Design and Performance of Waveguide Mixers with All NbN tunnel junctions on MgO substrates

Wenlei Shan[1], Masanori Takeda[2], Takafumi Kojima[3,4], Yoshinori Uzawa[3], Shengcai Shi[1], and Zhen Wang[2]

[1] *Purple Mountain Observatory, Nanjing, China.*

[2]*Kansai Advanced research Center, National Institute of Information and Communications Technology, Kobe, Japan.*

[3]*National Astronomical Observatory of Japan, Tokyo, Japan.*

[4]*Graduate School of Science, Osaka Prefecture University, Osaka, Japan.*

* Contact: shawn@mwlab.pmo.ac.cn, phone +86-25-8333 2229

***Abstract*—In this paper we present the development of low-noise waveguide mixers with NbN/AlN/NbN tunnel junctions at frequency approaching 1THz. The mixer was designed to be compatible with MgO substrate. Mixers of such a design demonstrated much improved receiver sensitivity. The improvement is a result of reduction of signal dissipation in waveguide and leakage into IF port by adopting a full-height waveguide and an effective RF choke filter respectively. Two types of tuning circuit, namely parallel-connected twin-junction (PCTJ) and half-wavelength self-resonance distributed junction (DJ), are designed and evaluated. Both theoretical and measurement results show that the PCTJ design is superior in terms of gain and sensitivity due to smaller loss in the tuning circuit.**

I. INTRODUCTION

Niobium Nitride (NbN) tunnel junctions are potentially applicable to low-noise frequency-mixing up to 2.6-2.8THz determined by a gap voltage as high as 5.3-5.6mV [1,2]. The large gap voltage results in a favorable wide bias region and causes the mixer to be less affected by Josephson effect [3]. With the Tc of NbN as high as 15-16K, a stable performance against temperature vibration can be expected when 4K closed-cycle cryocoolers are used for laboratory experiments and practical applications. In addition, high quality crystalline NbN film of perfect surface smoothness can grow on MgO substrate at ambient temperature [4]. That allows the fabrication of low leakage tunnel junctions [5] and the realization of lower RF loss than low-resistivity normal mental film up to about 1THz [6]. For the above reasons, NbN SIS mixers incorporated with NbN or normal mental microstrip tuning circuits are feasible and attractive in the applications of THz radio astronomy and atmosphere spectroscopy.

Effort to develop NbN SIS mixers has been made both on waveguide and quasi-optical designs in a wide frequency range [7-13]. Below Nb gap frequency (700GHz), low as it is, the noise is still higher than that achieved by Nb SIS mixers by a factor of two to four. This can be attributed to relatively larger leakage current of NbN tunnel junctions since leakage current results in the loss of high nonlinearity of quasi-partial tunneling onset and excessive shot noise. Above 700GHz where film loss tunes to be pronounced in Nb SIS mixers, NbN mixers of quasi-optical designs have provided quantum-efficient sensitivity comparable to that achieved by the state-of-the-art Nb mixers incorporating tuning microstrip-lines made of NbTiN ground plane and Al wiring at 800GHz band [14-15]. Waveguide NbN mixers, however, showed an averagely higher noise than that of the quasi-optical ones by a factor of two [13]. Since it is preferable for many practical applications to use horn antennas that generate well-controlled beam pattern, developing low noise waveguide type SIS mixers with horn antenna is of great interest.

There are two possible reasons for the lower sensitivity of waveguide mixers than quasi-optical ones at frequency approaching to 1THz: (1) As a rule, waveguides with reduced height are adopted in published experiments. At THz frequencies, waveguides of reduced height may suffer from transmission loss that can be considerably high. (2) Since the high dielectric constant of MgO (ε~9.6) causes the conventional design of RF choke filters to become less effective, leaking of signal to IF port leads to reduction of sensitivity. MgO substrates are preferred because epitaxial growth of NbN film on MgO substrates offers lowest film resistivity, while growth on quartz, which makes the mixer design much easier, results in poor film quality [16]. The purpose of this work is to demonstrate low noise NbN mixers at 780-950GHz band using a waveguide design. Adopting a full-height waveguide-microstrip transition on MgO substrate, into which a resonance choke filter is integrated, we have dramatically improved the performance. The measured uncorrected DSB receiver noise is as low as 280K at 830GHz at an ambient temperature of 4.2K that is comparable to that achieved by using best NbN quasi-optical SIS mixers.

