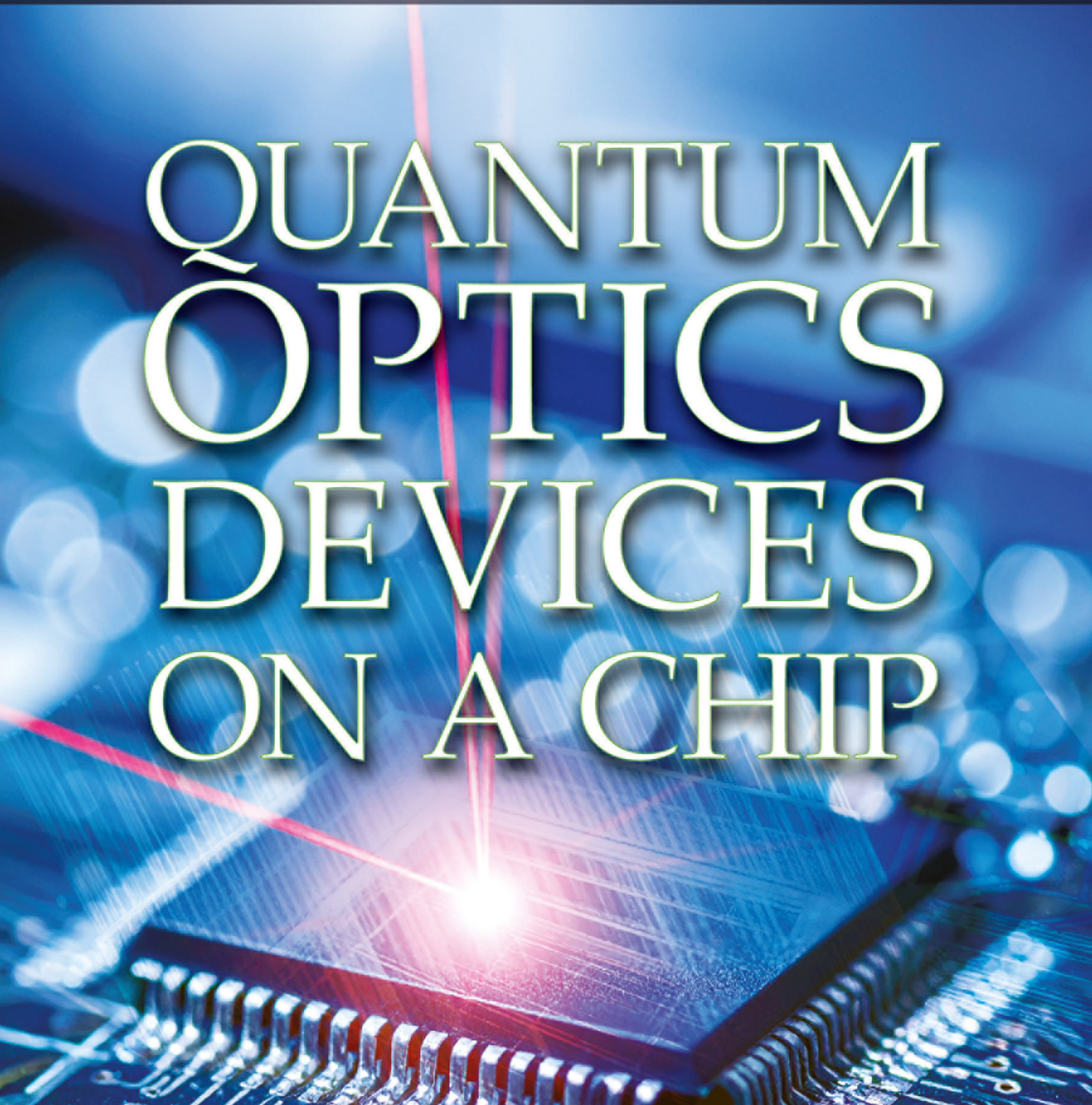
QUANTUM OPTICS DEVICES ON A CHIP



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Preface

The topic of the book, "Quantum Optics Devices on a Chip," is situated at the intersection of several disciplines and industries, driving advancements in quantum technology and integrated photonics. In the realm of disciplinary development, quantum optics is a branch of physics that focuses on the behavior and properties of light at the quantum level. It explores the fundamental principles of quantum mechanics applied to optics, including the wave–particle duality of light and the quantized nature of energy. Quantum optics plays a crucial role in understanding and harnessing phenomena such as entanglement, superposition, and quantum interference, which are essential for quantum information processing, communication, and sensing.

