2.8 THz heterodyne receiver based on a surface plasmon quantum cascade laser and a hot electron bolometer mixer

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***Abstract*— This work focuses on surface plasmon quantum cascade lasers (QCL) as a local oscillators (LO) for heterodyne receivers operating above 2 THz. The far-field beam pattern of a 214 μm wide and 1500 μm long 2.84 THz surface plasmon QCL is measured and found to be less divergent compared to metal-metal waveguide QCLs, which is preferable for coupling the radiation to a quasi-optical mixer. We successfully used this QCL to pump a NbN HEB mixer integrated with spiral antenna. At optimized LO power and bias voltage we measured double side band receiver noise temperatures of 1150 K and 1050 K at bath temperature of 4 K and 2 K respectively. To the best of our knowledge these represent the highest reported sensitivities at such a high frequency.**

I. INTRODUCTION

Nowadays heterodyne receivers operating up to 2 THz use a combination of an electronically tunable solid state LO source [1], with either a superconductor-insulator-superconductor (SIS) [2] or a hot electron bolometer (HEB) mixer [3]. The latter type of mixer is the detector of choice for frequencies above 1.5 THz. Future space borne missions require an increase in frequency, e.g. 2-6 THz [4]. The development of new receivers operating at such high frequencies is limited by the availability of suitable LO sources. Existing solid state LOs [1] are unlikely to generate sufficient output power at such high frequencies since the power falls off rapidly with increasing frequency due to reduced multiplication efficiency. Optically pumped gas lasers can operate at higher frequencies, but are in general not suitable for space borne applications. Recently, a new type of solid-state THz source has been developed based on quantum cascade laser (QCL) structures [5]. This new source holds great promise for LO applications because of its compactness and high power efficiency. The demonstration of a HEB-QCL receiver at 2.8 THz has recently been reported using a HEB mixer and a QCL as LO [6]. In this case a QCL based on a double-sided metal-metal waveguide, developed at MIT/Sandia [7], was used. The far field beam patterns of this type of devices have also been measured [8] and modeled [9], showing that the beam is not only strongly divergent but also presents ring-like interference features. These characteristics are the consequence of the small lateral dimensions of the QCL cavity (at the limit of subwavelength) and of the interference due to the coherent emission from all the facets. Obviously, such beam pattern prevents an efficient optical coupling of the radiation to a mixer.

In this work we exploit a different type of QCL, which is based on surface plasmon waveguide. Because of the different cavity design and the geometry difference in lateral dimensions, a better quality beam pattern is expected compared to metal-metal waveguide QCLs. Here we measure the beam pattern of a 2.8 THz surface plasmon QCL and also determine the heterodyne sensitivity obtained by using the QCL with a HEB mixer. A similar surface plasmon QCL has been used as LO source for a 2.5 THz, HEB-based heterodyne receiver [10].

However, here we demonstrate a substantially lower receiver noise temperature at a slightly higher frequency.

II. QCL CHARACTERIZATION

The QCL used in this work is reported in reference [11] and is based on a bound-to-continuum active region design and a surface plasmon waveguide. The active region consists of 90 GaAs/Al$_{0.15}$Ga$_{0.85}$As repeated modules grown by MBE, giving a total thickness of 11.64 μm. A 214 μm wide ridge waveguide was cleaved at both ends to form a 1500 μm-long Fabry-Perot cavity. The active layer grown on top of a semi-isulating GaAs substrate is sandwiched between a metallic top contact and a heavily n-doped GaAs bottom contact channel. As a consequence, unlike metal-metal QCLs, the optical mode is not confined within the active region, but penetrates inside the substrate down to a depth of approximately 100 μm at λ_0=107 μm (f=2.8 THz). Fig. 1 shows a schematic drawing of the QCL and the computed one-dimensional mode intensity profile.

