On the Quantum Electrodynamics of Nanophotonic Systems

Alexander Gritsunov, Igor Bondarenko,
Alexey Pashchenko, Oksana Babychenko
Department of Microelectronics, Electronic Devices and Appliances
Kharkiv National University of Radio Electronics
14, Nauky Ave., Kharkiv, 61166, Ukraine.
Tel. +380 57 7021362
E-mail: gritsunov@gmail.com

Eugene Odarenko
Department of Physical Fundamentals of Electronic Technology
Kharkiv National University of Radio Electronics
14, Nauky Ave., Kharkiv, 61166, Ukraine.
Tel. +380 57 7021484
E-mail: yevhen.odarenko@nure.ua

***Abstract*—Problems of quantum electrodynamics of nanoobjects essential for development of new nanophotonic systems are discussed. According to the theory of natural oscillatory systems (NOSs), "interaction" between the objects is interpreted as a quantum-dynamic phenomenon meaning a stable trend arising from the quantum chaos. As an opposite, "interchange" is denominated as the permanent stochastic exchange with action quanta between different NOSs in 4D spacetime, being the physical base of the quantum chaos. The Tetrode-Wheeler-Feynman's concept of "direct interparticle action" is reconciled with both the quantum radiation-absorption and the Coulomb interaction. A conservation law for the action is supposed to be a necessary condition for the momentum-energy conservation. The "classic" conservation law for the momentum-energy is considered as derivative, being valid for the momentum as well as some physical value that is an integral over 3D space from a linear combination of stress-energy tensor principal diagonal terms. Such redefinition enables the unconditional quantization of the energy unlike "orthodox" quantum theory.**

Keywords*—*nanotechnology; nanophotonics; distributed oscillatory system; matter wave; action; momentum-energy

I. Introduction

Nanophotonics is a new, very dynamic branch of physical and technical science which studies the interaction processes between photons and nanoscale objects. This discipline is a modern and actual ligature of the quantum optics, nanotechnology, computer technique, electrical and electronic engineering. Under some assumptions, nanophotonics may replace "classic" electronics in the foreseeable future, as possessing the ultimate speed of signal processing.

The matters of nanophotonics are nanometer-scale material objects whose sizes are comparable with wavelengths of photons or less. The electrodynamics of such radiator-absorbers is typically near-field [1]. By combining with the quantum field theory (QFT), this results in so-called near-field optics, which "wounds" chronic and fundamental problems of theoretical physics.

As this is described by Novotny, "part of the problem of defining a near-field photon is associated with the fact that the near-field is not purely transverse, which can be easily verified for an evanescent wave and its excitation. Standard quantum electrodynamics (QED) proceeds by invoking the Coulomb gauge and quantizing the retarded transverse field. It gives little attention to the 'attached' field. However, from single molecule experiments it is known that a molecule close to an interface interacts with the *total* field and not only with its transverse part (…). Future theories and experiments will shed more light on the existence of *near-field photons*" ([2], p. 160). Such opinion is confirmed, e.g., by the recent experimental discovery of abnormally high radiation-absorption factor for nanoscale emitting systems [3], as well as other surprising quantum effects.

Considering the above described, as well as the practical importance of the near-field scanning microscopy [4], as another area of the quantum near-field electrodynamics application, this may be claimed that an advance in fundamental QFT is opportune. In particular, a more consistent theory of QED radiation-absorption phenomena is wanted.

Concepts of natural electromagnetic (EM) and electron-positron (EP) distributed oscillatory systems (NEMOS, NEPOS respectively), as alternatives to the "physical vacuum" of QFT and real physical bases for de Broglie matter waves, were proposed in the past ten years by one of us. A discipline named as "Theory of natural oscillatory systems" (TNOS) is developing basing on this idea [5]. Bold yet logically consistent physical concepts like Wheeler-Feynman's (and, earlier, Hugo Tetrode's) idea of "advanced" electromagnetic interactions along with "retarded" ones [6, 7] or Everett's many-worlds interpretation of quantum mechanics [8] are concordant with TNOS. Some fundamental problems of QED [9], in their specific interpretation, are considered below with reference to nanophotonics objectives.

II. Basic Physical Issues

According to TNOS, no "hard" particles exist in the atomic world, only waves and vibrations. Electron cannot be considered as a tiny yet shaped clot of charged matter. Only

NEPOS oscillations produce all observable "electron" or "positron" manifestation effects. The occupation numbers for eigenmodes of natural oscillatory systems (NOSs) are only strict objective values, while NOS wave packets ("particles") have no clear shapes, coordinates and velocities. Generally, there are no too principal differences between wave packets of NEMOS ("photons") and of NEMOS ("electrons").

