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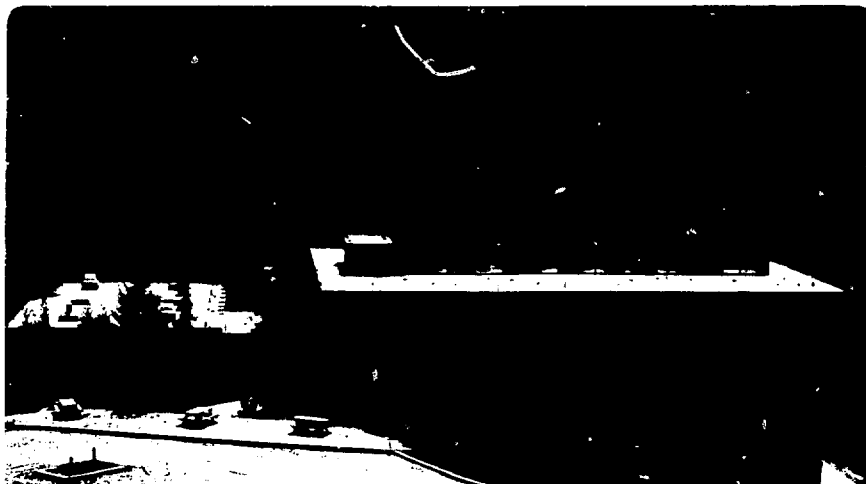# Materials & Chemical Sciences Division

MM Wave Quasioptical SIS Mixers

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MM WAVE QUASIOPTICAL SIS MIXERS*

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Abstract

We have tested the performance of planar SIS mixers with log-periodic antennas at near millimeter and submillimeter wave frequencies from 90 to 360 GHz. The large $\omega R_N C$ product (~10 at 90 GHz,) of our Nb/NbO$_x$/Pb-In-Au junctions requires an integrated inductive tuning element to resonate the junction capacitance at the operating frequencies. We have used two types of integrated tuning element, which were designed with the aid of measurements using a Fourier transform spectrometer. Preliminary results indicate that the tuning elements can give very good mixer performance up to at least 200GHz. An inductive wire in parallel with a 5-junction array gives a minimum mixer noise temperature of 115K (DSB) at 90GHz with a FWHM bandwidth of 8GHz. An open-ended microstrip stub in parallel with a single junction, gives minimum mixer noise temperatures of 150 and 200K (DSB) near 90 and 180GHz with FWHM bandwidths of 4 and 3GHz respectively. The relatively high mixer noise temperatures compared to those of waveguide SIS mixers in a similar frequency range are attributed mainly to the losses in our optical system, which is being improved.

I. Introduction

SIS receivers using planar antennas and quasioptical coupling schemes have shown good performances at millimeter and submillimeter wavelengths.[1-4] Advantages over waveguide mixers include ease of construction at high frequencies and broad instantaneous bandwidth. One of the major problems encountered at near millimeter and submillimeter frequencies is the capacitive roll-off, which can significantly decrease the RF coupling efficiency of the mixer. In a waveguide mixer, this capacitance can be tuned out by the backshort or other mechanical adjustment. However, in quasioptical mixers, we must either fabricate high current density, small area (<<1μm^2) junctions so that the capacitance does not dominate the RF coupling, or use a lithographed inductive element to resonate the capacitance at the signal frequency.[4-5] The first approach requires difficult microfabrication techniques that are not widely available. The use of an inductive tuning element relaxes the requirement on junction size and current density. It will be especially useful for all-refractory metal junctions, which are normally made with relatively large areas by the window-junction technique.

We have tested two types of integrated tuning element. One is an inductive wire in parallel with a 5-junction array; the other is a microstrip snub with an inductive admittance at the desired frequency. The preliminary results show that the SIS junctions with tuning elements exhibit well developed photon-assisted-tunneling steps up to 360GHz when pumped near their resonant frequencies. Very good mixer performance is obtained up to 200GHz.

