Demonstration of a fully integrated superconducting receiver with a 2.7 THz quantum cascade laser

Wei Miao,[1,2] Zheng Lou,[1,2] Gang-Yi Xu,[3] Jie Hu,[1,2] Shao-Liang Li,[1,2] Wen Zhang,[1,2] Kang-Min Zhou,[1,2] Qi-Jun Yao,[1,2] Kun Zhang,[1,2] Wen-Ying Duan,[1,2] Sheng-Cai Shi,[1,2,*] Raffaele Colombelli,[4] Harvey E. Beere,[5] and David A. Ritchie[5]

[1]*Purple Mountain Observatory, CAS, Nanjing, 210008, China*
[2]*Key Lab of Radio Astronomy, CAS, Nanjing, 210008, China*
[3]*Key Lab of Infrared Imaging Materials and Detectors, Shanghai Institute of Technical Physics, CAS, Shanghai, 200083, China*
[4]*Institut d'Electronique Fondamentale, Univ. Paris Sud, UMR8622 CNRS, 91405 Orsay, France*
[5]*Cavendish Laboratory, University of Cambridge, Cambridge CB3 0HE, UK*
[*]*scshi@mail.pmo.ac.cn*

Abstract: We demonstrate for the first time the integration of a superconducting hot electron bolometer (HEB) mixer and a quantum cascade laser (QCL) on the same 4-K stage of a single cryostat, which is of particular interest for terahertz (THz) HEB/QCL integrated heterodyne receivers for practical applications. Two key issues are addressed. Firstly, a low power consumption QCL is adopted for preventing its heat dissipation from destroying the HEB's superconductivity. Secondly, a simple spherical lens located on the same 4-K stage is introduced to optimize the coupling between the HEB and the QCL, which has relatively limited output power owing to low input direct current (DC) power. Note that simulation techniques are used to design the HEB/QCL integrated heterodyne receiver to avoid the need for mechanical tuning. The integrated HEB/QCL receiver shows an uncorrected noise temperature of 1500 K at 2.7 THz, which is better than the performance of the same receiver with all the components not integrated.

OCIS codes: (040.0040) Detectors; (040.2840) Heterodyne.

References and links

1. E. M. Gershenzon, G. N. Gol'tsman, I. G. Gogidze, Y. P. Gusev, A. I. Elant'ev, B. S. Karasik, and A. D. Semenov, "Millimeter and submillimeter range mixer based on electron heating of superconducting films in the resistive state," Sov. Phys. Supercond. **3**, 1582 (1990).
2. W. Zhang, P. Khosropanah, J. R. Gao, E. L. Kollberg, K. S. Yngvesson, T. Bansal, R. Barends, and T. M. Klapwijk, "Quantum noise in a terahertz hot electron bolometer mixer," Appl. Phys. Lett. **96**(11), 111113 (2010).
3. I. Tretyakov, S. Ryabchun, M. Finkel, A. Maslennikova, N. Kaurova, A. Lobastova, B. Voronov, and G. Goltsman, "Low noise and wide bandwidth of NbN hot electron bolometer mixers," Appl. Phys. Lett. **98**(3), 033507 (2011).
4. J. Faist, F. Capasso, D. L. Sivco, C. Sirtori, A. L. Hutchinson, and A. Y. Cho, "Quantum cascade laser," Science **264**(5158), 553–556 (1994).
5. J. R. Gao, J. N. Hovenier, Z. Q. Yang, J. J. A. Baselmans, A. Baryshev, M. Hajenius, T. M. Klapwijk, A. J. L. Adam, T. O. Klaassen, B. S. Williams, S. Kumar, Q. Hu, and J. L. Reno, "Terahertz heterodyne receiver based on a quantum cascade laser and a superconducting bolometer," Appl. Phys. Lett. **86**(24), 244104 (2005).
6. H. W. Hübers, S. G. Pavlov, A. D. Semenov, R. Köhler, L. Mahler, A. Tredicucci, H. E. Beere, D. A. Ritchie, and E. H. Linfield, "Terahertz quantum cascade laser as local oscillator in a heterodyne receiver," Opt. Express **13**(15), 5890–5896 (2005).
7. M. Hajenius, P. Khosropanah, J. N. Hovenier, J. R. Gao, T. M. Klapwijk, S. Barbieri, S. Dhillon, P. Filloux, C. Sirtori, D. A. Ritchie, and H. E. Beere, "Surface plasmon quantum cascade lasers as terahertz local oscillators," Opt. Lett. **33**(4), 312–314 (2008).
8. P. Khosropanah, W. Zhang, J. N. Hovenier, J. R. Gao, T. M. Klapwijk, M. I. Amanti, G. Scalari, and J. Faist, "3.4 THz Heterodyne receiver using a hot electron bolometer and a distributed feedback quantum cascade laser," J. Appl. Phys. **104**(11), 113106 (2008).

