Chapter

Nanophotonics: Fundamentals, Challenges, Future Prospects and Applied Applications

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Abstract

Nanophotonics encompasses a wide range of nontrivial physical effects including light-matter interactions that are well beyond diffraction limits, and have opened up new avenues for a variety of applications in light harvesting, sensing, luminescence, optical switching, and media transmitting technologies. Recently, growing expertise of fusing nanotechnology and photonics has become fundamental, arising outskirts, challenging basic experimentation and opportunities for new technologies in our daily lives, and played a central role in many optical systems. It entails the theoretical study of photon's interactions with matter at incredibly small scales, known as nanostructures, in order to prepare nanometer scale devices and accessories for processing, development, slowing down, influencing, and/or regulating photons through comprehending their behavior while interacting with or otherwise traveling via matter. This multidisciplinary field has also made an impact on industry, allowing researchers to explore new horizons in design, applied science, physical science, chemistry, materials science, and biomedical technologies. The foundations, nano-confinements, quantum manifestations, nanoscale interactions, numerical methods, and peculiarities of nonlinear optical phenomena in nano-photonics as well as projected nano-photonics consumption's in our cutting-edge world, will be covered in this chapter.

Keywords: nanophotonics, foundations, nano-confinements, quantum confinements, optical interactions, numerical simulations, nonlinear optical phenomena

1. Introduction

Nanophotonics is concerned with light-matter interactions at the nanoscale, which poses challenges to fundamental science while also opening the door to technological innovations. It encompasses the investigation of novel optical interactions, materials, manufacturing techniques, and models, as well as the exploration of organic and inorganic, or chemically manufactured structures such as holey fibers, photonic crystals, sub-wavelength structures, quantum dots, and plasmonics [1, 2]. Photonic medicine has become a rapidly emerging and theoretically incredible methodology for detection, disease prevention, and treatment. Because of the extremely fast rate of light modulation and the remote nature of optical procedures, light could be able to recover diagnostics, medications, and, unexpectedly, treatment course in a single theranostic procedure mixture of therapeutics and diagnostics, which provide clinical screening and therapy tracking [3]. It is concerned with the use of photonics in nanostructure media, when light is compressed down through nanometer scale volume and field enhancement effects emerge, resulting in new optical wonders that can be used to counter current advanced cutoff points and produce dominant superior photonic devices, which include a wide range of topics, such as metamaterials, quantum dots, quantum nanophotonics, high resolution imaging, plasmonics, and functional photonic materials. It has recently become a broadly recognized research field, and it will play an incredible role in the advancement of groundbreaking emerging innovations, ranging from high-efficiency solar cells to customized health tracking instruments that can detect the chemical structure of molecules at ultralow concentrations. Nanomaterials establish a substantial space in nanophotonics, and as we can see in this section and others to come, nanoscale optical materials span a wide variety of optical applications and have an incredibly diverse spectrum of nanostructure architecture. The optical properties of these nanostructures can be closely monitored by modifying them, allowing for the enhancement of one photonic function when presenting another photonic manifestation, and also the convergence of several functions to achieve multifunctionality [4].

2. Foundations of nano-photonics

2.1 Confinements approaches

Nanophotonics combines many important innovation thrust fields, including lasers, photovoltaics, biotechnology, photonics, and nanotechnology. Recently, growing expertise of fusing nanotechnology and photonics has become fundamental, arising outskirts, challenging basic experimentation. It can be divided into three types of confinement techniques: The first is to create nanoscale connections between light and matter by confining light to nanometer-sized dimensions far less than the light's wavelength. The approach that follows is to confine matter to nanometer range, restricting light-matter interactions to nanoscopic scales and characterizing the world of nanomaterials. The final method requires the nanoscale confinement of a photo-process through photochemistry or a light-induced phase transition, and it is used to fabricate photonic structures and functional units at the nanoscale. One method for confining light to a nanometer scale is to use near-field optical transmission, a model in which light is compressed via a metal-coated, tapered optical fiber and then exudes through a tip with an aperture far smaller than the wavelength of incident light. Different methods of confining the dimensions and producing nanostructures for photonic applications are used in nanoscale matter confinement; for example, nanoparticles with exceptional electronic and photonic properties. It's promising to hear that these nanoparticles are now being used in nanophotonic applications including UV absorbers that are used in sunscreen lotions. These nanoparticles may be composed of organic or inorganic materials, such as nanomers, having size-dependent optical properties as they are nanometer-sized oligomers (with a finite number of identical units) complexed with monomeric organic analogues, and polymers, which are long chain structures with a large number of repeating units. The field of "plasmonics" is made up of metallic nanoparticles that have an interesting optical reaction and an improved electromagnetic field. There are nanoparticles that can up-convert two absorbed IR photons into a visible UV photon, as well as quantum cutters that can down-convert an absorbed vacuum UV photon to two-visible UV photons. A photonic crystal is a hot field of nanomaterials that refers to a periodic dielectric structure with a repeated unit of the order of wavelength of light. Nano-composites are made up of phase-isolated nano-domains of at least two dissimilar materials on a nanometer scale. Each nano-domain in the nano-composite will give the bulk media a unique optical property. Controlling the flow of optical energy between various domains through an energy move (optical communications) is also possible. Nanolithography can be used to build nanostructures, which can then be used to fabricate nanoscale sensors and actuators using nanoscale photo-processes. The ability to confine photo-processes to all around characterized nano-regions, allowing structures to be fabricated in exact geometry and arrangement, is a key feature of nanofabrication. This section will illustrate the fundamentals of nanophotonics by describing the similarities and variations between photons and electrons, as well as confinement effects on photons and electrons caused by optical and electronic interactions at nanoscale range.

