# ALL-SOLID-STATE RADIOMETERS FOR ENVIRONMENTAL STUDIES TO 700 GHZ

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## ABSTRACT

We report results with an all-solid-state radiometer for measurements of the ClO molecule at 649 GHz. The project is part of a program to provide low-noise, low-weight, low-power radiometers for space operation, and special effort has been expended on the development of high-efficiency solid-state frequency multipliers and Schottky-barrier mixers with low local oscillator power requirements.

The best measured system noise temperature was 1750 K with the mixer and preamplifier cooled to 77 K. The mixer diode was easily pumped into saturation, indicating that the design has excellent prospects of operating at higher frequencies - our present design goal being 1 THz. We comment on the principal design features of such systems and will report on stratospheric measurements performed with this system.

## INTRODUCTION

All solid-state radiometers in the frequency range 60-560 GHz have been reported [1], [2], [3], [4], and the measured parameters for the highest frequency receivers are tabulated in Figure 1. The ever-increasing importance of atmospheric investigations in the higher sub-millimeter wavelength-range has led to a consolidated program to reach 1 THz with such instruments. To this end a radiometer (s. Fig.2) has been constructed for the detection of the ClO molecule at 649 GHz; this is the subject of this paper.

The three principal sections of the system are the optics, the all solid-state local oscillator and the low-noise mixer-preamplifier.

## QUASI-OPTICS

At frequencies above 200 GHz the losses of waveguide components are too high for sensitive radiometers, and quasi-optical systems become increasingly compact. The prime component requirements for coupling the antenna and local oscillator into the mixer are high efficiency feed-horns, precisely machined ofset-mirrors and low-loss wire grids for polarising couplers and filters. All mirrors are ellipsoids, whilst grids comprise 20 µm diameter tungsten wire with 50 µm spacings (between centres). For IF bandwidths $\Delta f/f \leq 0.5$ the Martin-Puplett coupler is preferred.

Figure 2 shows the total front-end schematic, including a single-sideband filter and path-length modulator (from University of Bremen, to be reported at this conference). The quasi-optical beams, beam-waist locations and sizes are also shown. The feedhorns in this receiver are dual-mode horns as shown schematically in Figure 3 [5]. These horns have been measured at lower frequencies and have in all cases symmetrical near gaussian beam-patterns, to at least -15 dB. The losses of the optics plus feedhorns were measured by connecting the output of the frequency multiplier directly to the mixer, and then feeding the l.o. to the mixer via the two horns and the quasi-optics: the loss was around 1 dB.

## LOCAL OSCILLATOR

The local oscillator power requirement for a mixer depends strongly on the diode quality and on the mixer mount- and coupling-losses between source and mixer. Particularly in the submillimeter-range these parameters are not easy to determine. By extrapolating from lower submillimeter-wavelength, we estimate the l.o. power requirement to be in the range 100 µW to 1 mW for a cooled mixer. The requirement was to build an all solid-state source for later space application.

In this paper the source comprises a Gunn oscillator, a waveguide cross-coupler plus harmonic mixer, a waveguide frequency doubler and tripler. All components are directly connected together, to reduce losses (Figure 4).

### (a) Gunn-Oscillator

A Varian InP Gunn diode is mounted into a WR-8 waveguide (Figure 5). Bias is supplied to the diode via a coaxial low-pass filter held by teflon spacers.

The frequency is pretuned by a cap-resonator, fine adjustment over several GHz being provided by a dielectric tuning rod sliding under the cap. A waveguide back-short allows adjusting for maximum power. The power output is shown in Figure 6.

## (b) Frequency Multiplier

There are several possibilities of attaining power at 650 GHz from a solid source followed by a multiplier. Gunn oscillators deliver output power up to 50 mW at frequencies up to 115 GHz. For this reason a sixtupler seems a natural choice. Though we build one with ~100 μW output power, it was very difficult to tune, as several idlers had to be optimised simultaneously. The better choice is a doubler-tripler or tripler-doubler combination, where each stage can be developed separately. Calculations using the program by Siegel et al. [6] showed that the doubler-tripler combination should result in higher efficiency; hence this combination was chosen.

To facilitate easy system construction and testing, especially for the case of cascaded multiplication stages, Radiometer-physics developed in 1987 "in-line" waveguide frequency multipliers (Figure 7). This means, that input- and output-waveguide are in-line, compared to the standard crossguide-type structure.

A schematic for both multipliers is shown in Figure 8. Input power is coupled from the input waveguide via a probe and coaxial filter to the diode which is part of the last section of this filter. The filter is of the low-pass Tchebycheff-type and has been modelled a lower frequencies. Probe and diode are located in the bend of input- and output-waveguides respectively.

The DOUBLER input waveguide dimensions are 2.0x1.0 mm, which are tapered to 2.0x0.5 mm at the probe. The dimensions of the output waveguide are 0.6x0.3 mm Backshorts are provided for tuning. The diode is a 6P4 from University of Virginia, with the following DC-parameters $R_S$ = 12 ohm , $C_j$ = 18 fF, $V_{br}$ = 20 V. It is contacted by a whisker of length 0.3 mm and diameter 25 μm.

With 50 mW input signal an efficiency of 20% was achieved, compared with a theoretical efficiency of 37%. Power was measured with a Hughes Thermistor mount at the input. Output power was measured with an Anritsu power head 140-220 GHz with a tapered transition to match the input waveguide of the multiplier

The TRIPLER input and output waveguide dimensions are 0.6x0.3 mm and 0.4x0.2 mm respectively. It operates with a diode 2T2 again from University of Virginia. Its DC-characteristics are $C_j$ = 6.0 fF, $R_s$ = 12 ohm, $V_{br}$ = -11V. The whisker is 0.2 mm long, with 12 µm diameter. An important feature of the tripler is the idler tuning circuit in form of a stub waveguide with a moving short. The output waveguide contains a short section of reduced-width waveguide to prevent idler propagation to the output. Low frequency modelling was important in attaining optimum waveguide dimensions. The output power achieved was 300 µW, which means an efficiency of 3% compared to 17% theoretical.

