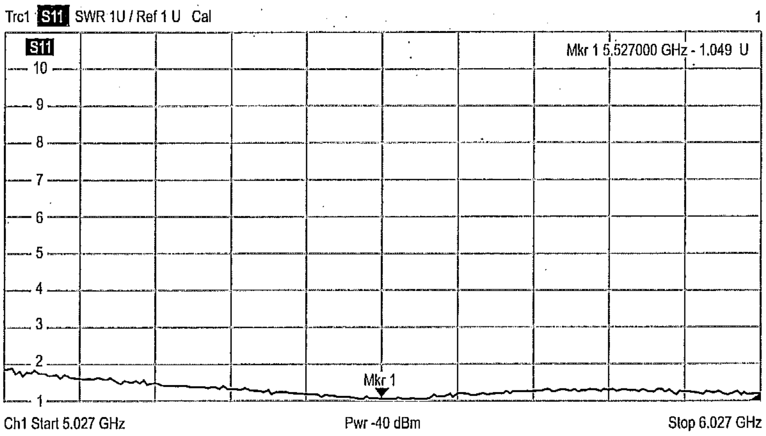

Fig. 7 (c): S_{11} (SWR) parameter of LNA

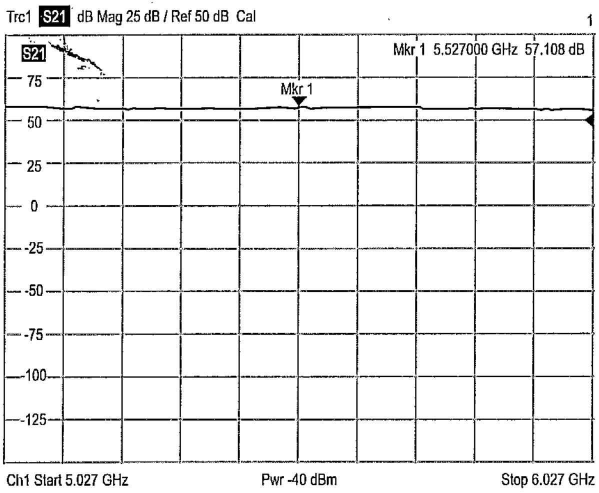

Fig. 8: S_{21} (dB) parameter of LNA

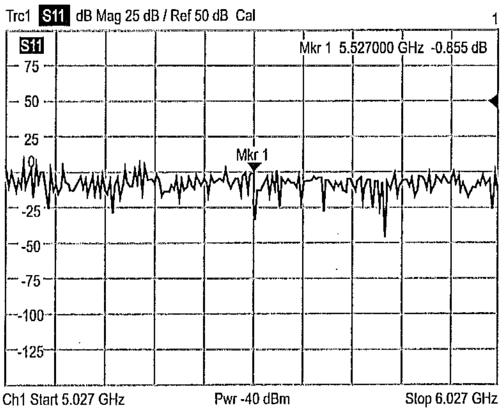

Fig. 9: S_{11} (dB) (Rev)

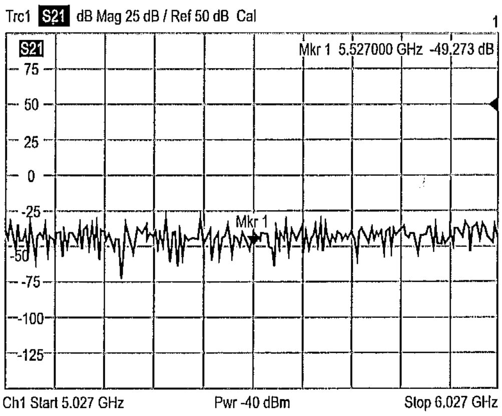

Fig. 10: S_{21} (dB) (Rev)

Table 2: Measurement results for LNA

Sr. No.	Parameter	Specified Value*	Measured Value
1.	Input Return Loss S_{11} (dB)	> 9.5	> 12.5
2.	Input Impedance (Ohm) at IF of 5.527 GHz	-	49.409 + j 2.205
3.	Input VSWR	≤ 2	< 1.9
4.	Gain (dB)	> 52	> 57
5.	Isolation** (dB) at IF of 5.527 GHz	-	49.273
6.	Output Return Loss S_{11} (Rev)** (dB)	> 9.5	10 (Av)
7.	Output Impedance** (Ohm) at IF of 5.527 GHz	-	19.007 + j 20.300
8.	Output VSWR**	≤ 2	3.2 (Av)

* The specified values are for the LNA from Endwave Corporation (model no. JCA48-600 with serial no. 108)
** Measurements taken with LNA reversed

Using single path calibration, LNA is operated in reverse direction to measure its reverse isolation. In this reverse mode of operation, again S_{11} (representing output side) and S_{21} (representing reverse isolation) are measured and they are shown in Figure 9 and 10. The higher value of S_{21} (Rev) guarantees the reflected signal, if any due to any mismatch, not reaching towards the isolator and protects the isolator from damage.