2.2 Photons and electrons: a comparison of their similarities and dissimilarities

Photons and electrons are subatomic elementary particles that can function as both particles and waves. Electrons are negatively charged subatomic particles with the smallest mass, while photons are massless quanta of energy that leads to electromagnetic radiations. The intrinsic angular momentum of an electron is a half integer of ħ (spin = 1/2), indicating that it is a fermion. As a result, if more than one electron occupies the same space, each electron's properties should be unique and conform to Fermi-Dirac statistics. The Pauli's exclusion principle depicts the strong interaction of electrons (fermions). Photon, on the other hand, is an elementary particle with both electric and magnetic fields governed by Maxwell's equations, as well as an inherent angular momentum of integer magnitude of ħ (spin = 1), indicating that it is a boson. According to Bose-Einstein statistics, photons do not associate with other photons, so more than one photon can occupy a single quantum state. There are two ways in which photons differ from electrons: (I) Photons are vector fields (light has the ability to be polarized), while electron wavefunctions are scalar; and (II) Electrons have charge and spin, while photons do not.

Atoms are made up of nuclei (neutrons and protons) surrounded by electrons. Since light (photons) that interacts with nuclei need a lot of energy (gamma rays), hence X-ray to infrared light only interacts with electrons, regulating photon/electron interactions. Light energizes an electron cloud with one particle, which emits a photon, which interacts with another electron cloud in transparent materials, while light can be absorbed and emitted in opaque materials by a resonant electron and photon connection. Quantum representation shows that electrons and photons are analogous and have several characteristics. **Table 1** summarizes the similarities in features of electrons and photons.

2.3 Confinement of photons and electrons

Photon and electron propagation can be dimensionally restricted by reflecting or backscattering these particles in spaces of varying interaction potential along their propagation path, thereby confining their propagation to a single direction or range of directions. According to classical mechanics, electrons and photons are fully confined in confinement areas. Since the energy of electrons trapped within potential energy limits is less than the potential energy due to the boundary, they remain

Characteristic	Photons	Electrons
Wavelength	$\lambda = \frac{h}{P} = \frac{c}{\upsilon}$	$\lambda = \frac{h}{P} = \frac{h}{mv}$
Wave Equation	$\{\nabla \times \frac{1}{\varepsilon(r)} \nabla \times\}\, B(r) = (\frac{\omega}{c})^2 B(r)$	$\hat{H}\Psi(r) = -\frac{\hbar^2}{2m}\nabla.\nabla + V(r)\Psi(r) = E\,\Psi$
Free-Space Propagation	Plane wave $E = (\frac{1}{2})E^0\,(e^{ik.r-\omega t} + e^{ik.r+\omega t})$ K is a wave vector and a real quantity	Plane wave $\Psi = c\,(e^{ik.r-\omega t} + e^{ik.r+\omega t})$ K is a wave vector and a real quantity
Interaction Potential	Dielectric constant (refractive index)	Coulomb interactions
Propagation in Classically Forbidden Zone	Photon tunneling (evanescent wave) with imaginary wave vector k and exponentially decaying amplitude	Electron tunneling with exponentially decaying amplitude (probability).
Localization	Strong scattering caused by massive dielectric constant variations (Photonic Crystals)	Big differences in coulomb interactions cause strong scattering (Electronic Semiconductor Crystals)
Cooperative Effects	Interactions between nonlinear optical systems	Many-body correlation Superconducting Cooper pairs Bi-exciton Formation

Table 1.
An overview of similarities in characteristics of electrons and photons.

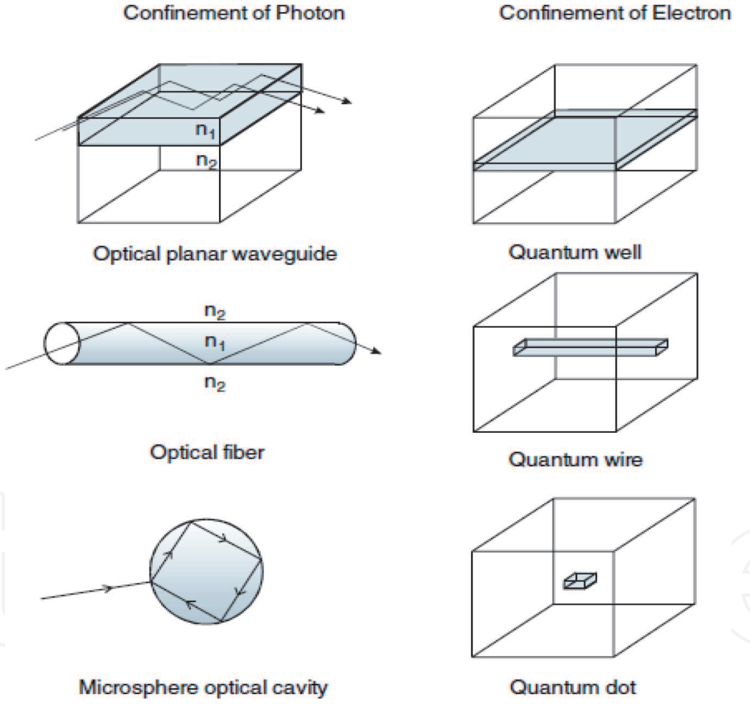

Figure 1.
Confinement of photons and electrons in different dimensions with propagation along z-axis [6].

completely enclosed within the walls. The wave picture of photons and electrons, on the other hand, does not indicate this. Photons can be used to envision confinement by collecting light in an environment with a high refractive index or high surface reflectivity, whereas a waveguide or cavity resonator can serve as a confining field [5]. The **Figure 1** depicts the classic picture of light direction (trapping) due to total internal reflection using a beam line. The confinement in a planar waveguide is only along the vertical x-direction, while the propagation direction is along the z-axis whereas the confinement of a fiber or a channel waveguide is in the x and y directions. A microsphere is a three-dimensional representation of an optical medium that confines light in all directions by comparing the refractive index of the leading and surrounding mediums. As a result, the disparity n1/n2 functions as a scattering potential, obstructing light propagation. Light functions as a plane wave with a continuous propagation constant, similar to the propagation vector k in free space; the electric field circulation has a distinct spatial profile in the direction of propagation (z axis) and in the confining direction [6].

