RECENT PROGRESS IN MICROWAVE METROLOGY AT MILLI-KELVIN TEMPERATURES FOR QUANTUM TECHNOLOGIES AT THE UK's NATIONAL PHYSICAL LABORATORY

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Abstract:

Quantum technologies are rapidly enabling new scientific advances, from unprecedented increases in computing power to precision sensing and secure communications. Most of these technologies depend on reliable operation of quantum and microwave circuits at cryogenic temperatures. For example, the most promising quantum computing technologies poised to achieve near-term quantum advantage rely on microwave components and systems operating reliably at cryogenic temperatures down to tens of milli-kelvin (mK) to control and readout quantum bits. It is, therefore, critical to characterise the performance of such microwave devices at their cryogenic operating temperatures to ensure optimal functioning of the overall system.

The UK's National Physical Laboratory (NPL), based in Teddington, has developed new microwave measurement capabilities at cryogenic temperatures through the UK's National Quantum Technologies programme to address the shortage of cryogenic microwave test and measurement facilities in the UK. This includes the development of scattering (S-) parameter measurement capabilities to characterise the microwave performance of connectorised devices packaged with coaxial connectors and non-connectorised on-chip devices and substrate materials. This paper will briefly describe the various capabilities at NPL for S-parameter measurements at temperatures of tens of mK. These cryogenic measurement capabilities will help industry and academia in creating new and improved devices and products to accelerate the commercialisation of quantum technologies. The capabilities will also provide confidence to microwave component manufacturers to commercialise their cryogenic microwave components, providing a pathway to enter the emerging quantum technologies industry.

1. Introduction

Advancements in the commercialisation of quantum technologies have prompted the UK's Department for Science, Innovation and Technology (DSIT) to announce Quantum as one of the five priority technologies of tomorrow [1]. The UK government has announced £2.5 billion investment in quantum technologies over the next ten years through the National Quantum Strategy published in 2023 [2]. The commercialisation of quantum technologies will require specialists from inter-disciplinary areas to work together to address the engineering and measurement challenges limiting the scalable practical deployment of such systems. Microwave engineers and metrologists will also play a significant role in addressing these challenges. The development of one of the most promising quantum technologies, quantum computing, relies significantly on overcoming microwave engineering challenges to enable near-term quantum advantage through microwave-based platforms, one of which is superconducting quantum computing. The design and operation of fundamental building blocks (known as quantum bits or qubits) in such systems rely on principles of microwave and quantum engineering. The quantum operations are orchestrated using pulsed microwave signals (waveforms) from control and test equipment, typically, operating at room temperature which pass through various cryogenic temperature stages to the quantum processors deployed at temperatures down to tens of milli-kelvin (mK) [3]. Consequently, this control and readout chain utilises a network of microwave circuits and components operating at various cryogenic temperatures. Similarly, microwave components operating at cryogenic temperatures will be utilised in other quantum technologies such as quantum sensing and quantum communication applications [4]. It is critical to measure the characteristics of these waveforms, components, circuits, networks, and the overall system at their cryogenic operating temperatures, to develop commercial quantum technologies. The microwave performance of these elements can be characterised by measuring various electrical parameters such as scattering (S-) parameters, power, noise, and electrical phase. A number of aspects of microwave metrology applicable to quantum technologies are summarised in Fig. 1.

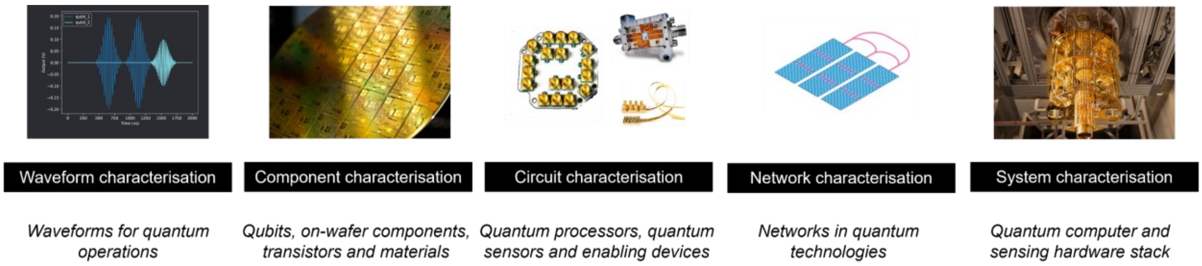


Figure 1 – Aspects of microwave metrology in quantum technologies

New measurement capabilities are currently being developed at NPL to characterise components and circuits at temperatures down to tens of mK. Some of the typical connectorised and non-connectorised microwave devices used in quantum technologies are shown in Fig. 2. These devices can be characterised by measuring their S-parameters. The S-parameters describe the electrical properties of a device in terms of the magnitude and phase of its reflection and transmission coefficients. For example, the magnitude of the transmission coefficient of a device specifies its loss or gain and the phase specifies the phase change experienced by a signal passing through the device. Assessments of these properties are fundamental for the accurate evaluation of the performance of a device. The changes in electrical behaviour and mechanical properties due to lower temperatures can be assessed by evaluating the measured S-parameters of the device under test (DUT) with comparison to those measured at standard operating (room) temperature. This enables manufacturers to evaluate the suitability of their existing components at cryogenic temperatures. The measurement capabilities at NPL also facilitate development of new and improved cryogenic products through several cycles of the design, manufacturing, and cryogenic testing processes. Therefore, it is expected that these capabilities will help to boost the supply chain of cryogenic microwave components and support the rapid growth of quantum technologies.

