Temperature-to-Phase Conversion THz Radiation Sensors (T-CONVERSE)

Federico Paolucci,[1,2*] Vittorio Buccheri,[2,1] Paolo Spagnolo,[2] Giovanni Signorelli,[2] Massimiliano Bitossi,[2] Oleg Mukhanov,[4] Riccardo Paoletti,[3,2] Francesco Giazotto[1]

[1] NEST, Istituto Nanoscienze-CNR and Scuola Normale Superiore, Piazza S. Silvestro 12, I-56127 Pisa, Italy.
[2] INFN Sezione di Pisa, Largo Bruno Pontecorvo 3, I-56127 Pisa, Italy.
[3] Dipartimento di Scienze Fisiche, della Terra e dell'Ambiente dell'Università di Siena, Strada Laterina 8, I-53100 Siena, Italy.
[4] SeeQC-EU, Via dei Macelli 66, I-00187 Roma, Italy.

*federico.paolucci@nano.cnr.it

ABSTRACT

The goal of T-CONVERSE is to develop ultra-sensitive and tunable superconducting detectors working in the GHz and THz bands. To this end a detector based on the conversion of temperature into a phase difference (TPC) in a Josephson device was proposed. Beyond the TPC detector, we envisioned, fabricated and demonstrated a nanoscale transition edge sensor (nano-TES) pushing the limits of this technology, and a Josephson escape sensor (JES) showing a record noise equivalent power of about $1\text{x}10^{-25}$ W/Hz$^{1/2}$. The T-CONVERSE technology finds application in basic science, industrial quality inspections, security scanners, telecommunications, and medical imaging.

Keywords: Quantum sensing, Terahertz techniques, Astrophysics, Security

1. INTRODUCTION

Electromagnetic radiation in the 10 GHz-10 THz band shows interesting applications in both basic science and industry. On the one hand, Cosmic Microwave Background (CMB), Axion-Like Particles (ALPs), arrangement of proteins and electron/hole/phonon dynamics are characterized by faint distinctive signals in this frequency band. On the other hand, THz radiation is a non-ionizing alternative to X-rays for security scanners, materials inspection, packaged food quality control, and biological imaging for medical purposes. In fact, THz photons are able to pass through non-polar materials, such as paper and plastic. Furthermore, many materials including explosives and drugs show specific spectroscopic features in the THz band.

T-CONVERSE aims to revolutionise GHz and THz detection by developing extra-sensitive and in-situ superconducting sensors. Thanks to their unparalleled performances, our detectors will enable innovative GHz and THz imaging and spectroscopy technologies. In particular, they could be extensively used for

- *basic research* in biology, condensed matter, astronomy and particle physics.
- *homeland, border and citizen security* applications: GHz - THz sensors detecting in real-time weapons, illegal goods, drugs or explosives in packs.
- *food security and citizen health* in quality controls of food packaging/adulteration, suspect pharmaceutical freight, fraud inspections and medical imaging.
- *telecommunications*: detectors for amplification systems of hi-speed 5G (or 6G) lines.

The main result of T-COVERSE is the design, realization and experimental demonstration of several superconducting radiation detectors outreaching state-of-the-art performance in the GHz and THz bands. In particular, we designed and realized a nanoscale transition edge sensor (nano-TES) with noise equivalent power (NEP) of ~$5\text{x}10^{-20}$ W/Hz$^{1/2}$. Furthermore, we conceived and demonstrated an innovative current-tunable Josephson escape sensor (JES) with record NEP of about $1\text{x}10^{-25}$ W/Hz$^{1/2}$ and unprecedented frequency resolution of 2 GHz. In addition, we fabricated the temperature-to-phase conversion (TPC) detector, which is currently under investigation. Moreover, we conceived a novel superconducting bolometer based on the electron cooling of graphene. Finally, T-CONVERSE partially funded the development of field-effect superconducting transistors, that could serve as amplification and read-out ultrafast electronics for our sensors.