2.4 Confinement of optical interactions at the nanoscale

Numerous geometries will confine the electric field associated with a photon (electromagnetic field) to initiate optical interactions at the nanoscale, including axial and lateral localization approaches that can be used to reduce the optical field on the nanoscale, as seen schematically in **Table 2**.

2.4.1 Axial nanoscopic localization

This technique employs the evanescent wave and surface plasmon methodologies, which are discussed further below.

I.Evanescent Wave

In the field of optics, evanescent waves, are oscillating electric and/or magnetic fields that may not propagate like electromagnetic waves but whose energy is spatially amassed near the source rather than moving waves of

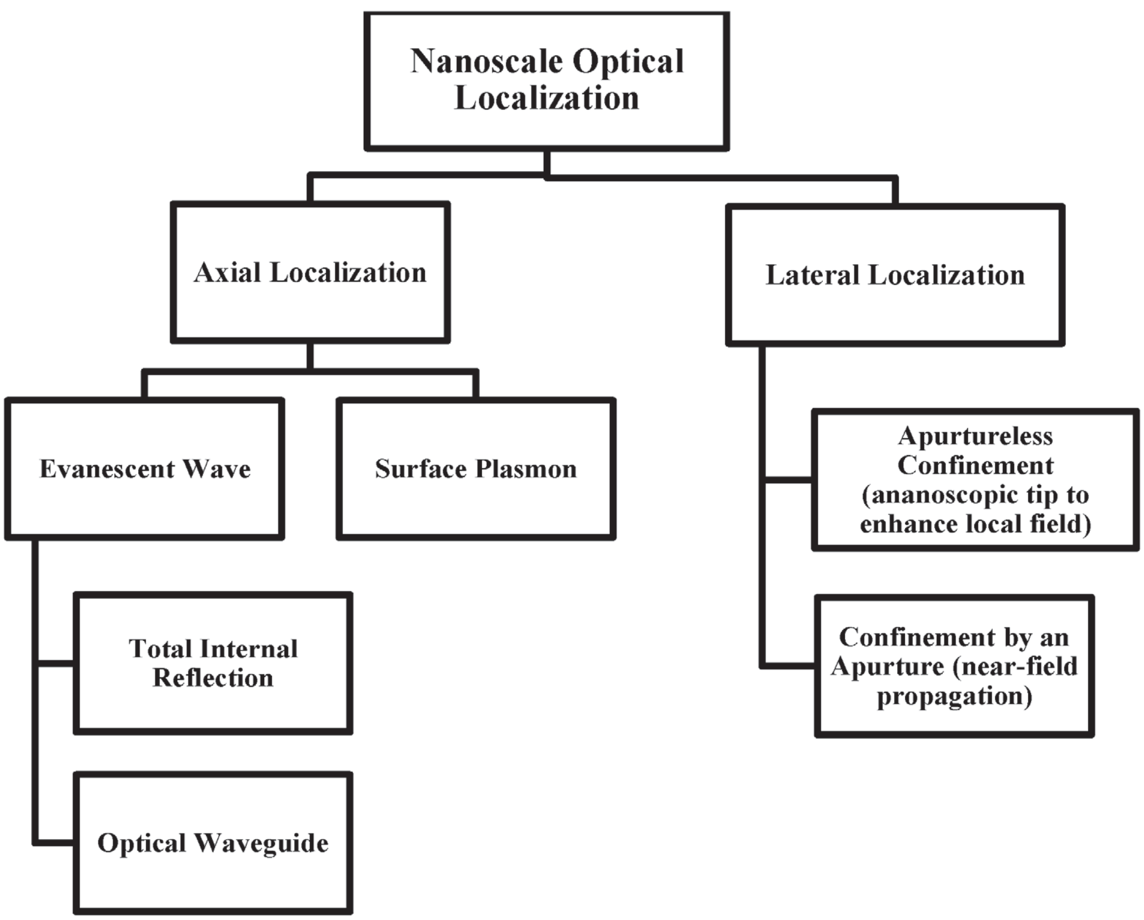

Table 2.
An overview of confining optical interactions at nanoscale.

gradually decaying field intensity in a specific spatial direction that are often encountered. They also do not contribute to energy transfer in that direction; despite the fact that the Poynting vector (averaged over one oscillation cycle) can have non-zero segments in various ways. Evanescent waves can also occur in various types of waves, such as sound waves and quantum-mechanical waves. There are likewise situations where a light field can be disintegrated into an evanescent and a propagating part. A light field may also be disintegrated into an evanescent and a propagating element under some circumstances. As a waveguide surface reaches a lower refractive index medium, an evanescent wave is formed, which decays exponentially in the axial direction (away from the waveguide) and this evanescent field has a magnitude of 50–100 nm that can be used to cause nanoscale optical interactions as well as evanescent wave excitation for high near-field fluorescence sensing [7]. The coupling of two waveguides by an evanescent wave is another example of nanoscale optical interaction, as seen schematically in **Figure 2(a)**, in which photons are launched from one waveguide to another, and these evanescent wave-coupled waveguides can be used as directional couplers in an optical communication network to relay signals. It has also been proposed that evanescent wave-coupled waveguides be used for sensor applications, where sensing induces a transition in photon tunneling from one waveguide channel to the next. There are optical sensors for specific material species where one can experiment with how a light field, which is essentially directed, such as in a glass structure, is connected to an evanescent field and atoms or molecules in that area will be able to interact with the light field; for example, after being excited by light, they could emit fluorescence [6].

