Performance of a Twin-Slot Antenna Coupled NbN Hot Electron Bolometer Mixer at 2.5 THz

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Abstract—**We demonstrate a quasi-optical NbN hot electron bolometer (HEB) mixer using a twin-slot antenna on a Si lens to couple terahertz radiation. The mixer shows a receiver noise temperature of 1150 K at 2.5 THz, which is expected based on a model that includes quantum noise. The measured direct response is understood by taking into account the main beam efficiency and the parasitic reactance due to the geometric change between bolometer and transmission line. The measured beam of the mixer is nearly collimated and has a Gaussian beam efficiency of 90 % with side-lobes below -16 dB.**

***Index Terms*—hot electron bolometer, direct response, receiver noise temperature, beam pattern.**

I. Introduction

Terahertz quasi-optical mixers [1] combining a superconducting NbN hot electron bolometer (HEB) with a dielectric lens-planar antenna coupling scheme for radiation have played a crucial role in astronomy in the THz frequency region. Such mixers offer not only low noise but also a high radiation coupling efficiency. Among different planar antennas, a twin-slot antenna [2] becomes preferred for astronomic applications because of the following expected characteristics: a high coupling efficiency, a Gaussian beam, linear polarization, and a reasonably wide RF bandwidth. Quasi-optical mixers of superconductor-insulator-superconductor (SIS) [3] and HEB [4] using twin-slot antennas were successfully applied to the high frequency bands (≤ 1.9 THz) in the Heterodyne Instrument for the Far Infrared (HIFI) on the Herschel Space Observatory[1]. Although twin-slot antennas have been reported at 2.5 THz for Nb HEB mixers [5]-[7] and NbN HEB mixers [8]-[10], they showed lower sensitivities than spiral antenna coupled HEB mixers. Although similar sensitivities have been observed at 1.6 THz [11], where both types of HEB mixers were fabricated in the same way and in the same wafer, it is unclear whether the lower sensitivities at 2.5 THz are due to the twin-slot antenna or the detector. The (far-field) beam pattern of a quasi-optical mixer is also a crucial performance parameter particularly when it has to match the incoming beam from a telescope and when it is for a mixer array. The beam pattern study was pioneered in [6], however, the result is not conclusive.

In this letter we report on a twin-slot antenna coupled NbN HEB mixer at 2.5 THz that demonstrates low noise temperature, excellent beam pattern, and direct response, which are in agreement with predictions. Such a mixer is suitable for observations of the astronomically-interesting lowest rotational transition of HD at 2.7 THz, which can be observed with Stratospheric THz Observatory (STO) [12], Stratospheric Observatory for Infrared Astronomy (SOFIA) [13], and future space observatories [14].

II. HEB Device And Measurement Setup

Figure 1 shows a lens-twin slot antenna coupled HEB mixer. The HEB consists of a 1.5 μm wide, 0.2 μm long, and 5.5 nm thick NbN bridge on a highly resistive Si substrate. The bridge is connected to the central conductor of a coplanar waveguide (CPW) transmission line by NbTiN-Au superconducting bilayer contact pads [15]-[17]. The HEB has a normal-state resistance (R_N) of 124 Ω at 11 K, a superconducting transition temperature of 10 K, and a critical current of 133 μA at 4.2 K. To have a center frequency at 2.8 THz, we designed a twin-slot antenna with the following dimensions: the slot length L is $0.3\lambda_0$ with λ_0 (=107 μm) the free space wavelength; the slot separation S is $0.17\lambda_0$; and the slot width W is $0.02\lambda_0$. The CPW line has a central conductor with a width of 2.8 μm and two gaps of 1.4 μm, yielding a characteristic impedance of 51 Ω. To avoid leakage of the RF signal via the intermediate frequency (IF) output line, a RF choke filter is used with three sections consisting of three alternating high (75 Ω) and low impedance

Manuscript received July 7, 2011. The work was supported in part by the NSFC under Grant Nos. 10803021, 10933005 and 10621303, the Ministry of Science and Technology under Grant No. 2010CB327401, CAS KeyLab for Radio Astronomy, KNAW China Exchange Programme, NWO, and the AMSTAR+ project of RadioNet under FP7.

