Generation of Quantum States of Mechanical Excitation in Nanowires

Research Proposal

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A source of quantum states of phonons is considered as an experimental challenge and has been widely studied mainly in the frame of cavity quantum optomechanics. Mechanical excitation on the level of single phonons require the preparation of the system in its ground state. Such a state is achievable through side-band optomechanical cooling scenarios. An efficient and controllable source of phonons is a basic element of the recently developing subject of phononics, which have applications in information processing, communications and metrology. In the present proposal we suggest nanoscale wires as a strong candidate for the formation of quantum states of propagating phonons. Nanowires made of dielectric materials (e.g. of silicon) are solid components that can be easily integrated into all-optical on-chip platforms and are an ideal environment for photons and phonons to coexist and interact. Here photons and phonons can propagate along the nanowire axis and their transverse confinement result in rich photonic and phononic multi-mode. Stimulated Brillouin Scattering (SBS) have been demonstrated experimentally to be significantly enhanced inside naonoscale waveguides due to the new mechanism of radiation pressure beside the conventional electrostriction one. We have developed a microscopic quantum theory for the coupling of photons and phonons through SBS inside a nanowire. Our work extended the subject of conventional cavity quantum optomechanics into continuum quantum optomechanics, where we investigated quantum phenomena of strongly coupled photons and phonons.

We plan to suggest SBS as an efficient mechanism for the generation of quantum states of phonons inside nanowires by exploiting our recent quantum theory. We start by studying the influence of thermal phonons and the effect of phonon lifetimes on SBS processes. We target to get the conditions for achieving efficient control of the phonon states, and which are related on several parameters, such as photon-phonon coupling, photon and phonon lifetimes, photon coupling in and out the nanowire, and the average number of thermal phonons. We will adopt sideband optomechanical cooling scenarios for achieving mechanical ground state of gega Hertz frequency phonons at low temperatures. We aim to introduce SBS as a tool for controlling the generation of phonon quantum states. Depending on the input light field we expect to fix the appearance of specific phononic states. We target to study the formation of phonon Fock's states and phonon coherent states. In adopting the quantum Langevin equations with the aid of Green's functions we will extract the physical properties of the system by calculating various correlation functions. We target to figure out useful applications of the phonon quantum states, e.g. "phonon laser" and probing organic molecules by a source of single phonons. At high density of phonons, we expect the harmonic model to break down and an-harmonic effects will take place. We target to derive the phonon-phonon coupling parameter in naowires and to search for fruitful applications such as phonon information processing and phonon-soliton behavior.

I. SCIENTIFIC BACKGROUND

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A. Stimulated Brillouin Scattering

Light propagate in the forward direction inside isotropic dielectric media, whereas fluctuations in the optical properties of the homogeneous medium result in light scattering. Two categories are usually presented in the literature for the classification of light scattering. Spontaneous scattering in which the medium optical properties are unmodified by the presence of the light, and stimulated scattering where fluctuations are induced by the presence of the light. Spontaneous scattering appears usually at low intensity of light, while at high intensity stimulated scattering take place. In addition, the scattering of light can be elastic or inelastic, in which the energy of the light is conserved or un-conserved, respectively. Moreover, at inelastic scattering two processes are possible. Stokes processes where the scattered light is shifted toward lower frequencies, and anti-Stokes processes where the scattered light is shifted toward higher frequencies.

Scalar fluctuations in the thermodynamics quantities of the medium (e.g. pressure, density, entropy, and temperature) could lead to fluctuations in the medium dielectric constant and as a result to scattering of light. Several channels for the scattering of light inside solid material can actually open. The significant ones are the elastic Rayleigh scattering and the inelastic Brillouin and Raman scattering. Rayleigh scattering is the scattering of light from localized density fluctuations (mainly entropy fluctuations). In Brillouin scattering the light is scattered from sound waves, namely scattering from pressure and density fluctuations. On the other hand, in Raman scattering the light is scattered from localized vibrational modes that appear due tensor-type fluctuations.

