IQubits

D5.2 Cryogenic measurement set-up (to 110 GHz & 4 K)

November 2020

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EXECUTIVE SUMMARY

This deliverable describes the design, manufacturing and functional testing of the equipment for cryogenic microwave and millimeter-wave (mm-wave) on-chip ("on-wafer") characterization of semiconductor chips up to 110 GHz and down to 4 K. This equipment allows IQubits to carry out the on-chip cryogenic measurements for qubit transistors and qubits in an extended frequency range from 0.1 GHz to 110 GHz, which was not entirely covered by other commercial equipment available on the market. Thought initially as an upgrading of the existing similar equipment, built at IMT for frequency operations up to 67 GHz, the purchase of a new cryostat for dc measurements, from Janis, through national founds, has made possible to build this equipment independently from the one available initially. The characterization system is based on a SHI-4-2-AC cryostat by Janis, which has been adapted to allow on-chip microwave and mm-wave measurements with 110 GHz probes, by manufacturing a special probe head and custom holder specifically for this purpose, as well as by equipping it with a system of coaxial cables and suitable connectors. One of the big challenges of this setup are the very low dimensions of the mechanical components of the test fixture, as it had to be introduced in the very small space available in the cryostat.

The S-parameter results in the 0.1-110 GHz frequency range measured at room temperature and at 4.3 K demonstrate the functionality of the measuring set-up and validate the demonstrator. Then, following these results, also the milestone associated to this deliverable, MS4, is achieved and validated.

1 INTRODUCTION

A measuring system able to perform DC and microwave/mm-wave on-chip measurements up to 67 GHz, in a wide temperature range (5 K-500 K), was developed at IMT Bucharest a few years ago, by adapting a JANIS cryostat devoted only to DC measurements in the same temperature range. A special setup was built in-house for on-wafer measurements up to 67 GHz; the big challenge of this setup was not only the high level of the microwave/mm-wave measurement performances, but also the very low physical dimensions of the mechanical components of the test fixture, as it had to be introduced in the very small space available in the cryostat. Also cables and connectors necessary for the connection of the setup with the Vector Network Analyzer and a mm-wave generator overcrossing the cryostat have been used. This set-up has been successfully used in measurements of low temperature characteristics of qubit transistors (i.e., transistors as qubit), and evidencing Coulomb “diamonds” in quantum dot p-type transistors obtained in the 22nm FDSOI CMOS technology, as reported in D1.4 [1]. Also, microwave measurements on a Transimpedance Amplifier (TIA) developed in the same technology have been performed [2].

At the beginning of the project IQubits, this setup was the only one existing in the Consortium, able to perform cryogenic measurements down to 5 K to characterize the transistors, also as qubits. Two of the major objectives of the project, in WP5, are to upgrade this equipment (or to manufacture another one) to be able to operate up to 110 GHz (D5.2 and MS4, M22) and also later at 140 GHz (D.5.8, M44).

After the beginning of the project, owing to the support of an infrastructure national project, IMT had the opportunity to purchase an equipment able to measure, at cryogenic temperatures down to 2 K and at frequencies up to 67 GHz, qubit transistors (CPX-VF from Lake Shore Cryotronix, USA). The equipment is functional since September 2019 and results of measurements performed in IMT, on p-type qubit transistors, in magnetic field, were presented in [1]. UofT also purchased recently a similar equipment. Beside of its advantages (lower temperature and access to move the probes on pads of the chip at cryogenic temperatures, which improves the quality of calibration for low-temperature high-frequency measurements, as well as the possibility to apply high magnetic fields on the DUT, this equipment has the important disadvantage of expensive liquid He consumption, and relatively short time available continuous measurements. A Dewar with 100 l of liquid He ensures 5-6 hours of operation, of which 1.5 hours are required for the cooling time. Several measurements require more time. The Coulomb diamond measurements, due to the very small voltage steps used, need more than 36 hours of continuous operations, which cannot be ensured by this equipment.

The necessity to develop a set-up for measurements up to 110 GHz and down to 4 K (D5.2), set-up that is presented in this report, and the set-up for 140 GHz, which will be developed in the frame of D.5.8 at M44, arose because of the lack of commercial availability of an equipment able to perform cryogenic temperature on-chip measurements in the frequency range of interest from 67 GHz to 140 GHz.