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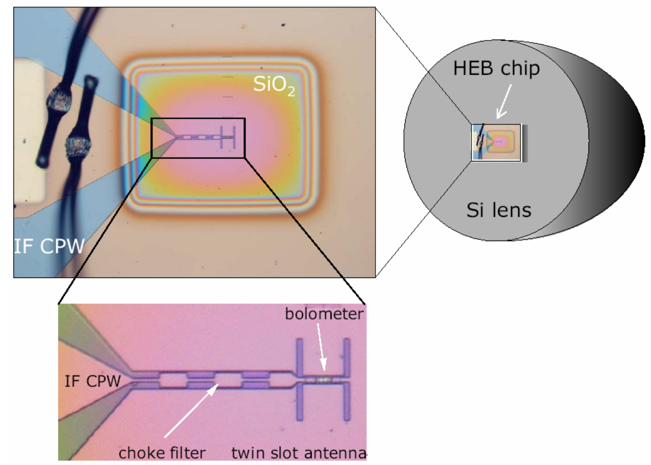

Fig. 1. Schematic drawing of a quasi-optical mixer where a HEB chip is glued to the backside of a Si ellipsoidal lens. As shown in the optical micrograph the NbN HEB consists of a twin slot antenna, a coplanar waveguide (CPW) transmission line (in the center), a choke filter, and a wide CPW line for intermediate frequency (IF) output.

(34 Ω) segments, each being a quarter wavelength (10.7 µm) long.

To determine the double sideband receiver noise temperature ($T_{N,rec}$), we performed the measurements in a vacuum setup [see Fig. 2(a)] as described in [18]. The HEB chip is glued to the backside of a Si ellipsoidal lens without antireflection coating, mounted in a mixer block that is placed in a liquid helium cryostat. A hot (295 K) and cold (77 K) load can be selected by rotating a mirror. The radiation from the hot/cold load is combined with that from the LO by a 3-µm Mylar beam splitter. Before reaching the HEB, the radiation passes through the metal-mesh heat filter at 4.2 K that blocks infrared radiation.

The LO is an optically pumped Far Infrared (FIR) ring gas laser, operated at a frequency of 2.523 THz using CH_3OH gas. The LO power coupled to the mixer is regulated by rotating a wire grid in front of the gas laser.

The IF signal, resulting from the mixing of the LO and the hot/cold load signal, first passes through a bias-T, a circulator, and then a cryogenic low noise amplifier (Berkshire 1.3-1.7 GHz) operated at 4.2 K, followed by room-temperature amplifiers. This signal is filtered at 1.5 GHz within a band of 80 MHz. Between each two components in the IF chain, an attenuator is added to avoid standing waves. The entire IF chain has a gain of about 80 dB and a noise temperature of 7 K.

To verify the antenna design, the direct response $\Delta I(f)$ of the mixer as a function of frequency is measured by operating it as a direct detector using an evacuated Fourier-transform spectrometer (FTS) [7]. The beam splitter used inside the FTS is a 12.5 µm thick Mylar sheet. Additionally, there is a high density polyethylene (HDPE) thin lens inside the FTS to collimate radiation. It is worthy to note that the optics are different from $T_{N,rec}$ measurement and contain a 2-mm thick HDPE window and a heat filter of two layers of Zitex G104.

We also characterize the beam pattern of the same mixer using a computer controlled measurement setup [6], [19], where the gas laser at 2.5 THz is applied as a signal source as shown in Fig. 2(b). The HEB is heated to a temperature that is slightly below the superconducting transition temperature of the NbN bridge. At a fixed bias voltage (0.6 mV), a lock-in amplifier is used to record the current changes due to the modulated defocused laser beam as a function of the tilt and rotation angle of the HEB cryostat. The dynamic range of the current signal is about 25 dB. The twin-slot antenna is positioned in such a way that its E plane is horizontal, and the H

