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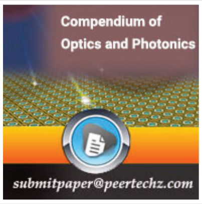

Review Article

Optomechanics and Sensing Phenomena: An Analysis in Classical-quantum Relationship

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Abstract

As a multi-approach sensing field optomechanics is primarily related to the interaction between optical and mechanical modes interaction. Light-matters dealings in linear to non-linear routes are trails of precision and Quantum Sensing (QS). Light is a wave-matter quantum entity from the classical Electromagnetic (EM) field in which matter is entangled with waves in space-time dimension. The interaction of electromagnetic radiation with the motion of objects and the gravity action is an energy perturbation and complex phenomenon. The energy-mass relation is like wave matter in which a possible link between classical and quantum mechanics is imperative for advanced opto-mechanical sensing. The quantization of mechanical energy and its interaction with light is a process that can be used for diverse sensing purposes. In this study light and gravity-related electromagnetic and mechanical system linkage has been elucidated systematically at macro and micro levels for optomechanical sensing system further development.

Introduction

Everything in the universe is in a particular process of mechanical interaction whether it is visible or not. Whenever we realize it then it turns into light–mechanical motion or light-matter interaction. The light-matter interaction and energy or information exchange between light and matter is very crucial in photo sensing, optoelectronics, and materials design for quantum computing. Quanta of light as photon deals with electromagnetic radiation whereas quanta of atomic vibration within a lattice as phonon is characterized by mechanical vibration. Photon-phonon interaction exchanges their energy level and photon-phonon coupling is resulting significant changes in quantum phases of matter that are related to quantum information as emergent properties of matter. Moreover, controlling heat flow in the process of photon-phonon interaction is key to dealing with optomechanics. Any stimuli converted into mechanical motion followed by optical interaction with mechanical motion suitable for high-level sensing in optomechanics. Light is an Electromagnetic (EM) entity and its interaction with mechanical systems diverse band EM interacts with mechanical motions. This interaction typically involves the transfer of energy between the optical and mechanical degrees of freedom. It relies on linear momentum exchange between light and matter. However, in the optical field, the polarization and orbital angular momentum are the ultimate path of light-matter interactions [1]. Particle polarization determines the charged state and its interaction with light is optomechanical which involves an exchange of energy and its dynamics towards a nonlinear platform. Diverse band light interaction in the non-linear environment based on its fundamental reflection, transmission, absorption, and emission properties are vital for sensing. Different energies including phonon energy, and their analysis in the optomechanical system is a new dimension of precision sensing [2]. From the cosmic model to the localized atomic or molecular sensing model, the EM and gravitational fields are linked with mechanical modes of interaction [3,4].

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Gravity interactions at large scales are significant phenomena like gravitational lensing, while the electromagnetic field dominates interactions at atomic and molecular scales. It is crucial to understand the behavior of the interaction of light with matter at these scales. So, light-matter interaction in EM and gravity field interface is a more realistic idea. Through the process of exchange of photons-phonon energy at the material's interface is the accessing of quantum mechanics at a more macroscopic level as shown in Figure 1. To bring the mechanical system to the quantum field and light momentum exchange to the mechanical system diverse optomechanical sensing is forthcoming. Quantum mechanics matter is entangled with waves where gravity itself is a space-time curvature model of mass and energy. Hence, the quantized nature of both the electromagnetic field and mechanical motion is quantum optomechanics. The use of quantum objects such as quantized electrical, magnetic, or vibrational energy for superconducting, spin qubit, natural atom, and trap ion or their superposition to measure a physical quantity precisely is the key target in Quantum Sensing (QS). Opto to electromechanical energy transformation for several physical quantity precision sensing is the ultimate route that is a great deal in micro and nanophotonics and quantum computing.

