Proceedings Paper:
Vaughan, M. orcid.org/0000-0002-8336-2183, Michailow, W., Xia, R. et al. (8 more authors) (2024) Developing Free-space and Polarization Control of THz QCL Radiation Inside a Dry Dilution Refrigerator. In: 2024 49th International Conference on Infrared, Millimeter, and Terahertz Waves (IRMMW-THz). The 49th International Conference on Infrared, Millimeter and Terahertz Waves (IRMMW-THz), 01-06 Sep 2024, Perth, Australia. IEEE ISBN 979-8-3503-7033-1

https://doi.org/10.1109/IRMMW-THz60956.2024.10697903

Developing Free-space and Polarization Control of THz QCL Radiation Inside a Dry Dilution Refrigerator

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***Abstract*—Previously we demonstrated integration of a THz quantum cascade laser (QCL) within a dry dilution refrigerator, directing its output using a hollow metal waveguide (HMWG) into the sample space [1]. Here, we show that the waveguide can be replaced successfully by free-space optics within the refrigerator; this allows polarization of the QCL output to be maintained along the way to the sample at milli-kelvin temperatures. We also show active control of polarization using a mechanical filter wheel able to insert different optical components into the beam path during experiments. Our system overcomes waveguide dispersion and losses intrinsic to prior system designs. The results pave the wave to THz polarization control of radiation from THz QCLs at sub-Kelvin temperatures.**

Keywords— Dilution Fridge, Freespace, THz, Quantum Cascade laser

I. Introduction

Many condensed matter systems such as 2-dimensional electron gases (2DEGs), topological insulators, and antiferromagnetic systems benefit from study at very low temperatures [2,3,4,5]. Such systems have energies or intrinsic transport timescales that are commensurate with terahertz (THz) radiation, so that their low temperature excitation by THz radiation is often required.

In our previous work we demonstrated THz illumination of a 2DEG within a dilution refrigerator, detecting cyclotron resonance at temperatures as low as 160mK [1]. Thermal isolators and IR filters were found to be critical to prevent heat leaking into the lowest stages of the refrigerator.

II. Freespace Optics and Polarization

A. Free-space lenses

In our current experiments we use a 12mm diameter aspheric lens with a focal length of 9mm made from Zeonex E48R plastic to shape the light output from a THz QCL into a collimated beam (Fig.1a.1) [6]. The beam is focused and then collimated again by two 17.5mm focal length E48R plastic lenses (Fig.1a.2). This is done to limit thermal IR leaking into cooler stages. The THz beam also pasted through a 2mm HDPE filter to further improve thermal isolation. These thermal isolation measures worked successfully to reach a base temperature of 30mK.

The THz optics of QCL and collimated lens, as well as, the double lens assembly were initially characterized on an optics benchtop with the QCL cooled by a small 50K cryostat. The THz from the QCL was collimated into slight divergent beam profile starting at 5.5mm and expanding to 20.9mm over a distance of 21cm. The double lenses were aligned with as little beam distortion as possible. This double lens assembly had a loss of 85%. The HDPE filter has a loss of 50%. Longer focal length lens, and thus thinner, would have a lower loss. It was estimated from calibrated thermometry data that ~28μW of THz power was reaching the mixing chamber.

B. Polarization filter wheel

The output from our THz QCL was found to be strongly polarized in the QCL growth direction, as typical for surface plasmon waveguide QCLs. A filter wheel was fitted with a selection of waveplates (Fig.1b) and inserted into the beam path within the dilution refrigerator to manipulate polarization. Quarter-waveplate filters were made from Z-axis-cut quartz with a thickness of 0.652mm. The thickness was chosen such that the slow versus fast axis of the Z-axis quartz yielded a quarter wavelength phase difference at our QCL frequency of 2.6 THz. Two filters stacked together in one position of the filter wheel formed a half-wave waveplate.