Total internal reflection, which involves the scattering of light through a prism with a refractive index of n1 to an atmosphere with a lower refractive index of n2, is just another illustration of a geometry that produces an evanescent wave [7, 8]. As the incidence angle is small enough, light refracts and passes through the second medium to some degree, such that as the incidence angle reaches a critical angle, the light ray is reflected from the interface, as seen in **Figure 2(b)**.

II.Surface Plasmon Resonance (SPR)

At its most basic form, the Surface Plasmon Resonance (SPR) technique is an extension of the evanescent wave interaction depicted above, in which the waveguide or a metal–dielectric interface replaces the prism. Electromagnetic waves that propagate across the interface between a dielectric organic material and a metal film are known as surface plasmons [9, 10]. Since surface plasmons propagate as a wavevector with a specific frequency band in a metal film, no light may travel across any media, and no direct excitation of surface plasmons can be achieved immediately. The most popular approach for producing a surface plasmon wave is attenuated absolute reflection (ATR).

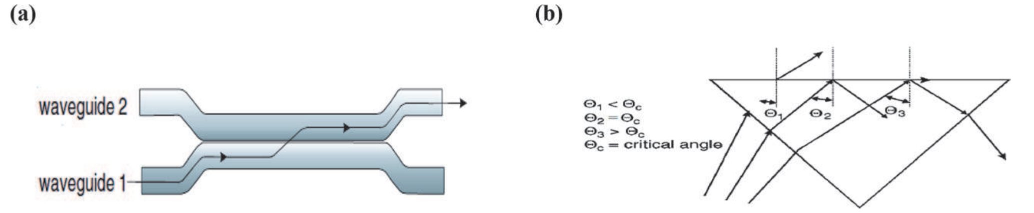

Figure 2.
(a) *Evanescent wave-coupled waveguides* ***(b)*** *principle of total internal reflection [6].*

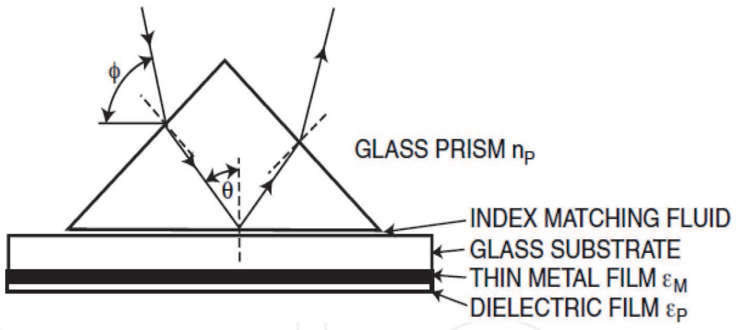

Figure 3.
Excitation of Plasmons using Kretschmann geometry [9].

Figure 3, depicts the Kretschmann structure of ATR, which is commonly used to excite surface plasmons [9].

2.4.2 Lateral nanoscopic localization

A near-field geometry in which the illuminated sample is located within a fraction of the wavelength of light emitted by the source or aperture, can be used to achieve lateral nanoscale light confinement [8, 10] and an electric field propagation around a nanoscopic system generates spatially localized optical interactions. Further, owing to the virtual values of wavevector-like characteristics, the distribution of the spatially localized electric field has a significant evanescent form, that is, it decays exponentially. To study near-field geometry, a near-field scanning optical microscope (NSOM) with aperture based and appertureless configurations may be used, and an aperture-based NSOM uses a submicron-sized 50–100 nm aperture, near to the tapered optical fiber's opening tip, utilized to keep light confined, while an apertureless structure maximizes the local field by a nanoscopic metal tip or a metallic nanoparticle [11].

2.5 Nanoscale confinement of electronic interactions

This section focuses on a few basic examples of nanoscale electronic interactions that cause drastic changes in the optical properties of a material. The results of confining electronic interactions at the nanoscale involve a variety of factors that control them, which are discussed below.

2.5.1 Quantum confinement effects

Quantum confinement alters the optical properties of semiconductors in a number of ways, and these variations have practical applications. As a semiconductor's length is limited to a similar order of exciton radius, i.e. a few nanometers, hence the quantum confinement effect happens. The dimensionality of electrons is reduced by confining them to a thin semiconductor surface, resulting in a dramatic increase in exciton properties and behavior. QuantumDots, Quantum Wires, and Quantum Wells are the three kinds of quantum confined structures that have been described so far based on the function of confinement [6]. The optical transformations caused by different confinements are mentioned in **Table 3**.

