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Short Review

Engineering Macro-Sized Optical Materials, Miniaturized Instrumentation and Methods: Tuning Quantum-, Nano-Scales from the Near Field to Far Field Applications

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Abstract

In this commentary article, the discussion is about how optics from tiny-sized structures formed by a few atoms and molecules was the beginning of higher-sized effects and phenomena forming part of micro- and macro-sized materials with targeted functions, smart responses, and instrumentation of varied dimensions used daily for well-being. In this manner, the optical properties developed by varied molecules with particular capabilities to absorb and filter intervals of wavelengths and related colours could participate in the development of colored lens and crystals. In this context, the importance of spectroscopic techniques and methods in the characterization of new synthetic molecules as well as from natural sources in many Green chemistry approaches, and related soft materials is noted. Moreover, the control of quantum and nanoscale phenomena provides new types of high-brightness emitters that could tune optoelectronics and light emissions incorporated in many optical setups, instrumentation, and tools. This is the case of LEDs (Light-Emitting Diodes), lamps, Lasers, and more innovative sources of light. In this context, it should be noted that the performance of these new materials available on the market and the low cost related to high-impact research are still under focus. The generation of non-classical light and applications by tuning highly intense electromagnetic fields are of current interest in multidisciplinary developments. In addition, energy generation, conduction, and quantum and optical computing signaling are currently the highest-ranked industries advancing new instrumentation, devices, and the next generation of technology. In this regard, chips, telephones, solar cells, semiconductors, and computers are involved in our daily tasks and routines. So, by tuning optics and photonics at different levels, it can foster well-being, peace, and security in current times. In this way, it was possible to highlight the main recent developments associated with high-impact technology.

Keywords

Communications; energy; light sources; smart optical materials; photonics; nanophotonics; optics

1. Introduction to Optics and Applied Materials

The development of materials for optics with targeted functions is part of varied levels of technologies, wearables, instruments, and gadgets, towards other more complex ones such as transport, aerospace, communications, and security worldwide. In this regard, the materials and functions are varied; however, from an overview, it could be highlighted the need for support of high-technology materials and materials of high precision within a targeted function (Figure 1) [1]. Thus, (i) the generation of light with the possibility to tune power of irradiances [2], (ii) the development of performed optical signaling [3], (iii) quantum signaling in the top of the next generation of technology [4], (iv) electronic conductions [5], (v) optoelectronics development [6]; (vi) super-conductors, and supercapacitors and energy absorber materials [7], (vii) switch on/off systems based on varied strategies considering varied physics and chemistry phenomena [8], (viii) soft materials with incorporation of optical phenomena with smart responsive in the top as well of new dynamic materials with changes in their colors overtime as well as in their general properties or functions [9]; and in this direction is noted that materials based on their intrinsic matter constitution are not static in their functions due to the need to response depending of their environment.

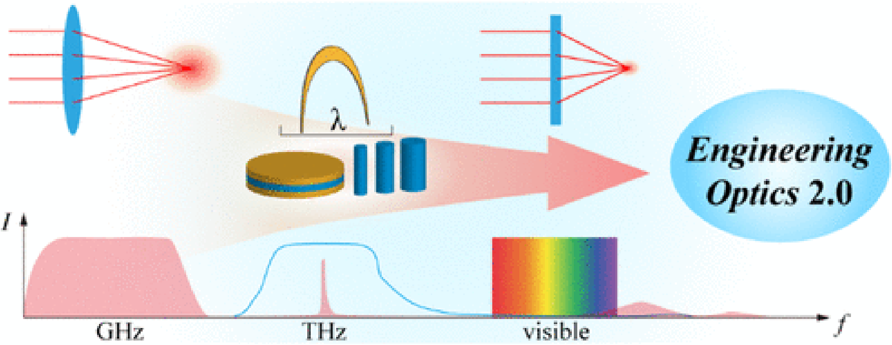

Figure 1 Scheme of development of micro/nanofabrication joined to advancement of electronic computer and numerical simulation algorithms, modern engineering optics has entered a new phase termed Engineering Optics 2.0 (EO 2.0), which breaks the fundamental limitations of classic optical laws with respect to many aspects of optics (including reflection, refraction, diffraction, absorption and radiation, etc.). Reprinted with permission from X. Luo et al., 2018 ACS Photonics, ACS [1].