II. Design and testing of tuning elements

The mixer system can be represented by the simplified equivalent circuit shown in Fig. 1. The RF input is represented by an RF current source in parallel with the antenna impedance. For our self-complementary planar antennas, this impedance is 120Ω at all frequencies.[6] The junction capacitance, lead inductance, and the tuning element are represented by C, L$_L$, and X. The nonlinear quasiparticle tunneling is represented by its RF resistance R$_{RF}$, which depends on the LO pump and DC bias. It is usually in the range of R$_N$/2≤R$_{RF}$≤R$_N$, where R$_N$ is the normal state resistance of the junction. The conversion gain and noise temperature of a mixer are

very complicated functions of the imbedding admittance, which includes the junction capacitance, the tuning element, and the antenna admittance. To a rough approximation, the mixer gain is proportional to the RF coupling coefficient C$_{RF}$, which is given by

$$C_{RF} = 1 - \left| \frac{Y_A - Y_J}{Y_A + Y_J} \right|^2,\qquad(1)$$

where Y_A is the antenna admittance, and Y_J is the admittance of the right side of Fig. 1.
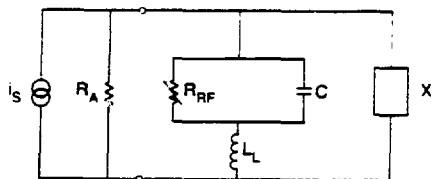

Fig. 1 Equivalent circuit of quasioptical SIS mixers. The signal at the terminals of the planar antenna is represented by the current generator i$_s$ and the resistance R$_A$. The pumped junction is represented by the nonlinear resistance R$_{RF}$ and the geometrical capacitance C, the leads to the junction by the inductance L$_L$ and the tuning element by the reactance X.

The Nb/NbO$_x$/Pb-In-Au junctions used in this study are limited by fabrication techniques to a 1.7×1.7μm^2 area, so that C=380fF. Without tuning elements, Eq. (1) predicts a very poor coupling coefficient of -11dB at 100GHz and very poor mixer performance.[2] This performance can be improved by the use of an integrated tuning element.

The first type of tuning element is the inductive wire shown in Fig. 2(a). One end of the inductive wire is conneted to the junction array through a 10-μm wide, open-ended quarter-wavelength microstrip stub, which provides an RF short and DC isolation. For junctions with large ωRC and short leads, that is, for R$_{RF}$>>(L$_L$/C)$^{1/2}$, the resonant frequency is given by[7]

$$f_0 = 1/2\pi\, [C\,(L_W + L_L)]^{1/2}.\qquad(2)$$

where L$_W$ and L$_L$ are the inductances of the wire and the leads. From our estimated parameters, the resonant frequency is 100GHz.

The second type of tuning element, an open-ended microstrip stub, is shown in Fig. 2(b). For a single junction, the lead inductance L$_L$ can be neglected, so the resonance condition is given[8] by

$$\omega_0 C Z_n - \tan(\omega_0 l / v) = 0.\qquad(3)$$

where Z$_n$ is the characteristic impedance, v is the phase velocity, and l is the length of the stub. In contrast to (2), Eq. (3) predicts an infinite number of resonances. The dimensions of the stub are chosen that $\omega_0 C Z_n = 1$ to obtain the broadest bandwidth.

We have measured the frequency characteristics of the tuning elements by using an SIS junction connected to the antenna as the direct detector for a Fourier transform spectrometer.[4] The agreement between the measured results and the computations based on the equivalent circuit of Fig. 1 is excellent, both for the resonant frequency and the bandwidth. The frequency dependence of the
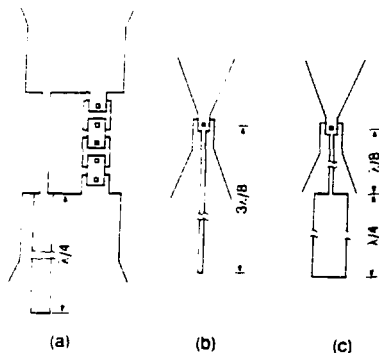
Fig. 2 Diagrams of SIS junctions with tuning elements: (a)
Five-junction array with inductive tuning wire. (b) Single junction
with open-ended microstrip stub. (c) Single junction with RF
shorted-end microstrip stub.

mixer gain is essentially the same as that of the coupling coefficient
C_{RF}. This indicates that the operating frequency and the bandwidth of
the quasioptical mixer are determined mainly by the frequency
characteristics of the tuning element. For the open-ended stub, a
small amount of loss and dispersion has to be introduced in the
calculation to fit the experimental result. The effects of the loss and
the dispersion become noticeable only when $f \geq 200$GHz.[7]

The inductive wire has the advantage of broader bandwidth than
that of the open-ended stub. Because of its high lead inductance,
however, it is impossible to use it for frequencies above 150GHz for
our values of junction capacitance. The open-ended stub has
narrower bandwidth because its impedance varies rapidly with
frequency. However, it can be used up to 400 GHz for our junctions.
An alternative stub configuration which is RF shorted at the end as
shown in Fig. 2(c) has been suggested[5]. Its bandwidth is expected to
be twice that of an open-ended stub and it is expected to be useful
up to 300GHz for our junctions. The fabrication of such shorted-end
stubs is in progress.