The interaction between optical and mechanical degrees of freedom in light-matter interface is classical optomechanics. Light-matter interactions light is wave stuff, and matter is mechanical stuff in the classical field but earlier it was considered truly optical phenomena. In the classical field, the Electromagnetic (EM) force (Coulombs or Lorentz force) is the charge domain while the gravity force is the mass domain. Typically, the charge domain EM force is functionalized light-matter interactions. As a fundamental energy, the gravity effect is another dimension between the light-matter interactions. Light has both wave and particle nature and in its dealings with matter, the matter-matter interaction is plausible. The theory behind it is that the quantum nature of gravitation determines matter-matter interaction, and their harmonic trap is quantum gravity-induced entanglement of masses [3]. The external perturbation and mechanical mode of oscillations against quantum gravity is an induced entanglement between the ground and excited states. As a result, light interaction with matter is complex, and wave-matter entanglement may be involved in this process. It is mentioned that the optical mode interaction with the mechanical mode is gravitationally induced while mechanical mode interaction with the optical mode is electromagnetically induced and both are optomechanically coupled [4]. In the quantum field superposition principle is a key to the understanding of wave (energy)-matter entanglement. The state of one particle is directly related to the state of another, even if they are physically separated. There seems to be a very close relation between the particles and the transmission of quantum information. As a charged matter, electrons are common particles available in bulk, and the tiniest materials are classified as classical, and quantum features respectively. The light and electron relationship in the double slit experiment and its quantum phenomena (particle and wave nature) make them alike. Rest massless and charge-free light interaction with the charged particle electron is associated with the duality nature of quantum-mechanical phenomena. The electron and its interaction with the light as an EM wave leads to strong coupling. It is generally known that light-matter interaction consists of absorption, emission, reflection, and transmission effects. In quantum mechanics, the understanding of light-matter interaction opto-electromechanics, nanophotonics, piezo-phototronic, and diverse advanced energy sensing technologies under optomechanics are vital for QS, and computing. It is also related to photon-phonon dealings and coupling. Therefore, the main objective of this work is an optomechanical perspective light and its interaction analysis with matter at macro and micro levels at the interface of EM and gravity field. For that purpose, light and gravity-related electromagnetic and mechanical system linkage has been elucidated systematically in this study.

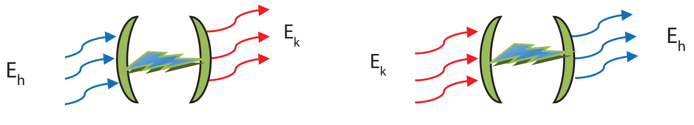

Figure 1: Photon–phonon coupling in materials interface.

Micro and macro-level light-matter interaction and gravity

Matter is nothing but the association of particles in a bond stage. Microlevel light interacts with nanostructure, molecules, and atomic scale. X-rays and gamma-rays at the highest frequency interact with a subatomic level like the core electrons of the atom. It could be either an elastic or inelastic scattering. In inelastic scattering the scattered photon energy or wavelength is varied with the incident photon. Eventually, absorption-emission, transmission, and reflection are involved in this elastic and inelastic interaction process. Through the process energy and momentum exchange is substantial. As a charged particle an electron moves in the electromagnetic field, light appears, and the light interacts with a core electron in the atom.

Quantum energy, $E = h\vartheta = hc / \lambda = mc^2$ (i)

In case of nonzero mass

$$m = E / c^2 = h\vartheta / c^2 = h / \lambda c \quad \text{(ii)}$$

If we discussed the cause and effect of this transformation and from the double slit experiment, it is conceptualized that they are complementary to each other. Light as energy and electron as matter the light-matter or wave-particle interface is the energy-mass entanglement in space. It may have a relation to classical and quantum mechanics. EM interaction is nothing but a photonic interaction in which wave and particle nature persist. The charge domain field and force would appear due to an external charge brought towards a similar field or vice versa.