Moreover, smart responsive materials, from sport wearables to textiles, could be afforded by innovating optics within applied materials sciences [10]. In addition, smart homes incorporate sensors, enhanced windows, smart lighting, and energy-responsive home materials, etc. [11]. This broad overview could be unrelated between them; however, it should be highlighted that optics and functional materials begin from simple light-matter interactions involving molecular, quantum, and nanomaterial interactions accurately placed. In this manner, the concept could be explained, for example, with molecular absorbers forming part of energy collection and energy storage [12] and within optically active nanoplatforms forming part of the lab. On particles [13] as well. In this context, it is also important to note Quantum optics towards the far field, showing the transition of quantum light-matter interactions, such as within nanostructures or microcavities generating freely propagating, detectable radiation. Bridging the near-field and far-field enables the engineering of quantum networks, quantum sensing, and sub-wavelength imaging. It is intended to guide readers towards the study and manipulation of non-classical light from tiny sizes and beyond [14].

Moreover, as a multidisciplinary research field with a huge potential to generate Big Data, it is open to Artificial Intelligence (AI) developments. The development or application of an appropriate AI could record data and make decisions from varied inter-branched sources of information involving fine tasks from optical, quantum, and electronic computing data. So, in these multidisciplinary developments, there is much fundamental knowledge and applied research transferred to different levels of technologies used daily, such as nanotechnology accompanied by quantum ones too, maybe less tangible but involved as well towards the micro- and macroscale [15]. It means that today, products are available in the market at low cost with a high level of knowledge involved, forming part of current research at the same time today. In this way, in the next section, highlights of different research lines with potential new insights and performances for innovation and development of disruptive and emerging technologies where advanced optics and more are joined [16] are noted.

In this regard, many examples are presented from different research fields involving multidisciplinary collaborations for Engineering Macro-Scale Optical Materials, considering in particular miniaturized Optical Instrumentation, and smart optical active materials within different sizes. These expected responses are afforded by a large number of methods and techniques that exceed the scope of this article; however, it is open to readers to continue on that if it is really desired to design their own new prototypes.

2. Overview and Discussion About Current Photonics Materials

Photons are massless particles that can move at only one speed, known as the velocity of light, measured in vacuum. So, optical communications and translation of optical properties through space and time seem to be impossible to improve; however, current research inquires about media from confined matter for optimal conduction in real studies and applications [17]. In this regard, the resolution and source of photons within different scales and sizes are of high interest when looking for engineering new materials. For these reasons, developments of different manners of labelling of biological surfaces are desired by applying the more developed commercial microscopes. Moreover, these approaches can be easily applied for Biodetection using commercial in-flow instruments with fluorescence detection and Imaging, and they can also be included in new optical arrays in order to enhance even more the resolution of the images obtained from the biological event detection. The challenge for NanoImaging resolution by fluorescence, for example, could be developed by tuning the right ratio of nanodimension and luminescence intensity to permit surface labelling and overcome the fluorescence intensity overlapping between different nanoparticles when they are so close; however, they should be intense enough for individual nanoparticle and bacteria labelled tracking at a low number of nanoparticles per mL. One of the principal parameters to take in account it is the lateral resolution [18], in which the point separation (r) in the image plane is the distance between the central maximum and the first minimum intensity from an individual Nanoparticle Imaging: rlateral = $1.22 \times \lambda/(2 \times NA) = 0.6 \times \lambda/NA$; where λ is the emitted light wavelength and NA is the numerical aperture of the objective. Enhanced detail from image analysis is important for many reasons. Still, it could be mentioned that studies about plasma membrane topography and interpretation of single particle tracking over the surface [19], based on single particle tracking (SPT) by light microscopy on live cells and electron microscopy, where it was shown the importance of the membrane constitution and topography [20] in the folding process.

