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A rapid sample-exchange mechanism for cryogen-free dilution refrigerators compatible with multiple high-frequency signal connections

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ABSTRACT

Researchers attempting to study quantum effects in the solid-state have a need to characterise samples at very low-temperatures, and frequently in high magnetic fields. Often coupled with this extreme environment is the requirement for high-frequency signalling to the sample for electrical control or measurements. Cryogen-free dilution refrigerators allow the necessary wiring to be installed to the sample more easily than their wet counterparts, but the limited cooling power of the closed cycle coolers used in these systems means that the experimental turn-around time can be longer. Here we shall describe a sample loading arrangement that can be coupled with a cryogen-free refrigerator and that allows samples to be loaded from room temperature in a matter of minutes. The loaded sample is then cooled to temperatures ~10 mK in ~7 h. This apparatus is compatible with systems incorporating superconducting magnets and allows multiple high-frequency lines to be connected to the cold sample.

1. Introduction

Over the past century studying condensed matter systems at extremely low temperatures, and often in extremely high magnetic fields, has lead to the discovery of several new states of matter, such as: superconductivity in mercury [1]; superfluidity in ^{4}He [2,3]; superfluidity in ^{3}He [4]; the integer quantum Hall effect in silicon MOSFET devices [5]; the fractional quantum Hall effect in GaAs–AlGaAs heterojunctions [6].

More recently there has been a drive to harness these quantum systems to realise devices that exploit their quantum nature, for example in the field of quantum information processing [7], with the realisation of a general quantum computer [8] being the holy grail. Inevitably the development of these quantum devices requires temperatures <10 mK, and possibly magnetic fields >10 T, however in addition to these environmental constraints device characterisation and development also requires the necessary experimental services be installed at the sample position: most challengingly high-bandwidth, high-fidelity micro-wave cabling.

In the following sections we describe briefly a suitable experimental environment for quantum device development (or any other experiments requiring high-frequency measurements at low-temperatures), then we show that device characterisation is more convenient with a sample loading mechanism, and describe its realisation, operation and performance, before providing a brief conclusion.

2. Experimental environment

Pulse-tube precooled dilution refrigerators [9] are becoming increasingly popular. Initially this popularity stemmed from the fact that they were cryogen-free, meaning that they could be installed at institutions without the associated low-temperature research infrastructure, such as a helium liquefaction plant, or in remote locations. Additionally, there are benefits from an operational point of view as such systems can be automated to a higher degree than their "wet" counterparts. It has also been found that these cryogen-free systems have further benefits when compared to wet systems with regards to the installation of experimental services, as will be discussed in the following sections, and this has driven the recent rise in their uptake.

With the installation of high-frequency wiring these refrigerators have been developed into measurement systems for circuit quantum electrodynamics [10] and superconducting qubits [11]. The integration of superconducting magnets [12], with the entire system able to be run from a single pulse-tube cooler, has enabled

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a wider range of experiments (those requiring magnetic fields) to be performed using this cryogen-free technology [13].

2.1. Low-temperatures and high magnetic fields

Cryogenic systems using liquid helium are usually designed to minimise its consumption. This is because liquid helium is expensive, refilling the system can be time consuming, and refilling the system may perturb the experiment to an unacceptable level. The central neck of a cryostat is often responsible for the biggest single heat load into the helium bath, and as a result these necks are usually made as long and as narrow as possible. Dilution refrigerators designed to be inserted into such a cryostat have to inherit this aspect ratio, which has tended to limit the experimental real estate available for the installation of services.

With no boil-off considerations, cryogen-free systems have evolved to be much wider than their wet counterparts with experimental plates (to which services can be mounted) typically several hundred mm in diameter [12]. This has enabled more and/or more complex services to be installed on dilution refrigerator systems, in particular bulky signal conditioning elements such as cryogenic amplifiers, microwave components (bias-tees, circulators, switches, etc.) and filtering (such as metal powder filters, for example [14] and the references therein).

Cryogen-free systems can also be designed without the need for a low-temperature, vacuum-tight vessel, the so called inner vacuum chamber (IVC), which makes the routing and heat-sinking of the installed services much more straightforward, see Section 2.2.2.

The range of magnets that are able to be produced for cryogen-free operation is also continually expanding with higher fields (>16 T) and vector-rotation (>6–1–1 T) available.

For these reasons cryogen-free dilution refrigerators with integrated magnets have become the workhorse of quantum device development laboratories around the world.