The measurement of output power in the range 600-700 GHz is not trivial, and caution should be taken in specifying power at such high frequencies - in particular the power standards should be quoted. In our case <u>relative</u> measurements were performed using the same Anritsu thermistor power-head as for the doubler, with appropiate waveguide transitions. The <u>absolute</u> power output was then measured with the Queen Mary College acoustic calorimeter at 624 GHz, where an absolute calibration exists: this showed that the absolute power from the l.o. input is about three times greater than the Anritsu reading. Hence to a first approximation we can multiply all Anritsu readings by factor 3. Absolute measurements were also performed at 690 GHz with a similar frequency multiplier chain, whereby 30 µW were measured with the Anritsu head and 90 µW with the QMC instrument - once again a factor 3.

It is relevant to draw attention to the problems arising due to using different lower frequency thermistor heads, this is illustrated in Figure 10 for three measurements from a 345 GHz frequency multiplier.

To show the possibilities of achieving l.o. power from solid-state sources in the submm-range we have included Figure 10.

## MIXER

The mixer is shown schematically in Figure 11. The dual-mode horn is identical to that used for the l.o. output. The waveguide dimensions are 0.6x0.2 mm and the contacting back-short is gold-plated beryllium-copper. The diode chip (type 1T6 from the University of Virginia) is mounted on the coaxial choke structure, as shown in Figure 12. The chip is turned down to a cylindrical form and gold plated on the cylindrical surface, so that the chip is also the first choke-section. It is seen that the choke is supported by a Macor disc: the dimensions of this disc are important for obtaining a broad i.f. bandwidth. The calculated impedance of the choke is shown in Figure 14 from d.c. to 1100 GHz. Figure 15 shows the measured output impedance of the mixer across the i.f. band 9-11 GHz, without and with an i.f. matching transformer

The 1T6 diode has the following d.c.-characteristics: $R_s = 30$ ohm $C_{jo} = 0.35$ fF, $V_{br} = -6$ V. The whisker is of gold-plated phosphorbronze, diameter 7 µm; the total whisker length is 0.2 mm, and includes a loop to take up slight changes in waveguide and choke dimensions on cooling the mixer to 77 K. To test that there was adequate l.o. power the diode was biased at room-temperature to 0.86 V, whereby the diode drew a current of

10 µA without l.o. and >600 µA with l.o.: hence there was adequate l.o.-power for optimum mixer operation.

## SYSTEM RESULTS

The system was tested using standard hot-cold foam absorbers from Emerson and Cuming at the input to the diplexer for DSB- and at the input to the SSB-filter for SSB-measurements. In the final configuration the cold image termination was replaced by an absorber for constructional reasons, without any appreciable sacrifice of performance.

The cryogenic i.f. preamplifier was developed at Chalmers Technical University and had a noise temperature of 35 K at 77 K ambient. All other i.f. components preceding the spectrometer were commercially available.

Double-sideband system tests with a 2 GHz i.f. bandwidth yield the following results:

| Tamb | Tsys | Tm | Lo |
|---|---|---|---|
| 300 K | 3800 K | 1900 K | 8.0 dB |
| 77 K | 1750 K | (1500 K) | (8.0 dB) |

Tsys-values are measured directly, whilst $T_M$ and $L_M$ are corrected for residual power mismatch of 0.15, and we assume the same conversion loss at 77 K ambient.

For single-sideband system tests the SSB-filter was adjusted by using a tunable Gunn-oscillator and multiplier chain, identical to the l.o. chain and a spectrum analyzer. The sideband rejection was at least 25 dB.

The result was:

Tusb = 3800 K at 77 K

More than adequate l.o. power was available to reach minimum Tsys. It was noted that the noise temperature was fairly insensitive to changes in diode current in the range 400-800 µA.

The system has been flown on an aircraft contracted by the University of Bremen. A first uncorrected result shows the ClO line in Fig. 15.

## PROSPECTS

It appears reasonable to expect spaceborne all-solid-state radiometer system to be feasible at least to 1 THz, using only waveguide techniques. Calculations using the computer model of Siegel and Kerr yield l.o. output powers of 360 µW at 1 THz; taking into account losses this still implies that sufficient l.o. power will be available at 1 THz to pump a Schottky-barrier mixer diode; such a development program has commenced at Radiometer-physics. Since completing the 650 GHz system new Schottky-barrier mixer diodes have been reported [7] , [8] . Hence, with improvements in multiplier- and mixer-technology it should be possible to operate such systems at even higher frequencies.

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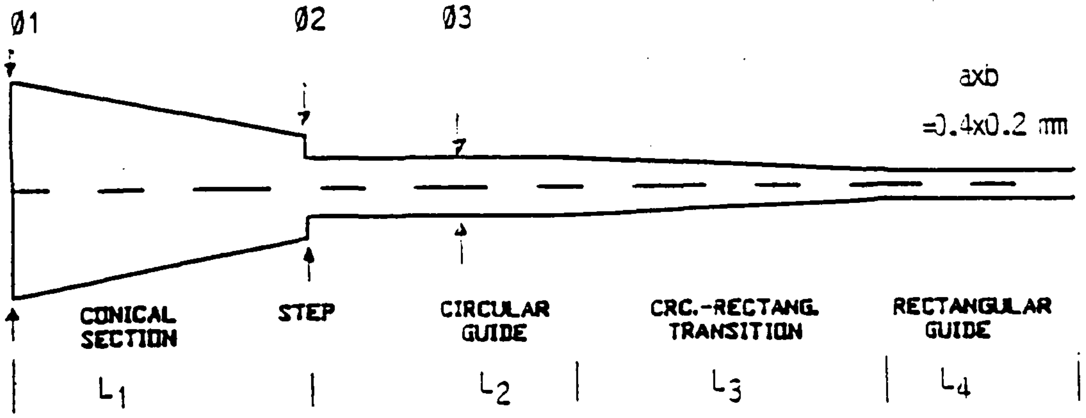
| | 345 GHz [2]<br>cooled 20 K | 490 GHz [3]<br>cooled 20 K | 557 GHz [4]<br>uncooled | 650 GHz<br>cooled 77 K |
|---|---|---|---|---|
| IF: | 1.5 ± 0.25 GHZ | 1.5 ± 0.3 GHZ | 1.4 ± 0.3 GHZ | 10 ± 1 GHZ |
| $T_{IF}$: | 10 - 20 K | 10 K | 60 K | 35 K |
| $T_{MIX,DSB}$ | n.m. - | n.m. - | 1200 K | 2000 K * |
| $L_{C,DSB}$ | n.m. - | n.m. - | 8 dB | 8.5 dB* |
| $T_{sys,DSB}$ | 350 K | 550 K | 1600 K | 1750 K<br>(3800 K SSB) |