#226864 - $15.00 USD Received 18 Nov 2014; revised 5 Jan 2015; accepted 9 Feb 2015; published 12 Feb 2015

9. H. Richter, A. D. Semenov, S. G. Pavlov, L. Mahler, A. Tredicucci, H. E. Beere, D. A. Ritchie, K. S. Il'in, M. Siegel, and H. W. Hubers, "Terahertz heterodyne receiver with quantum cascade laser and hot electron bolometer mixer in a pulse tube cooler," Appl. Phys. Lett. **93**(14), 141108 (2008).
10. G. Sevin, D. Fowler, G. Xu, F. H. Julien, R. Colombelli, H. Beere, and D. Ritchie, "Continuous-wave operation of 2.7 THz photonic crystal quantum cascade lasers," Electron. Lett. **46**(22), 1513 (2010).
11. W. Zhang, W. Miao, J. Q. Zhong, S. C. Shi, D. J. Hayton, N. Vercruyssen, J. R. Gao, and G. N. Gol'tsman, "Temperature dependence of the receiver noise temperature and IF bandwidth of superconducting hot electron bolometer mixers," Supercond. Sci. Technol. **27**(8), 085013 (2014).
12. G. Y. Xu, L. H. Li, N. Isac, Y. Halioua, A. G. Davies, E. H. Linfield, and R. Colombelli, "Surface-emitting terahertz quantum cascade lasers with continuous-wave power in the tens of milliwatt range," Appl. Phys. Lett. **104**(9), 091112 (2014).
13. G. Y. Xu, Y. Halioua, S. Moumdji, R. Colombelli, H. E. Beere, and D. A. Ritchie, "Stable Single-Mode Operation of surface-emitting terahertz lasers with graded photonic heterostructure resonators," Appl. Phys. Lett. **102**(23), 231105 (2013).
14. G. Y. Xu, R. Colombelli, S. P. Khanna, A. Belarouci, X. Letartre, L. Li, E. H. Linfield, A. G. Davies, H. E. Beere, and D. A. Ritchie, "Efficient power extraction in surface-emitting semiconductor lasers using graded photonic heterostructures," Nat. Commun. **3**, 952 (2012).
15. M. Cui, J. N. Hovenier, Y. Ren, N. Vercruyssen, J. R. Gao, T. Y. Kao, Q. Hu, and J. L. Reno, "Beam and phase distributions of a terahertz quantum cascade wire laser," Appl. Phys. Lett. **102**(11), 111113 (2013).
16. J. J. A. Baselmans, A. Baryshev, S. F. Reker, M. Hajenius, J. R. Gao, T. M. Klapwijk, Y. Vachtomin, S. Maslennikov, S. Antipov, B. Voronov, and G. Gol'tsman, "Direct detection effect in small volume hot electron bolometer mixers," Appl. Phys. Lett. **86**(16), 163503 (2005).

1. Introduction

The very rich molecular rotational lines and atomic fine structure lines in the THz frequency regime 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 composed 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) have emerged as a good candidate [4]. Most of them, however, have large heat dissipation (namely large power consumption), besides a fairly limited frequency tuning range. To use a QCL as the LO of a heterodyne receiver, it is in general necessary to either rely on a separate cryostat to cool 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 cooled cryostat [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. Furthermore, some additional optical components are necessary 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. A demonstration is also given with a pulse tube cooled cryostat.

2. Integrated receiver

Figure 1 shows the schematic of the 2.7 THz HEB/QCL integrated heterodyne receiver and its view inside the 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.