Two kinds of NOSs are considered: fermion and boson; the difference lies in their cutoff wavenumber. This is non-zero for the former and zero for the latter. NEPOS is a typical fermion NOSs; NEMOS is one of the boson NOSs.

Natural non-harmonic processes are assumed to be statistical ensembles of monochromatic processes in the spacetime. This ensemble cannot be only linear superposition of excited eigenmodes of an alone NOS, because of their orthogonality in the 4D Universe. Instead, a nonlinear swap with quanta of action between different NOSs must occur. Such statistical process, presumably, may be considered as an "overspacetime" act, randomly changing the state of total 4D Universe (like "many-worlds interpretation" [8]). Each concrete "embodiment" of possible NOS states ("instances") coexists conjointly with other in the spacetime yet having specific likelihood of detectability of just this instance in experiment. A moving in time 3D observer shows excited NOS eigenmodes from different instances simultaneously but with fractional (proportionally to their square-rooted probabilities) amplitudes. Those are harmonic components of finite in space and time wave packets ("particles").

In TNOS, the action is supposed to be a principal "measure of activity" in the 4D spacetime, not momentum-energy. Momenta-energies of interacting NOS eigenmodes are strictly defined by the laws of action and "classic" momentum-energy rigorous conservation. Accordingly, the spatio-temporal coordinates of the swaps with quanta of action and momentum-energy between NOSs cannot be defined; the interaction occurs "simultaneously" in the whole 4D volume of Universe. Besides, "pure" free oscillations of NOSs cannot be excited; all NOS wave packets are just stochastic ensembles of forced oscillations.

Thus, excited eigenmodes of different NOSs may be considered as the most fundamental physical objects of nature. The random swap with quanta of action between eigenmodes of fermion and boson NOSs ("interchange") is the principal physical process in the 4D Universe. These action quanta can gradually transfer momentum-energy from one wave packet of a fermion NOS to another via a boson NOS. If some stable trend in the above described quantum chaos exists, this cause evolution of two or more spatially localized wave packets in time (e.g., their mutual "repulsion" or "attraction") while the movement of our 3D world in the 4D spacetime occurs. The interchange with action quanta means that the interaction between natural objects is possible only due to the spatio-temporal localization of fermion NOS wave packets consisting of "forced" eigenmodes exclusively, not free oscillations.

The interchange with stochastic quanta of action between different NOSs also conciliates the law of rigorous conservation of momentum-energy in all interactions, on the one hand, and the Heisenberg's "uncertainty principle," on the other hand. Each "particle" in TNOS is a coupling of wave packets of two or more different NOSs (fermion and boson). The total action, stress and energy of this stochastic aggregate are quite defined and invariable until an interaction with another "particle" happens. But the action, stress and energy taken separately vary randomly for the wave packet producing "uncertainty" of their values. For example, the non-uniformity of electrostatic potential of an "electron" in space "completes" respective irregularity of its "mechanical" momentum to perfect definiteness. The spin magnetic moment uncertainty of an "electron" "recompenses" its spin orientation ambiguity assuring the strict conservation of the angular momentum for the insulated system.

Generally, the essence of the observation (measurement) of a quantum system in TNOS substantially differs from the same for the Copenhagen interpretation. A measurement plays too "sacral" role for the "Copenhagen school," which considers it rather as "auto-da-fé" for a quantum system through the wave function collapse than as man's ordinary intervention in natural course of events. From the "orthodox" point of view, the Schrödinger's cat cannot have his own fate (even may not decay if dead) until the experimenter will find time to investigate the box. On the contrary, TNOS claims that the cat's destiny is decided with practically total-lot probability only with the quantum statistics objective laws long before the experimenter gets to know it.

III. Mathematical Tools

The "canvas" for all NOSs is a 4D pseudo Euclidean spacetime with real-valued spatial coordinates *x*, *y*, *z*, and imaginary temporal coordinate *t* having dimension of length (so-called "1, 1, 1, *i*" formalism). The Cartesian coordinate system is used as the most consistent.

