A 345 GHz waveguide mixer with two mechanical tuners using an array of four of Nb-Al-Al_2O_3-Nb SIS junctions .

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Abstract

A waveguide mixer at 345 GHz, with both an E-plane tuner and a backshort as mechanical tuning elements is described. The guide has a two times reduced height and the tuners are contacting sliding shorts. As a detector we use an array of four Nb-Al-Al_2O_3-Nb SIS junctions in series. The area of one junction is 4 μm^2 and its normal state resistance is about 12 Ω, yielding at 345 GHz, $\omega RC \sim 5$.
The receiver noise temperature is below 550 K from 330 to 375 GHz with best results around 350 K measured with a hot and cold load calibration. The instantaneous bandwidth of the mixer is around 2 GHz. The performance of the receiver has been verified by measuring the gas emission line of CO.

Introduction

Our purpose is to build a sensitive receiver for astronomy applications. We study mixer performance at 345 GHz as a first step in building receivers for higher frequencies. Since space qualification is a long term goal of the project we focus on all-niobium junctions. They have proven to be very stable in time and have a reliable and reproducable performance. At 345 GHz no problems with the gap frequency of the material are expected. We find that a magnetic field is necessary to suppress the Josephson effect.

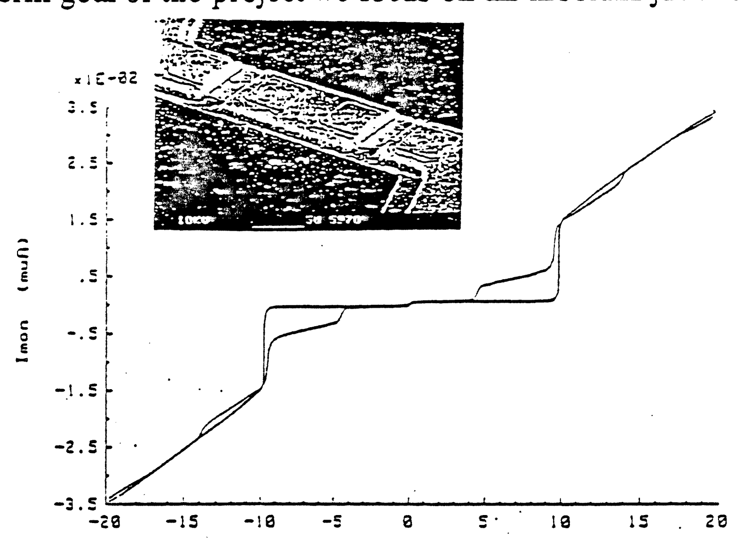

Figure 1a IV-characteristic of four Nb-Al_2O_3-Nb junctions in series. A magnetic field is applied. The pumped stepheight (345 GHz) shows the optimum mixer power level. The inset shows the actual array (SEM).

Design considerations

The junctions have areas of 2x2 μm^2 with a normal state resistance of 12 Ω. Taking 50 fF/μm_2 for the Al_2O_3

barrier this means that an impedance of (0.45 + 2.2j) Ω must be matched to the antenna.
To realize maximum tuning possibilities we chose a waveguide environment for the junctions. The best receivers built at lower frequencies used waveguides [1],[2]. At 345 GHZ waveguide technology is still possible and good mixer performance has been demonstrated using small area lead-junctions [3].
We use a two times reduced heigth waveguide (625 μm x 150 μm) to compromise between matching requirements and controlled fabrication. An additional advantage is that such a conservative design can still be scaled to higher frequencies. The waveguide is cut out in OFHC copper and so far not gold plated. Radiation is coupled into the waveguide with a diagonal horn [4] modified [5] for ease of fabrication . The distance between the E-plane tuner and the junctions is roughly half a guide wavelength. The substrate with the junctions lies symmetrically across the waveguide. The plane of the junctions is in parallel to the narrow wall of the waveguide. The substrate material is fused quartz and the dimensions are 2.5mm x 190 μm x 92 μm. The substrate channel is 220 μm x 200 μm.
With the two tuners the impedance of the junction can be matched to the waveguide. The quality of the tuners expressed in their VSWR should roughly be equal or less than the ratio of the waveguide impedance and the real part of the junction equivalent impedance. For one tuner this requires a VSWR of 250. It is reasonable to expect [6] a best VSWR of the order of 100. This means that with the given junction parameters an array of four junctions in series is sufficient.
An measured IV-curve of four junctions in series is given in Fig.1a. The inset shows the actual array. To minimize the effects of stress we applied an underlayer [7]. The Nb underlayer is 150 nm thick. The base and counter electrode are 50 nm thick, the Nb wiring layer is 700 nm and the Si insulating layer is 350 nm thick.

