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REVIEW

Insights on Tuning Directional Quantum Nanophotonic and Waveguiding Energies Through Space and Time: From Nano- to Miniaturized Optics and Instrumentation

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Abstract: In this review article, the concept of directional quantum, photonics, and energy emissions from the molecular to the nanoscale and beyond is developed and introduced. In this regard, insights into enhanced phenomena from the nanoscale are presented to be incorporated as a strategy for enhanced phenomena with perspectives of waveguiding signals. Prototyping of hybrid substrates to tune single nano-optics, couple optical components, and add gaining media with diminished optical losses through optically active substrates with perspectives of waveguiding and the generation of directional emissions. Therefore, it is proposed to modulate light propagation highlighting multimodal energies from tuned nanoplatforms with targeted functions, where varied physical phenomena could be proposed to route emissions. Thus, it is proposed to stimulate and show from pioneering phenomena toward recent innovative research focusing on tuning and use of optically active nanoplatforms for the modulation of arrays, assemblies, and conjugated systems with intended directional optical properties. In this context, cutting-edge nanotechnologies and nanophysics were involved. Enhanced phenomena were presented as a strategy for controlled directional properties, affording in this manner as, for example, metal-enhanced fluorescence, fluorescence resonance energy transfer, and coupled phenomena. In this regard, programming photonics toward the design of circuits, modified substrates, and waveguides of different types modified with nanostructured patterns could incorporate enhanced phenomena. The development of enhanced resonances such as enhanced plasmonics and pseudo-electromagnetic fields by carbon-based materials was considered as well to tune faster ballistic photonics through materials.

Keywords: quantum properties, nanophotonics, directional emissions, nano-optics, optical setups

1. Introduction

In this short communication, insights into directional energy translation through space and time, such as that produced by energy transfers and waveguiding light signaling, are presented. About the sources, it focuses on quantum emitters and nanophotonics, where the entire electromagnetic field could produce varied energies. In this way, the tuning of nano-optics from spherical dimensions toward varied shapes could generate new topological energy modes that overcome limitations within the near fields and beyond [1]. The nanoscale provides a versatile platform to build varied nanoplatforms, looking for new studies focused on nano-optics and further applications. Well-controlled nano-optically active materials lead to the generation of new collective optical behaviors, properties, and functions. Thus, micro-sized surfaces and substrates could permit the prototyping of new optically active materials. In this regard, epitaxial growth, asymmetry, chirality, and 3D spatial distributions of atoms afford vectorial properties. Thus, directional electromagnetic fields could cover varied energy modes that require targeted enhancements. The asymmetry could contribute to the directional target; however, considering energy losses and high-precision scales, new energy paths with improved efficiencies should be generated [2]. Thus, asymmetrical and directional emissions refer to the capability to control and manipulate on-demand photons, electrons, and optoelectronic signaling passing through structures [3].So, in this context, the capability to generate emissions from the quantum to the nano- and higher scale extends to longer distances nominated as far-field phenomena. In a first step, the accurate and high-precision energies involved should be located within the large interval of electromagnetic fields involved in the electromagnetic spectra. Thus, the concept is to stimulate one targeted point and translate the energy stimulated through space toward a unique direction, as occurs between two blocs containing different energies. The flow passes in this manner in one targeted direction.

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These phenomena should be studied at the quantum, molecular, and nanoscale levels for higher-sized phenomena (Figure 1(a)). The strategy could be developed in a different manner; however, differences between the input and output of signals should show the movement of the energy through space and time. This concept could be used in a similar manner to translate different energies, levels of energies, emissions, colored emissions, etc., through properly modified substrates and connectors to link and couple phenomena (Figure 1(b)) such as for waveguiding of optical signals. The waveguides are specialized structures that guide electromagnetic waves from one location to another and are often used to connect two or more components. These could be formed by different materials and designs intended to avoid energy losses out of the guided path [4]. The energy path is defined by its topography defined as a way as well as by a proper combination of conductive and insulating materials. Waveguides could be designed on different platforms and setups based on their shape, material, and confinement, with common types including hollow metallic tubes (rectangular, circular) for microwaves, dielectric structures (like optical fibers or planar waveguides for light), and specialized designs like coplanar or flexible waveguides, all guiding waves by restricting energy propagation in specific directions, primarily as transverse electric or transverse magnetic modes, distinct from transmission lines that can carry direct current as well [5]. So, depending on the materials developed, varied energy translations can occur.

In this regard, the development of research fields related to the generation of localized, highly intense electromagnetic fields from the nanoscale and beyond, controlling materials, sizes, and assembling characteristics is of high impact [6]. The control of shapes and geometries from single nanoplatforms could be tuned, as well as the distribution of energies. Thus, classical spherical shapes within the nanoscale permitted the comparison of materials. Thus, aluminum-, indium-, gallium-, rhodium-, and Ti-based nanomaterials could be noted within the ultraviolet (UV) interval of wavelengths [7]. These UV nanomaterials showed varied absorption properties around "250–295 nm of wavelength." In particular, Ti-based nanomaterials are more known for their intrinsic properties to generate electron holes and shuttle participating in nano-catalysis; however, joined to other ones, it could be interesting to enhance optoelectronic properties. Meanwhile, toward longer wavelengths, it could be noted that silver and gold nanoparticles have maximal absorption properties centered at 395 nm and 540 nm, respectively [8]. From these nanomaterials, strong near fields could be developed that afford interaction within their near surrounding for biosensing, enhanced emission based on metal-enhanced fluorescence (MEF), and further phenomena [9]. In this context, for neophytes, the MEF [10] could be explained by different radiative pathways from the interaction of a fluorophore placed at the right distance from a highly intense electromagnetic field generated by the electronic oscillation of the metallic core [11]. Therefore, it is highlighted that enhancements occur by (a) enhanced absorption and (b) excitation of the fluorophores generating increased emissions and (c) enhanced radiative decays accompanied by (d) diminished non-radiative decays as well [12]. Depending on the fluorophores and nanoarchitectures, the radiative pathways involved could vary; however, in the presence of MEF effects, enhanced fluorescence emission was accompanied by fluorescence lifetime decays shortening [13].

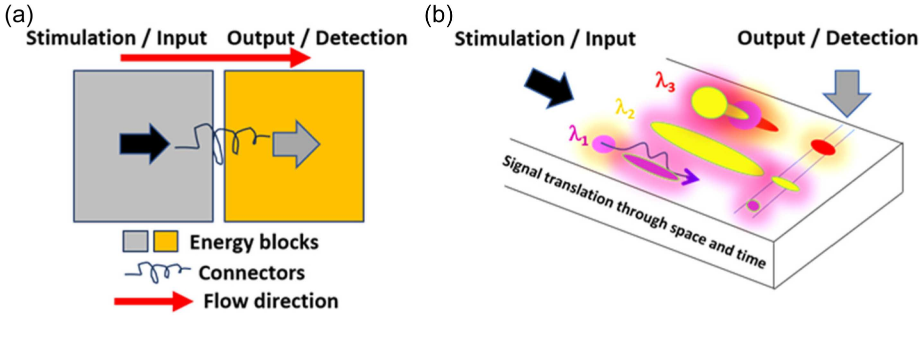
Moreover, by tuning diameters and confined electronic properties, it is possible to arrive even at quantum dimensions. For example, with gold nanoparticles, it could be achieved with 4 nm diameters of spherical nanoparticles and $Ti0_2$ until 1–2 nm sizes as well with simple chemical reduction reactions. Then, by tuning spherical nano-assembling and aggregation, it could generate varied types of resonant structures with the generation of new energy modes toward the near field and far fields [14]. Thus, nanotubes of gold and silver nanoparticles could be obtained. In a similar manner, by modifying shapes and geometries of single nanomaterials, they could be tuned to generate different localized high near fields within longer wavelengths such as the infrared. In this manner, varied energies are able to be used up on needs from single nano-emitters.

Finally, carbon nanotubes, carbon-based quantum dots, C nanoparticles, graphene, and graphene quantum dots are able as well to generate pseudo-electromagnetic fields within different regions of the electromagnetic field spectra. Thus, it is afforded to UV absorbers, near-infrared (NIR) materials, and even toward longer Terahertz antennas. In this context, other optical setups, such as resonators and higher-sized resonant surfaces, can also be considered [15].

So, varied materials and frequencies, wavelengths, and energies involved could be generated for tuning optoelectronics, non-classical light, conductions, and absorbers, reflective materials, and more technological approaches, where precise signaling is required. In this regard, this article intends to show an overview

Figure 1

Schema of energy translation based on different strategies and concepts: (a) representative two optical blocs with different energies involved in the unidirectional flow using an optical connector between them and (b) representative waveguide substrate where it is shown the channels with different colors, wavelengths and types of data input and output passing through different mechanisms involved in the signal translation spatially and over time



of the most well-known and used materials. However, the spatial direction of phenomena and energies involved should be considered. In this way, it could be proposed that directional coupling of phenomena provides the light, photonics, or quantum signaling path in one direction. This could be achieved in different manners, and in this short revision and discussion article, it is intended to present insight about them, showing recent results related to coupling fluorescence resonance energy transfer (FRET), enhanced phenomena, directional metal-enhanced phenomena (MEF), FRET biophotonics, quantum and nanophotonics waveguiding, and new resonant energy modes based on hybrid silicon materials (Figure 2). In this context, it should be mentioned that this short article doesn't intend to present waveguiding as a technological approach well known and developed by different and specific materials on pre-designed architectures. At the place, it is shown how waveguiding could be produced directionally within the nanoscale and beyond. So, the concept of waveguiding is used, and it is accompanied by some of the art of the cutting edge of the technology where it is very well performed. In this regard, the resonant energy modes are generated by joining free nanomaterials with targeted properties on their surfaces (Figure 2(a)). These properties are unique and well explained by phenomena intrinsically produced by the material and shape of the surface, focusing on the nanoscale and below, even reaching the molecular level. Then these properties are closely joined within short distances controlled by different strategies nominated schematically in this case as spacer (Figure 2(b)). For example, this concept is shown in the formation of optical nanoresonators, where nanoparticles between spacers form hot spots, while the entire new nanomaterial shows different electronic configurations in comparison to the initial free forms.

