Premises of Communication and Processing on Photons in *Natural* and *Engineered* Systems: Implication to Science and High-Technology Market

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ABSTRACT

In various photonic, optoelectronic and microelectronic systems, new communication and processing solutions are under intensive studies. New technologies emerge to design, fabricate and commercialize communication, processing and sensing platforms. Transformative fundamental findings, engineering developments and practical technologies are implemented and substantiated. New proof-of-concept multi-physics photonic and optoelectronic *macroscopic*, *mesoscopic* and *microscopic* systems are designed, fabricated, tested, characterized and demonstrated reaching a sufficient technology readiness level. Our goal is to further enhance physical foundations, enable engineering premises and advance information technologies of classical, quantum and *mixed* communication and processing. This paper examines emerging quantum-enabled and quantum technologies aimed for communication and data processing. The studied premises: (i) Unify and enable concepts of computer science, engineering and technologies; (ii) Consistent with quantum informatics, communication, computing and processing schemes; (iii) Comply with emerged software and hardware solutions; (iv) Exhibit sufficient technology readiness and technology transfer capabilities.

Keywords: communication, electronics, microelectronics, nanotechnology, optoelectronics, photonics, processing

1. INTRODUCTION

New *engineered* and *natural* photonic and biophotonic systems are under intensive studies, research and technology developments [1-4]. Quantum phenomena, exhibited by *microscopic* and *macroscopic* systems, are utilized. Quantum photonic and optoelectronics are used in biotechnology, electronics, medicine and other applications. Basic research and discoveries in photonics and biophotonics are foundations of science and engineering in developing new knowledge bases and technologies beyond currently available.

In biotechnology and medical applications, advances are needed to enable computer–brain interfacing, optogenetics, neurophotonics, etc. Practical quantum-centric technologies must be developed. Our three-fold objectives are: (1) Examine quantum-enabled, *mixed* and quantum communication and processing schemes; (2) Study phenomena, effects and mechanisms utilized by living organisms to accomplish sensing, communication and processing; (3) Enable a knowledge base and discover new processing schemes comparable to exhibited by living organisms. Our transformative findings are substantiated by means of basic and applied studies which are consistent with experiments, biophysics and quantum mechanics. In particular, extensive studies on central and peripheral nervous systems have being conducted for many decades. Biophysics of chemoelectro-mechanical, electrostatic and quantum energy conversion, sensing, *signaling* and *computing* were studied in [3-7]. In *engineered* systems, photonics and photoelectronic *mesoscopic fabrics*, structures and devices exhibit quantum phenomena which are utilized ensuring communication, energy conversion, data storage, processing, sensing, etc. The *microscopic*, *mesoscopic* and *macroscopic* (microelectronic) devices exhibit quantum electromagnetic radiation, energy absorption, energy conversion, energy transfer, etc. Photons emission, photon absorption, photon-electron interactions and other phenomena are utilized. Quantum-centric technologies are commercialized in a wide range of communication, data storage, electronic and other devices [1-4]. These quantum phenomena, effect and mechanisms:

1. Result in energy-relevant quantum-centric transitions and transductions defining sensing, communication, data storage and data processing in *engineered* systems;
2. Enable analysis of quantum communication, sensing and information processing in living organisms as biomolecules in molecular *fabrics* undergo transitions and transductions.

Invertebrates, which exhibit information processing, over-perform any envisioned *engineered* platforms including supercomputers. Our overall goal is to devise enabling, verifiable and practical processing schemes utilizing photon-induced phenomena. In this paper, we: (i) Analyze quantum-mechanically-consistent and technology-coherent sensing and processing paradigms; (ii) Analyze sensing and processing in living organisms; (iii) Design practical *all-quantum* and *mixed* quantum↔classical sensing and processing systems; (iv) Contribute to developments of invasive and non-invasive brain–computer interface, direct neural interface, brain–machine interface, neural prosthesis, brain and other implants for which it is imperative to comprehend quantum processing.