Electric force $F_E = \dfrac{KQ_1Q_2}{R^2}$ (iii)

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Electric field potential, $V_E = \int_R^\infty E_E .\mathrm{dR} = \int_R^\infty \frac{F_E}{Q_1} .dR$ (iv)

Newtonian mechanics the field and force are acted between two masses and their linear distance, it is due to the gravity effect. In space-time geometry by space contraction, any particle escape velocity is required very high as a result, time dilutes, and the relative gravitational effect becomes reality. In classical mechanics, acceleration due to gravity is a continuous hidden action supposed to be associated with the universe. It differs from energy in the space-time dimension in quantum mechanics. At the same time, the position and momentum are accurately measured the uncertainty as per the *Heisenberg* principle. It is the relationship of mass, energy, and wave nature. In this process, *de Broglie's* wavelength and momentum relationship is unified. Energy-mass entanglement in gravity space is like wave-matter entanglement. There may have been a relationship developed between classical and quantum mechanics.

Gravity force, $F_G = \frac{GMm}{R^2} = mg$ where, g = GM /R² (v)

Gravity field energy, $E_G = \int_R^\infty F_G .\mathrm{dR}$ (vi)

$$\frac{1}{2} mV_{esc}^2 - \frac{\mathrm{GMm}}{R} = \frac{1}{2} m0^2 - \frac{GMm}{\infty} = 0 \quad \text{(vii)}$$

$V_{esc} = \sqrt{[\frac{GM}{R}]} = c$, velocity of light (viii)

Schwarzschild radius, $R = \sqrt{[\frac{GM}{c}]}$ (ix)

The velocity of light is, $c = \frac{GM}{R^2}$ (x)

We can see mass, energy, and its relative velocity in the space-time dimension. If we see R from equ. (ix), the radius is too tiny that the light velocity is required by a particle to escape from the gravitational field. The R in equ. (v) and (x) both Newtonian gravity and general relativity have an interrelationship. Schwarzschild radius, R of equ. (x), in which dimension becomes too tiny as a result it attains enormous density, time dilutes as a result gravitational wave velocity attains as the same as light velocity, c. Gravitation to photon conversion theoretical pathway, massive object transforms into tiny point objects; the time dilutes. In this situation change in light radiation energy within the gravity space is equivalent to the gravitational potential energy change [5-7]. Therefore, gravitational redshift or time dilation

$m = \frac{\hbar\omega}{c^2}$ where, $\hbar\Delta\omega = mg\Delta z = \frac{\hbar\omega}{c^2} g\Delta z$

$$\frac{\Delta\omega}{\omega} = \frac{g}{c^2}\Delta z \quad \text{(xi)}$$

happens as it is mentioned in equ. (xi). We can speculate that the relationships between light and gravity, the energy and mass are set in a complex facet. Light velocity, like escape velocity, can only be attained if the reference space contracts to a single point, and time dilutes. Therefore, only the rest-massless particle photons can attain such velocity. *So, for any massive body yield reference space expands, and time becomes finite.* The gravity phenomena in space-time frame in which relative gravity effect is the cautious measurements of the curved path motion of objects and light. The electromagnetic spectrum corresponding to the gravitation wave event has been made for gravitation to photon conversion as a phenomenological comparison [5]. The plank's mass transforming into an energy dimension and quantum gravitation effect is reported. The motion of an object is dampened due to Newtonian gravity. It has been revealed recently that the motion of an object is also dampened by light [6]. Hence, it appears that the interaction of electromagnetic radiation with the motion of objects and the gravity action on it is supposed to be simultaneous [3,4]. It is associated with different energies in space-time dimensions. Quantum EM from classical phenomena, the charged particle renders into mass and charge-free photon that has both particle and wave nature. Gravity in a relativistic viewpoint is considered as a space-time curved path of mass entanglement. As a universal conservative field, both EM and gravity interrelationships in opto-mechanics are fascinating for diverse sensing technologies. The gravitation redshift is the gravity potential variations equivalent to quantized mechanical energy as the key relationship between classical and quantum mechanics. To represent the interrelationship between electromagnetic fields and gravitational waves, a recent mind-bending paper reported that gravity can transform into light [7]. It is something as mentioned earlier between Newtonian gravity and relative gravity interrelationships in equ. (v) and (ix). In the relativistic aspect mass and energy are a deep clue within space and time dimension, hence masses and mechanical motion interaction with light is the multi-sensing approach in optomechanics.