These are nanostructured materials within tens to hundreds of nanometers that could confine light, enhance light–matter interactions by trapping photons, and enable electronic conductions. Thus, it enables applications in sensing, lasers, quantum computing, and advanced optical devices by manipulating light at the subwavelength scale with high performances. These materials are formed from varied materials like silicon, diamond, or metals. The nanoscale act depending other variables as well such as designs and the combination of materials. Therefore, tiny optical cavities could even produce stronger light fields and lower energy thresholds for quantum and photonics emissions. These mentioned ongoing themes and topics are still under study toward directional emissions and targeted applications based on asymmetric material constitution and optical properties. The technological challenge is how to develop a bottom-up hierarchical material. In this regard, it is intended to draw attention to concepts and innovative research with perspectives within functional nanomaterials from dimeric, small assemblies to chips, devices, waveguides, and miniaturized instrumentations, where directional properties and functions are correlated.

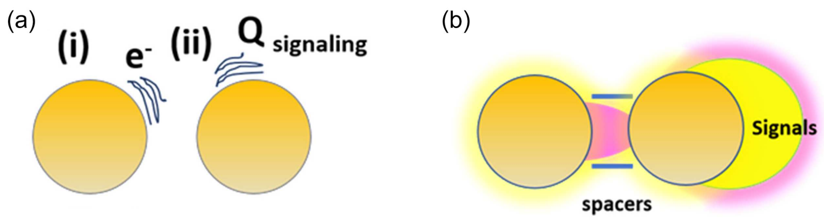
2. Controlling Directional Emissions from the Nanoscale and Beyond

The quantum, luminescence, fluorescence, and related emissions are associated with energies from different levels and energy modes that could vary. These properties from tiny sizes such as atoms and molecules toward the nanoscale and beyond could be guided in one direction. Many examples from nature could be mentioned such as energy transfer through photosystems, photosynthesis in plants collecting light from the sun, unicellular and pluricellular microorganisms developing energy pathways, and bioluminescence phenomena within different levels, from insects to higher-sized animals, small marine animals, fishes, sharks, and more. The controls are associated with a gradient of energies and coupling modes augmenting the flow in one direction. These could be achieved by varied mechanisms; however, the control of enhanced techniques and methods is not completely understood, and it is under study. In this regard, techniques such as fluorescence could be enhanced by the modification of electromagnetic fields surrounding the emitters. This phenomenon, named metal-enhanced fluorescence (MEF), could show directionally emissions properly tuned. In a similar manner, controlling distances from donor/acceptor molecules could be used to develop FRET. The direction is governed by different mechanisms whose basis should be known to propose new paths through space and time. Then, this phenomenon of short distances could be overcome by longer lengths. In this regard, in the next subsections, the basis of these phenomena and associated examples toward directional emissions is discussed.

2.1. MEF and FRET and coupling phenomena within the nanoscale

The design and synthesis of new small and ultrasmall tuneable nano-emitters have been shown to be of high interest and impact within the frontier of optical quantics and plasmonics phenomena. Quantum dots related to sizes below 10 nm [16, 17] showed strong emissions at variable wavelengths. However, modified plasmonic surfaces enhanced their emission properties based on MEF [18]. This phenomenon was explained by enhanced excitation of the emitters within the near field of a high electromagnetic field from metallic nanoparticles [19–21]. In this manner, metallic core-shell nanoparticles showed high emission enhancements accompanied by diminished photobleaching

Figure 2
Schema of nano-physical phenomena occurring: (a) within free and separated two nanoparticles associated with targeted electronic and quantum properties across their surfaces and (b) within confined hot spots generated by dimer formation of nano-assemblies



properties based on accurately tuneable 50.0 nm silver nanoparticles and silica spacers for varied fluorescence probe applications and energy modes involved [22]. The MEF, it is a physical phenomenon of enhanced fluorescence emission in the far field based on an interaction of the metallic nanoparticles' plasmon and fluorophores in the near field [23]. The electromagnetic field intensity from the electronic oscillation of the metallic nanoparticles that generates the plasmonic properties depends on the nanoparticle size, shape [24], and distance between metallic nanoparticles or degree of aggregation due to an enhanced plasmonic coupling effect [25]. These plasmonic enhancements can be used for MEF applications [26, 27]. Many theoretical studies exist reported in the literature, but not so many experimental studies related to this field. Varied energy paths and coupling phenomena are focusing based on electromagnetism and quantum phenomena. In this context, the need for further research and development is highlighted in order to afford platforms to study and apply targeted new materials and properties.

In this regard, the concept of core shells in the design of nanoarchitectures affords many uses. It is noted that this nanoarchitecture serves as a strategy to provide a hierarchized cargo-loaded symmetrical and unsymmetrical confined matter [28]. This fact is the key factor to control searching for the development of new nano-matter properties or applications. Thus, it is important to mention the most important and different types of core-shell structures reported in the literature as well as insights into new ones for further discussion, accompanied by their corresponding highlights of synthetic methods [29]. From these capabilities, the intrinsic versatility of the nanoarchitecture and properties is generated as well.

In addition, Multilayered Fluorescent silver core-shell nanoparticles showed improved enhancements based on FRET [30] coupled to MEF [31–33] that permitted ultra-low DNA detection of different human genes [34]. Moreover, 40.0 nm gold core-shell nanoparticles showed ultra-luminescent properties [35] even if their plasmonic intensities were lower than silver nanoparticles due to their intrinsic electronic properties. Then, these proofs of concept and strategies based on improved and enhanced luminescent properties were applied for bacteria labeling. Thus, it was applied to individual biostructure detections within varied bioassays incorporating different nanotechnology approaches [36].

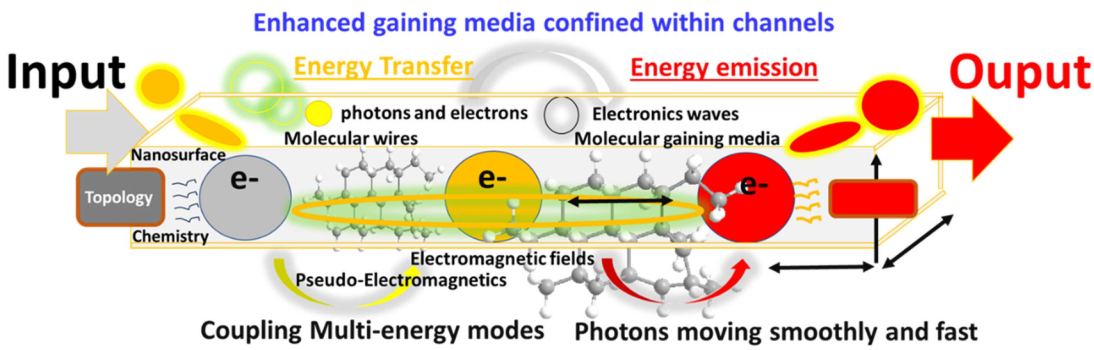
The mentioned enhanced luminescent properties were shown to be of high impact for biophotonics applications; however, for biological applications within cells, their sizes should be smaller for organelle labeling. These types of applications were reported by immunoassays and fluorescent labeling [37]. At this point, it is important to highlight the dependency of materials, sizes, geometries, biosurface interactions, and biocompatibility of nanomaterials for their incorporation [38–40]. Moreover, the application of FRET for biological event detection and tracking, which permitted, for example, molecular detection within cells and cellular cancer tracking [41], was shown to be widely applied in fluorescence-lifetime imaging microscopy [42].

About the FRET phenomenon, this is an effect of energy transfer produced from a donor–acceptor pair with high sensitivity and dependency on controlling inter-emitter and acceptor distances (*R*). From this *R* parameter, the Forster distance (R_0) parameter is generated as the main resonant energy pair characteristic of the system [43]. The (R_0) was defined as the distance between the donor and acceptor, where the energy transfer efficiency was 50%. For optimal FRET, donor emission and acceptor absorption should overlap, with decreased overlap between the absorption and emissions of the donor–acceptor pair. With these simple parameters, performances of different systems with the capability to produce energy transfers could be evaluated. However, the challenge still remains when new donor/acceptors change and further coupled phenomena affect electronic distributions from the basal to the excited state. Thus, FRET is still under study involving directional factors such as highly sensitive quantum coupling [44]. The design of new nanoplatforms and controlled spatial distributions of emitters is under focus, looking for the control of further variables.