III. Mixer testing apparatus

The mixer test apparatus, which is shown in Fig. 3, allows us to
make measurements of the mixer noise temperature in addition to the
receiver noise temperature. The LO and the signal from the RF
hot/cold load are combined by a 0.075mm Mylar beamsplitter, which
has 97% transmittance at 90GHz. The combined LO and signal are
focused by an f/1 off-axis paraboloidal mirror onto the window of the
cryostat. The vacuum window for the cryostat is a 0.02 mm
polypropylene film. A 12.7 mm-diameter, 0.83mm quartz window,
which absorbs most of the thermal radiation in the infrared range and
has almost 100% transmission at multiples of 90GHz, is attached to
the liquid nitrogen cooled radiation shield. The LO and the signal
inside the cryostat are focused by an on-axis ellipsoidal mirror onto a
hemispherical quartz lens. The edge of the mirror is 50° from the
normal of the antenna plane. The hemispherical quartz lens provides
heat sink for the mixer as well as a dielectric half-space through
which the planar antenna couples most efficiently to the input
radiation.[6] The planar antenna is located on the flat side of the
hemispherical lens.

We have used the circular-toothed log-periodic antenna shown
in Fig. 4. Both the tooth angle and the bow angle are 45°, and the
ratio of the radii of the adjacent teeth is 2. The choice of the angle and
the ratio is a compromise between antenna beam width and cross
polarization.[9-11] This antenna is designed to be operated from 20
GHz to 500 GHz. The self-complementary antenna shown in Fig. 4
has a real and frequency independent impedance.[6] For quartz, with ε_r
= 3.83, the antenna impedance is 120Ω. The log-periodic antenna has
a much better antenna pattern[9-11] than that of bow-tie antenna used
in the previous work,[5] which has its main lobes 60° away from the

normal in the E-plane.[9] The SIS junction or junction array and its
integrated tuning element are located at the center of the antenna.

Our IF system includes a transformer[4] with center frequency at
1.3GHz, an L-band isolator, and an IF amplifier beginning with a
cold HEMT (high electron mobility transistor) in the first stage. The
overall noise temperature of the IF system including the isolator is
typically 6K at 1.3GHz measured with an IF hot/cold load.[4]
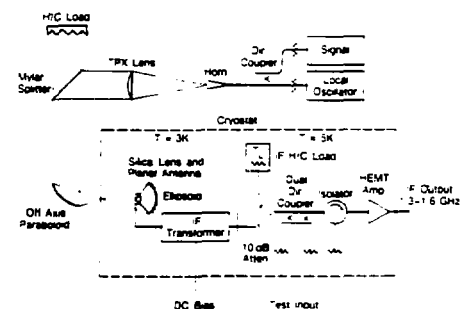

Fig. 3 Quasioptical SIS receiver testing apparatus.

Care has been taken to ensure that the SIS junction and the
antenna are well heat sunk to the cold plate through the quartz
hemispherical lens and its copper support, and the heat flow through
the leads to the junction is minimized. We have measured the
temperature at the center of the antenna by using a miniature doped
Ge thermometer. For a 1.8K bath temperature, it is 2.8K when the
IF amplifier is on and 2.6 K when the IF amplifier is off.

We have studied the effect of temperature on the mixer
performance. One of the SIS mixers has a mixer noise temperature of
133 K(DSB), and a coupled mixer gain of -3.9 dB (DSB) when the
helium bath temperature is 1.8K. The same mixer has a mixer noise
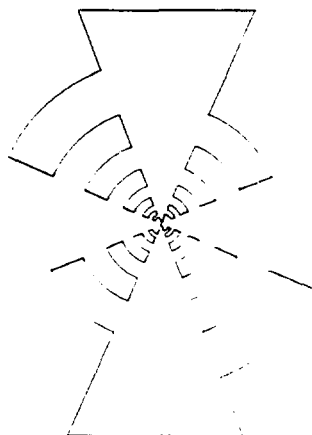temperature of 133 K (DSB), and a coupled mixer gain of -6.5 dB

Fig. 4 Circular-tooth log-periodic antenna.

(DSB) when the bath temperature is 4.2K. Although the gain of the warmer mixer is significantly less, the mixer noise temperatures are almost identical. This evidence suggests that the warmer physical temperature of our quasioptical mixer compared to that of the waveguide mixer tested previously[8] is not responsible for the higher mixer noise temperature of the quasioptical mixer. Because of the decrease in mixer gain, however, the receiver noise temperature increases from 150K for a 1.8K bath temperature to 174K for a 4.2K bath temperature.