* only uncooled results; n.m. not measured

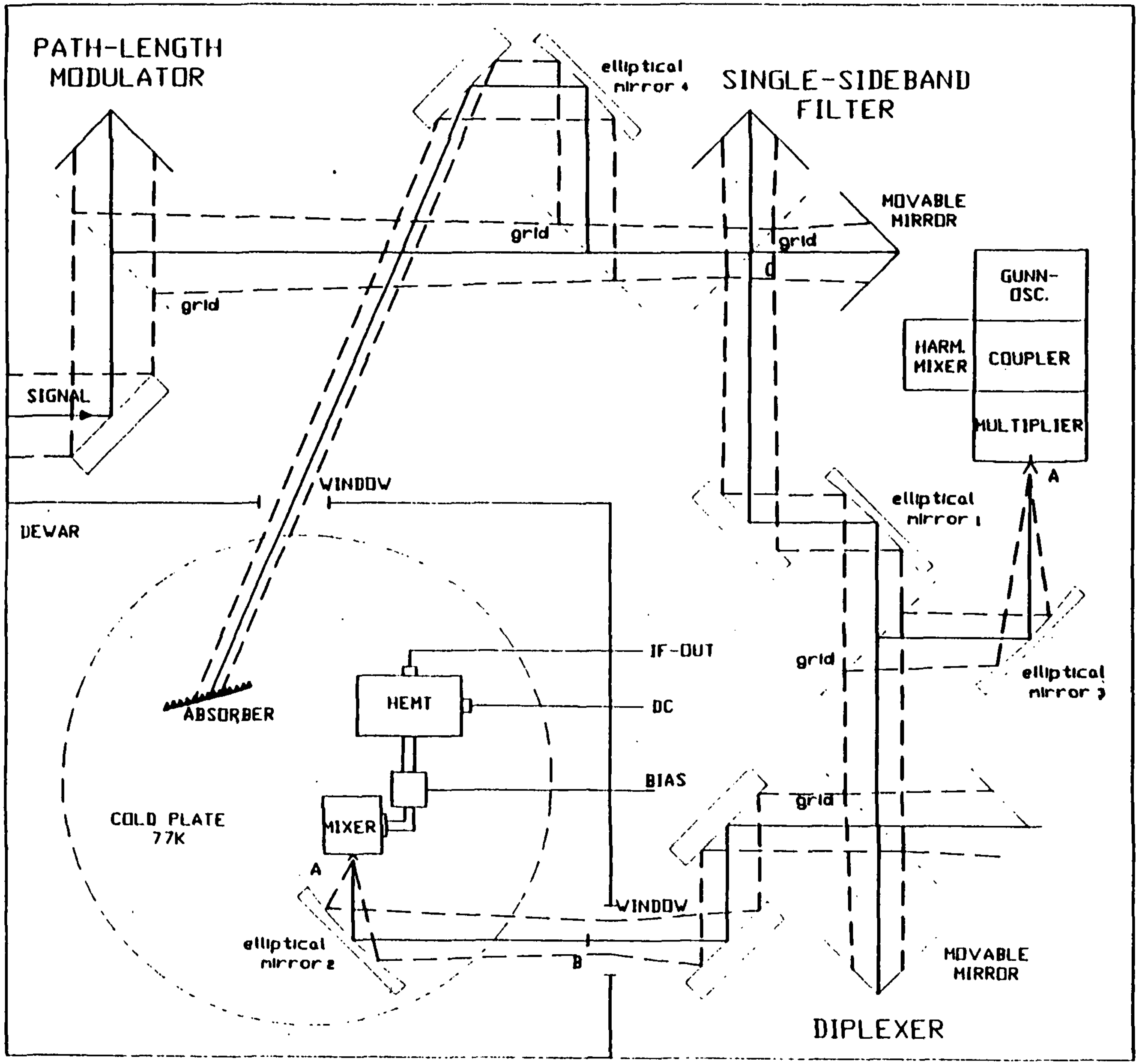
Fig. 1: RESULTS OF SYSTEMS WITH MIXERS AND MULTIPLIERS FROM RADIOMETER-PHYSICS



$\varnothing_1 = 2.96$ mm
$\varnothing_2 = 0.60$ mm
$\varnothing_3 = 0.47$ mm

$L_1 = 4.9$ mm
$L_2 = 3.0$ mm
$L_3 = 2.3$ mm
$L_4 = 3.0$ mm

Fig. 3: DUAL - MODE HORN (SCHEMATIC)



# 650 GHz COOLED SCHOTTKY RECEIVER BLOCK DIAGRAM

DIMENSIONS IN MM

BEAM WAISTS:

