Characterization and Application of Nanomaterials 2025, 8(3), 11474.
https://doi.org/10.24294/can11474

Review

Insights of prototyping Hierarchical bottom-up of optical active materials for multimodal energy coupling and functional biophotonic nano-, microwearable devices

Sofia Mickaela Martinez[1], Cecilia S. Tettamanti[1], M. Valeria Amé[2], Daniela Alejandra Quinteros[1], A. Guillermo Bracamonte[3,4,*]

[1] Unity of Research and Development in Pharmaceutical Technology (UNITEFA), CONICET, Department of Pharmacy, Faculty of Chemical Sciences, National University of Córdoba (UNC), Córdoba 5000, Argentina
[2] Research Center in Clinical Biochemistry and Immunology (CIBICI), Department of Biochemistry, National University of Córdoba (UNC), Córdoba, Córdoba 5000, Argentina
[3] Academic Department, Faculty of Chemical Sciences, National University of Córdoba (UNC), Córdoba X5000HUA, Argentina
[4] National Scientific and Technical Research Council (CONICET), Córdoba Research Institute in Physical Chemistry, Córdoba X5000HUA, Argentina
*** Corresponding author:** A. Guillermo Bracamonte, gbracamonte@fcq.unc.edu.ar, guillermobrac@yahoo.ca

CITATION

Martinez SM, Tettamanti CS, Amé MV, et al. Insights of prototyping Hierarchical bottom-up of optical active materials for multimodal energy coupling and functional biophotonic nano-, microwearable devices. Characterization and Application of Nanomaterials. 2025; 8(3): 11474. https://doi.org/10.24294/can11474

ARTICLE INFO

Received: 5 February 2025
Revised: 16 March 2025
Accepted: 21 March 2025
Available online: 20 June 2025

Abstract: In this review are developed insights from the current research work to develop the concept of functional materials. This is understood as real modified substrates for varied applications. So, functional and modified substrates focused on nanoarchitectures, microcapsules, and devices for new nanotechnologies highlighting life sciences applications were revised. In this context, different types of concepts to proofs of concepts of new materials are shown to develop desired functions. Thus, it was shown that varied chemicals, emitters, pharmacophores, and controlled nano-chemistry were used for the design of nanoplatforms to further increase the sizes of materials. In this regard, the prototyping of materials was discussed, affording how to afford the challenge in the design and fabrication of new materials. Thus, the concept of optical active materials and the generation of a targeted signal through the substrate were developed. Moreover, advanced concepts were introduced, such as the multimodal energy approach by tuning optical coupling from molecules to the nanoscale within complex matter composites. These approaches were based on the confinement of specific optical matter, considering molecular spectroscopics and nano-optics, from where the new concept nominated as metamaterials was generated. In this manner, fundamental and applied research by the design of hierarchical bottom-up materials, controlling molecules towards nanoplatforms and modified substrates, was proposed. Therefore, varied accurate length scales and dimensions were controlled. Finally, it showed proofs of concepts and applications of implantable, portable, and wearable devices from cutting-edge knowledge to the next generation of devices and miniaturized instrumentation.

Keywords: nanomaterials; modified substrates; nano-optics; nanophotonics; nanodevices; microdevices

1. Basis of prototyping new nanomaterials towards modified substrates and devices

In this first part of the communication, it is intended to highlight why it is important to prototype nanomaterials in the design and synthesis of new nanomaterials. In this regard, the methodology to afford new designs nominated as "prototypes" is highlighted. Incorporate the concept of prototyping macromaterials in the absence of developing reactions, and wet chemistry could be proposed theoretically by the use of micro- and macroscopic materials that could be held by hands. From this theoretical proposal based on fundamental knowledge, the strategy for the study and applied research is begun. This is the beginning, and we contemplate the basis and fundamental knowledge in relation to the desired matter incorporation and potential new chemical properties. Therefore, the design using real materials in the macroscale with shapes that emulate the nanoscale and contemplating chemical surfaces could be visualized. Sometimes the use of the blackboard and 3D imaging software could provide interesting approaches; however, the capability to manipulate real materials emulating the molecular and nano-world is the final targeted aim that should be developed and shown. The prototyping could facilitate different strategies using varied materials to support the idea of the use of the nanoscale for the targeted objective. Then, after obtaining the design and developing the synthetic methodology, it could be applied to the iteration and optimization depending on the results obtained. Maybe these first insights could produce advice for students and young researchers for the next generation of experiments and materials [1,2]. In these perspectives is noted the important theme of nano-optics that could be developed in order to study and design optical active nanomaterials, light matter interactions, quantum phenomena, and metamaterials as well [3]. The metamaterials are generated by the incorporation of different optical active materials confined that produce unexpected electronic properties. In this regard, nanomaterials could produce meta-material properties based on their close matter compositions. The electron and photonic matter coupling modify their intrinsic free properties, accompanied logically by new electronic densities from the bulk. In this context, quantum phenomena could provide high sensitivity to modulate new properties. As an example, from recent advances and the perspective of quantum metaphotonics, it is highlighted that meta-optics employ subwavelength resonators and their planar structures, such as metasurfaces, to generate, manipulate, and detect quantum states of light. In this approach to developing materials, the design of nano-patterns by laser-assisted techniques affords coupling optics from individual signaling to collective nano-arrays. Thus, electronic waves and quantum properties interact between nano-volumes surrounded with optical active matter that modify signaling. Thus, it is recently noted from literature that the proper selection of polarization states in the heralding arm of the entangled photon source, either normal image or edge image, was obtained. Thus, a high signal-to-noise ratio at the same photon flux level was generated. This improved state of quantum light was applied for nonlocal weak-measurement microscopy imaging [4]. Thus, quantum light affords high nanoscale resolution by diminishing sizes and augmenting intensities.

In this context, it is important to note that from this point of view, the prototyping is related as well to the methodology to develop the know-how to create a new nanomaterial with particular new non-classical optical properties. It involves the design of the idea based on the incorporation of varied physical and chemical phenomena. Thus, it should incorporate many strategies from different sources of materials and associated properties. This fact could be achieved by incorporating different optical components within varied scales and physical phenomena associated (**Figure 1**). Schematically, in the prototyping, it is possible to organize 3D structures from nano-spheres connecting molecular interphases of varied optical components activated by different sources depending on the targeted modified substrates to be incorporated in devices and miniaturized instrumentation. The schema looks easy; however, it is the current challenge to develop further knowledge as well as to improve the performances of optical materials from the market.