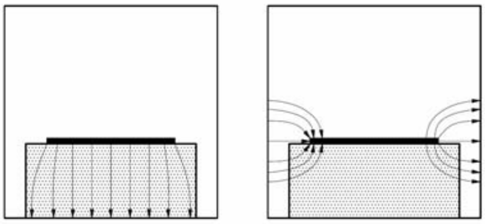
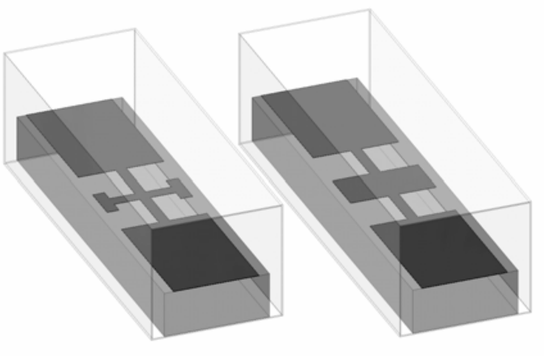


Fig. 1 The schematic plot of electric field of the fundamental mode and the second mode in a shielded microstrip line.

II. DESIGN OF THE SIS MIXER

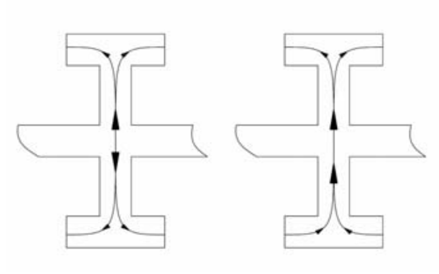
A. RF choke filter and waveguide-microstrip transition design

Down-converted IF signal propagates to IF port through a choke filter that blocks RF signal from leaking out. The choke filter of a standard approach is incorporated with a series of high-low impedance lines having lengths close to the quarter wavelength of the fundamental mode of shielded microstrip line at RF center frequency. The choke filter becomes less effective if high order modes are propagative, since signal leaking due to high-order modes to IF port will obviously make additional loss. In particular, much attention should be paid to the second transmission mode, i.e. the first high-order mode, because its cutoff frequency is relatively low. Fig. 1 depicts the fundamental and the second mode in a shielded microstrip line. The cutoff frequency of the second mode depends on the effective dielectric constant (ε_{eff}) of the transmission line, which is determined by the dielectric constant of the substrate, strip width as well as chip thickness. The smaller the ε_{eff} is, the higher the cutoff frequency of the second mode will be. As a result, to make use of MgO substrate that has larger permittivity than quartz, thinner thickness is needed to prevent high-order mode propagation. However, it is not expedient to reduce ε_{eff} by means of using extremely thin chip for the reason of reliably mounting. In this work, we adopt the chip size of 80 μm in width and 30 μm in thickness. In this case, the cutoff frequency of the second mode of a 65μm-wide microstrip line, which is supposed to be the low impedance section of conventional choke filter, will be much lower than 780GHz.



(a) (b)

Fig. 2 Two simplified choke filter designs. (a) shows a filter with transverse resonators, while (b) is a filter of the conventional design..



(a) (b)

Fig. 3 The schematic drawing of current distribution on transverse resonators. (a) shows the case when it is stimulated by the fundamental mode, and (b) shows the case when it is stimulated by the second mode.

As a solution, a pair of quarter-wavelength open-ended brunches is used as a substitute for low impedance section in conventional design. Fig. 2 shows a simplified model of this design on a 30μm-thick substrate together with a conventional design in comparison. The open-ended brunches are bifurcated in the end to enhance the bandwidth. The structure is stimulated in even manner by fundamental mode and in odd manner by the second mode as illustrated in Fig. 3. In both cases, it only conducts the local fundamental mode and forms a transverse resonator realizing low impedance at the joint if the length of each brunch is around quarter wavelength at center frequency of the mixer. The performance of the filter shown in Fig. 2a is compared with a conventional design shown in Fig. 2b by using an EM simulator with the results plotted in Fig. 4. We find that this resonance choke filter better suppresses both the fundamental and the second mode than the conventional design does. The discontinuities at about 920GHz of the fundamental mode transmission coefficient in both cases are due to the onset of the third mode, which does not considerably affect the