Four-vectors in the spacetime are mixed-valued with real-valued spatial components and imaginary temporal one. The braces are used to joining their components, e.g., $\vec{a} = \left\{a_x, a_y, a_z, a_t\right\}$. The scalar multiplication of four-vectors $\vec{a}$ and $\vec{b}$ is written as $\vec{a}\cdot\vec{b} = a_x b_x + a_y b_y + a_z b_z + a_t b_t$; square of four-vector $\vec{a}$ is $(\vec{a})^2 = a_x^2 + a_y^2 + a_z^2 + a_t^2$. Four-tensors are enclosed in brackets, e.g., $\left[c\right]$. Their spatio-temporal terms (e.g., c_{xt}) are imaginary; all other components are real-valued.

It often used so-called generic symbols instead of several spatio-temporal coordinates at once; ξ is a generic symbol for *x*, *y*, or *z* while τ is a generic symbol for *x*, *y*, *z*, or *t*. If one of the generic symbols appears in the summation sign (Σ), it means summation over all respective coordinates.

Four-gradient operator $\vec{\nabla} = \{\partial/\partial x, \partial/\partial y, \partial/\partial z, \partial/\partial t\}$, four-divergence $\vec{\nabla}\cdot\vec{a} = \partial a_x/\partial x + \partial a_y/\partial y + \partial a_z/\partial z + \partial a_t/\partial t$, D'Alembert $\nabla^2 = \partial^2/\partial x^2 + \partial^2/\partial y^2 + \partial^2/\partial z^2 + \partial^2/\partial t^2$, and Klein-Gordon $\nabla_*^2 = \nabla^2 - k_*^2$ operators are used. A relativistic scalar k_*^2 is a square of cutoff wavenumber for some fermion NOS (e.g., k_e^2 for NEPOS).

"Elegant" enumeration of NOS eigenfunctions is performed with so-called four-numbers $\vec{m} = \{m_x, m_y, m_z, im_t\}$, where $m_\tau = 0, \pm 1, \pm 2, \ldots$. Four-infinity sign $\vec{\infty} = \{\infty, \infty, \infty, i\infty\}$ also used in sums. The summation over the four-number assumes four consecutive summations over its components:

$$\sum_{\vec{m}=-\vec{\infty}}^{\vec{\infty}} H_{\vec{m}} = \sum_{m_x=-\infty}^{\infty} \sum_{m_y=-\infty}^{\infty} \sum_{m_z=-\infty}^{\infty} \sum_{im_t=-i\infty}^{i\infty} H_{m_x, m_y, m_z, im_t} .$$

So-called Hartley functions (linear combinations of sine and cosine of the same argument) $\mathrm{cas}(\theta) = \cos(\theta) + \sin(\theta)$ are used for Fourier decompositions of NOS wavefunctions. They are no subjects of eigenvalue and eigenfunction degeneracies for positive and negative values of wavenumber four-vector $\vec{k}$, ensuring the biunique correspondence for the wavenumber signs, on the one hand, and "particle" or "antiparticle" wave packets, on the other hand).

IV. QUANTIZED OSCILLATORY SYSTEMS

The action of total Universe is assumed as consisting of mutually dependent (by means of permanent stochastic interchange with random number of action quanta $\pm\eta$) actions of all NOSs. The real-valued action H of each NOS is produced by squared variations in spacetime of specific four-vector wavefunction $\vec{\aleph}(x, y, z, t)$ (for fermion NOSs, also by squared value of this wavefunction itself):

$$H = -\frac{i}{2}\int_V \vec{\aleph}\cdot\Lambda\vec{\aleph}\, dxdydzdt = \int_V h dxdydzdt , \qquad (1)$$

where Λ is so-called Euler-Lagrange operator, describing dynamics of the NOS by substitution in the Euler-Lagrange equation $\Lambda = 0$; V is the Universe imaginary total four-volume. Four-tensor (gravitational) and scalar (Higgs) wavefunctions also may be introduced to TNOS.

The action four-densities $h(x, y, z, t)$ for NEMOS and NEPOS can be coupled with the local deviations of these NOSs and their first-order derivatives as respectively

$$h^\gamma = \frac{i}{2}\left[(\vec{\nabla}\aleph_x^\gamma)^2 + (\vec{\nabla}\aleph_y^\gamma)^2 + (\vec{\nabla}\aleph_z^\gamma)^2 + (\vec{\nabla}\aleph_t^\gamma)^2\right] \text{ and} \qquad (2)$$

$$h^e = \frac{i}{2}\left[(\vec{\nabla}\aleph_x^e)^2 + (\vec{\nabla}\aleph_y^e)^2 + (\vec{\nabla}\aleph_z^e)^2 + (\vec{\nabla}\aleph_t^e)^2 + k_e^2(\vec{\aleph}^e)^2\right] \quad (3)$$

