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RF and microwave metrology for quantum computing – recent developments at the UK's National Physical Laboratory

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Research Paper

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Abstract

Development of large-scale quantum computing systems will require radio frequency (RF) and microwave technologies operating reliably at cryogenic temperatures down to tens of milli-Kelvin (mK). The quantum bits in the most promising quantum computing technologies such as the superconducting quantum computing are designed using principles of microwave engineering and operated using microwave signals. The control, readout, and coupling of qubits are implemented using a network of microwave components operating at various temperature stages. To ensure reliable operation of quantum computing systems, it is critical to ensure optimal performance of these microwave components and qubits at their respective operating temperatures, which can be as low as mK temperatures. It is, therefore, critical to understand the microwave characteristics of waveforms, components, circuits, networks, and systems at cryogenic temperatures. The UK's National Physical Laboratory (NPL) is focussed on developing new microwave measurement capabilities through the UK's National Quantum Technologies Programme to address various microwave test and measurement challenges in quantum computing. This includes the development of various measurement capabilities to characterize the microwave performance of quantum and microwave devices and substrate materials at cryogenic temperatures. This paper summarizes the roadmap of activities at NPL to address these microwave metrology challenges in quantum computing.

Introduction

Quantum technologies, such as quantum computing, utilize quantum mechanical principles such as superposition and entanglement to achieve significant advances in computing power. This requires the development of quantum components such as qubits and microwave and electro-optic components that function at extremely low temperatures to implement, observe, and manipulate these phenomena in a precisely controlled manner. The development of quantum computing technologies must also be underpinned at every level with traceable metrology to ensure consistent capability and market confidence.

The most promising quantum computing technologies poised to achieve near-term quantum advantage rely on RF and microwave waveforms, components, circuits, systems, and networks operating reliably at temperatures from room temperature down to tens of milli-Kelvin (mK) to perform quantum operations [1]. The performance of these RF elements needs be characterized at their operating temperature by measuring various electrical parameters such as scattering (S-) parameters, power, and noise. Some aspects of microwave metrology applicable to quantum computing are summarized in Fig. 1.

The quantum operations are orchestrated using pulsed RF 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 mK as shown in Fig. 2. Consequently, this control and readout chain utilizes a network of RF components and circuits operating at various temperatures including cryogenic temperatures. For example, the control system consisting of RF signal generators and analyzers (for qubit control and readout) is typically operated at room temperatures, whereas low noise amplifiers (used to improve qubit readout fidelity) are operated at around 3 K while qubits and parametric amplifiers are operated at mK temperatures. It is critical to characterize the microwave performance of such devices at their operating temperature to ensure optimal performance of quantum computers developed using such components.

RF metrology capabilities at room temperatures have been developed principally to address measurement challenges in telecommunications and defense industries. Recently,

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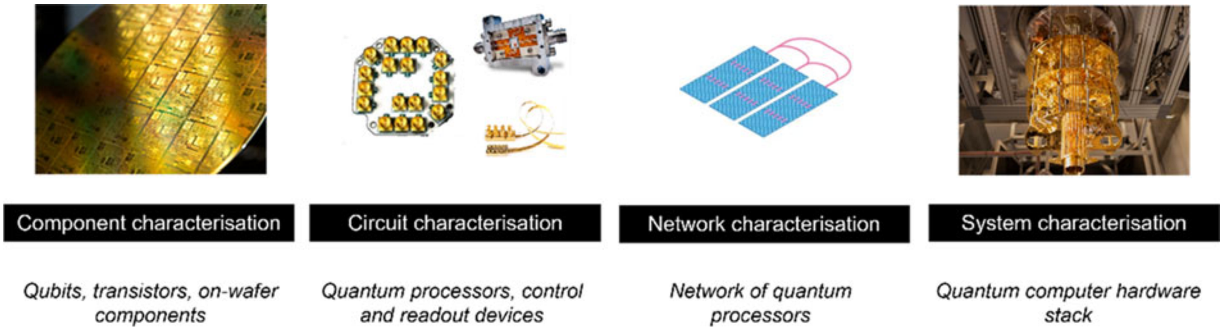


Figure 1. Aspects of RF metrology in quantum computing.