The development of quantum optics devices on a chip represents a significant breakthrough in the field. Chip-scale integration involves designing and fabricating optical devices, such as waveguides, modulators, detectors, and light sources, on a micro- or nanoscale chip. This miniaturization enables the integration of multiple components on a single chip, leading to compact, efficient, and scalable quantum optical systems. The impact of quantum optics devices on a chip extends beyond the realm of physics and has far-reaching implications across various industries. In quantum computing, the ability to manipulate and control quantum states of light on a chip paves the way for the development of quantum processors capable of solving complex problems at unprecedented speeds. Quantum communication benefits from chip-scale devices by enabling secure transmission of information through quantum key distribution protocols. Quantum sensing applications, such as magnetometry, gyroscopy, and biosensing, can benefit from miniaturized, high-performance devices integrated on a chip. Moreover, the integration of quantum optics on a chip has implications for the field of integrated photonics. It allows for the seamless integration of quantum optical functionalities with existing photonic circuits, enabling the development of hybrid systems that leverage the advantages of both classical and quantum technologies. This integration holds promise for applications in telecommunications, data communication, and optical signal processing.

Overall, the development of quantum optics devices on a chip represents a significant step forward in the advancement of quantum technology. It brings together principles from physics, materials science, engineering, and computer science to enable the practical implementation of quantum phenomena for a wide range of applications across industries. The book serves as a comprehensive guide to this rapidly evolving field, providing insights and knowledge to researchers, scientists, and industry professionals seeking to explore and contribute to the disciplinary and industrial development of quantum optics devices on a chip. The book's content is carefully structured to appeal to a wide audience, from graduate students and researchers entering the field of quantum optics to experienced scientists and engineers who want to expand their knowledge. The comprehensive and accessible approach will enable readers from diverse scientific backgrounds to understand fundamental concepts, explore cutting-edge research, and visualize the future prospects of on-chip quantum optics devices. The chapters included in the book are summarized below:

Chapter 1 reviews different quantum-limited microwave amplifiers for various quantum technological applications. The chapter details current progress related to quantum-limited microwave amplifiers, types of amplifiers, their design and structure, advantages and limitations, and future development. The outlook discusses controlling operating parameters, materials geometry, and fabrication techniques.

Chapter 2 provides a brief introduction to the field of quantum optics. It includes an overview of key scientific developments that led to the field of quantum optics and a discussion of the physical phenomena covered within the field.

Chapter 3 covers the significance of carbon nanotubes in molecular electronics. It emphasizes several intriguing ways to alter the fundamental properties of the carbon network by adding defects and examines their creation in depth.

Chapter 4 introduces quantum dots (QDs) and their medical applications, detailing synthesis methods, properties, and biocompatibility. It highlights their superior fluorescence for imaging, roles in drug delivery, and diagnostic uses. Ethical, safety, regulatory, and environmental issues are discussed, emphasizing QDs' potential in diagnostics and therapy while addressing associated challenges.

Chapter 5 describes fascinating areas in quantum optics and quantum information, revealing unique quantum properties with essential characteristics and principles governing the quantum state of light. The study discusses superposition, entanglement, and quantum coherence, techniques for generating and manipulating light quantum states, and applications in communication, computing, and metrology.

Chapter 6 details the historical development of quantum technology, the fundamentals of quantum chip-scale devices, and the revolution that these technologies bring to the fabrication of next-generation devices. Various quantum chip-scale architectures and circuits are discussed in detail to elaborate on their effectiveness in device fabrication. The benefits, challenges, and financial aspects of investing in quantum chip-scale devices have opened the market for innovation and research. With the latest technologies like artificial intelligence and machine learning, this industry is poised to deliver better and more customer-friendly products.

Chapter 7 delves into the cutting-edge realm of quantum-enhanced THz spectroscopy and the integration of on-chip devices. It explores the generation and detection of THz radiation, emphasizing the pivotal role of femtosecond lasers, photoconductive antennas, and quantum cascade lasers. Advanced THz spectroscopy techniques, including terahertz time-domain and time-resolved spectroscopy, are discussed in detail, showcasing their potential to unravel dynamic material properties. The chapter also highlights innovative THz imaging methodologies, particularly near-field imaging, and groundbreaking biomedical applications such as early-stage cancer detection. Concluding with a forward-looking perspective, the chapter provides insights into future breakthroughs and opportunities, inviting interdisciplinary collaboration to push the boundaries of this dynamic field.

