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Student review of innovations in quantum biophotonics, part 2

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***Abstract*—This article presents a student review on several selected disciplines that can collectively be classified as quantum biophotonics technologies. Discussed topics represent students' areas of interest, showing their perspective on the development of emerging technologies and their potential implications. The covered subjects range from novel fields, such as optically pumped magnetometers, to new applications of widely studied processes, such as photosynthesis. This paper briefly describes these disciplines and highlights emerging research gaps created by capabilities of these findings.**

***Keywords*—quantum technologies, biophotonics, optogenetics, optofluidics, super-resolution microscopy, photosynthesis, optically pumped magnetometer, molecular machines**

I. Introduction

QUANTUM biophotonics is a rapidly developing interdisciplinary field with significant potential for future scientific advancements. In this paper, ICT students conducted in-depth research on selected topic and described recent discoveries within this area. This article is the second part of student's review on quantum biophotonics [1]. In this series of articles students from the Faculty of Electronics and Information Technology at Warsaw University of Technology have the opportunity to gain their first experience in scientific publishing by presenting their perspectives on emerging biophotonic technologies.

The topics discussed in this work encompass novel disciplines such as optogenetics, optofluidics, molecular machines and quantum sensors, as well as recent advancements in super-resolution microscopy and the potential applications of artificial photosynthesis. Through this review, students present their perspectives on current developments in quantum biophotonics and offer predictions regarding its future directions.

II. Wireless Methods in Optogenetics

Optogenetics is a branch of biophotonics focused on controlling neurons using light-sensitive opsins. This technology enables the study of the nervous system and the investigation of potential therapies for various neurological disorders. In principle the stimulation method is based on illuminating opsins expressed in selected neurons, inducing ion currents in target neurons and consequently triggering neuronal activity. The principal advantage of optogenetics is selectivity, ensured by activating only neurons with encoded opsins, unlike conventional electrical stimulation.

The standard method for conducting optogenetic experiments involves delivering light directly to target neurons in studied organisms, which are commonly mice, via optical waveguides. This approach is highly invasive and limits natural movement of studied animals [2], [3]. As a result, some behavioral studies could not be conducted under these conditions. Another, more novel approach for conducting optogenetic experiments involves implantable wireless devices that enable remote neural stimulation. These systems consist of an experimental arena equipped with a transmitter antenna that generates magnetic field within the experiment area and implants that capture magnetic flux and use this energy for powering micro light-emitting diode (μ-LED) positioned above the target neural tissue. A particularly promising advancement in wireless optogenetic stimulation systems is the development of subdermal implants capable of transcranial stimulation, significantly reducing invasiveness of optogenetic experiments [2].

A. Working principle of wireless optogenetic implants

A wireless optogenetic system consists of a power transmitter and an implanted power receiver with a μ-LED. The first component of a power transmitter is a RF generator operating at 13.56 MHz [2], [3], a frequency belonging to the industrial, scientific and medical (ISM) radio band.

The second element is impedance matching circuit, followed by the transmitting antenna responsible for generating the magnetic field within the arena, where animals are placed during experiments. The purpose of this circuit is matching the generator's output impedance to impedance of the antenna. While generator output impedance is resistive, the impedance of an antenna has significant reactive component. Therefore, directly connecting the generator and antenna would cause substantial reflected power, and in consequence only a small fraction of power would be converted to magnetic field [3].

The transmitter antenna is specifically designed for the geometry of the experimental arena to ensure uniform magnetic field distribution throughout the area occupied by the animals

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while conducting experiments. Electromagnetic simulations are used during design process to account for animal mobility, its height and body orientation, ensuring sufficient power delivery to the implant [3].

The implant consists of a primary circuit board and a μ-LED connected to the primary circuit board via elastic interconnects, allowing positioning light source at some distance from primary circuit board. Crucial element on a primary circuit board is a receiver antenna which captures energy from magnetic field. The induced electrical power is subsequently conditioned by receiver-side impedance matching circuit and a power supply circuit to provide appropriate voltage and current levels for system operation. In [2], control electronics enabled pulsed μ-LED stimulation, whereas in [3], the light source was connected to power conditioning circuits directly. Source of light may be positioned separately from the main implant body, directly above the neurons, which are illuminated during experiment.

In [2] both primary circuit board and μ-LED were implanted subdermally, so opsins were stimulated transcranially. This approach required increased optical power required for opsin stimulation due to losses in bone tissue. Alternatively, in [3] main implant body was implanted subdermally while light from μ-LED was delivered through cranial opening directly to the brain.

B. Considerations of wireless energy transfer

The two cited articles employed different strategies to ensure sufficient power level for the μ-LED. In [2], researchers positioned the primary circuit board with power receiving antenna subdermally on the mouse's head. While this paper studied neurons in the brain, distance from primary circuit board to the position of a light source was close. This allowed to integrate both the main implant body and light source onto single flexible printed circuit board (PCB), with the μ-LED connected via stretchable piece of PCB. A notable challenge was the relatively large arena size (70 cm $\times$ 70 cm), which resulted in uneven coverage with magnetic field. Taking into account uneven electromagnetic field distribution and rapid animal movement, the system incorporated a capacitor bank, ensuring sufficient power delivery for stable light source operation even during periods of reduced induced current.