This paper summarises the various capabilities for device characterisation at mK temperatures developed at NPL. Section 2 focuses on highlighting some of the measurement challenges in characterising the S-parameters of devices at mK temperatures and how NPL has tackled some of these challenges. This section also demonstrates the need for the calibration process in order to achieve accurate device characterisation at mK temperatures and explains the architecture adopted by NPL to perform cryogenic calibrations. The cryogenic calibration units to characterise coaxial devices, on-chip devices and substrate materials are described in section 3. The error sources affecting measurement accuracy at these extreme cold temperatures are summarised in section 4.

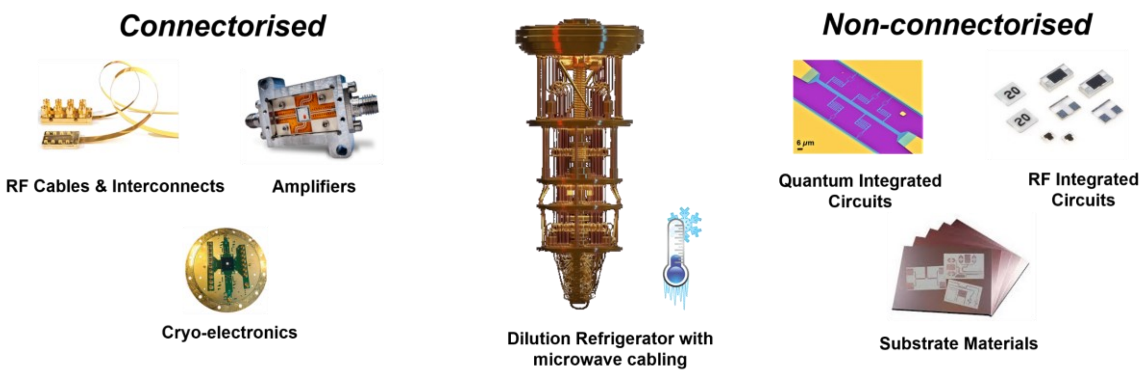


Figure 2 – Typical microwave devices used in quantum technologies at cryogenic temperatures

2. Challenges in S-parameter characterisation at cryogenic temperatures

Recent research in this area has focused on developing S-parameter measurement systems to characterise microwave and quantum devices at temperatures down to tens of mK [5-8]. These devices are typically operated inside a cold, isolated environment such as a dilution refrigerator and interfaced to room temperature test equipment such as a Vector Network Analyser (VNA) using microwave cabling and components. Such a setup is shown in the schematic in Fig. 3.

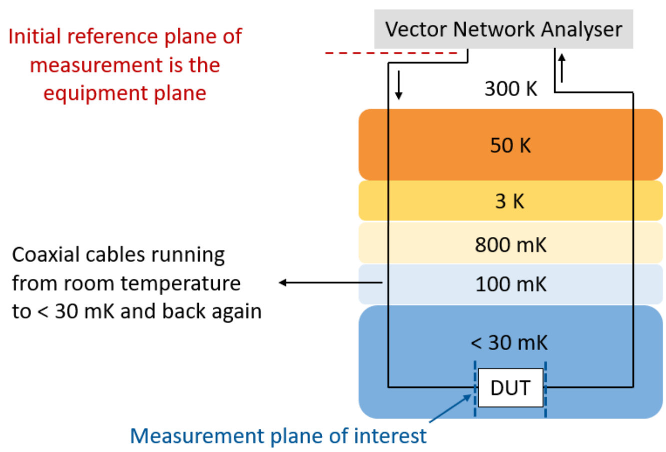


Figure 3 – Typical interfacing of DUTs at cryogenic temperatures

In order to measure the “true” S-parameters of the DUT at mK temperatures, a calibration scheme that shifts the reference planes of the measurement to the ends of the DUT, needs to be implemented. In this way, the effects due to the intervening passive and active components up to the ports of the VNA are de-embedded from the measured results. For example, Fig. 4(a) and Fig. 4(b) compares the reflection and transmission coefficients of a superconducting qubit with and without implementing a calibration scheme at cryogenic temperatures. It is really only possible to extract more meaningful information from the calibrated results. For example, parameters such as loss, resonant frequency and impedance mismatch of the qubit circuit can only be extracted from the calibrated S-parameters, such as in Fig. 4(b). NPL has developed calibration units to facilitate calibrated S-parameter measurements at mK temperatures. The following sections will describe the measurement architecture and the design aspects of the cryogenic calibration unit.