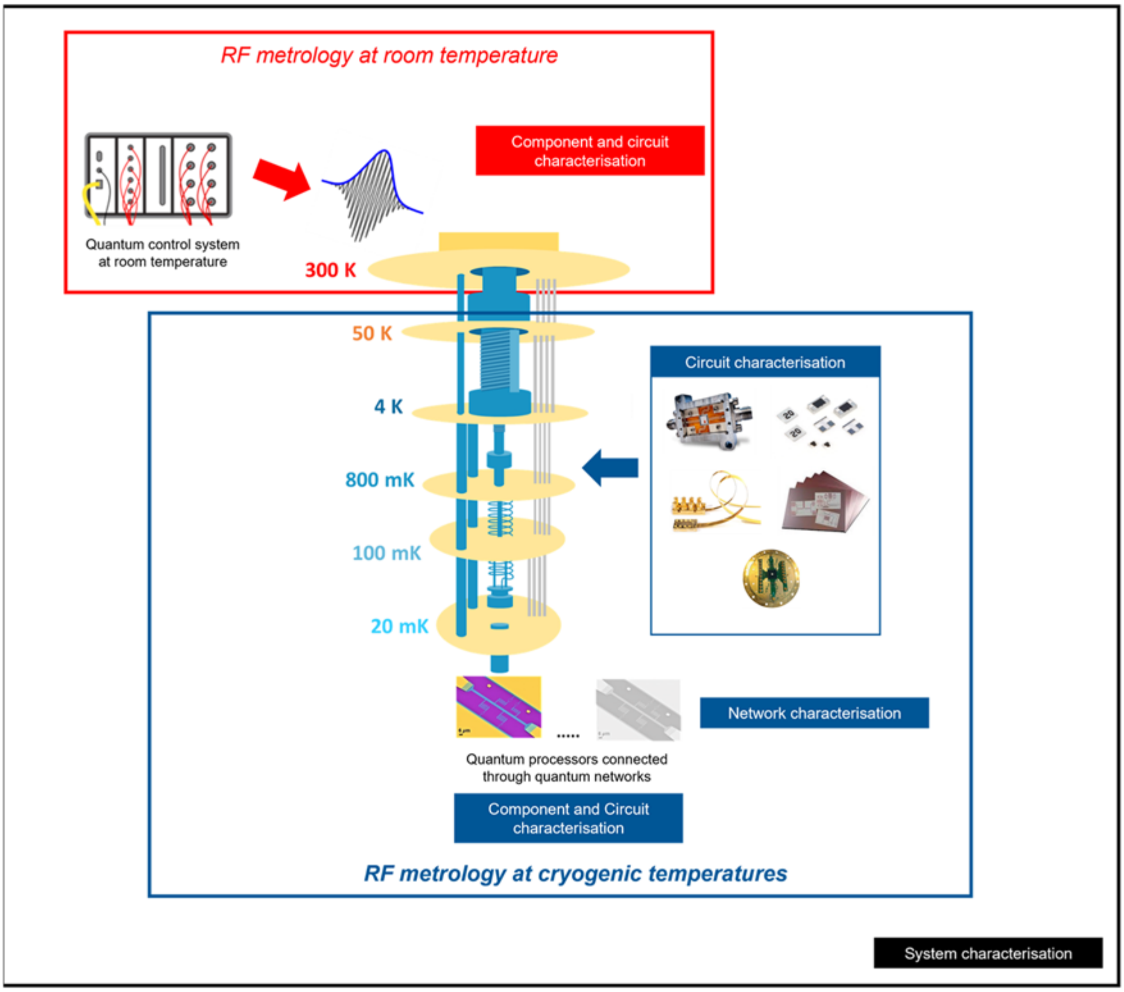


Figure 2. Detailed diagram of a superconducting quantum computing system with the different RF metrology aspects highlighted at the various stages.

research labs have been adapting these measurement facilities to support quantum computing applications. While RF and microwave metrology at room temperatures are mostly well understood and at an advanced stage of maturity, its implementation at cryogenic temperatures requires a lot more understanding and development to address the measurement challenges at these temperatures. This paper summarizes the measurement facilities at National Physical Laboratory (NPL) to facilitate RF and microwave-related metrology requirements for quantum computing.

Challenges in RF characterization at cryogenic temperatures

Accurate characterization of microwave devices in the cryogenic environment benefits quantum computing by supporting the development of active and passive cryo-electronic devices, cables and interconnects, multiplexers, quantum and RF integrated circuits (ICs), flux quantum electronics, cryo-CMOS technologies, quantum hardware packaging, and parametric amplifiers. Typical

