

LOW NOISE 500–700 GHz RECEIVERS USING SINGLE-DIODE HARMONIC MIXERS

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ABSTRACT

A second harmonic mixer has been built using a single Schottky diode achieving an overall noise temperature only 25% higher than that of a fundamental mixer at the same frequency. This mixer has been built in two models for center frequencies near 600 GHz. These mixers are pumped by frequency multiplied InP Gunn oscillators providing about 2 mW output. The theory of mixer noise and conversion loss agree fairly well with the experimental results. The best results are a receiver noise temperature of 5300 K SSB at 550 and 665 GHz. This mixer design will be used in receivers for 490 and 550 GHz in the Submillimeter Wave Astronomy Satellite.

INTRODUCTION

Harmonic mixers have long been used to frequency convert signals at a frequency where it is inconvenient or impossible to obtain a fundamental local oscillator source. However they have not offered noise performance comparable to fundamental mixers except at low frequencies where two diode balanced designs are available [1]. Even these have proven difficult to make work at their full potential, because of the need to match the two diodes and embed them in a stripline structure. While single diode harmonic mixers are much simpler, previous single diode mixers have not been designed to achieve an optimum set of embedding impedances at the LO and signal frequencies, nor has any detailed theoretical study been done to investigate the full potential of such a mixer. In this work we have made a computer study of a submillimeter harmonic mixer using a single Schottky diode to determine the optimum LO and signal impedances and have

constructed a mixer for 550 GHz which largely agrees with this theory and compares favorably with a fundamental mixer at the same frequency.

THEORETICAL STUDIES

A mixer analysis program [2] may be used to derive the optimum embedding impedances, bias current and LO power for a single diode mixer using an idealized Schottky diode. While this program is written for fundamental mixing, its output may be used to predict harmonic mixing results as well. This program includes all diode parameters including junction capacitance, and allows inputs of circuit impedances at three harmonics of the LO. Mixer bias voltage and current are also parameters (and thus indirectly the LO power). Outputs are conversion loss for conversion products up to the third harmonic, and the mixer noise temperature.

One way to achieve a low conversion loss in harmonic mixing is to suppress fundamental mixing (conversion of the signal to a frequency near that of the LO in this case), by severely mismatching the diode at the LO frequency and then using large amounts of LO power. Since this work was aimed at a submillimeter mixer, this approach is not practical, as LO power is quite limited. In this analysis the program was modified to fix the available LO power in order to use it as a constraint. The LO power was chosen to be 2 mW since this is all that is typically available from multipliers near 300 GHz.

The goal of the original work was to build a harmonic mixer for a frequency of 550 GHz in single mode waveguide, using a crossed waveguide structure to bring in the LO power. This allows a free determination of the impedances at the LO and signal harmonics. We made the assumption of a mixer with a low IF having identical embedding impedances at the LO harmonics and the two adjacent signal sidebands. The impedance at the signal frequency was determined by scale modeling the signal waveguide in the mixer mount and determining in an iterative process the closest impedance match achievable without resorting to extreme dimensions in the mount. This impedance was determined to be $80 + 120j \Omega$ while the third harmonic impedance was chosen at an estimated value of $50 + 50j \Omega$ (this value is not critical). The important variable to be determined was then the impedance at the LO fundamental frequency. Once an approximate value was found, the mixer bias current was optimized and then fixed at this value of 0.2 mA.

At this point the conversion loss and mixer noise temperature were calculated for a range of fundamental impedances. The mixer noise is found to have a broad minimum

which is not coincident with the conversion loss minimum. The best compromise depends on the IF noise temperature, but in most cases favors the lower mixer noise. This results in a predicted mixer noise temperature of 2100 K SSB and a conversion loss of 11.5 dB, at an impedance of $50 + 150j \Omega$. A 1 dB lower loss may be achieved with a 10% increase in mixer noise at an impedance of 100Ω . Even lower conversion loss may be reached at much higher impedances but at the cost of much higher noise. Over the region of minimum mixer noise, the effective diode noise temperature (the equivalent attenuator temperature of the diode) was found to be 200 to 250 K, which is lower than seen in most fundamental mixers in the submillimeter. In addition, the predicted conversion loss is only about 2 dB higher than predicted for a typical fundamental mixer, so the expectation is that a harmonic mixer should be fairly competitive, with perhaps a 25% higher noise. A practical single ended mixer also has input losses associated with coupling in the LO which are typically 10% in the submillimeter. One surprising result is that the IF impedance is predicted to be 1000Ω , resulting apparently from the low bias current, and the relatively large LO drive. This makes IF matching over a wide bandwidth more difficult.