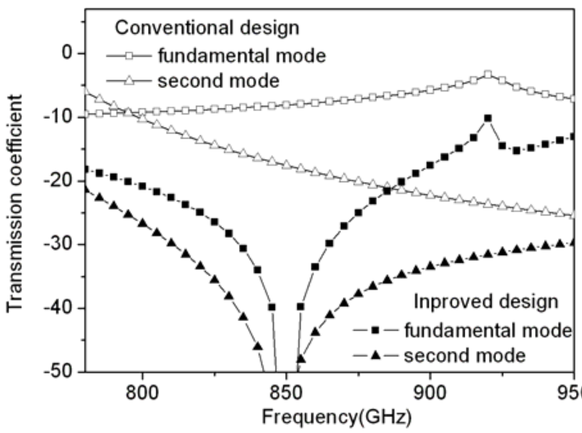


Fig. 4 The transmission coefficients of both the fundamental mode and the second mode of the two choke filters shown in Fig. 2.

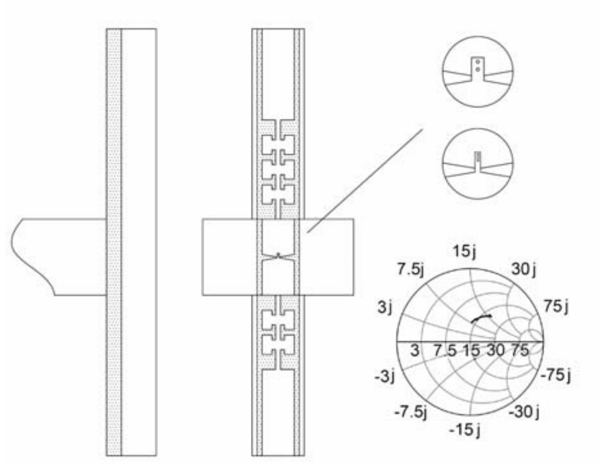


Fig. 5 The design of a full-height waveguide-microstrip transition. The cross-sectional dimensions of the chip and the waveguide are 30μm x80 μm and 304μmx152 μm respectively. The tuning circuit are illustrated in enlarged views. The probe impedance is plotted in a Smith chart normalized to 15Ω.

performance. We also noticed that the propagation properties of above shielded microstrip line are influenced by the gap between substrate and ground. In the practical mixer mounting, a gap unavoidably exists due to the substrate bending from its internal stress. Fortunately, a small gap of several micrometers can reduce the ε_{eff} of the microstrip line and thus acts positively to make the choke filter more efficient.

Through a waveguide-microstrip transition SIS tunnel junctions couple the LO and signal from waveguide. Waveguide loss rising with the increase of frequency plays an important role in receiver sensitivity at THz range. We have measured a loss as large as 0.6dB/10mm for a hull-height WR1.2 waveguide at cryogenic temperature, which is much larger than simple theoretical prediction [17]. Obviously, waveguides with reduced height, which are widely used in waveguide mixer designs, will bring about more serious problem. Therefore, a full-height waveguide-microstrip transition that allows the use of full-height waveguide and can provide broadband performance is of great advantage. Fortunately, a bow-tie waveguide-microstrip transition in full-height waveguide has been designed and tested in our previous work [18]. We extend such a design with combining the RF choke-filter introduced above as shown in Fig. 5. With intensive numerical simulation, the probe impedance was optimized to be as weakly frequency-dependent as we could by adjusting the taper angle and the length of the first section of choke-filter. For the sake of machining simplicity, a waveguide backshort cavity is not used and the probe is placed close to the waveguide end to achieve low impedance that is desirable for coupling of SIS junctions. The impedance of probe feed has a real part of 15Ω as well as an imaginary part varying with frequency. According to simulation results, this inductive part is helpful to achieve high mixer gain in spite of slight degradation of the LO coupling efficiency.

B. Mixer tuning circuit Design

We have designed two tuning circuits, namely parallel-connected-twin-junction (PCTJ) and half-wavelength self-resonance distributed junction (DJ), whose compactness and relatively wider RF bandwidth are suitable for THz applications. The PCTJ is composed of two parallel-connected SIS junctions at the two ends of an inductive NbN/MgO/NbN microstrip line that compensates for the geometric capacitance of SIS tunnel junctions at a desirable frequency. Half-wavelength distributed junction is essentially similar to PCTJ since the active areas for mixing locate at the two ends of a long junction with the quasi-particle tunneling transmission line in the center area acting as tuning inductance. The principles of NbN tuning circuit designs are basically the same as those already applied to Nb mixers, but some distinctive differences due to the larger gap voltage of NbN SIS junctions and longer penetration depth of NbN films deserve a clarification.