In [3], a different strategy was adopted by designing the system to ensure sufficiently strong continuous power without the need for onboard energy storage. For that reason primary circuit board with receiver antenna was placed on the animal's back, where movement was less dynamic than on the head. Furthermore, the arena was much smaller (5 cm radius cylindrical chamber) compared to [2]. Detailed electromagnetic simulations ensured reliable power transfer throughout the experiment without requiring capacitor bank.

Additional notable aspect in [2] was optical attenuation through the skull due to transcranial stimulation. This led to selecting ChrimsonR opsin activated by longer-wavelength red light, which penetrates bone more effectively than shorter wavelengths. Another important feature of optogenetic stimulation is its pulsed mode of operation. In paper [2] power was supplied continuously and pulse timing of the implant was controlled by a microprocessor. In this approach, by storing power in capacitors, pulse power could be significantly higher than average power induced in an implant, which helped to further compensate for the light absorption in skull.

C. Experiments using wireless implants

Both cited studies successfully demonstrated the functionality of wireless optogenetic implants. In [2], the secondary motor cortex responsible for motor behavior in mice was stimulated using a subdermally implantable transcranial stimulation device. The experiment began with injecting virus encoding ChrimsonR opsin in secondary motor cortex. After 2 to 3 weeks, wireless implants were surgically placed, followed by recovery before behavioral testing. As expected, optogenetic stimulation induced significantly increased turning behavior in mice with injected opsins and implants compared to control group. To further validate neuronal activation of secondary motor cortex, tissue samples of some mice were collected immediately following stimulation. Studying tissues of both study and control group revealed significantly higher c-Fos neuronal activity markers expression in study group compared to control group.

In [3], some functionalities provided by wireless implant design were validated in experiment. Study was focused on stimulating hypoglossal nucleus as a therapeutic strategy for obstructive sleep apnea. This sleep disorder results from reduced tongue muscle tone, which is stimulated by hypoglossal nerve. In experiment, virus encoding opsin was injected in hypoglossal nucleus of mouse, which controls hypoglossal nerve. Following opsin delivery, mouse was anesthetized and μ-LED was implanted into the brain, while the main implant body was positioned on the back of a mouse. Animal was placed inside a cylindrical enclosure consisting of transmitter antenna. Stimulation effectiveness was validated by increased genioglossus electromyography (ggEMG) readings during optogenetic stimulation, indicating increased tongue muscle tone.

These experiments collectively demonstrate the potential of wireless optogenetic stimulation. Such implants enable behavioral neuronal studies under conditions that more closely resemble natural animal living environment compared to conventional tethered approaches. The two studies illustrate distinct engineering strategies, each with unique advantages and trade-offs.

III. Optofluidics

Optofluidics is an area of technology and research that combines microfluidics and photonics. Its applications include imaging techniques, optical components such as lenses, lab-on-chip devices, biosensing, and energy-related processes. Biooptofluidics is a subfield that focuses on applications in biological research and diagnostics. Compared to conventional large-scale diagnostic methods, optofluidic systems require significantly smaller sample volumes and a reduced amount of reagents (nanoliters and below) leading to lower costs and faster analysis. Moreover, the high predictability of laminar microfluidic flows enables precise control of experimental

conditions and allows continuous monitoring of single live cells. These technologies are often implemented in lab-on-a-chip systems that integrate multiple laboratory functions into a single, compact device. Such systems can be designed for ease of use, making them possible to use even by personnel without advanced medical training, and therefore suitable for rapid and widely available diagnostics, particularly in the detection of infectious diseases.

The basic optofluidic system consists of a light source (laser), an optical alignment unit, a light-matter interaction unit, and a decoding unit (e.g. interferometers, spectrometers, polarimeters). Waveguides are commonly used components in optofluidics, serving as channels that guide both light and fluid. Their use allows light to propagate along the fluid channel, significantly increasing the interaction length, which is especially beneficial in Raman spectroscopy.

Changes of the refractive index (RI) of a fluid, for example when one fluid is replaced by another, can alter the propagation of the light. This effect enables detection of fluid properties based on optical signal changes. It is also applied in tunable microfluidic lenses, where replacing or modifying fluids changes their optical properties dynamically. A graded refractive index (GRIN) can be achieved by applying external stimulation such as acoustic waves, temperature gradients, or electric fields, allowing precise tuning of optical behavior in the fluid.

Another mechanism for manipulating light in optofluidic systems is fluid–interface deformation. Polymer materials such as polydimethylsiloxane (PDMS) allow more flexible interface shaping compared to rigid materials like glass. These solutions can be implemented in an in-plane configuration, where the entire device is integrated on a single plane, enabling easier embedding into larger optofluidic and micro-opto-electro-mechanical systems (MOEMS).

Decoding units can also be integrated on-chip. For example, a Mach–Zehnder interferometer can be implemented in-plane by introducing a fluidic channel in one of its arms. Changes in refractive index affect the optical path difference between the arms, enabling precise detection of fluid changes [4].