A: 0.82 mm
B: 6.0 mm
C: 4.65 mm
E: 4.0 mm

FIG. 2:
RECEIVER BLOCK DIAGRAM

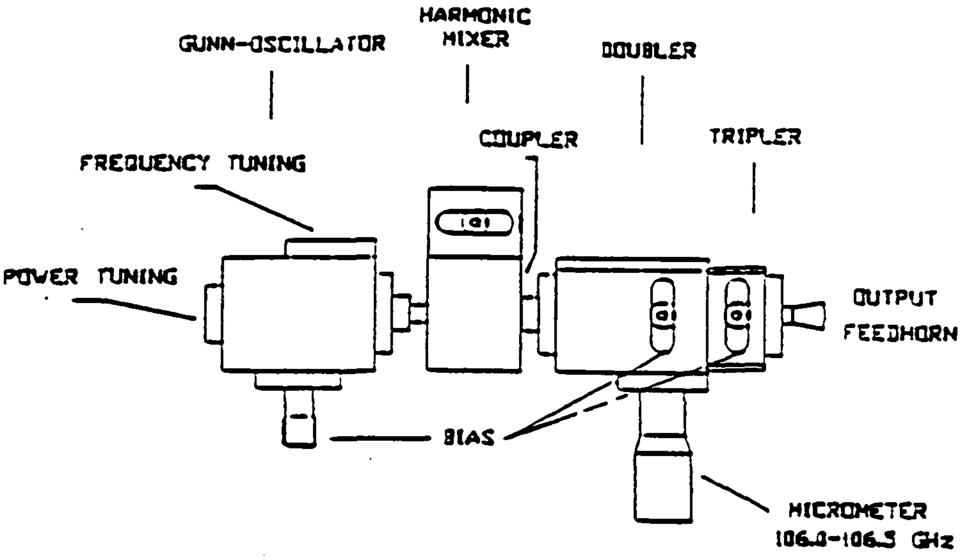


Fig. 4: LOCAL OSCILLATOR

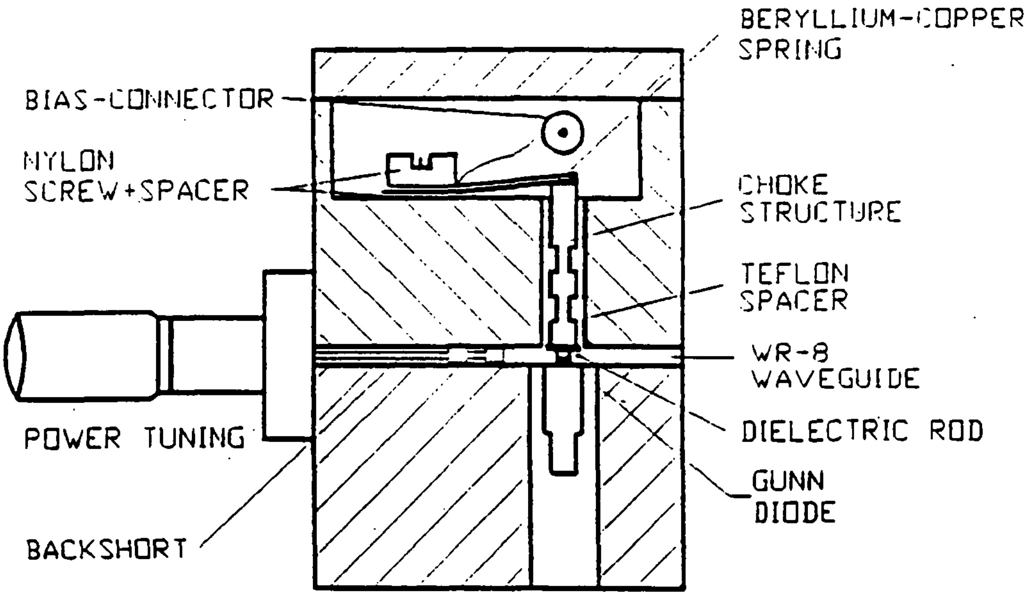


Fig.5: GUNN-OSCILLATOR

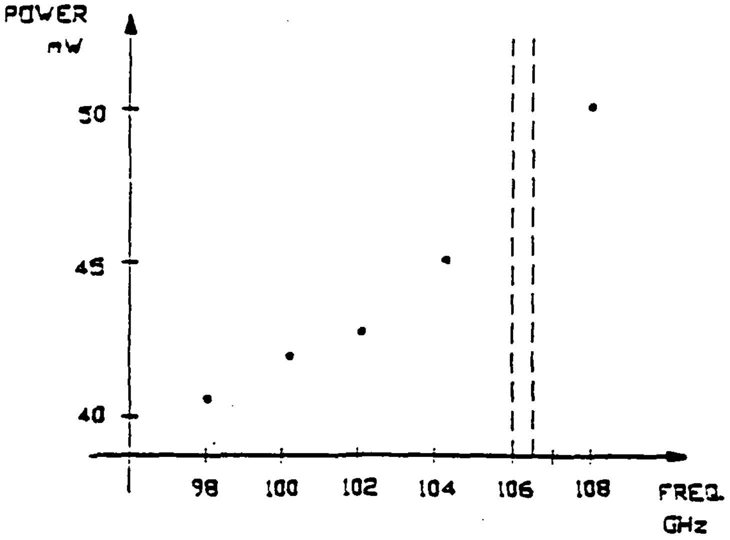