SCALE MODEL STUDIES

In order to design an actual mixer having the optimized impedances it was necessary to do some scale modeling in order to fully understand the waveguide embedding structure. Initially the signal waveguide dimensions and contact whisker length were chosen to achieve a reasonable impedance match at the signal frequency. With the diode mounted in the signal waveguide this problem may be separated from the LO waveguide if the filter coupling in the LO is assumed to present a short circuit at the signal frequency. The waveguide height was chosen to be as low as practical for reasonable fabrication (0.10 mm high for a width of 0.35 mm at the actual size) since even the lowest practical height was too great for optimum matching. These dimensions resulted in the signal frequency impedances used in the computer studies.

Using a computer aided design program, a three section coaxial filter with air dielectric was designed to present a short circuit at the top wall of the waveguide at the signal frequency but a nearly optimum LO impedance when the effect of the contact whisker and LO waveguide are taken into account. The LO backshort was assumed to be $\lambda/4$ away from the coupling post in this design to maximize the fixed tuned bandwidth and minimize losses. In designing this filter, coaxial impedances were constrained to the range 20 to 60Ω to avoid excessively difficult construction. The LO waveguide

impedance was optimized at 150Ω . The filter was then incorporated into the mount and its effect verified. The circles of impedance as the LO backshort is tuned pass near the expected optimum impedance, with fairly minimal frequency dependence.

The construction of the mixer is shown in Fig. 1. The filter uses variations in the inner and outer conductor diameters to achieve the largest impedance ratio. In addition only the first section of the filter is designed to be cut off to higher modes at the operating frequency. Note that the first section of the center conductor of the filter consists entirely of the diode chip, which is cut into a roughly circular shape. Another filter is used on the other side of the LO waveguide to eliminate loss of power out the IF port. The filter center pin is supported by a machinable ceramic (Macor) ring, with 50Ω impedance through this ring (the highest impedance practical) to minimize problems with the IF match.

EXPERIMENTAL RESULTS

The mixers of this design were built with an electroformed signal waveguide with an integral conical feed horn. The LO waveguide was machined as a channel in a block attached to the electroform. The mixer diode in the first mixer for 550 GHz is a type 1E13 from the University of Virginia, with $C_j(0) = 1.5 \text{ fF}$, $R_s = 22 \Omega$ and epitaxial doping optimized for room temperature operation. This diode was contacted by a $4 \mu\text{m}$ diameter NiAu wire with a length of $60 \mu\text{m}$. Local oscillator power was provided by a frequency tripled InP Gunn oscillator, with about 2.5 mW output at 275 GHz. This mixer was used with a 1.4 GHz IF amplifier having a noise temperature of 50 K. An IF matching circuit was designed to provide an IF VSWR of less than 2:1 over a 500 MHz bandwidth. The unmatched IF impedance was measured to be 350Ω , which is significantly lower than the prediction of 1000Ω , but still higher than normal for a fundamental mixer at this frequency.

Local oscillator noise was found to be a potential problem with this mixer since there is no rejection of noise sidebands on the LO, which produce IF noise with a lower order mixing than that for the signal. However, this is found not to be a problem when an InP Gunn oscillator is used. When a GaAs Gunn is used the noise can be substantial, particularly at certain settings of the LO backshort, and thus these oscillators are not suitable for this application, unless perhaps a very high IF is used.

This receiver achieves a best noise temperature of 5300 K SSB at 550 GHz and a conversion loss of 12.8 dB with the mixer at room temperature. Optimum bias current is 0.2 mA as predicted, with the bias voltage varying from 0.5 to 0.65 V. The diode

effective noise temperature is 240 K, also as predicted. The higher than predicted conversion loss may result from input losses. The tripler was connected to the mixer with a 3.7 cm length of waveguide with a loss of 0.7 dB. While the mixer and tripler could be connected directly together, they could be made to work better with the long connecting guide because the length of the guide in combination with the tripler output mismatch modulates the LO impedance at the diode. If the phase is correct, the mismatch can favor coupling of LO power to the diode while simultaneously enhancing the impedance at the signal and image. With the incorrect phase the situation can be made worse. Thus the "low IF" approximation with identical impedances at all nearby frequencies used in this design is not strictly true.