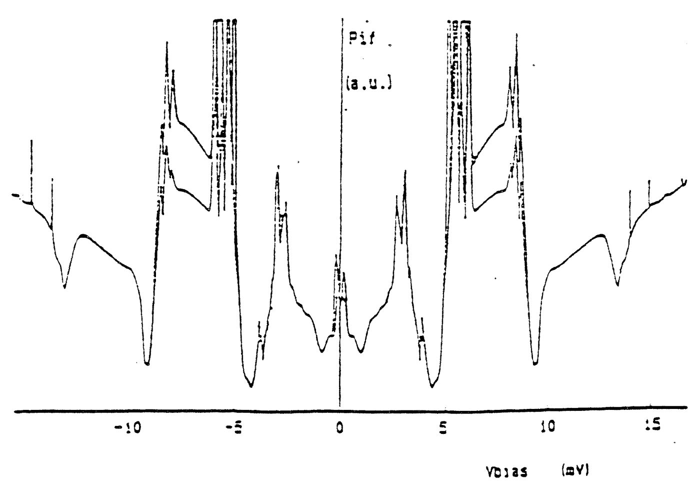

Figure 1b IF-output power as a function of bias voltage at a hot (upper) and cold load input of the mixer. The same magnetic field as in Fig. 1a is applied.

Measurements

The measurement set up is shown in Fig.2. The optimum pump power for various junctions is measured with a Golay cell. When the optimum pump power is low the noise temperature of the mixer is generally also low. The heigth of the quasiparticle step is roughly the same for all measured junctions at optimum pump power, an example is shown in Fig.1.
The noise temperature of the mixer is determined using a hot (300 K) and cold (80 K) load measurement. Results are summarized in Fig.3a.
For each frequency the optimum tuning point is used. The results are corrected for the beamsplitter transmission with 15 %.

As shown in Fig.2 we use a beamsplitter with a low transmission/reflection ratio, because the LO-source has not enough output power over the whole band.

From 330 GHz-375 GHz the noise temperature is below 550 DSB with best results around 350K.

The instantaneous bandwidth around 347 GHz is of the order of 2 GHz (Fig. 3b).

A plot of the IF-output as a function of bias voltage is given in Fig.1b. Because the four junctions of the array are not sufficiently identical the Josephson effect cannot be fully suppressed without reducing the gap of the niobium. The third minimum of the Fraunhofer dependency is used. For incomplete suppression of the Josephson effect the noise temperatures increase.

So far, no impedance transformer is used at the IF-frequency to match the junction to the 50 Ω IF-chain. The measured dynamic impedance of the junction is around 220 Ω.

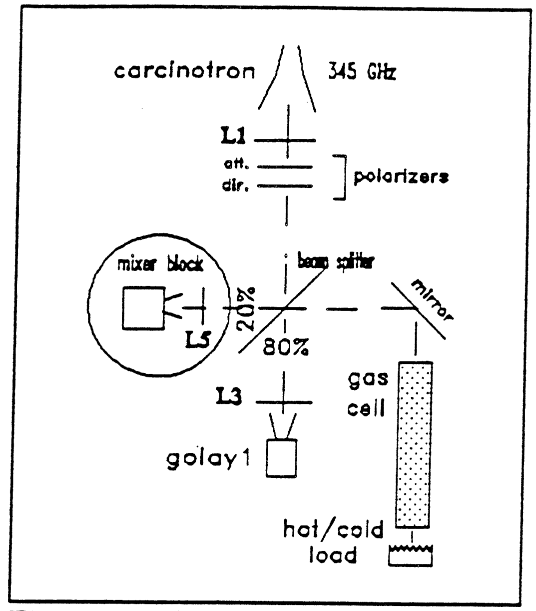

Figure 2 Schematic drawing of the measurment set-up. L1, L3 and L5 are HPD lenses. The beam splitter is made of 50 μm thick mylar foil.

