MICROWAVE METROLOGY FOR SUPER-CONDUCTING QUANTUM CIRCUITS

SCIENTIFIC OBJECTIVES

1

Optically integrated Josephson Arbitrary Waveform Synthesizer with unprecedented bandwidth

2

Cryogenic quantum-traceable 1 THz sampling oscilloscope

3

Scattering-parameter measurements in situ at low temperatures

4

New superconducting quantum sensors for microwave power

We are pleased to welcome you to the 3rd newsletter of the "SuperQuant" Project. The project started in September 2021 and will end in August 2024. Thus, we have reached the last year of the project. We are confident that we will succeed in establishing novel metrological and scientific tools for the measurement of microwave signals in circuits in-situ in cryogenic environments down to the millikelvin range using a combination of super-conducting, semiconducting, integrated and conventional photonics, and plasmonic techniques. This includes the development of a quantum standard of microwave power and a quantum-traceable cryogenic sampling oscilloscope and an optically integrated quantized arbitrary waveform generator that will enable energy- and cost-efficient generation of thousands of microwave signals at cryogenic temperatures.

The aim of this newsletter is to summarize selected work that has been performed within the previous months. More details will be available through another, final newsletter and on our webpage.

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CONSORTIUM:

Highest-speed photodetection by combining graphene with metamaterials

With more devices and application requiring more and more interconnectivities, there also comes an ever-growing demand for higher data rates. To enable such high-capacity optical links faster photodetectors are required. Graphene is a potential candidate as active medium in such fast photodetectors; the carrier dynamics are extremely fast, and graphene absorbs almost spectrally independent. Yet, this absorption is also very low.

Within the framework of SuperQuant, ETH has developed a metamaterial-graphene photodetector architecture. The metamaterial perfect absorber layerstack consisting of a mirror, oxide and metallic resonators is able to trap the light and leads to an enhanced localized absorption in the graphene. The fast carrier dynamics and localized absorption enables a fast extraction of carriers. The measured bandwidth of these devices showed a flat behaviour up to 500 GHz; the limit of the measurement setup. These devices are thereby the fastest photodetectors up to this point.

With the emerging field of quantum computers, the optical interconnects could also serve to enable high-speed links from room temperature to the cryogenic environment. Not only would this enable higher bandwidths and lower losses compared to electrical connection lines but would also drastically reduce the heat exchange with the environment as glass fibers are weak thermal conductors.

The developed metamaterial-graphene photodetector platform therefore was also tested for the operation under cryogenic temperatures. When cooling down the device and measuring the frequency response, it was found that the bandwidth not only remains for >100 GHz, but there is also an increase in response. Furthermore, these devices are operated fully passively; meaning there is no external bias or gate voltage control. It is therefore possible to have these photodetectors in a cryogenic environment to generate an electrical signal from an optical signal without the need for electrical control lines. Next, performance improvements and combination with other devices operating at cryogenic are targeted within SuperQuant.

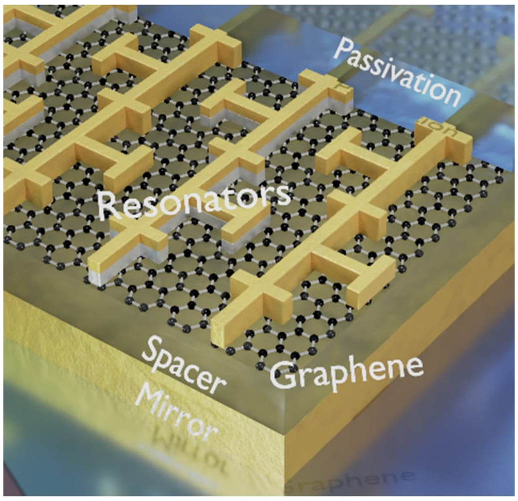

Figure 1. Visualization of the metamaterial-graphene photodetector architecture.

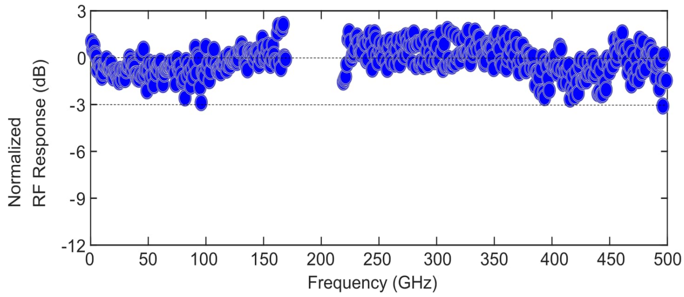

Figure 2. Frequency response of the metamaterial-graphene photodetector at room temperature showing no roll-off up to 500 GHz.