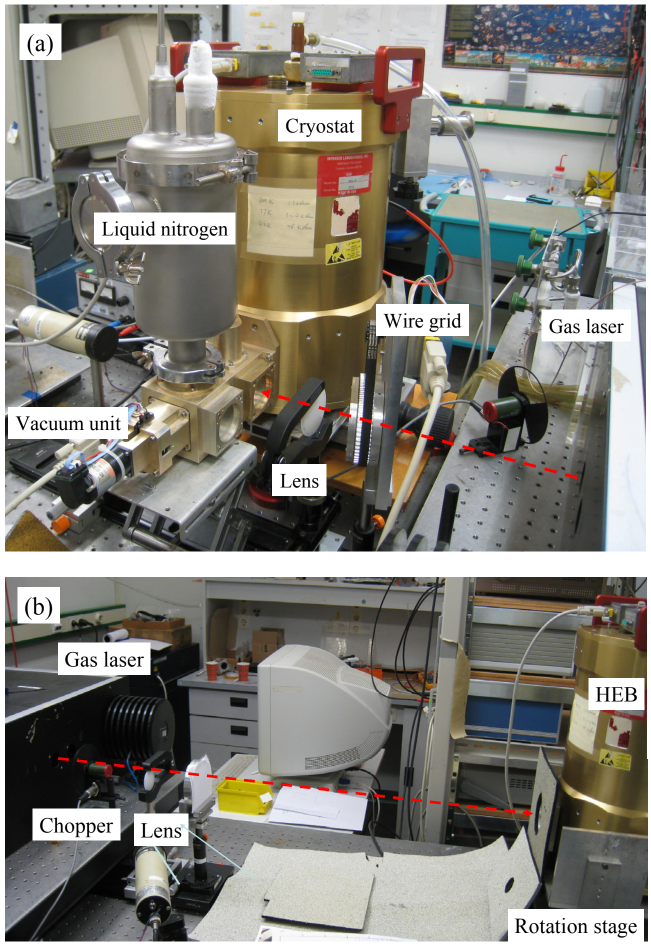

Fig. 2. (a) Receiver noise temperature measurement setup, where vacuum unit consisting of hot/cold loads, beamsplitter, and rotating mirror is directly connected to the HEB cryostat. Hot and cold loads can be selected by rotating the mirror. (b) Beam pattern measurement setup, where gas laser works as a signal source. The current change due to the modulated laser beam as functions of tilt and rotation angles of the HEB cryostat is recorded using a lock-in amplifier.

plane is vertical.

III. Direct Response

$\Delta I(f)$ is measured using a lock-in amplifier at a constant bias voltage and at a temperature close to the transition temperature of NbN bridge. Fig. 3(a) shows the measured normalized direct response of the mixer. We find a peak response at 1.8 THz, and other two lower peaks at 2.7 and 1.2 THz, respectively. The former is the designed center frequency, relative to the slot length (half-wavelength), and the latter might be due to full-wavelength resonance. The dip at 2.2 THz is due to the absorption of the HDPE thin lens inside the FTS and 2 mm HDPE vacuum window of HEB cryostat. $\Delta I(f)$ should be governed by the multi-factors expressed as $S\eta_{int}\eta_{opt}\eta_{FTS}P_I$, where S is the frequency independent current responsivity; η_{int} the intrinsic coupling efficiency for THz radiation power transmitted from the antenna to the bridge; η_{opt} the transmission due to the HDPE thin lens, HDPE window, and heat filter; η_{FTS} the power transfer function of the FTS; P_I the power spectrum of the lamp in the FTS, which is virtually constant within the frequency range of interest [7]. The transmission of the Si lens is not included since the absorption loss is negligible based on our measurement. Thus the measured relative response reflects the product of η_{int}, η_{opt}, and η_{FTS}. Fig. 3a also shows the product of $\eta_{opt}\eta_{FTS}$, where η_{opt} is obtained based on measured power transmission data and η_{FTS} is calculated for Mylar beam splitter. To derive η_{int} we divide $\Delta I(f)$ by the product of $\eta_{opt}\eta_{FTS}$. The result is a relative η_{int} that is plotted in Fig. 3(b). We find the 3 dB intrinsic response bandwidth to be approximately 2.1 THz, which is relatively wide.

