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Terahertz multiheterodyne spectroscopy using laser frequency combs: supplementary material

YANG YANG,[1,†,*] DAVID BURGHOFF,[1,†,*] DARREN J. HAYTON,[2] JIAN-RONG GAO,[2,3] JOHN L. RENO,[4] AND QING HU[1]

[1] Department of Electrical Engineering and Computer Science, Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, Massachusetts, 02139
[2] SRON Netherlands Institute for Space Research, 9747 AD, Groningen, The Netherlands
[3] Kavli Institute of NanoScience, Delft University of Technology, Lorentzweg 1, 2628 CJ Delft, The Netherlands
[4] Center for Integrated Nanotechnology, Sandia National Laboratories, Albuquerque, New Mexico, 87123
[*] Corresponding author: yang_y@mit.edu, burghoff@mit.edu

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ADDITIONAL DETAILS, CONTINUOUS WAVE MODE

Two THz quantum cascade lasers from a heterogeneous gain medium are mounted in the same pulsed-tube cryocooler and are cooled down to 37 K. Both of them are driven through bias-tees using a Keithley 2602A dual-channel Source Meter, under constant current mode. When device A is biased to 0.177 A/10.65 V and device B is biased to 0.174 A/10.5 V, the two lasers are operated in a comb regime. The repetition rates of the combs are measured from one bias-tee's RF port with a spectrum analyzer (HP 8592B). The lasing spectrum shown in Fig. 1(c) is measured using an FTIR with resolution 0.2 cm^{-1}. The output power of device A was measured with a calibrated terahertz power meter (Thomas Keating Instruments) to be 0.168 mW, yielding an average power per mode of about 6.7 μW. This power is limited by the intrinsic properties of the gain medium and by the cooling capacity of the cryocooler.

In Fig. 2, two detectors are used and the multi-heterodyne signals from each of them are simultaneously recorded. One detector is a superconducting hot electron bolometer (HEB) maintained at 4 K, and the other is a room temperature Schottky mixer (Virginia Diode's WR-0.34HM). The intermediate frequency (IF) chain of the multi-heterodyne signal from the HEB consists of a cryogenic low noise amplifier (CITLF4, noise figure 0.12 dB, gain 36 dB) and a room-temperature low noise amplifier (MITEQ AMF-5D00101200-23-10P, noise figure 2.5, gain 43.25 dB). The IF chain of the Schottky mixer has only one low noise amplifier (MITEQ AMF-7D-00101800, noise figure 2.23 dB, gain 60 dB). Because the multi-heterodyne signals are centered around 2.4 GHz, to avoid using a high-speed data recorder we I/Q demodulate (ADL5380, noise figure < 12 dB, conversion gain 7.4 dB) at an LO frequency of f_{LO} =2.364 GHz. This brings the signal into the the bandwidth of the oscilloscope (Picoscope 6404C, 1.25GS/s/channel sampling rate). The four channels of the multi-heterodyne signals (I and Q from each detector) are recorded simultaneously. Figure S1 illustrates the entire experimental setup and emphasizes the data collection scheme described above.

For the etalon transmission measurement of Fig. 3, the two devices are measured at the same biases as before, and the etalon is placed into the beam path of the HEB and then removed. In each case, the data is recorded for 300 μs. Following this, the data is then divided into 15 mini-batches of 20 μs each, phase-corrected, and Fourier-transformed, resulting in an effective resolution bandwidth of 50 kHz. The power is obtained from the peaks of the transform, and the statistics of the two sets of power spectra are then used to compute the mean and variance of the etalon transmssion function. The theoretical etalon transmission is found by calculating the optical transmission of a 625 μm semi-insulating GaAs sample tilted by 25°, whose losses and refractive index are calculated theoretically using the model in Ref. [1] at a temperature of 300 K.

ADDITIONAL DETAILS, PULSED MODE

For the pulsed mode demonstration of Fig. 4, two THz QCLs from a broadband homogeneous gain medium are mounted in the same pulsed-tube cryocooler and cooled down to 38 K. The experimental setup is similar to Fig. S1, but in this case the repetition rates of two devices are measured from one laser's bias tee's RF port and then I/Q demodulated with a frequency synthesizer, $f_{LO,1} = 4.745$ GHz. Only the HEB is used to collect the multi-heterodyne signal, which uses the same IF chain described previously. Once again, the multi-heterodyne signal is

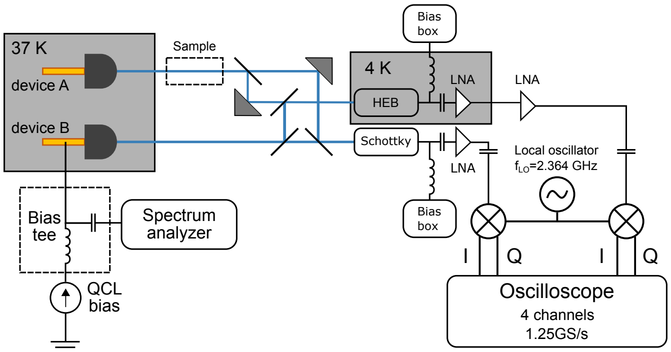

Fig. S1. Actual implementation of the balanced reference scheme used for the experiment. The IF chain of the HEB provides a total of 87 dB of gain, and the IF chain of the Schottky mixer provides 67 dB of gain.

I/Q demodulated, this time with an LO frequency of $f_{LO2} = 2.96$ GHz. The four channels (I and Q of the beatnote, and I and Q of the multiheterodyne signal) are then recorded with the same oscilloscope as before.

The output lasers used for this demonstration were measured by a calibrated power meter to have a peak output power of 1.76 mW each. Although this power is much larger than the power of the heterogeneous lasers used in continuous wave mode, since each laser independently saturated the HEB, they had to be severely attenuated using an iris. This eliminated any potential SNR benefits.

REFERENCES

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