A Fully Integrated Heterodyne Receiver Based on a Hot Electron Bolometer Mixer and a Quantum Cascade Laser

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***Abstract*—We report on a very compact heterodyne receiver by integrating a superconducting NbN hot electron bolometer (HEB) mixer and a semi-insulating surface-plasmon quantum cascade laser (QCL) operating at 2.5 THz as local oscillator in a single block. To ensure effective pumping of the HEB mixer, the QCL's beam is collimated with a parabolic mirror that is integrated in the block too. After the collimation, the beam coupling efficiency between the HEB mixer and the QCL reaches approximately 0.9 and the superconducting HEB mixer can be easily pumped by the QCL. We then measured the receiver noise temperature of the integrated HEB/QCL receiver with a vacuum experimental setup. The lowest uncorrected receiver noise temperature is found to be about 750 K at 2.5 THz.**

I. INTRODUCTION

It is well known that the terahertz (THz) frequency region is featured by a diversity and large number of fine structure and molecular lines. They are very important tracers for studying the energetics and kinematics of astronomical objects such as stars and planetary systems. To detect these spectral lines with high frequency resolution, a sensitive and compact heterodyne receiver is essentially required. At frequencies up to 1.9 THz, heterodyne receivers based on superconducting mixers [1, 2] and solid-state multiplier-chain local oscillator (LO) sources have been realized for many space and ground-based telescope applications [3, 4]. At higher frequencies, the development of heterodyne receivers is seriously limited by the availability of suitable LO sources although superconducting hot electron bolometer (HEB) mixers have shown a superior sensitivity up to 5.3 THz [5]. Recently, THz quantum cascade lasers (QCLs) have been developed as a new LO source at frequencies above 1.9 THz, with high output power and good power stability [6]. Much progress has been made in using a THz QCL as an LO for superconducting HEB receivers, such as QCL's frequency and amplitude stabilization [7-10], and gas phase spectroscopy [11]. However, due to the high power dissipation of the QCL, most of them use an additional 4-K cryostat for the cooling of the QCL. It makes the receiver system fairly complicated. To simplify the receiver system, Richter et al. integrated the HEB mixer and the QCL on the different cold stages of a pulse-tube (PT) cooler [12]. Such integrated receiver, however, requires a THz QCL of good performance at relatively high temperatures. Recently, we have also demonstrated the integration of a HEB mixer and a 2.7 THz QCL on the same 4-K stage of a cryostat [13]. However, the HEB mixer and the 2.7 THz QCL are still mounted in two separate blocks and the noise performance of the integrated receiver is largely limited by optical losses. In this paper, we report on the demonstration of a fully integrated heterodyne receiver with a superconducting HEB mixer and a THz QCL in a block. The noise temperature of the integrated receiver is characterized using a vacuum experimental setup.

II. HEB/QCL INTEGRATED RECEIVER

Fig. 1 (a) shows the photograph of the integrated receiver, in which a superconducting niobium nitride (NbN) HEB mixer and a semi-insulating surface-plasmon QCL operating at 2.5 THz are integrated in a block. The superconducting NbN HEB mixer used in this work was fabricated at Laboratoire d'Etudes du Rayonnement et de la Matiere en Astrophysique (LERMA). The HEB mixer consists of a 0.2 μm long and 2 μm wide NbN microbridge (connected to a log spiral antenna). The mixer has a normal resistance of 90 Ω and a critical temperature of 9.7 K.