2. STATE OF THE ART

Ultra-sensitive radiation detection in the GHz band is still in its infancy. The development of GHz bolometers and calorimeters is usually pursued by improving the detectors normally employed in the THz frequency band. Nowadays, the most sensitive THz detectors are the superconducting sensors, such as transition edge sensors (TESs) [1] and kinetic inductance detectors (KIDs) [2]. The state-of-the-art detection performance in the bolometric operation provides a best NEP of about 10^{-19} W/Hz$^{1/2}$ for TESs, and about 10^{-18} W/Hz$^{1/2}$ for KIDs. Furthermore, these sensors are able to detect THz single photons. As a consequence, TESs and KIDs are widely used in THz astronomy and space missions due to their high sensitivity, robustness and mature technology.

To improve sensitivity and transitioning towards GHz photons detection, novel TESs and KIDs have been developed by miniaturizing their active region, i.e., the portion of the device subject to the action of radiation absorption, and drastically lowering their operation temperature. Indeed, these devices take advantage of the Josephson coupling in complex hybrid nanostructures. For instance, detectors based on superconductor/normal metal/superconductor (SNS) Josephson junctions showed a record NEP of the order of 10^{-20} W/Hz$^{1/2}$ [3].

Despite being the most sensitive radiation sensors on the market, the properties of superconducting detectors are defined during the fabrication process and cannot be in-situ tuned during the operation. Therefore, it is not possible to adjust their sensitivity and working conditions with the specific application and experimental set-up.

3. BREAKTHROUGH CHARACTER OF THE PROJECT

The ultimate goal of T-CONVERSE is to establish an innovative platform for sensitive superconducting radiation detection in the GHz and THz frequency bands with unprecedented sensitivity. To this end, we proposed the development of a novel class of radiation sensors based on the innovative TPC mechanisms. The TPC sensor is expected to operate down to the GHz range. Furthermore, it is proposed to work in a wide frequency range (10 GHz - 10 THz) with the possibility of simply in-situ tuning its sensitivity. As a consequence, these detectors would revolution radiation detection. In fact, the TPC sensor shows remarkable potential applications in several fields, such as astrophysics, new particles search, industrial quality control and homeland security.

The main application of the TPC sensor is the detection of radiation in the band 10 GHz - 10 THz (with straightforward extension to higher and lower frequency). In a single photon regime, signal-to-noise ratios (SNRs) higher than 100 in the complete frequency range operating at temperatures lower than 50 mK (reaching 1000 for f=10 GHz and T=10 mK) and resolving powers higher than 100 are theoretically achievable. In continuous illumination, unprecedented NEPs on the order of 10^{-23} W/Hz$^{1/2}$ are predicted. Importantly, its operating frequency can be easily tuned by changing the magnetic flux biasing the superconducting ring. As a consequence, potentially TPC sensors will show unprecedented extremely high sensitivity, possibility to detect GHz single photons, and complete tunability of the operation frequency.

Moreover, the study of the building blocks of the TPC sensor, that is the single Josephson junctions, enables the design of other tunable superconducting sensors with remarkable performance. In fact, we experimentally realized a nanoscale TES and an innovative tunable JES that allows to in situ tune its sensitivity via current injection with world record sensitivity, as reported in the next section. We are also interested in a fully metallic superconducting field-effect electronics, that could serve as read-out scheme for our sensors enabling the development of a complete on-chip detection architecture.

Finally, our consortium brings together researchers in condensed matter, astrophysics and particle physics, with experts in the commercialization of hi-tech electronics and detectors. This synergetic composition allows T-COVERSE to tackle the problem of extra-sensitive radiation detection in the GHz-THz bands from different and complementary points of view. As a consequence, T-CONVERSE own all the peculiarities to push radiation detection to the next level.

4. PROJECT RESULTS

Beyond the TPC detector, we developed several radiation detectors outreaching state-of-the-art performance in the GHz and THz bands. Furthermore, T-CONVERSE partially funded other complementary works about field-effect superconducting transistors [4], that could serve as amplification and read-out ultrafast electronics for our sensors. In the following, we will outline the main results on detection and compare them with TESs and KIDs (see the Tab. 1).