Another important method used in biooptofluidics is spectroscopy. anti-resonant reflecting optical waveguides (ARROWs) allow the co-propagation of light and fluid within the same on-chip waveguide, significantly increasing interaction length compared to point-based detection systems. This leads to higher sensitivity and enables detection of low concentrations. By using this method it was possible to detect 2.5 nM concentrations of Cy5 dye in water solutions [5].

Optical tweezers are one of the instruments used in optofluidic systems for the manipulation of microscopic particles and biological objects. They operate by using a highly focused laser beam to trap and move particles with sizes comparable to the wavelength of light. The trapping mechanism is based on the transfer of momentum from photons to the particle, effectively holding it in place. The gradient force pulls the particle toward the region of highest light intensity (the focal point), while the scattering force pushes it along the direction of light propagation. When these forces are properly balanced, the particle can be stably trapped and precisely manipulated in three dimensions [6].

Another approach allowing trapping and analyzing single cells in microfluidic systems is the use of passive microfluidic traps. One of the ways to implement them are conical dielectric structures covered by thin metal layers. These microstructures are integrated along microfluidic channel that transport cells to cavities. At the tip of the cone there is a cavity smaller than molecule that immobilizes the passing cell in a trap. These conical structures utilize surface-enhanced Raman scattering (SERS), in which localized surface plasmon resonance amplifies the Raman signal by up to 10^{12}. This allows detection of very weak signals. Passive microfluidic traps do not require prior cell labeling or chemical modification, preserving natural conditions for the cell. Additionally SERS-based techniques can provide nanoscale sensitivity inaccessible for optics, allowing detection of molecular features on the cell surface with spatial resolution down to 10 nm [7].

Classic microfluidic technologies are currently widely used in biomedical diagnostics, particularly in point-of-care testing devices such as cartridge-based polymerase chain reaction (PCR) systems, as well as in tissue engineering applications. Despite their high level of maturity, these systems are still under continuous development, especially in terms of integration and miniaturization. In contrast, optofluidic technologies, which combine microfluidics with optical components, are not yet widely commercialized and remain largely at the research and early development stage. Further advancements in this field may significantly reduce implementation costs and improve accessibility, particularly for imaging and diagnostic applications. In nearby future, optofluidic systems are expected to contribute to further progress in biology, medicine, and pharmaceutical research.

IV. Quantum-enhanced Super-resolution Microscopy: Current State and Future Directions

Until recently, crossing certain observational boundaries hampered the further development of science and technology. The main problem that prevented us from making progress was the scale of the objects and our inability to discern information. The last three decades have proven crucial in overcoming - or even shattering - the literal glass ceiling imposed on us by traditional microscopy.

The utilization of quantum phenomena has allowed us to explore the smallest, atomic-scale particles and make significant advancements in many key fields. This is a remarkable example of how a breakthrough in research paves the way for improved medical diagnostics, drug production, more efficient solar cells, miniaturized processors, and the advancement of the modern world as a whole. The current state of microscopy is attributable to the evolution of super-resolution microscopy (SRM) methods, particularly stochastic optical reconstruction microscopy (STORM) and stimulated emission depletion (STED), which have given rise to the revolutionary minimal emission flux (MINFLUX) [8] and reversible saturable optical fluorescence transitions (RESOLFT).

MINFLUX requires up to 100 times fewer photons than STORM to achieve the same localization precision. It allows

for the full-contrast resolution of molecules separated by as little as 6 nm. A notable example is the tracking of individual proteins in living E. coli bacteria at a frequency of 8 kHz [8]. This level of accuracy is unattainable even for digital cameras. The key concept is overcoming the diffraction limit. The resolution does not have to depend on the wavelength of light (λ), but rather on the precision with which we can locate the "zero" point of the intensity of the beam. It is worth noting that, while techniques such as STED and STORM have revolutionized biology, their success relies mainly on clever manipulation of the photophysics of dyes.

True quantum microscopy goes a step further - it not only bypasses the diffraction limit, but challenges the very statistics of photons. In quantum microscopy, the goal is to reduce shot noise - the statistical fluctuations resulting from the quantum nature of light - and when state-of-the-art observation methods achieve a resolution of 1 nm using a minimal number of photons, we have essentially exhausted these considerations. The use of entangled states, in particular the so-called NOON states, theoretically allows for sensitivity scaling as $1/N$ instead of the classical $1/\sqrt{N}$, where N denotes the number of photons [9].

Meanwhile, the MINFLUX method continues to evolve. Gwosch et al. [10] have presented a three-dimensional multicolor version of this technique, achieving an isotropic resolution of the order of 2 to 3 nm within mammalian cells [11]. Importantly, the number of photons required for a single localization has dropped to a few dozen - a level that was considered physically unattainable for such high precision just a decade ago [12]. This allows for the real-time tracking of conformational changes in individual proteins without the risk of photodamage. Dynamic nanometrology is a relatively new field that transforms a fluorescence microscope into a precise metrological tool capable of recording the trajectories and kinetics of intracellular processes with a level of accuracy previously reserved only for computer simulations.

Data from quantum microscopes are inherently sparse and noisy. Deep learning methods specifically adapted for the reconstruction of super-resolution images are playing an increasingly important role in this field. Ouyang et al. [13] demonstrated that a neural network trained on simulated data can reconstruct subcellular structures with a resolution comparable to STORM, with an acquisition time ten times shorter. Combining this class of algorithms with quantum light sources points to a natural direction for next-generation microscopy.