In the design of prototypes incorporating nanostructured materials, optical components could be varied based on varied optically enhanced phenomena with proper connectors and gaining media within hybrid modified 2D and 3D substrates (Figure 3). In this manner, it is possible to place between optical components varied molecular wires, passivating agents, to tune the generation of electromagnetic fields affecting the confined spaces and molecular interactions. Therefore, there is input of energy and output as energy transferred and energy emission, respectively, with variable conductions depending on further materials incorporated.

The proposal could show innovation and challenges associated. After prototyping, it should answer how such types of new metamaterials could be afforded. In this context, knowledge about nanochemistry is required for the bottom-up development

Figure 3
Scheme of prototyping hybrid modified substrates. The substrate represents an orthogonal polyhedron incorporating 3D dimensions with different functional nanomaterials as sources of electrons, e-shuttles, photons, or quantum particles



Note: topological nanostructures could tune nano-optics to modulate properties through directional emissions.

of 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 straightforward 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. In this manner, it is possible to think of the potential performances as well as any inconvenient interferences, etc., in the process of fabrication. In addition, resonance and coupling energy modes considering different types of particles such as bosons, photons, and further quantum properties [45].

These incorporations and 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, spectroscopic 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 toward the control of multimodal signaling [46].

The FRET from simple and well-controlled systems with a donor-acceptor pair to the incorporation within the natural environment in cells, membranes, and proteins was always a challenge; however, it permitted the study of complex systems by controlling the fluorescent targets and conditions of measurements. In this manner, FRET was used for signaling transduction and 3D analysis of Biostructures due to their highly sensitivity with the inter-donor–acceptor distances [47]. As it is known, FRET between fluorescent dyes [48] and fluorescent nanoparticles [49] is a short-range phenomenon where the emission of a fluorophore is absorbed and re-emitted at longer wavelengths. It also depends on their quantum yields, and in this manner, the emission signal could be transduced and enhanced.

In a similar manner, electron transfer processes activate a cascade of reactions in biological systems as, for example, in mitochondria by photoestimulation [50]. However, FRET as an advanced analytical tool has shown a larger number of applications. For example, FRET was used to study protein metabolite binding [51]. Imaging protein–protein interactions by FRET within the signal cascade in living cells was studied by laser fluorescence microscopy [52], and even genetically encoded fluorescent reporters of protein tyrosine kinase activities in living cells were studied [53].

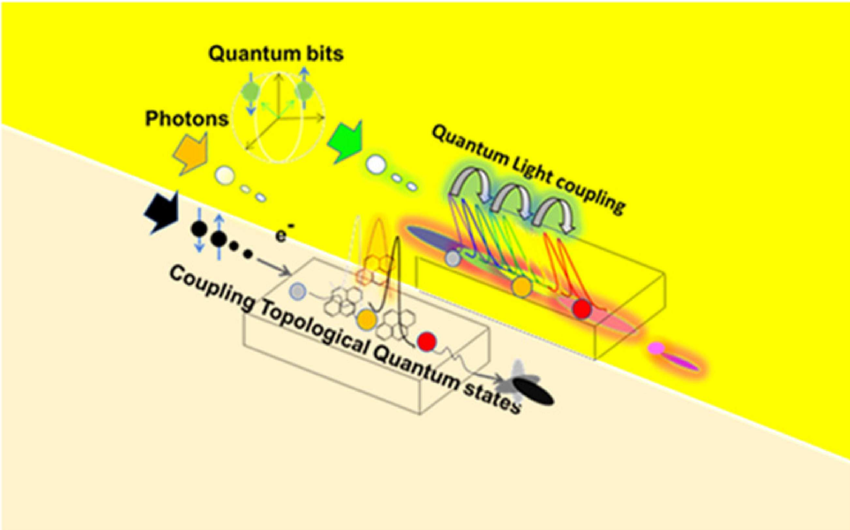
In addition, molecular sizes toward quantum and nanoscales improve energy transmission mechanisms when properly tuned. So, the design of a reduced size of nanoplatforms for enhanced FRET at the frontiers of quantum and nano-scales is of high impact for a huge number of biophotonics applications for Advanced Precision Nanomedicine Diagnostics. For FRET applications, the control of the inter-donor–acceptor spacers showed a highly sensitive dependency of $1/R_0^6$ (defined as R_0 equal to the spacer length where the FRET efficiency was 50%) [54]. In this manner, it was possible to record FRET with variable donor/acceptor spacers lengths within shorter nanoscale lengths from 1.0 nm for fluorescent proteins interactions [55, 56], 4.0 nm for dimeric quantum dots by non-covalent interactions with diameters below 10.0 nm [57], as well as for hybrids dimmers of quantum dots and gold nanorods [58], and 7.0 nm for silver multilayered core-shell nanoparticles (NPs) with diameters below 100.0 nm [59]. So, the inter-donor–acceptor distances could vary depending on the intrinsic properties and dimensions of the materials. However, it was reported from nanophotonics studies of energy transfer based on longer distances within confined optical cavities [60]. So, the developments of new approaches to nanomaterials that can overcome optical limitations even for pulsed photon microscopy techniques are highly desired. For these reasons, it was of interest the development of enhanced luminescent nanoplatforms for nanoimaging, photonic surface modifications, and biolabeling applications. So, based on these challenges and discussed needs, in this research communication, the FRET coupling was tuned over reduced sizes of tuneable plasmonic gold NP diameters for MEF applications. These nanoarchitectures were based on multilayered fluorescent shells in the presence and absence of the gold core used as a template. Their coupled emissions were evaluated between the emitters with the plasmonic cores, as well as the generation of ultra-luminescent bioimaging for improved resolutions by laser fluorescence microscopy.

In order to control directional fluorescence emissions, it is required to design proper and accurate optical setups with high precision and resolution within the different scales of length generating coupling in one direction. Normally, emissions are produced in all ways around 360 degrees forming bright spheres. However, the mechanism involved in the final emissions could be tuned as well within tiny spheres or dimeric molecular species such as for molecular FRET produced by gradients, quantum yield coupling, and other physical localization of optical materials fixing pathways. These are just mentions, and the challenges opened to show and prove from fundamental studies to applied approaches. The challenges and potential limitations depending on the new system proposed open new research and development aimed at building the right and desired path of energy and directional flow upon needs.

3. Waveguiding Programmable Nanophotonics

So, in the first sections, examples were shown afforded by tuning nano-optics focusing on the nanoscale; however, the far field and macroscale are achieved by a proper modulation of optically active components. In this regard, the design, synthesis, fabrication, and packaging offer high-impact optically active and functional materials. Thus, the waveguides are structured miniaturized paths to produce controlled flow of light. It could be described as spatially inhomogeneous structures for guiding confined in a given direction. The space through which photons pass should be carefully designed in order to generate ballistic photons containing a region of increased refractive index protected or wrapped by a surrounding medium defined as cladding. In this manner, it is possible to translate optoelectronic signaling, guiding high light-speed with low loss through the waveguide substrate. The materials exhibit various optical properties, including semiconductive lasers, excellent dielectric properties, and high refractive indexes providing highly sensitive media for photonic movements. However, tuning optical properties adding or improving gaining media is currently under study in order to develop enhanced photonics. Thus, key technologies include silicon photonics, wavelength division multiplexing, and embedded active optical materials that are able to convert electrical signals to optical signals and vice versa. These modifications are able to convert electrical signals to optical ones. These smart optically active systems are able to produce highly sensitive photonic counting and delivery through space and time (Figure 4). This capability originated chip-to-chip communications, fiber optics developments, and on-chip networking allowing by this manner higher data rates and associated perspectives in cutting-edge technologies such as light-based technologies and quantum computing.

Figure 4
Scheme of confined waveguides modified with varied optically active nanomaterials including quantum graphene dots, nanoparticles, optically active molecules, connectors and further optical components to modulate quantum, photonics, topological light modes and optoelectronic signaling



Tuning combinations of optically active materials and designs could simultaneously record different energy modes represented by different colors that increase potential optical information generated through the substrate [61]. In this modified substrate, it is possible to generate quantum and optical circuits and more affording to new properties and metamaterials.

Moreover, their uses are highlighted as a strategy and basis for further optical setups and systems such as for the development of (i) integrated photonics circuits involving waveguides and materials such as polymers and hybrid silicon-based materials that produce properties of materials able to guide light signaling at the microscale and noted as very important for optical interconnections nominated as optoelectronic multi-chip modules.

In this context, the integration of active components, such as sensitive InGaAs-based photodetectors, into waveguide layers, or their integration with them via flip-chip bonding, enables efficient signal coupling. Therefore, the tuning of nano-optics is focused on single components; however, the modulation considering the whole interconnected system should be addressed. Thus, the optical signals could be transmitted through waveguides via total internal reflection accompanied by switching techniques to control the flow of energy. After that, the applications could even open more challenges and needs to be optimized depending on the specific use. It is noted that data centers and computing using chip-to-chip connectors generate high bandwidths (e.g., 4 × 10 Gb/s) and overcome electronic constraints. In a similar manner, it only mentioned communication networks, involving high-speed optical fiber networking, and waveguide-based devices used in varied applications such as optical couplers and switchers.