In this context, physics and chemistry involve different electronic and quantum properties that could govern the final optics developed. This principle is related to the atomic level interacting with other ones with different optoelectronic properties, as for example [5]. Thus, the knowledge about nanochemistry is required for the bottom-up of the nanoplatforms. Spectroscopy of materials should also be considered in order to produce smart, optically active matter. This is the theory, and sometimes it is not as straight as expected. In this context, it could present many challenges in this theme, where prototyping is a very important step in the design and synthesis of the nano-optical material. By this manner it is possible to think of the potential performances as well as any inconvenient interferences, etc., in the process of the fabrication. Hence, these concepts focused on how to proceed; it could be expected to develop nano-optics from the desk to the bench and laboratory.

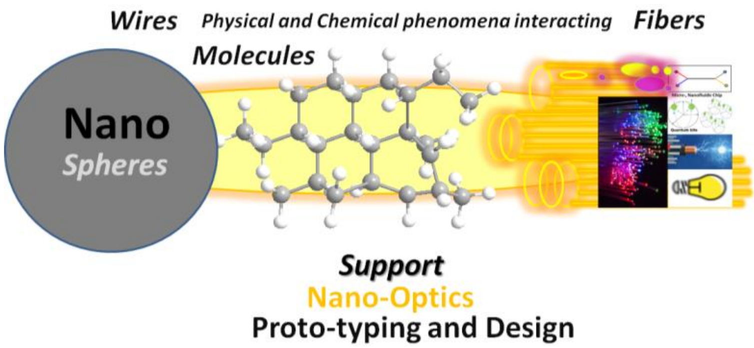

Figure 1. Scheme of prototyping hybrid modified optical active nanomaterials controlling the molecular level, nanoscale, and higher-sized substrates in the micro- and macro-scales. Therefore, opto-electronics and biophotonics applications could be proposed for targeted applications.

Notes: Nanospheres are supports of varied chemical structures such as single molecules, molecular wires, and polymeric fibers acting as linkers with varied functions to switch different targeted functions schemed as fibers, lamps, chips, etc.

In these perspectives, it was led to highlight some reports in literature showing varied approaches and strategies depending on the involved study or targeted application. Hence, prototyping nanomaterials is a basic step in the design, synthesis, and fabrication of optical active single nanoplatforms and nano- and microarrays. It was noted that the concept is related to the proposal of the targeted design based on well-known molecular and nanocomponents joined in a way not previously achieved before for a desired functionality of study [6]. In this manner, innovation could be proposed as challenges as well.

In this manner, physics below the nanoscale could be tuned and generate improved performances, such as plasmonics coupling within core-bi-shell structures [7]. This approach was formed by a silver core (Ag) covered with titania (TiO_2 NPs) and an extra organic layer of benzoic acid-fullerene (Ag@TiO2@Pa). The optical setup showed improved properties based on synergistic effects (optical and electrical phenomena). For example, organic solar cells led to enhancements of 12%–20% with a maximal power conversion efficiency of 13%, while the plasmonic core-bi-shell nanostructure produced an enhancement of 10%, from 18.4% to 20.2%. The constitution of this bi-layered core-shell permitted an improved short circuit current from within the nanoparticle and through the cell material by light excitation with electronic current generation. This fact could lead to the development of enhanced light emitter devices (LEDs) [8] and new futuristic non-classical light generation by plasmonics-LEDs [9]. Therefore, opto-electro-active materials could afford to further fundamental studies as well as applied technology.

The same concept is developed when different materials are combined with unknown properties looking for the study of some property not well known or a new one. This last mention is because not always are all the properties of materials known. In many cases they were recently synthesized, and partial characterization was developed. In this context, the prototyping of optical active nanomaterials by the combination of different matter compositions is an interesting fundamental research field as well as an applied field and is required for the fabrication of new optical materials within a varied scale of lengths [10]. The prototype is the first proposed model of the design of the nanomaterial. This should be logically well justified based on knowledge and hypothesis of functionality. It could be related to inventions as well as fabrication processes, or both at the same time. As all prototypes, it should be developed from an idea to a simple scheme, theoretical model, calculation, and physical model fabricated maybe in the macroscale to show the nanoarchitecture, permitting in this manner the visualization of the different components and functions [11]. All these strategies can provide different manners of evaluation of the fundamentals or basis involved in the targeted final properties of the desired proposed study. When it is mentioned the targeted property or function [12,13], it is focused on the objective of the research work or fabrication process [14]. In this context and just to finish, it highlighted the need to keep in mind a large window of materials types from where it could be prototyped new ones. Thus, soft materials, organized systems, and biomaterials could be joined to inorganic and hard materials depending on the targeted function or study of interest. In this regard and considering methodological issues, it is noted that the required multidisciplinary research to develop these types of projects. So, in the next subsection, it was afforded the development of nano-optics and beyond from varied sources of materials.

2. From prototyping towards the design of multi-modal energy approaches for fundamental research and applications

So, prototyping from atoms to molecules, joining different fragments with different functions and properties, could afford interesting insights in varied research fields depending on the material involved. This need should be planned on a larger scale, affording the different challenges related to the bottom-up. Thus, the incorporation of optically active materials could tune optics by adding optically active molecules and tuning the nanoscale. In this direction is involved fundamental research where the characterization of nanochemistry with varied spectroscopical properties would be of interest, looking to go up in the micro-scale by assembling or applying laser-assisted techniques to make nanopatterned surfaces.

About methodologies involved, it could be mentioned that wet chemistry methods [15] are used to manage colloids and nano-optics, while laser-assisted techniques are used for solid nanopatterned surfaces of substrates [16].

In this regard, it is expected to control the nanospectroscopy from single particles within colloids or placed modified substrates towards collective behaviors from nano-arrays [17]. Naturally, materials and methods are different; however, this broad overview should be mentioned to afford a large spectrum of possibilities to produce different properties within the nanoscale. Thus, from optics, it is needed to control and track single energy modes that require; i) high accuracy and precision in the measurements, ii) analysis of data, iii) interpretation, and iv) development of applications. This could be the case of near infrared (NIR) nanoemitters for labeling and the generation of bioimaging [18]. In this regard, the design and synthesis incorporating different energy modes is highly required for many reasons. Thus, whatever expected property with attended applications always involves different phenomena at the same time. But not always are all the possibilities under focus because there are many optical setups to fix in order to record multi-signaling at the same time [19]. In this context, the coupling of different optical set-ups is a challenge to afford. When the properties are originated from the same material, such as for an absorber with the capability to generate electron conduction, the set-up could be simplified [20]; while incorporating different materials accompanied by different properties and generating new ones, it could require more complex optical set-ups for multi-modal signal recording in real time and time-resolved ones as well [21].