C. PCTJ Design

The SIS tunneling junctions in this study are formed by epitaxial NbN/AlN/NbN trilayers. Compared with Nb SIS junction, NbN SIS junction has higher gap voltage (V_{gap}) and larger capacitance ratio (C_s) [19]. It suggests that to achieve the same RF bandwidth NbN PCTJs must have larger current density (J_c) by a factor of 2~3 because the tuning circuit quality factor is proportional to $V_{gap}C_s/J_c$. However, the increase of Jc will result in the rise of leakage current and thus lead to the rise of the shot noise. Given the difficulty of the fabrication of low leakage NbN SIS junctions with high current density, we have to find a compromise between RF bandwidth and sensitivity to determine the Jc. This work is aimed at achieving junctions with quality factor of over 10, which is the ratio of resistance at 4mV and the normal resistance, and current density about 15kA/cm^2. The nominal junction size is 1μm in diameter realizing a resistance suitable to directly couple the waveguide-microstrip transition without any impedance transformer. Therefore, the transmission loss can be minimized. To realize a center frequency of about 850GHz, the distance of two junctions of PCTJ is about 3 μm, much shorter than Nb PCTJ at this frequency due to the larger penetration depth of NbN film.

The loss in tuning circuit is in fact composed of two parts. One is measured by $Q_J=\omega R_n C_J$, which takes account of the quasi-particle tunneling, where ω, R_n and C_J are angular frequency, normal resistance and capacitance of single junction respectively. The other part representing the dissipation loss in tuning inductance can be written in the form of $Q_T=\eta Q_J$. If Q_J>>1, (it is usually true for THz SIS mixers,) η can be expressed by

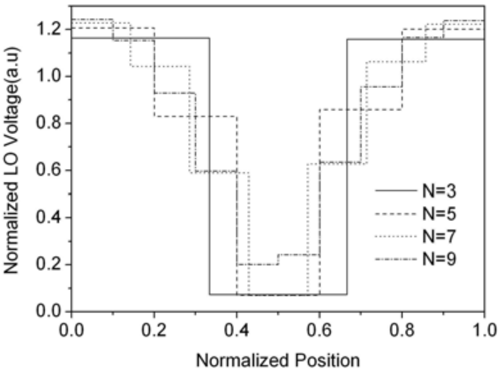


Fig. 6 The approximation of the LO voltage distribution along a half-wavelength distributed junction at center frequency. The simulations are performed with the junction is divided into 3,5,7, and 9 sub-sections.

$$\eta \approx \frac{Z_0^2 \beta^2 L_T}{2R_n R_s}, \qquad (1)$$

in which Z_0 and β are characteristic impedance of tuning transmission line and wave number respectively, L_T is the tuning length and R_s is the RF surface resistance of NbN thin film. The overall Q factor is a combination of Q_J and Q_T, i.e. $1/Q=1/Q_J+1/Q_T$. When η>>1, the transmission loss can be neglected. From (1) we see the reduction of Rn, corresponding to the increase of current density, is helpful not only for broad RF band but also for high conversion efficiency. Since the improvement of conversion efficiency partly makes up for the rise of leakage current, we can expect good results for a relatively leaky NbN SIS mixer with high current density.

D. DJ Design

Half-wavelength distributed junction can be regarded as merging of the two junction of PCTJ to form a long one that self-resonates at a desired frequency. Such a scheme has been well studied theoretically [20] and experimentally [11,21]. We followed the theoretical approach introduced in [20] to optimize the mixer design. The long junction is uniformly divided into a number of sections which are modeled by lumped junctions separated by transmission lines taking account of the capacitance and inductance of each section. Based on this circuit model, the LO distribution can be calculated by solving a nonlinear equation numerically. Fig.

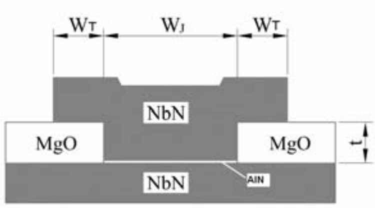


Fig. 7 The schematic cross-sectional view of a DJ. W_J and W_T are the barrier width and the width of overhanging part of wiring respectively.