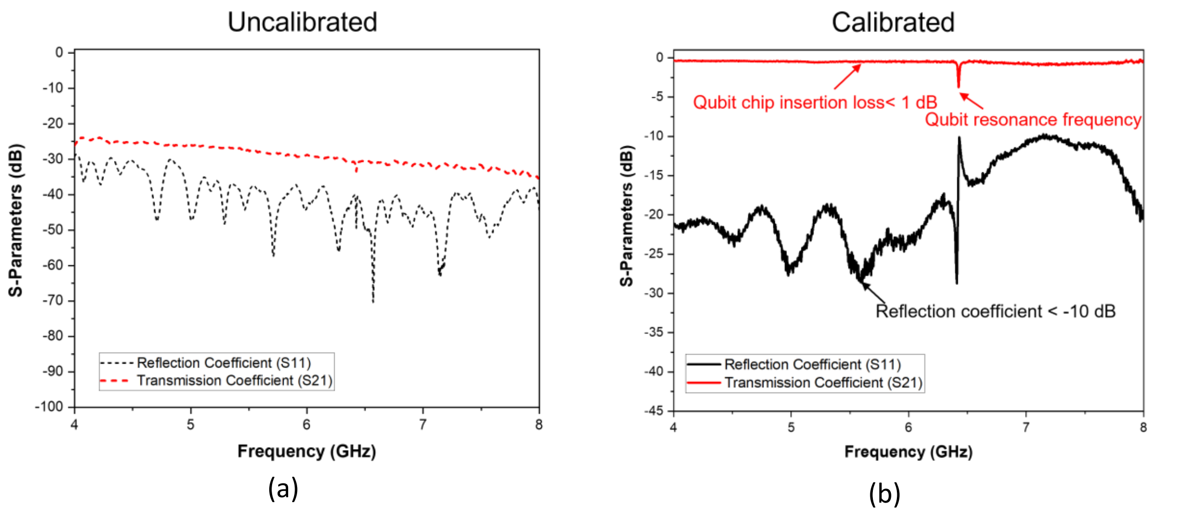


Figure 4 – Importance of calibration in cryogenic S-parameter measurements demonstrated through comparison of (a) uncalibrated and (b) calibrated measurements of a superconducting qubit chip at around 20 mK.

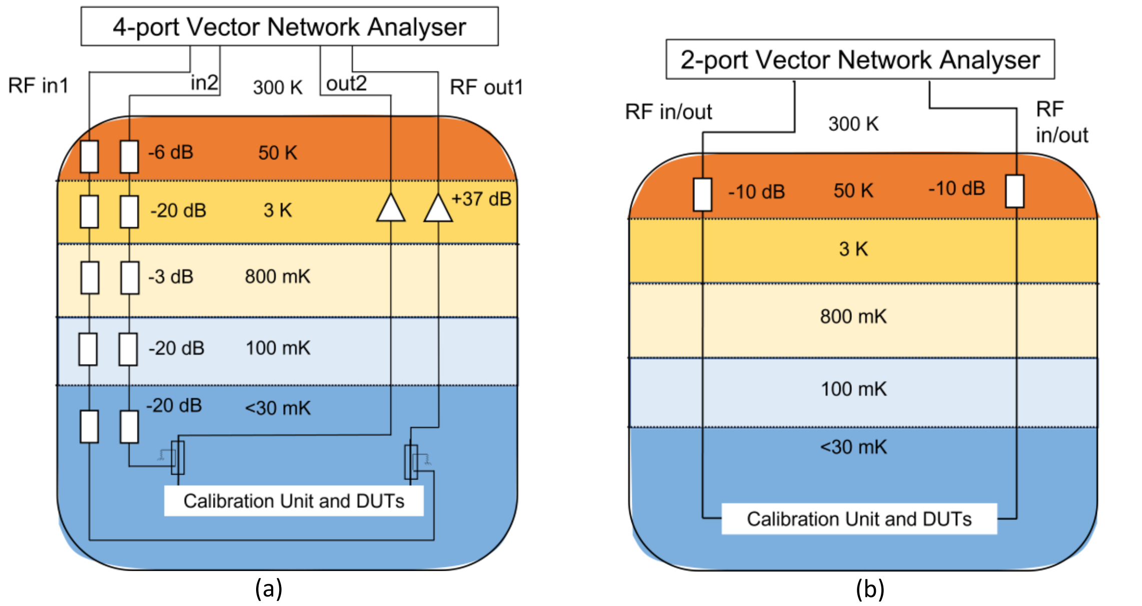


Figure 5 – Measurement architecture optimised to characterise (a) quantum devices (b) microwave devices.