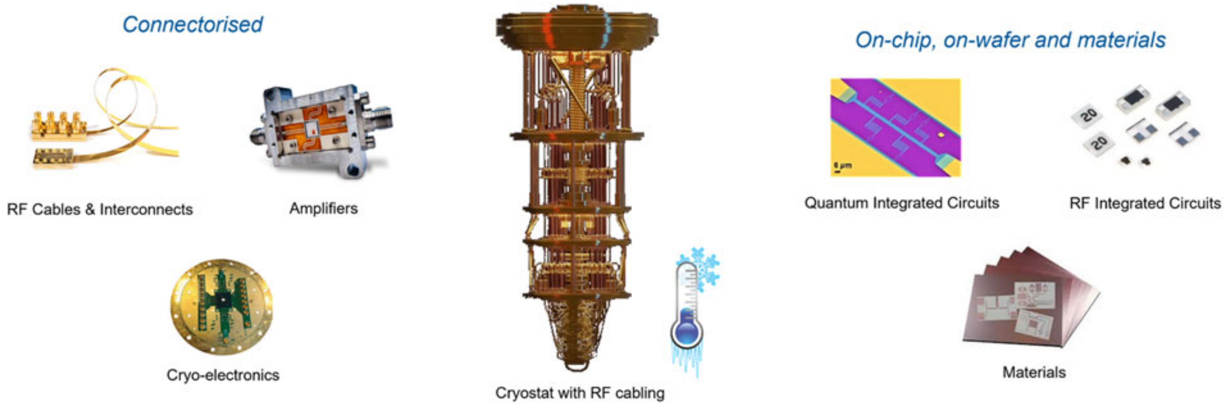


Figure 3. Typical RF and microwave components used in quantum computing.

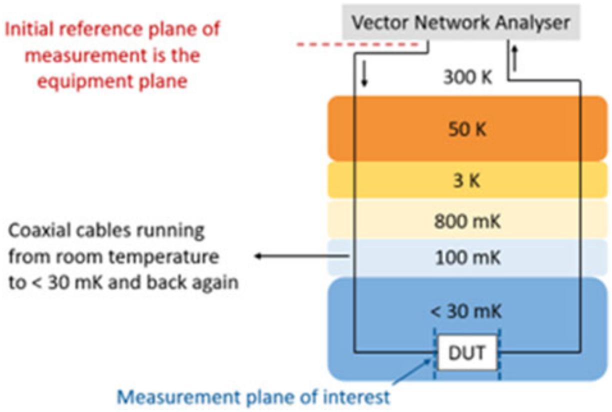


Figure 4. Typical interfacing of DUTs at cryogenic temperatures.

RF and microwave components used in quantum computers are shown in Fig. 3.

Recent research in this area has focused on developing measurement systems to characterize microwave and quantum devices at temperatures down to tens of mK. These include the S-parameter measurement system to characterize coaxial connectorized devices [2–6], on-chip devices [7–9], on-wafer devices [10], and substrate materials [11]. These devices under test (DUTs) are typically operated inside a cold, isolated environment such as a dilution refrigerator and interfaced with room temperature test equipment such as a Vector Network Analyzer (VNA) using microwave cabling and components. Such a setup is shown in the schematic in Fig. 4. The cryogenic device measurements are usually adversely affected by the cables and other components inside the dilution refrigerator, which need to be "corrected" using specialized calibration techniques to gain a better understanding of the device behavior.

S-parameter characterization

The RF performance of components used in quantum computers can be characterized by measuring their S-parameters. These describe the relationship between different ports of the electrical network at RF frequencies in terms of the amplitude and phase change of the transmitted and reflected signals as a function of frequency, rather than the voltage and current representation used at lower frequencies. These can be utilized to extract other useful information such as the electrical properties of transmission lines, equivalent circuit models, material properties, crosstalk, and losses. A comprehensive characterization of active and nonlinear devices also requires RF power and noise measurement capabilities in addition to S-parameter characterization.

In order to measure the "true" S-parameters of the DUT, a calibration scheme that shifts the reference planes of the measurement to the terminals of the DUT needs to be implemented. In this way, imperfections in the VNA itself as well as effects due to the intervening passive and active components up to the ports of the VNA are de-embedded from the measured results. 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. Mechanical connection of calibration standards to perform calibration at cryogenic temperatures requires multiple cooling cycles to perform complete measurement of standards and devices. This is not a very practical approach and creates drift-related measurement errors. ECal units consist of electronics devices and standards which could change in performance at cryogenic temperatures. Hence, it is not practical to implement either of these approaches at cryogenic temperatures. Instead, specially developed calibration standards and techniques are deployed close to the DUT to perform calibrated S-parameter measurements at cryogenic temperatures.

Various capabilities and techniques have been developed at NPL to characterize accurate calibrated S-parameter measurements of devices at room temperature at RF and microwave frequencies. These capabilities are useful to understand the variation in performance of RF and microwave devices due to variations in temperature. In addition to this, there are extended capabilities at millimeter wave and sub-terahertz frequencies at room temperature to characterize coaxial connectorized devices (up to 90 GHz), waveguide connectorized devices (up to 750 GHz), on-chip and on-wafer devices (up to 750 GHz), and dielectric materials (up to 750 GHz). Most of the quantum computing applications are currently utilizing RF and microwave frequencies (40 GHz and below) or optical frequencies to control and readout qubits. However, with advancements in test and instrumentation capabilities at millimeter-wave frequencies due to requirements in 6G + communication systems, it is possible that future quantum computing systems would utilize intermediate millimeter-wave frequencies to address some of the scaling challenges in quantum computing. This is evident from recently published research trials for testing wireless interface in these frequency bands [12].