To simulate η_{int}, each slot of the antenna is considered as a voltage generator in series with the antenna impedance [21]. The RF choke filter is assumed in series with one voltage generator/antenna impedance. Furthermore, the NbN bridge sees an impedance equal to both the added choke filter and the slot impedance transformed by the CPW transmission line on one side, while seeing only the transformed slot impedance on the other side. In addition, a capacitance C in parallel and an inductance L in series with the bolometer are added to the embedding impedance (Z_{embed}) to take into account the electromagnetic current crowding effects due to the abrupt change between the bridge and the central conductor [21]. We took a calculated C of 0.4 fF and a fitted L of 10 pH for the calculation. The impedance of the twin-slot antenna as a function of frequency is calculated using a simulator "PILRAP" [22]. η_{int} is derived by the impedance mismatch between the embedding impedance (Z_{embed}) seen at the bridge terminals and the bolometer impedance Z_{HEB} (equal to its R_N)

$$\eta_{\text{int}}(f) = 1 - \left| \frac{Z_{HEB} - Z_{embed}}{Z_{HEB} + Z_{embed}} \right|^2 \qquad (1)$$

In addition to Eq. 1, we also consider the effect of main beam efficiency in the final result of $\eta_{int}(f)$. When the frequency is much higher than the design frequency, the main beam efficiency suppresses the response due to the second antenna resonance. The calculated $\eta_{int}(f)$ is also plotted in Fig. 3b for comparison and shows good agreement with the measured one with respect to the frequency dependence and the overall shape.

IV. Receiver Noise Temperature

Double sideband receiver noise temperature ($T_{N,rec}$) of the mixer was measured by fixing the bias voltage of the HEB, but varying the LO power [18], [23]. At a bias voltage of 0.6 mV, we measured the receiver output power as a function of bias current, which is the result of varying LO power. Two such data sets are recorded, $P_{out,hot}$ responding to the hot load and $P_{out,cold}$ to the cold load. The Y-factor can be obtained by $Y(I)= P_{out,hot}(I)/P_{out,cold}(I)$ at the same current using the fitted polynomial curves to the $P_{out,hot}$ and $P_{out,cold}$ data points. The derived $T_{N,rec}$ as a function of bias current is plotted in Fig. 4(a), where the lowest $T_{N,rec}$ is 1150±50 K at a current of 24 μA, found from a broad minimum. As discussed in [18], a clear advantage of this method is that the $T_{N,rec}$ can be determined without suffering from the effect of direct detection. We also estimated the total conversion loss at the same operating point using a known method in [25] and find it to be 12.2 dB. The total loss in front of bolometer is 4.52 dB, in which the optics contribute 1.9 dB and the intrinsic coupling efficiency of the antenna contributes 2.62 dB, obtained from $\eta_{int[}$ [see Fig. 3(b)]. The optimum LO power absorbed in the HEB is 130 nW.

For comparison, $T_{N,rec}$ was also obtained in a conventional way, in which we measured the receiver output power, $P_{out,hot}$ and $P_{out,cold}$, responding to the hot and cold load as a function of bias voltage under a constant optimum LO power. The results are plotted in Fig. 4(b). The lowest $T_{N,rec}$ is 1250±300 K, which is 9 % higher than the previously determined 1150 K due to the direct detection effect. Note that at the optimum operation point the bias current changes ~0.3 μA when the hot and cold load is switched. Because of the limited RF bandwidth, the influence on $T_{N,rec}$ for the twin-slot antenna coupled HEB mixer is, as expected, considerably smaller than that for a spiral antenna coupled NbN HEB mixer [19].

$T_{N,rec}$ can be predicted using the quantum noise theory for terahertz HEB mixers based on a distributed hot-spot model