The dilution refrigerator (Bluefors XLD series) used for our cryogenic measurements is split into six stages of decreasing temperatures (~300 K, ~50 K, ~3 K, ~800 mK, ~100 mK, and 30 mK) and consist of thermalized and attenuated RF lines and DC lines running through each of these stages. The RF lines are realized as semi-rigid microwave cables and contain various microwave components such as attenuators, filters and amplifiers from the input side to the output side to support operation of quantum circuits. The cryogenic measurement setups used in [5-6] to characterise quantum circuits typically consisted of coaxial lines of high attenuation (i.e., of 60 dB or more) as shown in Fig. 5(a). These limit the thermal microwave photon energy entering the fridge to ensure proper functioning of the quantum devices. This also minimises the heating inside the dilution refrigerator and locally at the devices. This measurement architecture requires use of multiple amplification stages to generate acceptable signal levels for the VNA measurements. However, these architectures present difficulties, in terms of VNA receiver linearity, as summarised in [9]. This architecture also required a 4-port VNA for precise characterisation of 2-port devices. Use of room temperature switches can enable measurements using a 2-port VNA, albeit with reduced measurement accuracy [10]. These architectures also present difficulties in measuring the VNA switch terms, which are used to account for the change in reflection coefficient of the VNA's internal switch ports. Furthermore, this measurement system also requires cryogenic compatible broadband components such as directional couplers and low noise amplifiers to perform S-parameter measurements over a broad frequency range.

When characterising classical microwave devices at mK temperatures, such high attenuation in the RF lines of the order of 60 dB is not required as the performance of microwave devices are not sensitive to thermal energy of microwave photons. Therefore, lower attenuation (in the order of only 10 dB) is used. This lower level of attenuation is just sufficient to minimise heating of the base plate or DUT itself in the mK stage in a dilution refrigerator due to input RF power. These attenuators are added to each of the coaxial lines connecting DUTs to VNA test ports. This eliminates the need for broadband cryogenic components such as amplifiers and directional couplers as shown in Fig. 5(b). However, additional care must be taken to ensure that the calibration unit consisting of standards and DUTs are properly thermalised to the base plate temperature. This is to reduce any local heating at the DUT terminals due to the relatively higher microwave power reaching the DUT ports. The heating up of the DUTs is further minimised by reducing the microwave output power level in the VNA [11-13]. This architecture is more straightforward and achieves improved measurement accuracy at the expense of a slight reduction in dynamic range.

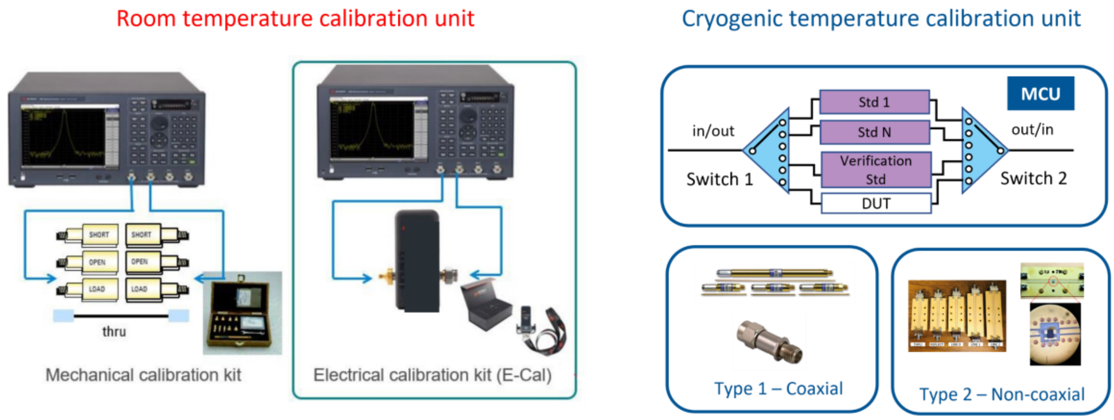
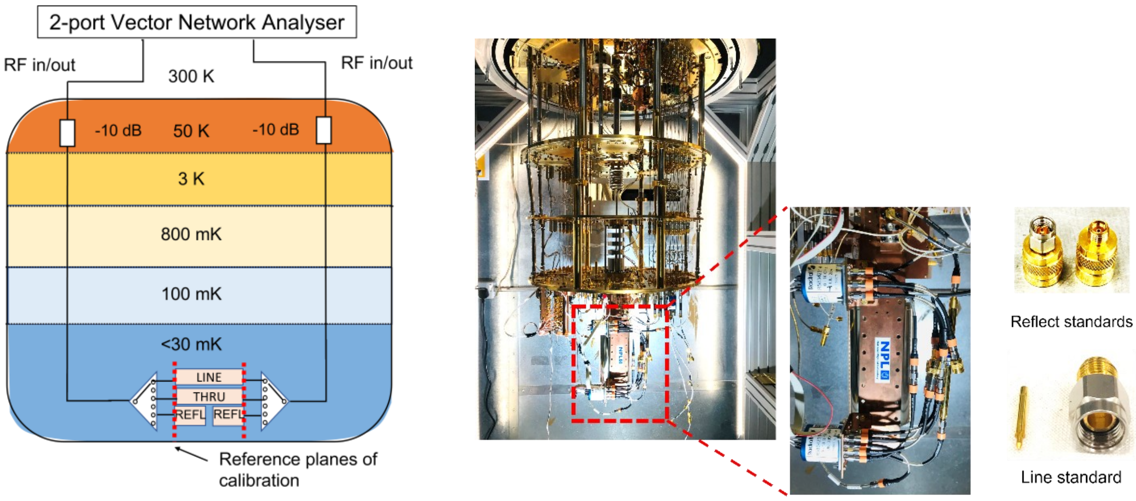


