A Quantum-limited Submillimeter Mixer with an Inhomogeneous Distributed SIS Junction Array

Wenlei Shan, Shengcai Shi, Yutaro Sekimoto and Takashi Noguchi

***Abstract*—Heterodyne mixing performance of a waveguide SIS mixer with inhomogeneous distributed junction (DJ) array composed of 3 SIS junctions is experimentally investigated at 375-500GHz. Quantum-limited noise temperature of 3-DJ mixer is demonstrated. Besides its low noise temperature, the mixer conversion gain of 3-DJ mixer is found to be more uniform over RF band than that of a PCTJ (parallel-connected twin junctions) mixer. The FTS (Fourier transform spectrum) response indicates a broad RF bandwidth of the 3-DJ mixer that is limited by the bandwidth of waveguide probe instead of mixer's tuning circuit.**

***Index Terms*—SIS mixers, Submillimeter wave, Distributed junction array, Noise temperature, Gain flatness.**

I. INTRODUCTION

THE RF bandwidth of an SIS mixer is restricted by the bandwidth of antenna (waveguide probe) or the tuning circuit used for tuning out the geometric capacitance of tunnel junction. The bandwidth of waveguide probe can be as wide as 30% and be much wider in the case of quasi-optical mixer. The bandwidth of tuning circuit, usually the actual threshold of overall bandwidth, is determined by the quality factor of a resonator-like tuning circuit composed of a microstrip inductive line and the capacitive tunnel junctions. The quality factor Q is proportional to the frequency and inversely proportional to the current density $Q \sim \omega/Jc$. Therefore, the current density must be high in order to achieve broad RF band at submillimeter range. However, Jc cannot exceed the fabrication limit around 10kA/cm^2 when the conventional Nb/AlO$_x$/Nb technique is employed. At 500GHz the Q factor is normally larger than 5, determining a relative RF bandwidth about 20%.

Mixer designs involving multi-junctions (N>2) or SIS non-linear transmission lines are found to have broader RF bandwidth even with relatively low Jc. These designs characterized by distributed mixing with either SIS tunnel microstrip line [1][2][3][4] or parallel-connected multi-junctions [5][6][7][8] or a combination of above two [9]. Most of these designs have demonstrated wide RF bandwidth within submillimeter range as predicted by theoretical calculation. Noise temperature as low as 5 times of quantum limits at 4.2K bath temperature has been achieved at 600GHz band by using a half-wavelength SIS non-linear microstrip line of a width 0.55μm [3] and at 200GHz band with an inhomogeneous 5-DJ mixer [7]. These designs are potentially useful in some applications that require wide-band fix-tuned mixers at low device impedance such as integrated receiver with built-in FFO (flux flow oscillator).

In contrast to SIS non-linear microstrip lines, lumped DJ arrays allow large-size junctions that can be easily fabricated with conventional photolithography. An inhomogeneous DJ array composed of junctions with different dimensions non-uniformly located along a microstrip transmission line is predicted to be more efficient and therefore less noisy than a homogenous DJ array [10]. In this paper we present a measurement result of 3-DJ mixer that demonstrates an overall receiver noise temperature as low as 3 times of quantum limits at 4.2K at frequencies ranging from 375 to 500GHz and with 4-8GHz IF. Correcting for the contribution from IF chain and RF optics, the mixer noise is found to be about one quantum limit. The result indicates that the quantum-efficient mixing can be achieved with distributed mixing scheme. The RF bandwidth (in sense of noise temperature) of PCTJ is found to be similar to 3-DJ at this frequency range since the current density is rather high. However, the gain fluctuation of 3-DJ is found to be much smaller, reflecting a uniform signal coupling between source and detector over the RF band. This feature is beneficial for actual radio telescope to achieve good linearity of backend.

