Quantum Science and Technology

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Superconducting Devices in Quantum Optics

Springer

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Quantum Science and Technology

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The book series Quantum Science and Technology is dedicated to one of today's most active and rapidly expanding fields of research and development. In particular, the series will be a showcase for the growing number of experimental implementations and practical applications of quantum systems. These will include, but are not restricted to: quantum information processing, quantum computing, and quantum simulation; quantum communication and quantum cryptography; entanglement and other quantum resources; quantum interfaces and hybrid quantum systems; quantum memories and quantum repeaters; measurement-based quantum control and quantum feedback; quantum nanomechanics, quantum optomechanics and quantum transducers; quantum sensing and quantum metrology; as well as quantum effects in biology. Last but not least, the series will include books on the theoretical and mathematical questions relevant to designing and understanding these systems and devices, as well as foundational issues concerning the quantum phenomena themselves. Written and edited by leading experts, the treatments will be designed for graduate students and other researchers already working in, or intending to enter the field of quantum science and technology.

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Preface

Over the past decade, superconducting devices have risen to prominence in the arena of quantum optics and quantum information processing. Superconducting detectors provide unparalleled performance for the detection of infrared photons. These devices enable fundamental advances in quantum optics, the realization of quantum secure communication networks, and open a direct route to on-chip optical quantum information processing. Superconducting circuits based on Josephson junctions provide a blueprint for scalable quantum information processing as well as opening up a new regime for quantum optics at microwave wavelengths. We have endeavored to provide a timely compilation of contributions from top groups worldwide across this dynamic field. This volume provides both an introduction to this area of growing scientific and technological interest, and a snapshot of the global state-of-the-art. Future advances in this domain are anticipated.

Part I of this volume focuses on the technology and applications of superconducting single-photon detectors for near infrared wavelengths.

Chapter 1 provides an authoritative introduction to superconducting nanowire single photon detectors by leading researchers from the Massachusetts Institute of Technology, the NASA Jet Propulsion Laboratory, and the National Institute of Standards and Technology (NIST), USA. The superconducting nanowire device principle is discussed in detail. Key concepts are introduced such as detection efficiency, dark count rate, and timing jitter. The use of amorphous superconducting materials to achieve high device yield and extended mid-infrared sensitivity is highlighted. Parallel wire architectures are presented and an outlook is given on the scale-up to large area arrays.

Chapter 2 introduces another key superconducting detector technology, the superconducting transition edge sensor. The chapter is contributed by the team at NIST, USA, who has been in the vanguard of developments in this technology. The device operation principle is introduced, including key considerations for maximizing sensitivity for the detection of infrared photons and photon-number resolving capability. A range of important quantum optics experiments exploiting the unique capabilities of transition edge sensors are reviewed. Finally, the integration of transition edge sensors with optical waveguide circuits is discussed.

Chapter 3 focuses on superconducting nanowire detectors integrated with GaAs photonic circuits. The chapter is contributed by a team of authors from the Technical University of Eindhoven, the Netherlands, Consiglio Nazionale delle Richerche (CNR) Rome, Italy and the University of Bristol, UK. This approach is compatible with quantum dot single photon emitters, opening the pathway to fully integrated quantum photonic circuits.

Chapter 4 reviews progress on superconducting nanowire detectors on silicon-based photon circuits. This work is contributed by researchers at Yale University, USA, and the University of Muenster, Germany. The marriage of superconducting detectors with mature planar lightwave circuits is a compelling alternative for on-chip quantum information processing. A range of technological applications are discussed, including single photon characterization of on-chip resonators and optical time domain reflectometry for long haul fiber links.

Chapter 5 gives an overview of applications of superconducting nanowire single photon detectors in the realm of quantum communications. The chapter is authored by a team of researchers from the National Institute of Information and Communication Technology (NICT) in Japan. The chapter describes how low noise superconducting nanowire single photon detectors enabled the world's most ambitious quantum cryptography network to be realized in Tokyo, Japan. This chapter also describes developments in heralded single-photon source and quantum interface technology, enabled by high-performance superconducting detectors.

Part II switches the emphasis to quantum optics in the microwave regime using superconducting circuits at millikelvin temperatures.

Chapter 6 gives an authoritative introduction to the emerging field of microwave quantum photonics. It describes the basic building blocks including transmission lines, cavities, artificial atoms (qubits), and measurement setups. This chapter is authored by researchers from the University of Queensland, Australia, and Jiangxi Normal University, China. This chapter highlights the potential of superconducting circuits to access and control quantum phenomena in the realm of microwave photons.

Chapter 7 explores the role of continuous weak measurements as a probe of quantum dynamics in superconducting circuits. In particular, it discusses the possibility to experimentally characterize the systems evolution in terms of quantum trajectories and also how to use the feedback from weak measurements to stabilize Rabi oscillations. This chapter is contributed by experts from Washington University, St. Louis, USA, the University of California, Berkeley, USA, and the Tata Institute of Fundamental Research, Mumbai, India.

Chapter 8 focuses on digital feedback control methods for superconducting qubits. In particular, it describes the use of projective measurements and feedback for fast qubit reset and deterministic entanglement generation. This chapter is contributed by leading researchers at the Delft University of Technology, the Netherlands, and Raytheon BBN Technologies, USA. This high fidelity projective measurement-based technique now allows fast initialization of superconducting qubits and brings deterministic generation of entangled states by parity measurement within reach.