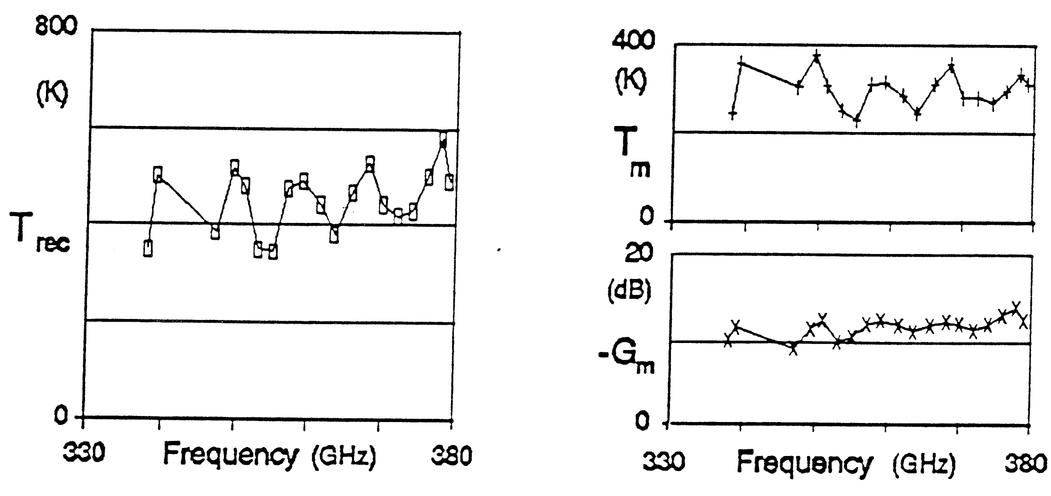

Figure 3a Receiver(T_{rec}) and mixer(T_m) noise temperature, and mixer conversion loss(G_m) obtained from a hot/cold load calibration. At each frequency the optimum tuning point of the mixer is used.

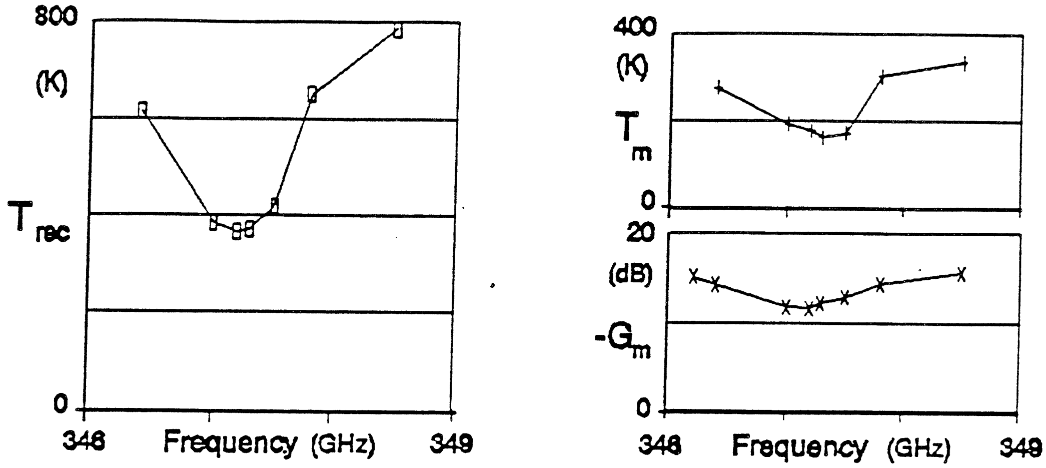

Figure 3b Receiver and mixer noise temperature, and mixer conversion gain as in Fig. 3a. The mixer is optimized at 347 GHz. At the other frequencies the tuning is not changed only the LO-power is adjusted.