Nano-TES

We experimentally demonstrated an extra-sensitive nano-TES [5]. The ultra-low volume of the active region and the exploitation of heat barriers, the so-called Andreev mirrors, ensure optimal thermal efficiency (see Fig. 1). Furthermore, we can control the nano-TES performance by engineering the working temperature through the superconducting inverse proximity effect. To extract all the device parameters and determine the nano-TES performance both in the bolometer and calorimeter operation, we performed a complete series of electronics and thermal transport experiments. When operated as bolometer, the nano-TES reaches a total noise equivalent power of ~5x10^{-20} W/Hz$^{1/2}$, only limited by the thermal fluctuations. As calorimeter, our device shows a frequency resolution of ~100 GHz with a relaxation time of ~10 ns. The nano-TES could be implemented in widespread multiplexing circuits (FDM and MW Resonators) for multipixel detector arrays in gigahertz cameras.

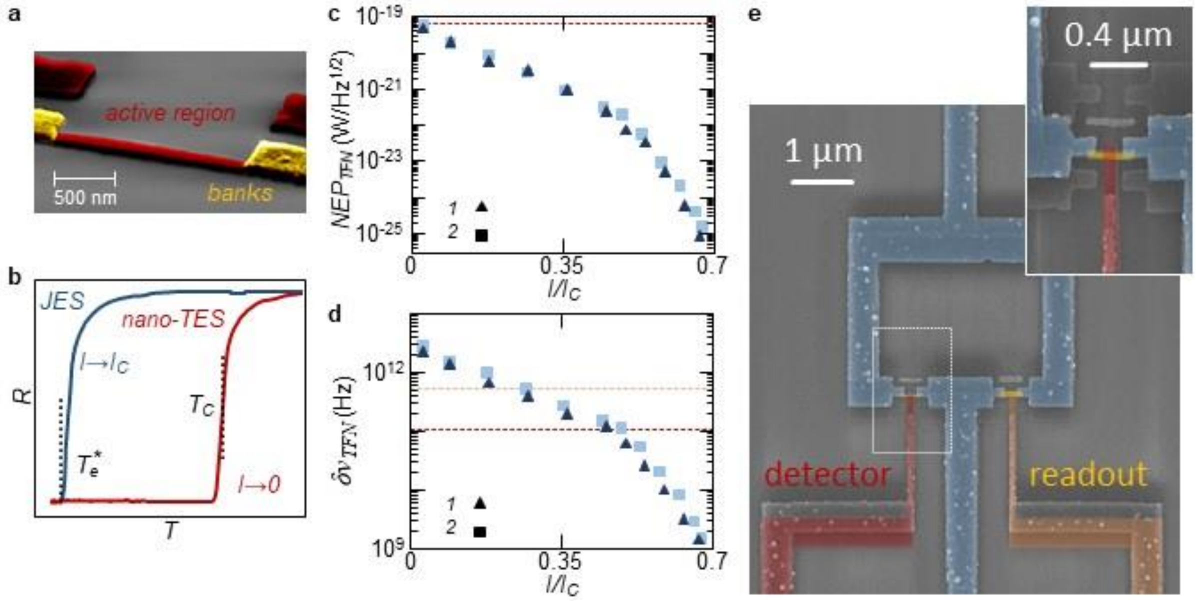

Fig. 1. a Scanning electron micrograph of a sensor that can be operated as nano-TES or JES (adapted from [6]). The active region is red, while the Andreev mirrors are yellow. **b** Resistance versus temperature characteristic of a nano-sensor when operated at $I \longrightarrow 0$ as nano-TES or at $I \longrightarrow I_C$ as JES. The critical temperature (T_C) and the escape temperature (T_e^*) are indicated. **c** Noise equivalent power as a function of current bias for two JESs. The red line is the value for the same structure operated as a nano-TES. Adapted from [6]. **d** Frequency resolution as a function of current bias for two JESs. The red lines are the values for the same structure operated as a nano-TESs. Adapted from [6]. **e** Scanning electron micrograph of a typical TPC sensor.