In addition, the control of flow and direction is already developed but still under study due to the complex matter involved and new light pathways under focus [21]. The control of photons and non-classical light delivery could be achieved from varied optical setups and scales. It is noted that the large variety of Lasers with different power and irradiance permits high-precision cuts of varied sources of materials, from metals to soft materials as sensitive as within eye surgical interventions [22]. Materials and optical setups are so different in both extremes mentioned; however, amplification of the signal involved is applied. The amplification of the signal in this case is associated with improved and augmented energy generated within the optical setup to produce the final emission at a given wavelength, frequency, and delivered within ultra-short time frequencies. In this manner, high-precision cuts within the nanoscale are achieved. Then, miniaturized lasers provide other intensities that are still as high as previously mentioned in relation to the molecular and quantum levels. In this context, it is noted that the optical strategy should contain enhanced optical systems where the initial energy stimulation could produce amplified emissions. In brief, an emitter agent or device is used through an optical amplification mechanism based on stimulation of electromagnetic radiation with coherent properties in space and time [23]. The amplifications are produced by multiple opto-electronic resonances between optical lenses that augment the reflected energy [24]. Thus, sharp energy distributions centred at an optimal frequency are emitted. In this way, the energy transference begins from molecular structures and intrinsic matter constitutions. In this manner, the sources of emissions could be produced from molecules, to quantum sizes and beyond the nanoscale. For example, the Molecular Laser dyes [25] to Nanolasers [26] towards Biolasers and Nano-Biolasers known as Living lasers [27] are many of the tiny sizes from where laser properties could be delivered as needed. For the control of the energy, frequency, and wavelengths of lasers, it could involve varied materials and setups.

Therefore, Quantum-, Nano-, Bio-, Hybrid-Laser systems could tune light for Life Sciences illuminating cells, creating imaging, providing new Optics that afford to watch in real time other level of resolution and matter composition depending of the strategy and mechanism used [28] These effects of high energies produced from the intrinsic matter composition is translated over time and space combining varied optical active molecules, assemblies, arrays of quantum materials and nanoparticles and more. In this context, the generation of ultra-luminescent single cells, unicellular microorganisms, bacteria, and even viruses is currently possible [29]. However, there are still further challenges related to higher power of irradiances, stabilities, and functions delivered over time and space. The conduction of signals in these systems is very important to provide energy from different optical components. In a similar manner, as light is conducted through waveguides and semiconductive materials, energy is conducted through biological media to stimulate quantum biology as well. Therefore, photonics tuning synthetic materials for technology afforded to tune quantum computing and next generation of computers and communications are intended to develop. So, the flow of light, photons, and quantum properties are under focus to still tune their properties [30]. The light propagation explained by a dual behavior of quantized photons and electromagnetic fields could generate new structured modes of light after specific light-matter interactions. Therefore, it is possible to tune light by interaction with optically active components accurately located in 3D. For example, plasmonic metamaterials related to complex high-energy electromagnetic fields interacting could produce non-and new-expected optoelectronic properties, nominated as completely different from synergistic combinations of them. So, it is a new electronic state related to a different chemical composition considering electronic interactions. In this context, it is possible to develop enhanced nonlinear optical processes by plasmonic resonances based on dipole Nanoantennas [31]. In this manner, the quadrupolar third-harmonic response of dolmen-type plasmonic Fano structures was observed. It was found that the third-harmonic polarization field of the quadrupolar mode did not radiate to the far-field due to destructive interference. Therefore, depending on their intrinsic matter constitution, variable-energy modes could be enhanced or quenched, taking relevance to the new shapes of energy delivered, assigning structures and forms detected with appropriate imaging technologies.

In addition to the structuration of light and related to further interactions, it is highlighted as well the capability to rotate the front phase of the electromagnetic field in a given direction. It is noted that enhanced chiro-optical phenomena are associated with light-matter interactions with varied types of materials, such as engineered ultrathin optical devices within the nanoscale, which permit the enhancement of the CD response of Chiral media [32]. At this point, it is important to mention that the Chiro Optical response (CO) from Nano-Optical devices is not completely understood [33].