In this regard, as an example, it could be required to track electrochemical signaling and luminescence emissions from single nano-optical systems, from where it is unless it needs the incorporation of potentiostats to vary voltages while on the other side laser dyes for light matter interactions [22]. In a similar manner, the optical disposition of optical elements and detectors in the optical bench could add more requirements. By this manner, the matter could be applied a programmed stimulation by different energy pathways upon needs controlled remotely [23]. As an example, it could be mentioned that the design and application for theranostics uses of fluorescent and magnetic nanoparticles [24]. In this study it was fabricated light-responsive Janus nanoparticles based on poly (styrene-methyl methacrylate-acrylic acid). This nanoplatform permitted supporting two photobase generators that could react with fluorescamine to produce varied colors. In addition, the incorporation of magnetic Fe_3O_4 afforded the control of nanoparticles by the use of a magnet at the same time that fluorescence with varied colors was produced.

Previously, the development naturally should have proposed a retro-synthesis in order to link the different optical active parts of the molecules, nanoplatforms, and by this manner, add up on the needs of the required optical set-ups. This planning involves the spatial distribution of atoms and molecules within the nanoscale if it is expected to develop nano-optics; while to focus light, it could be contemplated to vary supports to contain, depose, and get in flow the nano-optical active particles. In this context, it could also be considered the topological factor for photonics developments. Thus, topological photonics based on asymmetrical bottom-up nanomaterials and higher-sized substrates are important further considerations in the development of multimodal approaches [25]. In this manner and incorporating different materials, it was possible to generate even more energy modes from interactions of different optical matter components accurately placed in 3D spatial distributions (**Figure 2**).

The concept could be summarized by the combination of different optical active nanoparticles by molecular wires. By this manner, focusing a laser or applying electron conduction from one side, it stimulates the first energy modes such as plasmonics or semiconductive to then generate in the second electron optical nanomaterial a response modifying the conduction of photons or electrons. This could be applied in varied substrates and techniques such as laser-assisted light waveguiding and light scattering by the use of advanced spectroscopical techniques available on the market such as WOLS (Waveguiding Optical Light Scattering).

These interactions generate variations in the electronic distributions, and in many cases, they could modify the waves after interactions. Therefore, the electronic density of the material is different, and logically, the optics too. This is the basic concept; however, it is the challenge waiting for further research. In this regard, the pattern of molecules, spectroscopical properties, quantum phenomena, and optics incorporated on the surface and through substrates as well are of interest for a full coverage of possibilities in the tuning towards the control of multimodal signaling [26].

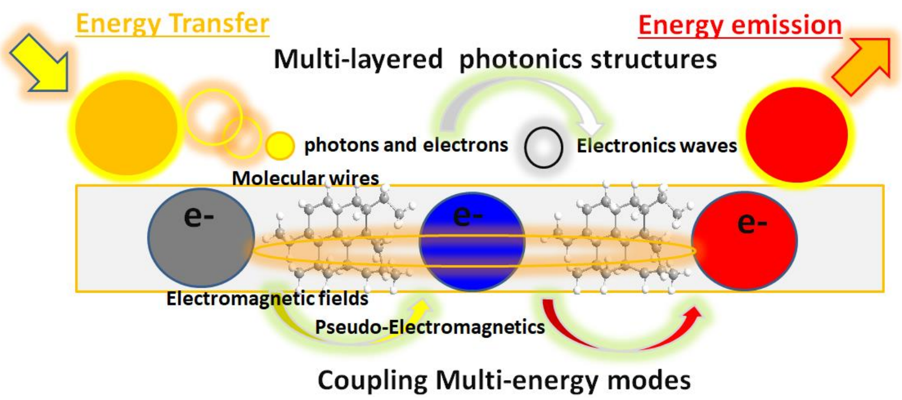

Figure 2. Modified substrates for nano-, micro-devices, capsules for implantable and wearable therapeutic approaches. The substrate, represented by a rectangle, incorporates different functional nanomaterials as sources of electrons, e-shuttles, photons, or quantum particles. Between them there are molecular wires and electromagnetic fields involved affecting the confined spaces. Therefore, there are input of energy and output as energy transferred and energy emission, respectively.

So, the control of materials, space, distances, patterns, and distributions on surfaces and substrates considering varied scales not only contemplates the energy modes known to be added from materials; it is also the beginning of fundamental research towards the generation of new unknown non-classical energy modes and opto-electronic matter constitution.

3. Hierarchical bottom-up of materials: design from molecules towards nanoplatforms and higher sizes of modified substrates

There is a broad spectrum of research within functional nanomaterials for varied applications [27]. In this regard, research focuses on specific functions or multifunctional materials for nanomedicine under development and transfer. This is the case of precision medicine [28] by genotyping, early diagnoses, genomic treatments [29], drugs, and light delivery [30]. Particular interest has been paid to the control of chemistry to manipulate chemical bonds to design new pharmacophores [31] and mimetic synthetic membrane ligands such as coronavirus variants [32]. Moreover, switch on/off molecular systems to be activated by different strategies [33] for personalized treatments in oncology [34]. These insights and advances showed how the hierarchical structure provided the final targeted function based on accurate compositions and mechanisms involved to accomplish the target function. Therefore, it is intended to propose the generation of new ideas for future multidisciplinary studies by controlling the matter constitution. This is mainly focused by incorporating the control of the nanoscale [35], looking for functional nanoplatforms within colloidal dispersions [36]; however, it is desirable as well to scale up the bottom up depending on the aims. In this context, the nanochemistry allowed the design of different sizes of functional platforms in close contact and related with cells and membrane components. By this manner, controlled interactions could be provided with interesting perspectives such as for nano-immune platforms and further biotechnology applications [37].