The receiver noise temperature is 5300–7000 K across the frequency range 535 to 572 GHz with a ripple on a very fine scale due to the interaction with the LO multiplier. This frequency dependence is shown in Fig.2. No real trend is seen in the noise vs frequency. This mixer was also tested at 632 GHz where the noise is 6800 K. An identical mixer has been tested at just 637 GHz where it is about 5% noisier than the first. This bandwidth of operation with only backshort tuning exceeds that of fundamental mixers with similar waveguide dimensions. This may result from a higher operating impedance level which matches better to the relatively high mixer mount impedance. Since LO power is relatively difficult to obtain even for a harmonic mixer, we also measured the behavior of the conversion loss and noise as the LO power varies. A reduction of the tripler output by about a factor of two caused only a 10% increase in conversion loss and a 7.5% increase in receiver noise. Thus the mixing is fairly well saturated at 2 mW input, although more power will always work better, since the LO tuning may be altered to suit the power available.

A third mixer of identical design except scaled to higher frequency has been tested at 665 GHz using a U.Va. type 1I8 diode having a capacitance of 0.8 fF which also yields a best room temperature noise of 5300 K SSB. If the behavior as a function of frequency is the same as the first mixer tested, then similar results should be obtained up to 750 GHz. LO in this case is provided by an InP Gunn oscillator followed by a cascaded pair of frequency doublers producing 3 mW at half the signal frequency. This performance is superior to the 6300 K measured for a waveguide fundamental mixer of similar construction using a laser LO at 690 GHz, although the results are not directly comparable since this fundamental mixer was used with an older diode with $C_j(0) = 2$ fF. Use of the newer 1I8 diode in this mixer as well as in the 550 GHz harmonic mixer could be expected to lower the noise.

Two of these mixers were tested at lower temperatures to determine the noise

reduction with cooling. A temperature sensor was bolted to the mixer block and the complete mixer, IF amplifier and LO multiplier were slowly cooled in a styrofoam box partially filled with liquid nitrogen, with data taken over a range of temperatures. It is essential to cool the multiplier with the mixer since the connecting waveguide must be too short for effective thermal isolation. Multipliers have proven to be quite reliable at low temperature and even increase in output power. The Gunn oscillator was maintained at room temperature. Unfortunately, these tests were not begun with the diode contacts producing the very best results, so the room temperature noise was 6000 K SSB in both cases. However the cooling curve should be similar for all contacts. For the 665 GHz mixer the data showed a nearly linear decrease in noise with temperature, with a minimum value of 4300 K at 208 K. It became impractical to continue cooling below this temperature with such a crude setup. The 550 GHz mixer was also tested with the cooling continued down to 106 K in this case, resulting in a reduction of the receiver noise to 3100 K. This data is shown in Fig. 3. This noise is fit quite well by assuming that the mixer noise scales with ηT as measured from the dc IV curve, while the IF noise scales linearly with T. There is evidence from these curves and the IV data that even lower temperature operation would be beneficial, even though the diodes in these tests are very highly doped and show a rather nonthermal IV curve even at room temperature ($\eta = 1.2-1.3$). This doping is necessary in order to achieve the highest cutoff frequency and thus optimized coolable diodes are not presently practical for this frequency.

APPLICATIONS

The advantages of a harmonic mixer are quite substantial when the difficulties of producing the LO are considered. For Schottky diodes sufficient power is presently not available except from lasers for frequencies above 500 GHz. The constraints on the IF of a mixer used with a laser may significantly increase the receiver noise for many applications. The principal drawback of the harmonic mixer over a fundamental mixer is the higher IF impedance which limits the IF bandwidth for achieving a good match. A bandwidth of about 1 GHz with a VSWR of 2:1 is the best that can be done with the present design using the ceramic support ring. Also the interaction with the LO source would ideally require some way to adjust the phase of the LO path which appears a bit impractical for a widely tunable application.