In this context, the coupling of energy modes and interactions with optically active materials could produce different emissions associated with particular optical properties. Enhanced phenomena related to the optically active tuning by high-intensity electromagnetic field applications produced from the Nanoscale and coupling with targeted laser dyes could transfer energy beyond the nanoscale. Thus, it is under study and applied within new sources of light such as LEDs, Lasers, new Nano-emitters and labellers for Life Science applications, waveguides, chips, and energy applications [34].

Moreover, high-precision optics could be tuned as well, highlighting recently reported space-time coupling and Orbital Angular Momentum (OAM) modes (Figure 2), which afford new structured modes of light and conductivities (Figure 2) [35]. The tuning of varied emissions was afforded by induction using a toroidal light excitation required to generate higher-order multipoles. These are time-domain optical phenomena related to the ability to generate OAM. In this manner, it tunes different field distributions based on mapping spiral phases to produce these varied structured fields.

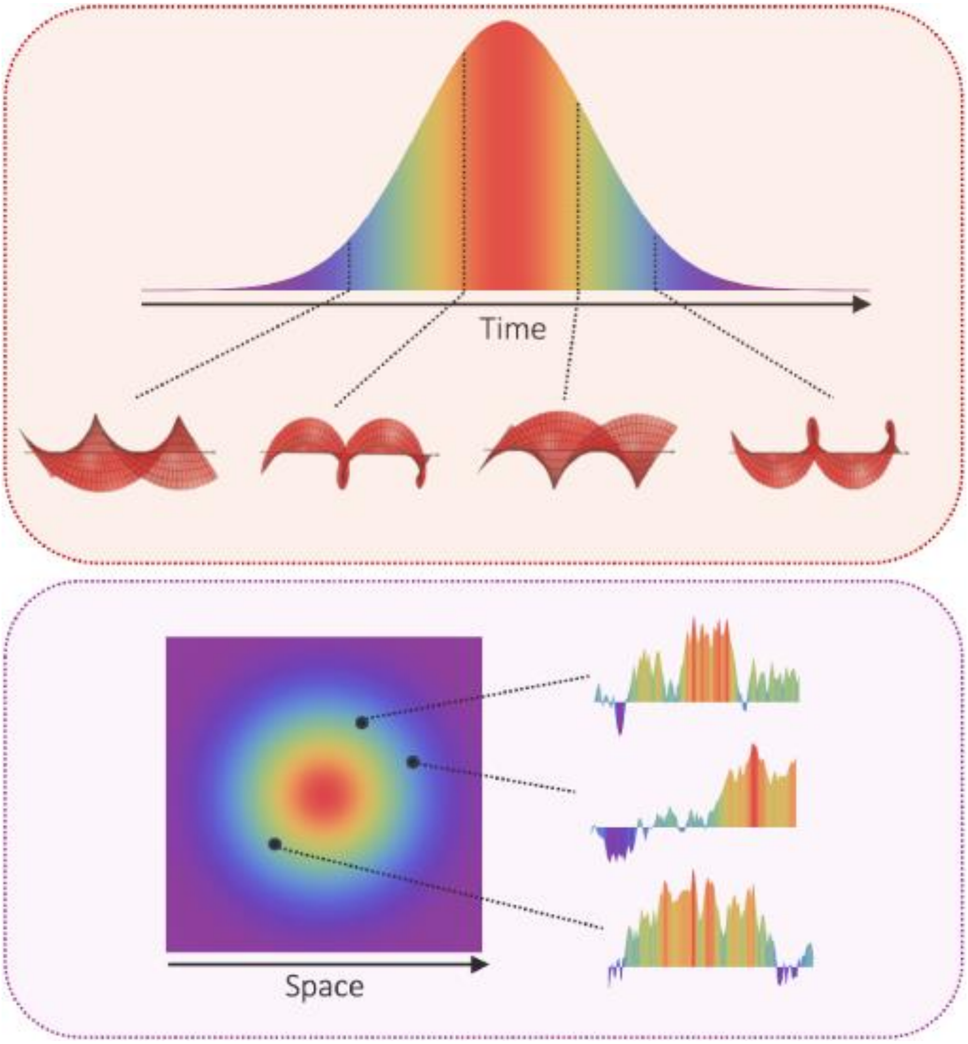

Figure 2 In the top panel, space-time coupling results in different time slices returning different spatial structures, shown here as four OAM modes. In the bottom panel, space-time coupling results in the time signal altering for each location in space, shown for three illustrative examples. Reprinted with permission from A. Forbes, 2025, Photonics Insights, SPIE [35].