In the current experiment, the output of LNA is connected to input of spectrum analyser. Such characterized LNA is ready for amplifying the IF signal in spectroscopy of nitrogen dioxide (NO_2). Table 2 gives measurement results for LNA.

Establishment of Data Transfer Facility

It is essential to transfer the SMM spectroscopic data to computer since the spectrum analyser is limited in memory and also further data processing needs to be done offline to extract the science. The Agilent IO Libraries Suite 14.2 and Agilent IntuiLink have been made available and set for its operation through LAN port of spectrum analyser. The demonstration of the facility has been shown using the example spectrum of frequency doubler, which is tested using microwave generator and spectrum analyser. Figure 11 below shows screen shot of the testing and Figure 12 below shows spectrum regenerated using the data transferred to excel file in PC.

Quasi-Optics

Quasi-optics include SMM reflector, power splitter, lenses and transmission windows of gas cell. These components are needed in the experimental set up to control the beam in a desired way, e.g., reflectors and splitters are used in the Martin-Puplett diplexer while lenses are used for focusing the beam. The developmental work of reflectors (metal mirrors) is discussed initially while that of lenses and transmission windows of the gas cell is described in the latter section.

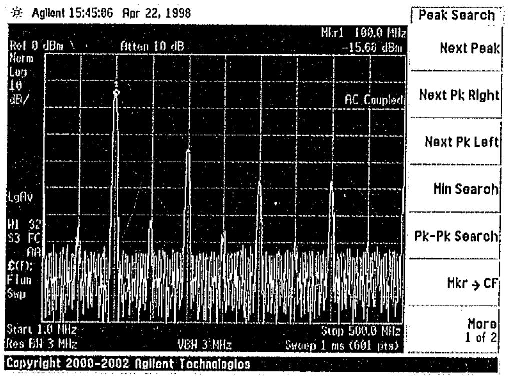
Agilent 15:45:06 Apr 22, 1998
Ref 0 dBm Atten 10 dB
Mkr1 100.0 MHz -15.60 dBm
Norm Log 10 dB/
AC Coupled
LgAv
Start 1.0 MHz Stop 500.0 MHz
Res BW 3 MHz VBW 3 MHz Sweep 1 ms (601 pts)
Copyright 2000-2002 Agilent Technologies

Fig. 11: SA screen shot of output spectrum of frequency doubler

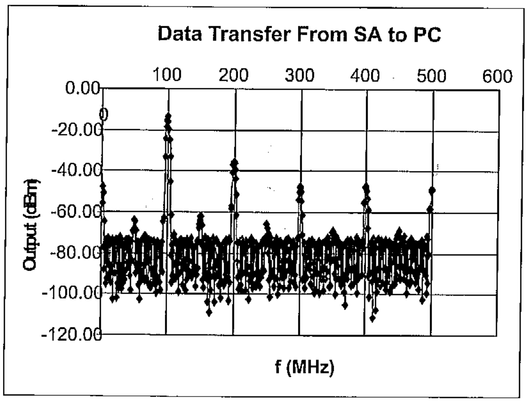

Fig. 12: Regenerated output spectrum of frequency doubler on PC

Metal Mirrors

Stainless Steel material with aluminum coating was selected for metal reflector, which could provide reflectivity of 95 % in the optical range. Basically, there are three processes involved in the development of metal mirrors, i.e., machining, polishing and coating. The machining was carried out up to 10 micron accuracy. Diamond polishing was done on the objects with expected surface finish of about 20 micron. Finally coating was carried out on the polished object at PRL Infrared Observatory, Mt. Abu using aluminum as a coating material. The skin depth of a signal contributes in deciding the thickness of coating material used for reflection. The skin depth of a signal at a frequency of operation f in a material with permeability μ and conductivity σ is given by following equation given by Griffiths [1995]

$$\delta = 1/\sqrt{(\pi f \mu \sigma)} \qquad (10)$$

Considering σ = 3.583 x 10^7 mho/m, μ_r = 1 (for non-magnetic), $\mu_o = 4\pi \times 10^{-7}$ H/m for aluminum, the skin depth at frequency of 700 GHz is 1005 Angstrom. The coating achieved on SS was 1045 Angstrom, which is more than the skin depth ensuring the good reflection properties. The initial result for the reflector obtained at optical frequency is shown in Figure 13.

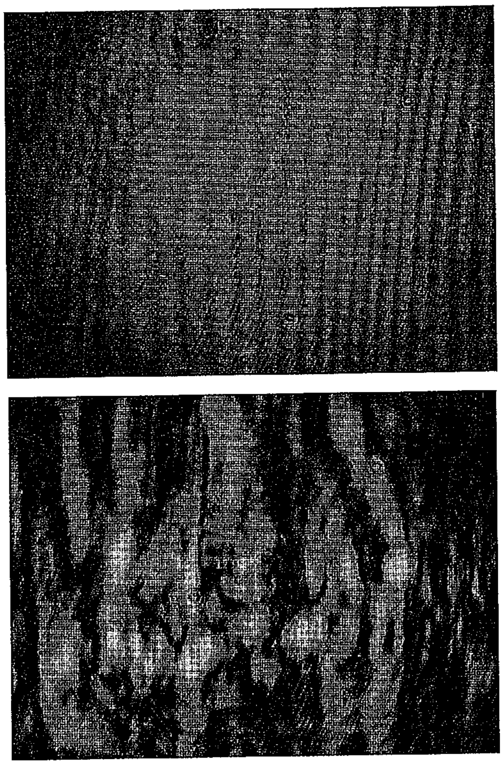

Fig. 13: Interferometric images of standard (glass) reflector and metal reflector

