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Improving the performance of THz delivery from a quantum cascade laser within a dry 3He dilution refrigerator

M. Vaughan,[1] W. Michailow,[2] M. Tan,[2] M. Salih,[1] L. Li,[1] H. Beere,[2] D. A. Ritchie,[2] E. H. Linfield,[1]
A.G. Davies,[1] and J. E. Cunningham[1]
[1]School of Electronic and Electrical Engineering, University of Leeds, Leeds, West Yorkshire, LS2 9JT, UK.
[2] Cavendish Laboratory, University of Cambridge, Cambridge, CB3 0HE, UK.

***Abstract*— We demonstrate a substantial enhancement to the integration of a quantum cascade laser into a dilution refrigerator via waveguides by the inclusion of a multi-mesh 6THz low-pass filter to block IR radiation, and a Winston cone to focus light output from the waveguide. These alterations allow us to lower the base temperatures to ~114mK, and the sample temperature to ~160mK while detecting a cyclotron resonance (CR) response in a 2DEG illuminated within the refrigerator. For comparison, before these changes we achieve a base temperature of 206mK and an effective sample temperature of 430mK while detecting CR [1].**

I. INTRODUCTION

Many condensed matter systems have properties that can be probed or altered by exposure to THz radiation, including topological materials, antiferromagnets, and semiconductor mesoscopic systems [2-5]. Such systems often either have energies commensurate with THz photon energies, or intrinsic timescales in the picosecond range, commensurate with the THz cycle time. Many of these states or interactions are easier to study or indeed are only observable at very low temperature. Common sources of THz radiation such as THz-QCLs produce too much waste heat to be compatible with a milli-kelvin environment. Instead, we have shown that a THz QCL can be sited within a dilution refrigerator on one of the higher temperature stages, and the light emission from it coupled to the sample space by means of a THz power delivery system built using hollow metal waveguides (HMWG) made of 4.6mm internal diameter copper tubing [6].

II. INTEGRATION OF HMWG AND IMPROVEMENTS

The THz QCL was mounted to the first stage of the pulse tube cooler where ~40W of cooling power is available at 48K; we limited waste heat dissipation from our QCL to a maximum of 2W (Fig.1.a) to achieve reasonable base temperature. Our QCL was a bound-to-continuum design, with a center frequency of 2.68THz, with a 25mW peak output power measured at 47K before mounting in the dilution refrigerator.

Sections of HMWGs were used to couple the QCL to the sample space, with each being thermally isolated from the next by a 2mm resin-epoxy spacer (Fig.1.b). The HMWG were supported by brass compression fittings and ferrules (Fig.1.c). Inspection of the internal diameter (ID) showed no significant deformation from introducing these components [1].

Our HMWG had -6±0.5 dB/m of loss with a total length of 1.2m between QCL and sample space; other component losses comprised: -0.88±0.04 dB for thermal isolators, 0.10±0.02 dB for brass fittings, and -0.8± 0.04dB for S-bend, resulting in a total end-to-end loss of -12±1dB. Given this amount of loss and our high QCL power, if we were to use the maximum THz power available from the QCL we could still induce substantial heating to the sample space raising the temperature from the intended milli-kelvin environment to over 1K. We are then limited in the minimum temperature by the sensitivity of the device under test.

With the goal of measuring a THz response at the coldest possible temperature we need to minimize all forms of heating to the sample space, including any heat leaks through the HMWG or direct heating by THz radiation from our QCL.

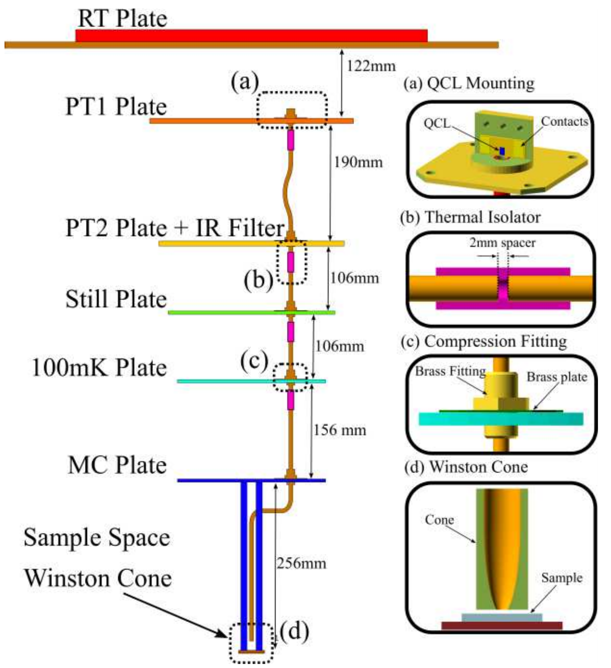

Fig. 1. Waveguide system inside the refrigerator with QCL located on the 1st pulse tube stage (PT1) at ~48K (a) THz propagated by HMWG down through each stage with thermal isolators (b) and compression fittings for mechanical support (c). 6THz low-pass filter located inside the compression fitting on the PT2 plate. (d) Winston cone was position as close as possible to the sample to maximize coupling.

The opening of the HMWG was exposed to the room temperature walls of the cryostat; in a worst-case scenario calculation this gives ~6mW of 295K IR radiation entering the HMWG. By placing a 6THz multi-mesh low-pass filter (QMC Instruments [8]) immediately below the PT2 plate we reduce IR radiation from propagating down into the sample space. The original (unmodified) fridge base temperature was 99mK before the waveguide was added increasing to 206mK when the HMWGs were installed. The inclusion of the filter reduced the base temperature to 114mK. The filter introduced a loss of -0.9dB at 2.68THz.