Moreover, as stated previously, amplified phenomena are still under focus and largely incorporated in technology used daily. In this regard, the multimodal approaches offer varied sources of energy and functions, as actually offered for diagnoses by imaging-based instrumentations in Clinics and Hospitals [36]. In addition, up scaling towards optical active materials but within the macroscale the application of new optical materials for smart windows, security systems, metrics, and even aerospace is already incorporated and the industry beyond the molecular, quantum-, and Nano-scale appeared so far and long [37]. Thus, it could describe many systems developed by different techniques and methods; however, light-matter interactions and further energy modes and quantum particles are the factors in common within the different effects, phenomena, and applications. In this context, thinking out of the box for materials for devices and chips with targeted life sciences, it could be noted that highly sensitive optical materials against photons and other energy modes, such as heat, could be developed to develop new strategies for outer space sailing developments. Thus, Photonic Crystal Light Sails (PCLS) are next-generation spacecraft membranes engineered at the nanoscale to be propelled by high-powered lasers. By using a repeating pattern of voids, polymer matrices, and high-index materials, like germanium, they act as highly selective mirrors that reflect laser light while letting ambient sunlight and infrared heat pass through [38].

Another need seriously focused on in this context of design and fabrication of instrumentation is related to metrics, where metrology focusing on nanometrology for nanotechnology is highly appreciated in the optics market. These are just highlights in the regard of designs of materials for optics that could be so different. Still, they merit being mentioned due to the high sensitivity required and involved in common as well within the aim of designing optically active materials.

In this manner, this short commentary is expected to awaken interest and communicate many reasons why photonics, nanophotonics, and quantum photonics involving tiny sizes accompanied by larger instrumentation could still be of interest to humankind and well-being from the early years when humans discovered the first sources of light and energy until today, managing complex matter constitutions.

3. Future Perspectives

From previous facts and current developments, it could be noted that designs of varied emerging technologies incorporate strategies made of light or controlling different levels of energies with targeted applications. In this regard, from gadgets to advanced lasers, they incorporate the delivery of different levels of emissions. Photons and light delivery could be used for Health, Nutrition, Illumination, communication, energy production, and more. Brain stimulation at this moment is advanced, developing varied lamps with controlled light emission; at the same time, current research is focused on implantable miniaturized sources of non-classical light incorporating LEDs, tiny Lasers, and new approaches for performing and enhancing properties for single neuron stimulations at the level of single biostructures [39]. The incorporation of miniaturized instrumentation on the skull of small animals in vivo permitted high-impact behaviour studies and more focus on biomolecular, cellular, and tissue levels. The biocompatibility and absence of toxicity of devices and implants should be close to zero. Therefore, the management of materials used and evaluated is very important in the study and application too [40].

In addition, new technologies of sensing and imaging are advancing from the bench to Clinics and Hospitals. Thus, Opto-electrodes towards imaging-based technologies such as endoscopes are used to track in vivo varied biological phenomena. In a similar manner, tomographies produce varied levels of imaging and diagnostics of different matter constitutions, such as Computed Tomography and advanced multimodal approaches arriving from fundamental optics research and development. The incorporation of Radio-nuclides as molecular labellers and related technologies associated with labelling cells and generating different targeted contrasts of matter opens up even more the versatility of diagnoses and applications within Life Sciences.