Finally, it should be known that there are many types of waveguides highlighting planar, channels, and fiber optics-based setups. Thus, additional optical design and architectures should be considered. The planar waveguides used for on-chip light manipulation involve in many cases challenges of manipulations from single atomic compositions to the nanoscale. While, optical fibers used for long-distance communications provide optical cladding and gratings that protect and enhance signaling. In this regard, polymeric waveguides, surface chemistry, crosslinking, and the incorporation of varied materials based on covalent and non-covalent strategies are part of the current challenges of multidisciplinary research, engineering, and development. Thus, the development of efficient optical drivers focuses on decreasing coupling losses and improving signal speed and data communications.

3.1. Nanopatterned substrates for waveguiding

The modification of silica waveguides with different materials has led to different types of wave routing, as reported recently in the strongly confined surface plasmon polariton (SPP) waveguiding achieved by planar staggered plasmonic waveguides [62]. In this sense, signal transductions and detections were observed in the far field from electromagnetic fields generated by laser excitation in the near field of metallic surfaces within silica waveguides. It should be mentioned that the near field is defined by short distances within the nanoscale around highly intense electromagnetic fields produced from metallic surfaces and nanoparticles. These highly intense electromagnetic fields are known as plasmons, and they are associated with specific absorption of energies with consequent near-field emissions from electronic oscillations. Noble metals in particular are characterized by showing low energies associated with electronic movements; therefore, they are under focus, varying in size and shape. In this regard, the development of nano-optics [63] based on controlled nanopatterned and assembled materials is of high interest. These photonics studies and applications could involve many research fields and large variety and different targeted interests and applications. From a nanophotonics point of view, it should be highlighted that these properties have been shown to be highly sensitive to their surface topologies, sizes, and shapes within the near-field surrounding and media [64]. Moreover, these high-energy electromagnetic fields could be even enhanced based on inter-metallic surface interactions. The confined volumes within the near field, generated between metallic films or nanoparticles, it is produced electronic oscillation interactions that generate the enhanced plasmonics (EP) phenomena [65]. It should be highlighted that both phenomena showed a highly sensitive dependency on small length modifications even within the near field. These modifications in their inter-nanostructure distances containing resonant electromagnetic densities produce higher ballistic electronics and photonics movements. These phenomena led to a study focused on MEF in plasmonic waveguides, where the importance of accurate and high-precision control of spacers and nanostructured materials was highlighted [66]. The nanomaterials could shape the light through waveguides depending on the associated wavelengths and resonances involved. The main factors and variables are still under study depending on the emitters and new metamaterials incorporated; this is important to note due to varied sources of photonics pathways that could produce fast and ultrafast light pathways explained and based on different phenomena [67]. It means that not all the chemistry and physics of confined optical matter produce the delivery of enhanced light by the same mechanisms. Thus, as an example, the Metal-Enhanced Fluorescence Platforms Based on Plasmonic Ordered Copper Arrays: Wavelength Dependence of Quenching and Enhancement Effects [68] can be mentioned. Well-organized 2D and 3D arrays of copper-based nanostructures modified with porphyrin molecules were generated to produce enhanced fluorescence signaling. The wavelength at which the surface plasmon resonance of the nanostructures was generated was tuned to a longer wavelength than the inter-band transitions in the region of copper (>590 nm) by controlling the diameter of embedded silica particles. The porphyrin monolayers onto the nanostructures were joined *via* self-assembly of 16-mercaptohexadecanoic acid, which also suppressed the oxidation of the copper surface. The maximum fluorescence enhancement of porphyrin was determined with a factor of around 90 times the increase compared with a planar Cu plate (CuP). This enhancement factor determined was explained by the generation of surface plasmon resonances and coupling with fluorescent species. These achievements could be considered as excellent optical properties to be translated toward further communications and applications such as biophotonics, optoelectronics, and communications. So, the open research within nanoplasmonic waveguides toward applications in integrated nanophotonics is of high interest from different research fields [69]. For example, from nanophysics studying, the properties of propagating SPPs along one-dimensional metal structures have been investigated for more than 10 years, and they are now beginning to be well understood by applying high-confinement electromagnetic energy setups. Moreover, the need to improve circuits that use light to overcome speed limits of electronics and even optics is mentioned. New states of light applying drastic controlled conditions with ultra-low temperatures are under study due to the discovery of new states and physics of light arriving at liquid-type modes of energy [70]. Additional needs and challenges are focused on the incorporation of high power of irradiances from emitter devices, lasers, and related technology in order to control photonic delivery [71].

3.2. Advances and highlights about classical waveguiding and new insights within the nano- and microscale

The incorporation of important variables and research topics, such as energy loss engineering, nanoscale positioning precision and metrics, reproducibility, biocompatibility, complementary metal–oxide–semiconductor (CMOS) compatibility [72], and scalable fabrication, highlighted as targeted final developments in many cases, shows the complex multivariable and multidisciplinary nature of this research field. In this regard, combining optical strategies and materials could highlight some important recent reports with results toward improved performances highlighting directional emissions. Thus, heterojunctions in waveguides integrate two different semiconductor or dielectric materials to create sharp optical or electronic interfaces. In photonics, they are used for light confinement, routing, and tunable emission. In optoelectronics, they act as active photodetectors, modulators, or optical switches [73]. In this way, just to mention the improved properties incorporated, it is noted that the possibility exists to add the combination of two types of polymers doped for optical microwiring via micro-manipulation. One of the microstructures contained carboxyfluorescein and photochromic spiropyran that produced FRET activated by external light stimulation, while the other wire microstructure contained a rhodamine 6G-loaded channel permitted to open an acceptor energy channel to interact with photons arriving from different sources. Therefore, an innovative heterojunction with dual color was proposed that could guide light interacting with photons passing through in different manners and mechanisms depending on their intrinsic light nature.

In addition, highlighting materials such as CMOS considered a fundamental architecture used to build 99% of modern microchips, it should be noted that high sensitivity should be incorporated within the interphase of contacts. It is noted that CMOS is a functional and accurate pair of two opposite types of transistors—p-type and n-type—to process digital signals with near-zero power usage when the circuits are properly designed and connected. Some common design guidelines are still valid, including effective index matching among optics and electronics and impedance matching between the far-end termination and characteristic impedance of the coplanar waveguide electrodes [74]. In this context, for energy efficiency improvements within optical transmitters, the intuitive solution is to again reference successful design approaches developed for electrical amplifiers and focus at this step on the modulation of the light pathway within complex circuits. Thus, tuning nanophotonics from higher designs within the micro- and macroscale is highly desired and required. This is the directional path that should be predesigned and evaluated toward directional emissions, considering single nanophotonics, assemblies, and arrays, and even biological mimetic systems [75].

In addition, an integrated silicon photonic microelectromechanical system (MEMS) could be another example where directional nanoscale properties are required [76]. Higher-sized designs such as those based on silicon photonics for MEMS technology are highlighted. These approaches can enhance silicon photonics by combining building blocks that are compact, low-loss, broadband, and fast and require very low power consumption [77]. It is known that MEMS in photonics combines tiny mechanical actuators with optimally pre-tuned optical components. Therefore, it overcomes traditional silicon photonics limitations such as high-power consumptions and energy losses by enabling nanometer-scale movement to route energies and communications. Thus, the nanoscale and beyond could be part of that select group of key components supporting enhanced directional energy emissions. In this context, it is presented for neophytes in this theme that silicon photonic MEMS platforms could consist of high-performance nano-optoelectromechanical devices fully integrated alongside standard silicon photonics foundry components [78]. These components are based on wafer-level sealing for long-term reliability, flip-chip bonding to redistribution interposers, and fiber-array multi-port count optical and electrical contacts interfacing further applications or functions.

4. Current Research and Future Perspectives Toward Nanoresonators, Arrays, and Waveguides

There is considerable broad offer of versatility to develop uses and applications and even instrumentation with the need for optoelectronics and optical communications. In this insight, this section is intended to open this high-impact theme that opens a lot of topics as well. Thus, recently, studies have been reported analyzing and evaluating performances by applying tuning materials for light modulation and waveguiding. Just to begin, a well-known technique that was afforded by directional emission recording such as optical waveguide lightmode spectroscopy is mentioned. This technique showed a versatile technique for real-time label-free biosensing [79]. It was shown that well-organized bi-lipidic layers could incorporate varied receptors and optically active components with smart responses only in the presence of the proper distances between targeted analytes and an optically active resonator placed at the side [80]. This principle could be tuned by evaluating varied types of resonances where directional and asymmetrical properties are involved such as asymmetric transmission in nanophotonics [81]. This transmission asymmetry refers to a phenomenon where the total transmittance of an electromagnetic wave traveling in a predefined direction after passing through a subwavelength structure involving the nano- and quantum scales produces different directions and transmittances. Thus, a mathematical difference in forward and backward transmittances recording is generated. In this context, the importance of the asymmetry of optically active materials that begin from the molecular level and beyond is highlighted. Enhancements in these phenomena are of interest as well. Thus, the design and fabrication of varied optically active substrates considering nanoporous and waveguide-type materials are under focus incorporating proper combinations of materials [82]. At the cutting edge of the state of the art, it is possible to find recent reports developing the nanoscale for nanohole array waveguide couplers where efficiencies reached 45.4% applying array periods of 690 nm and hole diameters of 350 nm. This performance was raised to 47.5%, while the use of conventional 2D grating coupler values was around 20%.