Secondly, a Winston cone was inserted at the end of the HMWG to increase the power density on 2DEG device in the sample space. The nominal area of the HMWG was 16.6mm^2

versus the Winston cone's aperture of 0.8mm^2, giving a power density increase of around ~21 times. Concentrating THz radiation to only the area of interest clearly reduces the total THz radiation needed for the same signal-to-noise ratio while also reducing unnecessary heating to the surrounding sample space, thus leading to an overall reduction in device temperature.

III. RESULTS

We used a two-dimensional electron gas (2DEG) sample made from a heterostructure of $GaAs/Al_{0.33}Ga_{0.67}As$, with a 11.7±0.5nm-thick NiCr semi-transparent top gate to control carrier concentration that also allowed us to optimize detection of the THz radiation. The gate itself modified the carrier concentration such that a positive bias of > 0.25V was needed to enable channel conduction. The device showed a strong peak in the diagonal resistance when illuminated by the QCL frequency at the expected position for CR absorption.

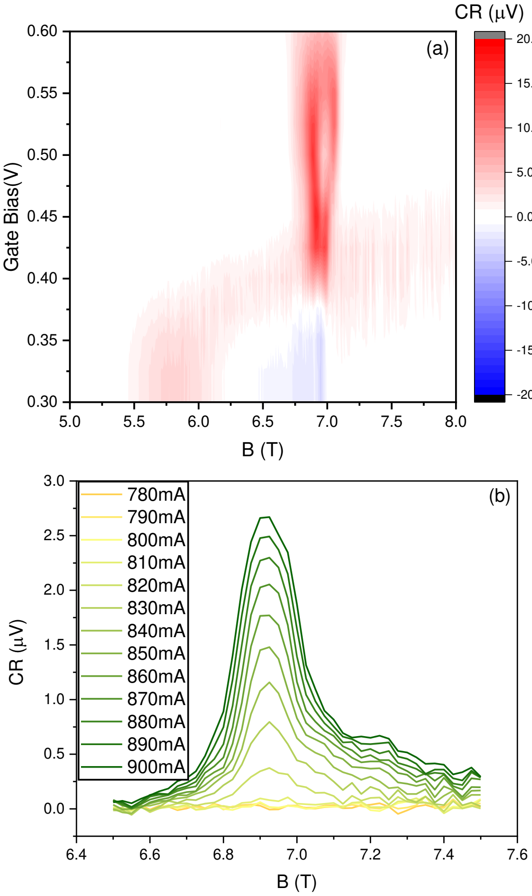

Fig. 2. **(a)** 2D plot of the cyclotron response at 950mA and 10% duty cycle QCL power versus gate bias and magnetic field, as measured by a constant 100nA DC current and locking into the QCL pulse frequency. (b) Lowest QCL currents for which a CR response was still observed, taken at 0.36V gate bias.

Figure 2 shows the sample response obtained. We calculated the effective mass using the amplitude of the Shubnikov–de Haas oscillations by applying the Lifshitz-Kosevich equation, obtaining a value of 0.0713±0.0008 m_e; we then expect a CR peak at 6.83±0.07 T from our 2.68 THz QCL. By changing the top gate bias voltage we can increase the size of the CR response, allowing for detection of the THz power for lower QCL currents, resulting in a corrospondingly lower sample temperature (see Fig. 2).

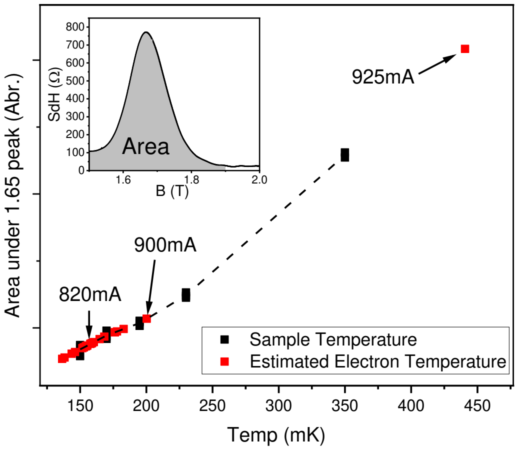

Fig. 3. (Inset) The area under the SdH peak close to 1.65T was used to estimate the sample temperature. Sample temperature points were then used to generate a calibration curve for the heating effect from the QCL. The minimum detectable response (820mA) produced an electron temperature of ~160mK.

To measure the temperature of the Hall bar as accurately as possible during QCL illumination, we first use the area under the SdH peaks in magnetoresistance to calibrate their response to temperature [7]. Using the peak close to 1.65T we observe a significant monotonic response to temperature when heating (Fig.3 insert). We then use this area to determine the electron temperature during illumination by the QCL. The lowest QCL current for which a cyclotron response was observed was ~ 820mA, at which point the estimated sample temperature was 160mK (Fig.3b), substantially lower than our previous lowest temperature of 430mK obtained before both the cone and filter were introduced [1].

IV. SUMMARY

We have demonstrated very low temperature excitation of 2DEG within a dilution refrigerator by the introduction of a 6THz low-pass filter and Winston cone. We demonstrated the system using a gated $GaAs/Al_{0.33}Ga_{0.67}As$ 2DEG. Our lowest temperatures for the sample space and effective sample temperature during observation of CR are 114mK and 160mK respectively. We anticipate that the improvements detailed here will enable very low-temperature excitation from THz QCLs for a range of condensed matter samples of contemporary interest.

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