IV. Results and discussion

The Nb/NbO$_x$/Pb-In-Au window junctions with planar antenna and tuning elements used in this work were made at National Bureau of Standards at Boulder. The current densities vary from 400 to 1000A/cm^2. The junctions can be thermally cycled many times without changing their characteristics as long as they are kept free from moisture. The microstrip stub is made from a Pb-In-Au film separated by a 300nm SiO layer from the Nb base electrode.

All the measured mixer noise temperatures and mixer gains are referred to the RF hot/cold load. No correction for optical losses is made. All the mixer measurements were performed in the double-sideband (DSB) mode. The accuracy of the measured noise temperature is ±10K.

Saturation is not very important at frequencies higher than 90GHz. Assuming an IF bandwidth of 2GHz, IF load resistance of 300Ω, and mixer gain of 0.5, the hot load temperature required to produce 1dB of gain compression is 750K at 90GHz for a single junction and 1.9×10^{4}K for a 5-junction array.[12] The saturation power is proportional to the square of the operating frequency.

Five junction array with inductive wire

Our best mixer performance at 90GHz is obtained from a five-junction array with an inductive wire. The total resistance of the array is 370Ω. Since the lead inductance L$_L$ acts like a transformer, this resistance gives a real part of Y$_J$ about 120Ω at the resonant frequency. This Re(Y$_J$) is well matched to the impedance of the planar antenna. The lowest mixer noise temperature is 115K at 87GHz and the coupled gain is -3.4dB. The FWHM bandwidth of the coupled mixer gain is 8GHz. This result is marginally (10%) better than that of an SIS array mixer with a bow-tie antenna measured with the same test apparatus.[2] Using a Gaussian beam pattern approximation, we estimate that the obscuration loss from the hemispherical lens is about 3dB for the narrow antenna pattern of the log-periodic antenna compared to that of 0.8dB for the much wider pattern of the bow-tie antenna.[2] Our quasioptical system has been improved by replacing the on-axis ellipsoidal mirror with an off-axis ellipsoidal mirror. The comparison tests between the two systems are yet to be made.

Single junction with microstrip stub

We have tested mixers with a single junction and microstrip stub which has resonant frequencies close to 90, 180, 270, and 360GHz. At 90GHz, we used a stub with the same dimensions used previously in the bow-tie antenna mixers.[2] The best mixer performance is obtained from a junction with 250Ω normal resistance. The mixer noise temperature is 150K and the coupled mixer gain is -6.5dB at 103GHz. The FWHM bandwidth of the coupled gain is about 4GHz. Again, this result is within 10% of that obtained from a similar mixer with a bow-tie antenna.[2]

Since the microstrip stub has multiple resonances, we have made mixer tests around 180GHz for a stub designed for 90GHz. The result is rather complicated because the frequency doubler produces both second and third harmonics. Since our mixer has resonances at the multiples of 90GHz, we observed steps associated with pumps at either 2×90GHz or 3×90GHz or at both frequencies. The mixing of these two frequencies also produces steps corresponding to 90GHz.

A mixer noise temperature of 250K and a coupled gain of -8.7dB were obtained when the doubler was pumped at 91GHz. However, since the width of the step at which the measurements were done corresponded to 90GHz, we do not know whether the mixer results are from 91GHz mixing or 182GHz mixing or a combination of both.

To avoid this complication, we have designed and fabricated stubs whose fundamental resonant frequency is 180GHz. The next resonance at about 400GHz is beyond the range of our frequency doubler.
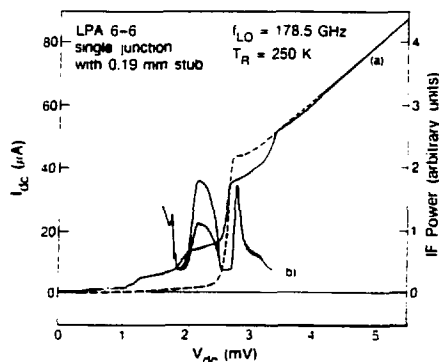

Fig. 5 (a) I-V curves of a pumped (solid line) and unpumped (dashed line) junction. (b) IF power as a function of dc bias voltage. The top curve is for the hot (300K) and the bottom curve is for the cold (77K) load.

Fig. 5 shows a pumped I-V curve for a single junction with a stub designed for 180GHz. The junction resistance is 64Ω, and the leakage current is 3.5μA at 2.5mV. The first step has a positive slope of about 200Ω. At this frequency (178.5GHz), the contribution to the noise from the Josephson effect is small on the first step. Applying a magnetic field does not improve the mixer performance noticeably.