Comparison of dielectrics and plasmonics waveguides with coherent readout for sensing uses was recently reported and discussed [83]. Biosensing using plasmonic waveguides afforded to high performances within reduced sizes, more compact prototypes. The incorporation of nanoplasmonics permitted higher sensitivity. This fact was already shown, and there is a huge quantity of research focused even in more topological advances associated with sizes, geometries, and higher shapes. The modification of these variables modifies the electronic oscillations toward coherence and amplified signaling [84]. Within complex enhanced systems, the minimum limit of detection that could actually be achieved was evaluated. Plasmonic and dielectric-based photonic waveguide biosensors embedded in a coherent-readout interferometric architecture are fairly and rigorously compared. With this miniaturized setup, theoretical limit of detection about 18 times and 110 times lower was exhibited for bulk and surface sensing, respectively, compared to plasmonic waveguide-based biosensors. These bioanalytical and technological performances were also valid when the respective waveguides were embedded in resonant-type sensing architectures such as those based on ring resonators. So, varied optical strategies could be achieved. Fine-tuning depending on targeted biostructures or media involved could need different optical approaches, resonant energies, and coupling mechanisms. Thus, the optical coherent transmission and directional energy transmission in molecular detection, for example, could achieve sensitive systems to identify protein asymmetry via electron transfers [85] and even coherence transfer within rotational-to-vibrational energy exchanges [86].

These research approaches to advanced signal waveguiding are in progress in search of potential high-impact applications for new analytical and bioanalytical methodologies. Then, the incorporation of graphene as an organic conductor in waveguides showed a highly sensitive plasmonic resonance waveguiding [87]. In particular, growing interest has been shown in graphene as a nanomaterial to be incorporated into waveguides due to its electronic and semiconductive properties, allowing, from modified substrates with different thicknesses, periodic control by voltage modulation of their bands coupled to plasmonics for band rejection applications.

Moreover, from previous basic and advanced studies, it is known that the need to underline the importance of signal transduction and routing within devices in the development of waveguides and their incorporation into on-chip setups for different applications. Therefore, optical connectors and low optical losses are required. Thus, interesting studies of MEF resonance modes are noted, including those by incorporating core-shell nanoarchitectures in silica plasmonic waveguides, direct on-chip optical plasmon detection through an atomically thin $IMoS_2$ wire semiconductor [88], and incorporating quantum dots on-chip via semiconductive GaAs ridge waveguides for routing and detection of resonance fluorescence. As evident from the accurate control of the nanoscale for the nanoarchitectures, it was possible to design, test, and apply different approaches. At this order of lengths, the controlled positions of the different parts of the micro- and nano-devices were essential for optimal performances.

In relation to miniaturization, rapid sensing, and diagnosis, a monolithically integrated mid-infrared (mid-IR) lab-on-a-chip was designed using plasmonic and quantum cascade structures [89]. This microdevice was devised on a monolithically integrated sensor based on mid-IR absorption spectroscopy. A bi-functional quantum cascade laser/detector was used, where, by changing the applied bias, the device switched between laser and detector operation, while the chemical sensing was within a dielectric-loaded SPP waveguide. The thin dielectric layer enhanced the confinement and enabled efficient end-fire coupling from and to the laser and detector.

Finally, important advanced technologies, new techniques, and methods to design the future next generation of miniaturized instrumentation such as on-chip spectroscopy are highlighted [90, 91]. These approaches are versatile with high potential to develop varied new optical signaling and energy modes, shaping new technologies. Thus, it can also be considered for spontaneous parametric down-conversion spectroscopy, performing mid-IR spectroscopy without the need for dedicated sources and detectors in the mid-IR, which can be expensive and limited in performance and which consists of an integrated on-chip version using lithium niobate waveguides. In this respect, the implementation of molecular bottom-up approaches and nanostructures with controlled nanoarchitecture and patterning for specific functional devices has been briefly discussed.

5. Concluding Remarks

About the concluding remarks and perspectives, it is noted from reports in the literature that improved strategies toward enhanced signaling and amplified laser signaling showed trends and challenges within varied approaches and prototypes. Coherent emissions coupled with directional light–matter interactions with enhanced energy transfers for varied studies and uses are highlighted. The enhanced quantum directional properties based on the accurate coupling of well-defined states, such as dipolar momentum of excitations and emissions from excited states, showed impact in higher resolution of signaling with varied applications. Diverse uses from biomolecular detections to communications involving waveguides, devices, and tiny lasers have also been highlighted. Therefore, programming photonics involves the tuning of single optical components such as absorbers, switch on/off systems, connectors, gaining media, donor/acceptors, and more. From the different examples described, it should be highlighted that for efficient signal transduction through planar surfaces, the type and mode of energy to be transferred should be considered in the development of the required material. Then, the strategy applied for the enhanced signal waveguiding should incorporate gaining media accompanied by diminished optical losses. Therefore, it is possible to design and fabricate micro-waveguide chips and optical waveguide lightmode spectroscopy (OWLS). This standard advanced instrumentation is available for the detection of proteins based on chemical surface modification with fluorescence resonance routing from quantum particles. Thus, it is highlighted the versatility of new optical instrumentation that afford toward further developments for light waveguiding. In this context, it is noted that signal waveguiding has also been demonstrated to be the basis of different types of energy routing through optical and quantum circuits, opening new venues toward new technologies. The optimization of new techniques and availability on the market such as surface-enhanced Raman spectroscopy (SERS). SERS is a highly sensitive analytical technique based on the enhancement of Raman scattering by molecules adsorbed on metallic surfaces. These metallic surfaces could produce even higher sensitivity against molecular detection by adding nanostructured surfaces accurately designed, contemplating variables of enhanced physics involving resonances of electromagnetic fields [92]. The enhancement factors could reach 10^{10} to 10^{11}, which produce the potential capability of the single molecule detections (SMD). An example of this is mentioned in this article; however, further developments are expected for miniaturized instrumentation and further research and development applying different enhanced nanophotonic systems and waveguides [93]. Moreover, spatial distributions of optically active components, light structuring, and interactions with surrounding material to produce enhanced phenomena should be highlighted. Spatial variables for optimal MEF, such as distances, wavelengths, and accurate spatial localization relative to the phase of the electromagnetic field generated from the nanoplasmonic core, are also noted [94]. In addition, beyond the nanoscale, the design of the light path produced in the MEF generation was highlighted, where high technological methods for design and fabrication of modified channels with optically active materials guide the directional phenomena [95]. In these perspectives and involving EP and nanoresonators, further designs are being considered for enhanced directional emissions and applications. It is highlighted that unprecedented plasmonics and quantum coupling of light–matter interactions involves control of the nanoscale, linking of surface plasmonics focusing on absorptions and emissions of quantum dot emitters and SMD. These regimes facilitated ultrafast energy transfers, directional radiations, and enhanced quantum yields with high-impact perspectives toward advanced nanophotonics, encryption of information, and quantum computing [96].

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Ethical Statement

This study does not contain any studies with human or animal subjects performed by the author.

Conflicts of Interest

The author declares that he has no conflicts of interest to this work.

Data Availability Statement

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

Author Contribution Statement

A. Guillermo Bracamonte: Conceptualization, Validation, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization, Supervision, Project administration.

References

[1] Xie, C., Wilson, B. A., & Qin, Z. (2024). Regulating nanoscale directional heat transfer with Janus nanoparticles. *Nanoscale Advances*, *6*(12), 3082–3092. https://doi.org/10.1039/D3NA00781B

[2] Lin, H., Wen, T., Tang, J., Ye, L., Zhang, G., Zhang, W., . . . , & Lu, G. (2023). Directional emission of nanoscale chiral sources modified by gap plasmons. *Nanotechnology*, *34*(24), 245201. https://doi.org/10.1088/1361-6528/acc2c8

[3] Yu, J., Qin, R., Ying, Y., Qiu, M., & Li, Q. (2023). Asymmetric directional control of thermal emission. *Advanced Materials*, *35*(45), 2302478. https://doi.org/10.1002/adma.202302478

[4] Mitchell, K. J., Gradauskas, V., Radford, J., Starshynov, I., Nerenberg, S., Wright, E. M., & Faccio, D. (2024). Energy transport in diffusive waveguides. *Nature Physics*, *20*(12), 1955–1959. https://doi.org/10.1038/s41567-024-02665-z

[5] Meng, Y., Chen, Y., Lu, L., Ding, Y., Cusano, A., Fan, J. A., . . . , & Ni, X. (2021). Optical meta-waveguides for integrated photonics and beyond. *Light: Science & Applications*, *10*(1), 235. https://doi.org/10.1038/s41377-021-00655-x

[6] Geddes, C. D (Ed.). (2010). *Metal-enhanced fluorescence*. USA: John Wiley & Sons.

