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Sensing of cryogenic temperatures by superconducting NbTi(N) thin-film S-shaped Split Ring Resonators

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Abstract

In the last decades, the precise control of ultra-low temperature environments has turned out to be of primary importance for the development of novel cryogenic applications. As a matter of fact, the accurate monitoring of temperatures well below 10 K is crucial for preserving the quantum properties of superconducting and spin qubits [1-2]; moreover, recent superconducting high-energy particles detectors strongly rely on radiation-induced or thermally-assisted breaking of Cooper pairs [3-4], for which sensing temperatures with a sub-millikelvin resolution is necessary.
Nowadays, the state-of-the-art for cryogenic thermometry mainly consists of thermistors in 4-wires configuration, for instance based on Pt capsules [5] or CERNOX® thin-films [6]. Such devices, showing wide temperature ranges, more than 10³ Ω/K sensitivity for T < 10 K, mechanical robustness and compact dimensions, are currently widely exploited in standard multiple-stages cryostats. Nevertheless, one of the main drawbacks of this technology is the need for at least 4 DC wires for each sensor in the cryostat, which potentially increases the amount of heat conduction paths and the complexity of cables assembling. Alternative solutions to this market-leading technology include the recent development of thermometric systems exploiting different physical principles, such as kinetic inductance variations of transmission line superconducting resonators [7] and two-levels systems inside superconducting circuits and resonators [8-9].
In this work, we present a superconducting thermometer consisting of a S-shaped Split Ring Resonator (S-SRR), for which T-induced variations of its kinetic inductance result in resonance frequency shifts. The choice of such a scheme is motivated by the possibility to ideally excite multiple sensors, situated in different locations of a cryogenic environment, with only one single RF transmission line. Moreover, S-SRRs have also proved to optimally couple to standard CPWs [10], whose technology is nowadays massively exploited in the design of quantum electrodynamics (QED) circuits. Therefore, such a thermometer could be also non-invasively integrated to directly monitor the cryogenic temperature of operative DUTs.
Such devices consist of 100 nm thick films of both NbTi and NbTiN patterned on sapphire substrates, respectively showing 1.46 ± 0.04 pH/□ and 1.62 ± 0.06 pH/□ sheet kinetic inductances. Basing on preliminary studies [11], a microfabrication process flow, relying on a combination of standard direct laser writing and SF₆-based reactive ion etching (RIE), has been optimized to accurately microstructure the superconducting thin-films, with a limiting lateral resolution of 700 nm and a line-width transfer accuracy better than 100 nm. Several NbTi(N) S-SRRs, with resonance frequencies around 1 GHz, have been fabricated and tested in the variable temperature insert (VTI) of a superconducting cryo-magnet. Resonance frequency shifts of 4.5% for NbTi and 7.5% for NbTiN, in the range from 3 K to their critical temperature (8.3 K and 11.8 K, respectively), have been recorded, together with maximum Q-factors up to 40'000. Such results validate the implementation of these resonators as cryogenic thermometers over all their superconducting range, showing performances comparable with the devices previously reported in literature [7-9].

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