(k_e is the NEPOS cutoff wavenumber). The Euler-Lagrange operators are calculated as

$$\Lambda\vec{\aleph} = \sum_\tau \frac{d}{d\tau}\left[\frac{\partial h}{\partial(\partial\vec{\aleph}/\partial\tau)}\right] - \frac{\partial h}{\partial\vec{\aleph}} , \qquad (4)$$

so, the wave equation $\nabla^2\vec{\aleph}^\gamma = 0$ for $\vec{\aleph}^\gamma$ and the Klein-Gordon equation $\nabla^2\vec{\aleph}^e - k_e^2\vec{\aleph}^e = 0$ for $\vec{\aleph}^e$ are finally obtained.

The NOS $\vec{m}$-th and $\vec{m}'$-th eigenfunctions orthogonality condition of the first kind [10] is written as

$$\frac{i}{2}\int_V \vec{\aleph}_{\vec{m}}\cdot\vec{\aleph}_{\vec{m}'}\, dxdydzdt = \begin{cases} 0, \text{ if } \vec{m}' \neq \vec{m}; \\ -\tilde{H}_{\vec{m}}, \text{ if } \vec{m}' = \vec{m}, \end{cases} \qquad (5)$$

where $\tilde{H}_{\vec{m}}$ is pseudoaction of $\vec{m}$-th eigenmode. The orthogonality condition of the second kind [10] for the same eigenfunctions is defined as

$$\frac{i}{2}\int_V \Lambda\vec{\aleph}_{\vec{m}}\cdot\vec{\aleph}_{\vec{m}'}\, dxdydzdt = \\ = \frac{i}{2}\int_V \vec{\aleph}_{\vec{m}}\cdot\Lambda\vec{\aleph}_{\vec{m}'}\, dxdydzdt = \begin{cases} 0, \text{ if } \vec{m}' \neq \vec{m}; \\ -H_{\vec{m}}, \text{ if } \vec{m}' = \vec{m}, \end{cases} \qquad (6)$$

where $H_{\vec{m}}$ is the action of $\vec{m}$-th eigenmode.

Only the natural normalization of NOS eigenfunctions $H_{\vec{m}} = \eta L_{\vec{m}}$ is reasonable. This is a variant of squared ("energy") normalization of the second kind [10] producing a physically admissible system of NOS eigenmodes.

Arbitrary oscillation of the NOS can be decomposed in a Fourier series

$$\vec{\aleph} = \sum_{\vec{m}=-\vec{\infty}}^{\vec{\infty}} U_{\vec{m}}\vec{\aleph}_{\vec{m}} , \qquad (7)$$

where $U_{\vec{m}}$ are some dimensionless coefficients (amplitudes of $\vec{m}$-th eigenmodes).

The quantization rules for a NOS as a whole and its $\vec{m}$-th eigenmode are respectively

$$H = L\eta ; \qquad H_{\vec{m}} = L_{\vec{m}}\eta , \qquad (8)$$

where $L = 0, \pm 1, \pm 2, \ldots$ and $L_{\vec{m}} = 0, \pm 1, \pm 2, \ldots$ are so-called enforce numbers indicating how many positive or negative quanta of action keep the whole NOS and each its eigenmode away from the pure free oscillation (with $H = 0$). The quantization of NOS eigenmodes is performed by calibrating the squared normalizing factors $A_{\vec{m}}^2$ for the eigenmodes. For NEMOS, a simple formula can be obtained:

$$A_{\vec{m}}^2 = \frac{2i}{V|L_{\vec{m}}|} \qquad (9)$$

(remember that V is imaginary). If the natural normalization is chosen, the statistically averaged action of the eigenmode is of

$\bar{H}_{\vec{m}} = \eta \bar{K}_{\vec{m}} L_{\vec{m}}$, and $U_{\vec{m}}^2 = \bar{K}_{\vec{m}}$ ($\bar{K}_{\vec{m}}$ is the statistically averaged occupation number for $\vec{m}$-th eigenmode).

V. The Coulomb Interaction

The longstanding Wheeler-Feynman's (and, earlier, Hugo Tetrode's) idea of "advanced" EM interactions along with "retarded" ones [6, 7] was nowadays [11] revitalized by Y. Aharonov. Such notion completely adjusts with the basic concepts of TNOS. Localized in spacetime "photon," as ensemble of harmonic components, arises from multiple bidirectional acts of action interchange between NEPOS and NEMOS, possible only for two-way EM interaction in time.