2 DESCRIPTION OF THE CRYOGENIC 110-GHz S-PARAMETER MEASUREMENT SETUP

According to the objectives of the project, IMT had to design and fabricate an on-wafer cryogenic measurement setup for device and circuit characterization up to 110 GHz and at temperatures down to 4 K. At the time of writing this report, no commercial equipment capable of performing on-wafer cryogenic S-parameter measurements single-sweep up to 110 GHz is available on the market. Therefore, the reported equipment is the first cryogenic equipment covering the DC to 110 GHz range (single frequency sweep).

As mentioned in the progress report in June 2020, the initial idea was to simply upgrade the existing 67-GHz cryogenic setup in IMT's lab but, due to the possibility to purchase a new cryostat as part of a national infrastructure project, we decided to keep the existing 67-GHz setup for current measurements (including qubit transistors) and to design and manufacture a new setup able to perform on-chip ("on-wafer") measurements in the frequency range from 0.1 GHz to110 GHz, using a new cryostat.

The new measurement system is based on a new SHI-4-2-AC cryostat by Janis, dedicated to DC measurements down to 4 K, purchased by IMT in 2019. This cryostat has been adapted to allow microwave and mm-wave measurements by manufacturing a special probe head and custom holder for this purpose as well as by equipping it with a system of coaxial cables and suitable connectors. Commercial Picoprobe 110 GHz probes have been fitted to the custom fixture and are connected with corresponding commercial 110 GHz coaxial cables and connector system to the 37397D Anritsu Vector Network Analyzer (VNA) in the 110 GHz configuration, already existing in IMT.

The SHI-4-2-AC cryostat is composed by:

i. A non-magnetic metal enclosure in which advanced vacuum can be achieved (better than $5\cdot10^{-5}$ Torr at room temperature and better than 10^{-6} Torr at 4 K) and which is provided with 4 quartz windows (40 mm diameter) for viewing;

ii. A cooling system with recirculated helium that allows the temperature to drop to about 4 K in the test area where the DUT is placed;

iii. A heating circuit which ensures the stabilization of the temperature (+/- 50 mK) in the test area at any value in the range from 4 K to 300 K;

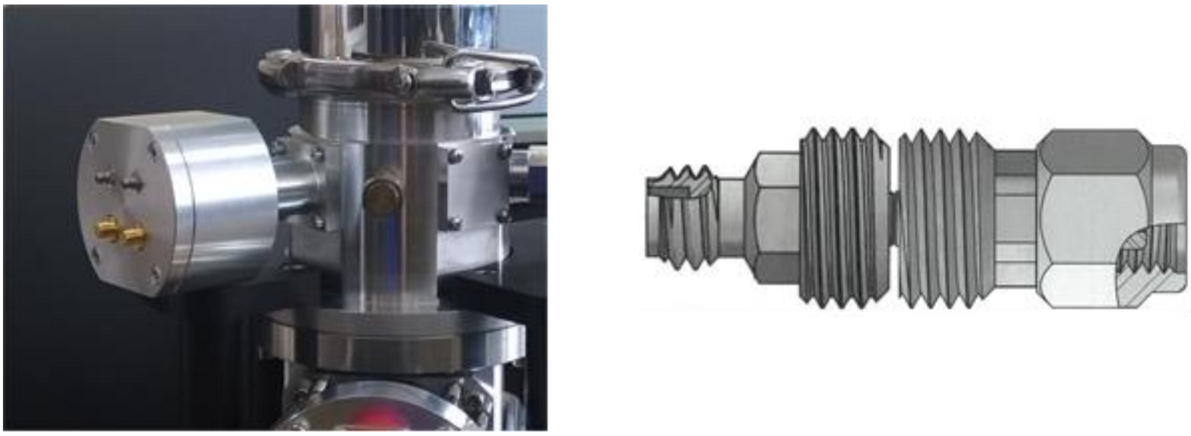
iv. A gilded copper support that ensures an efficient heat transfer and on which the DUT is placed;

v. A Lake Shore Cryogenic Temperature Controller, Model 335, connected both to the temperature sensor located inside the test area and to the resistive heating circuit; the temperature control resolution is 0.01 K.

The cryogenic system includes a Sumitomo (SHI) air-cooled compressor unit, Model HC-4E2, for the circulation of helium and a TS-85-D Edwards T-Station system of vacuum pumps (a XDD1 preliminary vacuum pump of dry type with diaphragm and an advanced vacuum turbomolecular pump with nominal 47 l/s capacity).