Figure 6 – Room temperature calibration units versus cryogenic MCU.

The S-parameter calibration process implemented at room temperature typically involves connection of calibration standards, either manually or automatically using an electronic calibration (Ecal) kit, to the measurement reference planes. It is not practical to implement either of these approaches at mK temperatures. Therefore, a microwave calibration unit (MCU) utilising electromechanical microwave switches is used to select each of the standards and DUTs at mK temperatures as shown in Fig. 6. Modern dry dilution refrigerators, which utilize pulse-tube cooling in place of liquid cryogens, have adequate space at the mK stages to deploy microwave calibration unit(s). The microwave switches used in NPL's MCU are commercially available mechanical pulse latched SP6T switches that operate by means of electrical pulses of short duration to latch the switch to different positions. This involves software-controlled activation/deactivation of the respective standard/DUT during the measurements. The voltage pulse from the switch control unit is tightly controlled to activate the switch ports while minimising heating of the mixing chamber plate (<30 mK stage) inside the dilution refrigerator. The calibration standards are designed and implemented inside the MCU depending on the type of DUT packaging. For example, coaxial calibration standards (Type 1) have been developed and are utilised for characterising devices packaged using coaxial connectors. Non-connectorised substrate-based transmission line standards (Type 2) have been developed to characterise on-chip devices or substrate materials as shown in Fig. 6.

3. Cryogenic device characterisation capabilities at NPL

The core of NPL's cryogenic device characterisation capability lies in the MCU that is deployed inside a dilution refrigerator that interfaces with a VNA at room temperature. This enables calibrated S-parameter measurements of DUT's at cryogenic temperatures down to tens of mK. The MCU houses the cryogenic compatible calibration standards and DUTs. A Thru-Reflect-Line (TRL) technique can be used to calibrate at mK temperatures which is then subsequently used to measure one- and two-port DUTs. This technique was chosen due to its advantage of not requiring precise knowledge of the microwave properties of the calibration standards at the operating temperature to achieve a high-quality calibration. The TRL technique requires measurements of two transmission standards (Thru and Line) and a pair of reflect standards to determine the VNA two-port error correction coefficients. The TRL technique can be utilised as a primary calibration technique to characterise the performance of other devices, including other calibration standards (e.g., Shorts, Opens and Loads). These characterised devices can be used subsequently to develop other calibration techniques such as Short-Open-Load-Thru/Reciprocal Thru (SOLT/SOLR), Thru-Reflect-Match (TRM), etc at cryogenic temperatures. The various TRL-based MCUs used to characterise coaxial connectorised devices, on-chip devices and substrate materials are hereby described.



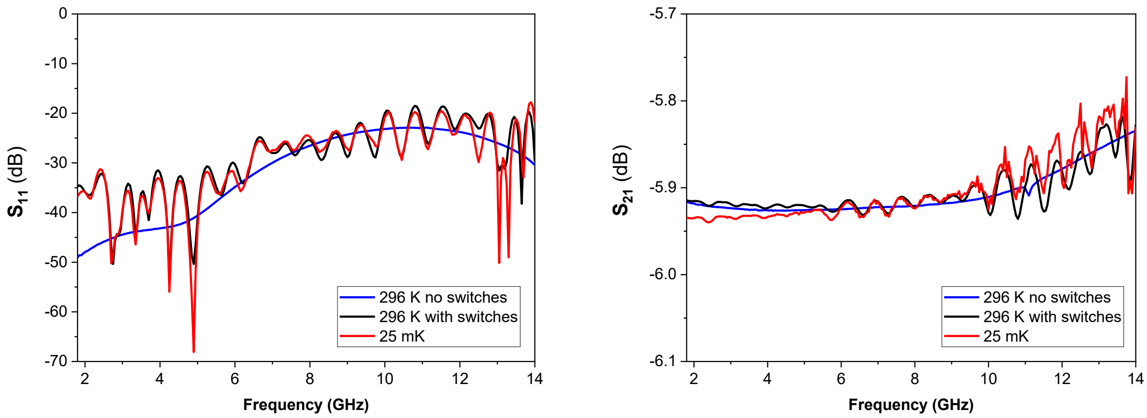
(a) (b)

Figure 7 – NPL S-parameter measurement system used to characterise coaxial connectorised devices (a) Block diagram; (b) MCU consisting of standards and DUTs inside the mK stage of a dilution refrigerator.