To dig the matter into a more generalized pathway let's discuss the linear to rotational path transformation of particles. Suppose a particle is in a box, the trajectory of the particle is shown in the arrow line in Figure 2. That is formed a standing wave. If we consider the three-dimensional trajectory of the particle then due to the particle trace of movement spherical space (imaginary) will be formed. As a result, particle existence and wave existence will be entangled within the sphere. The sphere can be extended to infinity and the waves can also be extended to infinity. It is the particle and wave nature coexistence accomplished. Newtonian classical mechanics inertia also appears to be independent of mass. The mass into energy interchange is an interesting phenomenon. The empirical process of a rotational object transitional acceleration has been analyzed more specifically below in Figure 3. In this analysis let us consider a cylinder of radius R and it has two

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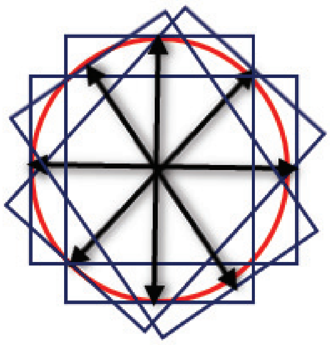

Figure 2: Trajectory of the particle in the spherical system as standing wave dynamics.

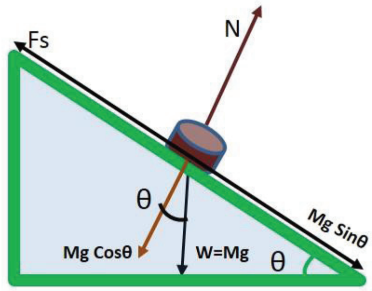

Figure 3: Example of mass-independent force dynamics in rotation phase.

structural patterns. One solid and another hollow of different masses M_1 and M_2. The mass in the hollow cylinder is just concentrated on the periphery. The moment of inertia, I of a solid cylinder is ½ M_1R^2 and the hollow one is M_2R^2. The rotation is regulated by the center of gravity, and they are rolling at a certain angle in the gravity field. According to the relationship between solid and hollow cylinders, transitional acceleration, is varied, and they

So, action force, $F = Ma = MgSin\theta - Fs$ (xii)

Here, $Fs = Ma = (I/R^2)a$

$I = MR^2$, the Newtonian inertia. Hence,

$$Ma = MgSin\theta - (I/R^2)a$$

$$a\,(M + I/R^2) = MgSin\theta$$

$$a = \left[\frac{R^2 MgSin\theta}{MR^2 + I}\right]$$

I = ½ M_1R^2 for solid and $I = M_2R^2$ for hollow cylinder, the acceleration, a is shown independent of mass.

$$\boldsymbol{a} = (2/3)g\ Sin\theta \qquad \text{(xiii)}$$

$$\boldsymbol{a} = (½)g\ Sin\theta \qquad \text{(xiv)}$$

and they are independent of mass. It is like what was shown for gravity and relative gravity where it is supposed to know that mass and energy in the space-time dimension, are interchangeable. Each object in the universe is in movement either transitional or rotational. Relative movement is the reality to determine the transformation of mechanical effect.