The lasing spectrum of this QCL was measured at different bias currents using a Fourier-transform spectrometer (FTS). As shown in Fig. 2, we observe a single longitudinal mode at 2.835 THz (wavelength λ_0=105.8 μm). The measured linewidth of 1 GHz is limited by the resolution of the FTS [12]. The output power of this particular QCL was not measured directly. However, based on measurements done on similar devices, a few mW of output power is expected at around 5 K operating temperature. At maximum output power the laser is biased at 6 V and 900 mA, which means that the QCL dissipates a DC power of about 5.4 W in continuous wave (CW) operation mode.

Before undertaking heterodyne measurements, we measured the laser far-field beam pattern with the same setup used previously for the metal-metal waveguide QCLs [8]. A Schematic of the measurement setup is shown in Fig. 3. The QCL is Indium-bonded to a copper holder and is mounted on the cold plate of a He-flow cryostat. The output power was measured using a 5 mm diameter aperture pyrodetector, placed at a distance of about 90 mm from the QCL. The laser was operated in pulse mode and the emitted power was recorded at different positions of the detector using a lock-in amplifier. The measured beam pattern is shown in Fig. 4. We find that most of the power is concentrated in the center of the beam. Such good directionality allows for an efficient coupling to a HEB mixer.

III. HETERODYNE RECEIVER SETUP

Figure 5 shows a schematic view of the measurement setup. We use two cryostats, in which the QCL and the HEB are mounted separately.

As mixer, we used a NbN HEB mixer integrated with a spiral antenna. The NbN superconducting bridge is 2 μm wide, 0.2 μm long, and 5.5 nm thick. The normal state resistance of the device (at room temperature) is 80 Ω. The critical temperature is approximately 10 K and the critical current at 4.2 K is 180 μA. A similar HEB mixer from the same batch has been measured using a gas laser as LO at 1.63 THz, yielding an excellent receiver noise temperature of 700 K.

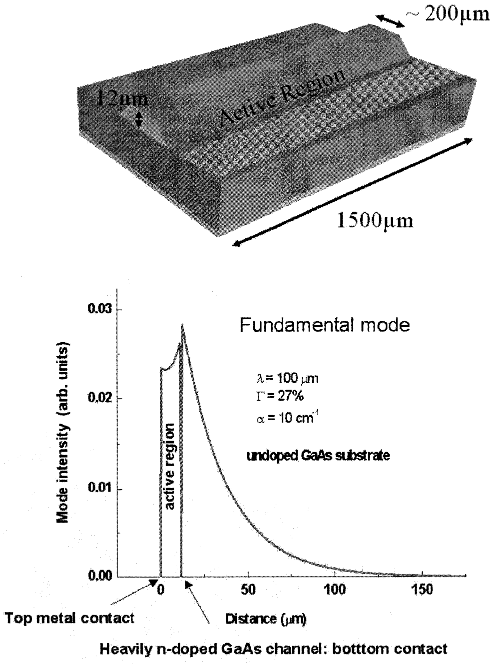

Fig. 1. Schematic view of the QCL ridge-cavity together with the computed mode intensity profile at λ_0=107 μm. The field penetration inside the substrate is about 100 μm. We compute waveguide losses (α) of 10 cm^{-1} and an overlap factor with the active region (Γ) of 27%.

A large vacuum liquid helium cryostat with a high cooling capacity was used to operate the QCL in CW mode. When operating in CW mode, as the QCL heats up, the output power drops until the temperature of the device is stabilized. Under stable CW operation the power of QCL is about half of the pulse mode operation. Nevertheless there is enough power to pump the HEB with a thin Mylar beam splitter (3.5 μm thick).

The output power of the QCL is coupled to the HEB antenna using a standard quasi-optical technique: the Si chip with the HEB is glued to the back of an elliptical, anti-reflection coated Si lens. The lens is placed in a metal mixer block, thermally anchored to the 4.2 K cold plate. The beam from the QCL passes through a high density polyethylene (HDPE) dewar-window and is collimated with a HDPE lens. The radiation is further guided to the HEB cryostat by a 3.5 μm thick Mylar beam splitter. The blackbody radiation from a slab of Eccosorb is used as a signal source defining a hot load at 295 K and a cold load at 77 K. The signal is combined with the QCL beam through the beam splitter. Both beams pass through the thin HDPE window at room temperature and a metal mesh heat filter (QMC Ltd.), mounted on the 4 K shield of the HEB cryostat.