The considerable simplicity of this design makes it very attractive for space applications, and it will be used in the Submillimeter Wave Astronomy Satellite (SWAS) in receivers for 490 and 550 GHz. We expect to operate these receivers at a temperature

of 100–150 K using passive cooling. Consideration is being given to this design for other space missions. The mixer tested at 665 GHz is intended for ground based observations in the 600–700 GHz window, particularly of molecular species such as ^{13}CO $J = 6 \rightarrow 5$ not yet observed using laser LO's.

REFERENCES

- [1]. Carlson, E.R., Schneider, M.V. and McMaster, T.F., "Subharmonically pumped millimeter-wave mixers," *IEEE Trans. Microwave Theory Tech.*, vol MTT-26, pp. 706–715, 1978.
- [2]. Siegel, P.H., Kerr, A.R. and Hwang, W., "Topics in the optimization of millimeter-wave mixers," *NASA Technical Paper #2287*, 1984.

FIGURE CAPTIONS

- Fig. 1. Cross section through the submillimeter harmonic mixer. The signal waveguide continues to an integral conical horn.
- Fig. 2. Noise temperature vs. frequency of the harmonic mixer designed for 550 GHz. All data is taken at room temperature.
- Fig. 3. Receiver noise temperature vs. physical temperature of two receivers using harmonic mixers tested at 550 and 665 GHz. Also shown is the best room temperature value for comparison.