Recently, NPL has initiated programs to develop S-parameter measurements systems at cryogenic temperatures down to mK temperatures. The S-parameters of the devices can be characterized at cryogenic temperatures using two approaches – cryostat-based *in-situ* characterization and characterization using cryogenic probe station. The respective approach is chosen based on the application, type of device packaging, measurement temperature, and accuracy requirement. For example, the cryostat-based approach is useful when the device requires continuous characterization as the quantum computer is in operation. Examples include the characterization of qubits and readout amplifiers which vary in performance due to operating conditions. Coaxial connectorized devices can only be characterized using the cryostat-based approach. Both approaches can be utilized for characterizing on-chip and on-wafer devices and dielectric materials. Characterizing on-wafer devices and materials using a cryogenic probe station has the potential to achieve better accuracy due to direct probing, eliminating the effects of interconnects used to interface DUTs to fixture such as bond wires. Currently, the cryostat-based approach can be used to perform device characterization down to temperatures of tens of mK, whereas characterization using probe station is typically limited to 2 K. Recently, an automated probing system inside the mK stage of a dilution refrigerator was implemented at NIST for characterization of on-wafer devices, which enabled on-wafer measurements at mK temperatures using a hybrid approach [10].

Cryostat-based in-situ *measurements*

The core of NPL's cryogenic S-parameter characterization capability lies in the microwave calibration units (MCUs) that are deployed inside a dilution refrigerator that interfaces with a VNA operating at room temperature. This enables calibrated S-parameter measurements of DUTs at cryogenic temperatures down to tens of mK. The calibration unit houses the cryogenic compatible calibration standards and DUTs.

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 consists 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.

Different measurement architectures have been developed to characterize S-parameters of classical RF and microwave devices [2–7] and quantum devices [8, 9] with up to two ports. These have been compared and summarized in paper [13]. There is ongoing activity at NPL to characterize devices with up to four ports at cryogenic temperatures down to tens of mK. This would help to characterize the performance of quantum processors and multiport microwave devices such as switches, circulators, etc. with more than two ports. When characterizing quantum devices at mK temperatures, high attenuation coaxial lines are used to minimize thermal radiation to the DUT to observe quantum phenomenon. This reduces the dynamic range of measurements and requires usage of broadband amplifiers and directional couplers to facilitate broadband S-parameter measurements [9].

Microwave switches that are operated by means of electrical pulses are used in NPL's calibration units to select the respective standard/DUT during the measurements as shown in Fig. 5.

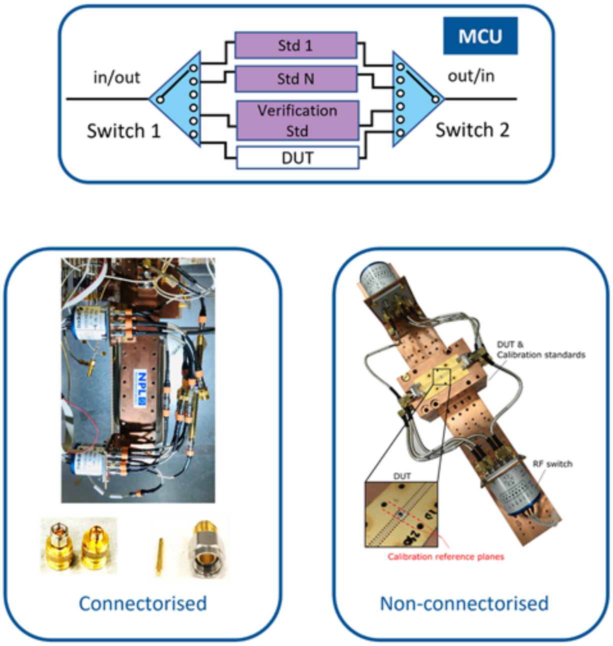
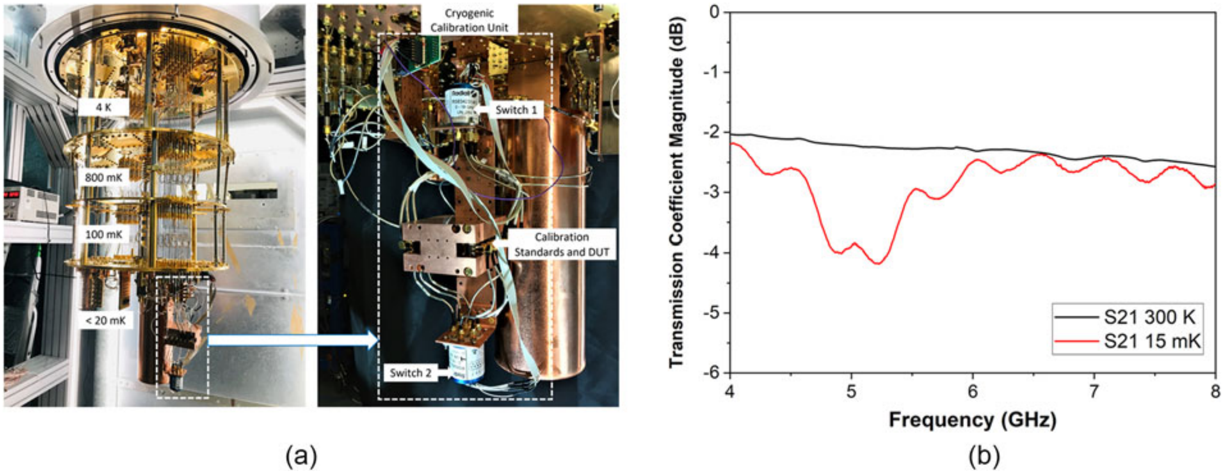