#226864 - $15.00 USD Received 18 Nov 2014; revised 5 Jan 2015; accepted 9 Feb 2015; published 12 Feb 2015

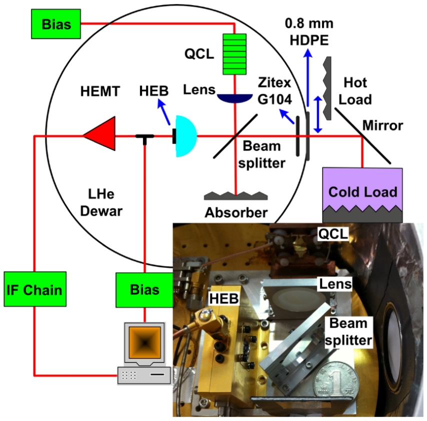

Fig. 1. Schematic view of the 2.7 THz HEB/QCL integrated heterodyne receiver. The inset shows a photo inside the 4-K cryostat.

3. Quantum cascade laser

For such a fully integrated THz superconducting receiver, a concern is that the QCL's heat dissipation may destroy the HEB's superconductivity. A QCL of low power consumption is therefore mandatory. 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 exhibits a reduced parasitic current and a low applied bias, and therefore its power consumption is limited. The measured dissipation power of the 2.7 THz surface-emitting QCL is about 1.1 W when the device is operated in continuous wave (CW) mode for an injection current of 268 mA. We found that such power consumption leads to a temperature increase of ~0.02 K on the 4 K stage of a liquid helium cryostat, or increases the temperature from 3.2 K to 4.5 K in a pulse tube cooled cryostat with a cooling capacity of 0.9 W at 4.2 K. Our previous study has demonstrated that the performance of NbN superconducting HEB mixers is nearly unchanged at bath temperatures below 0.8Tc, where Tc is the critical temperature of the HEB microbridge [11]. Hence integrating such a QCL on the same 4-K stage as the NbN superconducting HEB mixer will not result in considerable degradation of the mixer performance.

The adopted 2.7 THz surface-emitting QCL exploits a graded photonic heterostructure (GPH) structure [12] as the resonator, as shown in the inset of Fig. 2. The GPH resonator is realized by varying the lateral metal coverage, i.e., the grating filling factor defined as the ratio of the metallic finger width to the period width. The GPH resonator used in this work consists of 33 periods, and the grating period is 33.5 μm. In turn, the grating filling-factor decreases symmetrically and linearly from the center (95.5%) to each end (66.9%) of the ridge. The GPH resonator reverses the traditional mode competition in distributed surface-emitting QCLs, and selectively excites the symmetric mode with high radiation efficiency. As a result, single mode surface emission with high power efficiency can be realized. Figure 2 shows its frequency spectrum measured by a Fourier transform spectrometer with a resolution of ~2.5 GHz. As a matter of fact, single mode or monochromatic emission (within the resolution limit of the FTS) is realized in the whole laser dynamic range [12, 13]. The maximum output power of the 2.7 THz surface emitting QCL has been measured with a Thomas Keating absolute THz power meter in quasi CW mode (50% duty cycle at a repetition rate of 40 Hz). A value of 1.6 mW was obtained, which is relatively low owing to low input DC power, but still sufficiently high for pumping a superconducting HEB mixer with a LO power requirement of only a few tens or hundreds nW.

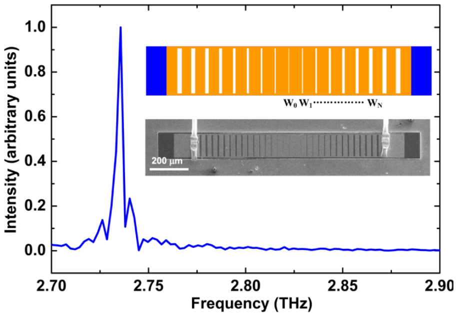

Fig. 2. Measured spectrum of the surface-emitting QCL biased at 268 mA. The inset shows a schematic diagram (Upper) and a SEM image (Lower) of the 2.7 THz surface-emitting QCL with a GPH resonator, in which the widths Wi of the opening slits on the top electrode of the QCL increase from the center to the end.