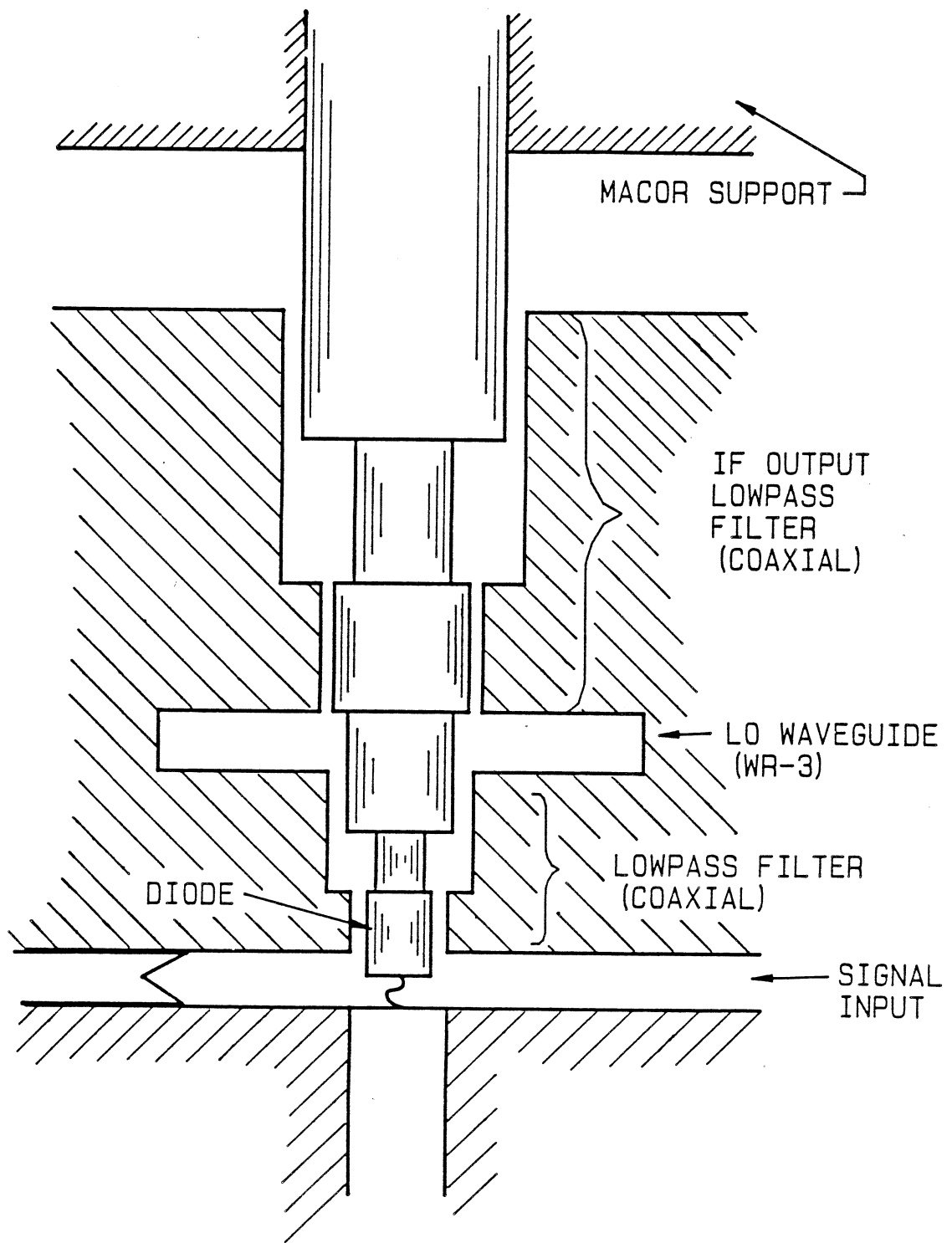


Fig. 1

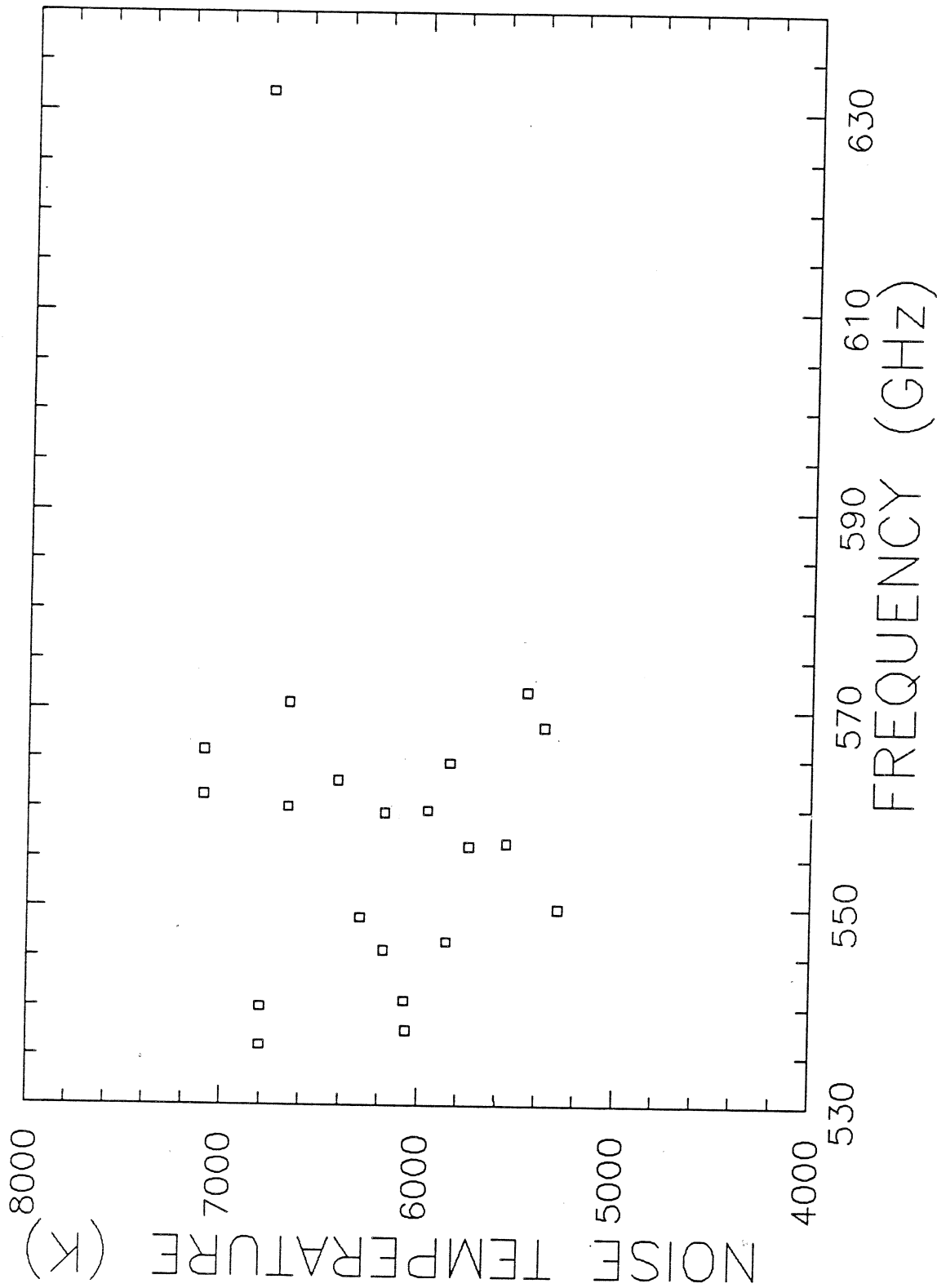