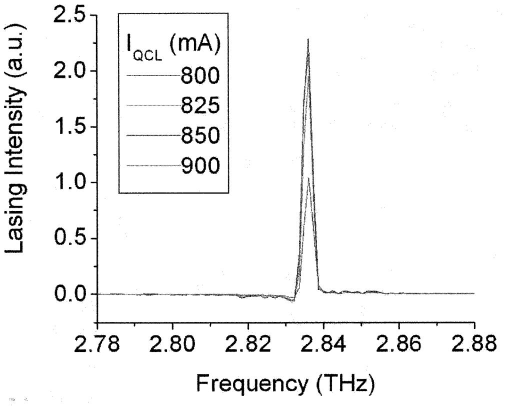

Fig. 2. Measured lasing spectrum of the QCL at different bias currents. The device radiates in a single mode at 2.835 THz. Changing the bias current does not affect the frequency.

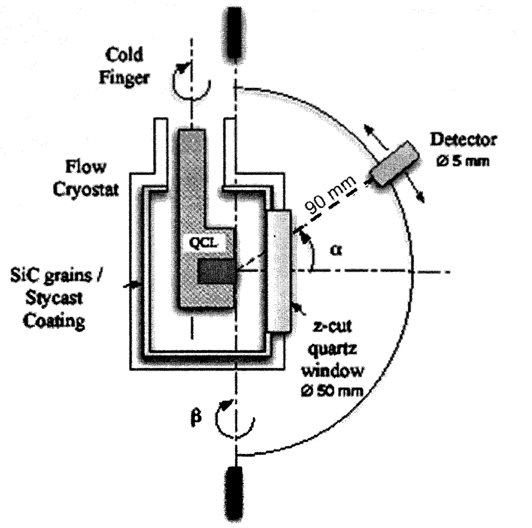

Fig. 3. Schematic picture of the beam pattern measurement setup. The power was measured using a 5 mm diameter aperture pyrodetector.

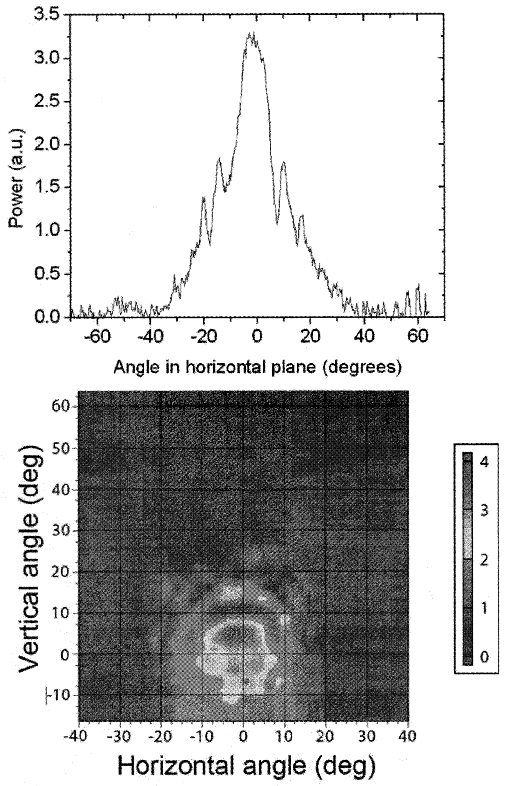

Fig. 4. Measured far-field beam pattern of the surface plasmon QCL. The upper panel: the profile alone the plane of the QCL, but measured at an offset of +5 degree in the 2D plot shown in the lower panel. The lower panel: the 2D plot of the beam pattern. Due to the tilt in the QCL mounting, the 2D plot has a negative offset of 5 degrees in vertical direction.