3.1. Coaxial connectorised devices

To characterise S-parameters of coaxial connectorised devices at mK temperatures, several measurement architectures have been proposed, utilising dielectric filled calibration standards as reference impedance standards [10,11]. However, the properties of the dielectric used in these devices may change at mK temperatures, thus affecting the reference impedance of the calibration, and therefore adversely affecting the accuracy of the S-parameter measurements. To address this issue, NPL uses air-dielectric coaxial transmission lines (also, known as air lines) as reference impedance standards at mK temperatures. These air lines have been characterised at mK temperatures. The subsequent measurements have demonstrated the feasibility of using such air lines as primary reference standards at mK temperatures [12]. This demonstrates the suitability of air lines as standards in cryogenic TRL calibration. For example, at NPL, a single 3.5 mm coaxial air line manufactured by Maury Microwave has been used as the TRL Line standard, with a nominal length of 10 mm. This line was designed to provide good calibration performance from 2 GHz to 14 GHz which covers the frequency band of interest for most quantum computing applications. Additional line standards can be utilised to extend the frequency range of calibrated measurements. The Thru standard is a zero-length insertable through connection of the coaxial test port cables. Commercial 3.5 mm coaxial male and female offset short standards have been used as the Reflect standards, as shown in Fig.7(b).

As an example, the calibrated S-parameters of a cryogenic attenuator have been determined at mK temperatures [13] as shown in Fig. 8. Two additional measurements at room temperature (296 K) – one with and one without the microwave switches have been made for comparison. Generally, the measurements at room temperature and mK temperatures shows that there is no significant observable temperature related difference in the performance of this cryogenic attenuator. This demonstrates its suitability for use as a verification device or "golden" device following a cryogenic calibration process. From Fig. 8, it is evident that the use of switches in the measurement setup introduced ripples in the measurements (both S_{21} and S_{11}) at both room and mK temperatures throughout the frequency range. This systematic effect is due to the differences in electrical length and loss of the microwave switch paths and the cables connected to it. Currently, there is an ongoing effort to quantify and correct for this effect to improve these measurements at cryogenic temperatures.



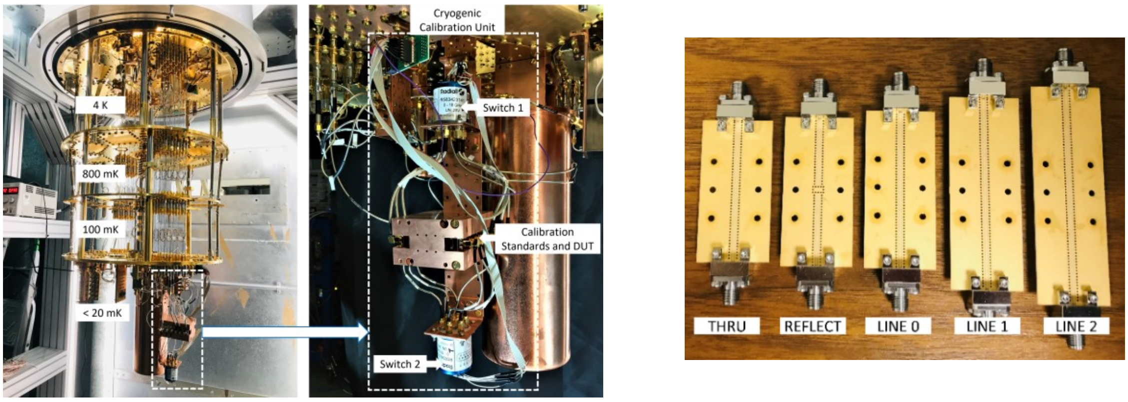
(a) (b)

Figure 8 – Measured S-parameters of a cryogenic 6 dB attenuator at room temperature (296 K) and mK temperature (25 mK) [12] (a) S11; (b) S21.

