International Journal of Recent Development in Engineering and Technology
Website: www.ijrdet.com (ISSN 2347-6435 (Online) Volume 15, Issue 07, July 2026)

A Theoretical Study on the Absorptive Characteristics of Electrokinetic Waves in High-Dielectric Ferroelectric Material in Quantum Plasma

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***Abstract*— This paper presents a theoretical investigation of the absorptive characteristics of electrokinetic waves (EKWs) propagating through high-dielectric ferroelectric materials like Lead Zirconate Titanate (PZT), using the quantum hydrodynamic (QHD) model. The study incorporates the quantum statistical effects, such as Bohm potential and quantum pressure, into the classical hydrodynamic framework to examine the role of quantum corrections in the energy dissipation of waves in a dielectric medium. The dielectric properties of ferroelectric materials are evaluated through a field-dependent permittivity, and a perturbative analysis is performed on the governing QHD equations. A dispersion relation is derived, from which the absorption characteristics are analytically extracted. The results highlight the significant role of dielectric permittivity and quantum effects in enhancing the absorptive behaviour of electrokinetic waves, especially at nanoscale regimes. This theoretical framework contributes to the foundational understanding required for the design of tunable wave-absorbing devices in advanced photonic and nanoelectronics applications.**

***Keywords*— Electrokinetic waves, Quantum hydrodynamic model, Ferroelectric materials, Dielectric constant, Wave absorption, Bohm potential, Quantum Plasma**

I. Introduction

Electrokinetic waves (EKWs) are a class of low-frequency waves that arise due to the interplay of charge dynamics and electrostatic fields in media with mobile charge carriers. These waves are critical to understanding energy transport in plasma-like systems and solid-state materials. Recent interest in ferroelectric materials, owing to their high dielectric constant and spontaneous polarization, has led to a renewed examination of wave-material interaction, particularly in nanoscale and high-field regimes. Classical hydrodynamic models, while successful in describing large-scale plasma behaviour, are inadequate in accounting for quantum phenomena such as electron tunnelling and diffraction, especially at high densities or low temperatures. The Quantum Hydrodynamic (QHD) model extends classical fluid theory by incorporating quantum statistical effects through additional terms, most notably the Bohm quantum potential. Periodic variations in the propagation parameters cause an electromagnetic wave traveling through plasma to be modulated.

A strong electromechanical connection proportional to the square of the field strength appears along with the electromagnetic wave's propagation in strain dependent dielectric constant (SDDC) [7]. Chourey et al. [18] discussed the classical effect and quantum effect in solid state plasma. Ferroelectric materials display a number of fascinating features that rely on temperature, strain, applied electric field, and other factors.

The ferroelectric semiconductors are used to explore the modulational instability of high-power laser light. And examined the processes by which electron pressure brought on by Fermi temperature produces electron acoustic waves. According to the analysis and comparison in the paper, ferroelectric semiconductor, and formed high growth rate as compared to piezoelectric semiconductor. Additionally, determine the electron density, the perturbation mode's wave number, and do numerical analyses of the with and without quantum and non-quantum effects [17]. As reported earlier the linear dispersion effects combined with the nonlinear processes cause diffusion-induced modulational amplification of the copropagating waves in the diffusive medium. The interaction between the electron-plasma wave and the generated acoustic wave is crucial for the amplification of modulated electromagnetic waves. Therefore, the carrier density of the medium, which controls the dispersion of charge carriers in the medium and the effective plasma frequency in the presence of an intense pump beam, can be used to control the amplification process [1]. In an electro strictive III–V semiconductor plasma medium, it is simple to modulate or demodulate the amplitude of an electromagnetic wave using an acoustic wave. Additionally, it is discovered earlier that choosing the side band mode and determining the parameter range are significantly influenced by the damping [3].

Using materials with a high dielectric constant makes it simple to modulate and demodulate the electromagnetic wave by the acoustic wave. It is discovered that choosing the side band mode and determining the parameter range are significantly influenced by the quantum effect. An intriguing medium for studying various modulational interactions is thus provided by the material with strain-dependent dielectric constant in the presence of a quantum term. It is hoped that this will open up a possible experimental tool for energy transmission and solid state diagnostics in crystals with high dielectric constant [2].