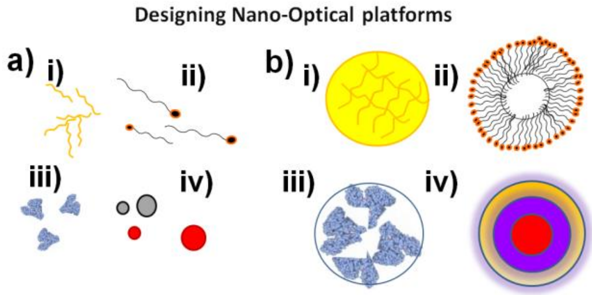

Figure 3. Scheme different levels of optical active materials from molecules to varied nanoplatforms and beyond. The nanoplatforms are: **(a)** i) polymeric chains and assemblies, ii) organized systems formed by lipids, iii) biomolecules and assemblies, iv) synthetic well-defined nanoparticles; **(b)** i) polymeric nanoparticles, ii) micelles or vesicle-organized systems, iii) nanostructured biomolecules such as protein-based nanoparticles, iv) multi-layered core-shell nanoparticles.

Different nanoarchitectures could be considered to develop targeted nanomedicine. This could be afforded by controlling small molecules, monomers, and atomic ions (**Figure 3a**) to build the nanoscale towards polymeric nanoparticles, organized systems, nanostructured biomaterials, and other bottom-up systems with different and accurately defined parts within the nanoscale, such as core-shell nanoplatforms (**Figure 3b**) [38]. Therefore, new research areas were addressed, and further perspectives could be developed as well. In particular, it could be aimed at being transferred to translating studies and applications in vitro and in vivo, such as for biophotonics clinical translations. In view of this, it is noted that there are varied and different functions, such as drug delivery [39], biosensing, non-classical light delivery [40], bioimaging [41], electronics [42,43], and quantum signaling [44]. However, the factor in common and challenge was focused on how to interact at the right place within close distance to achieve the desired function. Hence, right delivery and specific function were also of particular interest. Therefore, it was added higher sizes of substrates such as patches [45] and modified substrates [46] based on variable polymeric compositions [47] to support the materials and associated properties with functions. Thus, as stated, the bottom-up could be developed by a hierarchical material with different components acting in close contact with different types of real tissues in order to activate the function upon needs. For example, the permeability and dynamic skin tissue are used to incorporate varied drugs up to needs [48]. Moreover, surgical procedures or simple injections into deep tissues allowed being in close contact with the desired type of cells [49]. Therefore, implantable nano- and micro-devices could be new approaches to be developed in this regard.

Accordingly, the concept of nanodevices towards the bottom-up of microdevices to be incorporated by different strategies considers: i) implantable strategies by direct deposition and contact with the targeted tissue [50]; ii) injections [51]; iii) deposition or ingestion to be adsorbed through membranes and tissues [52], in addition to other types of strategies such as the use of microcapsules [53]. It is important to underline the role of the specific functions of devices, as well as the support material and strategy to record signaling from the mechanism developed as a strategy for the targeted and desired function. At the same time, colloidal dispersions could afford to nano-optics and drug delivery nanotechnologies that merit being studied and applied. In these perspectives, it is presented this package of ideas for further developments focusing research on nanomaterials and devices for biophotonics and nanomedicine applications to gain insight into implantable and related strategies to activate the desired function at the right place and time within complex biological systems.

4. Advances from the cutting-edge of the knowledge of modified substrates to implantable, portable, and wearable devices for biophotonics studies and applications

After considering the control on the molecular scale and nanoscale towards modified substrates with higher sizes and specific functions, it could be proposed to deposit the device on different tissues depending on needs in order to look for early diagnoses, biosensing, and drug delivery. It is possible to propose new treatments from precision medicine, where fundamental research and translational clinical applications are highly required. Material composition and biocompatibility to avoid immune reactions to the deposed material should be viewed as a device. This device could vary in size according to the application required. In these perspectives, it is known that there are different substrate materials for implantable devices and miniaturized instrumentation [54]. Similarly, wearable designs such as thin slides containing highly sensitive points of contact with the tissue provide signal tracking from biological variations (**Figure 4a**).

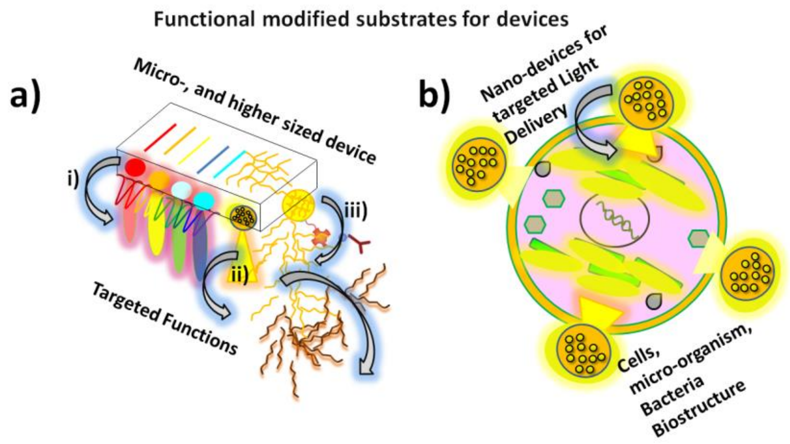

Figure 4. Schematic representation of devices within different intervals of sizes and dimensions: **(a)** multifunctional micro- and higher sizes of devices interacting with specific functional materials domains and nanoplatforms for multi-modal energy delivery modes, multi-photon delivery, and drug delivery based on variable different remote switch on/off strategies; **(b)** nano-devices placed on biostructures such as uni-cellular, and pluri-cellular micro-organisms for light delivery and coupling through optical active organelles.

For the design of a modified substrate for specific functions, different types of signaling could be tracked, such as light, electronics, quantum, electrical properties, electromagnetic fields, and thermal and chemical signals. All controllable physical and chemical properties are of interest to transduce through space and time. However, being able to record weak signals or amplify them through amplification strategies is still a challenge. And this is not as easy to achieve from the bulk of synthetic materials or synthetic real matrices as well. So, there is a lot of work involved that should be developed for each design and targeted function.

Light, managing photons and their transmissions through space and time, is particularly useful to develop implantable devices. In addition, other variables should be controlled at the same time, such as the biocompatibility of the materials added. Thus, photonic phenomena should be adapted to the desired application. Tuning photons and non-classical light should be compatible with tissues in order to avoid immune responses. Thus, new biomaterials are currently in progress and should be evaluated for new implantable substrates and related applications, as in signaling for biosensing and delivery treatments. In all these complex processes, interferences and background from tissues need to be considered.