3.2. Non-connectorised devices

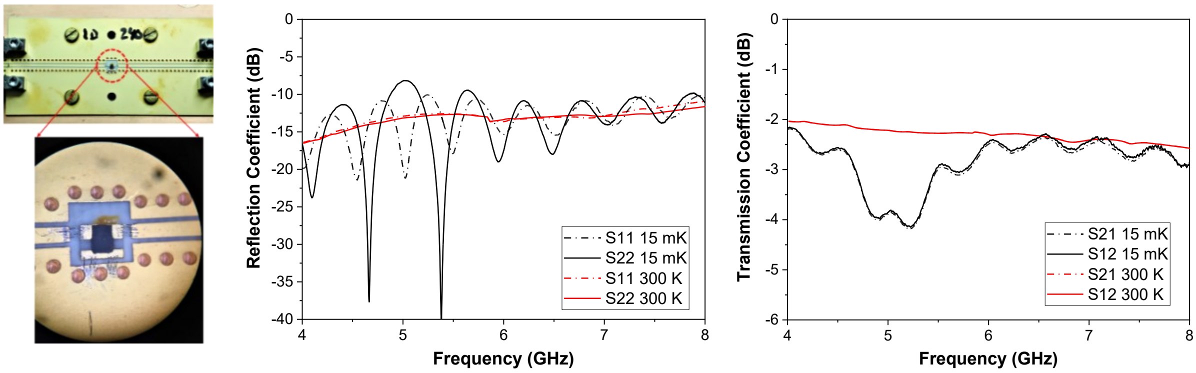
NPL has also developed an MCU to characterise the performance of on-chip devices [7] and substrate materials [14] at mK temperatures. The MCU deployed inside the dilution refrigerator is shown in Fig. 9(a). A TRL technique using multiple line standards is utilised to perform the cryogenic calibration. The calibration standards (Fig. 9(b)) are implemented using grounded co-planar waveguide (GCPW) transmission line technology on Rogers RO4350B substrates.

A 2 dB cryogenic attenuator IC wire-bonded to the GCPW transmission line has been measured to demonstrate the results from the system (Fig. 10(a)). The calibrated S-parameter measurements of the device at 15 mK are shown in Fig. 10(b). A strong impedance mismatch is observed at port 2 of the DUT, seen at around 5 GHz in Fig. 10(b). This has a consequent effect of reduced transmission around 5 GHz, shown in Fig. 10(c). The cause has been identified as degradation of the bond wire connected to port 2 of the device due to the effect of the low temperature. This was evident from the subsequent examination of the DUT after the measurements. This demonstrates that calibrated S-parameter measurements can shed light on the DUT performance as well as temperature related effects on the DUT interfacing to the PCB fixture.



(a) (b)

Figure 9 – (a) The NPL S-parameter measurement system for characterisation of non-connectorised devices; (b) Calibration standards.



(a) (b) (c)

Figure 10 – (a) Close-up of PCB fixture for 2 dB attenuator IC (DUT); (b) calibrated reflection coefficient; (c) calibrated transmission coefficient.

The effective permittivity of the substrate material in which these transmission lines are implemented has also been characterised at mK temperatures [14]. This was achieved by observing the experimentally determined propagation constant of the transmission lines after the calibration process. The effective permittivity was then extracted from the observed propagation constant. The measurements showed similar performance for the substrate material (Rogers RO4350B) at mK temperatures compared to room temperature, as shown in Fig. 11. Multiple transmission lines of different lengths have also been implemented to increase the bandwidth and reliability of these on-chip device and materials measurements.

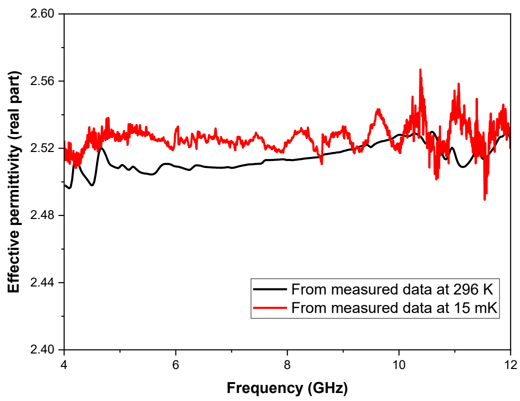


Figure 11 – Comparison of effective permittivity of substrate material (Rogers RO4350B) from measurement results at room temperature and cryogenic temperature.

With these capabilities, NPL can characterise integrated circuits and materials at these very low temperatures for the benefit of other organisations (e.g., end-users in the RF & microwave industry).

4. Overview of error sources affecting measurement accuracy

Cryogenic measurements can be susceptible to errors from a wide variety of error sources. If these errors are left unaddressed, measurements will not accurately represent the true performance of the DUT. Some of the main error sources in cryogenic measurements are detailed below. It is essential to understand and correct the effects from these error sources and perform uncertainty analysis, to progress the measurement capabilities and so offer commercial cryogenic testing as a service.