In our daily lives, we certainly don't realize that there is a reality somewhere below 200 nm, and that is precisely where absolutely everything that affects us takes place. Every disease, every drug, every processor, every solar cell - it all comes down to events at the molecular level that, for decades, we simply weren't able to observe. Super-resolution microscopy, enhanced by quantum phenomena, is the answer to this challenge and it is changing the rules of the game in a dozen or even several dozen key fields simultaneously.

In a groundbreaking 2024 study, Moosmayer et al. [14] from the Max Planck Institute in Göttingen demonstrated the imaging of mouse brain tissue with a spatial resolution of less than 5 nm at depths of up to 80 µm. For the first time, it was possible to simultaneously image the distribution of AMPA receptors and PSD95 protein at the level of a single synapse in three dimensions, with a resolution unattainable by any previous optical technique. AMPA receptors are crucial for learning and memory processes, and knowledge of their exact distribution opens up entirely new therapeutic targets for diseases that medicine has so far been unable to treat effectively.

Beyond neurological applications, super-resolution microscopy has proven equally transformative in the study of infectious diseases. The COVID-19 pandemic has painfully reminded humanity just how helpless we are in the face of pathogens we do not understand well enough. SARS-CoV-2 has a diameter of about 100 nm - ideally within the range of super-resolution microscopy. STORM and direct stochastic optical reconstruction microscopy (dSTORM) methods have made it possible for the first time to visualize the exact distribution of spike proteins on the virus's surface with a precision of less than 10 nm, revealing their heterogeneous, clustered arrangement [15].

The utility of super-resolution techniques, however, extends well beyond the life sciences. Semiconductor manufacturing represents an equally compelling domain of application. When engineers at TSMC or Intel talk about 2-nm lithographic processes, they are referring to structures where an error of just a few atomic units can destroy the entire chip. Quality control at this level requires measurement tools with nanometer-scale resolution. Fluorescence super-resolution microscopy, especially when combined with correlative light and electron microscopy (CLEM), is indispensable here for characterizing surface defects, grain boundaries in dielectric layers, or the distribution of dopants in transistor structures [16].

Returning to the biomedical domain, super-resolution imaging has also fundamentally reshaped the process of pharmaceutical drug discovery. Receptors coupled to G proteins (GPCRs) are the target of approximately 35% of all approved drugs on the market - ranging from hypertension medications and antidepressants to popular diabetes drugs such as semaglutide. Traditional drug discovery relied on observing the collective response of millions of cells. Super-resolution fluorescence microscopy has radically changed this - today, we can observe how individual receptor molecules assemble into nanodomains on the cell membrane, how they move after drug binding, and how these dynamics differ in healthy and diseased cells [17]. This provides a direct window into the drug's mechanism of action at the molecular level, reducing the time and cost of preclinical research - before a drug candidate enters costly animal trials, it is already possible to see whether it works as intended.

The ability to resolve molecular-scale dynamics is proving no less consequential in the development of next-generation photovoltaic materials. Perovskite solar cells have been breaking efficiency records in laboratories for several years, reaching over 26%, but their commercialization is hampered by one fundamental problem - the material's instability at the nanoscale. This very issue was addressed in 2024 by a paper by Louis et al. in Advanced Materials [18], which proposed

the correlation clustering imaging (CLIM) technique based on recording photoluminescence fluctuations in wide-field microscopy. The method allows researchers to literally see where unstable defects accumulate in the perovskite material, how ions migrate under voltage, and where charge carrier recombination occurs, which degrades cell efficiency. Importantly, the study was conducted on functioning cells under voltage, providing insight into the processes actually occurring during device operation. Understanding these mechanisms at the nanoscale is key to designing more durable cells that can finally be brought out of the lab and onto the roofs of homes.

All these fields share a common thread: it was once we learned to look closely enough that we finally began to truly understand. And although the road from laboratory demonstrations to routine clinical or industrial applications is still long, the pace of progress is astonishing. Beyond the technical achievement, there is something profound in what we have gained the ability to witness. At one extreme, super-resolution microscopy reveals processes of quiet elegance - the molecular structure of a synapse at which signals underlying thought and memory are transmitted. At the other, it renders visible what was once only inferred: the slow unraveling of a single cell in its final moments. For the first time, the most intimate events of life and death are not merely described, they are observed.

V. Photosynthesis

A. Principles of photosynthesis

Photosynthesis provides energy for the majority of known life on our planet. Energy of sunlight is converted into chemical bonds and mediates the synthesis of useful molecules, like oxygen, glucose, and hydrogen as an intermediate product. Human-made devices could greatly benefit from the use of this or a similar process and a significant amount of research is made in this field.