The cryostat can operate in any position (vertical, horizontal or inclined at a certain angle); however, the cooling power is maximized when the cryostat is in vertical position.

The cryostat also has three additional electrical access ports with sealed flanges. One of them is used to attach the in-house manufactured metallic adapter and flange carrying the RF and DC connectors for connecting the system to the measuring equipment (Fig. 1a). The connector flange is sealed on the cylinder, which is also sealed on that additional electrical access port.



(a) (b)

Fig.1. Connections of the cryostat toward the measuring instruments: (a) Adapter and flange with RF and DC connectors; (b) 1.0 mm coaxial back-to-back assembly with "thread-in step-thread" coaxial connectors.

During the design stage, the solution considered of using the female 1.0 mm connectors of internal ruggedized coaxial cables as RF output connectors of the cryostat, could not be applied since the dimensions of these connectors do not allow their mechanical processing in order to be assembled in the flange in conditions of good sealing and stable electrical contact to ground (i.e., the body of the cryostat). Consequently, for the passage through the flange, two 1.0 mm male-female coaxial adapters were built, each being made of two Southwest Microwave “thread-in step-thread” coaxial connectors (a female one, type 2420-05SF, and a male one, type 2421-03SF, as in Fig. 1b) that are screwed (and sealed) back-to-back in the flange, having special launch pins type 1490-12P (0.23 mm diameter) between their central conductors; the female ends are mounted to the outside of the cryostat.

The two connectors used for DC measurements and/or for biasing the devices to be tested are female-to-female SMA bulkhead feed-through straight adapters (type SMA7471B1-3GT50G-50, from Amphenol RF), which are screwed in the flange and sealed (see Fig. 1a).

A set of 1mm coaxial cables are used to connect each millimetre-wave probes to the VNA, as illustrated in Fig.2.

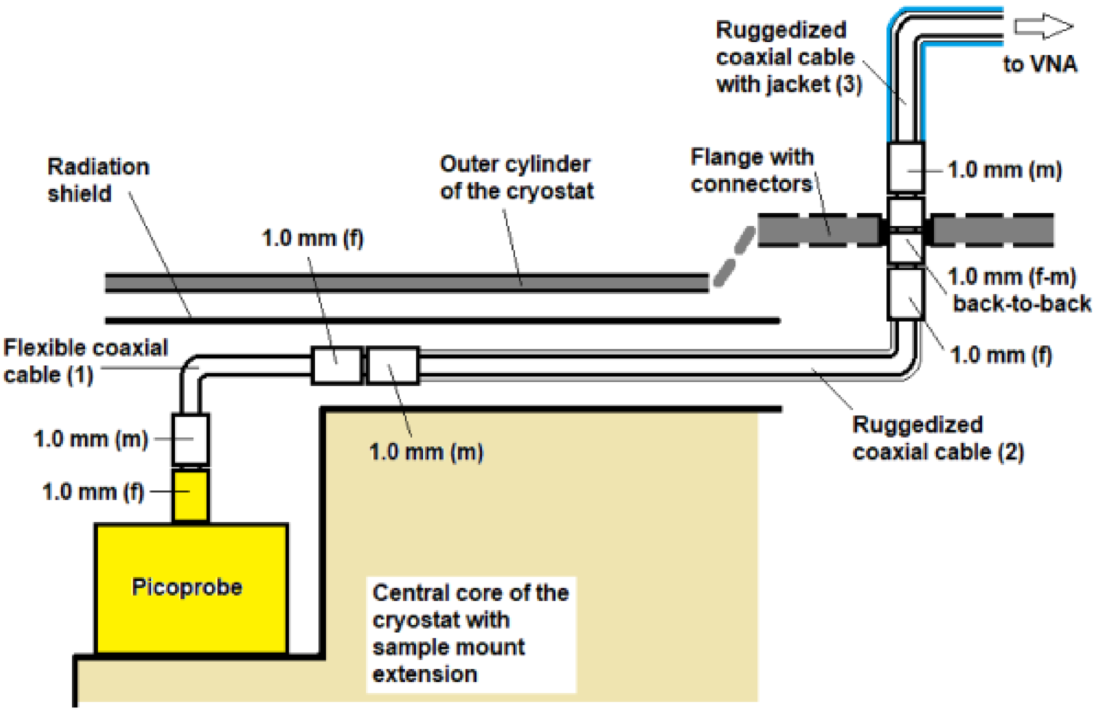
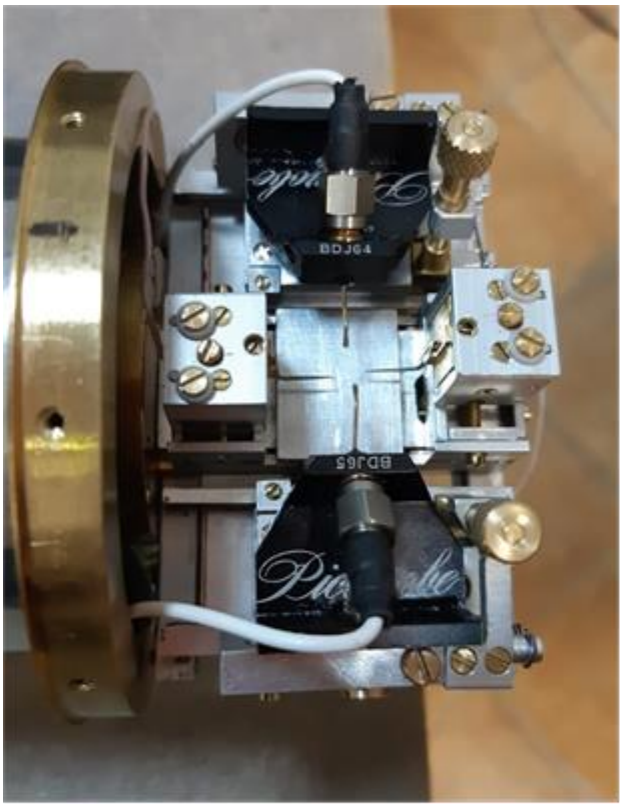


