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Behavioral Modeling and Harmonic Balance Analysis of Microwave Parametric Amplifiers for Quantum Computing

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Summary

Traveling-wave parametric amplifiers (TWPA) are promising candidates for low-noise amplification of microwave signals in superconducting quantum computers. The passivity of the nonlinear inductance of Josephson Junctions (JJ) in these amplifiers leads to very low noise (less than a photon) performance. As a result of strong nonlinearity in TWPA, a myriad of physical effects, e.g., pump depletion in the amplifier, occurs which mandates precise simulations to correctly predict the device performance before fabrication. The strong nonlinearity of the circuits renders traditional small-signal methods imprecise and time-domain methods very time-consuming.

In this talk, we aim to present the efficient and fast simulation methods of TWPA based on (a) behavioral modeling of nonlinear reactive elements, e.g., JJ, SQUID[1], and SNAIL[2] using symbolically defined device (SDD) method, and (b) Harmonic balance analysis of TWPA made of JJ and SNAIL.
In addition to the theoretical backgrounds of the harmonic balance method and physics of parametric amplification in nonlinear circuits, a comparison with experimental measurements is made. The match between our experimental and theoretical results highlights the reliability of the harmonic balance method in the design and simulation of strongly nonlinear circuits like TWPA.

References:

[1] Anita Fadavi Roudsari, et al, Three-wave mixing traveling-wave parametric amplifier with periodic variation of the circuit parameters, Appl. Phys. Lett. 122, 052601 (2023); https://doi.org/10.1063/5.0127690

[2] H. Renberg Nilsson, et al, A high gain traveling-wave parametric amplifier based on three-wave mixing, https://arxiv.org/abs/2205.07758

[1] SQUID = superconducting quantum interference device

[2] SNAIL = Superconducting Nonlinear Asymmetric Inductor (L)