Fig. 6: GUNN OSCILLATOR OUTPUT POWER

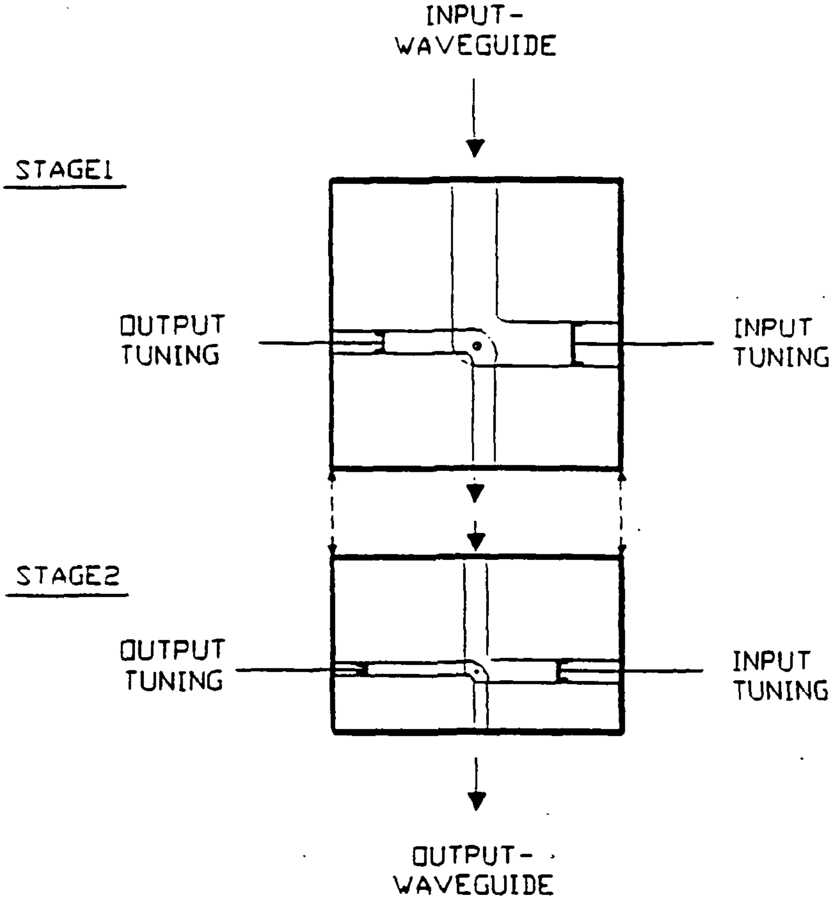


Fig. 7: ARRANGEMENT OF WAVEGUIDES FOR IN-LINE MULTIPLIERS

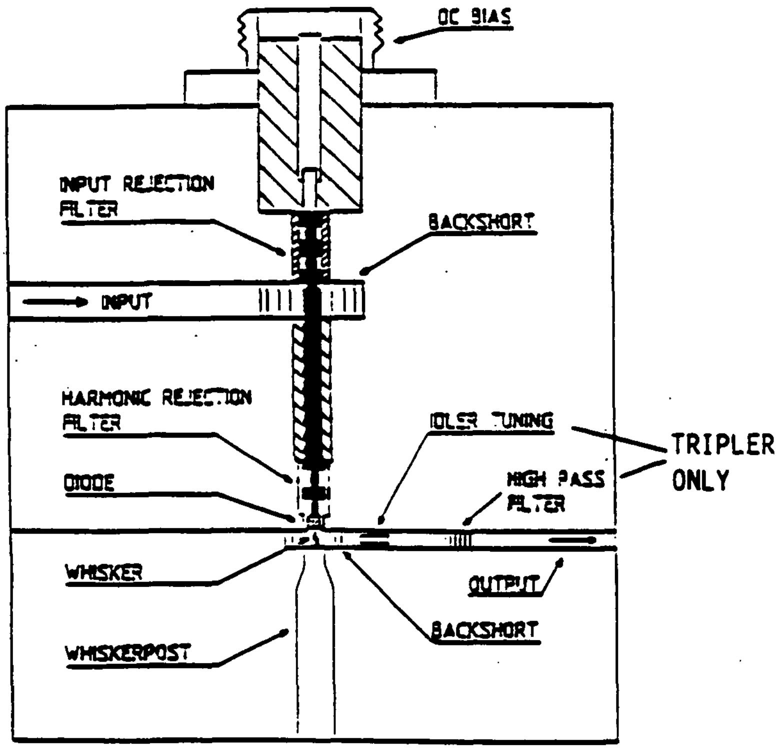


Fig. 8: MULTIPLIER (SCHEMATIC)