[7] Karpinski, K., Zielinska-Raczynska, S., & Ziemkiewicz, D. (2021). Aluminium-based plasmonic sensors in ultraviolet. *Sensors*, *21*(12), 4096. https://doi.org/10.3390/s21124096

[8] Hang, Y., Wang, A., & Wu, N. (2024). Plasmonic silver and gold nanoparticles: Shape-and structure-modulated plasmonic functionality for point-of-caring sensing, bio-imaging and medical therapy. *Chemical Society Reviews*, *53*(6), 2932–2971. https://doi.org/10.1039/D3CS00793F

[9] Prakash, S., Behera, T., Chowdhury, A., & Datta, A. (2023). Microscopic perspective of synergy between localized surface plasmon resonance and disruption of dye aggregates in metal nanoparticle-enhanced fluorescence. *ACS Applied Nano Materials*, *6*(19), 17539–17547. https://doi.org/10.1021/acsanm.3c02734

[10] Lee, D., Song, J., Song, G., & Pang, Y. (2022). Metal-enhanced fluorescence of dyes with quadrupole surface plasmon resonance of silver nanoparticles. *Nanoscale Advances*, *4*(13), 2794–2805. https://doi.org/10.1039/D1NA00837D

[11] Aguirre-Cruz, G., Vargas-Melo, M. C., & Stanciu, L. (2026). Design and evolution of metal-enhanced fluorescence (MEF) nanosystems for ultrasensitive diagnostics. *Trends in Chemistry*, *8*(5), 391–406. https://doi.org/10.1016/j.trechm.2026.03.008

[12] Lakowicz, J. R. (2005). Radiative decay engineering 5: Metal-enhanced fluorescence and plasmon emission. *Analytical Biochemistry*, *337*(2), 171–194. https://doi.org/10.1016/j.ab.2004.11.026

[13] Knoblauch, R., Ben Hamo, H., Marks, R., & Geddes, C. D. (2020). Spectral distortions in metal-enhanced fluorescence: Experimental evidence for ultra-fast and slow transitions. *The Journal of Physical Chemistry C*, *124*(8), 4723–4737. https://doi.org/10.1021/acs.jpcc.9b11055

[14] Ginis, V., Benea-Chelmus, I.-C., Lu, J., Piccardo, M., & Capasso, F. (2023). Resonators with tailored optical path by cascaded-mode conversions. *Nature Communications*, *14*(1), 495. https://doi.org/10.1038/s41467-023-35956-9

[15] Thakur, S., Badoni, A., Sharma, R., Panda, S., Samriti, Ojha., A, . . . , & Prakash, J. (2026). Graphene oxide as smart sustainable nanomaterial: A versatile multifunctional material with transformative potential in advanced materials science research. *Npj Materials Sustainability*, *4*(1), 8. https://doi.org/10.1038/s44296-026-00095-x

[16] Ding, F. (2024). Quantum dots get a bright upgrade. *Light: Science & Applications*, *13*(1), 267. https://doi.org/10.1038/s41377-024-01593-0

[17] Li, J., Lei, H., Wang, K., Li, X., Chen, Z., Lam, S., . . . , & Zhao, C. (2025). Quantum dot-enhanced dual-modality heterojunction optoelectronic synapse for neuromorphic computing. *Advanced Optical Materials*, *13*(13), 2403474. https://doi.org/10.1002/adom.202403474

[18] Can, V., Onat, B., Cirit, E. S., Sahin, F., & Canbek Ozdil, Z. C. (2023). Metal-enhanced fluorescent carbon quantum dots via one-pot solid state synthesis for cell imaging. *ACS Applied Bio Materials*, *6*(5), 1798–1805. https://doi.org/10.1021/acsabm.3c00040

[19] Rodriguez, H. M., & Ciampi, S. (2025). Metal-enhanced fluorescence via spacer-free and electrogenerated nanomaterials at oil-fouled electrodes. *Langmuir*, *41*(42), 28615–28625. https://doi.org/10.1021/acs.langmuir.5c03860

[20] An, J., Hu, N., Yin, C., & Liu, Y. (2024). Metal-enhanced fluorescence (MEF) effect based on silver nanoparticles with different UV spectra on a surface carbon dot-based novel dry platform. *Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy*, *322*, 124744. https://doi.org/10.1016/j.saa.2024.124744

[21] Geddes, C. D. (2013). Metal-enhanced fluorescence. *Physical Chemistry Chemical Physics*, *15*(45), 19537–19537. https://doi.org/10.1039/C3CP90129G

[22] Poulin-Ponnelle, C., Boudreau, D., & Larivière, D. (2025). Fluorescent probes for monitoring toxic elements from the nuclear industry: A review. *Sensors*, *25*(18), 5835. https://doi.org/10.3390/s25185835

[23] Sivashanmugan, K., & Lakowicz, J. R. (2025). Re-direction of surface plasmon-coupled emission using metallic nanoparticles. *Materials Letters*, *398*, 138981. https://doi.org/10.1016/j.matlet.2025.138981

[24] Nandhini, G. U., Minakshi, M., Sivasubramanian, R., & Dharmalingam, G. (2026). Metal manipulated fluorescence: Mechanisms, materials, and plasmonic strategies for enhanced emission. *Nanomaterials*, *16*(5), 298. https://doi.org/10.3390/nano16050298

[25] Fang, X., Liu, W., & Wang, J. (2025). The seed growth of chiral plasmonic nanomaterials with different rotational symmetries. *Materials Today Chemistry*, *47*, 102889. https://doi.org/10.1016/j.mtchem.2025.102889

[26] Zhang, J., Fu, Y., Chowdhury, M. H., & Lakowicz, J. R. (2007). Metal-enhanced single-molecule fluorescence on silver particle monomer and dimer: Coupling effect between metal particles. *Nano Letters*, *7*(7), 2101–2107. https://doi.org/10.1021/nl071084d

[27] Puchkova, A., Vietz, C., Pibiri, E., Wünsch, B., Sanz Paz, M., Acuna, G. P., & Tinnefeld, P. (2015). DNA origami nanoantennas with over 5000-fold fluorescence enhancement and single-molecule detection at 25 μM. *Nano Letters*, *15*(12), 8354–8359. https://doi.org/10.1021/acs.nanolett.5b04045

[28] Pankaj, P., Bhattacharyya, S., & Chatterjee, S. (2022). Competition of core-shell and Janus morphology in bimetallic nanoparticles: Insights from a phase-field model. *Acta Materialia*, *233*, 117933. https://doi.org/10.1016/j.actamat.2022.117933

[29] Li, T., Zhang, J., Guo, J., Sun, B., Han, Y., Xu, H., . . . , & Cao, Y. (2026). Engineered internal architecture of core-shell lipid nanoparticles promotes efficient mRNA endosomal release. *Nature Communications*, *17*(1), 2187. https://doi.org/10.1038/s41467-026-69017-8

[30] Zhang, J., Fu, Y., & Lakowicz, J. R. (2007). Enhanced Förster resonance energy transfer (FRET) on a single metal particle. *The Journal of Physical Chemistry C*, *111*(1), 50–56. https://doi.org/10.1021/jp062665e

[31] Lessard-Viger, M., Rioux, M., Rainville, L., & Boudreau, D. (2009). FRET enhancement in multilayer core−shell nanoparticles. *Nano Letters*, *9*(8), 3066–3071. https://doi.org/10.1021/nl901553u

[32] Chao, Y.-C., Shih, C.-T., Lin, J.-Y., Wu, J.-W., Ho, C.-C., Lai, M.-C., . . . , & Chen, Y.-F. (2024). Enhancement of fluorescence resonance energy transfer by coherent coupling in-between surface plasmon and volume plasmon polariton. *The Journal of Physical Chemistry C*, *128*(49), 21132–21141. https://doi.org/10.1021/acs.jpcc.4c06014

[33] Cui, Y., Fan, S., Zhai, Y., Liu, Y., Li, J., Hu, J., & Wang, L. (2024). "Turn-on" and pinhole-free ultrathin core–shell

$Au@SiO_2$ nanoparticle-based metal-enhanced fluorescent (MEF) chemodosimeter for Hg^{2+}. *Nanoscale Advances*, *6*(9), 2319–2327. https://doi.org/10.1039/D3NA00746D

[34] Choi, J.-H., Ha, T., Shin, M., Lee, S.-N., & Choi, J.-W. (2021). Nanomaterial-based fluorescence resonance energy transfer (FRET) and metal-enhanced fluorescence (MEF) to detect nucleic acid in cancer diagnosis. *Biomedicines*, *9*(8), 928. https://doi.org/10.3390/biomedicines9080928

[35] Gontero, D., Veglia, A. V., Bracamonte, A. G., & Boudreau, D. (2017). Synthesis of ultraluminescent gold core–shell nanoparticles as nanoimaging platforms for biosensing applications based on metal-enhanced fluorescence. *RSC Advances*, *7*(17), 10252–10258. https://doi.org/10.1039/C6RA27649K

[36] Yu, P., Liu, Y., Song, Q., Qian, S., Fan, J., Liu, Y., . . . , & Wang, Y. (2025). Recent progress on fluorescence labeling of bacteria: Binding strategies, probes, and applications. *Chemical Engineering Journal*, *520*, 166078. https://doi.org/10.1016/j.cej.2025.166078

[37] Yamauchi, K., Koike, M., & Hioki, H. (2025). A three dimensional immunolabeling method with peroxidase-fused nanobodies and fluorochromized tyramide-glucose oxidase signal amplification. *Communications Biology*, *8*(1), 903. https://doi.org/10.1038/s42003-025-08317-z

[38] Bilge, S., Dogan-Topal, B., Gürbüz, M. M., Ozkan, S. A., & Sınağ, A. (2024). Recent trends in core/shell nanoparticles: Their enzyme-based electrochemical biosensor applications. *Microchimica Acta*, *191*(5), 240. https://doi.org/10.1007/s00604-024-06305-4