IV. HETERODYNE MEASUREMENT RESULTS

The key results of the heterodyne measurements are displayed in Figure 6. A set of current versus voltage (I-V) curves of the HEB is shown for various levels of absorbed LO power in the HEB, together with the receiver noise temperature as a function of the bias voltage of the HEB mixer. The power level, which is estimated at the HEB by the isothermal technique [13], is varied by changing the bias current of the QCL. The receiver noise temperature is determined from the ratio of the IF output noise power when a hot and a cold load are used as signal source [14]. The best sensitivity of 1150 K is obtained for 300 nW LO power and 0.6 mV DC bias at a (HEB) bath temperature of 4 K. A slightly lower noise temperature of 1050 K is obtained at the same bias voltage, but with a reduced bath temperature of 2 K. The latter represents the lowest receiver noise temperature ever reported in literature and corresponds to $7.7\times hf/k_B$, where h is Plank's constant, f is the radiation frequency, and k_B is the Boltzman constant. This value is also approximately 25% lower compared to what we reported previously using a metal-metal waveguide QCL operating at nearly the same frequency [6].

V. CONCLUSIONS

The beam pattern of QCLs is a crucial parameter for their use as LO source. Compared to metal-metal waveguide QCLs, the surface plasmon QCL under test was characterized by a weaker mode confinement in the direction perpendicular to the surface and by relatively large lateral dimensions (larger or comparable with the wavelength), yielding a much improved beam pattern. This allows us to pump a HEB mixer to the optimum operating point, using a very thin beam splitter (3.5

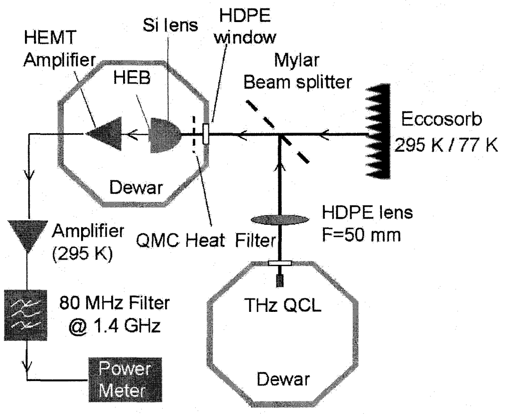

Fig. 5. Heterodyne measurement setup

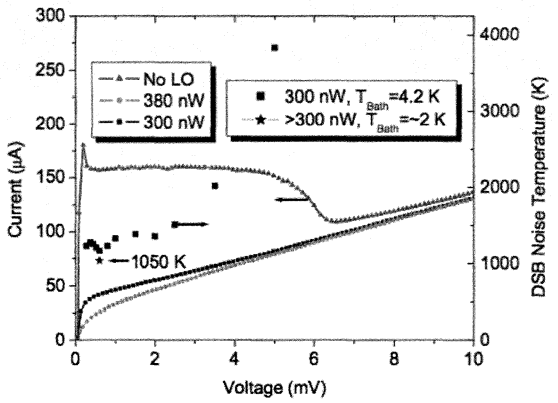

Fig. 6. Lines, left axis:Current-voltage characteristics of a spiral NbN HEB mixer with and without radiation from the QCL (LO) at 2.83 THz as LO. Symbols, right axis: The measured double side band (DSB) receiver noise temperature versus the bias voltage for the optimal LO power (300 nW).

μm Mylar). This way we obtained a measured DSB receiver noise temperature of 1050 K at a 2 K bath temperature, which represents the best sensitivity at $f\sim$2.8 THz ever reported in literature, uncorrected for any optical loss. This sensitivity corresponds to 7.7$\times hf/k_B$, suggesting that the receiver noise temperature of a NbN HEB mixer may remain below 10$\times hf/k_B$ even when the frequency is increased beyond 2.8 THz.

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