A 2.7 THz integrated heterodyne receiver based on a low power consumption quantum cascade laser

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Abstract— **We report on a compact and sensitive heterodyne receiver by integrating a superconducting hot electron bolometer (HEB) mixer and a 2.7 THz low power consumption quantum cascade laser (QCL) as a local oscillator on the same 4-K stage of a liquid helium cryostat as well as a pulse tube refrigerator. The QCL's small heat dissipation has very limited effect on the operation of the integrated superconducting HEB mixer. The superconducting HEB mixer can be easily pumped by introducing a spherical lens to collimate the QCL's beam. The 2.7 THz HEB/QCL integrated receiver shows an uncorrected noise temperature of 1500 K.**

I. INTRODUCTION

As is well known, there are very rich molecular rotational lines and atomic fine structure lines in the THz frequency regime. They are key diagnostic probes of the interstellar medium in astronomy and planetary atmospheres in atmospheric science. Observations of these spectral lines with high frequency resolution are therefore of particular interest. Such applications require a THz heterodyne receiver, which is typically made up of a sensitive mixer, a local oscillator (LO), and a low-noise amplifier. At frequencies between 1~10 THz, superconducting hot electron bolometer (HEB) mixers [1] are the most sensitive mixers, reaching nearly five times the quantum noise [2, 3]. On the other hand, THz sources that can be used as LOs for practical receivers beyond 2 THz are still under development. Recently, THz quantum cascade lasers (QCLs [4]) have emerged as a good candidate. Most of them, however, have large heat dissipation (namely large power consumption), besides a fairly limited frequency tuning range. To make use of QCLs as the LO of a heterodyne receiver, one has to either adopt a separate cryostat to cool down the QCL at 4.2 K [5-8] or place the QCL on the higher-temperature stage (e.g. 40-K stage) of a 4-K pulse tube refrigerator [9]. The integrated heterodyne receiver system in the former case becomes fairly complicated, while in the latter one it requires a QCL of good performance operating at relatively high temperatures and some additional optical components outside the 4-K cryostat for the coupling of LO radiation. Here we report on a compact and yet sensitive heterodyne receiver that integrates a log-spiral antenna coupled niobium nitride (NbN) superconducting HEB mixer and a low power consumption (~1.1 W) surface-emitting QCL at 2.7 THz on the same 4-K stage of a liquid helium cryostat as well as a pulse tube refrigerator.

II. INTEGRATED HEB/QCL RECEIVER

Fig.1 (a) shows the 2.7 THz HEB/QCL integrated heterodyne receiver inside a 4-K cryostat. The NbN superconducting HEB mixer (also including an elliptical silicon lens), the surface-emitting QCL, a spherical lens adopted to collimate the QCL's radiation beam, and a beam splitter for coupling the QCL signal are mechanically aligned to a mount anchored onto the 4-K stage of the cryostat. Obviously such an HEB/QCL integrated receiver is very compact. Furthermore, as the beam splitter is situated at the 4-K stage, its thermal noise contribution can be reduced to some extent and the instability caused by the air turbulence and the microphonic vibration in the beam splitter can be avoided.

As the QCL is located on the same 4-K stage as the superconducting HEB mixer, a QCL of low power consumption is highly required. The 2.7 THz surface emitting QCL used in this work is based on a bound-to-continuum active region design [10], and consists of 90 repetitions of GaAs/AlGaAs active region modules with a total thickness of 12 μm. The bound-to-continuum active region design can effectively suppress the parasitic current and decrease the applied bias, and therefore reduce the power consumption considerably. The measured dissipation power for the 2.7 THz surface emitting QCL is about 1.1 W when operated in the continuous wave (CW) mode. In order to improve the radiation efficiency, the 2.7 THz surface-emitting QCL exploits a graded photonic heterostructure (GPH) structure [11] as the resonator, as shown in the Fig. 1(b).