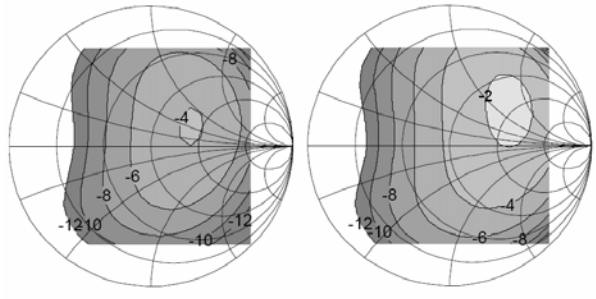


Fig. 8 Simulated DSB mixer gain of (a) a DJ mixer and (b) a PCTJ mixer as a function of embedding impedance at center frequency (865GHz). The Smith chart is normalized by 15 Ω.

6 shows an example of the approximation of LO voltage distribution along a DJ corresponding to various division numbers from 3 to 9. The portions at both ends of the DJ are normally pumped whereas those in the center are under-pumped and thus almost inactive for mixing effect. Compared with the tuning microstrip line in PCTJ, the quasi-particle tunneling transmission line suffers larger loss due to the leakage current and quasi-particle tunneling, which causes the degradation of tuning circuit efficiency.

The accurate modeling of the quasi-particle tunneling transmission line, the geometric structure of which is shown in Fig. 7, is essential for the correct determination of the tuning length and embedding impedance. It is particularly noticeable that unlike the electric field that is closely confined within junction barrier, the magnetic field spreads peripherally due to a long penetration depth of NbN film (about 200nm), which is much thicker than the barrier. As a consequence, a due emphasis should be put on the significance of the fringing effect of magnetic field. The character impedance (Z_0) and propagation constant (γ) determined by the serial impedance (z) and parallel admittance (y) of unit length are calculated by,

$$Z_0 = \sqrt{\frac{z}{y}}, \quad (2)$$

and

$$\gamma = \sqrt{zy}. \quad (3)$$

To involve the fringing effect, z and y can be written as:

$$z = [(Z_{ss} + Z_{sg})/W_J]/K, \quad (4)$$

and

$$y = (G + j\omega C), \quad (5)$$

where K (K<1) is the fringing factor; Zss and Zsg are the surface resistance of the strip and ground plane; W_J is the width of junction barrier; G and C are the tunneling admittance and junction capacitance of unit length of the transmission line respectively. The fringing factor K, calculated by means of numerical simulation [22], tunes out to be a typical value around 2 when the penetration depth of NbN is set around 200nm.

Along with the established circuit model and Tucker theory [3], we simulated the performance of DJs to find out the desirable embedding impedance. For example, the mixing

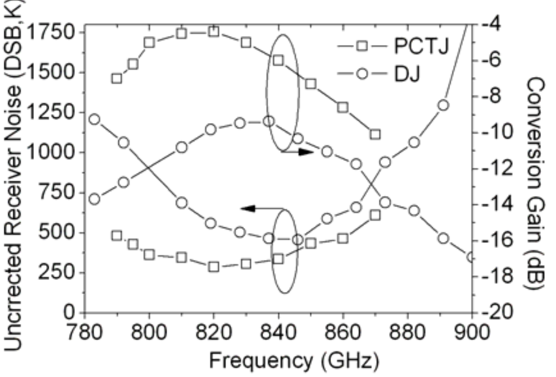


Fig. 9 The comparison of of a PCTJ and a DJ in terms of the measured receiver noise and conversion gain as a function of LO frequency.