2. Financial and Marketing

Product developments, commercialization and marketing are very important topics to be solved. Nanotechnology-relevant economics implies cohesive analysis of aerospace, automotive, defense, health, electronics, energy, industrial, financial, security and other sectors which are significantly affected by nano and bio technologies, nanomedicine, nanoelectonics and other developments. Nanotechnology drastically affected national and international markets, services, economies and security. This paper examines photonics- and optoelectronics-enabled defense, electronics and security sectors from economics and market prospects. The performance and growth of large-cap companies which utilize front-end enabling nanotechnologies are considered and analyzed. In particular, we considered the IBM, Intel, ST Microelectronics, Texas Instruments, and other companies which were affected by the technology developments and technology implications on market.

In the United States and worldwide, technology evolution and R&D significantly attributed to new products which enabled effectiveness, functionality, performance, affordability, safety, quality, etc. The effectiveness, strength and benefits of nanotechnology-enabled photonics and optoelectronics on major economic indexes and measures are demonstrated. The market refocusing and concentration on new technologies have positive implications and outcomes.

3. Nanotechnology and Quantum Processing

3. 1. *Microscopic* Platforms: Physical Systems and Models

The focused research activities are centered on photonic, optoelectronic and other quantum-effect devices. A significant progress is made in resonant-tunneling devices, solid-state, inorganic and organic lasers, photodiodes, etc. [1-4]. The compliant quantum↔classical processing and compatibility must be ensured in order to develop practical technologies. It is important to examine [3-7]: (i) Photons emission, photon absorption, photon-electron interactions and electronic transductions in *microscopic* and *mesoscopic* device; (ii) Photon propagation in organic and silicon optical waveguides; (iii) Information fusion and processing by photons and electrons; (iv) Photons detection and optoelectronic interface.

For physical *microscopic* systems, the input-output evolution *mapping* is

$$\mathcal{M}(\boldsymbol{\nu},\boldsymbol{u})\in\mathcal{V}\times\mathcal{U},\ \boldsymbol{\nu}\in\mathbb{R},\boldsymbol{u}\in\mathbb{R}, \tag{1}$$

while, the model *mapping* is

$$\mathscr{M}(k(\Psi),\hat{C},C,f(C),\hat{H},H)\in\mathcal{K}\times\hat{\mathbf{C}}\times\boldsymbol{C}\times\boldsymbol{C}\times\hat{\boldsymbol{H}}\times\boldsymbol{H}, \tag{2}$$
$$\Psi\in\mathbb{C},\ \hat{C}\in\mathbb{C},\ C\in\mathbb{R},\ \hat{H}\in\mathbb{C},\ H\in\mathbb{R},$$

where $\boldsymbol{\nu}$ are the *detectable*, real-valued and *measurable* physical variables, $\boldsymbol{\nu}\in\mathbb{R}$; $\boldsymbol{u}$ are the real-valued controls, $\boldsymbol{u}\in\mathbb{R}$; Ψ is the wave function, $\Psi\in\mathbb{C}$; C are the quantum canonical variables with associated operators $\hat{C}$, $C\in\mathbb{R}$, $\hat{C}\in\mathbb{C}$; $\hat{H}$ is the Hamiltonian operator for the associated Hamiltonian H, $\hat{H}\in\mathbb{C}$, $H\in\mathbb{R}$.

From science and engineering viewpoints, using the consistent, coherent and cohesive premises of quantum mechanics, one strives to develop the model $\mathscr{M}(\cdot)$ which matches the physical system $\mathcal{M}(\cdot)$. In (2), the mapping $k(\Psi)$ leads to descriptive quantitative estimates of physically-consistent mathematical and auxiliary variables, mathematical quantities and mathematical operators. By using quantum mechanics, we model the spatiotemporal evolutions of mathematical operators (wave functions Ψ, probability amplitudes c_n and others) which may yield a quantitative analysis on the quantum canonical variables C. For example, $C=[\mathbf{r},\ \mathbf{p},\ E]^T$. These quantum canonical variables C may be relevant to the *detectable*, real-valued and *measurable* physical *variables* $\boldsymbol{\nu}\in\mathcal{V}$ or $f(\boldsymbol{\nu})\in\mathbb{R}$. That is, if the model $\mathscr{M}(\cdot)$ matches the physical system $\mathcal{M}(\cdot)$, there could be the evolution similarity between ν and C, such that $\nu\equiv\varphi(C)$.