2.5.2 Quantum-confined stark effect

The quantum-confined stark effect explains how an applied electric field affects energy levels and thus optical spectra. Quantum-confined devices exhibit major

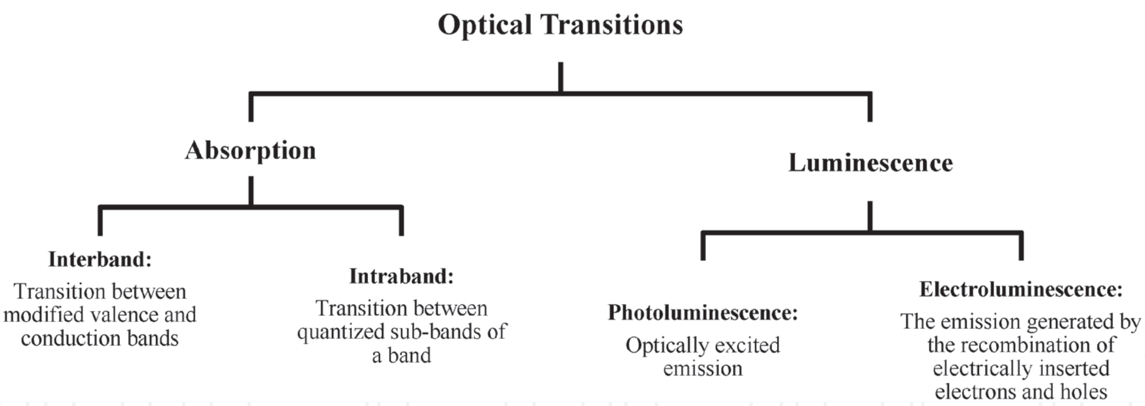

Table 3.
Optical transition under the effect of quantum confinement of electrons at nanoscale.

variations in their optical spectra where an electric field is applied in the direction of confinement [6]. The most important embodiments of quantum confinement effects are mentioned in the **Table 4**.

2.5.3 Dielectric confinement effect

The effects of dielectric confinement can be analyzed by adjusting the restricted semiconductor region's dielectric constant and the confining potential barrier that surrounds it. Since the potential barriers created by compositional changes in a quantum well do not create a large difference in the dielectric constant, this effect is always dispersed. Depending on the processing and fabrication process, a quantum rod, quantum dot, or quantum well may be inserted in another semiconductor or dielectric, such as glass or polymer, and these quantum designs may be characterized by organic ligands, dispersed in a liquid, or merely encompassed by air. When the surrounding medium's dielectric constant is ultimately smaller than that of the confined semiconductor system, such media will exhibit a greater shift in the dielectric constant and significant changes of optical properties due to dielectric confinement [12, 13].

2.6 Nanoscopic interaction dynamics

Controlling the dynamics of local interactions inside nanostructure media that enhance complex radiative transitions is a model accomplished using a nanocrystal host environment with low-frequency phonons to reduce multi-phonon relaxation of excitation energy in order to increase emission efficiency of rare-earth ion's. Since rare-earth ion's electronic transitions are highly susceptible to nanoscale interactions, manipulating the existence of electronic interactions requires only a nanocrystalline media, allowing for the use of a glass or plastic medium in a wide range of device technologies. As discussed further below, nanoscale electrical contacts between two electronic centers result in novel optical transitions and improved optical communications [6]. This sub-section will provide a glimpse of interaction dynamics occurred at nanoscale range.

2.6.1 New cooperative transitions

Two adjacent species may interact through a series of ions, atoms, or molecules to generate optical absorption bands or to allow novel multiphoton absorption

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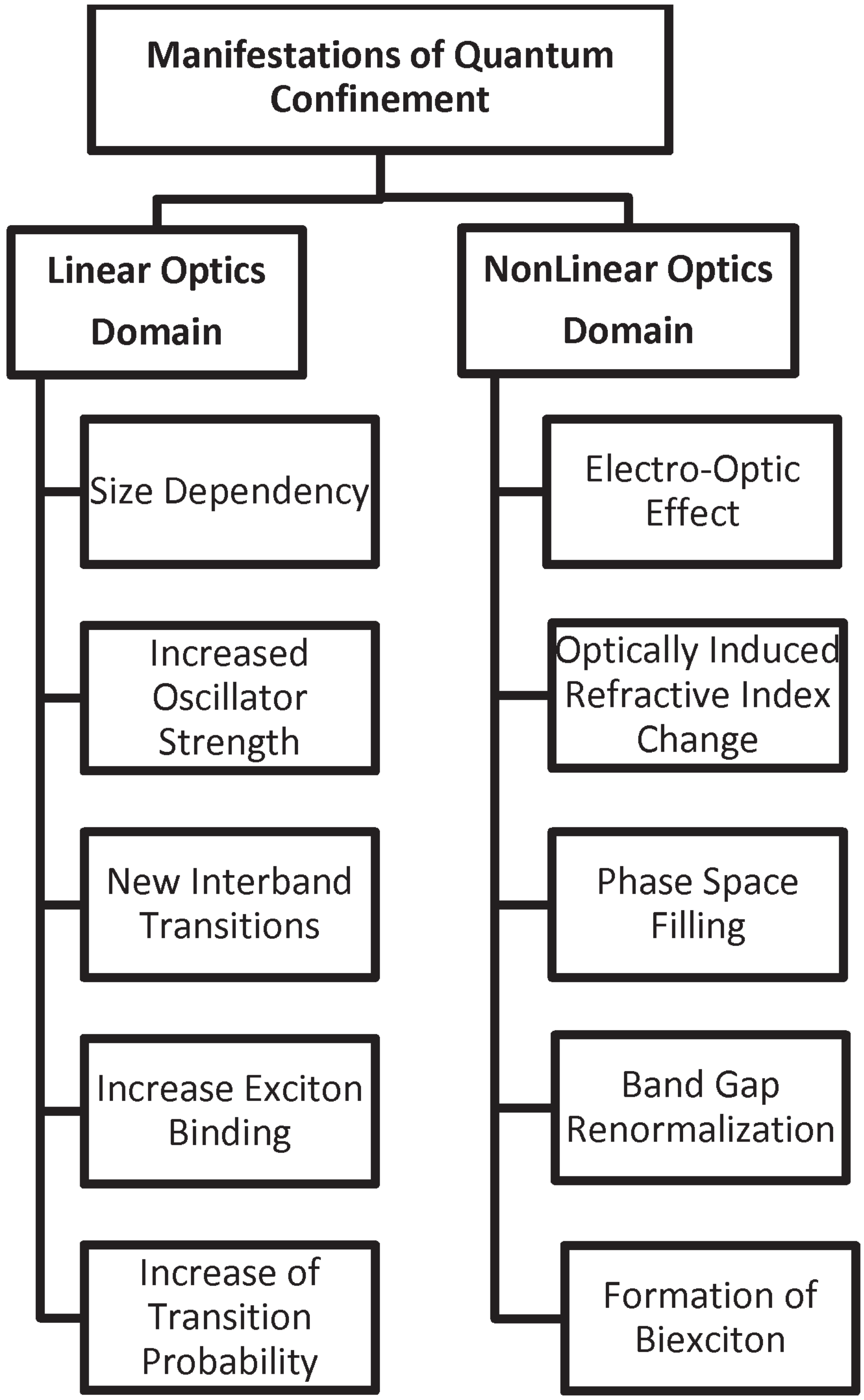