The light-matter interaction in the micro-level materials, inside the materials system spatial confinement of electrons and phonons leads to discrete energy levels, unlike in bulk materials where energy levels form continuous bands. This confinement alters the interaction between photons and phonons. Confined phonons have modified dispersion relations, affecting their coupling strength with photons. The enhanced control over the interaction can lead to more efficient light-matter coupling, making 1D systems promising optomechanical applications, such as phonon lasers or light-driven heat engines. In a 1D system, phonons are restricted in the way they propagate. This reduction in available vibrational modes can change the way phonons interact with photons. For instance, scattering rates and interaction strengths are different in 1D compared to 2D or 3D materials. Photon-phonon interactions in 1D structures can exhibit strong nonlinearities, which can lead to exotic effects such as Brillouin scattering, where photons exchange energy and momentum with phonons, giving rise to light shifting in frequency due to the phonon energy. In a 1D system, the overlap between the photon's electric field and the phonon's displacement field can be increased due to the spatial confinement. This can lead to stronger photon-phonon coupling as compared to higher-dimensional systems. This stronger coupling is advantageous for applications such as enhanced Raman scattering, where the efficiency of converting optical signals into vibrational energy increases significantly in nanowires or nanotubes. Thus, photon-phonon coupling is very significant for optomechanical systems, thermal management, and quantum computing. Because the rest massless light's optical angular momentum exerts torque on bulk matter that is related to momentum exchange in optomechanics [1]. Its angular momentum-related energy is exchanged when it interacts with atoms, molecules, and electrons. Their diverse kinematics and interatomic molecular spacing due to hot, cold, and condensation states set the variable de-Broglie wavelength as a result, variable energy transforms. The entanglement of the light-mater due to momentum conservation and the object's escape velocity relationship in the gravity field is quantified from the relative gravity. Light radiation energy causes displacement due to the tiny materials' inelastic scattering. In photonic-level cavity resonators, metamaterial, diverse low-dimensional semiconducting materials, and photonic crystals; the light-matter interaction is a new era of photonics, sensing, and computing as mentioned earlier. Currently, the photonic interaction the optical signal phase and other parameters change in nanoelectro-mechanics and nanoelectron-optomechancis are very fundamental analyses. In this optomechanical process, the outcome is electromechanical in which thermal energy is involved in materials thermodynamic level analysis. Mechanical motion and light interaction could be the root of their interaction analysis as both phenomena are related to gravity and electromagnetic fields in the classical and relativistic framework.

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Light-matter interaction: Classical and quantum analysis

The light-matter interaction process is the charge particle movement in an electromagnetic field (fundamental source of light) while the general relativity gravitational field is the space-time curvature path. Both affect the motion of particles. The space-time curvature pumping wave influences the EM or photon field due to its oscillation-related induced instability that continuously drains energy to the EM or photon field. Hence, light-matter interaction is the outcome we observed due to the transfer of momentum from photon to mechanical mode or vice versa and it is enhanced by system resonance [2,4]. Whether EM-associated microwave/optical field or gravity field will be dominant depends on the mechanical system size. The macroscopic scale is the gravity domain while the microscopic scale is the electromagnetic field domain. In classical mechanics, the mechanical mode of interactions with the optical mode, the angular frequency between linear one-dimensional diatomic systems in a lattice is set certain relationship between masses M and m, the wave vector, q, and the lattice spacing, a [8]. The angular frequency square,

$$\omega^2 = f\left(\frac{1}{m}+\frac{1}{M}\right) \pm f\left[\left(\frac{1}{m}+\frac{1}{M}\right) - \frac{4Sin^2\, qa}{Mm}\right]^{1/2} \quad \text{(xv)}$$

the optical mode frequency, $\omega_{+,}$ and the mechanical (acoustic) mode frequency, $\omega_{-,}$ for M>m.

$$\omega_+ = \left[2f\left(\frac{1}{m}+\frac{1}{M}\right)\right]^{1/2} \text{ and } \omega\_ = 0 \text{ for wave number, } q = 0 \quad \text{(xvi)}$$

$$\omega_+ = \left[2f\left(\frac{1}{m}\right)\right]^{1/2} \text{ and } \omega\_ = \left[2f\left(\frac{1}{M}\right)\right]^{1/2} \text{ for } q = \pm\pi/2a, \quad \text{(xvii)}$$

This is the representation of baseline $q = 0$ and $q = \pm\pi/2a$ for diverse amplitude A corresponding to mass, M and B corresponding to mass, m due to their ratio A/B the interaction between optical and mechanical degrees of freedom in light-matter interaction relies on classical mechanics. The optical and mechanical mode frequencies are mechanical system size dependent. The classical mode mass and energy are separate identities.

