Josephson devices for ac quantum voltage standard

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Thesis title: Josephson devices for ac quantum voltage standard

Subtitle: From dry-cooling to metrological application

Abstract

Superconducting devices based on Josephson effect are worldwide employed as primary dc voltage standards in National Metrology Institutes (NMIs). Nowadays, research on Josephson voltage standards (JVSs) is aiming at a fundamental change also in the metrology of ac and arbitrary signals: binary-divided programmable standards (PJVS) that convert a digital code into a quantum-based stepwise waveform are already available in primary laboratories, whereas more advanced standards for converting streams of sub-nanosecond pulses into very pure arbitrary signals are now actively developed. Furthermore, a user-friendly and liquid helium-free refrigeration system with adequate cooling power and minimum temperature below 4 K is favorable to the spread of these quantum standards outside NMIs. Commercially-available Gifford-McMahon (GM) and pulse-tube (PT) cryocoolers satisfy these needs, though some collateral effects related to the high-vacuum environment and to the cyclic thermal noise are to be faced. The dynamical thermal response of a GM cryocooler to programmed power stimuli has been experimentally studied, considering it as a linear system around 4 K. Its power-to-temperature transfer function has been then evaluated via two independent methods, providing comparable results useful to the analysis of cryocoolers behavior and to the development of techniques for actively and passively damp the temperature fluctuations.

The other major downside of cryocoolers is the difficulty of transferring the power generated within the Josephson chip to the cryocooler cold surface, which may cause the detrimental warming of the junctions. With the aim of enhancing heat dissipation of cryocooled PJVS devices, a special cryopackage has been realized and tested in different experimental conditions, with the chip integrated into a sandwich structure with low thermal resistance materials subject to a reproducible mechanical pressure. This cryopackage succeeded in dissipating hundreds of mW of power with a minor increase of the chip temperature.

Subsequently, in order to analyze the electrical properties of a PJVS array, an open-source software has been written. It allows to control the bias currents flowing into the PJVS binary segments and synthesize dc and ac quantum-accurate voltages. The code,

publicly shared on *GitHub*, is modular and easily expandable with the support of many libraries, thus allowing prompt reconfiguration for different experimental needs.
PJVS arrays with 8192 junctions have been electrically characterized in cryocooler and used to synthesize stepwise sine waves with amplitudes up to 2 V and frequencies up to the kHz range, though limited by the cryocooler thermal fluctuations and by frequent magnetic flux trapping events. In addition, the possibility of advantageously operating a binary PJVS array with a reduced number of bias lines was investigated. This feature can be achieved by simultaneously exploiting first and second quantum voltage steps, along with non-conventional codifications. Two newly devised bias techniques are described in detail and preliminary experimental tests on waveform synthesis are presented.
Cryocooler operation of pulse-driven Josephson devices fabricated at Physikalisch-Technische Bundesanstalt (PTB) has been investigated as well. In contrast with PJVS, these have to satisfy less stringent requirements in terms of power dissipation. On the other side, the rigid coaxial cable for the broadband high-frequency pulse transmission introduces a considerable thermal load to the cryocooler cold stage, which has been substantially reduced by means of proper thermal anchorings. Electrical characterization of pulse-driven arrays in cryocooler showed similar results of measurements in liquid helium. In particular, quantum step widths larger than 1 mA have been observed under constant pulse repetition frequencies around 6 GHz.
Afterward, ΣΔ modulation has been exploited to synthesize unipolar and bipolar sine waves with pulse-driven arrays at amplitudes ranging up to tens of mV, frequencies in the kHz range and higher harmonics suppressed by more than 80 dBc. Nevertheless, further studies are required to check degree of quantization and spectral purity with better resolution, especially at signal frequencies approaching the MHz range.
Finally, ac JVSs have been operated at metrological level during a three-month research period at PTB, funded by the European project ACQ-PRO. PJVS-PJVS and JAWS-PJVS indirect comparisons have been carried out via the calibration of semiconductor-based voltage generators at amplitudes and frequencies used in industry and scientific research. Relative differences at the µV/V level in the former case and more than 5 µV/V in the latter have been achieved, and the possible sources of the discrepancies are discussed.