Fig. 1 (c) shows the NbN superconducting HEB mixer used in this work. It has a log-spiral antenna originally designed for the 0.1-1.4 THz frequency band, but can also operate at 2.7

THz according to a simulation by Microwave Studio CST. The superconducting HEB mixer was fabricated by an in-situ process [3] and has a 1.5-μm wide, 0.15-μm long and 5.5-nm thick microbridge.

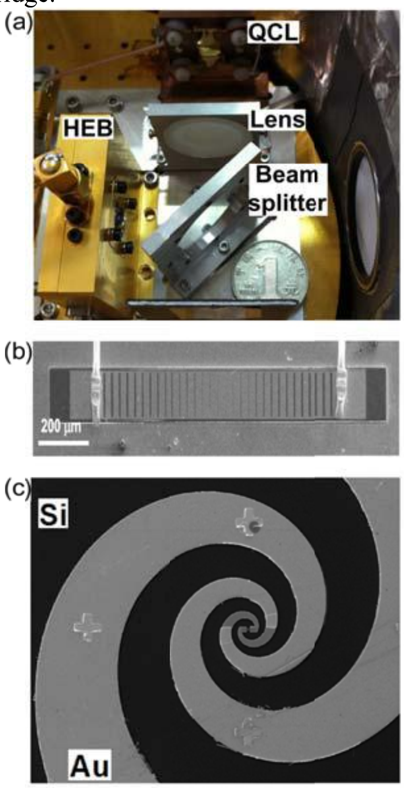

Fig. 1 2.7 THz HEB/QCL integrated heterodyne receiver. (a) Photo of the 2.7 THz HEB/QCL integrated heterodyne receiver inside a 4-K cryostat. (b) SEM image of the 2.7 THz surface-emitting QCL with a GPH resonator, in which the widths of the opening slits on the top electrode of the QCL increase from the center to the edges of the ridge resonator. (c) SEM image of the log-spiral antenna coupled superconducting HEB mixer.

III. Results and Discussions

For the HEB/QCL integration scheme we propose here, it is unlikely to adjust the optical coupling between the QCL and the HEB once the receiver is cooled down. Hence it is necessary to have a relatively precise optical design in advance. In order to precisely collimate the emission beam from the QCL, we firstly simulated the beam profile of the 2.7 THz surface emitting QCL by an antenna model [12]. The inset of the Fig. 2 (a) shows the simulated QCL far-field beam. It has a divergence of 10×40 degree which is difficult to match the beam of the adopted NbN superconducting HEB mixer with an elliptical lens of a 10-mm diameter. According to the simulated divergent angles of the beam, we collimated the QCL's beam by introducing a conventional high-density-polyethylene (HDPE) spherical lens of a radius of curvature of 15 mm and a diameter of 20 mm, which is positioned 37 mm away from the QCL. Fig. 2 (a) shows the collimated beam of the 2.7 THz surface emitting QCL calculated at the position of the NbN superconducting HEB mixer by the physical optics method. Obviously the collimated far-field beam of the 2.7 THz QCL has a much smaller divergence angle of only ~2×3 degree. The power coupling efficiency between the HEB and the QCL reaches ~8%, more than ten times better than the non-collimated case. Fig. 2 (b) displays the measured beam profile, which appears in good agreement with the simulated one.

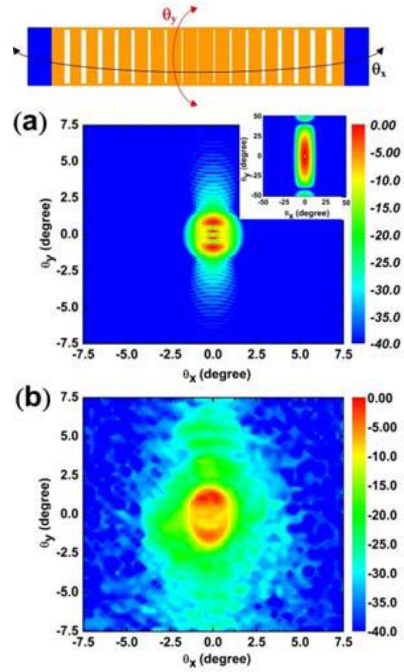

Fig. 2 Calculated (a) and measured (b) beam profiles of the 2.7 THz surface-emitting QCL after a HDPE spherical lens at the position of the superconducting HEB mixer. The inset shows the calculated far-field beam profile of the surface-emitting QCL itself.