The embedding impedance of the junction is analyzed with a 105x enlarged scale model (Fig.5). With a thin (D=1.25mm) coaxial cable the reflection of the mount is measured at the location of the junction. The impedance of the structure probing the waveguide with the two substrate channels shorted is given in Fig. 4A as a function of backshort position. Using the E-plane tuner the whole shaded region of impedances can be presented to the junction. The equivalent impedance of the four junctions in series (+) and its complex conjugate (x) are also indicated in Fig.4a. We ignored any possible induction in the interconnecting leads of the array.

The IF-filters are designed to form a short circuit at the waveguide wall. Without an E-plane tuner matching of the junction is impossible.

Future simpler designs of mixers at higher frequencies will preferably have only one mechanical tuning element. To anticipate on this development the length of the first section of the IF-filter is chosen to compensate the induction of the probe in the waveguide [8]. The resulting embedding impedance as a function of backshort position is given in Fig. 4b. First measurements [9] using a similar mixer with a single backshort done at the NFRA+ show receiver noise

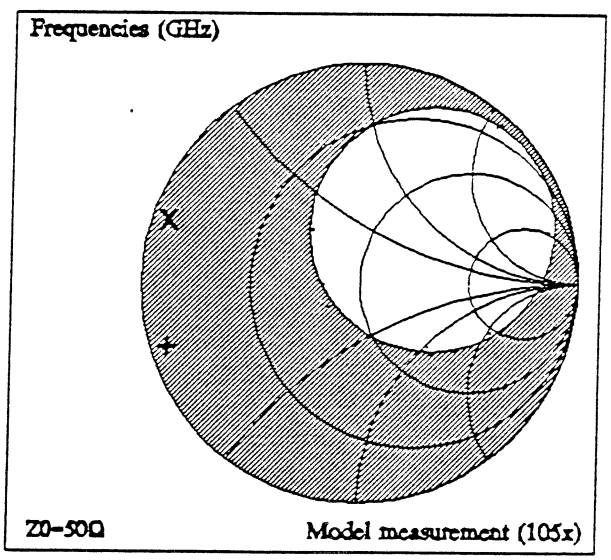

Figure 4a The circle shows the impedance of the probe in the waveguide as a function of backshort position. The angle of the probe is 70 deg., the substrate (εr=4) thickness is 6.5 mm.

temperatures of 300 K DSB. Similar designs without compensation of the inductance give in the same set up noise temperatures of 1000 K DSB.

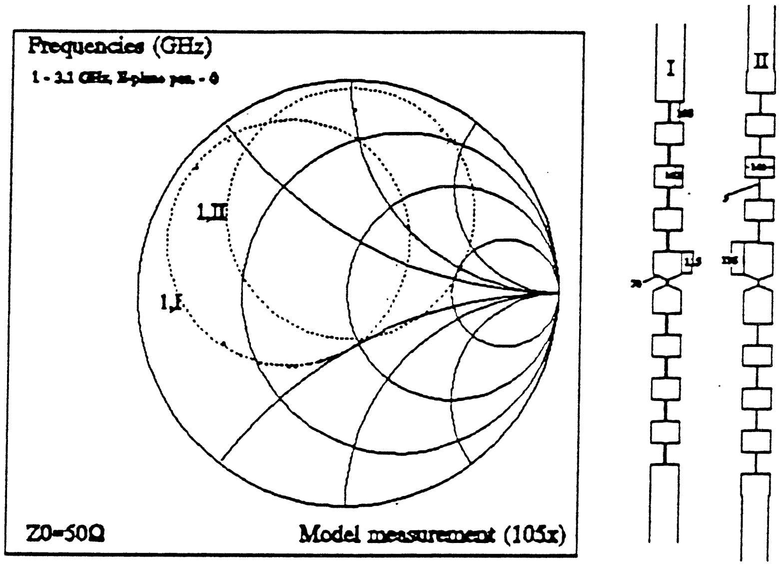

Figure 4b Effect of partly compensating the probe inductance by tuning the first section of the IF-filter. The dimensions in the corresponing filter drawings are in µm.