Moreover, the control of photons, quantum signalling, and electronics are logically involved in communications and high technology at the edge of fundamentals and applied developments. Thus, programming photonics and optoelectronics circuits with low-energy stimulations could produce or switch on/off functions in other dimensions in further higher technologies such as automotive and aerospace, with high precision of robotics working on surgical interventions. So, in this context, it is noted that the challenge is to tune light, from Nano-and Quantum-photonics approaches, in order to scale up effects and phenomena from the near field towards the far fields, where multidisciplinary research and development are currently in progress to enhance, amplify, control, and perform on the targeted property with varied power of irradiances (Figure 3) [41].

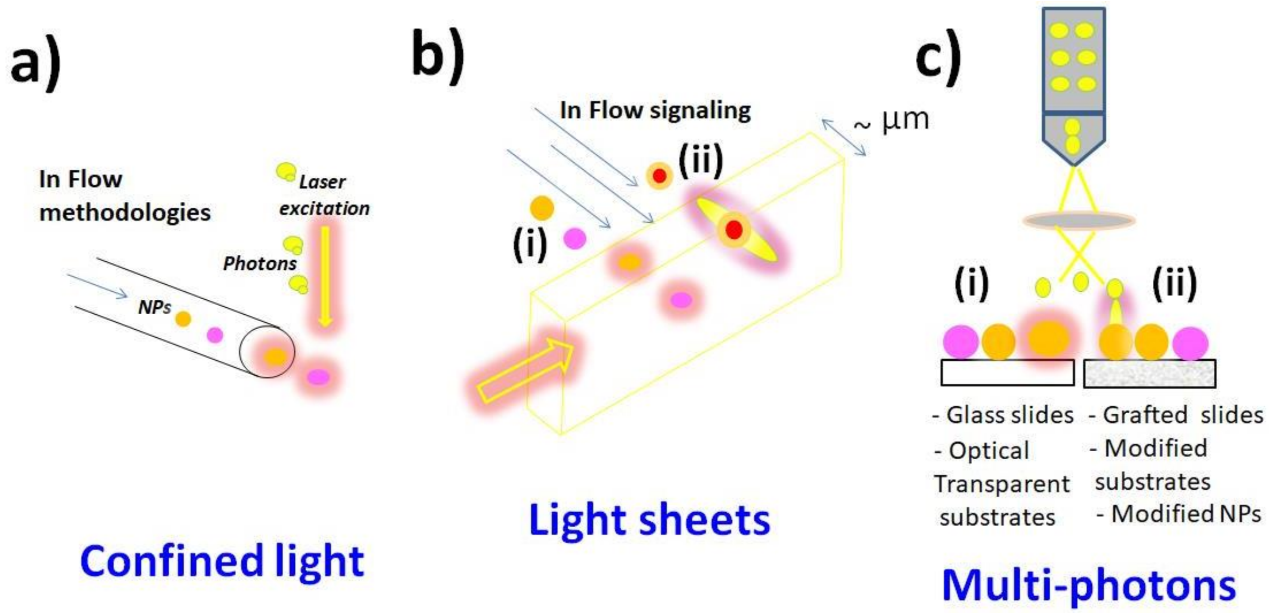

Figure 3 Schema focusing light on reduced-sized hot spots. (a) Laser excitation within Micro-, Nano-fluidics systems; (b) In-flow signalling within light sheets to track (i) Optically active Nanoparticles and (ii) Enhanced Optical Nanoplatforms by proper tuning of material components; (c) Controlled Multi-photon delivery on (i) glass slides, and (ii) modified substrates. Reprinted with permission from A. Guillermo Bracamonte, 2025 Taylor-Francis [41].

In this regard, there are many research lines evaluating higher performances of semiconductive materials, hybrid materials such as heterojunctions, modified waveguides such as plasmonic waveguides, and resonant architectures from tiny surfaces towards higher ones. Nano-plasmonics related to the generation of local high-energy electromagnetic fields to resonators and resonant surfaces involves enhanced phenomena from inter-nano-plasmonic field interactions, which is under focus of many studies and applications for enhanced photonics, quantum, and electronic conduction.