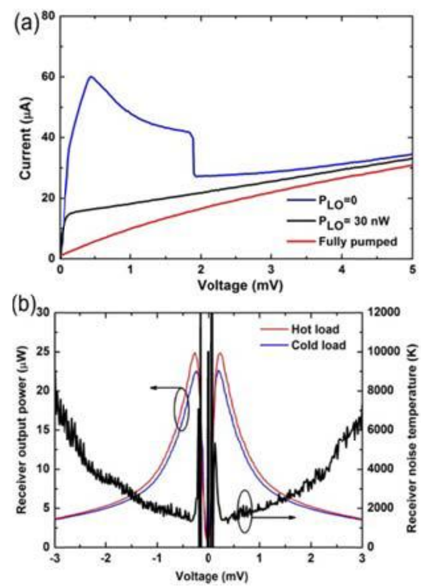

Fig. 3 Measured DC and mixing characteristics of an NbN superconducting HEB mixer. (a) Current-voltage curves of the NbN superconducting HEB mixer with and without radiation from the 2.7 THz surface-emitting QCL. (b) Measured receiver output powers (responding to the hot and cold load) and the resulting receiver noise temperature as a function of the DC bias voltage at the optimal LO power.

With the collimated QCL beam, we found that the NbN superconducting HEB mixer could be easily pumped at 2.7 THz. Fig. 3 (a) shows the current-voltage (I-V) curves of the NbN superconducting HEB mixer (with a critical current of 60 μA at 4.2 K) pumped at different LO powers by changing the direct current (DC) bias of the 2.7 THz QCL. At the optimal LO power the 2.7 THz QCL was biased at 4 V and 268 mA, corresponding to a power consumption of ~1.1 W. The temperature increase on the 4-K cold stage of the liquid helium cryostat was found to be only ~0.02 K. Fig. 3 (b) shows the measured intermediate frequency (IF) output powers responding to the hot (295 K) and cold (77 K) load, respectively, under the optimum LO pumping. The uncorrected receiver noise temperature by the standard Y factor method is also plotted in Fig. 3 (b). It can be clearly seen that the lowest receiver noise temperature with no corrections for optical losses is about 1500 K at a DC bias voltage of 0.5 mV. In our case, the total optical loss in the radio frequency (RF) signal path is estimated to be ~3.7 dB, with 0.5 dB due to the cryostat vacuum window (0.8-mm thick HDPE), 0.7 dB the IR filter (Zitex G104), 1.0 dB the beam splitter (6-μm thick Mylar) and 1.5 dB the silicon lens without anti-reflection coating. After correcting these optical losses, we found that the receiver noise temperature is as low as 600 K. The 2.7 THz HEB/QCL integrated receiver was also tested in a pulse tube refrigerator with a cooling capacity of 0.9 W at 4.2 K. We found that the temperature on the 4-K stage of the closed cycle cryocooler was increased from 3.2 K to 4.5 K with the QCL turned on. The measured receiver noise temperature was found to be similar to that measured in the liquid helium cryostat.

IV. Conclusions

In conclusion, we have demonstrated the integration of a superconducting HEB mixer and a QCL local oscillator on the same 4-K stage of a single cryostat. It has been found that with a low power consumption of 1.1 W, the heat dissipation of the 2.7 THz surface-emitting QCL has a very limited effect on the nearby superconducting HEB mixer in both a liquid helium and a closed cycle cryostat. And the NbN superconducting HEB mixer can be easily pumped by such a QCL with its beam simply collimated by a HDPE spherical lens. The measured noise temperature of the 2.7 THz HEB/QCL integrated receiver, even with a non-optimized HEB device, is about 1500 K. Fully integrated THz HEB/QCL receivers we propose here should be attractive to practical applications, especially to balloon- and space-borne applications.

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