Figure 5. Cryogenic microwave calibration unit for characterizing connectorized devices [5] and non-connectorized devices (on-chip, on-wafer, and materials) [7, 11] using cryostat-based approach.

The calibration standards are designed and implemented inside the MCU depending on the type of DUT packaging. For example, coaxial connectorized calibration standards have been developed for characterizing devices packaged using coaxial connectors. Substrate-based transmission line standards have been developed to characterize non-connectorized on-chip devices or substrate materials as shown in Fig. 5. An MCU deployed inside the mK stage of a dilution refrigerator to characterize on-chip devices is shown in Fig. 6(a). A 2 dB cryogenic attenuator IC was characterized as an example. The calibrated transmission coefficient measurements of the device at 15 mK is shown in Fig. 6(b). Reduced transmission can be observed at around 5 GHz, for the results at mK temperatures. This is due to the degradation of the bond wires connected to one of the device ports due to the low temperature, thereby, creating a strong impedance mismatch. The measurements demonstrated that calibrated S-parameters can shed light on the DUT performance as well as temperature-related effects on the DUT interfacing. The use of switches introduces systematic errors due to the differences in electrical length and loss of the microwave switch paths and the cables connected to it. These errors are not present in typical room temperature applications as switches are not used in metrology grade setup to perform device characterization. Currently, there is an ongoing effort to quantify and correct for this effect to improve these measurements at cryogenic temperatures.

The effective permittivity of a grounded coplanar waveguide (GCPW) line on the substrate material has been characterized at mK temperatures [11]. 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. This technique was used to characterize the performance Rogers RO4350B substrate at mK temperatures as shown in Fig. 7. This substrate material is commonly used in high-frequency applications.



(a) (b)

Figure 6. (a) The NPL S-parameter measurement system for characterization of non-connectorized devices with calibration unit deployed inside the mK stage of a dilution refrigerator [7]; (b) calibrated transmission coefficient of a 2 dB attenuator IC.

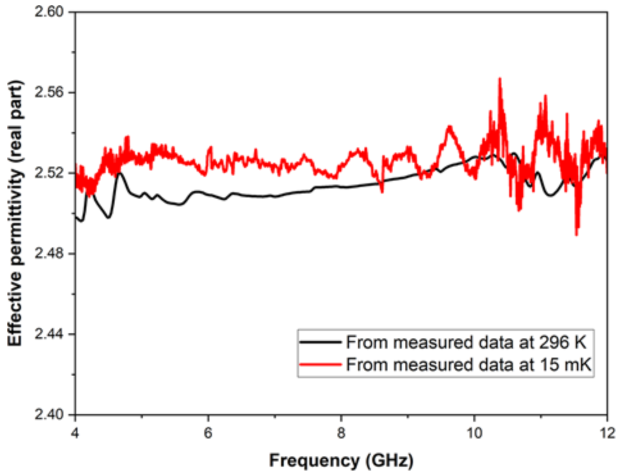


Figure 7. Comparison of the effective permittivity of a GCPW line on the substrate material (Rogers RO4350B) from measurement results at room temperature and cryogenic temperature [11].

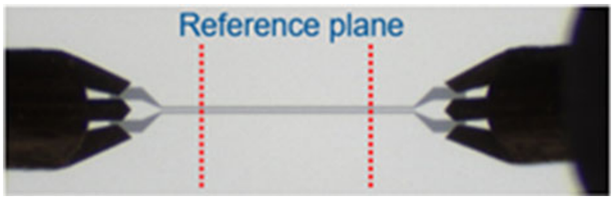


Figure 8. Microscopic image of an on-wafer S-parameter measurement of a CPW transmission line.