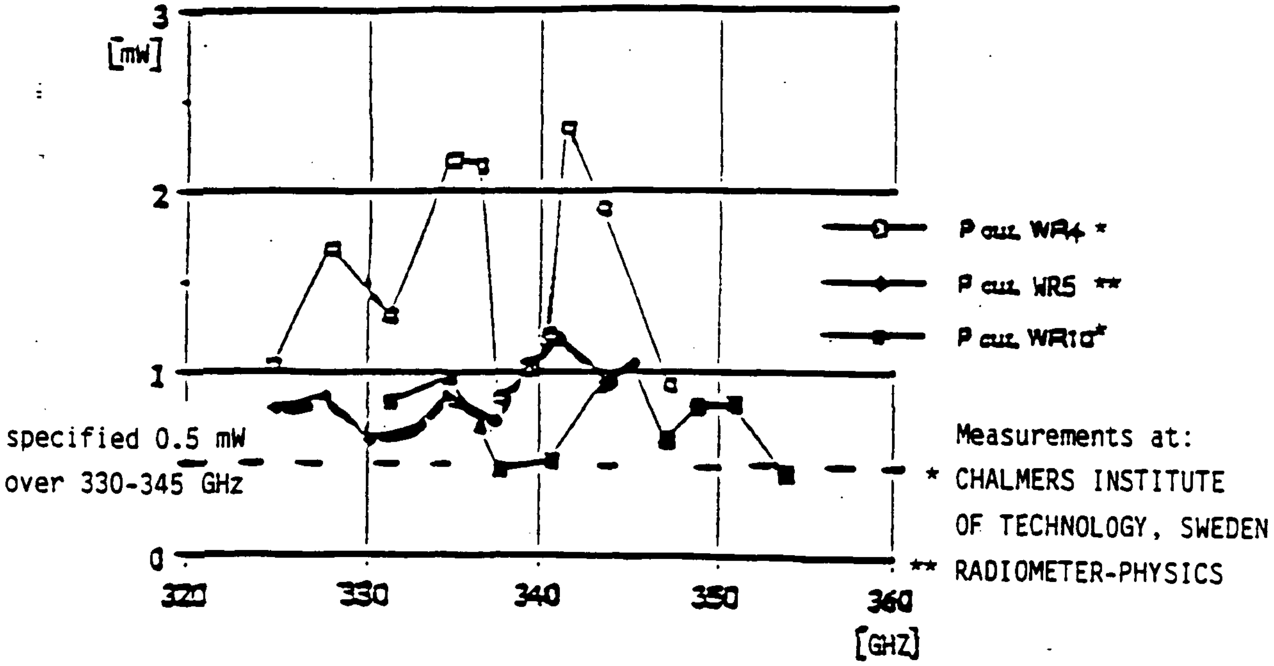


Fig. 9: MEASUREMENTS OF OUTPUT POWER WITH VARIOUS POWER METERS

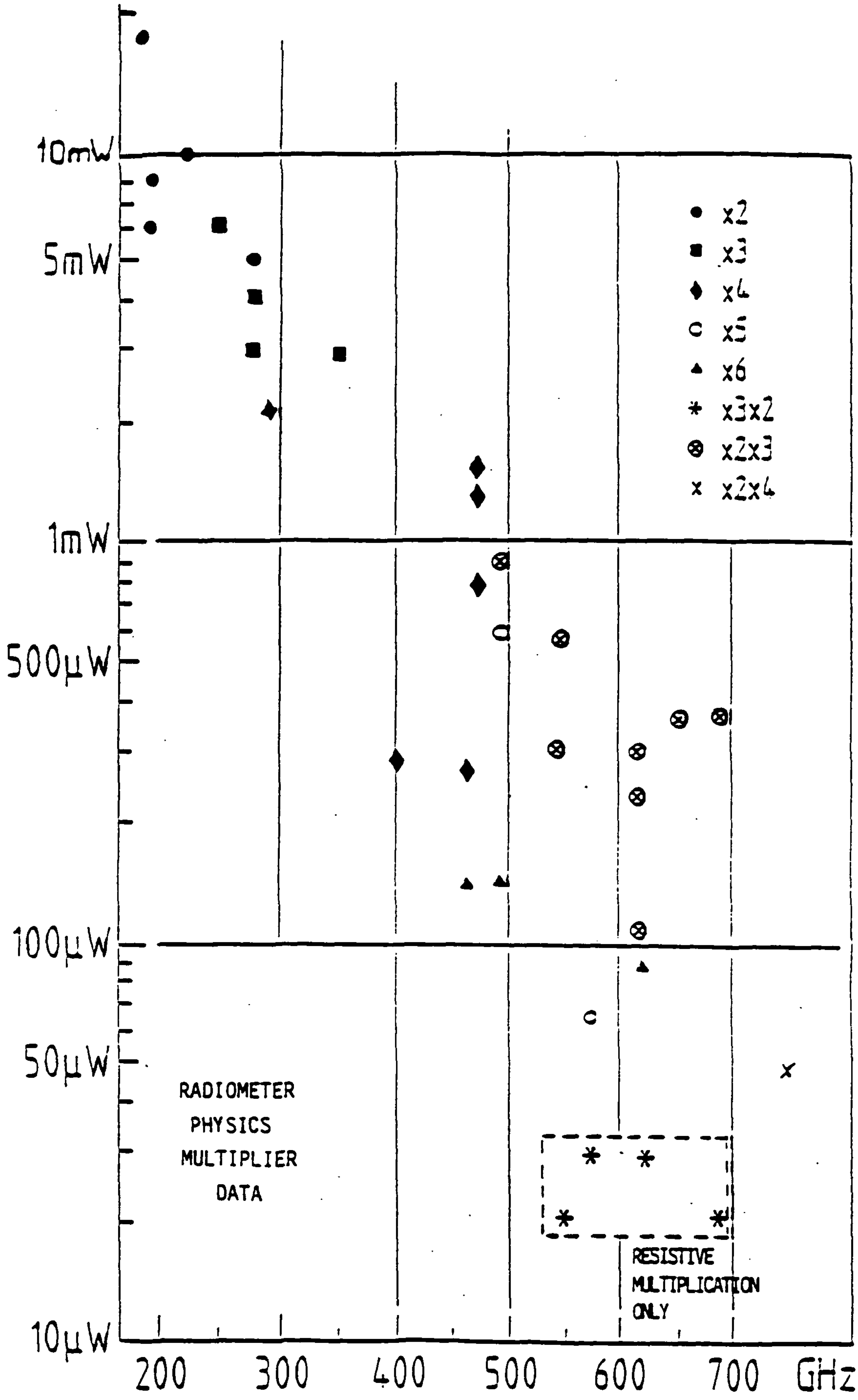


Fig. 10 POWER OUTPUTS FROM VARIOUS MULTIPLIERS

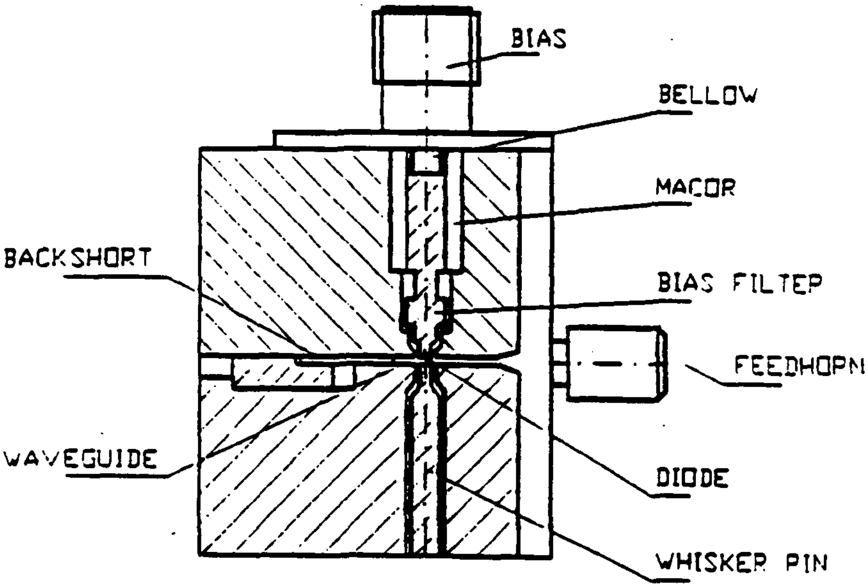