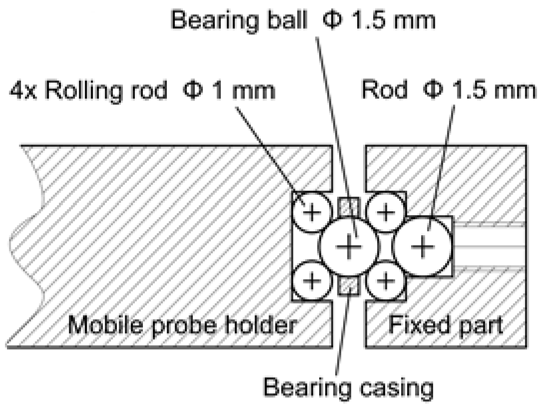
Fig. 2. Picoprobe and 1.0 mm coaxial cables and connectors assembly to connect probe tips to the mm-wave measuring instruments.

A short, flexible coaxial cable (1) with low insertion loss (SAGE Flexible Coaxial Cable, type SCW-1F1M005-F1, 1.0 mm connectors, 1 male /1 female, 12.5 mm long) is connected between the female connector of the mm-wave probe and the male 1.0 mm connector of the next coaxial cable. This second cable (2) is a ruggedized and low loss JUNKOSHA Coaxial Cable Assembly type MWX001-00500WFSWMT/B, with 1.0 mm connectors (1 male/1 female), without textile jacket, 300-mm long, and ensures the connection to the 1 mm male-female coaxial adapters (described above) mounted in the connector flange of the cryostat. To improve the mechanical/electrical stability of the measurement chain inside the cryostat, this cable is ruggedized. In order to preserve the quality of the vacuum during cooling/heating processes, it lacks the usual textile jacket. It is worth mentioning that the short SAGE flexible cable is the key element to allow the controlled movement of the mm-wave probes and to avoid possible mechanical stress on the probe, as the JUNKOSHA coaxial cable is rather rigid.

To perform on-wafer tests, we have been using Picoprobe model 110H-GSG-100-P (GGB Industries Inc.) non-magnetic, high performance mm-wave probes with 1-mm female connector, in the GSG (Ground-Signal-Ground) configuration and suitable for operation up to 110 GHz, to test DUTs with 100 µm pitch padframe. In order to avoid disturbing the magnetic field radiated by the electromagnet in the vicinity of the DUT (in case of tests under magnetic field), the probes are non-magnetic. They are fitted with independent spring-loaded Beryllium-Copper tips to provide reliable contact to the DUT, as the temperature changes from 300 K down to cryogenic temperatures. Since the tips are flexible, they minimize DUT pad damage and increase probe life.