To verify the heterodyne response of the mixer we studied the emission line at 345.795 GHz of CO-molecules in a gas cell (Fig. 6).
At the IF-frequency we use an Acousto Optical Spectrometer (AOS) with 1025 diodes in a bandwidth of 100 MHz, with an integration time of 32 seconds. Before measuring the emission line the density of CO molecules is measured in absorption. This is done (Fig. 2) by directing the LO-signal through the cell and scanning the frequency.
Because of the narrow instantaneous bandwidth of the mixer the incoupling is optimized at the frequency of the molecular line. After optimization the LO is detuned by 1.4 GHz. A cold load is placed behind the cell while measuring emission.

Evaluation

The absolute value for the output power of the IF-amplifier at a hot (or a cold) load input of the mixer is given by :

$$P_{out} = kB((T_i + T_m) G_m G_{if} + T_{if} G_{if}) \quad (1)$$

where k is the Boltzmann constant, B is the bandwidth of the IF-system, T_i is the temperature of the load. T_m is the noise temperature of the mixer and G_m the conversion gain. With the known gain (G_{if} = 40 dB) and noise temperature (T_{if} = 7±3 K.) of the IF amplifier G_m and T_m are determined from two measurements with different T_i.
The absolute output power depends on the exact value of the pump level and on the suppression of the Josephson effect. Especially the suppression of the Josephson effect

may vary from one measurement to another causing a rather large uncertainty in the output power. The results of the calculations are given in Fig.3a and 3b.
When the geometrical capacitance of the junction array is added to the embedding impedance measured in the scale model the optimum impedance circle in Fig.4c results. The expected frequency dependence of the incoupling is also given. The expected instantaneous bandwidth would be about 1.5 GHz where the measured one (Fig. 3b) is about 2 GHz. This would point a reasonable good tuning and contradicts with the results on conversion gain.

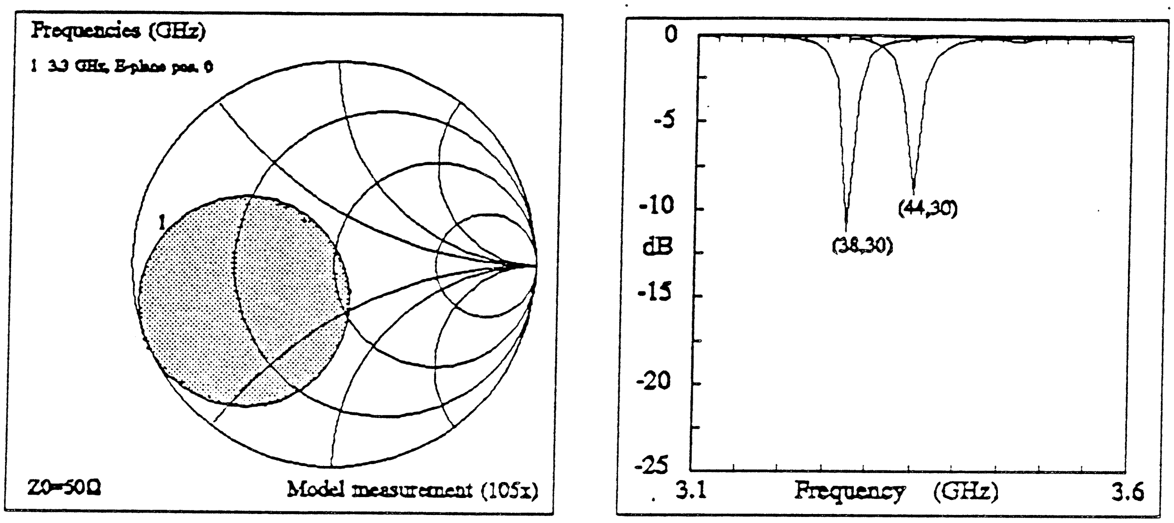

Figure 4c Resulting impedance and power reflection after adding 50 fF in parallel to the embedding impedance measured (to 50 Ω) in the scale model. The E-plane tuner is set at an optimum position.
The impedance is shown as a function of backshort position. The power reflection is given as a function of frequency at two different backshort settings.