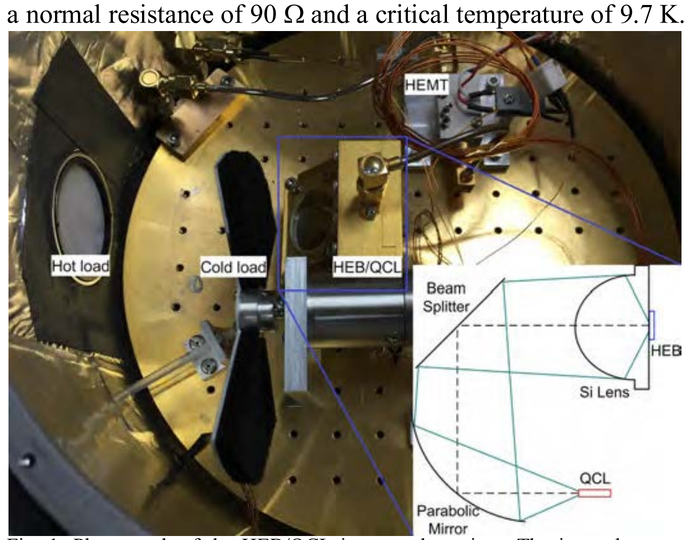

Fig. 1. Photograph of the HEB/QCL integrated receiver. The inset shows a schematic diagram of the coupling of the LO radiation from the QCL to the superconducting HEB mixer inside the block.

The QCL used here was fabricated at Shanghai Institute of Microsystem and Information (SIMIT), based on a bound-to-continuum (BTC) active region design and a semi-insulating surface-plasmon waveguide. The beam profile of the semi-insulating surface-plasmon QCL is known to be still divergent due to the sub wavelength lateral dimension of the cavity and the coherent emission from the facets and sides [13]. So we used a parabolic mirror to collimate the radiation of the semi-insulating surface-plasmon QCL (see the inset of Fig. 1). The parabolic mirror has a diameter of 20 mm and a focal length of 12 mm. After the parabolic mirror, the radiation is coupled to the HEB mixer with a 6 μm thick beam splitter.

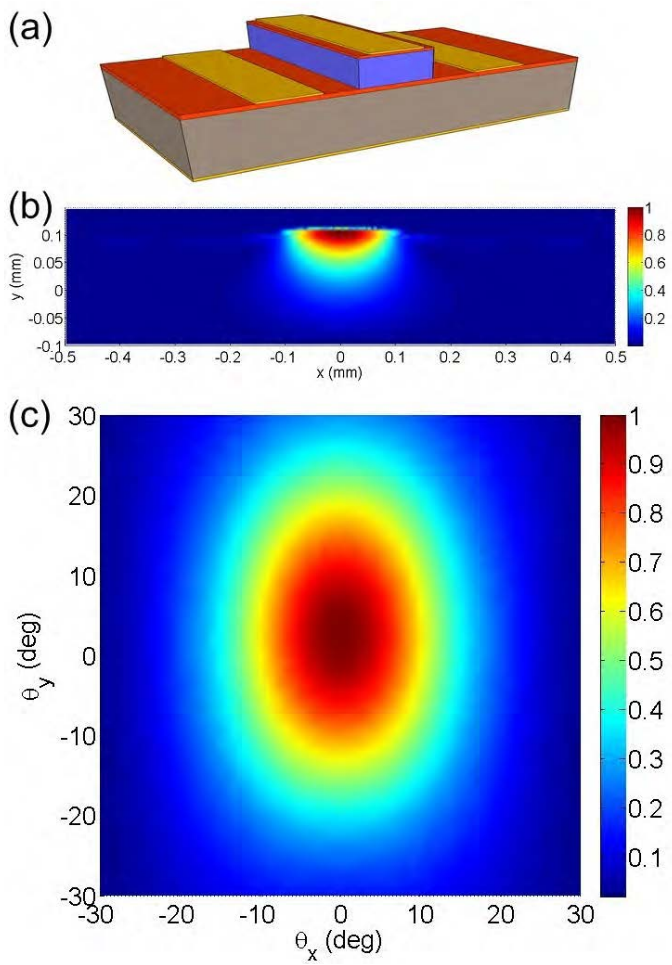

Fig. 2. (a) Schematic view of the semi-insulating surface-plasmon QCL. (b) Electric field intensity distribution at the front facet of the QCL. The electric field is simulated by using COMSOL. (c) Calculated beam pattern of the 2.5 THz semi-insulating surface-plasmon QCL after the parabolic mirror.

Fig. 2 (a) shows a schematic view of the semi-insulating surface-plasmon QCL. Fig. 2 (b) and (c) show the simulated electric field intensity distribution at the front facet of the semi-insulating surface-plasmon QCL and the calculated far field beam pattern of the QCL after the parabolic mirror. Here the far field beam pattern of the QCL is calculated from the electric field intensity distribution at the front facet by using spatial Fourier transform and physical optics propagation. It can be seen that the calculated far field beam pattern after the parabolic mirror is quite symmetric with a small angle offset in the vertical direction. We then evaluated the beam coupling efficiency between the superconducting HEB mixer and the QCL from the convolution of their far field beam patterns. We found that after the collimation, the beam coupling efficiency is as high as 0.9 (not including the reflection loss of the beam splitter).