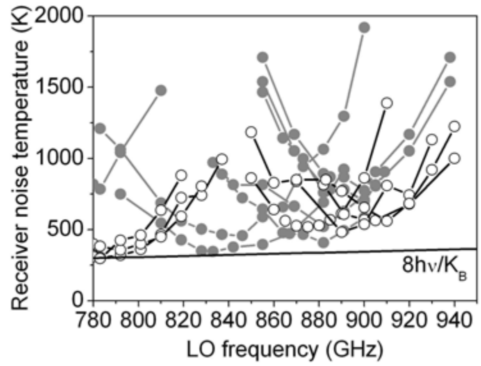
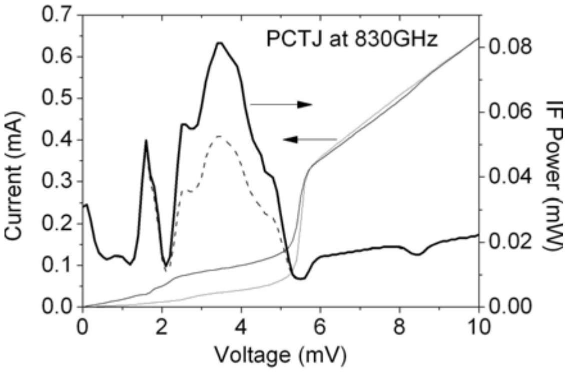
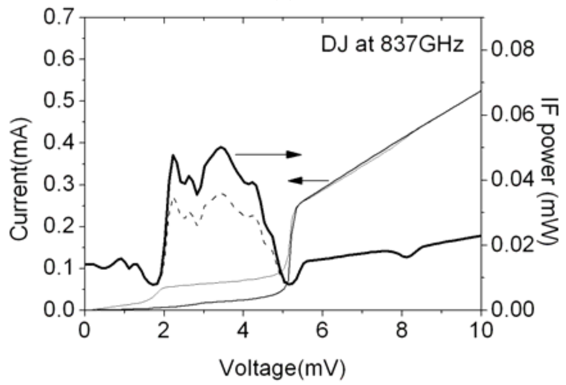


Fig. 11 Receiver noise of DJ mixers measured over a wide frequency range. Lines with closed circles are the results of all NbN junctions. As for those with open circles, devices incorporating NbTiN wiring layer were used.

conversion gain of the tuning circuit design is simulated at 865GHz with a parametric sweeping of the embedding impedance over most of area of Smith chart shown in Fig. 8a. We find that an inductive part is beneficial for the elevation of conversion gain as already mentioned and the mixer is unconditionally stable at this frequency. For a comparison, the same calculation was applied for a PCTJ of identical Jc and center frequency, shown in Fig. 8b. The maximum gain of PCTJ appears to be 2 dB higher than that of the DJ. It is understandable because of the larger loss in the tuning microstrip line of DJs.



(a)



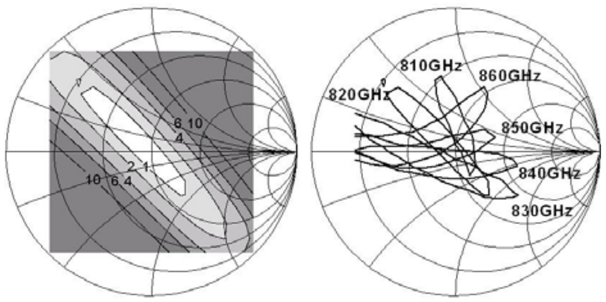
(b)

Fig. 10 Pumped and unpumped IV curves and IF responses corresponding to hot and cold loads of the PCTJ mixer (a) and DJ mixer (b) shown in Fig.9.

E. MEASURED PERFORMANCE OF DJ AND PCTJ MIXERS

A number of batches of DJ and PCTJ mixers of the above designs were fabricated with the technique described in [13]. The average quality factor of DJs of about 15 is slightly better than that of PCTJs (around 10). It is a result of the dependence of leakage current on junction size, since as a rule, the smaller the junction is , the larger leakage current tends to occur along the edge of the junction barrier. A low DC resistivity of NbN film, typically about 60μΩcm measured at room temperature, indicates rather good film quality.

The mixing performance was investigated in a 4K close-cycled cryogenic Dewar with the measurement setup described elsewhere [23]. The uncorrected receiver noise and gain of two typical devices, a PCTJ (nominal tuning length is 2.8 μm) and a DJ (junction length is 3 μm), is shown in Fig. 9 as a function of LO frequency. The current densities of both devices are similar ($17kA/cm^2$ and $13.5kA/cm^2$ respectively) and their center frequencies almost coincide with each other. This provides a good condition to see the differences caused mainly by the tuning circuits. As seen in Fig. 9, the conversion gain of the PCTJ mixer is about 2 to 4dB higher than that of the DJ mixer and correspondingly the receiver noise of the PCTJ mixer is also lower. This difference has been well predicted by theoretical results as already mentioned. Their IV-curves with and without pumping as well as the IF-responses corresponding to cold and hot loads are presented in Fig. 10 at frequencies of 830GHz and 837GHz respectively. Uncorrected receiver noises of about 280K for the PCTJ mixer has been obtained,