The *microscopic* systems $\mathcal{M}(\cdot)$ are modeled by using the following equations for the model *mapping* $\mathscr{M}(\cdot)$ [8]

$$\hat{H}\Psi(\mathbf{r},t)=i\hbar\frac{\partial\Psi(\mathbf{r},t)}{\partial t},\ \hat{H}=\hat{H}_0+\hat{H}_E+\hat{H}_P,\ \hat{H}\in\mathbb{C},\Psi\in\mathbb{C}, \tag{3}$$
$$\Psi(\mathbf{r},t)=\psi(\mathbf{r})\varphi(t),\ \hat{H}\psi_n=E_n\psi_n,\ i\hbar\frac{1}{\varphi}\frac{\partial\varphi}{\partial t}=E,\ \varphi(t)=e^{-i\frac{E}{\hbar}t}.$$
$$\Psi(\mathbf{r},t)=\sum_{n=1}^{\infty}c_n\Psi_n(\mathbf{r},t)=\psi(\mathbf{r})\varphi(t)=\sum_{n=1}^{\infty}c_n\psi_n(\mathbf{r})e^{-i\frac{E_n}{\hbar}t}=\sum_{n=1}^{\infty}c_n\psi_n(\mathbf{r})e^{-i\omega_n t},\ c_n\in\mathbb{C},$$
$$\langle C\rangle=\int\Psi^*(\mathbf{r},t)\hat{C}\Psi(\mathbf{r},t)dV,$$
$$\langle f(C)\rangle=\int\Psi^*(\mathbf{r},t)f(\hat{C})\Psi(\mathbf{r},t)dV,\ P=\int\Psi^*(\mathbf{r},t)\Psi(\mathbf{r},t)dV,$$
$$C\in\mathbb{R},\ f(C)\in\mathbb{R},\ P\in\mathbb{R},$$
$$\frac{d}{dt}\langle\hat{C}\rangle=\left\langle\frac{\partial\hat{C}}{\partial t}\right\rangle+\frac{1}{i\hbar}\langle[\hat{C},\hat{H}]\rangle,\ \hat{C}\in\mathbb{C}.$$

In (3), the conventional notations are used [6-8]. The *total* Hamiltonian operator $\hat{H}$ is comprised of unperturbed $\hat{H}_0$, excitation $\hat{H}_E$ and perturbation $\hat{H}_P$ Hamiltonians. The disturbances and perturbations affect $\hat{H}_P$, and, the *control function operator* is denoted as $\hat{u}$, $\hat{u}\equiv\hat{H}_E\in\mathbb{C}$. The complex probability amplitudes c_n satisfy $\sum_{n=1}^{\infty}|c_n|^2=1$.

One distinguishes the physical systems $\mathcal{M}(\cdot)$ with $\boldsymbol{\nu}\in\mathcal{V}$ and $\boldsymbol{u}\in\mathcal{U}$, and, the mathematical model $\mathscr{M}(\cdot)$. The real-valued control $\boldsymbol{u}\in\mathbb{R}$ (field strength, angular frequency of excitation and other physical quantities) affect the excitation Hamiltonian $H_E\in\mathbb{R}$ and $H_E\in\mathbb{R}$. Thus, $\boldsymbol{u}\equiv H_E\in\mathbb{R}$. The real-valued *detectable* and *measurable observables,* or physical quantities, yield the system states $\boldsymbol{\nu}$ to be controlled and utilized to accomplish sensing, communication and processing.