On-wafer probe station-based measurements

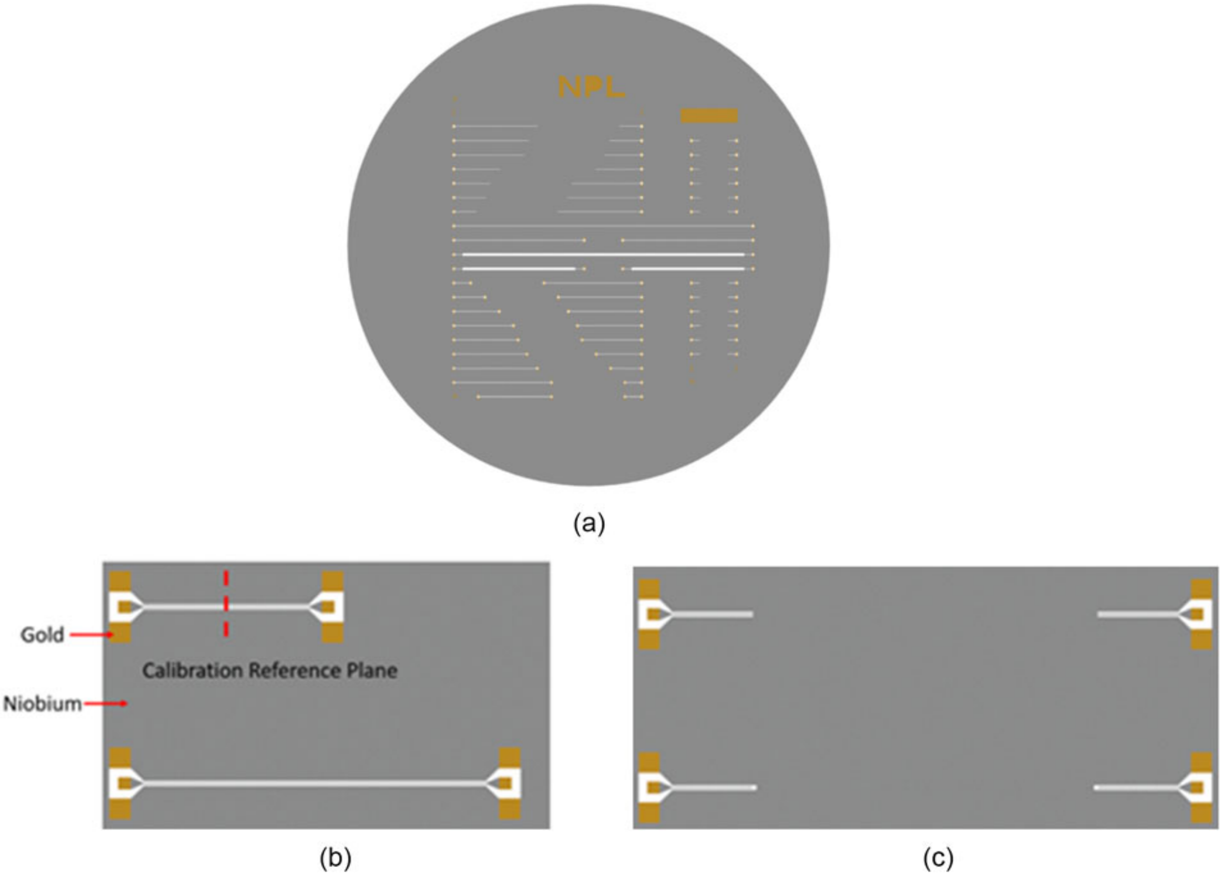
The realization of fully scaled-up quantum computers, based on many qubits, will require microwave on-wafer measurements of on-chip or wafer-level planar ICs. With cryogenic on-wafer measurements, the DUT can be characterized at cryogenic temperatures directly, without the need for additional connectors or interfaces. Figure 8 exhibits on-wafer S-parameter measurement of a coplanar waveguide (CPW) transmission line, with the reference planes indicated. These reference planes can be shifted through proper de-embedding. On-wafer S-parameter measurement at cryogenic temperatures has been reported in prior work, including those at 4 K [14, 15] and less than 20 mK [10] temperatures.

NPL has been developing cryogenic on-wafer S-parameter measurement capability, in collaboration with Royal Holloway, University of London (RHUL). More specifically, the adaptation and improvement of a cryogenic probe station for microwave probing (at around 4 K), and the development of bespoke calibration and verification standards based on CPW structures. These standards were fabricated from high-resistivity silicon substrates and selectively metallized using niobium and gold. Figure 9 shows CAD drawings of the wafer. Such cryogenic on-wafer measurement capabilities will help facilitate current and future developments in commercial quantum computers.