It is studied earlier simple to modulate and demodulate the amplitude of an electromagnetic pulse in an acousto-optic III-V semiconductor crystal. The CH effects always result in higher modulation/demodulation index values for both modes. For this reason, hot carriers are always beneficial to the modulation process. [4,10]. The acousto-helicon wave can be excited by the modulation of a high-power helicon pump wave in a longitudinally magnetized strain-dependent dielectric material, through either oscillating the applied electric field by altering the pulse duration or interacting with changes in interaction length (z), the CH effect always enhances the amount of the modulation and growth rate. It is usually far more advantageous to use hot carriers to modify the pump wave through the acousto helicon wave interaction [11].

The significant research conducted in specific areas of semiconductor plasma by many writers, help to understand the mechanisms of parametric and modulational instabilities in piezoelectric and ferroelectric materials and explain about the classical effect and quantum effect in solid state plasma. The QHD model has been used to study the parametric interaction of laser light in an unmagnetized piezoelectric semiconductor. In electron dynamics, it is shown that the Bohm potential increases the gain coefficient of parametrically created modes while decreasing the threshold pump intensity [20]. Also, Ferroelectric materials for high-power devices were reviewed [21].

Ferroelectric materials exhibit a variety of intriguing properties that are dependent on temperature, strain, applied electric field, and other variables. They are therefore helpful in a wide range of applications, including as energy storage, sensors, actuators, memory cells, capacitors, etc. [18]. Analytical and numerical studies of the linear features of longitudinal electrokinetic waves in a single component magnetized dense semiconductor quantum plasma, where quantum effects are integrated through the non-dimensional quantum parameter-H, have been conducted using the quantum hydrodynamic model [5]. It was observed that the dispersion relation of longitudinal electro-kinetic wave (LEKW) is considerably altered by the quantum parameter and magnetic field. In the absence of the magnetic field and quantum parameter-H, the resultant general dispersion relation simplifies to the standard electron plasma wave dispersion equation [5]. The dispersion and absorption characteristics of electrokinetic waves in unmagnetized extrinsic semiconductors with streaming carriers are studied analytically. A linear dispersion relation for longitudinal electrokinetic waves in colloids-laden semiconductor plasma under the slow electrokinetic mode regime is obtained using the quantum hydrodynamic model. longitudinal electrokinetic mode in semiconductor quantum plasma loaded with colloids using the QHD model under the slow electrokinetic mode limit.

The effects of streaming carriers brought on by a strong dc electric field and the quantum effect via the Bohm potential are discovered to considerably alter the propagation properties of all the modes. The findings show that the dispersion and absorption properties of the electrokinetic wave spectrum are considerably altered by the quantum effect via the Bohm potential [6]. By deriving a nonlinear Schrodinger equation, the modulational instability of electron plasma waves is examined using the quantum hydrodynamic (QHD) model for quantum plasma at finite temperature. It was discovered that the linear and nonlinear characteristics of electron plasma waves in quantum plasma are strongly influenced by the electron degeneracy parameter [8]. In an ion-implanted group III-V semiconductor plasma, the possibility of excitation and convective amplification of left-hand circularly polarized electrokinetic waves was examined analytically. It was demonstrated that the dispersion and absorption characteristics of these waves are significantly altered when certain colloids acquire negative charges, and that their function becomes more efficient as the number of charges adhered to them rises [9]. Under both slow and fast electrokinetic wave regimes, the first mode's phase constant varies in the same way. The interaction is improved when the quantum effect is present. In the longer wavelength regime, it is discovered that the phase speed is increased when the quantum effect is present. Under both speed regimes, the second and fourth mode phase constants are improved via quantum correction [13]. It has been reported that the quantum influence of the transverse magnetic field and the Bohm potential on the wave propagation of LEKW in multi-component plasma has been studied analytically. The current wave spectra of the slow and fast EKW branches have been significantly altered by the presence of quantum correction. For FEKM, it is discovered that one aperiodic mode is changed into a periodic mode when a magnetic field is present [12].