Historically, the first prediction of inelastic scattering of light from sound waves was reported by Brillouin in (1922). While Mandelstam suggested the possibility of light scattering from thermal acoustic vibrations in (1918), but it was only published in (1926). The required high intensity of monochromatic light sources delayed the observation of Brillouin scattering till after the invention of the laser, and was first reported by Chaio et al. in (1964) for bulk material. Stimulated Brillouin Scattering (SBS) appear when the light induces fluctuations that change the optical properties of the medium and cause scattering of the light. The physical mechanism behind such scattering is electrostriction that related to the tendency of dielectric material to get compressed in the presence of light, and which result in photoelastic effect where changes in the medium density produce changes in its optical properties [1, 2].

Let us explore first one-directional Stokes SBS, where we consider backward SBS of two counter propagating light fields, a pump field and a probe Stokes field. The pump field has frequency ω_p and wavenumber k_p, and the Stokes field has frequency ω_s and wavenumber k_s. The interference between the two fields forms a beat pattern that moves with velocity $v = \Delta\omega/\Delta k$, where $\Delta\omega = \omega_p - \omega_s$ and $\Delta k = k_p - k_s$. Due to electrostriction effect the beat pattern creates density fluctuations that give rise to sound waves, if the beat velocity v matches the sound velocity v_a in the medium.

This condition is accompanied with the conservation of energy and momentum that implies the sound wave frequency to obey $\Omega = \omega_p - \omega_s$, and the sound wavenumber to obey $q = k_p - k_s$. Afterwards, due to electro-optics effect, sound waves could generate a propagating index grating that stimulates scattering of the pump field into the probe field, and as a result generates a stimulated cycle that amplifies the sound waves.

Detail calculations of the backward Stokes SBS show that for an input probe field of intensity $I_s(0)$, the output probe intensity is given by $I_s(L) = e^G I_s(0)$, where the gain parameter is defined by $G = gP_pL/A$. Here g is the Brillouin gain factor, L is the device length, A is an effective area, and P_p is a given pump power. In general, g is relatively small, hence in order to achieve a large gain parameter at a moderate pump power, of about 10 mW, one either appeal to long propagating length L, or small effective area A.

Optical fibers made of silica material were among the first candidates that enhance significantly SBS, as for optical fibers with relatively large cross section the light can propagate tens of kilometers. For waveguides in general, and optical fibers in particular, only backward and forward scattering could exist. In the backward scattering the pump and probe fields are counter-propagating, while in the forward scattering they co-propagating. However, the forward scattering in waveguides is weak relative to the backward one. As mentioned above, in backward Brillouin scattering the Stokes field interferes with the pump field to generate sound waves that produces a moving density grating from which the light backward scatter. In the last decades several types of waveguide devices with different architectures and materials have been fabricated in order to improve the SBS gain parameter [3–5].

B. SBS in Nanoscale Waveguides

In the recent years big progress has been achieved in fabricating waveguides with smaller and smaller cross sections approaching the nanoscale dimension devices that open new horizons for SBS. For waveguides of relatively short lengths significant SBS can be obtained for small cross sections. Surprisingly a breakthrough in SBS has been appeared for waveguides at the nanoscale dimension due to a new mechanism that became dominant and which is induced by radiation pressure, as predicted in [6–9] theoretically and realized experimentally [10–13]. In such setups the light wavelength λ becomes of the order of the structure dimension d. Radiation pressure can provide strong coupling between light fields and acoustic waves that lead to a significant enhancement of SBS in nanoscale waveguides at relatively low pump field power. By contrast, radiation pressure found to be negligible at waveguides with dimension down to microscale. The confinement of light in nanoscale waveguides, at $\lambda > d$, produces strong interactions between the light and the boundaries that lead to radiation pressure. Radiation pressure implies high contrast nanoscale waveguides, which is the case for dielectric waveguides of relatively high refractive index that is embedded in free space. In such structures the combination of electrostriction and radiation pressure lead to backward as well as forward SBS, which is enhanced by orders of magnitude relative to the case of bulk materials. In particular a significant enhancement of the forward SBS relative to conventional waveguides is revealed. Just to mention that the gain parameter for a nanoscale waveguide of 100 μm length is equivalent to a kilometer of a conventional optical fiber.