Photosynthesis occurs in and around the thylakoid membrane found, e.g., in chloroplasts. The simplified process can be described as a sequence: light absorption, excitation, energy transfer, charge separation, and finally, using the electrochemical gradient generated in parallel across the thylakoid membrane, adenosine triphosphate (ATP) is synthesized. Although light-absorbing pigments are embedded in reaction centres (RCs), or photosystems I and II (PSI and PSII), their highest concentration is found in antenna-like light-harvesting structures surrounding the RCs. Antennae act as first-stage converters. They absorb photons and turn their energy into molecular excitations. PSI and PSII are large protein assemblies highly specialized in transforming excitations fed from antennae into electric potential, used for further chemical reactions. [19] The theoretical maximum efficiency of photosynthesis is 12%. However, in living organisms, due to metabolic limitations, it is only around 1-2%. [20]

Photosynthesis exploits quantum effects that allow for efficient energy transfer and collective behaviors of multimolecular complexes. The whole process is not fully understood yet, and contributions from quantum mechanics theory can push the research onward. [21] To make use of photosynthesis, artificial and semi-artificial processes are considered. Each of them faces different problems, which are subjects of research focus, and quantum mechanics may offer potential solutions.

B. Quantum mechanics in photosynthesis

Absorption and emission of photons are quantum processes themselves. Optical dipoles in molecular complexes may absorb light collectively or separately in each molecule, depending on whether quantum coherence is present or not. [22] Upon light absorption, chromophores are electronically excited. This way, excitons, bound electron-hole pairs, are created. [23] These quasi-particles, although electrically neutral, are the medium of energy transfer over short distances. [24]

There are two regimes of energy transfer. Each of them, under optimal conditions, has near-perfect efficiency. When electrostatic interactions between pigments are relatively weak, energy transfer is stated as incoherent. [24] In such a case, transfer can be described by classical probabilistic dynamics, e.g. Förster resonance energy transfer (FRET), where energy is transferred through electric dipole-dipole interactions between chromophores. [19], [24] The mechanism can be thought of as hopping between discrete energy levels, from higher to lower sites of the energy gradient. However, when the interactions between pigments are relatively strong or dynamics happen faster than on a 1 ps timescale, FRET is not applicable, and instead, coherent transfer is present. [19] In such a case, excitation is delocalized and behaves as a quantum wave-function. Furthermore, quantum superposition and phase coherence lead to wave effects, like interference. [24] In superconducting circuits and engineered quantum systems, coherent energy transfer enhances the efficiency beyond the limits of classical models. [24] Incoherent energy transfer, in thermally fluctuating environments, where system-environment interactions are relatively strong, is more robust, predictable and stable. Coherent transfer is highly susceptible to external perturbations. Any interaction introducing dephasing causes a change toward incoherent behavior. [24]

C. Bio-inspired and artificial systems

In recent years, PSI has gained significant attention as a potential sensitizer, or the core of photosynthesis, in artificial systems. [21] Advantages of PSI over silicon-based solar cells include high efficiency in light energy conversion with a potential for further optimization, potentially lower manufacturing costs compared to traditional devices, and, as a biological material, greater sustainability, biocompatibility, and lower environmental impact.

For Bio-PVs to operate, four main processes must be implemented. Light absorption by a sensitizer (e.g. PSI and PSII) causes an electron to be promoted to the lowest available molecular orbital. Thus, the sensitizer transitions into its excited state. Then, charge separation takes place. The excited sensitizer dissociates into an electron and a hole. The electron is injected into the conduction band of the semiconductor material of the anode, typically titanium dioxide (TiO_2) nanoparticles. After that, the electron travels through the load circuit into the cathode of the Bio-PV, typically made out of platinum (Pt), and the circuit is completed. After

the above steps, however, the sensitizer is left without an electron. To account for this, it is reduced by a reducing agent, commonly iodide ions (I^-), in the electrolyte by which it is surrounded. The redox mediator itself (I^-) is reduced back to its original state by the electron which came back via the cathode, e.g. in reaction $I_3^- + 2e^- \rightarrow 3I^-$. [21]

All developed designs struggle with the lack of input from quantum mechanical phenomena. Photogenerated electrons in reaction centres transform with no resistance, whereas artificial systems struggle with ohmic and capacitive resistances. Because of the above, the power conversion efficiency of Bio-PVs remains under 1%. [21] Currently, the main concerns of Bio-PVs are optimum orientation of photosystems (PSI and PSII) on semiconductor substrates, stability of photosystems in electrolyte, efficient electron transfer and injection yield, absorption of light within the highest possible spectrum with highest external quantum efficiency.

D. Quantum-inspired energy harvesting

A major problem of harvesting light with organic semiconductors is that during energy transfer, excitons are lost due to non-radiative and radiative recombination, before the charge is separated. Solutions to radiative recombination may be found in natural systems, where spatial superposition states and collective subradiance may be exploited. Inefficiency caused by re-radiation can also be a problem in primary absorbing dipoles, or antennae. A theoretical remedy for this has been proposed, relying on quantum-enhanced photocells. Piggybacking on natural photosynthetic structures gives another possibility to achieve efficient light energy harvesting. [22]