The light-matter interaction is for harvesting and transfer of light energy from optical to electrical energy and is opto-electrical. Photo energy detection purpose diverse interface materials energy transfer related opto-mechanical loss lessening by advanced materials interface design is imperative [9]. The inclusion of mechanical strain of a thin flexible material is apt to polarization effect. It supports electrical charge generation in an opto-mechanical process. Additional surface charge accumulations due to the *piezo-phototronic* effect are the potential scope of new mechanical pathway energy harvesting from an optoelectrical interface [10]. The concept of micro or nanostructure of interface design enriches optical absorption. Additionally, the flexibility or stain effect is increased carrier accumulation and transfer. Device interface engineering is expected to be very prolific for extra electrical energy harvesting from light. This light-matter interaction is the wavelength (energy) domain of light reference to materials' molecular dimension that is an optomechanical transformation in nature. In the classical world, mechanical motion is coupled with mass-like spring action, where the resonant angular wavelength is a function of mass and string constant. The string frequency is related to the tension, length, and mass [11].

$$\lambda \propto \sqrt{\left(\frac{k}{m}\right)} \quad \text{(xviii)}$$

The quantum world wavelength is a function of momentum as de Broglie wavelength. The wavelength variation and the diversity of intensity of light are associated with momentum exchange.

$$\lambda \propto \left(\frac{1}{mv}\right) \quad \text{(xix)}$$

In the classical world, the interaction force is mass string interaction while quantum world it relies on quantized energy or momentum change. The velocity of the interspace of atomic vibration is related to system temperature. The lattice temperature variation in the quantum mechanical mode is deliberated as mechanical energy transfer to quantized thermal energy.

$$\frac{k_\beta T}{2} = \frac{mv^2}{2}$$

$$T = \frac{p^2}{mk_\beta} < \frac{\hbar^2}{d^2} \cdot \frac{1}{mk_\beta} \quad \text{(xx)}$$

Where, momentum, p = m²v², and interatomic displacement, d are related to the **Heisenberg principle** of uncertainty. In this process temperature is a measure of length. The thermal energy relationship with mechanical energy is primitive thermomechanical nature where temperature, T is determined by molecular or atomic spacing.

The quantized nature of both the electromagnetic field and mechanical motion in the non-classical mechanics of the energy distribution Hamiltonian, Ĥ is operated between the optical and mechanical mode entanglement [12-14]. The mechanical resonator frequency ω_m and an electromagnetic cavity of optical resonant frequency $\omega_{c,}$ the interaction energy dynamics is given by

$$\hat{H} = [\hbar\omega_c x\, \hat{a}\dagger\hat{a} + \hbar\omega_m\, m\, \hat{b}\dagger\hat{b}] - \hbar g_0 \hat{a}\dagger\hat{a}(\hat{b}+\hat{b}\dagger) + \quad \text{(xxi)}$$

The optomechanical coupling, $H_{int} = -\hbar g_0 \hat{a}\dagger\ \hat{a}(+\dagger)$, coupling strength as the second term of Eq. (xxi) is given by

$$g_0 = \omega_c / L\,(x_{ZPF}) = \omega_c / L\sqrt{(\hbar/2m\omega_m)} \quad \text{(xxii)}$$

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The coefficient relates to the radiation force of a single photon on the position of a phonon. It describes the optomechanical interaction between the optical and the mechanical modes. The displacement operator of the mechanical mode is given by x = x_{ZPF} (b†+b), In quantum mechanics the commutation relations satisfy $[\hat{a}, \hat{a}\dagger] = 1$ and $[\hat{b}, \hat{b}\dagger] = 1$. High frequency mechanical vibrational motion resonator can be cooled to its ground state of temperature, $K_{\beta}T$; where the quantum mechanical energy $\hbar\omega_m >> K_{\beta}T$. m_{eff} being the effective mass of the mechanical mode and ω_m is its resonant frequency, then zero-point fluctuation is depicted.