3. 2. Quantum Evolutions and Processing

The uncontrollable and controllable *state* transitions and system evolutions are examined by using $\boldsymbol{\nu}\in\mathcal{V}$. Examining quantum transductions, one may use $\boldsymbol{\nu}=[\mathbf{p},E,\omega,\lambda,\ldots]^T$ as well as the probabilistic quantities. That is, the *microscopic* systems undergo within the *allowed states*, and, $\mathcal{M}(\cdot)$ evolves within initial (I), intermediate (T) and final (F) *allowed state* transductions $\mathcal{S}=[\mathcal{S}_I,\mathcal{S}_T,\mathcal{S}_F]^T$ on $\boldsymbol{\nu}=[\nu_1,\ldots,\nu_k]^T$. The physical devices may accomplish the following irreversible and reversible *utilizable* transductions

$$\mathcal{S}_I:\boldsymbol{\nu}_I\Rightarrow\mathcal{S}_T:\boldsymbol{\nu}_T\Rightarrow\mathcal{S}_F:\boldsymbol{\nu}_F \text{ and } \mathcal{S}_I:\boldsymbol{\nu}_I\Leftrightarrow\mathcal{S}_T:\boldsymbol{\nu}_T\Leftrightarrow\mathcal{S}_F:\boldsymbol{\nu}_F. \quad (4)$$

The evolutions of *distinguishable* quantum transductions $\mathcal{T}_j(\mathcal{S},\boldsymbol{v},\boldsymbol{u})$ are mapped as

$$\nu_{j,l}\to^{\mathcal{Q}}\nu_{j,l+1}=\mathcal{Q}_j(\nu_{j,l},u_{j,l}). \quad (5)$$

The controlled evolution of physically-realizable $\mathcal{T}_j(\mathcal{S},\boldsymbol{v},\boldsymbol{u})$ in $\mathcal{M}(\cdot)$ are defined by (5), where $\mathcal{Q}_j$ denotes quantum evolutions S_j and transductions $\mathcal{T}_j$ on ν_j. The transductions $\mathcal{S}_j(\boldsymbol{\nu},\boldsymbol{u})$ on $\boldsymbol{\nu}$ in physical *microscopic* systems are controlled by using device-specific admissible control schemes $u\in\mathcal{U}$. The system $\mathcal{M}(\cdot)$ may be controlled by varying systems energy, potential or field with the corresponding change of the system Hamiltonian $\mathcal{H}$.

3. 3. Heisenberg Uncertainty Principle and Processing

To perform experiments, characterize $\mathcal{M}(\cdot)$ and demonstrate a technology, the physical quantities in *microscopic* systems must be measured. The Heisenberg uncertainty principle specifies the position-momentum and energy-time limits on the measurements of *quantum observables*. In particular,

$$\sigma_x\sigma_p\geq\tfrac{1}{2}\hbar,\ \sigma_E\sigma_t\geq\tfrac{1}{2}\hbar, \quad (6)$$

The expression $\sigma_E\sigma_t\geq\frac{1}{2}\hbar$ specifies the uncertainties on the standard deviation on the energy E, yielding limits on σ_t. The Heisenberg uncertainty principle defines the fundamental limits on the *measurability*, testing and characterization of physical systems by using the specific real-valued physical quantities ν which must be *detectable*, *controllable* and *processable*. Using (6), for physical *microscopic* systems, one has $\nu=[\mathbf{r},\mathbf{p},E,t]^T$. There exist other $[\mathbf{r},\mathbf{p},E,t]$-dependent real-valued quantities, such as the wavelength, transmission coefficient, and transition probability. Thus, or $\nu=f(\mathbf{r},\mathbf{p},E,t)$. The aforementioned quantities also pertain to reported quantum-mechanical modeling where we used C and $f(C)$. However, the focus should be centered on physical systems.