[39] Weiss, C., & Diabaté, S. (2021). Toxicology and biocompatibility of nanomaterials. *Nanomaterials*, *11*(11), 3110. https://doi.org/10.3390/nano11113110

[40] Cho, Y., Choi, Y., Jang, Y., & Seong, H. (2025). Nanomaterial-enhanced biosensing: Mechanisms and emerging applications. *Advanced Healthcare Materials*, *14*(31), 2500189. https://doi.org/10.1002/adhm.202500189

[41] Xiong, Y., Huang, Q., Canady, T. D., Barya, P., Liu, S., Arogundade, O. H., . . . , & Cunningham, B. T. (2022). Photonic crystal enhanced fluorescence emission and blinking suppression for single quantum dot digital resolution biosensing. *Nature Communications*, *13*(1), 4647. https://doi.org/10.1038/s41467-022-32387-w

[42] Aslam, F., Guo, J., Khalid, A., Anwar, S., Arshad, K., Khan, M. N., . . . , & Liu, L. (2025). Carbon dots as probes in FLIM: A review of applications and advances in cellular imaging. *RSC Advances*, *15*(52), 44919–44960. https://doi.org/10.1039/D5RA05371D

[43] Agam, G., Gebhardt, C., Popara, M., Mächtel, R., Folz, J., Ambrose, B., . . . , & Cordes, T. (2023). Reliability and accuracy of single-molecule FRET studies for characterization of structural dynamics and distances in proteins. *Nature Methods*, *20*(4), 523–535. https://doi.org/10.1038/s41592-023-01807-0

[44] Li, H., Wang, T., Han, J., Xu, Y., Kang, X., Li, X., & Zhu, M. (2024). Fluorescence resonance energy transfer in atomically precise metal nanoclusters by cocrystallization-induced spatial confinement. *Nature Communications*, *15*(1), 5351. https://doi.org/10.1038/s41467-024-49735-7

[45] Lei, T., Song, Y., Xue, Y., Gong, Q., Lončar, M., & Hu, Y. (2025). Strong-coupling and high-bandwidth cavity electro-optic modulation for advanced pulse-comb synthesis. *Light: Science & Applications*, *14*(1), 373. https://doi.org/10.1038/s41377-025-02046-y

[46] Xiao, Z., Wang, K., Lu, X., Sun, X., & Lu, F. (2025). Fabrication of multimodal optical imaging agents through direct triplet energy transfer from rare-earth doped nanoparticles. *Journal of Luminescence*, *280*, 121092. https://doi.org/10.1016/j.jlumin.2025.121092

[47] Lezhennikova, K., Rustomji, K., Kuhlmey, B. T., Antonakakis, T., Jomin, P., Glybovski, S., . . . , & Enoch, S. (2023). Experimental evidence of Förster energy transfer enhancement in the near field through engineered metamaterial surface waves. *Communications Physics*, *6*(1), 229. https://doi.org/10.1038/s42005-023-01347-1

[48] Sahl, S. J., Matthias, J., Inamdar, K., Weber, M., Khan, T. A., Brüser, C., . . . , & Hell, S. W. (2024). Direct optical measurement of intramolecular distances with angstrom precision. *Science*, *386*(6718), 180–187. https://doi.org/10.1126/science.adj7368

[49] Huang, F., Xie, Z., Zhang, Q., Zada, S., Lin, R., Deng, Y., . . . , & Zhou, Y. (2025). Recent advances in fluorescence resonance energy transfer (FRET) biosensors for exosomes. *Current Issues in Molecular Biology*, *47*(4), 235. https://doi.org/10.3390/cimb47040235

[50] Zong, Y., Li, H., Liao, P., Chen, L., Pan, Y., Zheng, Y., . . . , & Gao, J. (2024). Mitochondrial dysfunction: Mechanisms and advances in therapy. *Signal Transduction and Targeted Therapy*, *9*(1), 124. https://doi.org/10.1038/s41392-024-01839-8

[51] Wan, Q., Mouton, S. N., Veenhoff, L. M., & Boersma, A. J. (2022). A FRET-based method for monitoring structural transitions in protein self-organization. *Cell Reports Methods*, *2*(3), 100184. https://doi.org/10.1016/j.crmeth.2022.100184

[52] Leblanc, J., Lombard, A. H., Saumureau, A., Costrel, S., Revilloud, J., Coullomb, A., & Dupont, A. (2025). Live-cell quantitative FRET imaging made simple by autocalibration in QuanTI-FRET. *The European Physical Journal E*, *48*(10), 74. https://doi.org/10.1140/epje/s10189-025-00541-z

[53] Suh, J.-S., & Kim, T.-J. (2023). A novel DNA double-strand breaks biosensor based on fluorescence resonance energy transfer. *Biomaterials Research*, *27*(1), 15. https://doi.org/10.1186/s40824-023-00354-1

[54] Montepietra, D., Tesei, G., Martins, J. M., Kunze, M. B., Best, R. B., & Lindorff-Larsen, K. (2024). FRETpredict: A Python package for FRET efficiency predictions using rotamer libraries. *Communications Biology*, *7*(1), 298. https://doi.org/10.1038/s42003-024-05910-6

[55] Zhang, Y., Ma, X., Zhu, M., Wang, V. Y.-F., & Guo, J. (2025). Progress and prospects in FRET for the investigation of protein–protein interactions. *Biosensors*, *15*(9), 624. https://doi.org/10.3390/bios15090624

[56] Meiresonne, N. Y., Costa, S. F., Schäper, S., Ferreira, M. J., Reed, P., Hensel, Z., . . . , & Pinho, M. G. (2026). FtsW protein-protein interactions visualized in live Staphylococcus aureus cells by FLIM-FRET. *Nature Communications*, *17*(1), 6280. https://doi.org/10.1038/s41467-026-72752-7

[57] Kurashvili, M., Llusar, J., Stickel, L. S., Würthner, T., Ederle, D., Infante, I., . . . , & Akkerman, Q. A. (2025). Efficient energy transfer from quantum dots to closely-bound dye molecules without spectral overlap. *Angewandte Chemie International Edition*, *64*(9), e202420658. https://doi.org/10.1002/anie.202420658

[58] Hu, A., Chen, G., Yang, T., Ma, C., Li, L., Gao, H., . . . , & Zhong, L. (2022). A fluorescent probe based on FRET effect between carbon nanodots and gold nanoparticles for sensitive detection of thiourea. *Spectrochimica Acta Part A: Molecular*

and Biomolecular Spectroscopy, *281*, 121582. https://doi.org/10.1016/j.saa.2022.121582

[59] Jones, C. F., Resina, L., Ferreira, F. C., Sanjuan-Alberte, P., & Esteves, T. (2024). Conductive core–shell nanoparticles: Synthesis and applications. *The Journal of Physical Chemistry C*, *128*(27), 11083–11100. https://doi.org/10.1021/acs.jpcc.4c02012

[60] Bhatt, P., Dutta, J., Kaur, K., & George, J. (2023). Long-range energy transfer in strongly coupled donor–acceptor phototransistors. *Nano Letters*, *23*(11), 5004–5011. https://doi.org/10.1021/acs.nanolett.3c00867

[61] Feng, Z., Li, J., Yang, P., Xu, X., Wang, D., Li, J., . . . , & Chen, X. (2025). Dynamic multimodal information encryption combining programmable structural coloration and switchable circularly polarized luminescence. *Nature Communications*, *16*(1), 2264. https://doi.org/10.1038/s41467-025-57649-1

[62] Shen, J., Lei, S., Hu, M., Zhou, C., Luo, S., & Wang, C. (2025). Voltage tunable spoof surface plasmon polariton waveguide loaded with ferroelectric resonators. *Coatings*, *15*(4), 378. https://doi.org/10.3390/coatings15040378

[63] Sethumadhavan, V., & Nonappa. (2025). Atomically precise noble metal nanoclusters for engineering self-assembled two-dimensional materials. *Dalton Transactions*, *54*(31), 11770–11789. https://doi.org/10.1039/D5DT01171J

[64] Baù, E., Heimig, C., Biechteler, J., Mangold, F., Schwab, J., Karmakar, M., . . . , & Tittl, A. (2026). Tunable polaritonic topologies generated by non-local photonic modes. *Nature Nanotechnology*, *21*(6), 794–802. https://doi.org/10.1038/s41565-026-02174-5

[65] Luchowski, R., Calander, N., Shtoyko, T., Apicella, E., Borejdo, J., Gryczynski, Z. K., & Gryczynski, I. (2010). Plasmonic platforms of self-assembled silver nanostructures in application to fluorescence. *Journal of Nanophotonics*, *4*(1), 043516. https://doi.org/10.1117/1.3500463

[66] Fitio, V., Holyboroda, S., & Yaremchuk, I. (2025). Waveguide resonant electromagnetic field enhancement in multilayer dielectric/dielectric grating structure under plane wave irradiation. *Physics Letters A*, *556*, 130835. https://doi.org/10.1016/j.physleta.2025.130835

[67] Kant, K., Beeram, R., Cao, Y., Dos Santos, P. S. S., González-Cabaleiro, L., García-Lojo, D., . . . , & Santos, I. P. (2024). Plasmonic nanoparticle sensors: Current progress, challenges, and future prospects. *Nanoscale Horizons*, *9*(12), 2085–2166. https://doi.org/10.1039/D4NH00226A