Development of this new cryogenic probing capability is facilitated by NPL's extensive knowledge and experience with on-wafer measurements at room temperature. Compared to on-wafer measurements at room temperature, measurements at cryogenic temperatures require more preparation time (to meet the vacuum and temperature requirements) and pose other challenges. These challenges include considerable vibrations generated from the cooling system, limited visibility during probing in that lights from the microscope increases the chuck temperature, and difficulty in landing the probes that are far away from the positioners. Additional efforts are also required to determine the expected behavior of the cryogenic calibration standards, which usually involve thin-film structures and substrates whose properties at cryogenic temperatures need to be characterized/understood beforehand. The room temperature probing system at NPL, shown in Fig. 10, enables accurate S-parameter measurement of planar passive or active circuits operating at frequencies as high as 750 GHz. Such measurements facilitate the development of monolithic microwave ICs for millimeter-wave and terahertz wireless communication systems, which are also being utilized for quantum computing applications [16]. The cryogenic probe station being developed at RHUL is shown in Fig. 11.

RF power characterization

Microwave power is one of the critical parameters for characterization of active and nonlinear microwave devices such as amplifiers,



(a)

(b)

(c)

Figure 9. CAD drawing (a) layout of cryogenic on-wafer calibration standards; (b) thru, including reference plane indicator (top) and line (bottom); and (c) reflect standards: open (top) and short (bottom).

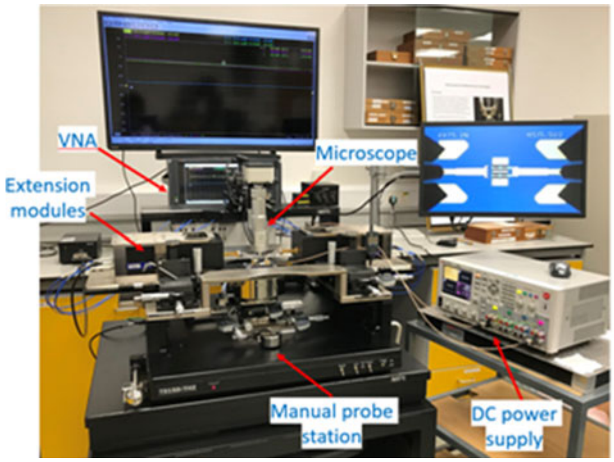


Figure 10. Photograph of the probing system for room temperature measurements at NPL.

filters, mixers, etc. It is also essential to know input and output powers which are necessary to operate the systems effectively and with confidence. Microwave power is defined through characterizing a measurement standard known as a thermistor mount or power sensor using a DC substitution method. The traceable dc parameters are voltage and resistance which are obtained using Josephson junction and quantum Hall measurement systems respectively.

The application of power metrology at room temperature is well known, and research has been ongoing for more than 60 years [17–20]. Capabilities have been developed at NPL to perform traceable and accurate power measurements for coaxial devices up to 50 GHz and waveguide devices up to 110 GHz. RF power measurements at cryogenic temperatures are needed to facilitate characterization of active and nonlinear devices for quantum computing. It is not possible to use the room temperature techniques directly for cryogenic applications. This is because of change in performance of the standards at cryogenic temperatures. This includes changes in impedance of resistors used in thermal-based sensors, response of power sensors (e.g., thermocouple or thermistor response), etc. There is very little published research on power measurement standards and methods to define microwave power with SI traceability at cryogenic temperature. One method is to produce microwave power in the cryogenic ambient. Reference [21] proposes to obtain microwave power from a Josephson arbitrary waveform synthesizer. This method is newly proposed and is currently at an early stage of development. Another method is to measure microwave power using a quantum-based power sensor. This method has been proposed in paper [22] to measure power from −110 dBm to −90 dBm. The power sensor uses dc power for SI traceability. Capabilities are also being developed at NPL to perform RF power measurements at cryogenic temperatures. This work includes power measurement at cryogenic temperatures down to 15 mK using various thermal-based sensing techniques. Another approach involving the transfer of known