Chapter 8 delves into the fascinating world of optical devices found on microchips incorporating plasmonics for sensor applications. The literature primarily focuses on plasmonic-based sensors, including SPR, LSPR, and SERS sensors. It explores their scope, advantages, and limitations.

Chapter 9 traces the evolution of quantum computing, highlighting silicon photonics' pivotal role in scalability and efficiency. Focusing on practical implementation, it explores scalable methods for silicon photonic chips and their advancements. In chip-based quantum communication, particularly quantum key distribution (QKD), integrated photonics enables real-world applications. The chapter discusses diverse QKD approaches, including entanglement-based and superposition-based methods, and introduces continuous-variable QKD for secure metropolitan communication. Addressing challenges, it covers quantum multiplexing techniques, emphasizing solutions to issues like spontaneous Raman scattering noise. Examining the intersection of silicon photonics and quantum computing, the narrative highlights applications in communication, imaging, and error correction. Persistent challenges like quantum noise and decoherence underscore the need for innovative solutions, showcasing silicon photonics' pivotal role in advancing secure communication and unlocking unprecedented computational power.

Chapter 10 navigates through the intricate landscape of quantum nanophotonics, with a spotlight on the indispensable role of rare earth ions. Key themes include the growth techniques and material topologies associated with rare earth-doped materials, the fundamental aspects of rare earth ions in solid-state materials, and their pivotal role in quantum optics. The chapter unveils applications spanning quantum devices, low-dimensional materials, insulators, and spectral hole burning. The convergence of ultrasound and optics in ultrasonic-optical tissue imaging and the transformative impact of solid-state optical devices in diverse industries further enrich the narrative.

Chapter 11 delves into the evolution of chip-scale quantum memories, highlighting their scalability, rapid communication, and low power consumption. It explores theoretical and experimental approaches, development challenges, and the significant roles of quantum dots and photonic methods in advancing chip-scale memories.

Chapter 12 discusses the integrated light sources that revolutionize applications with high efficiency. Several III-V-based inorganic semiconductor lasers, quantum dots, and germanium-on-silicon lasers are discussed, along with a tunable quantum light source, enabling on-demand tuning of spatial photon-pair correlations and entanglement in a nonlinear directional coupler for practical quantum information applications.

Chapter 13 delves into the progressive advancements of integrated optical systems, focusing on their significant influence on telecommunications, computing, and sensing technologies. It comprehensively examines the design principles, fabrication methodologies, and essential components such as waveguides, modulators, and amplifiers, underscoring their pivotal role in enhancing optical communication and information processing functionalities.

The Editors

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Quantum-Limited Microwave Amplifiers

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Abstract
Weak microwave signals and their amplification are gaining a great interest for numerous applications, especially in quantum-based applications. Lowest possible noise is ideal for quantum technologies. At present, quantum-limited microwave amplification is done through various types of amplifiers such as high-electron mobility transistors (HEMT), superconductor-based amplifiers, and MASER (microwave amplification by stimulated emission of radiation)-based amplifiers. Each technique has its unique advantages and limitations. In this chapter, current progress related to quantum-limited microwave amplifier, types of amplifiers, designs and structures, advantages and limitations, and future development are discussed.

***Keywords*:** Amplifiers, qubit, resonators, microwave amplification, microwave photon, superconductor, Josephson junction

1.1 Introduction

At present, detection and amplification of very weak microwave signals are attaining an interest for various quantum-based applications such as RADAR, space technology, communication, quantum computing, etc. For such amplification, the signal is usually very weak, and therefore it might

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get lost in the main signal due to the noise present. Microwave photons in the range of 3 to 12 GHz are very important for quantum applications as they reach the energy of a single photon. Single microwave photon at a few gigahertz level can be controlled with much better accuracy than THz photon [1–4]. There are numerous advantages of microwave photonics over quantum optics. Microwave components are much stable than optical components when they cool down. Additionally, an interface of electronics with microwaves is much simpler and faster than the optical way. Lastly, it is easy to pump the non-linear and non-dissipative Josephson junction with microwave.

The fundamental laws of quantum physics tell us that "any phase-preserving amplifier requires to add at least half a noise photon to the output signals in the high-gain limit". It is called "standard quantum limit" [5]. So, the device design for quantum applications must be processed such that the signal is near the quantum limit.

Basic amplifiers such as high-electron mobility transistors (HEMT), superconducting based amplifiers, and microwave amplification by stimulated emission of radiation (MASER)-based amplifiers have been explored for such applications [6]. Here the current development in the field of quantum-limited microwave amplifiers is presented.