It is particularly interesting to develop biomaterials in search of new substrates as in tuning light within waveguides [55], transducing signaling, delivering light, or even producing laser properties [56]. Here, plasmonics and control of high electromagnetic fields within the near field towards the far field are under study [57]. These enhanced properties could be generated from varied physical and chemical properties as well as coupling varied phenomena associated from the nanoscale to biostructures (**Figure 4b**).

Moreover, it could be highlighted how it was designed as a nano-bio-sensor for low concentration levels of DNA detection based on Metal Enhanced Fluorescence

(MEF) coupled to Fluorescence Resonance Energy Transfer (FRET) [58]. In addition, recent studies provide insights into light coupling and transmission through the space, addressing different photobiological receptors in unicellular microorganisms, probably developed from bi-colored FRET nano-emitters [59]. And this is based on the effect of energy levels and consequent properties by interaction with electromagnetic fields. The electromagnetic fields could be generated from the molecular scale to the nanoscale, varying in nature and intensity, which could also reach the quantum level [60]. Thus, it could be considered that the field is so high and versatile for tuning further opto-active properties. Note that many of these studies were inspired by the 1946 Nobel Prize in physics awarded to the study of spontaneous electromagnetic fields generated from metallic particles [61]. It means that these phenomena are relatively new and still studied on the nanoscale and beyond.

Plasmonic devices and enhanced photodetectors, the basis of new technology, have also been developed, in addition to new strategies in remote switch on/off laser-based applications and miniaturized instrumentation such as light-emitting devices (LEDs), related OLEDs, and new Plasmonics OLEDS (P-OLED) joined to mini-optical setups or within reduced sizes of pre-designed structures. These are new developments of biomaterials with biodegradable properties for biophotonics and implantable applications [62], such as flexible bioelectronic devices from conductive polymers based on living materials [63].

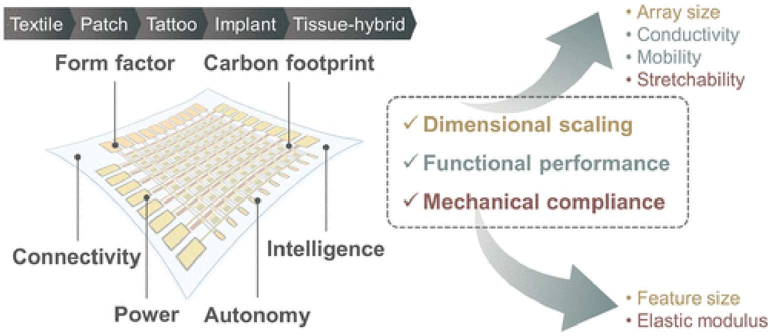

Figure 5. Schematic representation of flexible devices based on different materials to interact with living systems. Thus, the versatility in the design shows the incorporation of different further technological functions such as micro-electronics, circuits and connectivity.

Reprinted with permissions from Roblyer D. et al. [64].

Moreover, it should be mentioned that this focused interest on nanotechnology led later to ongoing insights and new roles of devices and data recording in vivo and in real time for remote sensing and diagnoses (**Figure 5**) [64]. Thus, it should be highlighted that the Internet of Nano Things is transforming healthcare with the cutting-edge technology in progress [65]. Further technological issues even could arrive to be proposed managing semiconductors and photoreceptors to incorporate connectivity and automation, desiring a higher level of bottom-up towards miniaturized instrumentation [66].

In this regard, the control of photons, the development of nanoelectronics, and improved electrical signaling are under study to record weak signals from tissues. As an example, it is noted that the development of implants with highly sensitive sensors and implants having wireless myoelectric sensors in their re-innervation sites after targeted muscle re-innervation (TMR) [67]. The TMR amplifies the electrical activity of nerves at the stump of amputees by redirecting them in remnant muscles above the amputation. This signaling could be collected and transduced to prosthetics. This technology is based on highly sensitive surface electrode developments using implanted systems. This is a higher level of signal transduction from molecular transduction and electrical signals. Thus, the signal was transduced from confined molecular levels towards longer lengths and scales, affording long-term implants of intramuscular sensors and nerve transfers for wireless control of robotic arms in above-elbow amputees.

Other highly sensitive implants and portable devices were reported from neuroscience, such as neurophotonics, neuroimaging, and neuromedicine, in addition to portable miniaturized instrumentation at different levels, such as mini-microscopes and mini-endoscopes. Then, higher-sized approaches and instruments for bioimaging afforded getting connections between neurons in vivo [68]; from where, ion, molecular, and neurotransmitter detections were recorded by a proper combination of miniaturized optical set-ups and molecular sensors, labellers, and nano-platforms [69]. Therefore, it was even scaled up the applications to replace the upper part of the human skull with a biocompatible, rechargeable, refillable, and cleanable electrical/molecular device to safely and effectively treat and cure severe and currently intractable brain disorders [70].

Nanochemistry and new modified substrates could lead to implantable approaches and wearable designs. The research for biosensing in cells for molecular targeting and tracking, as well as ion and neurotransmitter detection, is a high-impact field [71]. Then, if this level of signal transduction is amplified, enhanced, or improved by some strategy through space and time, these facts could afford multimodal imaging approaches. And by this manner, it could lead to new technologies within life science applications. Examples of technology already developed and placed on the market include, for example, portable PCR chips [72], lab-on-particles for early diagnosis of SARS CoV2 [73], and next-generation sequencing (NGS) [74]. The perspective of developments is particularly stimulating in the context of multidisciplinary research fields.

5. Conclusions and perspectives

This mini-review is intended to present and open the discussion about the design of new nanomaterials and reduced sizes of substrates with perspectives towards functional devices focusing on implantable and wearable applications. Thus, it was shown from insights and basis for prototyping molecules, nanomaterials, and substrates. The incorporation of different properties joining different materials controlling molecular connectors permitted proposing signal transductions through space and time. And this capability led to its being used within modified substrates with multifunctional perspectives. So, the fact of getting a micro- to millimeter-sized polymeric material with a controlled nanostructured and functional pattern showed interesting perspectives from recent reports. In addition, further development could afford to activate or track functionalities remotely.

Therefore, from the concept of functional materials towards the control of the nanoscale, it was shown the development of applications such as nanodevices and microdevices for sensing and biophotonics uses. Many of these new nanomaterials could be incorporated in substrates, improving performance. It means that within the bottom-up of the functional material, other enhanced pathways could be added. So, higher performances from nanotechnology are highly desired for signal detection and transduction.