2.2. High-frequency wiring

As was noted in Section 1 high-fidelity, high-bandwidth wiring is an experimental requirement for quantum device development applications. In addition to the quality of the signal transmission performance of these cables, they also need to be thermally anchored adequately to ensure that they do not affect adversely the base temperature performance of the system onto which they are installed. In this section we shall: review various options for the coaxial lines and some of the materials available for the lines themselves, and discuss their relative merits; describe a convenient method for mounting multiple high-frequency lines onto a dilution refrigerator; quantify the frequency dependence of signal transmission of installed lines with S_{12} measurements made with a vector network analyser; comment on the heat load to the mixing chamber likely to result from the installation of the type of wiring described.

2.2.1. Coaxial cables and materials

To date, most high-frequency cabling installed in dilution refrigerators have been of "semi-rigid" construction with the UT-85 cable (having an outer diameter of 85/1000 of an inch, approximately 2.16 mm) being commonly used. The optimal choice of coaxial cable, in terms of both size and material, depends on its intended application. Typically coaxial cables are used to (1) improve noise immunity for "small" signals and/or (2) transmit high-frequency signals to/from the sample.

If using coaxial cables for either of these reasons one should ensure that the cables themselves are suitable for the intended application. For dilution refrigerator based experiments, this suitability is generally determined by two key parameters: the heat load to the experiment due to the thermal conductivity of the cable; and its (frequency dependent) attenuation. Both of these parameters are affected by the choice of the cable geometry (size) and conductor materials.

The heat load conducted to the coldest parts of the dilution refrigerator is always to be minimised. For a given choice of coaxial cable material and geometry there is a lower limit to this heat load determined by the bulk thermal conductivity of the cable materials. This limit is approached as the cable (both the inner and outer conductor) is perfectly thermally connected to every available temperature stage in the refrigerator, of course the conducted heat load can be much higher than this limit if the thermal connections are inadequate. A convenient method of installing semi-rigid coaxial cables into a dilution refrigerator that gives good thermal performance is discussed in Section 2.2.4. The heat load can only be reduced further by using either cables with a smaller cross sectional area and/or cables made from materials with a lower thermal conductivity, however such changes may well have implications for the cable attenuation.

The frequency dependent attenuation of a coaxial cable is determined by the cable geometry (outer diameter of the inner conductor and inner diameter out of the outer conductor), the (temperature and frequency dependent) resistivity of the conductor materials and the dielectric losses [15]. In general smaller diameter cables have higher attenuation at high frequencies than larger diameter ones, and cables manufactured from materials with higher bulk resistivity have higher attenuation (at a given frequency) than low resistance ones. Depending on the application, this increase in attenuation can be fortuitous or problematic. In applications where coaxial cables are used for noise immunity for small, low-frequency signals, having increased attenuation at high frequencies is advantageous: in fact "lossy" coax cables have been used as microwave filters [16].

However, for high-bandwidth signals the change in attenuation, α, with frequency, f, is undesirable as it results in the "shape" of signals (in the time-domain) being modified as they propagate along the cable and this can cause problems with, for example, high-fidelity qubit control. Techniques borrowed from the NMR/MRI world for pulse preshaping using *a posteriori* knowledge of the cabling transfer function [17] can be applied to compensate for this effect, but it would still be advantageous to keep the frequency response of the cable as flat as possible. Using (lots of) large-diameter low-resistance cables can be incompatible with experiments at dilution refrigerator temperatures, as the thermal and electrical conductivity of a normal metal are closely related [18]. However, superconducting cables made from Nb, or preferably NbTi (due to its higher critical field and temperature, and lower thermal conductivity), can be used. Below their superconducting transition temperature these cables provide very low attenuation and have a small thermal conductivity [15] so in many cases are the ideal solution to this problem. However, with cryogen free dilution refrigerators enabling experiments over extended temperature ranges [12] some care needs to be taken, as the electrical performance of these lines will change (attenuation will increase) dramatically above their transition temperature.

One final point is that the desire to keep $\frac{d\alpha}{df} \approx 0$ is *not* the same as keeping $\alpha \approx 0$. Indeed, the types of cables described here are very good at transmitting "thermal noise" from warmer parts of the refrigerator to colder ones, equating $h\nu \approx K_B T$ gives a photon frequency of 20 GHz at 1 K and UT-85 cables operational range can extend to >60 GHz [19], and so having some attenuation in the line is desirable to reduce these thermal perturbations. Attenuators with a flat frequency response, compatible with cryogenic temperatures [20], can be used to increase the attenuation of a line whilst avoiding the complications of distorting high-bandwidth signals. Details of measurements of such lines will be given in Section 2.2.3.