4. Beam profiles

A challenge in making such a fully integrated THz superconducting receiver is that it will not be possible to adjust the optical coupling between the QCL and the HEB at low temperatures. It is therefore necessary to precisely align the optical components in advance. The beam profile of a surface-emitting QCL with a GPH resonator is known to be still divergent, although it is much improved compared with that of typical Fabry-Perot QCLs with metal-metal waveguides [12–14]. In order to collimate precisely the emission beam from the QCL, we firstly simulated the beam profile of the 2.7 THz surface-emitting QCL using an antenna model [15], which treats all the opening slits on the top electrode of the QCL as an array of dipole antennas and assumes a Gaussian distribution of electric field amplitude along the QCL ridge direction. As shown in the Fig. 3(b), the simulated far-field beam of the 2.7 THz surface-emitting QCL has a divergence of 10 × 40 degrees, in good agreement with the experimental measurement [13]. It is indeed difficult to match the beam of the integrated NbN superconducting HEB mixer with an elliptical lens of a 10-mm diameter. In terms of the simulation results, we collimated the QCL's beam by introducing a simple high density polyethylene (HDPE) spherical lens of a radius of curvature of 15 mm and a diameter of 20 mm. The lens is positioned 37 mm away from the QCL. Figure 3(c) shows the collimated beam of the 2.7 THz surface-emitting QCL, calculated at the position of the NbN superconducting HEB mixer (60 mm away from the HDPE spherical lens) by the physical optics method. The collimated far-field beam of the 2.7 THz surface-emitting QCL has now a much smaller divergence angle of only ~2 × 3 degrees. The power coupling efficiency between the HEB and the QCL reaches approximately 8%, more than ten times better than the non-collimated case. It should be pointed out that the power coupling efficiency could be further increased by using a lens of larger size or with a specially designed surface profile. The power coupling efficiency could also be improved by using a linear to circular polarization converter as a log-spiral antenna coupled superconducting HEB mixer accepts elliptically polarized radiation while the 2.7 THz surface-emitting QCL is linearly polarized. To validate the simulation result, we measured the beam profile of the 2.7 THz QCL combined with the HDPE spherical lens by scanning a pyroelectric detector with an aperture of 0.8 mm in diameter at the position of the NbN superconducting HEB mixer. Figure 3(d) displays the measured beam profile, which appears in good agreement with the simulated one.

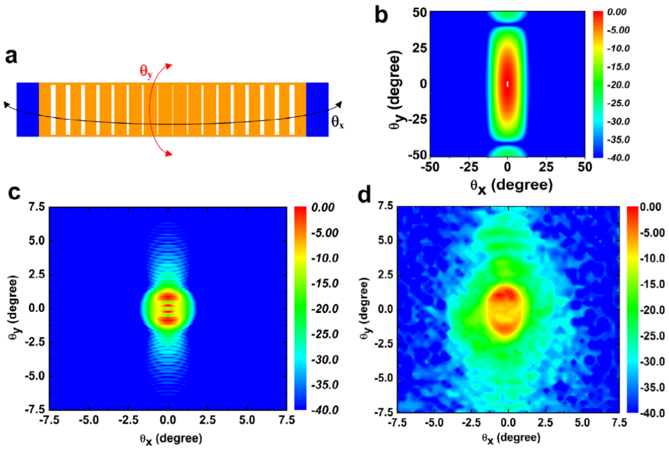

Fig. 3. Far-field beam profiles of the surface-emitting QCL. (a) Schematic diagram defining the scanning angles used in beam profile measurements and calculations. (b) Calculated far-field beam profile of the surface-emitting QCL itself. Note: the side lobes in the regions where θy is beyond ± 40 degree were not experimentally observed. The deviation may be caused by the simplified approximation used in our simulation. (c) Calculated beam profile of the 2.7 THz surface-emitting QCL after a HDPE spherical lens at the position of the superconducting HEB mixer. (d) Measured beam profile of the 2.7 THz surface-emitting QCL after the HDPE spherical lens.

5. Noise temperature measurement

With the collimated QCL beam, we found that the NbN superconducting HEB mixer could be efficiently pumped at 2.7 THz. The NbN superconducting HEB mixer, fabricated by an in situ process [3], has a 1.5-µm wide, 0.15-µm long and 5.5-nm thick microbridge. The HEB mixer has a room temperature resistance of 113 Ω and a critical temperature Tc of 7.5 K. Note that the NbN superconducting HEB mixer has a log-spiral antenna (see the inset of Fig. 4) 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 calculated power coupling between the log-spiral antenna and the microbridge is about 0.94 at 2.7 THz.