"Almost free" ("real") photons transfer both stress and energy jointly, i.e., too few action, from one zero-action fermion wave packet (e.g., excited atom) to another. On the contrary, the Coulomb interaction between fermions is a specific case of the radiation-absorption when photons are essentially "forced," i.e., having $\left|k_{\vec{m}x}^2 + k_{\vec{m}y}^2 + k_{\vec{m}z}^2\right| \gg \left|k_{\vec{m}t}^2\right|$, where $\vec{k}_{\vec{m}}$ is the wave four-vector of $\vec{m}$-th eigenmode. Those are called as "virtual" in "orthodox" QFT. The "interaction" is interpreted as a stable trend in variation of stresses (momenta) or energies of NEPOS wave packets, arising from the quantum chaos. The latter is a result of random mutual conversion with action quanta ("interchange") between NEPOS and NEMOS in 4D spacetime. If two or more rest "electrons" are placed in their "common" EM potential, NEMOS performs a stochastic mutual exchange with stress between ones (i.e., the Coulomb repulsion) in addition to the "localizing" effect for each wave packet taken separately [5]. For moving "electrons," this exchange includes also energy.

The spin magnetic moment uncertainty of "electron" is a result of the "indeterminancy" in its own angular momentum. Random changes of direction of an "electron rotation axis" are compensated by variations in magnetic moment of NEMOS, so, total angular momentum of the insulated system "electron in its own EM potential" remains unchanged.

VI. The Radiation-Absorption

The similar interaction process between atoms in the time domain, transferring both momentum and energy, is known as "radiation-absorption." Nature of the EM interaction is supposed to be similar for both time-dependent (e.g., radiating-absorbing atoms) and static (e.g., mutually repulsive "electrons") systems. We've put into TNOS the Tetrode-Wheeler-Feynman's concept of "advanced" EM interactions along with "retarded" ones [6, 7] to explain the temporal localization of EM wave packets, which transfer the energy.

E.g., if an excited atom #1 transferred a quantum of its extra momentum-energy (and, respectively, negative and positive quanta of the action) to an atom #2 via a "photon," this act may be still "rolled back" ("the Schrödinger's cat can be revivified"). Only if atom #2 has retransmitted the obtained quantum to an atom #3, this quantum no longer can be returned to atom #1 ("a measurement has been made, the cat is dead, sorry…").

Why atom #3 cannot return the obtained quantum to atom #2, so, one will return it to atom #1 (remember, these processes cannot be described as "flowing in time," so, "will" verb be not quite suitable here)? Such situation is theoretically possible; however, the probability of the "rolling back" just all events chain decreases dramatically as the number of possible variants of the events enlarges. Atom #3 can transfer the obtained quantum to an atom #4, or atom #5, *etc.*, not necessarily return it to the atom #2. Figuratively, the unhappy cat is a victim of the second law of thermodynamics.

Quantum oscillating systems having two and more stable or quasi-stable states (e.g., atoms) are the same "observers" as people with their "classic" apparatus. Just they seal the fate of the Schrödinger's cat long before the box is opened. A "macroscopic observer" can be sure what has happened in the quantum system only when the above process has gone far enough to make a "rollback" practically impossible. Until then, the observer's knowledge can be only probabilistic.

If a single excited atom is placed in the Universe, it would never radiate, because "almost free" photon cannot accumulate by oneself the difference between the actions of excited and unexcited atom (neither positive nor negative parts of their total actions). Further, if only two atoms exist in the world, some is excited while other is unexcited at some instant, they would "beat" like two weakly coupled harmonic oscillators. The mutual coupling factor is defined by the fine-structure constant α as well as spatial characteristics of the atoms. Three and more mixed excited and unexcited atoms in the Universe, evidently, must oscillate like a network of harmonic oscillators weakly coupled each with another.

VII. What Is the "Electron" Current?

The concept of "electric" or "electron" current is introduced to define some four-vector function $\vec{j}^e(x, y, z, t)$ in the right-hand side of the inhomogeneous Euler-Lagrange equation for NEMOS:

$$\nabla^2 \vec{\aleph}^\gamma = \vec{j}^e \tag{10}$$

Like $\vec{\aleph}^\gamma$, this function has probabilistic character, consisting of randomly replacing one another eigenmodes. However, unike $\vec{\aleph}^\gamma$, $\vec{j}^e$ has no its own material basis (any media). So, electron current is rather "mathematical," not "physical," concept yet.