(a)



(b)

Fig. 3. The 110 GHz test fixture: (a) on-wafer test head mounted on the central core of the cryostat; (b) mechanical system to move each mm-wave probe along each axis.

To allow on-chip measurements up to 110 GHz, at temperatures from 300 K down to 4 K, a dedicated mechanical fixture, shown in Fig. 3a, was designed and manufactured. It is firmly attached (for good heat transfer) to the gilded copper support mounted on the central core of the cryostat. This fixture ensures 3-axes controlled movement of the two mm-wave probes and of the two DC probes. The movement on each of the 3 axes is ensured by a linear bearing, like that shown in Fig. 3b. There are 4 bearing balls in each linear bearing for moving the millimetre-wave probes. The screw that is inserted in the threaded hole on the right side has the role of fixing the probe (after it has been positioned on the pads of interest of the tested circuit) by pressing the 1.5 mm diameter rod on the moving elements of the linear bearing. The mechanical system to control the movement of the DC probes is similar, but the bearing balls have a 1-mm diameter and the 4 rolling rods have a 0.5-mm diameter.

Fig. 4 shows the disassembled test fixture. The main part (on the right side), which is carrying the mm-wave probes, is mounted at the bottom of the gilded copper support. It is important noticing that the probe bodies are machined in-house to fit the dimensional limitations of the assembly. The second part of the test fixture (ion the left side), which is carrying the DC probes as well as the devices to be measured, is mounted on the top side of the gilded copper support, ensuring a good heat transfer from the cooled core of the cryostat to these devices. The DC probes are manufactured in-house and are placed perpendicularly to the direction of the mm-wave probes.

The positioning accuracy of the millimetre-wave and DC probes is about 5 μm.

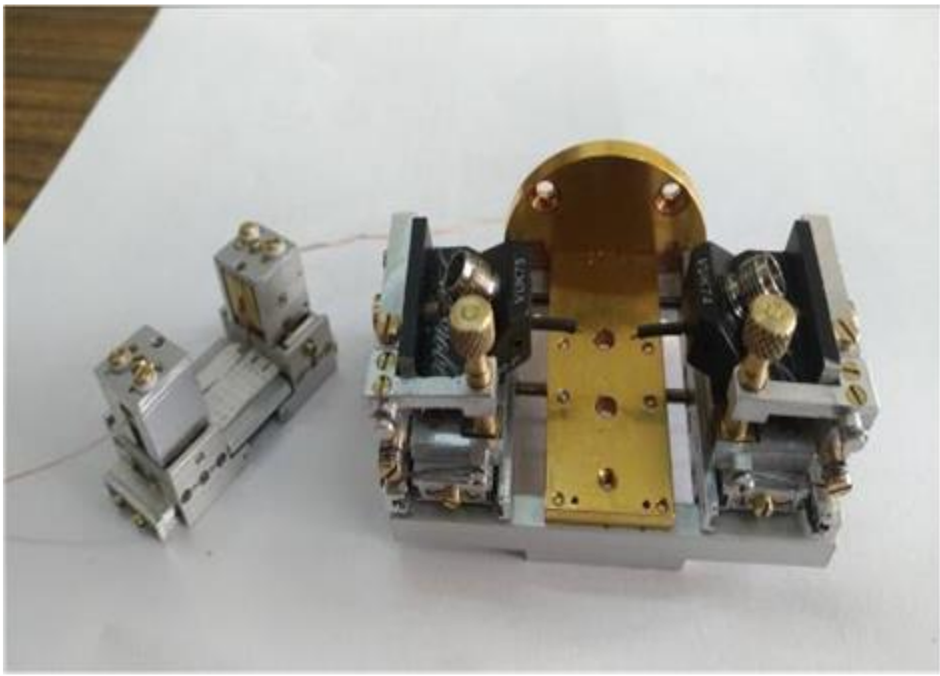


Fig. 4. The structure of the 110 GHz test fixture.

Also, to allow DC bias and current measurements through the 110 GHz GSG mm-wave probes, SHF BT110R-B 110-GHz broadband bias tees were purchased. They feature a 1.0 mm female connector at the AC port and a 1.0 mm male connector at the AC+DC port, with the latter port being connected on the connector flange of the SHI-4-2 cryostat by Janis.