Figure 14 (a) shows interferometric image of standard reflector (glass) and Figure 14 (b) to (e) show interferometric images of other metal reflectors. The reflector whose images are shown in Figure 14 (d) and (e) are used in diplexer which combines two far infrared signals, one from gas cell and the other from Optically Pumped Molecular Laser (OPML).

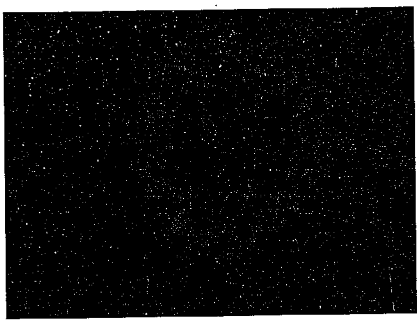

Fig. 14 (a) Standard

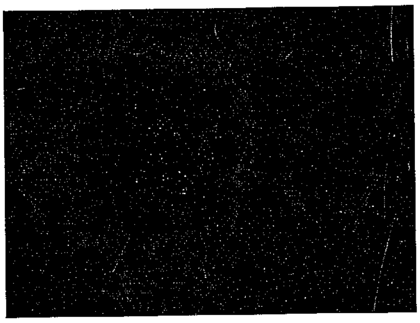

Fig. 14 (b) Metal - Circular (68 mm diameter)

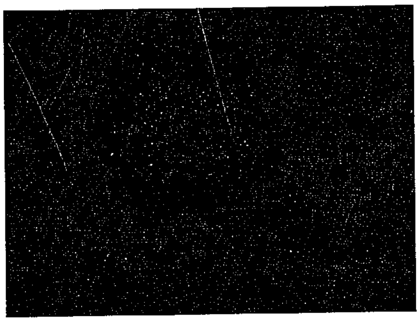

Fig. 14 (c) Metal - Square (75 x 75 mm^2)

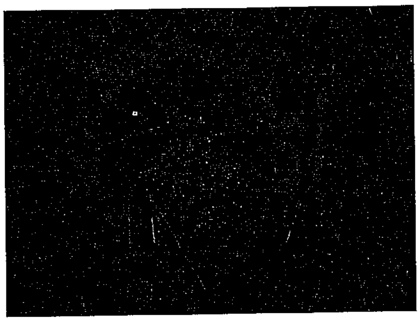

Fig. 14 (d) Metal - Rectangular (120 x 100 mm^2)

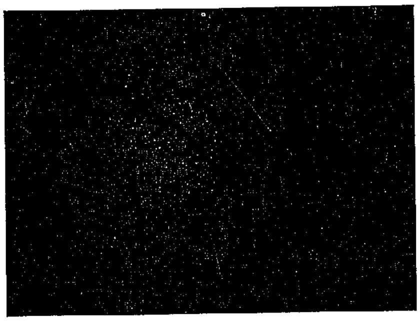

Fig. 14 (e) Metal - Rectangular (115 x 100 mm^2)

FIR Lenses

The gas cell is cylindrical with diameter of 50 mm and one plano-convex lens is mounted at each end of the cell with its convex side remaining outside the cell. Thus, beam coming from black body source should become parallel inside the cell and it should focus at output end of the cell. TPX (4-mithyle pentene-1) was selected as a material for lenses and transmission windows of gas cell since the TPX has more than 95 % transmission in far infrared region. Thin lens formula given by Hecht [1987] is given below to design the plano-convex lenses for transmission windows of gas cell.

$$(1/f) = (n-1)\,[(1/R1) - (1/R2) + \{(n-1)\,d\}/\{n\,R1\,R2\}] \qquad (11)$$

The prototype windows of gas cell were made using Teflon and the same design was repeated to make final windows of gas cell using TPX. Taking the TPX rod with diameter of 50 mm and refractive index n = 1.463 to design the lens with focal length (f) of 160 mm, the radius of curvature of one side of plano-convex lens could be found about 74 mm. Selecting 75 mm as radius of curvature of one side of the lens, its focal length becomes 162 mm. This focal length is sufficient to mount the blackbody source at necessary distance on one side of the cell and the diplexer on the other side of the cell.

Summary

The back end electronics of the Submillimeter spectroscopy set up for nitrogen dioxide play important role in handling the IF signal at 5.527 GHz and the same have been tested to make them ready for the application. Some quasi-optics were designed, developed and tested for the experiment. The measurements are necessary to calculate the actual overall performance of the receiver.

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