Finally, in the context of new materials as well as the generation of films and incorporation of single and collective optically active nanoplatforms, we are looking for optically active films and membranes for varied studies, uses, and applications. The development of modified films provides a broad view of applications depending on the materials involved. In this manner, the theme and topics related to the design and synthesis of new concepts of applied materials such as modified optically active films for varied applications. It could highlight diverse interests, such as going from skin bioelectronics to filters depending on their compositions. Modified substrates and films with supramolecular polymers, gels, and receptors could afford functional films [42, 43]. Therefore, it is also taken into account to afford further optical material challenges, soft materials incorporating optical functionalities, and smart responsive behaviors.

4. Conclusions

Tuning photons and electron conduction could provide varied types of materials and functions. The communication between different opto-electronic components showed high impact beyond tiny sizes. Therefore, from the control of Quantum-, nano-, and beyond, manipulating atoms, molecules, and higher bottom-up approaches achieves the targeted materials and functions. In this regard, the energies and different signal recording provide varied resolutions of information that could be translated to different pixels within images and more. Thus, photons and electrons are part of the higher-sized materials, instrumentation, and beyond. In this context, the design and synthesis of Nanomaterials involving different types of matter compositions, optical properties, and further ones associated with other functions are highly desired. Current challenges associated with tuning energies are under focus, where these levels could take place in different optical setups. For example, in inflow nano-optics, from the near-to the far-field detection based on Metal-Enhanced Fluorescence signaling showed how single Nano-Optics could be part of higher-sized and advanced Inflow optical systems for tracking single particles and biostructures (Figure 4) [44, 45]. For example, by In-flow cytometry Imaging (IFC), different scattered-light distributions were shown, depending on the nanoparticle concentrations in the colloidal dispersion and the size of modified ultra-luminescent core-shell nanoparticles with incorporation of Rhodamine B (RhB). Under continuous in-flow movement, it was possible to resolve differences within the nanoscale of a few nanometers of silica spacer around gold nanoparticles. (Au@SiO_2-RhB) based on the Metal Enhanced Fluorescence (MEF) phenomenon. Thus, varied fluorescent event detections and counting were recorded according to the SiO_2 lengths applied. A ratio of fluorescent event detection counting of core-shell/core-less of 40-42 was established for optimal MEF Enhancement Factors (MEF_{EF}) of 41-43 determined by Laser Fluorescence Microscopy. The Core-less nanoparticles showed a marked decrease in fluorescent event detection counting caused by higher photobleaching and absence of the MEF effect [46]. The plasmonics, nominated as highly intense electromagnetic fields generated from metallic nano-surfaces, could produce increased excitations of Fluorophores within the near-Field known as MEF [47].