In these regards, different nanoarchitectures that could be applied were presented. All these nanomaterials could act as support for optical active materials and functions. In addition, the combination of biocompatible materials and controlled physical and chemical properties could develop different strategies for the targeted functions. Thus, as an example, the knowledge from plasmonics and coupled phenomena had been shown to enhance signaling, thermal activations, and the development of laser properties. In addition, electrical signaling detection and molecular tracking applied to tissues and organs as in biological event detections to generate bioimaging and early diagnosis and also to optimize mechanical movements by prosthesis were presented as of high interest and impact. Hence, there is a broad spectrum of needs and interests that should be addressed by the next generation of therapeutics and new precision medicine accessed through implantable devices and encapsulated multi-functional nano- and micromaterials. In this context, the incorporation of non-classical light and new modes of energy based on coupling optical active materials could afford new implantables considering biocompatible photonic approaches.

Acknowledgments: Special thanks are given to the Science and Technology of UNC (SeCyT), Argentina, for the research grant provided. We would also like to thank COPL, Laval University, Québec, Canada, for the long-standing research Collaboration in progress, as well as to the Canadian Grants received.

Institutional review board statement: Not applicable.

Informed consent statement: Not applicable.

Conflict of interest: The authors declare no conflict of interest.

References

1. Kathuria Y. Chapter 6. Laser-produced Rapid Prototyping in Manufacturing. In: International Trends in Applied Optics. SPIE Digital Library; 2002. pp. 1-14.
2. Satzinger V, Schmidt V, Kuna L, et al. Rapid prototyping of micro-optics on organic light emitting diodes and organic photo cells by means of two-photon 3D lithography and nano-imprint lithography. Micro-Optics 2008. 2008; 6992: 699217. doi: 10.1117/12.781129
3. Maniewski P, Harvey CM, Mühlberger K, et al. Rapid prototyping of silica optical fibers. Optical Materials Express. 2022; 12(7): 2426. doi: 10.1364/ome.459400
4. Liu J, Yang Q, Shou Y, et al. Metasurface-Assisted Quantum Nonlocal Weak-Measurement Microscopy. Physical Review Letters. 2024; 132(4). doi: 10.1103/physrevlett.132.043601
5. Keskinbora K. Prototyping Micro- and Nano-Optics with Focused Ion Beam Lithography. SPIE; 2019. doi: 10.1117/3.2531118
6. Selin C, Boradkar P. Prototyping Nanotechnology: A Transdisciplinary Approach to Responsible Innovation. Journal of Nano Education. 2010; 2(1): 1-12. doi: 10.1166/jne.2010.1002

7. Yao K, Zhong H, Liu Z, et al. Plasmonic Metal Nanoparticles with Core–Bishell Structure for High-Performance Organic and Perovskite Solar Cells. ACS Nano. 2019; 13(5): 5397-5409. doi: 10.1021/acsnano.9b00135
8. Bandari VK, Schmidt OG. A bright future for micro-LED displays. Light: Science & Applications. 2024; 13(1). doi: 10.1038/s41377-024-01683-z
9. Kumar G, Lin CC, Kuo HC, et al. Enhancing photoluminescence performance of perovskite quantum dots with plasmonic nanoparticles: insights into mechanisms and light-emitting applications. Nanoscale Advances. 2024; 6(3): 782-791. doi: 10.1039/d3na01078c
10. Mark AG, Gibbs JG, Lee TC, et al. Hybrid nanocolloids with programmed three-dimensional shape and material composition. Nature Materials. 2013; 12(9): 802-807. doi: 10.1038/nmat3685
11. Li Y, Xia H, Xu J. Synthesis and Applications of Functional Nanomaterials. Journal of Physics: Conference Series. 2021; 2133(1): 012006. doi: 10.1088/1742-6596/2133/1/012006
12. Bracamonte, AG, Invited Guest Editor. Tuning Enhanced signaling from Optical active Nanoplatforms for Biophotonics and Bio-analytical applications. Available online: https://www.frontiersin.org/journals/chemistry (aceesed on 2 November 2024).
13. Advances in Research on Graphene and Related Materials: From Preparation and tuning properties to Applications. Materials.
14. Bracamonte AG. Frontiers in Nano- and Micro-device Design for Applied Nanophotonics, Biophotonics and Nanomedicine. Bentham Science Publishers (UAE); 2021.
15. Lv X, Zhang Y, Wang X, et al. Multilayer Graphene Oxide Supported ZIF-8 for Efficient Removal of Copper Ions. Nanomaterials. 2022; 12(18): 3162. doi: 10.3390/nano12183162
16. Ali SM, Noghanian S, Khan ZU, et al. Wearable and Flexible Sensor Devices: Recent Advances in Designs, Fabrication Methods, and Applications. Sensors. 2025; 25(5): 1377. doi: 10.3390/s25051377
17. Yan Y, Song C, Shen Z, et al. Programming structural and magnetic anisotropy for tailored interaction and control of soft microrobots. Communications Engineering. 2024; 3(1). doi: 10.1038/s44172-023-00145-5
18. Lu L, Chen N, Yuan B, et al. Illuminating the invisible: Advancing bio-imaging and diagnosis with modified near-infrared fluorescents. Applied Materials Today. 2024; 38: 102210. doi: 10.1016/j.apmt.2024.102210
19. Hansen AE, Henriksen JR, Jølck RI, et al. Multimodal soft tissue markers for bridging high-resolution diagnostic imaging with therapeutic intervention. Applied Materials Today. 2024; 38: 1-19.
20. Lin TE, Rapino S, Girault HH, et al. Electrochemical imaging of cells and tissues. Chemical Science. 2018; 9(20): 4546-4554. doi: 10.1039/c8sc01035h
21. Schneider C, Nikitichev D, Xia W, et al. Multispectral tissue mapping: developing a concept for the optical evaluation of liver disease. Journal of Medical Imaging. 2020; 7(06). doi: 10.1117/1.jmi.7.6.066001
22. Dong D, Huang X, Li L, et al. Super-Resolution Fluorescence Assisted Diffraction Computational Tomography Reveals the Three-Dimensional Landscape of Cellular Organelle Interactome. Imaging and Applied Optics Congress. Published online 2020: HF1G.6. doi: 10.1364/dh.2020.hf1g.6
23. Matsumoto K, Mitchell JB, Krishna MC. Multimodal Functional Imaging for Cancer/Tumor Microenvironments Based on MRI, EPRI, and PET. Molecules. 2021; 26(6): 1614. doi: 10.3390/molecules26061614
24. Chen Y, Lou Z, Chen Z, et al. Magnetic–Fluorescent Responsive Janus Photonic Crystal Beads for Self-Destructive Anti-counterfeiting. Langmuir. 2022; 38(46): 14387-14399. doi: 10.1021/acs.langmuir.2c02546
25. Heintz A, Sold S, Wühler F, et al. Design of a Multimodal Imaging System and Its First Application to Distinguish Grey and White Matter of Brain Tissue. A Proof-of-Concept-Study. Applied Sciences. 2021; 11(11): 4777. doi: 10.3390/app11114777
26. Xiao Z, Wang K, Lu X, et al. Fabrication of multimodal optical imaging agents through direct triplet energy transfer from rare-earth doped nanoparticles. Journal of Luminescence. 2025; 280: 121092. doi: 10.1016/j.jlumin.2025.121092
27. Sun Y, Guo Z. Recent advances of bioinspired functional materials with specific wettability: from nature and beyond nature. Nanoscale Horizons. 2019; 4(1): 52-76. doi: 10.1039/c8nh00223a
28. Hodson R. Precision medicine. Nature. 2016; 537(7619): S49-S49. doi: 10.1038/537s49a
29. Liang P, Ding C, Sun H, et al. Correction of β-thalassemia mutant by base editor in human embryos. Protein & Cell. 2017; 8(11): 811-822. doi: 10.1007/s13238-017-0475-6
30. Zeggini E, Gloyn AL, Barton AC, et al. Translational genomics and precision medicine: Moving from the lab to the clinic. Science. 2019; 365(6460): 1409-1413. doi: 10.1126/science.aax4588