1.2 Why Microwave Amplifiers?

It is known that every device has some fundamental detection limit generally decided by the mechanism of the device. Normally, a circuit that increases the input signal is called an amplifier. So, amplification is a process that increases the magnitude of the signal. Generally, a non-linear component such as a field effect transistor is used for this purpose (Figure 1.1). In this case, the gain of the device is used and given by the ratio of an output signal to an input signal [7, 8].

For fast signal attenuation, higher sensitivity is preferred because of the large reduction of power. This is highly required when the output signal is lower in magnitude and therefore is potentially required in several applications including space applications, RADAR, cosmos, microwave, and quantum-based applications. Normally, the signal level is faint at around tens to hundreds of microwave photons. Due to added noise, it becomes challenging to detect the main signal [3]. The concept of microwave amplifier was proposed by A. L. Cullen in 1959 [9]. It was studied that the regular transference of power among a pump tone and a signal drifting in

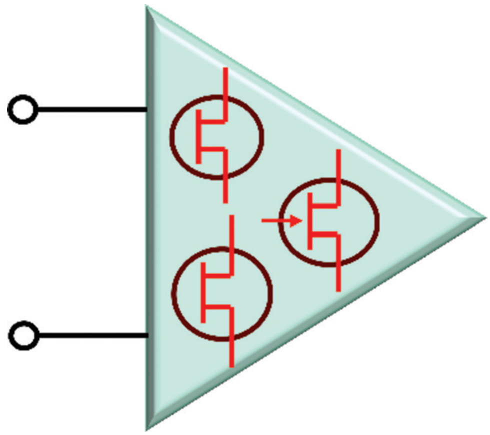

Figure 1.1 Typical diagram of an amplifier.

a transmission line constituted of a voltage-reliant capacitance per unit length. After this, the concept of using a non-linear component made using a superconducting material into a transmission line was established [10].

1.3 Quantum-Limited Amplifiers

Normally for electrical systems, the signal is recorded in the form of voltage and it is not hard to amplify the weak signal also. The weak signal can be amplified using an electrical amplifier. The microwave signal with low noise can be detected by a conventional electrical amplifier mainly based on HEMT. It has the capability to go below several critical temperatures up to 5 K and add around ~10 noisy photons/signal in 1 s at 1-Hz bandwidth. This could provide around 40 dB of amplified signal and noise of around tens of photons. However, it will further reduce the signal-to-noise ratio by the order of 50–100, and hence the noise also comes into play [11, 12]. In the case of quantum-based applications, there is a tremendous need to decrease the noise signal significantly. There is another alternative based on superconducting amplifiers that mainly work at an ultralow temperature. It goes up to ~10 to 25 mK and thus significantly amplifies the microwave signal with 0.5 noise photons/second at 1-Hz bandwidth. However, an operation is complicated and less suitable [13]. One more approach on microwave amplification by stimulated emission of radiation (MASER) mainly based on parametric material ions fixed in a crystallite like ruby and under static magnetic field and microwave pumping, population

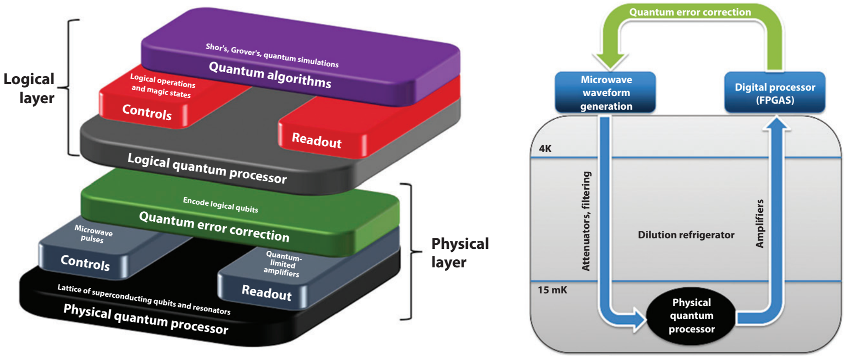

Figure 1.2 Use of a microwave amplifier and its typical experimental setup for quantum applications (reproduced with permission from [14]).

inversion occurs, which emits the stimulated amplified microwave radiation. Typically, it works at a low temperature of around ~1 K and has few noise photons for 1-Hz bandwidth [12]. The importance of an amplifier in a superconducting quantum computing system with logical qubits was also reviewed elsewhere (Figure 1.2) [14].