3 FUNCTIONALITY TESTING

3.1 S-parameters test measurements at room temperature

Testing of system functionality was done by performing the S-parameter calibration in the frequency range 0.1-110 GHz and by measuring a short test line.

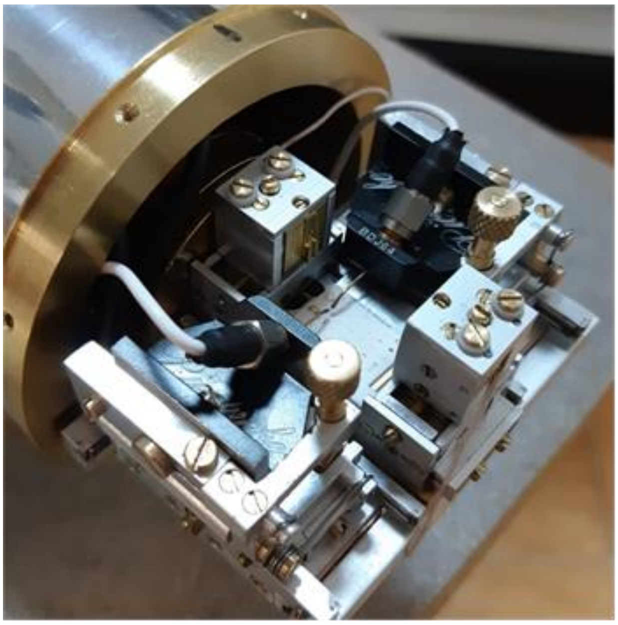


Fig. 5. System calibration with a CS-5 calibration kit.

To calibrate the system, a CS-5 calibration kit was placed on the test fixture (Fig. 5) and a SOLT calibration procedure was used. Calibration was performed with the 37397D Anritsu VNA in the frequency range 0.1-110 GHz. After calibration, the shortest coplanar waveguide (CPW) test through-line on the calibration kit was measured and the results are reported in Fig. 6.

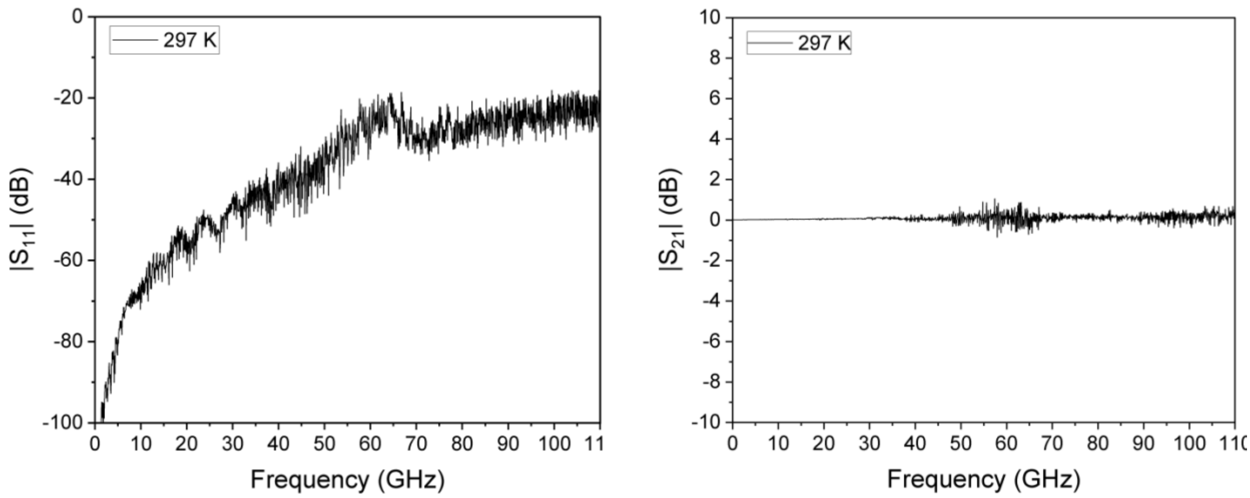


Fig. 6. S-parameters test results for 50Ω CPW through-line, measured on a CS-5 calibration kit at room temperature.

It should be mentioned that the noise that affects the S-parameter characteristics is due to the 37397D Anritsu VNA, which has had some noise problems, for almost a year, at frequencies exceeding 40 GHz. One can notice that the worst behaviour, as concerns noise, occurs in the range 45-67 GHz. These problems could not be solved yet because the company representatives could not travel to Bucharest due to the restrictions introduced in response to the SARS-CoV-2 pandemic.