31. Wang D, Heiss E, Šmejkal K, et al. Bioactive Molecules and Their Mechanisms of Action. Molecules. 2019; 24(20): 3752. doi: 10.3390/molecules24203752
32. Syed AM, Ciling A, Taha TY, et al. Omicron mutations enhance infectivity and reduce antibody neutralization of SARS-CoV-2 virus-like particles. Proceedings of the National Academy of Sciences. 2022; 119(31). doi: 10.1073/pnas.2200592119
33. Yao H, Yang Z, Fan X, et al. A light-tunable thermoresponsive supramolecular switch with reversible and complete "off-on"/"on-off" conversion. Materials Chemistry Frontiers. 2019; 3(6): 1168-1173. doi: 10.1039/c9qm00141g
34. Rosenblum D, Peer D. Omics-based nanomedicine: The future of personalized oncology. Cancer Letters. 2014; 352(1): 126-136. doi: 10.1016/j.canlet.2013.07.029
35. Kirschen WID, Hutchinson W, Bracamonte AG. Conjugation Reactions of Hybrid Organosilanes for Nanoparticles and surface modifications. J. Chem. Res. Adv. (JCRA). 2021; 2(1): 6-15.
36. Huynh MC, Thanh Diep T, Le TTT, et al. Advances in colloidal dispersions: A review. Journal of Dispersion Science and Technology. 2019; 41(4): 479-494. doi: 10.1080/01932691.2019.1591970
37. Luna RGP, Sofia M, Cecilia T, et al. Nano-chemistry and Bio-conjugation with perspectives on the design of Nano-Immune platforms, vaccines and new combinatorial treatments. Journal of Vaccines and Immunology. 2021; 049-056. doi: 10.17352/jvi.000047
38. Nguyen HL, Nguyen HN, Nguyen HH, et al. Nanoparticles: synthesis and applications in life science and environmental technology. Advances in Natural Sciences: Nanoscience and Nanotechnology. 2014; 6(1): 015008. doi: 10.1088/2043-6262/6/1/015008
39. Inda A, Martinez SM, Tettamanti CS, et al. Chapter 7 - Nanoengineering multifunctional organized systems highlighting hybrid micelles, vesicles and lipidic aggregates towards higher sized structures for theranostics perspectives.Theranostics Nanomaterials in Drug Delivery. 2025: 111-132. https://doi.org/10.1016/B978-0-443-22044-9.00020-6
40. Dalacu D, Poole PJ, Williams RL. Nanowire-based sources of non-classical light. Nanotechnology. 2019; 30(23): 232001. doi: 10.1088/1361-6528/ab0393
41. Gontero D, Veglia AV, Bracamonte AG, et al. Synthesis of ultraluminescent gold core-shell nanoparticles as nanoimaging platforms for biosensing applications based on metal-enhanced fluorescence. RSC Advances. 2017; 7(17): 10252-10258. doi: 10.1039/c6ra27649k
42. Bracamonte G. Advances in new Matter Properties and Applications of Hybrid Graphene-based Metamaterials. Current Material Science. 2022; 15(3): 215–219.
43. Bracamonte AG, Hutchinson W. Electronic Properties and Pseudo-Electromagnetic Fields of Highly Conjugated Carbon Nanostructures. Current Materials Science. 2022; 15(3): 204-214. doi: 10.2174/2666145414666211006124712
44. Nie L, Nusantara AC, Damle VG, et al. Quantum monitoring of cellular metabolic activities in single mitochondria. Science Advances. 2021; 7(21). doi: 10.1126/sciadv.abf0573
45. Choueiri RM, Galati E, Thérien-Aubin H, et al. Surface patterning of nanoparticles with polymer patches. Nature. 2016; 538(7623): 79-83. doi: 10.1038/nature19089
46. Meng L, Zeng T, Jin Y, et al. Surface-Modified Substrates for Quantum Dot Inks in Printed Electronics. ACS Omega. 2019; 4(2): 4161-4168. doi: 10.1021/acsomega.9b00195
47. Du J, Li Y, Wang J, et al. Mechanically Robust, Self-Healing, Polymer Blends and Polymer/Small Molecule Blend Materials with High Antibacterial Activity. ACS Applied Materials & Interfaces. 2020; 12(24): 26966-26972. doi: 10.1021/acsami.0c06591
48. Elsayed SM, Widyaya VT, Shafi Y, et al. Bifunctional Bioactive Polymer Surfaces with Micrometer and Submicrometer-sized Structure: The Effects of Structure Spacing and Elastic Modulus on Bioactivity. Molecules. 2019; 24(18): 3371. doi: 10.3390/molecules24183371
49. Cellesi F, Tirelli N. Injectable nanotechnology. Injectable Biomaterials. Published online 2011: 298-322. doi: 10.1533/9780857091376.3.298
50. Cheng Z, Shurer CR, Schmidt S, et al. The surface stress of biomedical silicones is a stimulant of cellular response. Science Advances. 2020; 6(15). doi: 10.1126/sciadv.aay0076
51. Li Y, Chen X, Jin R, et al. Injectable hydrogel with MSNs/microRNA-21-5p delivery enables both immunomodification and enhanced angiogenesis for myocardial infarction therapy in pigs. Science Advances. 2021; 7(9). doi: 10.1126/sciadv.abd6740