Table 4.
Manifestations observed under the effect of quantum confinement.

processes. The production of biexcitons in a quantum-confined system or a semiconductor yields new optical absorption and emission of lower energy than two individual excitons, and the energy difference correlates to the excitons binding energy. The joining of many excitons to form a multiexciton or exciton string has also been suggested as an expansion of the biexciton principle. In the context of a molecular structure, an example will be the creation of multiple aggregates, known as a J-aggregate of dyes, which is a head-to-head alignment of various dye dipoles [14]. The other kind of nanoscale electronic interaction takes place whenever an electron-donating group or molecule comes into close proximity to an electron-withdrawing group or molecule in nanoscopic space, new optical transitions occur. An organometallic structure is an example of association of an inorganic ion to a wide number of organic groups. Novel optical transformations engaging charge transfer from metal to ligand (MLCT) or, in some situations, light absorption causes a reverse charge transfers, provided by these types of organometallic structures [7]. An intermolecular organic donor (D)–acceptor (A) complex, is another example, which produces charge transfer species D + A in the excited state despite the fact that the constituents D and A are colorless and have no visible absorption. These charge-transfer complexes have clear visible color resulting from recent charge transfer transitions in the visible spectrum [6].

2.6.2 Cooperative emission

Cooperative emission is a manifestation of electronic interactions, which happens when two nearby centers are electronically excited within nanoscopic distances, resulting in a higher-energy photon being released as a result of a simulated state of the pair centers. This mechanism is seen in rare-earth ions, resulting in an up-converted emission of a higher energy photon than the excitation energy of actual ions [6]. The interaction reappears as two neighboring ions are separated by just a few nanometers and based on the form of electronic excitation of the individual ions, the interaction between these two ions can be multipole–multipole or electron exchange. It's worth noting that the emission comes from a virtual level rather than the ion pair's physical level.

2.6.3 Nanoscale electronic energy transfer

Additional electrical energy emitted by an optical transition occurred due to nanoscopic interaction dynamics may be transmitted from one center (atom, ion, or molecule) to the next, typically on a nanoscopic level, though long-range transfer of energy is also possible. This transfer of electrical energy does not require the flow of electrons, but rather the transfer of excess energy. As a result, one center of this mechanism has excess energy in an excited electronic state and serves as an energy donor by passing the excitation to an acceptor, resulting in an electron in the energy donor group becoming excited and returning to the ground state, whereas an electron in the energy acceptor group becomes excited. Exciton migration occurs as a result of interactions between energetically related centers, either coherently by a series of closely spaced levels creating an exciton band or by hopping an electron–hole pair from one core to another incoherently [6]. Fluorescence resonance energy transfer (FRET) is also another form of energy transfer that happens when two different kinds of molecules interact. Fluorescence from the energy acceptor can be detected by optically exciting a molecule to a higher electronic state, and this type of transition is frequently observed with two fluorescent centers separated by a few nanometers. FRET is a widely used bioimaging technique for probing nanoscale interactions between cellular components, such as protein–protein interactions [7]. Throughout this context, one protein may be identified with a fluorescent dye which, once electronically excited by light, behaves as an energy donor. If two proteins are well within 1–10 nm of one another, the other protein is identified as an energy acceptor, and will absorb energy when the two proteins are within this nanoscopic range of distances. This type of energy transfer occurs often in a dipole–dipole interaction with a distance dependency between the energy donor and acceptor. To maximize FRET activity, the donor's emission spectrum and acceptor's absorption spectrum may have significant spectral overlap [6].