In Fig. 6, we plot the receiver noise temperature, mixer noise temperature, coupled mixer gain, and available mixer gain as functions of the LO frequency. The lowest mixer noise temperature is 200K at 176GHz and the receiver noise temperature is 250K. The best coupled gain of -4.5dB occurs at the same frequency. The FWHM bandwidth of the coupled gain is about 3GHz.

Systematic behavior is apparent in Fig. 6 as is often seen in double sideband SIS mixers with parallel resonant RF coupling. At the optimum frequency where noise is a minimum and gain a maximum, the dynamic resistance is positive and much larger than R$_n$ (in this case 200Ω). At higher frequencies the dynamic resistance decreases rapidly and so does the gain. The mixer noise temperature increases only slowly. The rapid rise in receiver noise temperature is mainly due to the fall in gain. At lower frequencies, the dynamic resistance becomes very large, and even negative (between 168 and 174GHz in this case). We must over-pump the junction to avoid instability in this region. The gain is low and both the mixer and the receiver noise temperature increase rapidly.

Negative steps at a few GHz below the optimum frequency have been observed in all the junctions that showed good mixer performance, including the junction array with inductive wire. In our experiments, we have used this negative step as a guide for finding the operating frequency. Our numerical simulations have shown that in the frequency range slightly below the resonant frequency, the impedance match of the inductive imbedding impedance with the nonlinear quantum reactance causes negative steps.[13]

The mixer performance seems to be very sensitive to leakage current in the junction even at this high frequency, where the width of the photon-assisted-tunneling step is much larger than the nonlinear voltage scale of the I-V curve. Another junction with similar normal resistance to that of the one described above, but with a leakage current of 8μA at 2.5mV compared to 3.5μA for the junction described above, gives a much higher mixer noise temperature of 580K and much lower coupled gain of -14.5dB at its optimum frequency of 172GHz. This result is quite different from our observations at 90GHz, where T$_n$ is increased only slightly by an
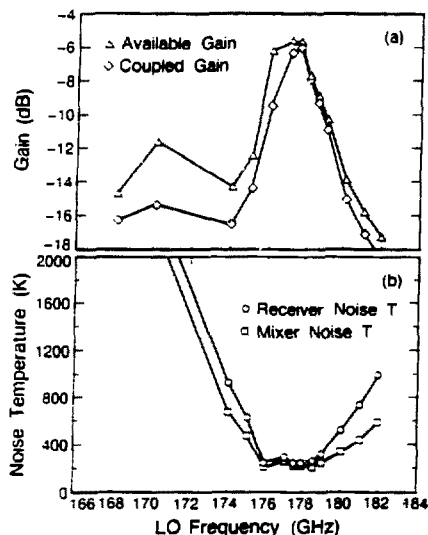
Fig. 6 (a) Coupled and available mixer gain as functions of LO frequency. (b) Mixer and receiver noise temperatures as functions of LO frequency.

increase in bath temperature. even though the leakage current and the current onset at 2Δ degrade significantly at warmer bath temperature. Thus observation suggests the possibility os some effect that attenuate the signal at high frequencies.

We have also measured the performance of mixers with stubs designed for 270GHz and 360GHz. The pumped I-V curves showed well developed steps: some of the junctions even showed negative steps. From the shape and height of the steps, we deduce the coupled LO power, which indicates that there is a resonant frequency. However, the mixer performance is very poor. The mixer noise temperature is higher than 2000K at 270GHz and even worse at 360GHz. The IF output power of the mixer for both RF hot and cold load is very low, only 2-3 times higher than that of the shot noise background. This suggests that the high mixer noise temperature does not arise because of some extra noise in the mixer but because of some attenuation of the RF signal which is occurring at low temperature. One possibility is the loss in the stub, which should increase as the square of the frequency. The effect of a lossy stub is being investigated.

Table 1 summarizes the best performance of our quasioptical SIS mixers.

Table 1

Frequency range	90GHz	180GHz	270GHz	360GH
Junction array with tuning wire	$T_m=115K$ $G_c=-3.4dB$ $\Delta f=10GHz$			
Single junction with stub	$T_m=150K$ $G_c=-4.8dB$ $\Delta f=5GHz$	$T_m=200K$ $G_c=-4.4dB$ $\Delta f=3GHz$	$T_m>2000K$	

Table 1. The best mixer performance of SIS mixers with integrated tuning elements and log-periodic antenna.

V. Conclusion

We have demonstrated that SIS junctions with a large ωRC product (>10) can be used in an open structure heterodyne receiver. With an integrated tuning element, the mixer gives good performance ($T_m\leq200K$) up to 200GHz. With improved RF optics, we expect to achieve better results. At higher frequencies, the mixer performance has been poor due to low temperature losses which are under investigation.

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