52. M. Rabanel J, Aoun V, Elkin I, Mokhtar M, Hildgen P. Drug-Loaded Nanocarriers: Passive Targeting and Crossing of Biological Barriers. Current Medicinal Chemistry. 2012; 19(19): 3070-3102. doi: 10.2174/092986712800784702
53. Jyothi NVN, Prasanna PM, Sakarkar SN, et al. Microencapsulation techniques, factors influencing encapsulation efficiency. Journal of Microencapsulation. 2010; 27(3): 187-197. doi: 10.3109/02652040903131301
54. Parlak O, Keene ST, Marais A, et al. Molecularly selective nanoporous membrane-based wearable organic electrochemical device for noninvasive cortisol sensing. Science Advances. 2018; 4(7). doi: 10.1126/sciadv.aar2904
55. Goodfellow KM, Chakraborty C, Beams R, et al. Direct On-Chip Optical Plasmon Detection with an Atomically Thin Semiconductor. Nano Letters. 2015; 15(8): 5477-5481. doi: 10.1021/acs.nanolett.5b01898
56. Chen S, Wang F, Kuang F, et al. Femtosecond Pulsed Fiber Laser by an Optical Device Based on NaOH-LPE Prepared WSe2 Saturable Absorber. Nanomaterials. 2022; 12(16): 2747. doi: 10.3390/nano12162747
57. Bracamonte AG. Design of new High Energy near Field Nanophotonic materials for far Field applications. In: Advances in Nanocomposite Materials for Environmental and Energy Harvesting Applications. Engineering Materials. Springer Nature, Switzerland; 2022. pp. 859-920.
58. Brouard D, Ratelle O, Bracamonte AG, et al. Direct molecular detection of SRY gene from unamplified genomic DNA by metal-enhanced fluorescence and FRET. Analytical Methods. 2013; 5(24): 6896. doi: 10.1039/c3ay41428k
59. Salinas C, Amé MV, Bracamonte AG. Synthetic non-classical luminescence generation by enhanced silica nanophotonics based on nano-bio-FRET. RSC Advances. 2020; 10(35): 20620-20637. doi: 10.1039/d0ra02939d
60. Fu Y, Zhang J, Lakowicz JR. Silver-enhanced fluorescence emission of single quantum dot nanocomposites. Chem Commun. 2009; (3): 313-315. doi: 10.1039/b816736b
61. Purcell EM. Spontaneous emission probabilities at radio frequencies. Phys. Rev. 1946; 69: 681.
62. Humar M, Kwok SJJ, Choi M, et al. Toward biomaterial-based implantable photonic devices. Nanophotonics. 2017; 6(2): 414-434. doi: 10.1515/nanoph-2016-0003
63. Wang Z, Bai H, Yu W, et al. Flexible bioelectronic device fabricated by conductive polymer–based living material. Science Advances. 2022; 8(25). doi: 10.1126/sciadv.abo1458
64. Roblyer D. Perspective on the increasing role of optical wearables and remote patient monitoring in the COVID-19 era and beyond. Journal of Biomedical Optics. 2020; 25(10). doi: 10.1117/1.jbo.25.10.102703
65. Maksimović M. The roles of nanotechnology and internet of nano things in healthcare transformation. TecnoLógicas. 2017; 20(40): 139-153. doi: 10.22430/22565337.720
66. Luo Y, Abidian MR, Ahn D, et al. Technology Roadmap for Flexible Sensors. ACS Nano. 2023; 17(6): 5211-5295.
67. Salminger S, Sturma A, Hofer C, et al. Long-term implant of intramuscular sensors and nerve transfers for wireless control of robotic arms in above-elbow amputees. Science Robotics. 2019; 4(32). doi: 10.1126/scirobotics.aaw6306
68. Larivière-Loiselle C, Bélanger E, Marquet P. Polychromatic digital holographic microscopy: a quasicoherent-noise-free imaging technique to explore the connectivity of living neuronal networks. Neurophotonics. 2020; 7(04). doi: 10.1117/1.nph.7.4.040501
69. Susaki EA, Shimizu C, Kuno A, et al. Versatile whole-organ/body staining and imaging based on electrolyte-gel properties of biological tissues. Nature Communications. 2020; 11: 1-10.
70. Ludvig N. Rationale of replacing the upper part of the human skull with a biocompatible, re-chargeable, re-fillable and re-cleanable electrical/molecular device to safely and effectively treat and/or cure severe, currently intractable brain disorders. Academia Letters. Published online August 31, 2021. doi: 10.20935/al3355
71. Bracamonte AG. Neurophotonics by controlled signal tracking from chemical structures, and Biostructures towards the Nanoscale and beyond. Frontiers in Drug, Chemistry and Clinical Research. 2022; 5(1). doi: 10.15761/fdccr.1000159
72. Schulz M, Probst S, Calabrese S, et al. Versatile Tool for Droplet Generation in Standard Reaction Tubes by Centrifugal Step Emulsification. Molecules. 2020; 25(8): 1914. doi: 10.3390/molecules25081914
73. Dahiya UR, Gupt GD, Dhaka RS, et al. Functionalized Co2FeAl Nanoparticles for Detection of SARS CoV-2 Based on Reverse Transcriptase Loop-Mediated Isothermal Amplification. ACS Applied Nano Materials. 2021; 4(6): 5871-5882. doi: 10.1021/acsanm.1c00782
74. Bracamonte AG. Microarrays towards nanoarrays and the future Next Generation of Sequencing methodologies (NGS). Sensing and Bio-Sensing Research. 2022; 37: 100503. doi: 10.1016/j.sbsr.2022.100503