Several proposals appear in the literature for the realization of nanoscale waveguides. Among the main factors that strongly limit the efficiency of each device is the waveguide mechanical quality factor that also fixes the sound wave lifetime. For example, in on-chip waveguides the quality factor is low, due to direct contacts between the waveguide and the substrate material, and that lead to relatively short lifetime for the sound waves. On the other hand, suspended nanoscale waveguides, e.g. of silicon nanowires, have higher quality factor with longer lifetime sound waves, but they are limited to a very short length that consequently reduces the gain parameter. A compromise has been suggested by using nanoscale silicon wires supported with a tiny pillar, the fact that keeps a reasonable quality factor and allows the achievement of relatively long waveguides [14].

SBS in waveguides can be involved in a wide range of applications for photonics, communications and information processing. Here we introduce results of importance for the current proposal. The significant enhancement of SBS in silicon nanowires lead to amplification of the Stokes field [12, 13, 15] and paved the way toward Brillouin laser [16]. Such laser exploits stimulated intermodal forward Brillouin scattering, which couples light fields from distinct optical spatial guided modes. A silicon Brillouin laser extend the use of silicon components from electronics into photonics. Moreover, controlling the propagation of light in an optical medium can be achieved in using electromagnetic induced transparency, which can produce fast and slow light. SBS has been suggested for the generation of fast and slow light [17]. In [18] they have demonstrated Brillouin scattering induced transparency in exploiting long-lived propagating light and phonons in a silica resonator under the required phase-matching. Furthermore, optomechanical cooling following sideband cooling scenarios in a continuous system have been demonstrated in [16] using SBS, where a continuum of traveling wave phonons in a nanowire has been cooled by tens of Kelvins.

Storage of light is an important step toward photonic information processing. Storing an optical pulse by converting it into long lived acoustic excitations in an optical fiber through SBS has been presented in [19]. The pulse can be retrieved later after a time shorter than the acoustic excitation lifetime. The method can be used efficiently to store data coherently for a while, that is of importance for application in communication processes. Recently coherent phonons have been directly excited by optical photons through acousto-optic strong coupling in integrated circuit realizing a coherent all-optical memory [20]. The experiment demonstrates a coherent on-chip memory that allows storing the entire coherent information carried by light as acoustic phonons.

II. CONTRIBUTIONS AND PRELIMINARY RESULTS

In our previous work we have introduced a microscopic quantum theory for SBS in nanoscale waveguides [9]. The study provides a deep understanding of the coupling between light fields and mechanical vibrations on the level of single photons and phonons, and lays the foundation for the current proposal. We have developed a systematic method for deriving a quantum optical multimode Hamiltonian for the interaction of photons and phonons in nanophotonic dielectric materials by applying perturbation theory to the electromagnetic Hamiltonian. The Hamiltonian covers radiation pressure and electrostrictive interactions on equal footing. As a paradigmatic example, we applied our method to a cylindrical nanoscale waveguide, and derived a Hamiltonian description of Brillouin quantum optomechanics. We have shown analytically that in nanoscale waveguides radiation pressure dominates over electrostriction, in agreement with recent experiments. The calculated photon-phonon coupling parameters are used to infer gain parameters of Stokes Brillouin scattering in good agreement with experimental observations.

Quantum optomechanics is the study of phenomena originating from the mutual interaction between electromagnetic radiation and mechanical motion [21]. In conventional cavity optomechanics both the electromagnetic field and the mechanical vibrations are effectively restricted to single modes, and the strong coupling among phonons and photons enables the demonstration of various quantum mechanical effects. Moreover, in the domain of optical frequencies strongest optomechanical coupling has been obtained in optomechanical crystals [22, 23] where nanostructuring of dielectric materials is exploited to generate phonon and photon modes with strong spatial localization in order to enhance the light-matter interactions.