Josephson Escape Sensor

We conceived and experimentally demonstrated an innovative hypersensitive superconducting radiation sensor based on a fully superconducting Josephson junction: the Josephson escape sensor [6]. The JES works totally in the superconducting state and exploits the transition to the normal state driven by radiation absorption. Interestingly, it is supplied with the capability of in-situ fine tuning its performance by a current bias (see Fig. 1). Our nano-sensor has the potential to drive radiation detection in the GHz band towards unexplored levels of sensitivity. In continuous illumination, the JES shows an unprecedented NEP as low as ~$1\text{x}10^{-25}$ W/Hz$^{1/2}$. In single photon detection, the device has an impressive limiting frequency resolution of about 2 GHz. Finally, the JES working mechanism and structure allow the immediate replacement of TESs in already existing experiments and detecting systems.

Design and Fabrication of TPC sensor

We designed and fabricated the TPC sensor. The device design follows the seminal work, where the detector is proposed [7]. Indeed, the TPC ring is made of aluminum, while the two Josephson junctions (JJs) are realized in the form of copper nanowires. In order to maximize the sensor performance, we designed two short JJs (200-nm-long) each equipped with aluminum tunnel junctions. One electrode serves as heater, while the second probe has the role of read-out electrode. Figure 1 shows the scanning electron micrograph of a typical TPC sensor. The device was fabricated by electron-beam lithography, three angles shadow-mask electron-beam evaporation of metals onto an oxidized silicon wafer through a suspended resist mask and in-situ oxidation. The fabrication process in quite robust and show a reproducibility of about 85%. The electronic and thermal characterization of the device is ongoing.

Simulation of suitable antennas

We performed the finite element simulation of suitable antennas in the 10 GHz – 10 THz range. We optimized bow tie antennas by considering: the structure of the substrate (silicon covered with 300 nm of thermal grown amorphous silicon dioxide), the transport properties of the aluminum thin film forming the antenna, and the real structure of the device. Note that these antennas can be straightforwardly adapted for the nano-TES or the JES, since they share the same material for the realization of the antenna (aluminum) and the inner structure (active region) is much smaller than the radiation wavelength (thus does not play role in the simulation).

Graphene/Superconductor tunnel bolometer

We conceived and theoretical validated an innovative GHz-THz radiation sensor based on electron cooling in graphene/superconductor tunnel hetero-structures [8]. This sensor should provide a NEP of about $1\text{x}10^{-18}$ W/Hz$^{1/2}$, a response time of 10 ns with the capability of being finely tuned by the use of an external gate bias. Furthermore, this device can operate up to 1 K, thus avoiding the use of bulky refrigeration systems. As consequence, this sensor, even if less sensitive than the others developed in T-CONVERSE, might be suitable for space application with pay load is fundamental. **Tab. 1.** Comparison between state-of-the-art THz detectors and the sensors developed in T-CONVERSE.

Detector	NEP (W/Hz$^{1/2}$)	Frequency resolution (GHz)
TES	10^{-19}	*>1000*
KID	10^{-18}	*>1000*
Nano-TES	10^{-20}	*100*
JES	10^{-25}	*2*
TPC	10^{-23} *(theory)*	*0.1 (theory)*

5. FUTURE PROJECT VISION

5.1. Technology Scaling

The T-CONVERSE technology developed in Phase 1 reached a TRL 3, since we demonstrated the proof of concept of the nano-TES and the JES. During Phase 2, we plan to build laboratory demonstrators of our technologies. Due to the target customers (researchers and specialized operators) and the working environments (laboratories, big industries, airports etc.) of the final products, the laboratory validation of our technology will allow us to reach TRL 6.

5.2. Project Synergies and Outreach

We plan to take advantage of the already well-established connections within groups of the intra ATTRACT THz alliance (established on a meeting in Pisa on December 17, 2019). A synergy with one or more of the other attract actions focused on THz technology, namely GRANT, HyperTERA, ROTOR and TACTICS would allow an exhaustive technological approach for THz detection, and increase significantly the success of the project.
To disseminate the results of Phase 2, we plan to organize other intra project meetings, to participate to conferences and fairs, and to organize student-oriented events. Furthermore, all the new regarding T-CONVERSE will be uploaded on *https://web.infn.it/T_CONVERSE/*.