As per quantum physics, any phase-preserving amplifier is essential to add at least half a noise photon in high-gain limit, and this is called standard quantum limit (SQL). Caves has defined the quantum limit of performance of a phase-preserving amplifier which normally amplifies all the inputs equally. For Caves' limit, the half of a photon at the signal frequency gets added and doubles the noise power of the input signal [15]. Therefore, this is called "quantum limited". Now, with the current rise in quantum-based technological applications, there is a special need of these types of quantum-limited amplifiers.

1.4 Types of Microwave-Based Amplifiers

Normally, there are three kinds of amplifiers adopted for amplification, namely:

1. Conventional electronic amplifiers or high-electron mobility transistor (HEMT) amplifiers
2. Superconducting circuit-based amplifiers

   a. Superconductor quantum interference device (SQUID) amplifier
   b. Radio frequency single-electron transistors
   c. Quantum Josephson parametric amplifier
   d. Kinetic inductance parametric amplifier
3. Solid-state MASER-based amplifier

1.4.1 Conventional Electronic Amplifiers or High-Electron Mobility Transistor (HEMT) Amplifiers

The HEMT was first proposed and studied by Mimura at Fujitsu Labs in the year 1980 [16]. Lots of semiconductor materials have been explored in the fabrication of HEMT. Normally, it is fabricated with very sophisticated techniques such as molecular beam epitaxy, atomic layer deposition, etc. It is desired to obtain a single layer along with doping for a good performance of the system. At present, numerous 0D, 1D, and 2D structures such as quantum dots and quantum wires have been utilized in HEMT. Even a single-electron transistor is realized for such application [17–19].

Working mechanism: The HEMT works on a heterojunction normally created by attaching different bandgap semiconductor materials. The flow of electrons and holes occur until it attains an equilibrium (Figure 1.3). Generally, without doped narrow bandgap material is exhibited by a majority of carriers, and thus a high switching speed is acquired. On the other side, a low bandgap material possesses no donors and thus can display high mobility [20, 21].

HEMT has the following major components [20]:

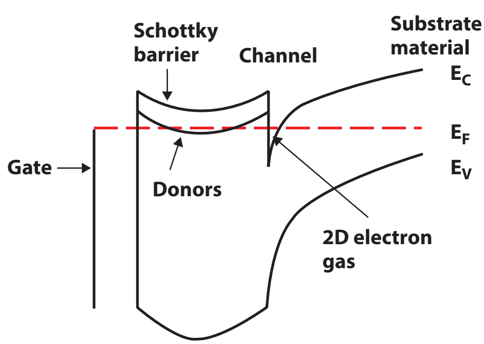

Figure 1.3 Schematic of energy levels for a high-electron mobility transistor (HEMT).

1. Substrate: This acts as a base, and the normally used materials are GaAs, silicon, etc.
2. Buffer coating: It is an additional layer and covered a top position on the substrate.
3. Channel: It is majorly deciding the movement of charge carriers and thus, exhibits a property like high mobility. Generally, materials like InGaAs are used.
4. Barrier: It plays a role of barrier which prevents the movement of charge carriers (materials used: AlGaAs).
5. Spacer: It is placed between the channel and barrier. It significantly reduces the scattering.

1.4.2 Superconducting-Based Amplifiers

1.4.2.1 Josephson Junction

This is a very significant part and a basic building block of superconductor-based amplifiers. It is a device consisting of two weakly bonded regions formed by using non-superconducting or weak superconducting materials (Figure 1.4). When the non-superconducting layer is an insulator, then it is called a superconductor–insulator–superconductor (SIS) junction. When it is a metallic one, then it is known as a superconductor–normal-superconductor (SNS) junction. Two weak superconducting materials also form a Josephson junction [22, 23]. The structure is very simple to construct. An insulating layer is placed between two superconducting layers. If the barrier is very thin, then the superconductor charge carriers (Cooper pairs) can be quantum-mechanically tunneled via a barrier height under no applied voltage, and thus there is a flow of current [24–27].

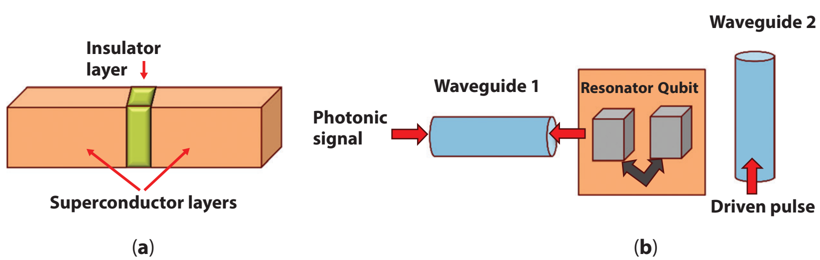

Figure 1.4 (a) Schematic of Josephson junction and (b) diagram of a three-level system for quantum applications.