Very recently, the experimental progress with nanophotonics waveguides supporting long-lived high-frequency phonon modes evidenced that quantum optomechanical effects may become accessible also within a multi-mode version of optomechanics involving continua of propagating phonon and photon modes [6, 8, 10–12, 24]. So far, the dominant mechanism for optomechanical coupling in waveguides has been electrostriction, that is the modulation of the index of refraction of the bulk dielectric material associated with its acoustic vibrations causing scattering of photons on these periodic index modulations. The recent experiments with nanophotonic waveguides entered a new regime where radiation pressure effects due to vibrational surface deformations start to dominate over electrostriction which result in vastly enhanced photon-phonon coupling [25–28]. At the same time, these devices can maintain large quality factors for GHz mechanical modes extending over long cm-scale nanowires providing large optomechanical interactions over significant time and length scales. Overall, these developments indicate Brillouin quantum optomechanics as a promising route towards integrable, broad-band platforms supporting strongly interacting fields of phonons and photons [29].

We have expanded the subject of quantum optomechanics dealing with coupled discrete localized photons and phonons into continuum quantum optomechanics in extended nanoscale waveguides in which both photons and phonons are delocalized and propagating [9]. Moreover, our study combines quantum optomechanics with classical Brillouin scattering into a new regime of Brillouin quantum optomechanics. In nanoscale waveguides the electrostriction mechanism of Brillouin scattering coexists with radiation pressure mechanism of quantum optomechanics.

Explicitly, we have developed a unified multi-mode photon-phonon interaction Hamiltonian that includes on equal footing electrostriction and radiation pressure mechanisms in dielectric materials, which provides a comprehensive basis for continuum quantum optomechanics. Our starting point was in applying perturbation theory to the classical electromagnetic field Hamiltonian in dielectric media. Perturbing the bulk value of the dielectric function and the material surface yields, respectively, the electrostrictive and the radiation pressure Hamiltonian. Afterwards, we followed a systematic canonical quantization procedure, following [30], that yields the coupled multi-mode photon-phonon interaction Hamiltonian.

Realizing the promise of quantum computers is dependent on the development of physical systems that can process quantum information. While several candidates have been suggested in recent years, each with its set of advantages and disadvantages, none fulfil the complete set of criteria for achieving efficient quantum computers. For example, photons are by nature non-interacting particles, a fact that makes them unsuitable for quantum information processing, but they are widely used in quantum communication. We introduce nanophotonic structures as a strong candidate for the physical implementation of quantum information processing using photons [9, 31]. Nanostructures are made of solid components and serve as quantum devices that can be easily integrated into on-chip platforms. Photons inside nanoscale structures have been shown to strongly interact, making them suitable for quantum information processing. Our study serves as an important step toward an all-optical on-chip platform in which the same photons that participate in quantum communication can be involved in quantum computing. We explore the possibility of achieving a significant nonlinear phase shift among photons propagating in nanoscale waveguides exploiting interactions among photons that are mediated by vibrational modes and induced through SBS [31]. We introduce a configuration that allows slowing down the photons by several orders of magnitude via SBS involving sound waves in the presence of pump fields. The nonlinear phase among two counter-propagating photons can be used to realize a deterministic quantum logic gate [32]. Such photon-phonon interactions are exploited in order to generate a coherent mix of photons and phonons with manifest quantum phenomena [32–34].