Chapter 9 highlights the use of surface acoustic waves (SAWs) in connection with superconducting quantum circuits. In particular, it describes the coupling of a superconducting artificial atom to propagating SAWs and also how to form SAW cavities in the relevant parameter regime of high frequency and low temperatures. This chapter is authored by a team from Chalmers University, Sweden, Columbia University, USA, RIKEN, Japan, and the University of Oxford, UK. This new technique enables exploitation of single phonons as carriers of quantum information between superconducting qubits as well as providing a method of storage of quantum information in high quality phononic cavities.

This book arose out of a special symposium on 'Superconducting Optics' at the joint Conference on Lasers and Electro-Optics—International Quantum Electronics Conference (CLEO ®/Europe—IQEC conference) which took place in Munich, Germany, in May 2013. One of us (R.H.H.) was a chair of the symposium and the other (G.J.) was an invited speaker. We thank Prof. Dr. Jürgen Eschner of Universität des Saarlandes, Germany, and the CLEO ®/Europe—IQEC programme committee for proposing the special symposium. We undertook the task of editing this book with encouragement from Dr. Claus Ascheron at Springer and Prof. Gerard J. Milburn of the University of Queensland, Australia, Springer Quantum Science and Technology Series Editor. We thank Praveen Kumar and his team at the Springer production office in Chennai, India, for their diligent handling of the proofs. We thank the authors for their high-quality contributions and their dedication in meeting challenging deadlines. We also acknowledge colleagues who proofread parts of the volume, including Dr. Chandra Mouli Natarajan, Dr. Jian Li and Dr. Robert Heath of the University of Glasgow, and Dr. Matti Silveri of Yale University, USA. Finally, we thank our respective families of their patience and forbearance as we guided this volume towards completion.

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Contents

Part I Superconducting Single Photon Detectors: Technology and Applications

Part II Superconducting Quantum Circuits: Microwave Photon Detection, Feedback and Quantum Acoustics

Part I
Superconducting Single Photon Detectors: Technology and Applications

Chapter 1
Superconducting Nanowire Architectures for Single Photon Detection

Faraz Najafi, Francesco Marsili, Varun B. Verma, Qingyuan Zhao, Matthew D. Shaw, Karl K. Berggren and Sae Woo Nam

Abstract Over the past decade, superconducting nanowire single photon detectors (SNSPDs) have emerged as a key enabling technology for quantum optics and free-space optical communication. We review the operating principle and the latest advances in the performance of SNSPDs, such as extending sensitivity into the mid infrared, and the adoption of amorphous superconducting films. We discuss the limits and trade-offs of the SNSPD architecture and review novel device designs, such as parallel and series nanowire detectors (PNDs and SNDs), superconducting nanowire avalanche photodetector (SNAPs), and nanowire arrays with row-column readout, which have opened the pathway to larger active area, higher speed and photon-number resolution.

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1.1 Introduction

Superconducting detectors can outperform other photon-counting technologies in a variety of performance metrics such as detection efficiency, dark count rate, timing jitter, reset time, and photon-number resolution [1]. As a result, superconducting detectors have found use at the cutting edge of basic research in astronomy, quantum optics, and free-space optical communication. In particular, single photon detectors based on superconducting nanowires [2] have been widely adopted due to their unrivaled performance in the infrared and due to advances in practical cryogenics.

In this chapter we discuss the design and performance of various types of detectors based on the superconducting nanowire concept, such as superconducting nanowire single photon detectors (SNSPDs or SSPDs) [3], superconducting nanowire avalanche photodetectors (SNAPs or Cascade-Switching SSPDs) [4, 5], multi wire photon-number-resolving (PNR) detectors [6, 7], and SNSPD arrays with scalable multi-pixel readout [8–10].

1.2 Performance Metrics for Photon Counting Detectors

In this section we review the definitions of the key metrics used to quantify the performance of photon-counting detectors, in order to assist with their direct comparison.

1.2.1 Detection Efficiency

The term *system detection efficiency* (*SDE*) describes the probability of registering an electrical signal produced by a photon once the photon has entered into the *input aperture* of the photon detection system. For example, for a fiber-coupled detector system, the input aperture would be defined as the fiber penetrating into the cryogenic vacuum chamber, which delivers photons to the detector itself. For a free-space coupled system, the input aperture would be the optical window into the cryogenic system. Conceptually, *SDE* can be thought of as the product of multiple efficiencies:

$$SDE = \eta_{coupling} \cdot \eta_{absorb} \cdot \eta_{internal} \cdot \eta_{trigger}, \tag{1.1}$$

where $\eta_{coupling}$ is the efficiency for the photons at the input aperture to be delivered to the active area of the device within the detector system, η_{absorb} is the probability that a photon incident on the active area of the detector is absorbed by the detector, $\eta_{internal}$ is the probability that an absorbed photon generates an observable electrical signal, and $\eta_{trigger}$ is the efficiency with which the counting electronics actually registers the electrical signal as a count. Note that for the photon-number-resolving (PNR) nanowire detectors discussed below, a separate $\eta_{trigger}$ must be defined for each photon number. While it is difficult to independently measure the four parameters in