In order to release a quantum-limited microwave amplifier, then the device needs to be in close proximity of the qubits without loss of heat. For this, a Josephson-based amplifier is needed. It might have several Josephson junctions to get the desired output. Normally, an amplifier is applied specifically with pump tones for precise frequency to activate gain activity, where it starts resonating, and we call it as superconducting parametric amplifier which operates at a very low cryogenic temperature near total zero Kelvin at which the Boltzmann energy is minor related to the lowest energy level. Here the microwave modes lead in the ground state with only present quantum-based variations. An input port is impedance coordinated with the transmission line which carries a weak microwave signal. Therefore, the signal fixed with qubit information is only passed and not reflected back [24–26].

The superconductor parametric amplifier is divided in two types, namely:

1. Cavity-based amplifiers
2. Traveling-wave parametric amplifiers

The cavity-based amplifiers consist of Josephson junctions like Josephson parametric amplifier (JPA) and Josephson parametric converter (JPC). The saturation power for these types of amplifiers is up to -120 to -100 dBm along with the bandwidth of 150 to 600 MHz [28, 29]. The traveling wave parametric amplifiers (TWPA) are based on transmission line structures like array of Josephson junctions or a long kinetic inductive structure. This type of device can achieve a bandwidth of around 3 GHz and power of 95 dBm [30]. For quantum-limited amplification, both types of amplifiers are utilized, i.e., circulators and isolators.

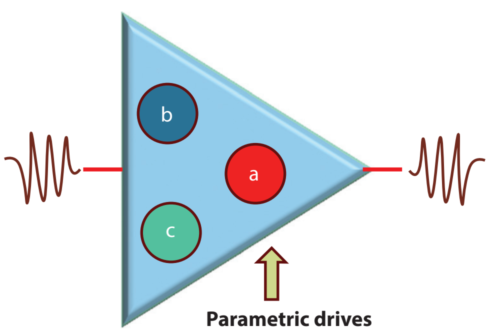

Figure 1.5 Schematic of a parametric amplifier.

1.4.2.2 Concept of Parametric Amplifier

The superconducting circuit contains a block having linear and non-linear modes and a non-linear Josephson junction. When a pump wave triggers the parametric non-linear element inside the circuit, an amplification occurs (Figure 1.5). The parametric amplification will be accomplished either as three-wave or four-wave mixing. Normally, three-wave mixing can be done using three electromagnetic waves, pump, signal, and idler with conservation of energy. Depending upon the signal and idler frequency, the degenerate and non-degenerate parametric process occur. In case of four-wave-mixing, two pump photons get transformed into one signal and one idler photon. The fourth-order terms in the Hamiltonian are used in this process.

Low-noise amplifiers are basically constructed on JPA and TWPAs configurations. In JPA, a coupling between pump tone to a signal via a non-linear Josephson junction is used. JPA shows a bandwidth in the range of 100 MHz. The good noise performance and small bandwidth allow a few qubits per amplifier to be read. However, the scale-up of this type of amplifier is limited due to restricted bandwidth [23, 31].

TWPA are suitable for quantum applications due to its quantum-limited amplifier and large bandwidth. These are designed using a transmission line and non-linear element such as Josephson junction with a large kinetic inductance, and thus a low pump power and dissipation are required [32–34].

1.4.3 Microwave Amplification by Stimulated Emission of Radiation (MASER)

MASER is an oscillator containing a source which excites atoms or molecules to the upper energy level. The microwave energy can be used to excite the electrons and obtain the population inversion condition required for amplification. At the population inversion, there will be more electrons than the lower energy level and the input microwave radiation will induce the stimulated emission; thus, amplification of the input radiation can be done (Figure 1.6). MASERS can operate at a higher temperature or even at room temperature, which is not possible for other types of amplifiers as discussed above. Normally, for wavelength in the range of millimeter or centimeter, the resonant modes can be tuned by choosing the size of the resonator metal box. So, only one resonant mode at a fixed frequency will be emitted. The losses inside the resonator can be lowered, which can significantly improve the amplification [12, 35, 36]. For device amplification,