III. RESEARCH OBJECTIVES AND EXPECTED SIGNIFICANCE

First, we would like to introduce the general frame for the current proposal. Nanophotonic structures have advantages over other setups in their simplicity and on-chip integration. Nanoscale waveguides as solid-state components can be easily implemented as device elements for all-optical platforms [29]. The microscopic theory we have developed for interacting photons and phonons in nanophotonic waveguides paved the way for further studies in different directions of importance for fundamental physics and applications [9, 31]. Our main concern here will be in quantum phenomena related to the coupled electromagnetic fields and mechanical excitations inside nanoscale waveguides. The emphasize will put on the strong coupling between photons and phonons inside those components that induced through electrostriction and radiation pressure, with consequences that can extend the horizon of the well-established subject of nanophotonics with applications for quantum information processing. Strongly coupled photons and phonons in nanoscale waveguides extends the subject of conventional quantum optomechanics into the continuum regime and open new domains of research for nanophononics with quantum phenomena involving phonons.

Before presenting the proposal aims we would like to emphasize some obstacles that stand in front achieving coherent phononic phenomena in nanowires and to provide ways in order to overcome such issues. In the setup the input light field is sent into the waveguide through the edges, and the scattered light that involved in SBS is observed also out of the edges. Namely one has a direct access to the photonic part but not to the phononic one. The information concerning the mechanical excitation can be extracted out of the output light field. Furthermore, thermal phonons are among the main obstacles in front of achieving efficient processes involving photons and phonons. For example, the amplification of the Stokes and anti-Stokes fields [35, 36], and the silicon Brillouin laser [37, 38], are limited by the appearance of thermal mechanical excitation. Optomechanical cooling in continuum systems provides a solution of such limitation [16]. Moreover, several phenomena are sensitive to the phonon lifetime. Storage of light implies a long lifetime of the phonon that is related to the mechanical quality factor [20]. Special engineering of nanoscale waveguides allows the achievement of mechanical high quality factor [10–13]. In our previous work effective photon-photon interactions and the formation of photon bound states have been predicted and which is of importance for optical quantum information processing [31, 32]. The effective photon-photon interaction is mediated by phonons and implies long phonon lifetime with average number of thermal phonons that is much smaller than one [39].

In all the above configurations the phonons are central and play important roles. They are treated as a source of noise or involved in phenomena related to SBS, but the main interest is on the photonic part and not on the phononic one. However, in part of the experiments coherent phonons are expected to appear within the system, such as for silicon Brillouin laser [16] and for light memory devices [20]. Moreover, in our previous work we studied the formation of photon-phonon collective states, in which the phonons are strongly entangled with the photons. For example the formation of polaritons that involve coherent oscillation between photons and phonons [33], and the appearance of squeezed states of mixed photon-phonon coherent states where photon-phonon pairs are created and annihilated [34]. But, the appearance of collective states is expected to be observed through the photonic part without direct access to the phononic one.

In the light of the above view, the current proposal is concentrated mainly in the phononic part. We aim to study the phonon properties and their behavior inside nanowires at different useful configurations. We start in studying the influence of thermal phonons and to survey the techniques in order to minimize them through optomechanical and thermodynamical cooling. We address the issue of phonon lifetimes and survey the setup engineering suggested in order to increase the mechanical quality factor. Afterward we target to investigate the use of SBS in nanowires as a controllable source of phonons. We explore the possibility of the appearance of phonon Fock's states, ranging from a single phonon up to several phonons, where we expect the system to serve as a source of single propagating phonons in demand. We aim to search for the appearance of phonon coherent states through SBS of laser fields in nanoscale waveguide. The case can be considered as a source of "phonon laser", which have a wide range of useful applications in biological nanoscience. Once achieving coherent states with high density of phonons, nonlinear phenomena become important. We target to study phonon-phonon interactions and their physical implementation for phonon information processing. In the following the main aims of the proposal are listed.