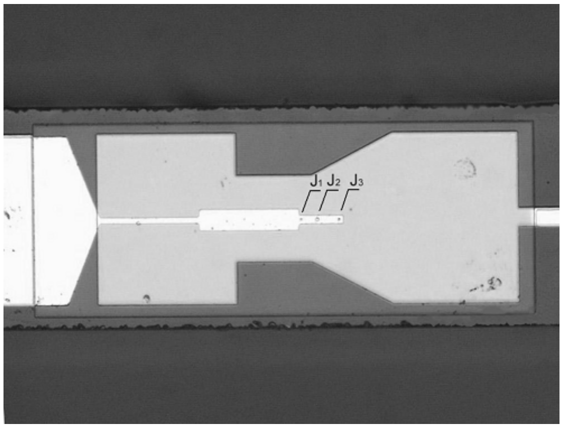

Fig.1 Inhomogeneous 3-DJ array Mixer

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TABLE I
PARAMETERS OF EACH DESIGN

Design	Junction Index	Junction Size (um)	Tuning Index	Tuning Length (um)
PCTJ				
	J_1	1.5	$L_{1,2}$	14.0
	J_2	1.5		
3DJ				
	J_1	1.4	$L_{1,2}$	10.0
	J_2	2.0	$L_{2,3}$	11.4
	J_3	1.4		

The junction is numbered form left to right in Fig. 1. $L_{m,n}$ indicates the tuning distance between junction m and n.

II. MIXER DESIGN

The first step of inhomogeneous DJ design is to determine the junction sizes and the length of microstrip line between adjacent junctions in order to achieve minimum return loss within a certain RF bandwidth. In principle wideband matching theory [11] can be applied for this purpose. Under the condition of available junction fabrication process, however, the application of this design method is impeded by the strong limitations on junction size, current density and linewidth of microstrip line. On this account, a random searching algorithm is employed to get minimum spreading of impedance over the frequency range 375-500GHz. For a 3-element DJ there are 5 variables listed in Tab.1 as well as some indirect parameters such as Jc and linewidth of strip. These variables are confined to certain limits. For example, the junction size limit is set to be 1.5~2.2um (for easy fabrication with a contact mask-aligner) and the current density less than 10kA/cm^2. The SIS junction is modeled by a combination of a capacitance and a resistance connected in parallel. The specific capacitance of SIS junction is supposed to be a function of current density and the resistance is the junction's small-signal resistance that is close to its normal resistance. A 5-dimension Sobol quasi-random sequence is [12] firstly employed to find a rough range and then a fine searching in a narrowed range is performed. In fact there are many solutions satisfying the goal of the optimization for the reflection coefficient. From those solutions, the best one is decided by carrying out a mixing performance calculation with our simulation software based on quantum mixing theory with a 5-port approximation.

The 3-DJ mixer is shown in Fig. 1 and the parameters in Table I , where PCTJ design is also listed for comparison. The normal resistances of PCTJ, 3-DJ are 8Ω and 3.7Ω respectively. The input impedances of 3-DJ and PCTJ are plotted in a Smith chart (Fig. 2) normalized by their normal resistance. Since the impedance difference of probe feed and 3-DJ is quite large, we incorporate a two-section impedance transformer, which is superior to a single section transformer because of its wider bandwidth.

A waveguide-microstrip probe is optimized in a half-reduced waveguide to achieve nearly frequency-independent impedance within 385-500GHz at the probe's feed point [13]. The feed-point impedance can be reduced to 30Ω by means of adding one section of impedance transformer and reducing the height of waveguide to half. With doing so, the matching of the low-impedance DJ over a wide frequency band is facilitated.

III. MEASUREMENT RESULTS AND DISCUSSION

The 3-DJ mixers are measured in a 4-K Gifford-McMahon/Joule-Thomson mechanical cryocooler. An isolator with a built-in bias-T, inserted between the SIS mixer and a 4-8GHz low noise amplifier, is cooled to 4K to reduce the thermal noise injection from its terminated port. An off-axis ellipsoidal mirror with an edge-taper of 30dB is put on the 4K stage to refocus the beam from the diagonal horn onto an external hot (300K) /cold (liquid nitrogen) load. A 100μm-thick polyimide film is used as the vacuum window while a 150μm-thick Zitex sheet cooled at the 70K stage blocks the infrared radiation. A 12.5μm-thick polyimide film is used as a beam splitter, coupling the LO signal generated by a Gunn oscillator followed by two Schottky-diode doublers with a factor of -15dB.