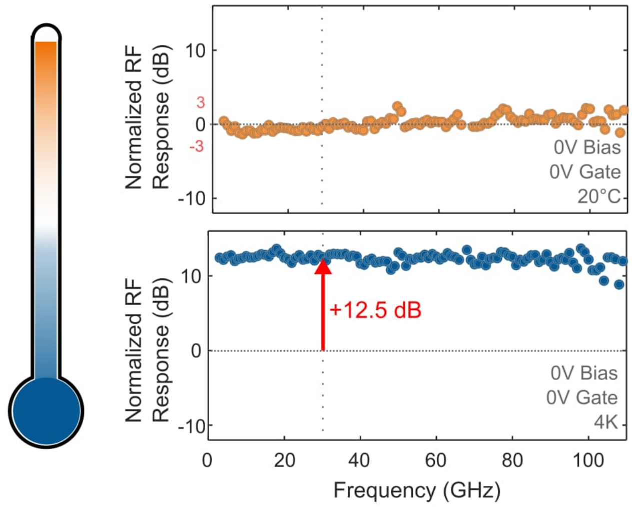

Figure 1. Temperature dependent frequency response of the metamaterial-graphene photodetectors. The detector retains its bandwidth down to 4K and furthermore also has an improved response.

This work is part of Objective 1: To develop an optically integrated Josephson Arbitrary Waveform Synthesizer (JAWS) with a bandwidth exceeding 100 GHz, including the development of different ultrafast cryogenic optoelectronic converters based on semiconducting and plasmonic techniques.

Photonic packaging for optical driving of superconducting electronics

Driving superconducting qubits requires individual microwave control signals often generated outside a cryostat at room temperature and thereafter transmitted via coaxial cables to cryogenic temperature (<50 mK). This is not a viable solution when targeting quantum processors with millions of qubits.

Optical transmission of signals between room temperature instrumentation and superconducting electronics is a promising method to eliminate excessive heat loads to cryostats, increase signal bandwidth and reduce distortion.

VTT has developed innovative cryogenic packaging to couple optical fibres to various detectors, like superconducting nanowire single-photon detectors (SNSPD), transitions edge sensors (TES) and photodiodes. To maximise robustness, differences in thermal expansion coefficients between elements must be managed. All-glass packaging is a promising option for this. By combining a multitude of optical fibres to a SiPh chip with multiplexing elements enables a large number of optical-to-electrical converters (OEC) with a small footprint.

We have introduced a glass wafer solution with through-glass-vias suitable for fibre optics insertion therein, Figure 4. Lithographically-obtained etched cavities (processed on glass wafer and on Si quantum devices' wafer) is an affordable and very accurate solution for precision placement of alignment members (e.g. spheres), allowing direct optical coupling with devices when paired and aligned underneath at wafer level. High count (currently 32 fibres, targeting for 32 × 32 matrices) fibre pigtails were demonstrated with this technique, Figure 5.

In addition, fibre connections for electro-optic sampling (EOS) were developed to characterise OECs, Figure 6. We expect that EOS can also be used to measure operation of superconducting electronics, like the input and output current pulses of a Josephson junction array, as well as the quantized voltage pulses. Coupling of probe pulses via fibres to the electrical transmission lines poses stringent demands on packaging (1 µm stability as a target).

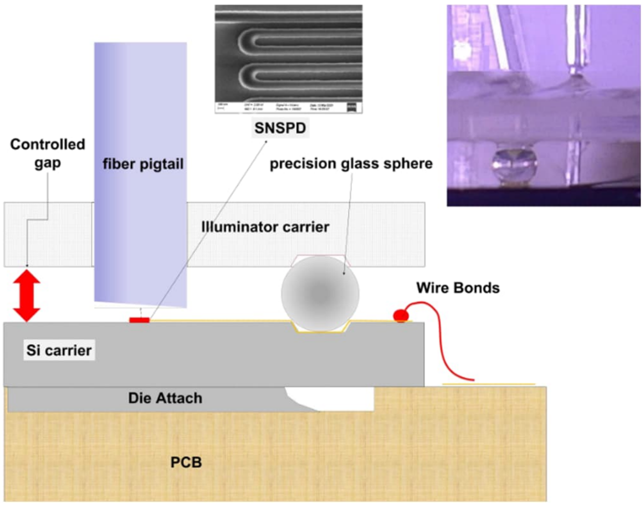

Figure 4. Glass wafer solution with through-glass-vias suitable for fibre optics insertion.

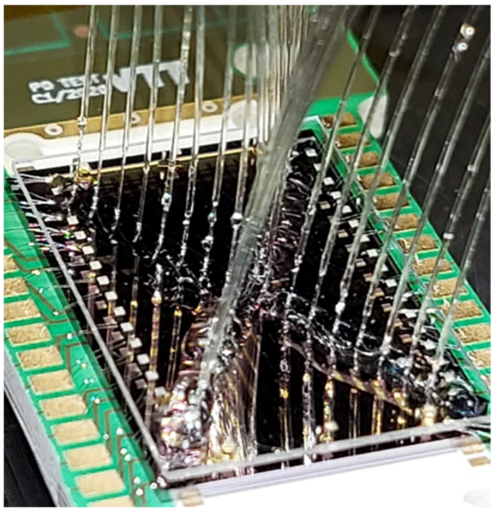

Figure 5. A bundle with 32 fibres mounted via a glass plate holder to illuminate photodetectors in a cryostat.