II. THEORETICAL FORMULATION

In the present study we have applied the QHD model to theoretically explore the absorptive behaviour of Electro Kinetic Waves (EKWs) in a ferroelectric material characterized by a high and potentially nonlinear dielectric response. The analysis is purely theoretical, and the study aims to derive the governing relations and quantify the effect of material permittivity and quantum parameters on wave absorption and to explore possibilities of new areas of research in the field of solid state quantum plasma.

The governing equations are,

$$\frac{\partial n}{\partial t} + \nabla(nv) = 0 \qquad (1)$$

Where equation (1) is continuity equation with n as number of particles. v being velocity of wave.

In ferroelectric materials like PZT or $BaTiO_3$, the mobile electrons and holes respond to electrokinetic waves. This equation enforces that as the wave propagates, any increase in carrier density at a point must come from carriers flowing into that point no spontaneous generation occurs. For small amplitude waves, the linearized form will connect density oscillations $n_1$to velocity oscillations v_1.

$$m\left(\frac{\partial v}{\partial t}+v.\nabla v\right)=-\nabla P+qE+\frac{\hbar^2}{2m^2}\nabla\left(\frac{\nabla^2\sqrt{n}}{\sqrt{n}}\right) \quad (2)$$

Equation (2) is momentum equation where E is electric field, P is the momentum and m is mass of carrier. The Bohm term represents quantum diffraction particles can tunnel into classically forbidden regions due to their wave-like nature. This force becomes significant when density gradients are steep (i.e., at short wavelengths `k~10^{14}–$10^{15}m^{-1}$) or when temperature is very low. In high-dielectric ferroelectrics, this term modifies wave absorption by introducing a nonlocal response.

$$\nabla.(\varepsilon_r\varepsilon_0\vec{E})=q(n-n_0) \quad (3)$$

Equation (3) is the Poisson equation Where, n is the particle density, v is the velocity,E is the electric fieldε_r is the material's relative permittivity, $\hbar$ is the reduced Planck constant, m and q are the mass and charge of carriers (typically electrons).

$$\vec{D}=\varepsilon_r\varepsilon_0\vec{E},\varepsilon_r\gg 1 \quad (4)$$

This high dielectric constant modifies the screening behaviour and significantly affects the wave propagation and absorption profile.

For Linearization and Perturbation Analysis, we introduce first-order perturbations to the steady-state background,

$$n=n_0+n_1e^{i(kx-\omega t)}$$
$$v=v_1e^{i(kx-\omega t)} \quad (5)$$
$$\emptyset=\emptyset_1e^{i(kx-\omega t)}$$

Substituting these into the QHD equations and retaining only first-order terms, we obtain the linearized set,

$$-i\omega n_1+ikn_0v_1=0\Rightarrow v_1=\frac{\omega n_1}{kn_0}$$

And

$$-i\omega mv_1=-qik\emptyset_1-ik\frac{P_1}{n_0}+ik\frac{\hbar^2k^2}{4mn_0} \quad (6)$$

Assuming isothermal pressure,

$$P=nk_BT\ \&\ P_1=n_1k_BT$$

Substitute v_1 and rearrange, we get

$$\omega^2=\frac{q^2n_0}{\varepsilon_r\varepsilon_0m}+\frac{k^2k_BT}{m}+\frac{\hbar^2k^4}{4m^2} \quad (7)$$

The dispersion relation is,

$$\omega^2=\omega_P{}^2+\frac{3k^2v_{th}{}^2}{\varepsilon_r}+\frac{\hbar^2k^4}{4m^2} \quad (8)$$

Where,$\omega_P=\sqrt{\frac{n_0q^2}{\varepsilon_0m}}$ *is the plasma frequency and* $v_{th}=\sqrt{\frac{k_BT}{m}}$ *is the thermal velocity.*

The imaginary part of ω, responsible for absorption, arises due to damping mechanisms (e.g., Landau damping in quantum systems), modelled as

$$\omega=\omega_r+i\gamma$$

And The absorption coefficient α is defined as

$$\alpha=\frac{2\gamma}{v_p}\ \&\ v_p=\frac{\omega_r}{k} \quad (10)$$

ω_r *is the o*scillation frequency of the wave it

determines the phase of the electrokinetic wave and γ is the damping rate, i.e., how fast the wave amplitude decays due to absorption or dissipative mechanisms.