Arbitrary function $\vec{j}^e$ can be expanded in a Fourier series

$$\vec{j}^e = \sum_{\vec{m}=-\vec{\infty}}^{\vec{\infty}} u_{\vec{m}}^e \vec{j}_{\vec{m}}^e , \tag{11}$$

where $u_{\vec{m}}^e$ are some dimensionless coefficients (amplitudes of $\vec{m}$-th harmonics). Due to the linearity of (10), electron current has the same as $\vec{\aleph}^\gamma$ Fourier basis $\vec{j}_{\vec{m}}^e(x, y, z, t)$, e.g.,

$j^e_{\vec{m}TEMx} = a^e_{\vec{m}TEM} \operatorname{cas}\left(\vec{k}_{\vec{m}}\vec{r}\right)$; $j^e_{\vec{m}TEMy} = j^e_{\vec{m}TEMz} = j^e_{\vec{m}TEMt} = 0$ for the *TEM* subset *etc*, where $a^e_{\vec{m}}$ is a normalizing factor for $\vec{m}$-th eigenmode. Only the natural normalization is advisable for the electron current eigenfunctions $\vec{j}^e_{\vec{m}}$. It is following from (6) and (10) that

$$i\int_V \vec{\aleph}^\gamma_{\vec{m}} \cdot \vec{j}^e_{\vec{m}'}\, dxdydzdt = \begin{cases} 0, \text{ if } \vec{m}' \neq \vec{m}; \\ -H_{\vec{m}}, \text{ if } \vec{m}' = \vec{m}, \end{cases} \qquad (12)$$

where $H_{\vec{m}}$ is the normalized action of the $\vec{m}$-th eigenmode.

After multiplication of (10) by $\vec{\aleph}^\gamma$, integration the product over the Universe four-volume, and application of the Green's first identity to the left-hand side, it can be obtained:

$$i\int_V \vec{\aleph}^\gamma \cdot \vec{j}^e\, dxdydzdt = -H^\gamma \,. \qquad (13)$$

[we considered (1) and (2) here]. Eq. (13) gives some physical sense to $\vec{j}^e$ and defines its measuring unit. Evidently, that is of $< action >^{1/2} / < length >^3$.

The quantization rules for electron current eigenfunctions follow directly from (12). Assuming $H_{\vec{m}} = \eta L_{\vec{m}}$ and considering that $\left|L_{\vec{m}}\right| = \left|\vec{k}_{\vec{m}}\right|$, an equality of $iVA^\gamma_{\vec{m}} a^e_{\vec{m}} = -\eta L_{\vec{m}}$ can be derived after the integrating over the Universe four-volume. Considering (9), a simple formula for the normalizing factor of $\vec{j}_{\vec{m}}$ can be obtained:

$$a^e_{\vec{m}} = \frac{\left|L_{\vec{m}}\right|^{3/2}}{\sqrt{V/i}} \qquad (14)$$

(remember that *V* is imaginary; $\eta = 1$ assumed).

The physical interpretation of $u^e_{\vec{m}}$ in (11) is the same as for amplitudes $U_{\vec{m}}$ of wavefunction harmonics in (7). Namely, squared amplitude $\left(u^e_{\vec{m}}\right)^2$ is proportional to the average "contribution" $\bar{H}_{\vec{m}}$ of $\vec{m}$-th harmonic of the electron current into the average total action $\bar{H}^\gamma$ of NEMOS, or, the same, is the statistically averaged occupation factor $\bar{K}_{\vec{m}}$ of $\vec{m}$-th NEMOS eigenmode.

VIII. The Momentum-Energy Relations

According to TNOS [5], the momentum-energy is a dynamic value arising from the "movement" of 3D world over 4D spacetime in the temporal direction. Excited NOS eigenmodes "vibrate" like animated cartoon from the point of view of a 3D observer. The frequency of this vibration describes the eigenmode's energy, while the quickness and the direction of spatial displacement of the oscillation's phase define its momentum. In other words, momentum-energy is defined as flow of the action through 3D world.

It is easy to see that the "orthodoxal" formula of QED for quantization of the total momentum-energy four-vector of a NOS $\vec{m}$-th eigenmode $\vec{W}_{\vec{m}} = \eta K_{\vec{m}}\vec{k}_{\vec{m}}$, where $K_{\vec{m}}$ is the mode occupation factor, is not so universal [5]. First, this is valid only for "free" or matter-like eigenmodes, i.e., having $k^2_{\vec{m}} \le 0$. Second, this does not consider the existence of both positive and negative action quanta as well as the same sign of energy for "particles" (with $k_{\vec{m}t} > 0$) and "antiparticles" (with $k_{\vec{m}t} < 0$). Real 3D observer cannot determine actual sign of $k_{\vec{m}t}$ component in direct way. Only hypothetic "4D observer" can distinguish "positive" and "negative" directions of the wave vector for fermions.