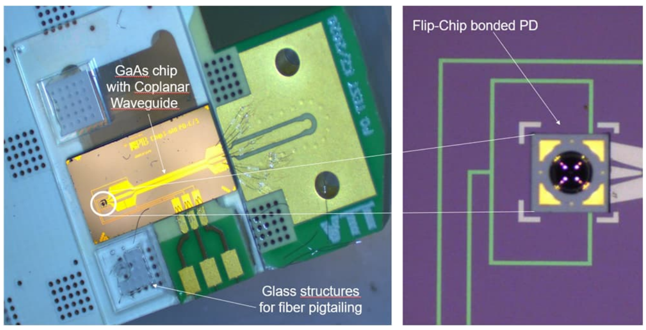

Figure 6. Left: Electro-optic sampling assembly to characterize the performance of various optical-to-electrical converters. Probe pulses are coupled via fibres to the electrical transmission lines. Right: Flip-chip bonded commercial photodiode.

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MW Power Probing at 4 K Using JAWS Circuits

Measuring microwave (MW) power at 4 K is important for the growing needs of cryogenic industry, but due to its challenges, no established MW power standard yet exist. TÜBİTAK UME has proposed a technique in which Josephson Arbitrary Waveform Synthesizer (JAWS) arrays are used as sensitive probes for microwave power.

In the proposed technique, the MW power probing is performed by using one of the arrays as a temperature sensor and the other one as a load for MW power. Attenuation of the stick used to immerse the JAWS circuit into the cryogenic environment is measured by measuring the microwave power in situ at cryogenic temperatures using the developed MW probing procedure.

First results show that the attenuation of the probe is almost constant versus the changing microwave power level, see Figure 7. The method is roughly validated by comparing conventional attenuation measurements and attenuation measurements obtained with the new procedure. The results are published and presented in a conference*.

To improve repeatability and accuracy through automation, which is essential for such measurement procedures, new superconducting circuits were designed and are currently being manufactured and will be tested in the near future.

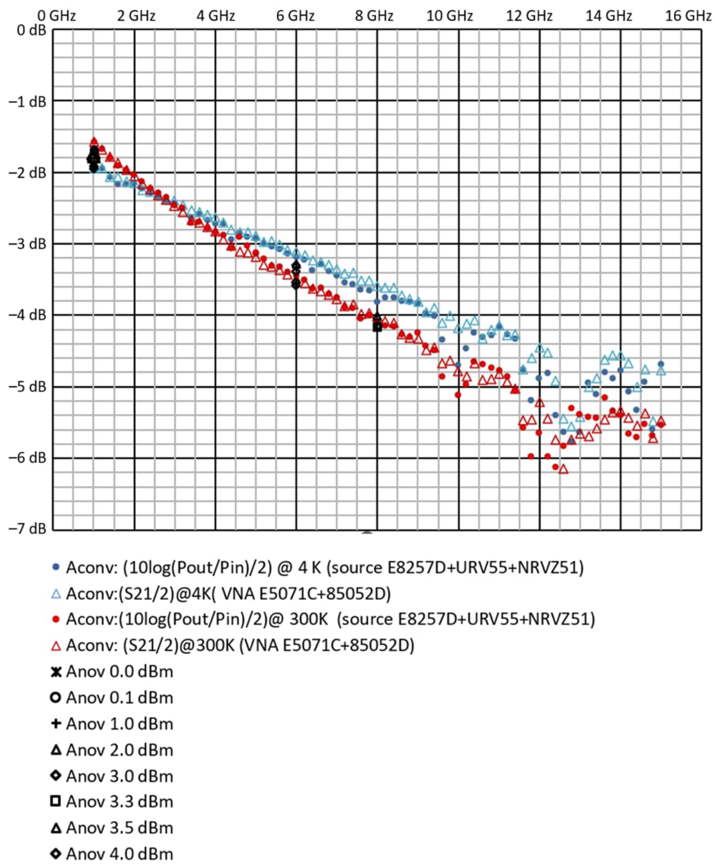

Figure 7. Average transmission of the waveguides and transmission calculated using the novel method at different power levels.

* Tezgül Öztürk and Oliver Kieler, "Investigating the Use of Super Conducting Josephson Circuits for Microwave Power Measurements at Cryogenic Temperatures", *14^{th} International Conference on Electrical and Electronics Engineering ELECO 2023*, Virtual Conference, ID 190.

This work is part of Objective 4: To model and develop novel superconducting quantum sensor technology and sensors for measurements of microwave power in the frequency range 1–12 GHz in-situ in superconducting circuits in cryogenic environments, including a full uncertainty estimation to validate the power sensors.