4.7-THz Local Oscillator for GREAT

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Abstract— **We report on the performance of a 4.7-THz local oscillator (LO) for the heterodyne spectrometer GREAT (German REceiver for Astronamy at Terahertz frequencies) on SOFIA (Stratospheric Observatory For Infrared Astronomy). The design of the LO and its performance in terms of output power, frequency accuracy, frequency stability, and beam profile as well as its implementation in GREAT will be presented.**

I. Introduction

Heterodyne spectroscopy of molecular rotational lines and atomic fine-structure lines is a powerful tool in astronomy and planetary research. It allows for the study of the chemical composition, the evolution, and the dynamical behaviour of astronomical objects such as molecular clouds and star-forming regions. For frequencies beyond 2 THz, SOFIA, the Stratospheric Observatory For Infrared Astronomy, is currently the only platform which allows for heterodyne spectroscopy at these frequencies. One example is the OI fine-structure line at 4.7448 THz [1], which is a main target to be observed with GREAT, the German REceiver for Astronomy at Terahertz frequencies. GREAT is a heterodyne spectrometer with four frequency channels at 1.25−1.50, 1.8−1.9, 2.5−2.7, as well as 4.7 THz [2] and has been operational on board of SOFIA since 2010. For all frequencies, superconducting NbN HEBs in a waveguide structure are used as mixers [3, 4]. Except for the high-frequency channel at 4.7 THz, the LOs are multiplied microwave sources. However, this type of LO is not available at 4.7 THz.

THz quantum-cascade lasers (QCLs) are a promising alternative solution. They can provide continuous-wave THz emission with high powers and a frequency tunability of several GHz. In addition, the intrinsic emission line width can be as small as 90 Hz [5]. In the past years, the feasibility of a QCL-based LO has been demonstrated by a number of experiments [6−9]. However, no such LO has been implemented so far in a real instrument. Here, we report on the design, implementation, and performance of a 4.7-THz LO for GREAT. It is based on a QCL and has been successfully operated during three observation flights in May 2014.

II. Design of the Local Oscillator

The LO is based on a QCL in a compact Stirling cooler with low input power. The 4.7-THz QCL is based on a hybrid design and has been developed for continuous-wave operation, high output powers, and low electrical pump powers [10]. Efficient carrier injection is achieved by resonant longitudinal optical phonon scattering. This design allows for an operating voltage below 6 V. The amount of generated heat complies with the cooling capacity of the Stirling cooler of 7 W at 65 K using 240 W of electrical input power [11]. The QCL has a lateral distributed feedback grating, which is optimized for 4.745 THz. This yields single-mode emission over most of the driving current range of the QCL. Out-coupling is achieved through one of the end facets of the single-plasmon waveguide.

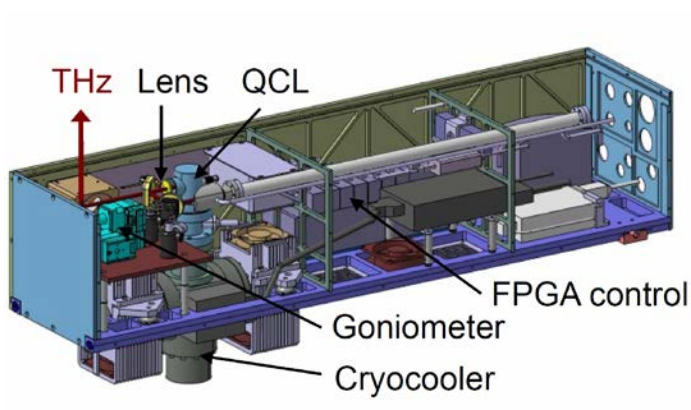

Fig. 1: Scheme of the LO.