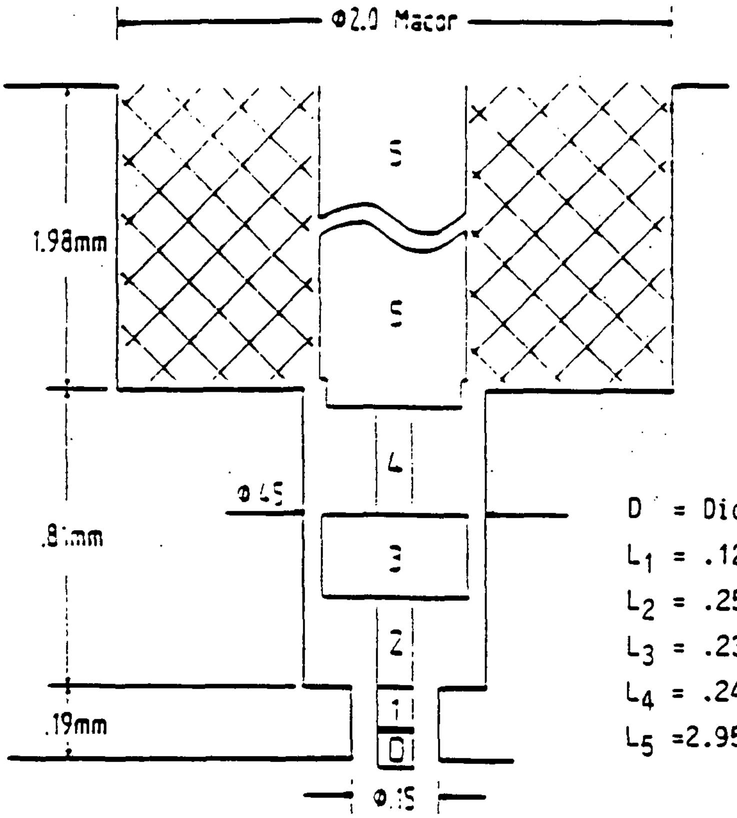


**Fig. 11: MIXER (SCHEMATIC)**



D = Diode
$L_1$ = .125 $Ø_1$ = .100
$L_2$ = .250 $Ø_2$ = .100
$L_3$ = .235 $Ø_3$ = .355
$L_4$ = .240 $Ø_4$ = .100
$L_5$ =2.95 $Ø_5$ = .40