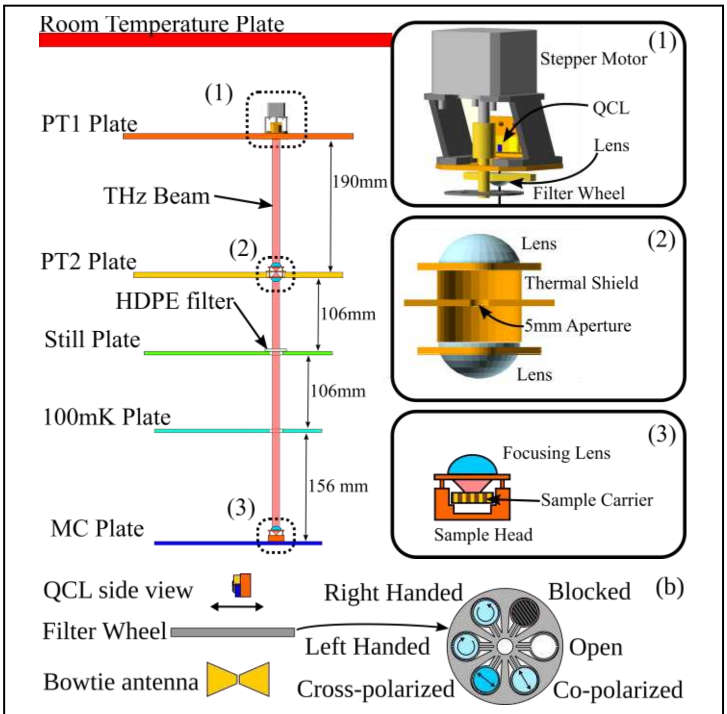

Figure 1: (a) The QCL is placed on a mount facing down toward the sample on the lower stage. The divergent THz radiation from the QCL is collimated by a lens. HDPE filters and double lens assembly shield thermal radiation entering lower stages. The filter wheel (b) has a selection of quarter waveplates and half waveplate as well as one slot empty and another block. The filter wheel is rotated by a stepper motor.

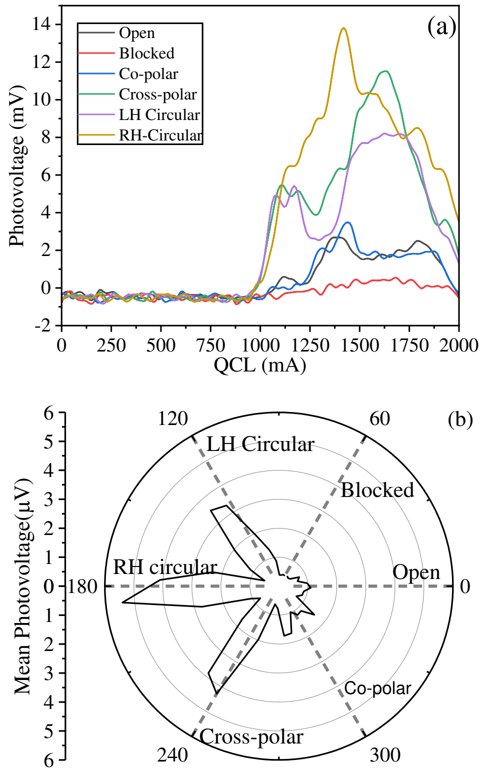

Figure 2: (a) The photovoltage from the PETS detector as a function of QCL voltage for each of the filter positions. (b) A polar plot of the stepper motor angle at 9° increments versus photovoltage maximum and mean value. As expected, between filter positions the beam is blocked and no THz signal is detected.

The rotation of the filters relative to the THz QCL polarization direction defines their effect on the polarization. A co-polarized filter had the fast axis aligned with the QCL polarization, yielding no effect to act as a reference for possible absorption or interference, while an cross-polarized filter was formed from a double stack of half waveplates aligned at 45°, thus able to rotate polarization by 90°. “Left handed” and “right handed” filters were single quarter waveplates, each rotated –45° and +45° respectively, to create a circularly polarized beam in each case.

One empty (“Open”) and one blocked slot in the wheel were also included as references for the unmodified beam, and to give a background measurement in case of background electrical noise, respectively.

III. PETS Detector as Device Under Test

The system performance was demonstrated using a photoelectric tunable-step (PETS) THz detector with a bow-tie antenna operating on the in-plane photoelectric effect [7]. The device responds to linear polarization, with maximum sensitivity obtained with the incident polarization parallel to the bow-tie antenna axis. The PETS detector was placed such that the polarization of the unmodified QCL THz beam was orthogonal to the antenna axis, in theory requiring a quartz filter to obtain a larger signal. The device features two gates that can be tuned by bias voltages allowing optimisation of its sensitivity to THz radiation.

IV. Detection and Polarization Control

Figure 2 shows a clear difference in PETS device signal for the different filters chosen. The filter wheel was moved between open and blocked positions to verify that the stepper motor was operating correctly both under vacuum and whilst at 50K. The lack of any response between slots, (e.g. at 30°), aided confirmation of the intended mechanical action of the filter wheel.

The difference between photovoltage response for the “open” position and “aligned” positions was minimal, as expected, as the aligned quartz filter should then have no effect on polarization (Fig.2b). By contrast, insertion of the half waveplate yielded a significantly increase in response. The left and right handed polarizations were found to be similar, but with the right-handed one being stronger, either as a result of some small increase in sensitivity for one chirality, or possibly due to some small ellipticity in the QCL output. Standing waves may also form along the beam path, so that the change of QCL frequency with drive current leads to inference extrema to move across the detector position, causing the response from the device to change significantly, but consistently (Fig.2a). This will be confirmed in future work.

V. Conclusion and Future work

We have investigated integration of a THz QCL with a dilution refrigerator using free-space optics within a dry cryostat, reaching a sample held at ~30mK. Further work is needed to reduce THz transmission losses, finer polarization, attempting at self-mixing and expending in the bore of the 12T magnet

We believe future work can achieve sub-Kelvin THz illumination along with polarization control, as well as offering potential for self-mixing as a detection mechanism.

Acknowledgment

We would like to thank our funders EPSRC through the NAME grant, EP/V001914/1, and European Horizons programme through the ExtremeIR grant, #964735.

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