Typical IV curves as well as IF responses are plotted in Fig. 3. The receiver noise and conversion gain of 3-DJ is plotted in Fig. 4 as a function of LO frequency between 376GHz and 496GHz. The performance of a PCTJ is also shown for comparison. It is worth noting that the PCTJ is fabricated on the same wafer and measured in the same mixer block. Both

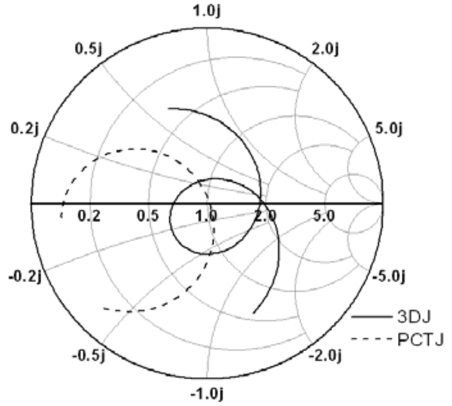

Fig. 2 Impedances of input port of PCTJ, 3DJ in 300-600GHz

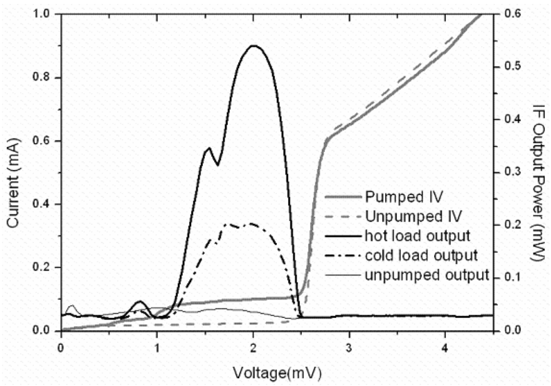

Fig.3 IV curves and IF output measured at 386GHz.

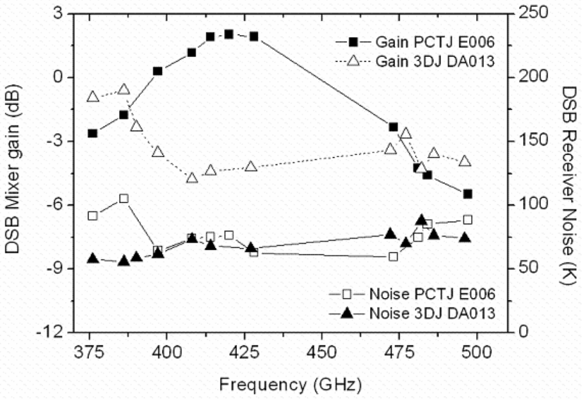

Fig.4 Comparison of receiver noise and gain of 3-DJ and PCTJ as a function of LO frequency.

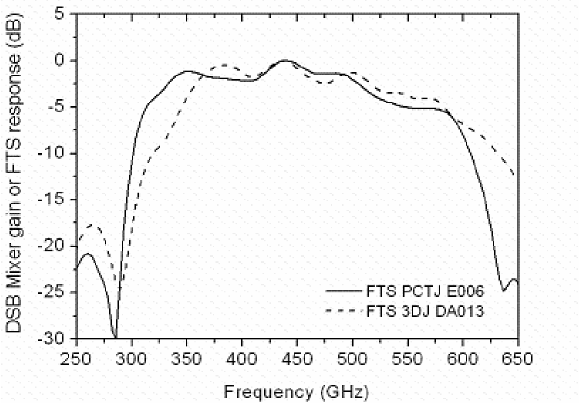

Fig. 5 The FTS responses of 3-DJ and PCTJ

mixers demonstrate excellent low noise temperature over the whole RF band from 375 to 500GHz.

A noise breakdown of the whole DSB receiver system at 427GHz is shown in Table II. The contributions of RF insertion loss and input noise from optics are estimated by theoretical calculation. The mixer noise is finally calculated to be 21.5K (about one quantum limit $hf/2K_B$, where h is the Planck's constant, f is the frequency and K_B is the Boltzmann's constant) at this frequency. Since several ellipsoidal focusing mirrors at signal path also introduce loss and noise, which are not included in this calculation, the mixer noise should be even smaller and close to zero-point fluctuation limit, which is half of a quantum limit.