Moreover, the Sii parameters are noisier because the line under test is a matched one (Zo = 50 Ω) and the reflected signals are low, forcing the receiver chains of the two measuring channels/ports to work - especially at high frequencies - close to their sensitivity limits. The output power at the test ports has been set to the maximum allowable value (+1 dBm) for the type of VNA we have; this is the maximum value for which the automatic level control (ALC) of the VNA is still operational.

3.2 Cooling down the system and test measurements at 4.3 K

The cryostat, including all internal cables and the test fixture, was cooled down in horizontal and vertical position. The system in horizontal position reached 4.7 K after 240 minutes and 4.24 K after 280 minutes (the lowest temperature was 4.234 K - see Fig. 7), while in vertical position it reached 4 K in about 300 minutes. The cooling time is higher than those specified by the provider of the Cryostat (150 minutes) because of the supplementary mass inside the cryostat due to the presence of the test fixture, as well as the DC and 110 GHz cables.

Fig. 7. Lowest temperature achieved during S-parameters tests on CS-5 kit, with the cryostat in horizontal position.

The results of the measurements performed at 4.3 K on the calibration kit CPW test line are presented in Fig. 8 (red curves); results of the measurements performed at room temperature (black curves) are also shown, for comparison.

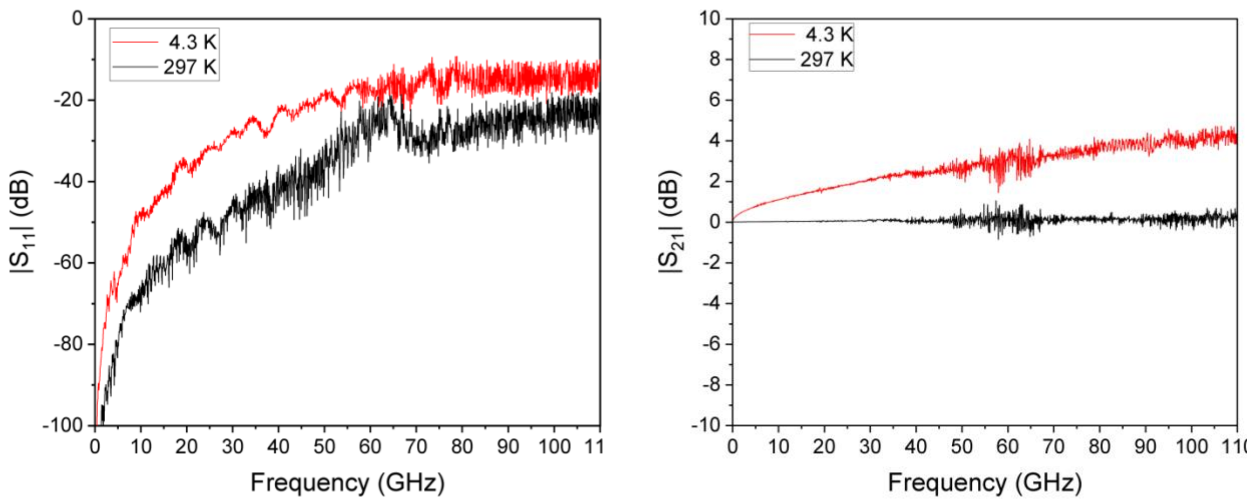


Fig. 8. S-parameters test results for 50Ω CPW through-line, measured on a CS-5 calibration kit at 4.3 K and 297 K.

One can notice the effect of the cooling process on the behaviour of the measured S parameters. It was measured as DUT a short 50Ω CPW through-line placed on the CS-5 calibration kit. As expected, the losses in cables, connectors and probes decrease significantly when the temperature decreases in the cryostat, so that the values of S21 (and S12) for the DUT - instead of staying around 0 dB - increases to positive values, approximately linear with frequency, reaching about 4dB at 110 GHz for T = 4.3 K. S11 (and S22) values are also affected by the decrease of temperature, as shown in Fig. 8.

This is the inherent disadvantage of such a low-cost S-parameter measurement setup, where calibration cannot be performed at the temperature at which it is intended to measure the S parameters. However, a de-embedding process can counterbalance this disadvantage.