Artificial photosynthesis systems convert light to electrical energy via completely abiotic chemical reactions, e.g. photocatalytic water decomposition, thus lacking at least some limitations of biological systems. Production of reduced nicotinamide adenine dinucleotide phosphate (NADPH) and ATP, CO_2 fixation, etc. need complex molecular and enzymatic interactions. Artificial models, where e.g. ATP and NADPH molecules are not necessary, are not bound by metabolic limitations, and thus can be optimized for maximum conversion efficiency. Photocatalysts in artificial systems are considered unstable because of susceptibility to rapid degradation, deactivation or poisoning due to light, heat, electrical and chemical interactions. Moreover, their conversion efficiency remains relatively low due to cumulative energy losses across subsequent conversion and transport steps, and many light-absorbing materials and catalysts are made of toxic elements. [20]

Semi-artificial photosynthesis integrates living organisms with engineered constructs. Excited sensitizers produce photogenerated electrons and donate them to biocatalysts, i.e. enzymes or microorganisms. Artificial sensitizers, more efficient than those found in nature, can greatly enhance the efficiency of light harvesting. Photosensitizers can be divided into inorganic and organic. An example of the former can be CdS, exhibiting favorable properties as a photocatalyst, e.g. appropriate band structure. It has, however, low charge separation efficiency and, as a heavy element, is toxic. In contrast, organic semiconductor photosynthesizers are highly biocompatible and their parameters, like absorption band gap, can be adjusted to match given needs.

Production of efficient organic materials is unfortunately complex, thus their cost-effective development remains a topic of research. Quantum dots (QDs) may constitute a solution. They are biocompatible - can be coupled with enzymes or whole living microorganisms. They exhibit the ability to capture light and transfer charges. QD's emission spectrum can be tuned, ranging from visible to infrared light, to match the reduction potential of biocatalysts, thus decreasing energy losses. The idea is that QDs, upon light absorption, would generate electrons that could be used in reduction and holes in oxidation reactions. Also, electron transfer via quantum dots shows superior efficiency over natural, biological structures. QDs could replace photosystems I and II, and thus decrease the complexity of light-harvesting systems. [20] Semi-artificial photosynthesis and integration of microorganisms with quantum dots are still in early development, but show significant promise. [20]

VI. Optically Pumped Magnetometer

Quantum sensing is what shifted our perspective on how we approach medical diagnostics. Measuring the body's internal signals required large, stationary machines that captured an average of many signals at once. However, quantum systems allow us to look at individual atomic states to get much higher precision. While classical sensors often rely on "super cold" temperatures to work, Optically pumped magnetometer (OPM) technology uses the atomic spin of a gas at room temperature. This makes it possible to detect low signals that were previously undetectable to standard medical measurement equipment. While other quantum platforms, like nanodiamonds, are often used for microscopic studies, OPMs are designed to measure larger magnetic fields, such as signals from the human heart or brain.

The physical OPM assembly consists of three main parts: a laser, a vapor cell, and a photodetector [25]. Before entering the vapor cell, the laser light passes through a polarizing beam splitter and a quarter-wave plate. These parts filter the light and change its shape so it can effectively pump the rubidium atoms inside the cell, aligning their spins in a specific direction. When the sensor is placed near a patient, the tiny magnetic fields from the body disturb this alignment. This disturbance changes how much light passes through the cell, which is then measured by the photodetector.

For the measurement to be accurate, the sensor must be shielded from the Earth's magnetic field, which is much stronger than any biological signal. To handle this, the OPM uses built-in coils that create a canceling field, effectively compensating for the background field [26]. Additionally, the entire device is protected by a ceramic housing. Ceramic is used because it does not conduct electricity, which is important because it prevents electrical interference from distorting the magnetic signal. Additionally, the ceramic acts as a thermal insulator, allowing the rubidium gas to be heated to the necessary temperature while keeping the outside of the sensor cool enough to touch the patient's skin.

The transition from stationary cryogenics to OPM technology has enabled a new era of wearable magnetoencephalography, which fundamentally changes how we observe neural processes during physical activity. Because these sensors operate at room temperature and are housed in a compact, lightweight casing, they can be placed directly in a 3D-printed helmet located on a patient's head [26]. This configuration is a significant improvement over traditional superconducting quantum interference devices (SQUID) systems, where the need for a vacuum insulated casing forces a 3 cm gap between the sensor and the measuring body part. OPMs reduce this distance to just a few millimeters, significantly increasing the signal-to-noise ratio. They also maintain high reliability even when the subject is performing natural tasks like drinking or moving their head. Additionally, those sensors remain responsive to the full spectrum of brain activity, maintaining a stable frequency response up to approximately 130 Hz [26]. This bandwidth is crucial for neurorehabilitation, as it allows to monitor high frequency brain waves during real world tasks, such as post stroke patients during their everyday tasks, while providing a precision that was previously limited to strict laboratory conditions.

In addition to mapping neural signals, OPM systems are able to monitor therapeutic agents in the body through magnetorelaxometry. In this application, medications are coupled with magnetic nanoparticles which act as local markers that can be detected by quantum sensors. These particles are typically modified with specific molecular keys that allow them to selectively bind to diseased tissues like tumors while bypassing healthy cells. Research involving live subjects demonstrates that OPMs can monitor the movement of these particles with nanogram precision even when significant background noise from breathing or the heartbeat is present [27]. This data allows for the creation of a precise spatial map where dense clusters of detection points indicate exactly where the drug has accumulated in the body. Furthermore, the system can distinguish between particles that are still circulating in the bloodstream and those that have successfully anchored to their target tissue. This is achieved by observing the magnetic decay curve of the particles where a faster drop in signal strength compared to a reference sample indicates that the particles have interacted with their cellular destination. This level of real-time quantification offers a significant advantage for cancer treatment because it allows clinicians to confirm the delivery of a drug to a tumor without delay and potentially adjust the dosage to minimize toxic side effects.