Phononics in nanoscale waveguides:

- *The influence of thermal phonons on processes involving SBS.*
- *A survey of mechanical cooling and nanowire engineering toward high quality factor.*
- *Nanowires as a source of single phonons and phonon Fock's states.*
- *"Phonon Laser": the appearance of phonon propagating coherent states in nanowires.*
- *Phonon nonlinear effects and phonon-phonon interaction in nanowires.*
- *Useful applications of phonon states for information processing and molecular biology.*

IV. DETAILED DESCRIPTION AND WORKING HYPOTHESIS

Nanophononics is the study of phonon dynamics in nanoscale structures in the frame of microscopic quantum theory. We plan to investigate quantum phenomena related to phonons in nanoscale waveguides by exploiting the rich spectrum of phonon modes. We use the strong Brillouin coupling between photons and phonons as an efficient tool for exciting and controlling quantum states of phonons. The majority of recent experiments are performed at room temperature, then thermal excitation has big influence and play a critical role in the appearance of coherent phenomena related to phonons. On the other hand, coherent states of light are observed in such same conditions, as thermal photons are negligible at room temperature. Therefore, the first step toward coherent behavior of phonons implies the removal of thermal phonons. The first part of the proposal aims to study the influence of thermal phonons in processes involving Brillouin scattering. We survey the scenarios that appear in the literature for optomechanical cooling of phonons, and we present the recent experimental progress in the subject. Furthermore, the issue of the phonon lifetime is of big importance for achieving coherent states of phonons in nanoscale waveguides. We search for the techniques that have been introduced for achieving long lifetime phonons.

In the central part of the proposal we target to exploit Brillouin scattering in nanowires as a mechanism for getting a source of single phonons in demand, and a source of Fock's states of phonons. We will extract the experimental conditions for such processes and figure out useful applications. We extend the study toward achieving a source of coherent states of phonons. We aim to develop a quantum theory of "phonon laser" and to provide their quantum properties and stability condition. Such coherent states imply high intensity of phonons, the fact that open the door to nonlinear effects of phonons. Hence, we target to study nonlinear phenomena in nanowires by deriving phonon-phonon interactions and their influence on the dynamics of the coherent states. Interactions between phonons are a mechanism for obtaining information processing of phonons.

A. Thermal Noise and Phonon Lifetime

In all processes involving SBS the light fields are sent through the waveguide. The Brillouin scattering of the light field off the thermal mechanical excitation inside the nanowire limit any efficient performance via SBS [35, 36, 38, 40, 41]. Thermal fluctuations lead to decoherence phenomena for both photons and phonons and destroy the formation of coherent states. Moreover, thermal fluctuations wash out any processes on the level of single phonons. Therefore, we aim to perform a deep study about the influence of thermal phonons on SBS inside nanowires. We target to achieve a condition on the average number of thermal phonons inside nanowires. In order to minimize thermal phonons one can thermodynamically cool down the nanowire at cryogenic temperatures [42], or to appeal to optomechanical cooling [16].

To achieve the efficient performance of quantum processing in nanoscale waveguides the phonons required to be near their ground state which implies phonon cooling, e.g., following sideband cooling scenarios [16, 26, 43, 44]. Brillouin scattering is exploited in order to cool thermal phonons in extended nanostructures by benefiting from the strong photon-phonon coupling due to radiation pressure. Here both phonons and photons are propagating fields with given wavenumbers, the fact that impose phase-matching condition on processes involving photons and phonons. Namely, the conservation of momentum is required besides the conservation of energy. The existence of several multi-mode phonon branches, of acoustic and vibrational modes, makes both Stokes and anti-Stokes processes to play significant roles in the Brillouin scattering. Moreover, in nanoscale waveguides both backward and forward Brillouin scattering can take place. Stokes processes can dominate due to the appearance of thermal phonons and that lead to heating. By careful choose of phase-matching of the fields one can achieve cooling by stimulating the anti-Stokes process while keeping the Stokes one off-resonance. The cooling is achieved by the scattering of a lower frequency photon into a higher one in absorbing a phonon. In principle the cascade of photons into lower frequency ones by the emission of phonon modes through Stokes scattering can be depressed by careful choose of the photons involved in the process.