III. Result And Discussion:

The PZT physical parameters used in the present analysis are material's relative permittivity $\varepsilon_r\approx 1000$, *wave number* $k\approx 10^{13}-10^{15}m^{-1}$, *plasma frequency* $\omega_P\approx 10^{13}-10^{14}rad/s$, $\hbar=1.055\times10^{-34}J-s$, *Damping rate* $\gamma\approx 1\times10^{12}rad/s$, *the o*scillation frequency $\omega_r\approx 10^{13}Hz$.

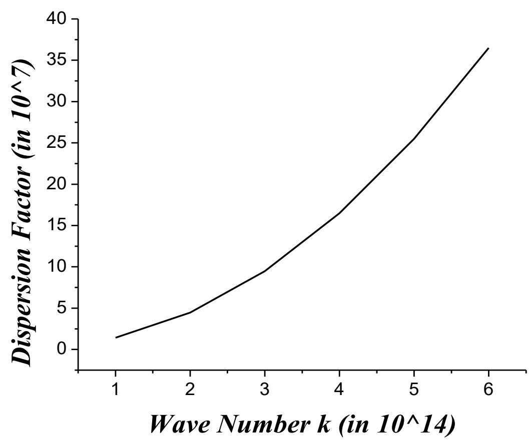

Figure 1 *shows the Dispersion relation between ω and k.*

International Journal of Recent Development in Engineering and Technology
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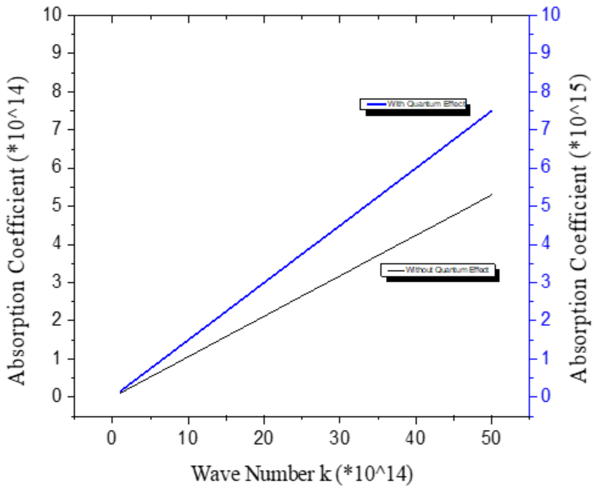

Figure 2 Relation between Wave number and Absorption Coefficient with and without quantum effect. Figure shows that absorption increases with wave number due to quantum dispersion. Quantum corrections more significantly modify wave absorption profile.

According to the effect of dielectric constant, higher $\varepsilon_r$results in lower effective wave velocity, enhancing field-matter interaction, and stronger screening alters the electric potential profile, reducing reflection and increasing energy dissipation. The $\hbar^2 k^4$ term leads to a nonlocal response, prominent at short wavelengths and it is clear that Quantum tunnelling and density gradients facilitate additional wave damping. We found that absorption increases with wave number due to quantum dispersion.

IV. Conclusion

This study provides a quantum hydrodynamic perspective on the absorptive behaviour of electrokinetic waves in high-dielectric ferroelectric materials. The analysis confirms that both the dielectric response and quantum corrections significantly modify the dispersion and absorption characteristics of Electrokinetic waves (EKWs). The derived dispersion relation incorporates both thermal and quantum pressure terms, demonstrating how quantum effects enhance absorption, particularly in ferroelectrics with large dielectric constants. This work lays the theoretical foundation for engineering wave-absorptive ferroelectric structures in future quantum, photonic, and nanoelectronics devices.

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