Therefore, it would be reasonably to evaluate the total momentum-energy of individual eigenmodes and of a while NOS by means of integrating the respective components of the four-tensor of stress-energy density over all 3D volume of Universe. There are two form of this tensor: "classic" $[w](x,y,z,t)$ and "quantum" $[p](x,y,z,t)$ ones. They differ only in the expressions for the principal diagonal terms.

"Classic" (conservative) stress-energy density four-tensor $[w](x,y,z,t)$ is derived from the Noether's theorem in assumption of the spacetime uniformity. General formula for the components of this tensor is based on the expressions for the Lagrange function three-density *h* (2), (3) as:

$$w_{\tau\tau'} = I_{\tau\tau'}h - \sum_{\tau''} \frac{\partial \aleph_{\tau''}}{\partial \tau}\left[\frac{\partial h}{\partial(\partial \aleph_{\tau''}/\partial \tau')}\right], \qquad (15)$$

where $[I]$ is the unit four-tensor.

Substituting (2) and (3) to (15), one can see that the parts of tensor $[w]$ for NEMOS and NEPOS are written as

$$w_{\tau\tau'} = I_{\tau\tau'}h - i\frac{\partial\vec{\aleph}}{\partial\tau}\cdot\frac{\partial\vec{\aleph}}{\partial\tau'}\,. \qquad (16)$$

"Classically" defined stress-energy density (16) always ensures the momentum-energy conservation in 3D Universe. Unfortunately, it can hardly be said that this agrees with the quantization basic principles. If energy is correlated with the temporal direction of a wave process, some forms of "classic" energy embodiment cannot be quantized (e.g., "energy" of EM potential of "rest electron"). The violation of the quantization rules, at least for one of kinds of energy existence, breaks down fundamentals of the quantum theory.

Unlike the classic EM theory, all components of the four-tensor of "quantum" stress-energy density $[p]$ of a NOS may be defined in simple and uniform manner:

$$p_{\tau\tau'} = -i\frac{\partial\vec{\aleph}}{\partial\tau}\cdot\frac{\partial\vec{\aleph}}{\partial\tau'}\,, \qquad (17)$$

differing from (16) in the principal diagonal terms. "Quantum" stress-energy density (17) is always quantized. E.g., a "quantum" energy always assumes some non-stationary (time-dependent) process and may be, from a "mechanical" point of view, interpreted as doubled "kinetic energy." So, EM potential of the "rest electron" possesses no energy. However, the "quantum" energy, as a dynamic entity, is, generally, non-conservative value for 3D Universe (the momentum is conservative as usual). Conservation rules, following from the Noether's theorem applied to the spatio-temporal coordinates, are fit now to other values, namely, for linear combinations of $[p]$ principal diagonal terms. According to (3) and (17), $h=\left[-p_{xx}-p_{yy}-p_{zz}-p_{tt}+ik_*^2(\vec{\aleph})^2\right]/2$ for a fermion NOS. For hypersurfaces of $\xi=\text{const}$, derived by comparing (16) and (17) conservative values are

$$w_{xx}=h+p_{xx}=\left[+p_{xx}-p_{yy}-p_{zz}-p_{tt}+ik_*^2(\vec{\aleph})^2\right]/2\,; \quad \text{(18a)}$$

$$w_{yy}=h+p_{yy}=\left[-p_{xx}+p_{yy}-p_{zz}-p_{tt}+ik_*^2(\vec{\aleph})^2\right]/2\,; \quad \text{(18b)}$$

$$w_{zz}=h+p_{zz}=\left[-p_{xx}-p_{yy}+p_{zz}-p_{tt}+ik_*^2(\vec{\aleph})^2\right]/2\,. \quad \text{(18c)}$$

For a hypersurface of $t=\text{const}$ (our 3D world), a value keeps:

$$w_{tt}=h+p_{tt}=\left[-p_{xx}-p_{yy}-p_{zz}+p_{tt}+ik_*^2(\vec{\aleph})^2\right]/2\,. \quad \text{(18d)}$$

Traces of tensors $[w]$ and $[p]$ are respectively of

$$\begin{aligned}\operatorname{tr}[w]&=w_{xx}+w_{yy}+w_{zz}+w_{tt}=\\&=-p_{xx}-p_{yy}-p_{zz}-p_{tt}+2ik_*^2(\vec{\aleph})^2=2h+ik_*^2(\vec{\aleph})^2\end{aligned} \quad \text{(19)}$$

and

$$\operatorname{tr}[p]=p_{xx}+p_{yy}+p_{zz}+p_{tt}=-2h+ik_*^2(\vec{\aleph})^2\,. \quad \text{(20)}$$

The conservative linear combinations and the traces for boson NOSs may be obtained from (18) – (20) under the assumption of $k_*=0$.

