Appendix 3

BEYOND THE STANDARD QUANTUM LIMIT OF PARAMETRIC AMPLIFICATION

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The low noise amplification of weak microwave signals is of relevance in modern quantum technology, but also in fields such as dark matter search. Quantum mechanics sets an ultimate lower limit of half a photon to the added input noise for phase-preserving amplification of narrowband signals, also known as the standard quantum limit (SQL). In terms of quantum efficiency, the SQL corresponds to a value of 0.5. This limit, however, can be circumvented by employing nondegenerate parametric amplification to broadband signals. We show that, in theory, a maximum quantum effciency of 1 can be reached. Experimentally, we observe a quantum efficiency of 0.69 by employing a flux-driven Josephson parametric amplifier and broadband thermal signals. Thus, we achieve amplification performance beyond the SQL. Based on this result, we envision improved sensing abilities for microwaves in quantum technology and elsewhere by applying broadband probe signals. This work is supported by the EU Quantum Flagship project QMiCS (820505).