The photon lifetime duration is usually enough long for photons to propagate along the nanowire length and for the appearance of coherent phenomena. The Phonon lifetime is much smaller than the photon one, and the sound velocity is much smaller than the light group velocity inside nanowires. Different techniques have been developed for increasing the mechanical quality factor and hence minimizing the phonon damping rate by reducing the direct contact between the nanowire and the on-chip substrate material and in the same time keeping the nanowire length enough long for the phonon to propagate. We aim to examine the condition on the phonon damping rate in order to minimize the decoherence effect and to allow the appearance of phonon coherent states of propagating phonons within the nanowire.

B. Phonon Fock's and Coherent States

A source of single propagating phonons in demand is of big importance for fundamental science and applications. All information processing involving phonons imply a controllable source of phonons. The formation of Fock's states of phonons is a big experimental challenge [45–47]. We propose nanowires (e.g. of silicon [13]) as a source of phonon number states in exploiting Brillouin scattering. Starting from a nanowire at the ground mechanical state, by sending pump and probe light fields on the level of single photons, Fock's states of phonons can be achieved through SBS. For example, a single pump photon scatters into a probe photon of lower frequency by the emission of a phonon. The process is of the Stokes type and obey conservation of energy and momentum. One can choose photons from different spatial modes such that the inter-modal SBS can suppress the anti-Stokes process and allows only the Stokes one [13, 48]. Inter-modal SBS provides a tool for avoiding cascaded processes of photons along a specific optical branch [28, 37]

We aim to explore the formation of Fock's states of phonons inside nanowires and to investigate their properties and the condition for their appearance and stability. For example, single propagating phonons inside a nanowire are important for studying the vibrational modes of organic molecules which is of importance for molecular biology, pharmacology and metrology. A ground state organic molecule can be excited to a fixed vibrational state in a controllable way by bringing it to direct contact with a nanowire containing propagating phonons.

We aim to extend the study toward "phonon laser", which is a demanding source of coherent states of phonons with application to physical and medical sciences. In shining the nanophotonic waveguide with external pump and probe laser fields at specific frequencies and wavenumbers that are close to resonance with a single phonon mode, one can obtain a coherent source of phonons by exploiting the strong photon-phonon coupling [49]. As in the case of phonon Fock's states, we consider inter-modal SBS that discriminate between Stokes and anti-Stokes processes. We target to perform a deep study in the frame of microscopic quantum theory with emphasize on thermal and quantum fluctuations. The transport of phonon coherent states and their transfer outside the nanowire is a big experimental challenge that need also much theoretical study.

Populating the nanowire with large intensity of phonons could break down the harmonic regime and to enter the nonlinear an-harmonic regime. High mechanical excitation strongly deforms the nanowire the fact that result in coupling between phonons. We aim to derive the phonon-phonon interaction due to both electrostriction and radiation pressure. An-harmonic phenomena can affect the phonon dynamics and can show soliton behavior [50]. Nonlinear phononic phenomena can be of interest for quantum information processing involving phonons [51]. We will develop a quantum theory of interacting phonons and investigate different useful applications.

V. RESEARCH DESIGN AND METHODS

In the following we present our research design including the methods we plan to use.

• We aim to develop a microscopic quantum theory of coupled photons and phonons inside a nanowire with emphasize on phononics. We will apply quantization of the classical electromagnetic field [52] and of the mechanical excitation [53], and use creation and annihilation operators in the second quantization formalism [54]. In the real space representation for time dependent signals we use field operators. In the papers [9, 31, 33, 34] we have developed a microscopic theory for investigating quantum phenomena of photons and phonons that are coupled through SBS.

• The system of a nanowire is open and coupled to the environment. The photons are coupled to the surrounding radiation field that serves as zero temperature reservoir. The photons can leak into the radiation field with a given damping rate. The wire material at finite temperature includes a reservoir of thermal phonons with a given average number of quanta. The reservoir induces thermal fluctuation and scattering of the photons and the phonons. Moreover, the phonons can leak out of the nanowire into the substrate material with a given damping rate. The coupling to thermal reservoir can be treated in using the Maser equation method [55]. Furthermore, the photons are injected into the nanowire through the edges that also allow the photon to leak outside the system. The photon coupling through the edges is treated by applying the input-output formalism [56].