$$x_{ZPF} = p\hbar / (2m_{eff}\omega_m) \qquad \text{(xxiii)}$$

and optical spring effect high-temperature limit the mean number of phonons $\langle n_m \rangle$ in the center-of-mass motion of an oscillator of resonant frequency $\omega_{m.}$

$$n_m = (k_{\beta} T) / \hbar\omega_m \qquad \text{(xxiv)}$$

The resonant frequency of mechanical mode, ω_m influences both zero-point fluctuation and the mean number of phonons otherwise quantifying both position and number of phonons are dependent on the resonant frequency, ω_m. The mechanical motion influences the optical mode due to back action consequently, energy exchange and optomechanical cooling are ensured. The light-matter interaction photonic energy is transferred into the lattice as phonon energy. The mechanical mode of quantum systems is close to their ground state where the quantization of energy levels and the uncertainty principle significantly affect their dynamics [2]. The vibration affects quantum mechanical mode, when ω_m is increased that eventually decreases $\langle n_m \rangle$. The spectroscopic analysis of optical field intensity variation due to stroke and anti-stroke components can determine nano system effective temperature variation [15]. As a result, $\langle n_m \rangle$ are decreased in the optomechanical coupling as quantum cooling phenomena [16,17]. It is realized that the classical mode vibrational frequency and the quantum modes are dissimilar. In two physical systems entanglement analysis, one system appears to be the measurement of another state. Quantum mechanical sensing is subject to its mass and vibrational energy that eventually changes sensing properties because they are entangled to each other. The diversity of atomic arrangement in different low dimensional materials structure electromechanical energy transformation in the optomechanical interface is an interesting area of advanced QS technologies. To boost the readout of information of classical systems and enhancement of standstill detection of remote objects QS is imperative. Photonic quantum technologies use classical integration technologies that can benefit from parallel development and are suitable for real-life applications [18]. Given other technologies, QS is robust enough to drive essential changes in most of the areas of quantum technologies.

Quantum sensing: Low dimensional system

Quantum technologies in low-dimensional systems have enormous potential in computing, sensing, and communication interfaces. The absorption or emission of light typically occurs on the sub-nanometer scale and the involved processes take place on attosecond to picosecond timescales [19]. The unique atomic arrangement and the very low surface-to-volume ratio of least mass per unit length and strain-related tension make it sensitive to the frequency of resonance for light and matter interaction. The stress or strain associated with the interatomic tension,

$$f = \frac{\left[\sqrt{\dfrac{T}{\frac{M}{L}}}\right]}{2L} = \frac{1}{2}(\sqrt{T} / LM) \qquad \text{(xxv)}$$

T and mass, M, or their atomic length distribution, L develop diverse resonance frequency $f_{matter} = f_{light}$ between light-matter interaction. So, perceptive frequencies of light that are absorbed by atoms or molecular structures can give us information about its structure. 2D materials ferroelectricity, spontaneous polarization, its reversal by applied electric field, and polarization modulation by incident light are potential materials of the 21st century for optoelectrical control of sensing [20]. The tunable quantum materials are promising for spintronics and quantum technologies [21]. Quantum computing based on semiconductor quantum dots (DQs) uses individual spin states of trapped electrons [22]. Single electron gate-controlled QD, and spin qubits are about to materialize in QS technologies [23]. Stationary qubits in 2DMs may couple to photonic qubits that are realized by Single-Photon Emitters (SPEs). Wide band-gap hexagonal boron nitride or Transition Metal Dichalcogenides (TMD), such as WSe_2 are suitable materials for these applications [21]. Low-dimensional material's Nanoelectromechanical (NEM) sensing is very promising for this purpose. Besides carbon nanotube, graphene, hBN, and TMDs; Black Phosphorus (BP) and MXenes have been featured as the latest nanomaterials in NEM resonators [24]. It is vastly prospective for mass detection, mechanical, biological, and chemical sensing, nanoelectronics, and quantum detection as optoelectrical readout. Even very tiny force and mechanical fluctuation can be detected with the high level of quality factor by NEMs at extremely high resonance frequency (GHz). The coupling of exciton, spin, phonon, and photon offers a promising arena for condensed matter physics of strongly correlated single electron investigations. Electron spin and quantum qubits sensing are also accomplished by mechanical NEMs with very high-quality factors [25]. Due to miniaturization more effective interaction with short wavelength devices and wide band supportive optical actuation instead of electric actuation has emerged. As the fastest speed and less power-consuming technology Nano - Electro-Opto Mechanical (NOEM) sensing is currently most promising in contrast to electric field-based NEM sensing [26]. The light coupling with the resonator can improve the opto-mechanical mode of interaction. It ensures very low energy-related fundamental sensing [27].