The LO consist of an air-cooled mechanical cryocooler (model Ricor K535). It is dynamically balanced in order to minimize mechanical vibrations. The nominal cooling capacity is 7 W at 65 K for an ambient temperature of 23 °C, which is reduced to 4 W at 35 K. In order to comply with the available space in the GREAT instrument, the cooling fins were replaced by custom-made ones, and the fans were exchanged. The QCL is attached to the cold finger of the cryocooler with a dedicated submount made from copper. The output window of the vacuum housing is made from high-density polyethylene (HDPE). The cryocooler is mounted in a dedicated LO box with dimensions of $100 \times 24 \times 21$ cm^3 with part of the cooling fins sticking out at the bottom as shown in Fig. 1. In front of the cryocooler, a small plate holds the optical components, in particular a lens made from polymethylpentene (PMP, trade mark TPX) for beam shaping. The electrical pump power for the QCL is provided by a commercial current source (SMU 2400, Keithley Instruments Inc.). To achieve a stable temperature, a control loop with a temperature sensor mounted closely to the QCL is installed. Both, the current source and the temperature controller are mounted outside of the LO box. The whole system is operated by a computer using a controller and a field-programmable gate array (FPGA) mounted inside the LO box and a laptop computer, which is connected with the LO via Ethernet, thus enabling remote control of the LO.

III. Performance

The beam profiles of the LO measured with a micro-bolometer camera [12] at several distances behind the TPX lens are almost Gaussian as shown in Fig. 2. Note, however, that the beam shape does not correspond to a purely fundamental Gaussian mode, although it is almost Gaussian. It is rather a superposition of a fundamental mode with higher-order Laguerre-Gaussian modes. Nevertheless, the beam shape complies with the optical requirements of the GREAT instrument.

Fig. 2: Beam profiles of the LO at 300, 373, and 576 mm distance from the TPX lens (from left to right). The profiles were measured with a microbolometer camera. The width of each snapshot is 4.5 mm and the height 4 mm.

In order to obtain detailed information about the QCL frequency, molecular absorption experiments were performed. For this characterization, a 30 cm long gas cell with HDPE windows was placed into the LO beam outside of the LO box. The transmitted power was measured with a Ge:Ga photoconductive detector. By varying the driving current of the QCL or its heat sink temperature, the frequency of the QCL is tuned across several rotational transitions of CH_3OH. This results in a fingerprint-like absorption spectrum as shown in Fig. 3, where the nonlinear shape of the light-current curve of the QCL is removed by subtracting a higher-order polynomial. The comparison with a spectrum of CH_3OH measured with a Fourier transform infrared (FTIR) spectrometer and the identification of the observed absorption lines allow for a precise frequency characterization of the QCL. The emission frequency of the QCL ranges from about –4 to +2 GHz around the OI rest frequency as shown in Fig. 3.

The output power of the LO was measured with a photo-acoustic power meter (Thomas Keating Ltd.). In the frequency range around the OI line, it reaches values up to 0.2 mW.

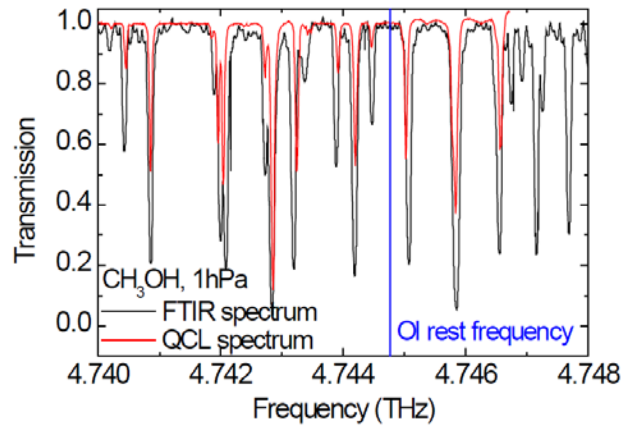

Fig. 3: Absorption spectrum of CH_3OH in the vicinity to the OI rest frequency (red line). The non-linearity of the light-current curve of the QCL is removed by subtracting a higher-order polynomial in order to obtain a flat baseline. The black line is a comparison with an FTIR spectrum of CH_3OH. This allows for a precise determination of the emission frequency of the QCL.

IV. Summary and Outlook

The design and the performance of a 4.7-THz QCL-based LO for the GREAT heterodyne spectrometer on SOFIA has been described. After passing a series of tests, the LO was operated during three subsequent flights of SOFIA in May 2014. All of these flights have been successfully completed, which demonstrates the capability of the LO. In the future, the single-pixel 4.7 THz channel will be upgraded to a seven pixel focal plane array. The described LO is a prototype LO for this array receiver.

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