3. Computational nano-photonics: standard problems and numerical methods

Nanophotonic structures are diverse, and their physical characteristics are related to one or more observables, that are required for their comprehension and design, including the distribution of an electric field inside a photonic cavity or a nanoparticle's scattering cross section. Depending on the extent of discretization, computational methodologies have been proposed to simulate the functional behavior of complex nanophotonics structures that do not have an analytical solution. This can be translated as approximating a physical problem with a set of appropriate analytical functions defined on a finite or infinite domain. Many common approaches that have been thoroughly studied in the context of computational electromagnetics [15, 16], with some of them have been quantitatively compared or validated to analytical or experimental findings in the field of nanophotonics [17–22]. However, finding functional cases that can equally compare the various numerical approaches remains a challenge. The methodology used to derive the approximated problem has a significant impact on the numerical method's strengths and disadvantages, including the kinds of challenges it is best suited for. Additionally, in comparison to calculating time and memory constraints, the performance of a numerical system requires a variety of other factors, including ease of execution, discretization complexity, and flexibility. Light propagation, localization, scattering, and multiscale problems are known as four types of problems that form the foundation for modeling nanophotonic systems and they can be handled with two categories of versatile approaches: integral (SIE, VIE) and differential (FE, FDTD, and hybrid FD/FE) methods. Time domain methods, like DGTD and FDTD, have now been described as being particularly suitable to light propagation problems, while the FE and SIE approaches are especially effective for problems involving light localization and finally, SIE and VIE based techniques, in addition of RCWA (unique to specific geometries), are well-suited to light scattering problems [23].

3.1 Finite differences in time domain (FDTD)

Due to the ability to tackle a wide range of problems, FDTD approach is one of the most common methods in nanophotonics [24]. A staircase approximation is used in this technique to define the volumes of the nanostructure, superstrate, and substrate that have both space and time discretized, and finite difference quotients are used to replace both spatial and temporal derivatives of Maxwell's curl Equations [15, 25]. The famous algorithm proposed by Yee [26] is an example of FDTD method in addition to numerous other approaches [15, 24, 25].

3.2 Finite elements (FE)

The finite elements (FE) method is another widely used differential technique in nanophotonics for calculating an effective frequency-domain electromagnetic field. The finite elements in time-domain (FETD) approach and the Discontinuous Galerkin time-domain (DGTD) method are two hybrid strategies that rely on the inside of each element, the DGTD approach explicitly solves Maxwell's equations and connects them to a quantitative flux [27, 28]. In a similar way to FDTD, the central difference principle can be used to discretize in the time domain. This approach allows for the use of higher level expansion and checking functions, as well as the local solution of equations in every element, resulting in high accuracy by combining high-order FE precision with a time-domain classification, allowing it to be used for large structures [29].

3.3 Volume integral methods

Volume integral (VIE) methods are used to determine the electric field on a smaller scale by modifying Maxwell's equations to integral form, and the numerical equations associated with these integral solutions can be obtained in a variety of different ways. The discrete dipole approximation (DDA) is a common implementation of the vectorial wave equation that can be used to derive numerical equations [30, 31].

3.4 Surface integral methods

Surface integral methods restrict an electromagnetic scattering problem with open boundary conditions to the surface limits of the substance. As a consequence, commonly used methods to piecewise homogeneous media, such as the boundary element method (BEM) [32] and the SIE method [20, 33], are best suited. The SIE process, like the FE and VIE methods, will specifically treat dispersive materials as a frequency-domain method [34].

3.5 Other methods

The hybrid differential–integral approaches are particularly useful in dealing with inhomogeneous scatters or anisotropic [27], and are an alternative to the integral and differential methods to solve Maxwell's equations. Brief overview of other methods used for simulation of nanophotonics includes;

3.5.1 Finite integration technique

The finite integration technique (FIT) is an integral form discretization scheme of Maxwell's Equations [35]. Unlike integral and differential approaches, which may cover a wide variety of structures, few other methodologies are considered to be very effective for unique conditions and geometries since they depend on electromagnetic field expansions on basis functions with specific symmetries [23].

3.5.2 T-matrix system

The incident and scattered electromagnetic fields are extended on a series of spherical basis functions in the T-matrix system, with boundary conditions imposed at the interfaces of the different materials. This approach excels at measuring the scattering of spherical and/or quasi-spherical particles [36] and extended to plasmonics, layered particles as well as particle-substrate interactions with applications in sensing, plasmonic trapping, and SERS [37, 38].

3.5.3 Multiple multipole approaches

The generalized multipole method is a semi-analytical technique, also known as the multiple-multipole approach that is used to extend the electromagnetic field in multipoles, allowing it to handle a wide variety of symmetries [39, 40]. In this method, only the domain boundaries are discretized and no integral is numerically solved. Multiple elastic scattering of multipole expansions disintegrates dispersed fields to multipoles with respect to centers near each cluster object, and this occurs until cluster convergence [41, 42].

3.5.4 RCWA approach

The RCWA uses intermittent grating systems to diffract electromagnetic waves. The periodic permittivity and electromagnetic field are expanded as Fourier series, and material boundaries are improved with boundary conditions [43], resulting in poorly produced abrupt surfaces with a large number of Fourier harmonics. This method is highly reliable for computing far-field reflection, propagation coefficients, and diffraction orders, while calculating the near field at material boundaries remains challenging [44].

4. Peculiarities of nonlinear optical phenomena in nano-photonics

Nonlinear Optics is the analysis of the mechanisms that occur as light manipulates a material's optical properties. Franken et al. [45] discovered second-harmonic generation soon after revealing the first working laser by Maiman in 1960 [46], and it is widely regarded as the start of the field of nonlinear optics. The discovery of saturation results in the luminescence of dye molecules identified by G. N. Lewis et al. [47] is the earliest known example to the author's. This section will explore the peculiarities of nonlinear optical phenomena in nanophotonics by including an overview of active nanophotonic devices, gain materials, plasmonic nanostructures, metamaterials, quantum dot lasers, and optical amplifiers.