Fig. 2

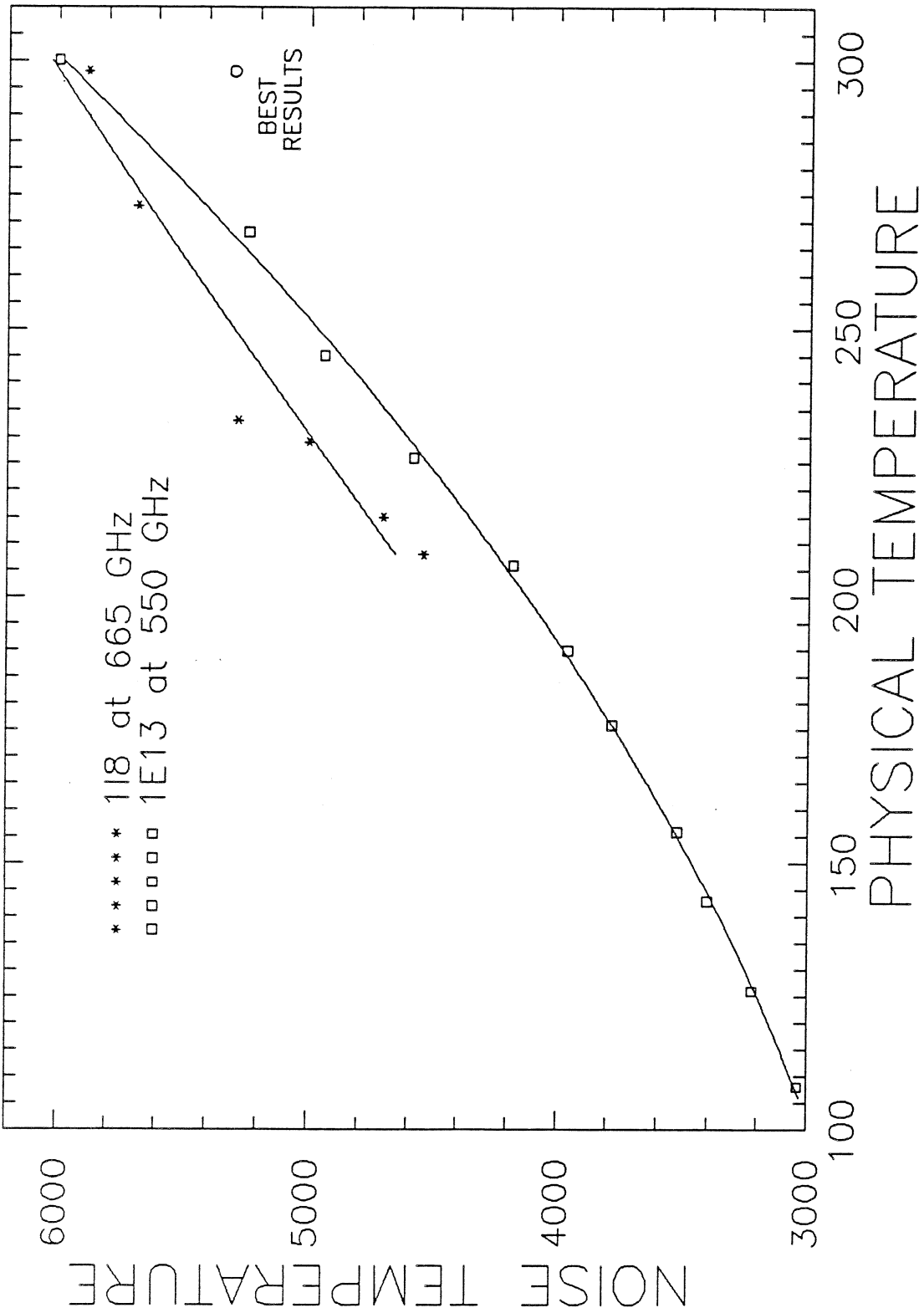


Fig. 3