Due to the limitation of LO frequency coverage, the performances of both mixers are compared to each other in wider frequency range by measuring their FTS (Fourier Transform Spectrum) responses. The FTS spectrums in Fig.5 shows a similar response bandwidth of 3-DJ and PCTJ. The lower cutoff frequency is caused by waveguide cutoff frequency. The upper cutoff frequency about 600GHz is found to be coincident with that of waveguide probe, which is simulated with a 3D EM simulation software Ansoft HFSS.

The measured noise temperatures of 3-DJ and PCTJ in frequency range 375-500GHz are quite similar. It is difficult to judge which one is superior to the other in sense of noise. However, Fig. 4 shows that 3-DJ has a more uniform conversion gain in measured frequency range. This should be attributed to uniform signal coupling efficiency that we aim to realize. Flat conversion gain has some advantages. For example, when the noise from IF chain is large, a mixer with uniform conversion gain results in uniform overall receiver noise temperature over the RF band. Large gain variation may also cause non-linearity problems of the backend of a radio telescope if no compensation is made to regulate the IF output. DJ mixers with flat gain can thus avoid such problems and improve the reliability.

One of the disadvantages of DJ SIS mixer is their relatively large LO power assumption, which is almost inversely proportional to the device normal resistance. It may limit their application in Terahertz regime since LO power is usually quite weak unless sub-micro size junction is adopted. Another disadvantage of DJ mixer is its relatively large junction capacitance that reduces the IF bandwidth. To study the influence of junction capacitance on the IF response, we measure the mixer's conversion gain as a function of intermediate frequency shown in Fig. 6. The 3dB IF bandwidth of 3-DJ narrower than that of PCTJ is indeed observed. Such a problem can be partly solved by inserting IF matching circuit that tunes out junction capacitance at certain IF frequency. However, the total IF bandwidth is still limited by the quality factor calculated at IF. In turn, small junctions are required to reduce the geometric capacitance to achieve

TABLE II
NOISE BREAKDOWN OF DSB RECEIVER SYSTEM AT 427GHZ

Element	T_{in} (K)	Gain(dB)	T_{front} (K)
IF amplifier	5.2		12.1
IF Isolator	4.2	0	9.8
SIS mixer	<21.5	-3.12	<24.5
IR filter	0.18	-0.18	0.2
Dewar window	4.9	-0.25	5.1
Beam splitter	9.6	-0.13	9.6
Receiver			61.3

The four columns show the element name, input noise, gain and equivalent noise referred to the receiver input respectively.

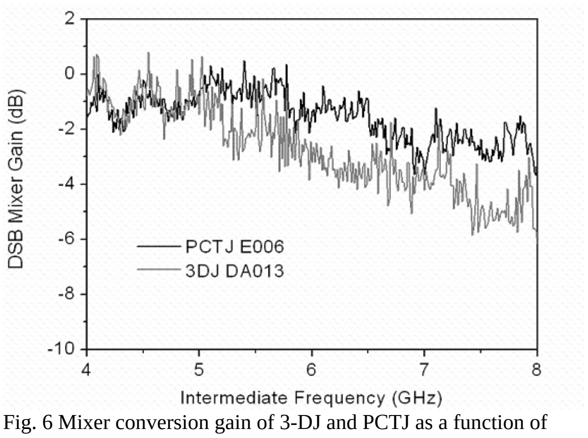

Fig. 6 Mixer conversion gain of 3-DJ and PCTJ as a function of intermediate frequency from 4 to 8GHz.

wide IF bandwidth.

IV. CONCLUSION

An inhomogeneous 3-DJ SIS mixer is designed to have a uniform signal coupling in the frequency ranging from 375 to 500GHz. The corrected noise temperature of 3-DJ SIS mixer is close to one quantum limit approaching theoretical minimum. Such a noise performance is comparable with a PCTJ mixer that is fabricated on the same wafer and mounted in the same mixer block. The 3-DJ SIS mixer demonstrates a uniform conversion gain over the measured RF band in contrast to the PCTJ, gaining advantages in some applications requiring gain flatness. The 3-DJ SIS mixer has a broad RF bandwidth (about 40%) measured from its FTS response. In this specific case, the RF bandwidth is determined by waveguide probe instead of tuning circuit.

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