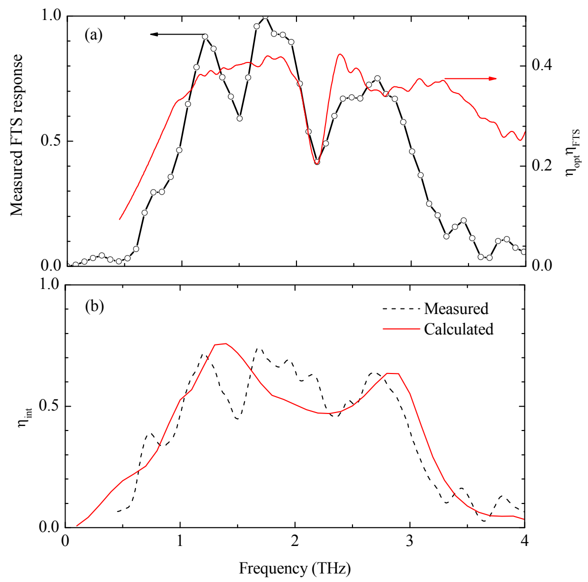

Fig. 3. (a) Measured, normalized direct response $\Delta I(f)$ of the twin-slot antenna coupled NbN HEB mixer and product of measured power transmission of HDPE lens, HDPE window, and heat filter (η_{opt}) and calculated power transfer function of the FTS (η_{FTS}) as a function of frequency; (b) Measured and calculated intrinsic direct response (η_{int}).

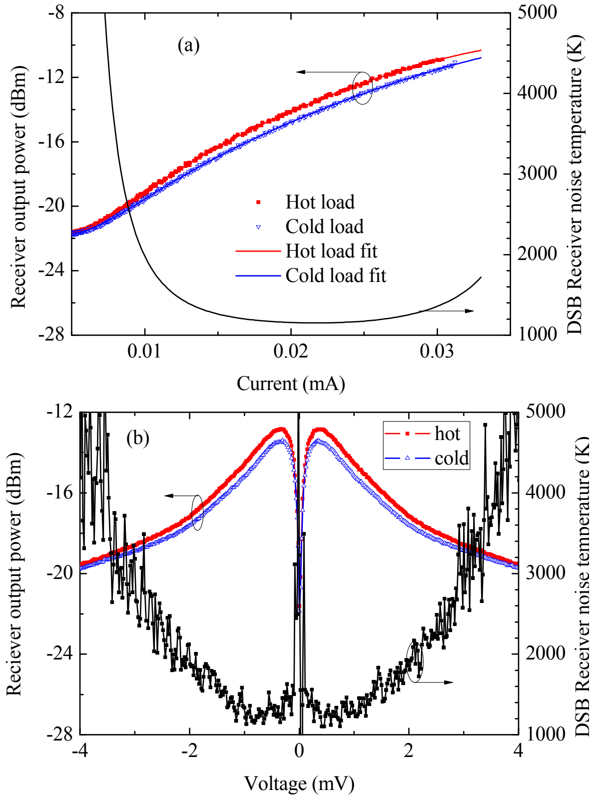

Fig. 4. (a) Measured receiver output powers (left axis) at the optimum bias voltage of 0.6 mV and the polynomial fit responding to the hot and cold load as a function of bias current of the HEB, which is varied by changing LO power. Double sideband receiver noise temperature $T_{N,rec}$ (right axis) of the HEB mixer is also shown as a function of bias current; (b) Measured receiver output power (left axis) responding to the hot and cold load at optimum LO power as a function of bias voltage. $T_{N,rec}$ is also plotted (right axis) vs. bias voltage.

[25], which includes the contribution of quantum noise (QN). We use the empirical values for the classical output noise and the quantum efficiency β-factor found in [23] to calculate $T_{N,rec}$. The calculated $T_{N,rec}$ is 1170 K, for which 40 % is contributed by QN. The result agrees well with the measured one (1150 K).

The measured $T_{N,rec}$ is comparable to the one found using a similar HEB but coupled with a spiral antenna at the same frequency [23], however, strictly speaking, is 25 % higher if we could have the same optical loss (see table 1). We attribute this difference to the parasitic reactance due to the abrupt change between the bridge and the CPW line, causing a slightly lower intrinsic coupling [21]. We also noticed that a new result of 600 K at 2.5 THz was very recently reported in [26], and 630 K in [27] using spiral antenna coupled NbN HEBs.

TABLE I

Comparison between spiral antenna and twin-slot antenna coupled HEB mixers at 2.5 THz, measured in vacuum setup. All the relevant parameters are also listed: optical loss of the 3-µm Mylar beam splitter at 300 K (L_{BS}, calculated), the IR filter at 4 K (L_{filter}, measured), the uncoated Si lens at 4 K (L_{lens}, reflection loss calculated; absorption loss is negligible based on our measurements on a Si wafer from the same material as used for our Si lens), intrinsic coupling between HEB and antenna (L_{coup}, from FTS response), and DSB receiver noise temperature ($T_{N,rec}$, measured).