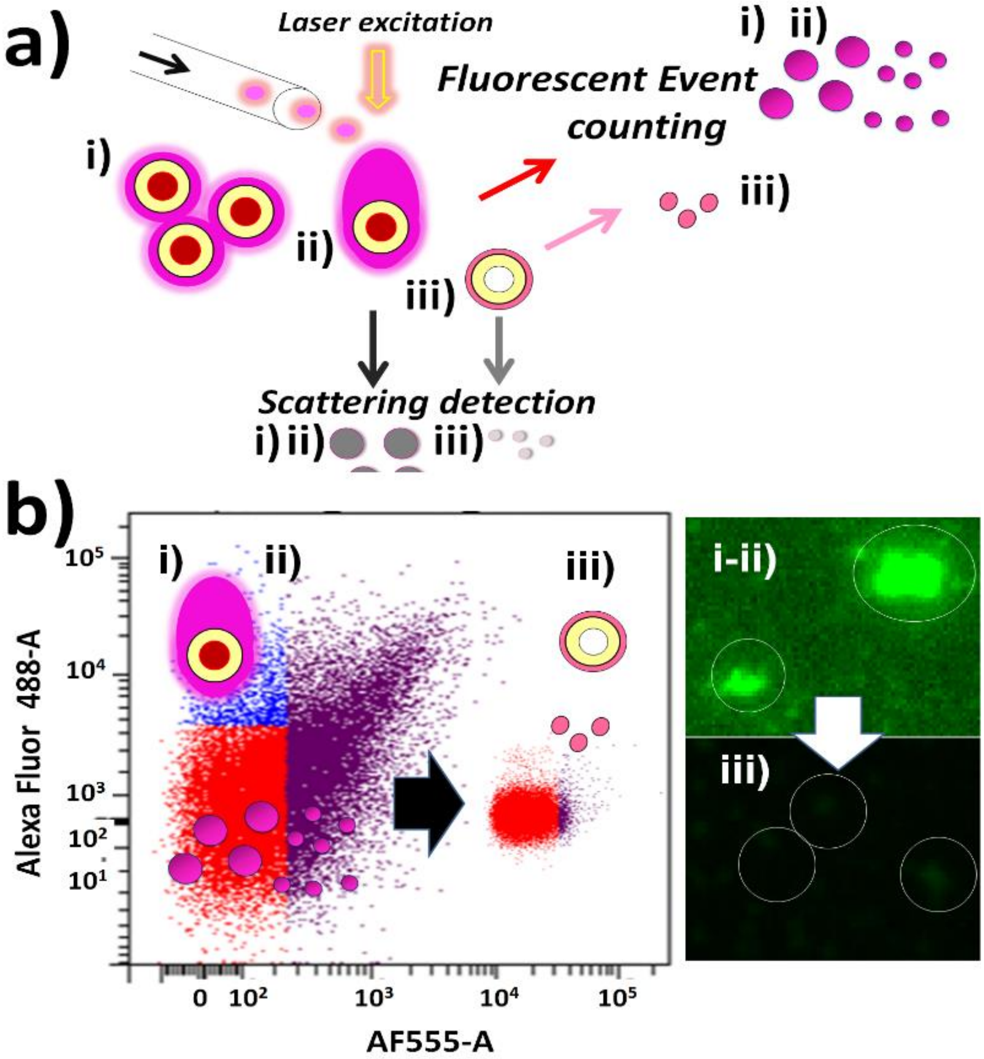

Figure 4 Enhanced nanoemitter detections: (a) Scheme of In-Flow detections of Ultraluminescent gold core-shell nanoparticles (Au@SiO_2-RhB NPs) and core-less nanoarchitectures ((-) @SiO_2-RhB). Distributions of Luminescent events of (i) small Au@SiO_2-RhB nanoaggregates, (ii) single Au@SiO_2-RhB detections, and (iii) core-less (--)@SiO_2-RhB were collected, while variable Scattered Light (i) and (ii) from core-shell nanoparticles, and (iii) from core-less structures were recorded; (b) In-Flow Cytometry by analysis of Alexa Fluor 488-A vs AF555-A contour plots from core-shell NPs (i) and (ii) to core-less NPs. Inset images (i)-(ii) corresponded to detection of core-shell NPs, and (iii) to core-less NPs by Laser Fluorescence Microscopy. Reprinted with permission from A. Guillermo Bracamonte et al., 2021 Microchemical Journal, Elsevier [44].

Further perspectives towards innovative methods and standard materials for In Flow uses highlight the optimization of single particles from which light is delivered, and further properties could be part of devices and In Flow miniaturized instrumentation.

It is important to highlight that the use of versatile immune assays on beads already developed and placed on the market, ready to be applied for targeted bioanalytical assays, showed a high impact in many Research areas, such as molecular detection and Biodetection. In this manner, the targeted beads could be confined within In-flow methodologies to track from single molecules at low concentrations to specific Biostructures. Moreover, by the incorporation of cameras and Optical setups, imaging detection systems could be recorded and generate new modes of imaging at different scales of resolution. These differences in the details from Image analysis could provide additional information depending on the phenomena exploited in the developed imaging. In this context of high-impact fundamental research, developments from in-flow methodologies, to microfluidics and Nanofluidics with different optical setups incorporated to study many Physical and Chemical phenomena could add new insights within all the mentioned Fields.

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Author Contributions

M.A.P.S. development of ideas, works on Research project related, and revision of English writing; A.G.B. write the manuscript, developed the idea, supervision of research related, and edition.

Competing Interests

The authors have declared that no competing interests exist.

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