Another application of OPMs is cardiac imaging, in which these sensors allow the measurement of magnetic field components across all three axes. This vector methodology bypasses the constraints of traditional measurements by recording the full three dimensional magnetic signature of the cardiac cycle instead of focusing solely on the field component perpendicular to the chest surface [25]. By recording signals in the X, Y, and Z directions, researchers can construct a vector magnetocardiogram which visualizes the movement of the magnetic vector throughout the cardiac cycle. This spatial information is particularly valuable for identifying secondary electrical currents that are often hidden in standard electrocardiograms due to the insulating properties of the lungs and skin. Because magnetic fields pass through biological tissues without distortion, OPM sensors can pinpoint deep conduction issues or subtle signs of ischemia with much higher accuracy. This capability allows for a detailed analysis of the P, QRS, and T loops in 3D space, offering a far more comprehensive assessment of heart health than is possible with surface-level electrical readings.

Practical quantum sensing is driving a transition toward a more data-centric understanding of human health. Particularly in rehabilitation, this approach allows for a direct assessment of how tissues are healing by tracking signals from within the body, moving past the limitations of simple visual observation. In contrast to earlier bulky systems, OPM sensors can monitor patients during actual physical activity. This gives doctors a more comprehensive view of recovery at a fundamental level. Because these quantum sensors work at room temperature, they are becoming a practical tool for daily medical practice, ultimately enabling the translation of advances in physics into improved patient outcomes.

VII. Molecular Machines

The concept of building devices on an atomic scale, presented in 1959 by Richard Feynman, remained purely theoretical for decades. The ultimate breakthrough in this field, for which J.-P. Sauvage, J. F. Stoddart, and B. L. Feringa received the Nobel Prize in Chemistry in 2016, enabled the synthesis of artificial molecular systems with precisely controlled kinetics. A molecular machine is defined as a set of components that, under the influence of an external stimulus and a continuous supply of energy, perform directed motion, converting the absorbed energy into useful mechanical work [28].

The fundamental difference between a simple molecular switch and a full-fledged machine boils down to the ability to generate useful work. In the case of a switch, the motion is limited to alternating between two states within its own reference frame, so no net work is generated. However, in a molecular machine, directed motion is coupled to an external system, resulting in the performance of specific work. When designing such systems, two specific physical problems must be taken into account: Continuous thermal chaos, namely Brownian motion, and functioning in a low Reynolds number environment. In such physical conditions, the phenomenon of inertia practically disappears, and the movement of molecules resembles the movement in a highly viscous liquid [29].

To address these issues, architectures based on mechanical bonds and isomerizable unsaturated bonds have been developed. Mechanical bonds involve the topological entanglement of components, as illustrated by catenanes (interpenetrating rings) and rotaxanes, in which a macrocyclic ring is trapped on an axis blocked by stoppers. The operation of the catenane was based on matrix methods in which Cu(I) ions were used to enforce the appropriate spatial orientation of the rings. For the rotaxane, this involved exploiting interactions between electron-rich and electron-poor aromatic systems. In parallel, a unidirectional molecular motor based on isomerizable unsaturated bonds was developed. The motion of such a motor is

based on the alternating execution of cycles of photochemical isomerization and thermal relaxation, acting as a mechanical latch. This forces the continuous rotation of the rotor relative to the stator strictly in one direction, eliminating the problem of random molecular motion [28].

To translate molecular motion into macroscopic dimensions in order to generate useful work, these machines are embedded in structured environments, such as crystalline structures. Studies have shown that multicomponent crystals composed of photoswitches (diaryl ethenes) undergo reversible bending under ultraviolet (UV) radiation due to the generation of asymmetric stresses in the surface layers. This process was used to drive the synchronized rotation of a millimeter-scale gear, directly converting the photochemical impulse into work. Another structured environment is metal-organic frameworks (MOFs), which provide high spatial organization. However, integrating machines into the interior of MOFs requires precise control over the void volume of the structure to allow for free conformational changes of molecules without destroying the crystal lattice [29].

The translation of molecular motion is also analyzed on solid surfaces. Deformations of gold micro-levers coated with a layer of rotaxanes were recorded. In response to chemical oxidation, electrostatic repulsion forced the rings to move along the axis, generating a net stress that caused the lever to bend by 35 nm. The application of switches on solid surfaces was also investigated for the control of biological processes. Attaching azobenzene to peptides allowed for the creation of a system in which isomerization influenced the activity of the motor protein kinesin. The trans form inhibited microtubule movement, while the cis form restored their mobility, enabling the selective activation and deactivation of cellular transport using light [29].