	L_{BS} (dB)	L_{filter} (dB)	L_{lens} (dB)	L_{coup} (dB)	L_{total} (dB)	$T_{N,rec}$ (K)
Spiral antenna HEB	0.2	0.73	1.5	0.07	2.5	974
Twin slot antenna HEB	0.2	0.2	1.5	2.62	4.52	1150

V. Beam Pattern

Fig. 5a shows the measured beam patterns in E and H planes at 2.5 THz. The main beams in E and H planes overlap exactly, indicating a symmetric beam. The full width at -10 dB level is 1.4°, implying that the main beam is well collimated. The side lobes are 16 dB below the main lobe, which is generally adequate for THz astronomical applications. For comparison, a calculated beam pattern using the PILRAP [22] is also plotted in Fig. 5a, which shows good agreement with the measured ones. Fig. 5b illustrates the same beam pattern, but in a two-dimensional plot. The Gaussian beam efficiency, defined as the coupling efficiency between the measured beam of an antenna and a fundamental Gaussian mode [28], is found to be 90 %.

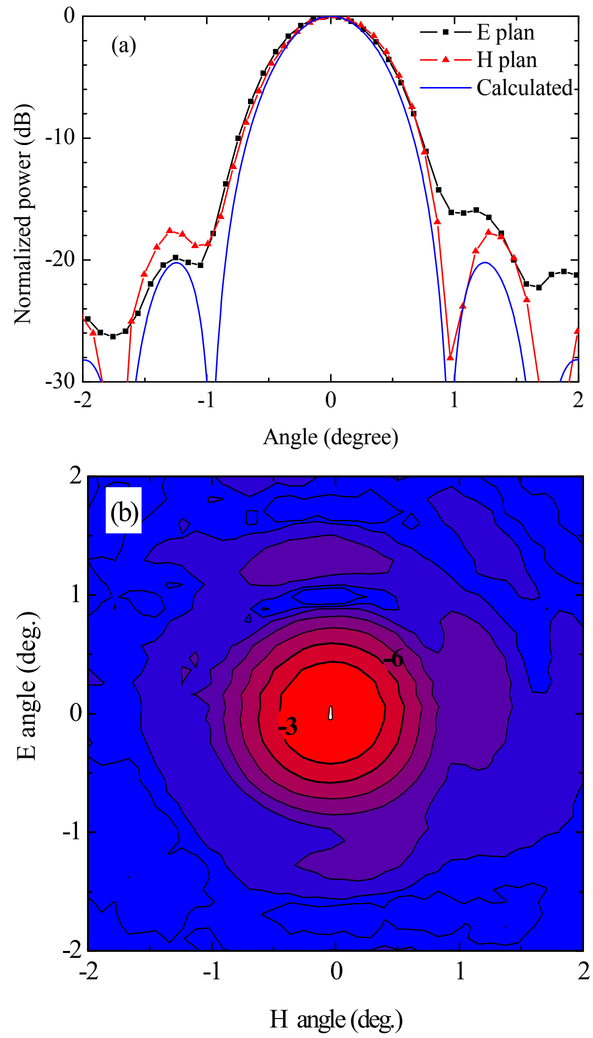

Fig. 5. (a) Measured and simulated far-field beam patterns of the quasi-optical mixer shown in figure 1 at 2.5 THz. (b) the same beam pattern, but plotted in two-dimensions.

VI. Conclusion

In summary we have demonstrated a practical quasi-optical NbN HEB mixer using a twin-slot antenna, which has a measured $T_{N,rec}$ of 1150 K at 2.5 THz (this can become 800 K if a lens with an antireflection coating were employed [20]), the main beam with a high Gaussian beam coupling efficiency and with sidelobes more than 16 dB below the boresight response, and an expected direct response. Our results are extremely encouraging for pushing the operating frequency of a twin slot antenna even higher, such as to 4.7 THz in order to study the OI fine structure transition.

Acknowledgment

We acknowledge L. de Jong, W.J. Vreeling, W. M. Laauwen, W. Horinga, and J. N. Hovenier for their technical support.

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