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Opto-mechanical sensing: Back action reduction

The mechanical process is prejudiced to light-matter interaction in which several stimuli interact with its optical, electrical, and mechanical modes of freedom. Precision measurement purpose quantum optomechanics is a powerful tool nevertheless, de-coherence and noise are the key obstacles for the accuracy of measurement. Photo sensing system generation and recombination loss impacts shot noise and it is related to back action. Back action due to system de-coherence, thermal and quantum fluctuation as a result, different noise contributions impede precision measurement at the quantum level. It means there is a tradeoff between back action and sensing accuracy. For achieving low noise operation or noise-related information sensing purposes control of photo-thermal noise in optomechanics is vital. The design and development of devices for quantum mechanical sensing of the back action of light can be controlled more accurately by controlling mechanical energy and thermodynamic action [28]. Control of quantum state dephasing that appears due to back action, as a result, noise can successfully scale, and it can ensure more precision sensing. It is the new pathway to the advancement of QS technologies where harnessing quantum coherence and entanglement is the key. Mesoscopic electronics and detector design would be the new era for materials scientists and engineers in the field of advanced sensing technologies. Low dimensional devices such as quantum dots and miniaturization of the transistor at the nanometer scale as a single electron device the electron, propagating phonons, and photons interaction is fundamental [29]. The measurement accuracy of photon-phonon interaction, high-precision measurement technology, quantum de-coherence reduction below the standard quantum limit, and control of mechanical motion are worthy. These actions enhance measurement sensitivity [30-33]. For sensitive measurements in the quantum regime entanglement of massive macroscopic systems can also limit quantum back action [34,35]. The light or dark, photon or phonon, tiny or gigantic, and their interrelationship as linear to the non-linear platform is the ultimate path to relate classic and quantum phenomena in EM and gravity field.

Conclusion

In this work, classical and quantum mechanics significance for advanced opto-mechanical sensing is reported. To boost the readout of information of classical systems and enhancement of standstill detection of remote objects quantum sensing significance hence, the intuitive interaction between light and mechanical motion has been illustrated. As a conservative field, both electromagnetic and gravity interrelationships are fascinating for diverse sensing technologies. Gravitation and photon relation are due to tiny objects' time dilution in which the gravitational wave velocity and light velocity relation is a theoretical pathway. Light as energy and electron as matter the light-matter or wave-particle interface is the energy-mass entanglement in the sensing system. In this pathway, phonon dispersion and enhanced photon-phonon coupling are exciting opportunities for developing advanced technologies in quantum computing, optomechanics, and thermal management.

Though the classical mode vibrational frequency and the quantum mode are dissimilar however, in two physical systems entanglement analysis, one system appears to the measurement of other state and electromagnetic frequencies related to the mechanical vibrational frequency. The quantized nature of both the electromagnetic field and mechanical motion in the non-classical mechanics of the energy distribution Hamiltonian is operated between the optical and mechanical mode entanglement. The unique atomic arrangement and very low surface-to-volume ratio of any material system are sensitive to resonance for light and matter interaction. It eventually makes a balance between light-matter interactions for the resonance frequency-based quantum system measurement. So, perceptive bands of frequencies of light that are absorbed by atoms or molecular structures provide precise information.

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