The strength in degrees K of the molecular emission line of CO is calculated from 80*(1-A)+300*A, where A is the measured percentage of absorption (The gas in the cell is at room temperature). The strength of the emission line at the input of the mixer, corrected for 15 % beamsplitter loss, is 157 K, i.e. A=48%.
The vertical scale of the AOS is calibrated in degrees K by a hot and cold load measurement through the gas cell. The detected line strength for CO is 83 K.
From the difference in input and detected line strength a SSB noise temperature of 420 K is found.

Conclusions

Using a conventional waveguide design, a heterodyne mixer with an array of all -niobium junctions at 345 GHz is constructed.
Putting junctions in series seems to work without problems at 345 GHz.

The instantaneous bandwidth of the receiver is about 2 GHz. This means that the noise temperature of the mixer observed from the broadband hot/cold load calibration is closer to a SSB noise temperature than to a DSB one. The SSB noise temperature is about 420 K at 345 GHz verified by a gas emission line measurement of CO.
The instantaneous bandwidth compares roughly with the prediction from the scale model measurements.
There are preliminary indications that it is advantageous to compensate the inductance of the waveguide probe by the design of the IF filter. This also compares well with what can be predicted from scale model measurements.
The calculated conversion loss is much higher than might be expected from a SIS mixer which may be due to the quality of the backshorts.

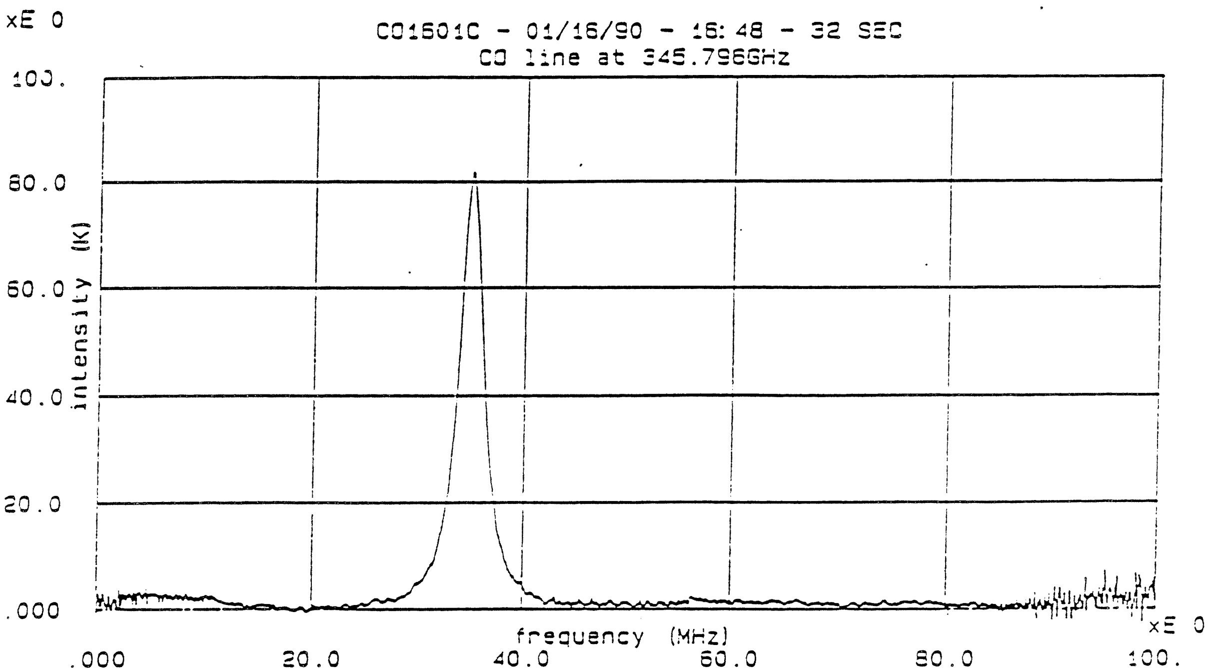

Figure 6 CO emission line at 345.795 GHz as measured with our receiver in the laboratory.