**Fig. 12: MIXER CHOKE STUCTURE**

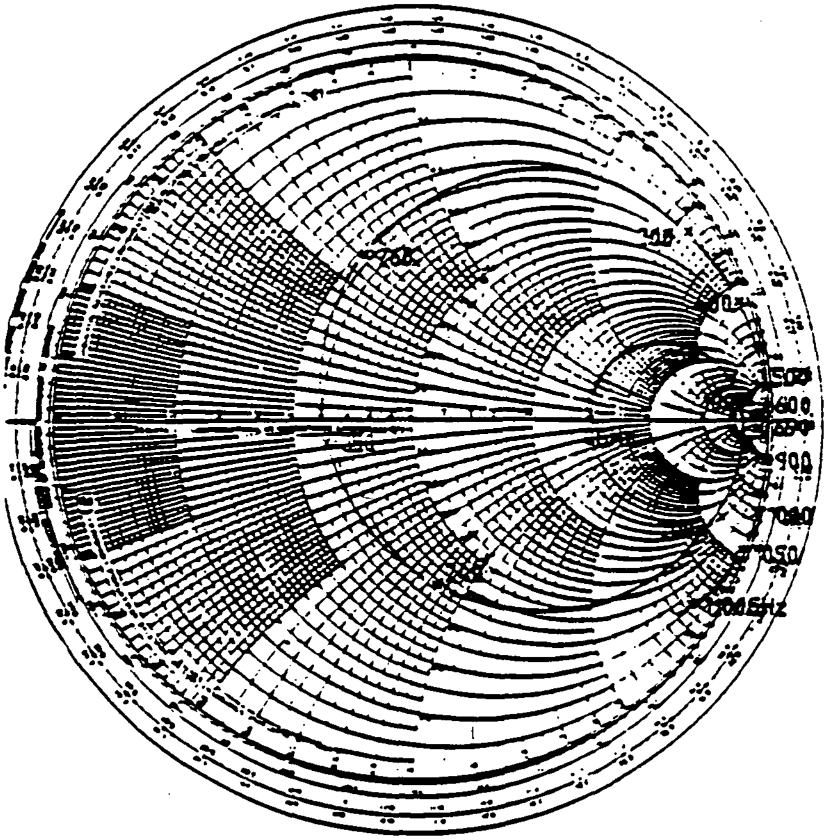


Fig. 13: MIXER CHOKE RF-IMPEDANCE

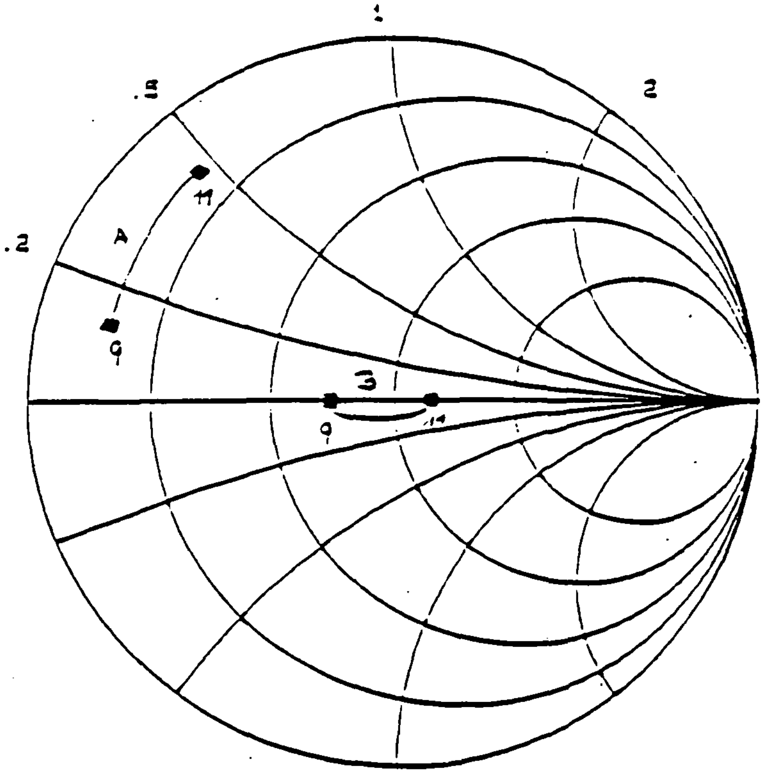


Fig. 14: MIXER IF-IMPEDANCE 9-11 GHZ
A: before B: after matching

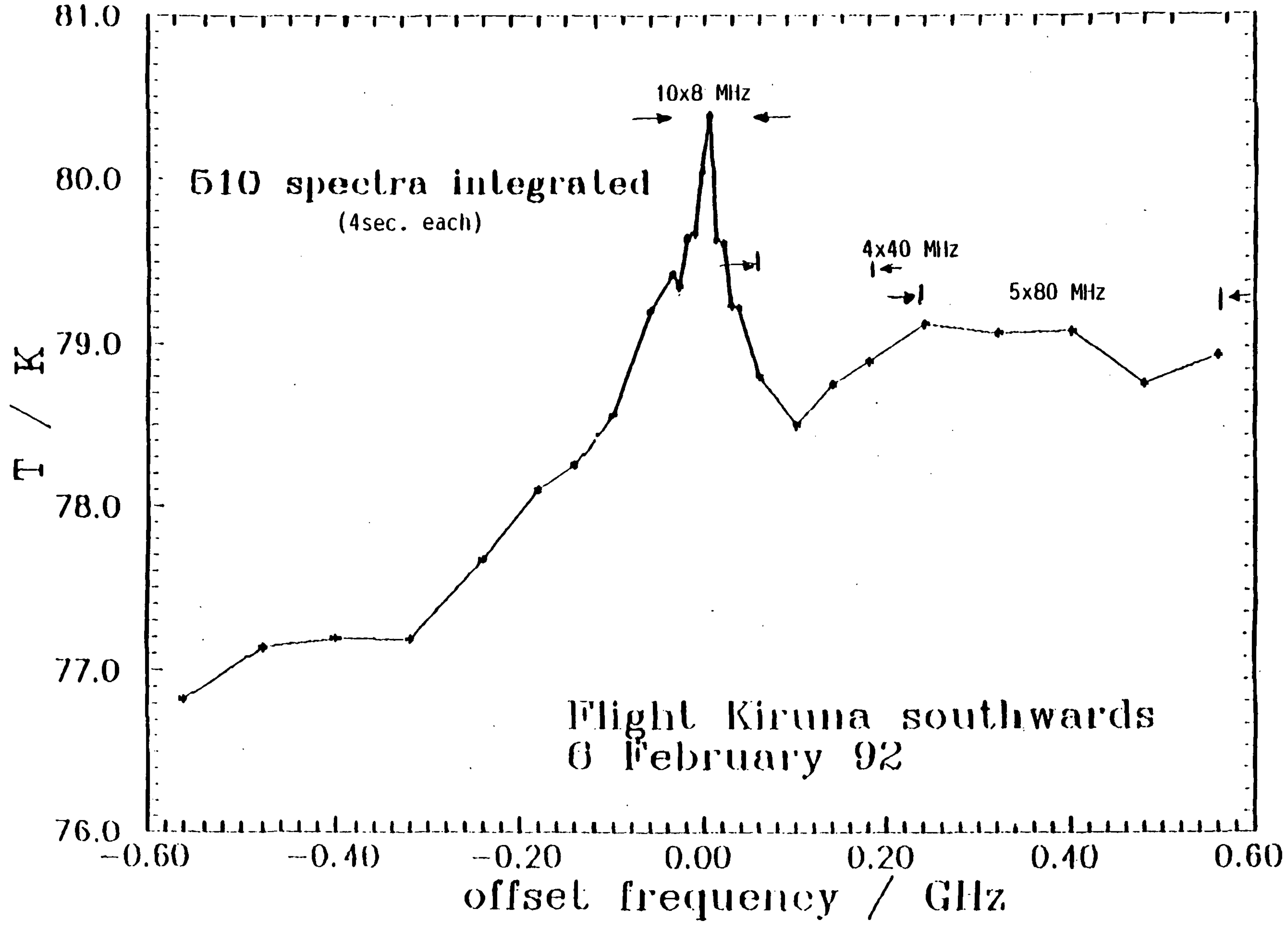


Fig. 15: ClO-LINE SPECTRUM