It is important to note that, for future measurements on active devices and circuits developed within the project IQubits, these temperature variation characteristics of the S parameters under calibration conditions will be used in the post-data processing as de-embedding elements to obtain the actual values of their S parameters at the temperature of interest.

4 THE DEMONSTRATOR

The demonstrator is shown in Fig. 9.

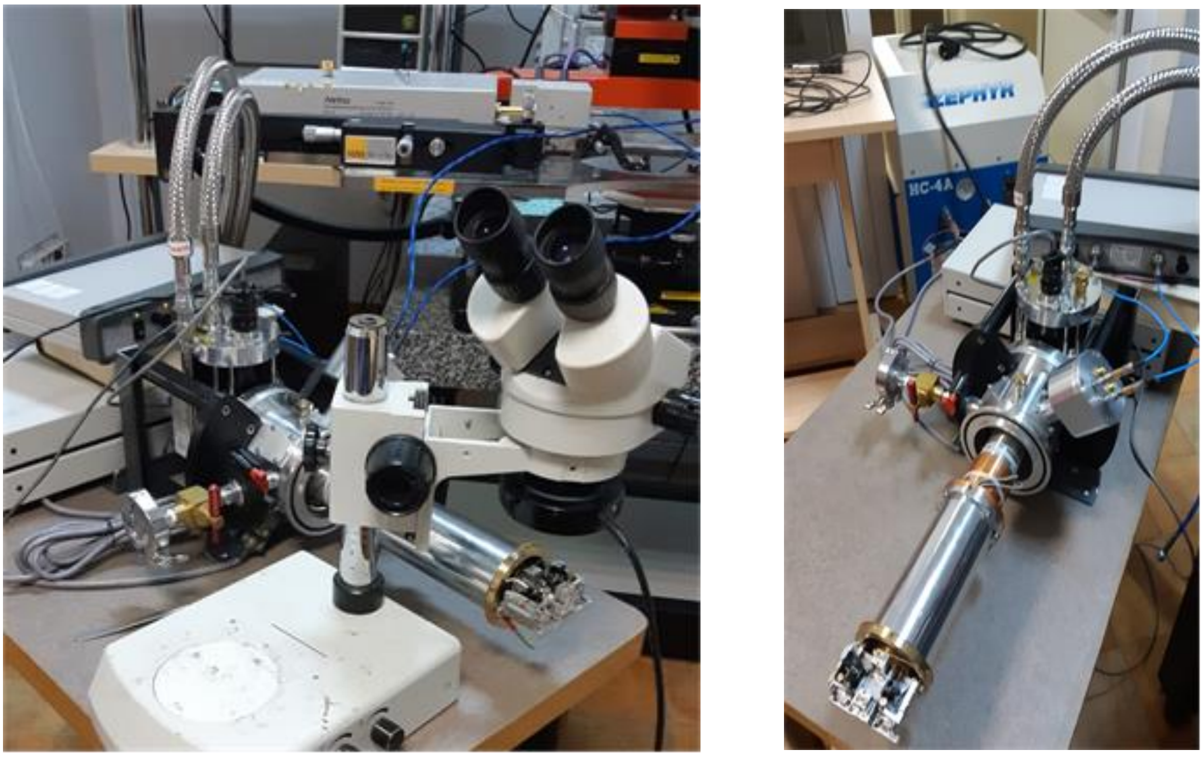


Fig. 9. The demonstrator setup for cryogenic S-parameters measurements up to 110 GHz and down to 4 K.

The S-parameter measurement setup in the 0.1-110 GHz frequency range are presented in Fig. 9. These, together with the capability to cool down the cryostat to 4 K in the vertical position and 4.3 K in the horizontal position, allow reaching the functionality expected for the demonstrator (MS4).

5 CONCLUSION

The low-cost experiemental test equipement set-up for cryogenic S-parameters measurements up to 110 GHz (single frequency sweep) and down to 4 K was successfully designed and manufactured as a demonstrator to be used in future measurements of the transistors, also as qubits. MS4, associated to this demonstrator, was successfully achieved.

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[1] D1.4 Project Review Meeting Documents 1 - Periodic Technical Report - Part B, WP5, June 2020.

[2] S. Bonen, et al., "Cryogenic Characterization of 22nm FDSOI CMOS Technology for Quantum Computing ICs," IEEE EDL, Vol. 40, No.1, pp.127-130, January 2019.