[68] Sugawa, K., Tamura, T., Tahara, H., Yamaguchi, D., Akiyama, T., Otsuki, J., & Ushijima, H. (2013). Metal-enhanced fluorescence platforms based on plasmonic ordered copper arrays: Wavelength dependence of quenching and enhancement effects. *ACS Nano*, *7*(11), 9997–10010. https://doi.org/10.1021/nn403925d

[69] Singh, A., Kavitha, S., Hazareena, A., Saxena, R. S., & Siddiqui, M. G. (2026). Plasmonic waveguide combiner coupled with nano antenna for optical IC applications. *Optik*, *351*, 172789. https://doi.org/10.1016/j.ijleo.2026.172789

[70] Lerario, G., Fieramosca, A., Barachati, F., Ballarini, D., Daskalakis, K. S., Dominici, L., . . . , & Sanvitto, D. (2017). Room-temperature superfluidity in a polariton condensate. *Nature Physics*, *13*(9), 837–841. https://doi.org/10.1038/nphys4147

[71] Grégoire, A., & Boudreau, D. (2017). Metal-enhanced fluorescence in plasmonic waveguides. In B. Di Bartolo, J. Collins, & L. Silvestri (Eds.), *Nano-optics: Principles enabling basic research and applications*, (pp. 447–447). Springer, https://doi.org/10.1007/978-94-024-0850-8_28

[72] Dumoulin Stuyck, N., Saraiva, A., Gilbert, W., Cifuentes Pardo, J., Li, R., Escott, C. C., . . . , & Dzurak, A. S. (2026). CMOS compatibility of semiconductor spin qubits. *Nature Reviews Electrical Engineering*, *3*, 300–315. https://doi.org/10.1038/s44287-026-00283-w

[73] Xia, H., Zhu, Y., Chen, X., Chen, T., Zhang, D., Li, X., . . . , & Xie, K. (2021). Tunable-emission microwire heterojunctions for optical waveguides. *Materials Chemistry Frontiers*, *5*(13), 5055–5062. https://doi.org/10.1039/D1QM00538C

[74] Li, K., Thomson, D. J., Liu, S., Zhang, W., Cao, W., Littlejohns, C. G., . . . , & Reed, G. T. (2023). An integrated CMOS–silicon photonics transmitter with a 112 gigabaud transmission and picojoule per bit energy efficiency. *Nature Electronics*, *6*(11), 910–921. https://doi.org/10.1038/s41928-023-01048-1

[75] Julian, V. R., Urquiza, N. A., Veglia, A. V., Quinteros, D. A., & Bracamonte, A. G. (2026). Determination of nanostructured human serum albumin assembly based on enhanced topological fluorescence lifetime decays by applying controlled spatial tiny gold Core-shell labelling. *Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy*, *359*, 127934. https://doi.org/10.1016/j.saa.2026.127934

[76] Flodgren, V., Das, A., Sestoft, J. E., Alcer, D., Jensen, T. K., Jeddi, H., . . . , & Mikkelsen, A. (2025). Direct on-chip optical communication between nano optoelectronic devices. *ACS Photonics*, *12*(2), 655–665. https://doi.org/10.1021/acsphotonics.4c01375

[77] Bogaerts, W., Pérez, D., Capmany, J., Miller, D. A., Poon, J., Englund, D., . . . , & Melloni, A. (2020). Programmable photonic circuits. *Nature*, *586*(7828), 207–216. https://doi.org/10.1038/s41586-020-2764-0

[78] Quack, N., Takabayashi, A. Y., Sattari, H., Edinger, P., Jo, G., Bleiker, S. J., . . . , & Bogaerts, W. (2023). Integrated silicon photonic MEMS. *Microsystems & Nanoengineering*, *9*(1), 27. https://doi.org/10.1038/s41378-023-00498-z

[79] Ramsden, J. J. (2026). Optical waveguide lightmode spectroscopy: A versatile technique for real-time, label-free biosensing. *Sensors*, *26*(4), 1183. https://doi.org/10.3390/s26041183

[80] Rascol, E., Villette, S., Harté, E., & Alves, I. D. (2021). Plasmon waveguide resonance: Principles, applications and historical perspectives on instrument development. *Molecules*, *26*(21), 6442. https://doi.org/10.3390/molecules26216442

[81] Sheikh Ansari, A., Iyer, A. K., & Gholipour, B. (2023). Asymmetric transmission in nanophotonics. *Nanophotonics*, *12*(14), 2639–2667. https://doi.org/10.1515/nanoph-2022-0820

[82] Chuang, Y.-L., Chang, S.-W., & Tsai, W.-S. (2025). Design of etch-through nanohole array waveguide couplers on an SOI platform. In *Photonics, Devices, and Systems IX*, 1369806. https://doi.org/10.1117/12.3072546

[83] Sanchez-Ramirez, A., Luque-Gonzalez, J. M., Wangüemert-Pérez, J. G., Ortega-Monux, A., & Molina-Fernandez, I. (2024). Comparing dielectric and plasmonic waveguides in a Mach–Zehnder architecture with coherent readout for sensing applications. *Optics & Laser Technology*, *168*, 109813. https://doi.org/10.1016/j.optlastec.2023.109813

[84] Kong, D., Liu, Y., Ren, Z., Jung, Y., Kim, C., Chen, Y., . . . , & Hu, H. (2022). Super-broadband on-chip continuous spectral translation unlocking coherent optical communications

beyond conventional telecom bands. *Nature Communications*, *13*(1), 4139. https://doi.org/10.1038/s41467-022-31884-2

[85] Zhang, Y., Liu, N., Niu, K., Wang, X., Yang, J., Lu, F., . . . , & Zhong, D. (2025). Optical coherent quantum control of ultrafast protein electron transfer. *Science Advances*, *11*(16), eado9919. https://doi.org/10.1126/sciadv.ado9919

[86] Chen, T. Y., Steinmetz, S. A., Patterson, B. D., Jasper, A. W., & Kliewer, C. J. (2023). Direct observation of coherence transfer and rotational-to-vibrational energy exchange in optically centrifuged CO_2 super-rotors. *Nature Communications*, *14*(1), 3227. https://doi.org/10.1038/s41467-023-38873-z

[87] Azar, M. T. H., Zavvari, M., Mohammadi, P., & Zehforoosh, Y. (2018). Periodically voltage-modulated graphene plasmonic waveguide for band-rejection applications. *Journal of Nanophotonics*, *12*(4), 046002. https://doi.org/10.1117/1.JNP.12.046002

[88] Goodfellow, K. M., Chakraborty, C., Beams, R., Novotny, L., & Vamivakas, A. N. (2015). Direct on-chip optical plasmon detection with an atomically thin semiconductor. *Nano Letters*, *15*(8), 5477–5481. https://doi.org/10.1021/acs.nanolett.5b01898

[89] Schwarz, B., Reininger, P., Ristanić, D., Detz, H., Andrews, A. M., Schrenk, W., & Strasser, G. (2014). Monolithically integrated mid-infrared lab-on-a-chip using plasmonics and quantum cascade structures. *Nature Communications*, *5*(1), 4085. https://doi.org/10.1038/ncomms5085

[90] Mitchell, C. J., Hu, T., Sun, S., Stirling, C. J., Nedeljkovic, M., Peacock, A. C., . . . , & Rowe, D. J. (2024). Mid-infrared silicon photonics: From benchtop to real-world applications. *APL Photonics*, *9*(8), 080901. https://doi.org/10.1063/5.0222890

[91] Lopez-Garcia, M. (2022). Versatile chip-based nanoscopy becomes ready for histopathology assessment. *Light: Science & Applications*, *11*(1), 87. https://doi.org/10.1038/s41377-022-00781-0

[92] Li, Z., Cheng, Y., Fernandes, C., Wang, X., & Ruda, H. E. (2025). Tuning surface-enhanced Raman scattering (SERS) via filling fraction and period in gold-coated bullseye gratings. *Nanomaterials*, *15*(24), 1863. https://doi.org/10.3390/nano15241863

[93] Bracamonte, A. G. (2025). *Development of advanced nano-optics: For miniaturized optical set-ups and instrumentation* (1st ed.). USA: CRC Press.

[94] Wang, X., Chen, Z., Wang, Z., Li, C., Feng, G., Xie, H., . . . , & Yang, Y. (2025). Directional and enhanced fluorescence emission in a semicircular microchannel with a nanogroove. *IEEE Sensors Journal*, *25*(6), 9585–9592. https://doi.org/10.1109/JSEN.2025.3535576

[95] Lee, S., & Kang, S. H. (2023). Wavelength-dependent metal-enhanced fluorescence biosensors via resonance energy transfer modulation. *Biosensors*, *13*(3), 376. https://doi.org/10.3390/bios13030376

[96] Khalili, F., Vendrell, O., Hosseini, M. S., & Jamshidi, Z. (2025). Quantum dynamics of plasmonic coupling in silver nanoparticle dimers: Enhanced energy and population transfer via emitter interaction. *The Journal of Physical Chemistry Letters*, *16*(10), 2661–2671. https://doi.org/10.1021/acs.jpclett.4c03609

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