- **Choice of calibration method** – depending on the method of calibration, different degrees of prior knowledge about the calibration standards at their operating temperature are required to then obtain accurate measurements. The TRL technique requires relatively little knowledge of the characteristics of the standards whereas SOLT requires accurate knowledge of all the standards.
- **Connection repeatability –** this includes variation in measurement path due to switch port variability and repeatability, variability of cables and repeatability in re-connection of standards and DUTs, when making measurements across cooling cycles. These factors will bring about differing physical signal paths, and different electrical responses in consequence.
- **Linearity of amplifiers** – when characterising quantum circuits, measurement setups utilising high attenuation and amplification are used to ensure proper functioning of the quantum devices. It is important to ensure that the amplifiers used in such measurements are operating in their linear regime for all the standards and DUT measurements for a given VNA output power.
- **Coupling** – when characterising non-coaxial devices such as on-chip devices and materials, electromagnetic coupling occurs between adjacent neighbouring structures (for e.g.: - calibration standards) if they are implemented together in the same PCB. In our setup, the standards and DUTs have been implemented separately on different PCBs to minimise the coupling effects.
- **Parasitic circuit elements** - associated with the interconnection between the transmission line and DUT, e.g.: - effect of soldering or bond wires on DUT measurements as seen in Fig. 10(a). These could be de-embedded to a certain extent by modelling the behaviour of the interconnect mechanism.
- **Thermal stability** – rise in temperatures caused when controlling microwave switches can create thermal gradient inside the dilution refrigerator, leading to drift related errors. The measurements are performed when the temperature has stabilised to the desired temperature.

Effort to assess and minimise each of these error contributions is part of NPL's ongoing programme of work as the UK's National Metrology Institute (NMI) to provide confidence to our customers and collaborators by enabling accurate and precise device measurements at cryogenic temperatures.

5. Conclusion

This paper has described some of the cryogenic microwave measurement capabilities at NPL. The challenges associated with cryogenic measurements have been discussed. Much of the work presented here was undertaken in collaboration with industry and academia. We welcome such collaborations and are open to supporting further research and development work through cryogenic testing and measurements.

6. Acknowledgements

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7. References

[1] Department for Science, Innovation and Technology, “UK Science and Technology Framework”, https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1140217/uk-science-technology-framework.pdf, Mar 2023.

[2] Department for Science, Innovation and Technology, “National Quantum Strategy”, https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1142942/national_quantum_strategy.pdf, Mar 2023.

[3] J. C. Bardin, D. H. Slichter and D. J. Reilly, "Microwaves in Quantum Computing," in IEEE Journal of Microwaves, vol. 1, no. 1, pp. 403-427, Jan. 2021.

[4] Mateo Casariego et al., “Propagating quantum microwaves: towards applications in communication and sensing”, Quantum Sci. Technol. 8 023001, Mar 2023.

[5] L. Ranzani, L. Spietz and J. Aumentado, “Broadband calibrated scattering parameters characterization of a superconducting quantum interference device amplifier”, Appl. Phys. Lett. 103, 022601, Jul. 2013.

[6] M. Stanley, S. De Graaf, T. Hönigl-Decrinis, T. Lindström and N. M. Ridler, “Characterizing Scattering Parameters of Superconducting Quantum Integrated Circuits at Milli-kelvin Temperatures”, IEEE Access, vol. 10, pp. 43376-43386, Apr. 2022.

[7] M. Stanley, R. Parker-Jervis, S. de Graaf, T. Lindström, J.E. Cunningham, and N.M. Ridler, “Validating S-parameter measurements of RF integrated circuits at milli-Kelvin temperatures”, Electron. Lett., 58(16): 614-616, Aug. 2022.

[8] E. M. Wei, R. A. Chamberlin, N. Kilmer, J. Kast, J. A. Connors and D. Williams, "On-Wafer Vector-Network-Analyzer Measurements at mK Temperatures," in IEEE Journal of Microwaves, vol. 3, no. 2, pp. 587-598, April 2023.

[9] J. Martens, “On VNA Calibration and De-embedding Considerations for Quantum Computing-related and Other Millikelvin Measurements”, Anritsu online: https://dl.cdn-anritsu.com/ja-jp/test-measurement/reffiles/About-Anritsu/R_D/Technical/98/98-07.pdf, Aug 2023.

[10] L. Ranzani, et.al, “Two-port microwave calibration at millikelvin temperatures”, Rev. Sci. Instrum. vol. 84, 034704, Mar 2013.

[11] S. Simbierowicz, et.al, “Microwave calibration of qubit drive line components at millikelvin temperatures”, Appl. Phys. Lett. 120, 054004, 2022.

[12] J. Skinner, M. Stanley, J. Urbonas, S. de Graaf, T. Lindström and N. M. Ridler, “Characterizing Precision Coaxial Air Lines as Reference Standards for Cryogenic S-Parameter Measurements at Milli-kelvin Temperatures”, IEEE MTT-S Int. Microw. Sym., USA, 2023, pp. 561-564.

[13] M. Stanley, S -H. Shin, J. Skinner, J. Urbonas, N. M. Ridler, “Characterising Scattering Parameters of Coaxial Microwave Devices at Milli-kelvin Temperatures for Quantum Computing Technologies,” European Microwave Conference (EuMC), Berlin, Germany 2023.

[14] M. Stanley, R. Parker-Jervis, J. Skinner, S. De Graaf, T. Lindström, J. E. Cunningham and N. M. Ridler, "Determination of the Permittivity of Transmission Lines at Milli-Kelvin Temperatures," in IEEE Access, vol. 11, pp. 60626-60634, 2023.