III. Measurement Results and Discussions

With the collimated beam, the superconducting NbN HEB mixer can be easily pumped by the semi-insulating surface-plasmon QCL. Fig. 3 shows the measured current-voltage (I-V) curves of the superconducting HEB mixer. We then measured the noise performance of the HEB/QCL integrated receiver by using a vacuum experimental setup (see Fig. 1). In the setup, a 295 K blackbody inside the liquid helium cryostat is used as hot load and a 4.2 K blackbody on a chopper is used as cold load. The two loads can be selected by rotating the chopper, controlled by a Phytron stepper motor. Fig. 4 shows the measured mixer's intermediate frequency (IF) output power (responding to the hot and cold loads) and the receiver noise temperature as a function of the bias voltage. We can find that the lowest uncorrected receiver noise temperature is about 750 K at 2.5 THz.

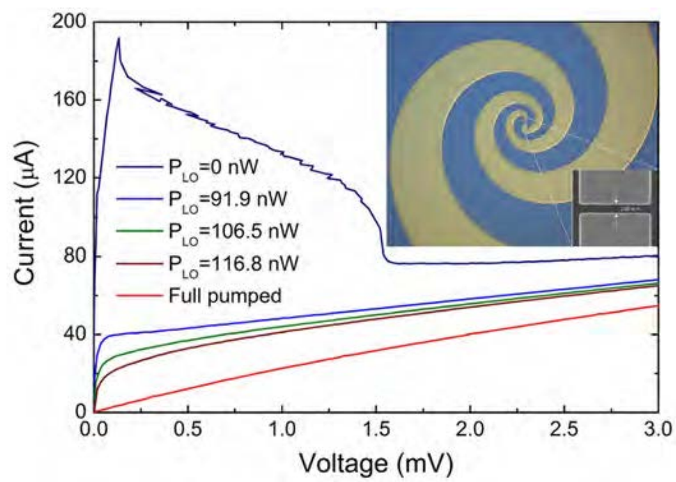

Fig. 3. Measured I-V curves of the superconducting HEB mixer. The inset shows a SEM micrograph of the superconducting HEB mixer.

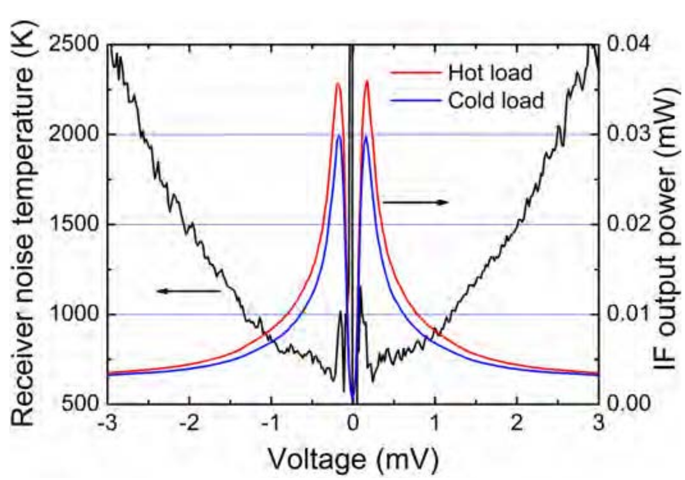

Fig. 4. Measured IF output power (responding to the hot and cold loads) and the resulting receiver noise temperatures as a function of the bias voltage.

Conclusions

We have demonstrated a compact and sensitive heterodyne receiver by integrating a superconducting NbN HEB mixer and a low power consumption QCL emitting at 2.5 THz as LO in a block. We have found that the superconducting HEB mixer can be easily pumped by the QCL with its beam collimated with a parabolic mirror. We have characterized the noise performance of the integrated HEB/QCL receiver using a vacuum experimental setup. The measured double sideband receiver noise temperature is as low as 750 K at 2.5 THz.

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