Substantial outcomes were likewise achieved with soft materials, including liquid-crystalline and amorphous polymers. The phenomenon of isomerization in these materials causes a change in the lattice order, which leads to the generation of deforming forces. This was used to construct a drive belt made of liquid-crystalline polymer, which, when irradiated on one side with UV radiation and on the other with visible light, forced the continuous rotation of a macroscopic pulley system. Another model is based on the use of linear liquid-crystalline polymers to form microscopic tubes. The light-induced change in the orientation of polymer molecules (the Weigert effect) generates asymmetric capillary forces capable of moving portions of liquid without the use of external pumps. The use of amorphous polymer gels, in turn, allowed for the incorporation of unidirectional rotary motors as network nodes. Their rotation under the influence of UV light intertwines adjacent polymer chains, resulting in the shrinkage of the material immersed in the solvent. The implementation of modifiers based on diaryl ethenes allowed the mechanical tension of the chains to be released using visible light, restoring the initial volume of material [29].

The creation of machines operating in solutions characterized by a high degree of disorder is based on strict control of kinetic and catalytic processes. Molecular pumps based on rotaxanes have been developed that utilize an energy trap mechanism. The use of a sequence of reduction and oxidation reactions forces the macrocyclic rings to move through a steric barrier into a collection area on the axis, where they undergo kinetic trapping. Other systems are based on information traps, in which the directional movement of components along the axis is regulated by the kinetics of the attachment and detachment of large steric groups. The transfer of this type of machine to flow systems is being investigated as a method to avoid the accumulation of chemical waste generated in reaction cycles [29].

The use of synchronized molecular machines is being extensively explored in biomedical engineering and cancer therapies. These molecules are used to perform precise operations at the cellular level in processes such as:

- Drug delivery systems: These systems utilize machines for targeted drug transport. Enzyme-sensitive rotaxane-type systems have been engineered that circulate in the blood and stabilize the active substance. Upon entering a cancer cell (e.g., KB line) and in the presence of the intracellular enzyme galactosidase, the molecule breaks down, releasing the lock and delivering the anticancer drug paclitaxel. Another strategy involves embedding hydrophobic, unidirectional rotary motors into the lipid bilayer of liposomes. Their rotation, initiated by UV light, physically ruptures the liposome structure, releasing its contents (e.g., calcein molecules) directly into the target tissue. The use of microrobots capable of active movement facilitates the overcoming of biological barriers and the accumulation of drugs in tumor areas [30].
- Molecular nanodrills (cell membrane permeabilization): This system is based on rotary motors coupled with targeting peptides, allowing them to selectively bind to the surface of cancer cells. Binding efficiency was confirmed in prostate cancer (PC3), cervical cancer (HeLa), and breast cancer (MCF7) cell lines. After the system is tethered to the membrane, it is triggered by near-infrared light (two-photon NIR, 710-720 nm), which can penetrate more deeply into tissues and is less harmful than UV radiation. Activation causes the nanomachines to rotate rapidly, mechanically piercing the lipid bilayer of the cell membrane, leading to the destruction of the pathological cell in approximately 3 minutes. Studies have also shown that artificial molecular machines serve as a tool in combating antibiotic-resistant microorganisms. The rapid light-induced rotation of the motors disrupts the integrity of the cell membranes of Klebsiella pneumoniae bacteria. This action increases the susceptibility of pathogens to carbapenems, such as meropenem, demonstrating a synergistic bactericidal effect in inhibiting cell wall synthesis [30].

The behavior of molecular motors is also being studied in the context of stem cell differentiation. Glass surfaces coated with rotary motors and exposed to UV light exhibit increased adsorption of bovine serum albumin. Human bone marrow-derived mesenchymal stem cells (hBM-MSCs) cultured on such surfaces exhibit good adhesion and changes in the actin cytoskeleton, which directs them toward differentiation

into osteoblasts. In non-irradiated systems, these cells retain their multipotency. In the field of nanotherapeutics, the pH-dependent heterogeneity of the tumor microenvironment allows for the adaptation of catenanes and rotaxanes as transition metal ion chelators. These systems serve as molecular markers in clinical imaging techniques such as magnetic resonance imaging (MRI) and positron emission tomography (PET) [30].

Although molecular machines is a field in its early stages of development, it requires overcoming challenges related to biocompatibility and functioning in complex biological environments. The development of engines powered by visible light reduces the negative impact of UV radiation on living cells. The use of 3D printing techniques to create elastomeric structures containing molecular motors enables the design of materials that respond to external stimuli. Experiments indicate that controlling motion at the molecular level can be translated into materials engineering systems, drug delivery systems, and diagnostic devices. Advances in molecular machine research enable the development of new methods in medicine, including highly precise nanomechanical interventions and improved therapeutic protocols [29], [30].

VIII. Conclusions

Presented work demonstrates the significant potential of applying quantum techniques in biophotonics, enabling discoveries that are unattainable with conventional macroscopic technologies. The research findings discussed in this article illustrate direction of current scientific advancements focused on deeper exploration of nature, higher-precision sensing of physical parameters, and improved understanding of living organisms. Furthermore, the increasingly detailed perspective provided by these emerging technologies creates new opportunities for scientists to investigate microscopic properties with unprecedented accuracy. As we observe an increasingly detailed picture of the world, new scientific questions continue to emerge.

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