5.3. Technology application and demonstration cases

For basic research, the T-CONVERSE radiation detectors represent a unique tool for the revealing faint signals arising from several phenomena in Astrophysics. For instance, CMB is characterized by a frequency range going from 0.3 GHz to 630 GHz. Existing studies performed with TES sensors reached a minimum frequency ~100 GHz, therefore our sensors push down the detection lower boundary of one order of magnitude. Furthermore, 10 GHz single-photon detectors are a breakthrough for the detection of Axions in laboratory experiments (Light Shining through Wall), where an axion immersed in a strong magnetic field is expected to emit a photon at that frequency. Therefore, the Italian Space Agency (ASI), the European Space Agency (ESA) and CERN could benefit from this technology. We are already in contact with these institutions, and we plan to establish dedicated collaborations based on the T-CONVERSE sensing platform.

For European citizens, T-CONVERSE sensors are turning technology for the production of THz and GHz cameras and spectrometers employed in medical imaging, homeland security screening, food packaging quality checks and identification of alimentary frauds. For citizen security, the higher sensitivity of our detectors are expected to double the working range of the scanning systems and to drastically improve the ability of finding hidden objects (40-50 m are expected) or illegal goods. On the other hand, the possibility of controlling the operation frequency allows to use the same sensor to find different drugs or explosives. Regarding food security and citizen health, our detectors will be the cornerstone of new quality control tools for food packaging, and spectroscopic instruments for inspecting for food adulterations and frauds.

5.4. Technology commercialization

To commercialise the T-CONVERSE technology, we plan the following tasks:

- Disseminating the achievements.
- Patenting the developed technology.
- Tracking competing technologies, defining market needs and business strategies.
- Designing and fabricating prototype devices accessible to partners/companies/investors.
- Development of partnerships for technology commercialisation.

O. Mukhanov from SQC-EU has a well-established track record in developing superconducting technologies and knowledge of commercialisation aspects of the superconducting detection market. Therefore, the T-CONVERSE consortium already has the necessary expertise for the commercialisation of the developed technology.

Envisioned risks

The risks are related to the demonstration of the TPC mechanism and the scalability of the technology. To minimize the probability of failure, we expanded our interest to other two sensors: the nano-TES and the JES. The devices have been already realized and the prove of principle is demonstrated. Furthermore, antennas and read-out technologies of the three sensors are interchangeable. So, we can develop more approaches with negligible additional work.

5.5. Liaison with Student Teams and Socio-Economic Study

In Phase 1 we did not opt for collaboration with MSc students essentially for matter of time within the tight schedule of the project. For ATTRACT Phase 2, instead, we will fully exploit the university capabilities for the interaction with MSc students by several means. Students will be introduced to the technologies pioneered by T-CONVERSE through dedicated seminars and in-lab experiences. PhDs, Postdocs and senior scientists will follow the students participating to the program.

For the Phase 1, a dedicated web site[1] has been built to disseminate the T-CONVERSE technologies as well as the ATTRACT project philosophy. The Phase 2 dissemination will be developed to ensure adequate exploitation of our results. This will include scientific publications as well as non-specialist publications (for public and stakeholders). The plan will comprise the communication objectives, target audiences, channels (including social media) and partners responsible for the campaigns. We plan project branding and graphical identity (e.g. all graphical elements of the project, logo, stationery, brochure, leaflet, slide and deliverable templates etc.). We will further disseminate by participating at dedicated events, like the “European Researchers’ Night”, “Pint of Science”, “Coffee with Science” or specialty workshops.

Exploitation, sustainability and business plan will be systematically developed to support commercialization and innovation. The business plan will be based on a broad analysis of the relevant market segments, to which the partners have close links and access. A validation of the market needs will be performed by key industrial representatives from the project. We plan the publication of a book on the T-CONVERSE technology and its application, targeting customs professionals, researchers and industry in the technological areas, and policy makers, as well as other stakeholders.

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