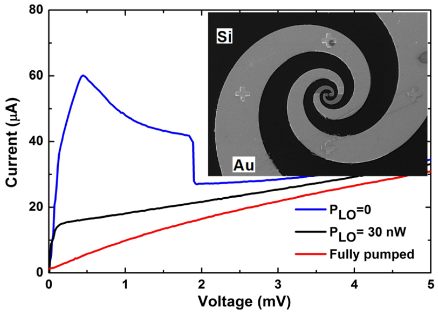

Fig. 4. Current-voltage curves of an NbN superconducting HEB mixer with and without radiation from the 2.7 THz surface emitting QCL. The inset shows the SEM micrograph of a log-spiral antenna coupled superconducting HEB mixer.

Figure 4 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 DC bias applied to the 2.7 THz QCL. At the optimal LO power, the 2.7 THz QCL was biased at 4 V and 268 mA. For this case, the cryostat (with 2.6 L of liquid helium capacity) is capable of providing nearly two hours of holding time. It should be pointed out that there is no such time limit if a closed-cycle cryostat is used for cooling the QCL and the HEB.

Figure 5 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 calculated by the standard Y factor method is also plotted in Fig. 5. Note that the direct-detection effect [16] was compensated by adjusting the LO power to keep the same DC bias for the superconducting HEB mixer irradiated by the hot and cold load. It can be clearly seen in Fig. 5 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. This noise temperature is mainly determined by our NbN superconducting HEB mixer as the measured one with all the components not integrated showed a higher noise temperature (~2000 K). For this integrated THz superconducting receiver, there are still some optical losses in the radio frequency (RF) signal path, with 0.5 dB due to the cryostat vacuum window (0.8-mm thick HDPE), 0.7 dB due to the IR filter (Zitex G104), 1.0 dB due to the beam splitter (6-μm thick Mylar) and 1.5 dB due to the silicon lens without anti-reflection coating. After correcting these optical losses, we found that the receiver noise temperature can be as low as 600 K. This result is comparable with the best results [2, 3].

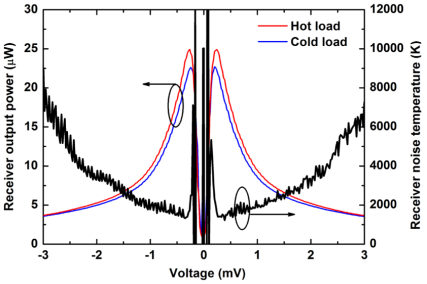

Fig. 5. Measured receiver output powers (responding to the hot and cold load) and the resulting receiver noise temperature as a function of the DC bias voltage at the optimal LO power.

The 2.7 THz HEB/QCL integrated receiver was also tested in a pulse tube cooled cryostat with a cooling power of 0.9 W at 4.2 K. As introduced before, the temperature on the 4-K stage of the closed-cycle cryostat increases from 3.2 K to 4.5 K when the QCL is in operation. The measured receiver noise temperature is about 1500 K, similar to that measured in the liquid helium cryostat.

6. Conclusion

In conclusion, we have demonstrated for the first time 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 the heat dissipation of the 2.7 THz low power consumption QCL leads to a small temperature increase on the 4-K stage and does not degrade the performance of the nearby superconducting HEB mixer in a liquid-helium or a closed-cycle cryostat. In addition, the NbN superconducting HEB mixer can be easily pumped by such 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 an un-optimized HEB device, is about 1500 K and can be reduced to 600 K after correcting the noise contributions of the quasi optical components. Fully integrated THz HEB/QCL receivers of the type that we propose here should be attractive for practical applications, especially for balloon- and space-borne applications.

Acknowledgments

We acknowledge G.N. Gol'tsman and B. Vorono of MSPU for fabricating the HEB mixer. This work was supported by CAS under Grant No. XDB04010300, NSFC under Grant Nos. 11127903, 11190012, and U1231109, and the CAS Joint Key Lab for Radio Astronomy. G.Y. Xu thanks the supports from "The Hundred Talents Program" of CAS and the "Shanghai Pujiang program" (14PJ1409700).

Received 18 Nov 2014; revised 5 Jan 2015; accepted 9 Feb 2015; published 12 Feb 2015