3. 4. Practical Communication and Processing by Physical *Microscopic* Devices on Quantum Phenomena

The *detectable*, real-valued and *measurable* physical *variables* $\boldsymbol{\nu}\in\mathcal{V}$ lead to quantum-mechanically-, device- and algorithmically- (arithmetically) consistent communication and processing. These *variables* $\boldsymbol{\nu}$ must be:

1. Detected, measured, controlled and evolved during controlled quantum transductions;
2. *Algorithmically processable.*

For example, one may control measurable $\boldsymbol{\nu}=[E,\omega,\lambda,\ldots]^T$, and, perform processing on *utilizable* initial (I), intermediate (T) and final (F) *state* transductions $\mathcal{S}=[\mathcal{S}_I,\mathcal{S}_T,\mathcal{S}_F]^T$ on $\boldsymbol{\nu}=[\nu_1,\ldots,\nu_k]^T$. The *microscopic* devices may accomplish the following irreversible and reversible *utilizable* transductions (4). A physical *microscopic* processing *fabrics* may comprise of processing primitives $\mathcal{P}_1,\ldots,\mathcal{P}_k$. Each $\mathcal{P}_j$ exhibits transductions $\mathcal{S}_j(\boldsymbol{\nu})$ on $\boldsymbol{\nu}_j$ yielding *distinguishable* and *computable* transforms $\mathcal{T}_j(\mathcal{S},\boldsymbol{\nu},\boldsymbol{u})$. Using $\mathcal{T}_j$, consistent with device physics and *admissible* arithmetic operand $\mathcal{A}_j$, one has $\mathcal{T}_\Sigma=\mathcal{T}_1\circ\ldots\circ\mathcal{T}_k$.

The processing can be accomplished by using the infinite- and finite-valued logics [4]. Analog, digital and *hybrid* processing schemes may be supported by *microscopic* devices. Considering multiple-valued logic, the switching function on r-valued ν_j is $f:\{0,\ldots,r-1\}^n\to^{\mathcal{F}}\{0,\ldots,r-1\}^m$ with a truth vector $\mathcal{F}$.

Any f can be represented as $f=\mathcal{A}(\mathcal{F},\mathcal{T})$.

The evolutions of quantum transductions are mapped as (5), which defines the evolution of physically-realizable *computable* transforms $\mathcal{T}_j(\mathcal{S},\boldsymbol{\nu},\boldsymbol{u})$. The transductions S_j on ν_j should be consistent with $\mathcal{A}(\mathcal{F},\mathcal{T})$.

4. Quantum Mechanics and Informatics

Various concepts of information theory and computer engineering are applied to examine classical and quantum communication and processing [4]. Conventional and quantum quantities, information measures and processing schemes are different. We focus on:

1. Analysis of electron- and photon-induced phenomena which lead to quantum *state* transitions and *utilizable* transductions on *detectable*, real-valued and *measurable* physical *variables* (*observables*). These *measurable variables* must be *controllable*, *algorithmically processable* and *hardware realizable*;
2. Analysis of device-physics consistent fundamentals of communication and processing by *microscopic* systems on quantum phenomena;
3. Development and substantiation of practical engineering paradigms and technologies of electronic and optoelectronic sensing, communication and processing.

It is important to progress from basic foundations to theory substantiation, practical engineering solutions and technologies by:

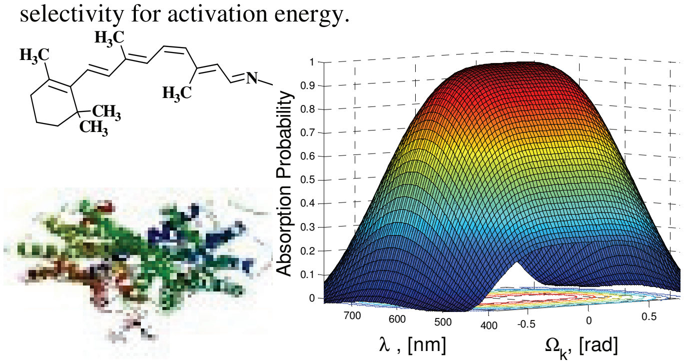
- Studying and applying *utilizable* quantum transductions on *detectable*, real-valued and *measurable* physical *variables*;
- Verifying coherent principles and mechanisms of energy-centric sensing and processing in *microscopic* systems as applied to practical solutions, schemes and technologies.