Multiplied by -0.5 trace of $[p]$ tensor is a four-scalar of the NOS action four-density produced by the anisotropic terms [5], e.g., entire (2) for NEMOS, or (3) after deduction of action of the "internal" ("Higgs") system for NEPOS:

$$-\operatorname{tr}[p]/2=h-ik_*^2(\vec{\aleph})^2/2\,. \quad \text{(21)}$$

Note that the above "quasi-classic" ("integral") definitions of $\vec{j}^e$ and $[p]$ differ essentially from their consistent "quantum" ones. Both $\vec{j}^e$ and $[p]$ are differential values, describing just the changes (quantized dispersion) in NOS eigenmode excitation states, not eigenmodes themselves. However, defined in "integral" manner value of $-\operatorname{tr}[p]\vec{v}_g/2$, where $\vec{v}_g$ is the wave packet group four-velocity, coincides with the "differentially" defined $\vec{j}^e$ function up to some coefficient ensuring the "quantization of electric charge."

IX. Conclusion

Nanophotonics is a very prospective discipline from the point of view of reaching ultimate speeds of future information processing devices, which studies the interaction processes between photons and nanoscale objects. Because typical sizes of nanometer-scale material objects are of the same order as wavelengths of photons and electron de Broglie wavelengths, the investigations and design of nanophotonic devices must be performed according to the QFT laws, not classical.

TNOS concepts consistently describe behavior of photons and de Broglie waves in vacuum, conductors, semiconductors, and superconductors. The described results may be useful for development of new nanophotonic components, near-field scanning microscopes, quantum computers, as well as improvement of some traditional quantum optical devices [12].

References

[1] Jackson, J. D., "Classical electrodynamics," John Wiley, 1962.

[2] Novotny, L.,"The history of near-field optics," in Progress in Optics 50, E. Wolf (ed.), Chapter 5, pp. 137-184, 2007.

[3] Slepyan, G., A. Boag, V. Mordachev, E. Sinkevich et al., "Anomalous electromagnetic coupling via entanglement at the nanoscale," New J. Phys., Vol. 19, 023014, 2017.

[4] Dürig U., D. W. Pohl, and F. Rohner, "Near-field optical-scanning microscopy," J. Appl. Phys., Vol. 59, p. 3318, 1986.

[5] Gritsunov, A. V., "Theory of natural oscillatory systems," ResearchGate project [Online]. Available: https://researchgate.net/project/Theory-of-Natural-Oscillatory-Systems

[6] Wheeler, J. A. and R. P. Feynman, "Interaction with the absorber as the mechanism of radiation," Rev. Modern Phys., vol. 17, no. 2-3, 1945.

[7] Wheeler, J. A. and R. P. Feynman, "Classical electrodynamics in terms of direct interparticle action," Rev. Modern Phys., vol. 21, no. 3, 1949.

[8] DeWitt, B. and N. Graham (Eds.) The many-worlds interpretation of quantum mechanics, Princeton: Princeton University Press, 1973.

[9] Berestetskii, V. B., L. P. Pitaevskii, and E. M. Lifshitz, "Course of Theoretical Physics," Quantum Electrodynamics, Vol. 4, Butterworth-Heinemann, Oxford, 1982.

[10] Gritsunov, A. V., "Expansion of nonstationary electromagnetic potentials into partial functions of electrodynamic system," Radioelectronics and Comm. Systems, Vol. 49, No. 7, pp. 6-12, 2006.

[11] Aharonov, Y., E. Cohen, and T. Landsberger, "The two-time interpretation and macroscopic time-reversibility," Entropy, vol. 19, 111, 2017.

[12] Semenets, V., M. Kopot, A. Gritsunov, I. Bondarenko, and E. Yunusov, "On the theory of a pulse microwave-pumped laser," 2019 IEEE 8th Int. Conf. on Advanced Optoelectronics and Lasers (CAOL'2019), Sozopol, Bulgaria, pp. 1-4, 2019.