Acknowledgements

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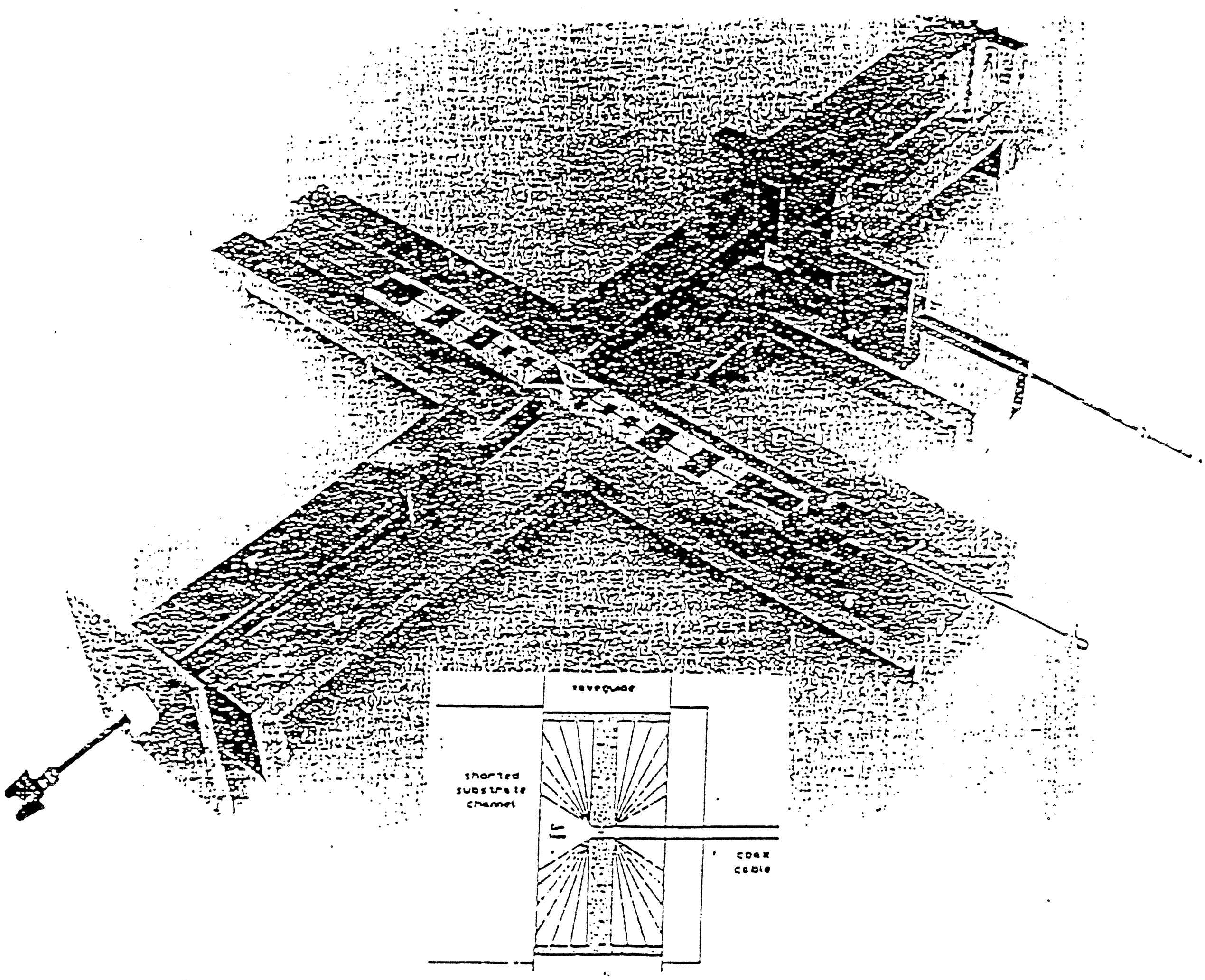

Figure 5 Photograph of the scale model. The coaxial cable is sitting at the right side of the substrate. The backshort is right behind the junction location and the E-plane tuner is constructed in the braod wall of the waveguide.
The inset shows the shows the probe in the waveguide as measured (see Fig. 4a) with different probe angles indicated. The substrate (hatched) has a diëlectric constant of 4 and is 6.5 mm thick.