• The photon and phonon dynamics are treated in using the Heisenberg-Langevin equations that combine the photon-phonon interaction and their spontaneous decay. The coupling to the thermal reservoir is including through the fluctuating Langevin force [57]. The hierarchy of equations can be simplified by applying known approximations, such as the rotating wave approximation and the Born factorization approximation. The behavior of the phononic part can be achieved by adiabatic elimination of the photonic part. A deep understanding of the phononic part can be achieved by appeal to Green's function methods that provide correlation functions and spectral functions, which are directly related to experimental observables [58–60]. In the paper [39] we have calculated the photon and phonon spectral functions in using the method of Green's functions, and in the paper [32] we explored the formation of photon molecules using effective photon-photon interaction mediated by phonons in using Keldysh-Baym formalism [61, 62].

• The solutions of the phonon equations of motion, obtained from the Langevin equations with inputs from the Green's functions, yield the physical properties of the phonons in nanowires. We will investigate the results under various input light fields and under different conditions of temperature and nanowire quality factor. We aim to find the condition for obtaining quantum states of propagating phonons. We concentrate in the two cases of phonon Fock's states and phonon coherent states. The quantum state properties will be extracted from the phonon Green's functions, such as fluctuations and coherent features.

• An-harmonic behavior of phonons appears at high density of phonons and is represented quantum mechanically as phonon-phonon interaction. The coupling will be extracted from higher order terms of the mechanical Hamiltonian perturbation theory [63–65]. The phonon dynamics in the an-harmonic model can be treated in solving the nonlinear equation in the mean field theory. We expect to obtain a soliton solution out of the interplay between phonon attraction and damping [50]. The soliton solution can provide a long-distance propagating phonon inside enough long nanowire and yield useful applications.

VI. RESEARCH PLAN AND RESOURCES

Time Plan: The project's time schedule is as follows:

- **1st year:** The influence of thermal phonons on SBS and the role of excitation lifetimes
- **2nd year:** Nanowires as a source of Fock's states of propagating phonons
- **3rd year:** The formation of phonon coherent states and "phonon laser"
- **4th year:** Phonon-phonon interactions and the appearance of solitons

Resources: All the topics presented in this proposal can be demonstrated with the current state-of-the-art at several experimental groups, and the results of the proposal are expected to be of importance for planning future experiments. The main components that are required in order to realize the proposal's targets are nanoscale wires, which are currently fabricated in labs worldwide. For example, nanowires made of different materials (e.g. silicon) are investigated by the Rakich group at Yale University (USA) [49], Eggleton group at the University of Sydney (Australia) [14], Safavi-Naeini group at Stanfod University (USA) [29], Sylvestre group at CNRS Besancon (France) [66], Van Thourhout group at Ghent University (Belgium) [10], and others. Moreover, tapered nanofibers made of silica are of use for realizing the current proposal's aims. Tapered nanofibers are fabricated by many groups worldwide, e.g., Rauschenbeutel group at Humboldt University Berlin (Germany) [67].

My vast experience in the field of light-matter interactions, in general, and nanoscale systems, optomechanics and quantum optics, in particular, and proficiency in a wide range of quantum theory methods and techniques, mainly in many-body physics and quantum field theory, ideally position me to perform the proposed research.

The suggested proposal is expected to take four years and requires computers with ordinary software and professional literature. A postdoc (TBD) will be responsible for realizing part of the aims of the proposal within the scheduled time plan (Years 2-4).

To realize the project's goals, I intend to collaborate with several theoreticians, including Klemens Hammerer (Hanover University), Helmut Ritsch (Innsbruck University), and Giuseppe La Rocca (Scuola Normale Superiore di Pisa), and experimental groups, such as Safavi-Naeini (Stanford University), and Peter Rakich (Yale University). Moreover, I will share and discuss the project's progress and findings at international conferences.

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