Under some hypotheses and conjectures, *microscopic* systems can be mathematically modeled and described by using wave functions in spatial, momentum and other spaces. The spatiotemporal wave function $\Psi(\mathbf{r},t)=\psi(\mathbf{r})\varphi(t)$ is found by solving the time-dependent Schrödinger equation (3). Quantum-mechanically-consistent modeling and analysis result in a set of equations (3).

5. BioPhotonics and Retinal Molecule

We examine photon absorption by a retinal molecule [4, 7, 8]. Rhodopsin is a membrane-intrinsic protein. A photon is absorbed by the retinal molecule $C_{20}H_{28}O$ which is bound to opsin as shown in Figure 1.a. Publications [4, 7, 8] examine quantum interactions, photon absorption and transitions in a retinal molecule which is a *microscopic* target. In the spherical coordinates $\Psi(t,\mathbf{r})=\Psi(t,r)\,\Psi(t,\theta,\phi)$.

Consider quantum-probabilistic photon absorption for a realistic wavelength $\lambda\in[400\ \ 800]$ nm and pointing angle $\Omega_{\mathbf{k}}\in[-\frac{1}{2}\pi\ \ \frac{1}{2}\pi]$ rad. The maximum probability of photon absorption is observed at λ=555 nm when the photon energy is 3.6×10^{-19} J. The *microscopic* sensors and detectors ensure high selectivity for activation energy.



(a) (b)

Figure 1. (a) Retinal molecule $C_{20}H_{28}O$ and ;
(b) Probability of absorption, $\lambda\in[400\ 800]$ nm, $\Omega_{\mathbf{k}}\in[-0.7\ \ 0.7]$ rad

6. Photonics and Nanotechnologies: Communication and Processing

Various organic and inorganic sensing, communication and processing devices are designed, tested and characterized. The photodiodes, photodetectors and phototransistors are studied in [1-4]. The designed and characterized organic *fabrics*, as well as organic and inorganic devices, are illustrated in Figure 2.

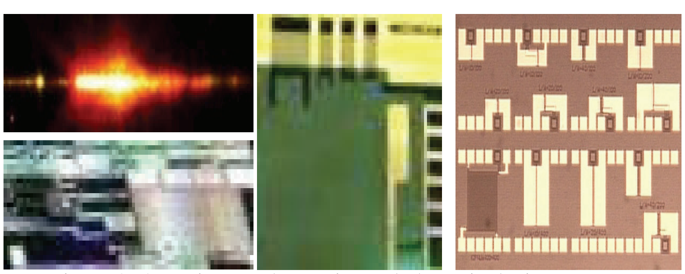


Figure 2. Organic optoelectronics and photonic devices

Advanced technologies and products are under intensive developments. Some technologies are commercialized. Due to unprecedented investments and market needs, *plastic* optoelectronics, resonant tunneling devices, biophotonics, neuro-electronics, nanoephrology, nanomaterials, photonics, 3D printing, sensors and other nanotechnology-enabled innovations are deployed.

7. Conclusions

We examined communication and processing paradigms which: (i) Ease enormous challenges in quantum and *mixed* sensing, communication and processing; (ii) Overcome foremost inconsistencies departing from all-algorithmic-centric computing towards practical technologies; (iii) Enable new practical inroads and solutions; (iv) Advances theory and practice of processing; (v) Enables unprecedented sensing and processing capabilities ensuring far-reaching benchmarks. Our findings support a broad spectrum of transformative research activities, engineering developments and technological advancements. Some core problems of physical and life sciences are studied and advanced. We enabled a knowledge base and proposed new solutions.

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