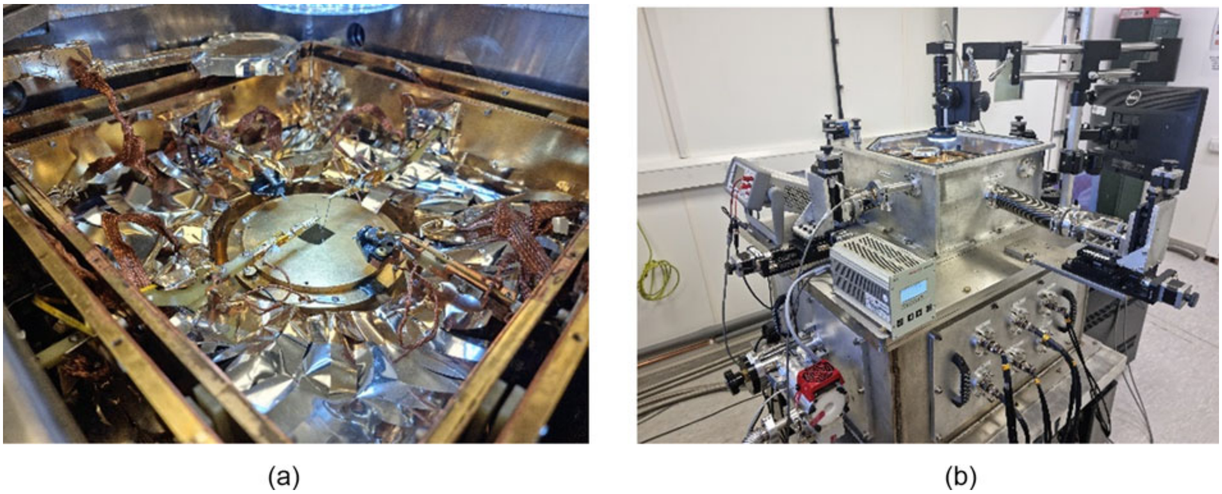

(a) (b)

Figure 11. Measurement setup showing the cryogenic probe station: (a) internal view showing the probe arms and the DUT chuck and (b) external view.

power at room temperature to cryogenic temperatures is also being investigated. This technique can be implemented by measuring loss in the transmission line using the S-parameter measurement techniques discussed previously.

Noise characterization

Noise in a receiving system obscures weak signals and sets a limit to the smallest signal that the system can reliably process, i.e., to the system sensitivity. In superconducting quantum computing low-noise amplifiers play a significant role in accurately inferring the qubit state. Accurate noise measurements are important for controlling and verifying the noise added by system components. Noise power is often expressed as a noise temperature. The noise added by an amplifier is expressed in terms of either noise figure or effective input noise temperature. The dependence of amplifier noise on source impedance is quantified by the noise parameters [23–25].

At NPL, amplifier noise figure (or, equivalently, effective input noise temperature) is measured at room temperature by the cold source method implemented using a VNA [26]. The S-parameters of the amplifier under test (AUT) are first measured using the VNA which allows the gain of the AUT to be computed. With the RF source in the VNA turned off, noise power at the output of the amplifier is measured for several different source impedances presented to the input of the amplifier. The different source impedances are realized by an ECal unit connected at the input to the amplifier. The noise figure of the AUT is extracted for each source impedance by de-embedding the noise figure of the noise receiver. The gain, bandwidth, and noise figure of the receiver are determined in a calibration step. From the measurements of noise figure of the AUT versus source impedance, the noise parameters of the AUT are determined. The noise figure of the AUT corresponding to any source impedance can be computed from the noise parameters. An alternative commonly used method for measuring amplifier noise, the Y-factor method, requires two noise sources with different known noise temperatures (a “hot” source and a “cold” source) to be connected in turn to the input of the amplifier and for the output noise to be measured for each. The two noise sources are assumed to have the same reflection coefficient. The Y-factor method can be applied in combination with varying the source impedance.

Implementing noise measurement system at cryogenic temperatures relies on the development of calibrated noise source and variable impedance generators suitable for cryogenic temperatures. Currently, NPL is investigating methods for measuring the matched noise properties of the amplifier which include (i) the cold attenuator method [27] in which an attenuator is placed at the amplifier input inside the cryostat with hot and cold noise sources applied at the input to the cryostat; (ii) the Y-factor method applied using a termination at the amplifier input inside the cryostat fitted with a heater and thermometer to control and monitor its temperature to provide different levels of noise [27]; and (iii) an application of the cold source method using a source termination at the input to the amplifier inside the cryostat with auxiliary measurements being used to characterize the amplifier gain and the properties of the input and output lines [28]. Methods for measuring the noise parameters of cryogenic amplifiers place the source impedance tuner either outside [29] or inside [30] the cryostat. With the source impedance tuner outside of the cryostat, losses in the input line may restrict the range of impedances that can be presented to the input of the amplifier. The receiver used to measure noise at the output of the AUT is generally placed outside the cryostat at the RF output port while the noise source(s) connected to the input of the AUT could be placed either outside or inside the cryostat. Implementing these techniques at cryogenic temperatures will require development and deployment of automated measurement and calibration techniques inside the cryostat.

Conclusion

The UK’s NPL is currently developing 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 capabilities to characterize S-parameters, power, and noise of various devices at temperatures down to tens of mK. The capabilities will help to characterize coaxial connectorized devices and non-connectorized devices such as on-chip, on-wafer devices, and substrate materials. These cryogenic measurement capabilities will be used to support industry and academia in creating new and improved devices for quantum computing.

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Competing interests. The authors report no conflict of interest.

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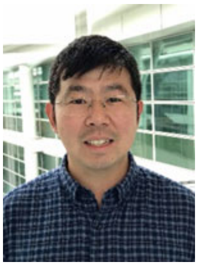

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