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論　文　名　「Theory of Optical Microcavity-based Laser Cooling for Indirect Control of Electronic States」
（電子状態の間接制御に向けた微小光共振器に基づくレーザー冷却の理論）

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論文要旨

Radiation force as one of key elements in this thesis has been widely studied in various research fields due to numerous potential applications for the dynamical control of small objects like laser cooling of atoms via reducing their kinetic energies. In the conventional measurements of weak signals, fluctuations in position and momentum from noise sources prevent the highly sensitive detections. Therefore, the novel principle of noise suppression is strongly required in the field of scanning probe microscope (SPM) and various sensitive measurements.

An optical microcavity (OMC) is the promising system to enhance the coupling between light and matter resulting in the enhancement of radiation force. In the mutual coupling between the light and mirrors, the delayed response of the light intensity with the change in mirror position leading to an effective mechanical damping. In red-detuned cavities, this damping is enhanced and the vibrating amplitude is suppressed. This mechanism has succeeded in cooling a SPM cantilever effectively based on the photothermal force. However, the cooling based on the delayed response time is ineffective for fast response forces such as the radiation force and an innovative cooling principle has been desired.

Therefore, in this thesis, the nonlinear dynamics of nano- and micro-mechanical systems based on the laser cooling with cavity-induced radiation force (CIRF) has been theoretically studied for the applications in sensitive measurements such as the SPM and for the cooling of mechanical modes with high frequency to indirectly control electronic states coupled with phonons.

Theoretical model and methods are summarized in Chapter 2. A real time analysis of dynamics of a SPM cantilver has been performed based on the extended Duffing equation including the CIRF exhibiting nonlinear position dependence. Furthermore, a frequency domain analysis based on quantum descriptions has been carried out to provide the deep physical insight on the results of real time analyses and future applications in nanoscale systems.

The main results are as follow:

(1) <Chapter 3> Nonlinear real time analysis of the dynamics of SPM cantilever has been performed with the extended Duffing equation including the CIRF. Vibration of the mechanical oscillator can be significantly damped with negative optical rigidity leading to the shift of the mechanical frequency with a near-resonant CIRF depending on the laser intensity. Remarkably, I have clarified the novel principle for the laser cooling of cantilever depending on the averaged collision velocity of ambient molecules. By selecting the medium, this principle is useful for the super-sensitive measurements of small molecular masses, weak signals in SPM with high spatial resolution, and quantum properties of nanoscale objects.

(2) <Chapter 4> Systematic analysis of the nonlinear mechanical dynamics of OMCs in frequency domain was performed based on the quantum approach. Coupled equations with Hamiltonian formalism are used to describe both the mechanical and optical modes to explore the mechanism of enhancements in mechanical damping and shifts in resonant frequency. Two types of systems are considered in this part: the first one, Model ⟨A⟩, is the low frequency system similar to that considered in (1), and the second one, Model ⟨B⟩, is the high frequency system with the intention to applications for the control of phonons coupled with excitons in low dimensional system. In the model ⟨A⟩ with sub-MHz frequency, it has been confirmed that the frequency shifts and mechanical damping enhancement play important roles for the cooling of SPM cantilever with increasing laser power. In the model ⟨B⟩ with sub-GHz oscillators, it has been clarified that asymmetric behavior of anti-Stokes and Stokes Raman scattering leads to the effective laser cooling at low initial ambient temperature to achieve an effective temperature of 0.5 mK corresponding to the effective quantum number of 0.5 under the optimum condition.

These results and discussion will open a way to apply the laser cooling to a novel guiding principle of SPM measurement in a particular fluid medium, and to the control method of the specific phonon modes interacting with electronic states, such as the excitons embedded in the OMC. In the future, applying the obtained cooling principle to other interaction mechanisms, e.g. acoustic phonons in low dimensional systems confining excitons such as nanotubes and quantum wells, or optical phonons in solids, we could realize effective interaction channels for the control of energy relaxation processes to facilitate the novel type of exciton Bose-Einstein Condensation.

審査結果の要旨

本論文は、微小光共振器(OMC)で増強された輻射力によるレーザー冷却による走査型プローブ顕微鏡(SPM)のノイズ制御や、フォノンの動力学制御の原理について理論的に議論している。原子のレーザー冷却は、光源に対向して飛来する原子の運動エネルギーを輻射力により減少させることで有効温度を極低温に導く技術として知られている。一方、SPM のカンチレバーのようなマクロな系でもその背面に高反射率の薄膜を付して光源との間に OMC を構成して輻射力を増強すれば、レーザー冷却が可能となり。本論文では、このような可動型 OMC の非線形動力学の解析を環境の効果も考慮して行い、マクロな系のレーザー冷却の新原理と応用可能性を探っている。得られた主な結果は以下のように要約される。

１）SPM カンチレバーの背面に OMC を構成した系を想定し、レーザー冷却の実時間解析を通じてナノ計測技術の高感度への応用可能性を議論している。
<1-a>OMC 中の光電場の急峻な変化による光学的な弾性率の変調によりカンチレバーの振動周期が非線形な時間依存性を示し、振動外場による共振を免れてレーザー冷却が可能であることを確認している。
<1-b>赤方離調の場合に、レーザーパワーによって負の弾性率が得られることや、有効温度が極小となる条件を明らかにした。特に、ランダムに媒質分子がカンチレバーに衝突する系を想定したモデル計算で、単位時間当たりの衝突頻度が高いほど冷却効率が向上する条件を明らかにしている。

２）量子力学的観点から可動型 OMC の非線形動力学解析を周波数領域で行っている。
<2-a>レーザーパワーの増加による光と振動子の結合パラメータの増強に伴い、機械的なダンピングが増大して振動子の振幅が大幅に減少することを確認した。また、初期の環境温度に依存して冷却効率が変化することを確かめた。
<2-b>高周波の振動子系を想定した計算で、同じ結合パラメータでも、反ストークス線とストークス線のピークの非対称性が低周波の場合よりも顕著となり、大幅に冷却効率が向上してサブ mK まで冷却できる可能性を示した。

以上の研究は、環境依存型のマクロな系のレーザー冷却の新原理を解明したと同時に SPM の高感度化に関する新しい選択肢を与え、低次元ナノ物質中のフォノン-電子結合系の制御に関する基礎的知見も与える重要な成果である。また、申請者が自立して研究活動を行うのに必要な能力と学識とを有することを証したものである。