(a) (b)

Fig. 12 (a) The normalized deviation of a measured pumped IV curve from simulated ones with parametric sweeping of embedding impedance at 820GHz. (b) The orientation of confidence region varies with frequency and the overlapping region is the most possible position where the actual embedding impedance locates.

which is the best result that has been achieved so far with NbN waveguide mixers and is comparable to the best result achieved by quasi-optical NbN mixers at this frequency.

Since no available device can cover the whole RF bandwidth due to limited current density (ranging from 5 to 15 kA/cm^2), a number of DJ mixers of various junction lengths ranging from 2.4um to 3.4um were measured to investigate the dependence of minimum noise temperature on frequency with the results shown in Fig. 11. Some of those DJ mixers are incorporating with polycrystalline NbTiN wiring layer, but the performance does not show obvious difference from all NbN junctions that are primarily used. The minimum uncorrected receiver noise remains around 8 times of quantum limits up to 880GHz and tends to surpass that. Such a tendency is also observed in quasi-optical NbN mixers and is attributed to the degradation of RF resistance of NbN film.

IV. ANALYSIS AND DISCUSSION

The effect of film loss on mixing performance can be estimated from the Q factor of the tuning circuit. The Q factor can be obtained by means of calculating the ratio of the center frequency and 3dB RF gain bandwidth. In cases of the above specific PCTJ and DJ mixers, their Q factors are found to be 13.4 and 11.4 respectively. Given that the overall Q factor is a combination of Q_J and Q_T representing the losses of quasi-particle tunneling and the tuning microstrip line respectively, it is straightforward to know $\eta=Q_T/Q_J$ that indicates the efficiency of the tuning circuit. To accurately estimate the Q_J, the junction capacitance was determined by fitting the measured mixer conversion gain versus LO frequency. In this way, we managed to obtain the Q_J's of 14.3 and 18.6 for PCTJ and DJ respectively. Consequently, the Q_T = 213 and 29 or η =16 and 1.6 for PCTJ and DJ respectively were calculated. It is found out that the PCTJ tuning circuit has much higher efficiency than DJ one. In addition, $\eta_{PCTJ} >> 1$ indicates that the surface resistance of NbN film is very low at this frequency.

Another issue of interest is whether the waveguide-microstrip transition can reproduce theoretically predicted impedance. [24] provides a technique to retrieve the embedding impedance by curve-fitting of the measured pumped IV curves. However a problem arises, i.e., the dependence of pumped IV curve on embedding impedance is rather weak. Consequencely the fitted impedance has rather large uncertainties. An example is plotted in Fig. 12 (a) at a LO frequency of 820GHz showing the calculated deviation between measured and simulated pumped IV curves with a parametric sweeping of embedding impedance. The confidence region of the fitting results appears to extend widely in a certain direction but concentrate within a narrow range in the perpendicular direction on the Smith chart. We found out that the confidence regions corresponding to different frequencies differ in orientations as shown in Fig. 12(b). If we assume that the probe impedance does not change rapidly with frequency, as predicted in the numerical simulation, the overlapping region should be the most possible position where the embedding impedance locates. The impedance value (~ 15 Ω) indicated by the overlapping region agrees with the simulation results shown in Fig. 5 with a reasonable accuracy if the uncertainties of junction parameters are taken into consideration.

CONCLUSIONS

In this paper, we have demonstrated low noise waveguide NbN SIS mixers at frequency approaching 1THz. High sensitivity is owed to the efforts to minimize the signal loss in the waveguide mounting structure by adopting full-height waveguide and a highly efficient RF choke filter on MgO substrate. Design techniques are presented for NbN PCTJ and DJ tuning circuits with emphasizing the impacts of the distinctive features of NbN mixers, namely high energy-gap of NbN SIS junction and long penetration depth of NbN film. By means of Q factor analysis we verified that the surface resistance of NbN film is rather low at measured frequencies. It was also confirmed that the PCTJ mixers are superior in sensitivity to DJ mixers, which suffers from a larger loss in tuning circuit.

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