4.1 Active nano-photonic devices

Active materials have recently appeared as a potential loss compensation technique, first in nanoparticles, metamaterials, and plasmonic waveguides, and then in novel functionalities such as signal amplification and lasing in the field of nanophotonics [48]. It's important to note that in nanophotonics, the word "active" refers to the manipulation of material properties like refractive index in phase-change materials to regulate or reorganize plasmon propagation. Nanolasers and surface plasmon amplifiers have piqued the attention of researchers since they enable the theory of coherent stimulated emission to be applied to the diffraction limit and beyond. The notion of a SPASER [49], acronym of "surface plasmon amplification by stimulated emission of radiation", was originally designed to amplify oscillating localized surface plasmons (LSP's), inside metal nanoparticles and it was eventually expanded to add traveling surface plasmon-polaritons (SPP's). Aside from their significance in optoelectronic and all-optical data processing, they are also used in sensing, biological and super resolution imaging [50].

4.2 New gain materials

Gain materials and parametric amplification through nonlinear effects are the key approaches for achieving optical gain in active systems. The standard active nanophotonic device scenario is depicted in **Figure 4**, in which a lossy resonator is surrounded by an active material and a bulk gain material may be used to explore this arrangement such as halide perovskite, chromophore, QD's scattered with metallic and/or dielectric nanoparticles or a gain material layer surrounding a nuclei core [50]. Material nonlinearity has been successfully used in metamaterials [51]

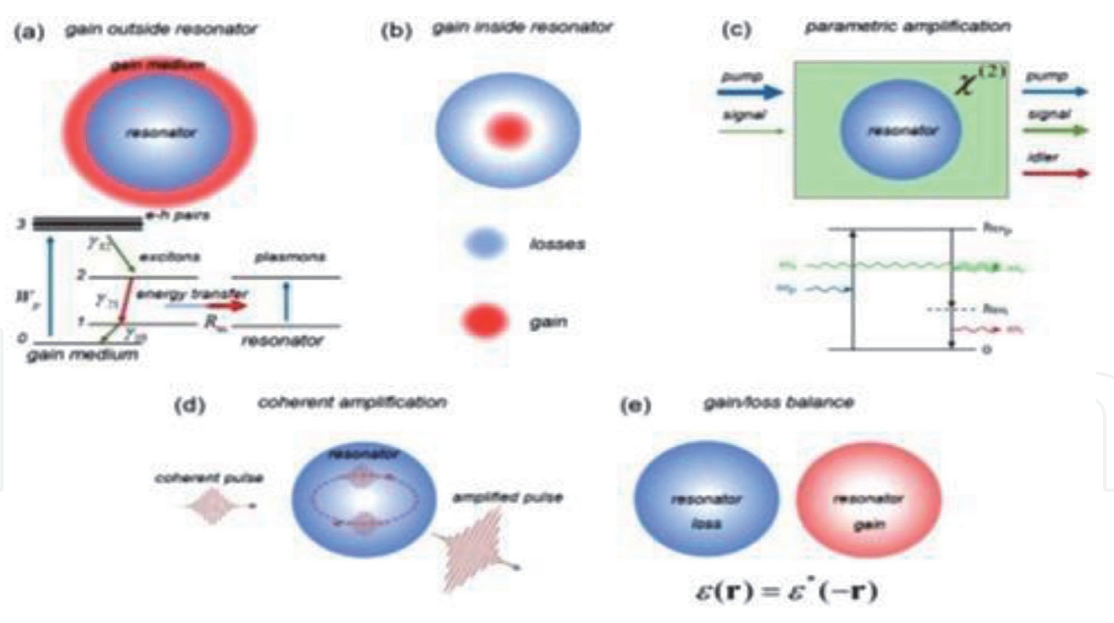

Figure 4.
Multiple approaches used for representation of active nanophotonics [50].

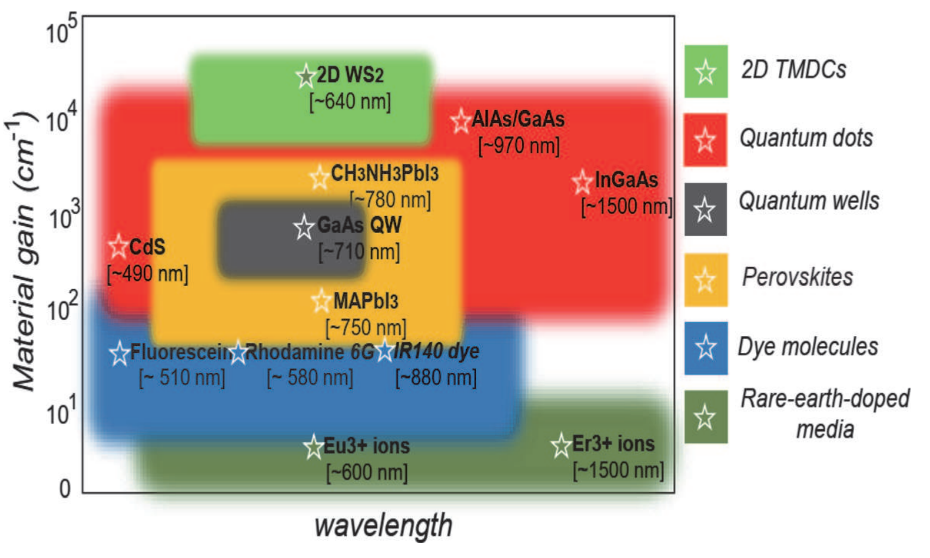

Figure 5.
Material gain parameter achieved for rare earth doped and other materials [50].

and nanostructures [52] for loss correction using optical parametric amplification (OPA), while coherent amplification, which is based on pulse amplification within a cavity through positive interference, may provide gain and has recently been suggested for loss compensation in plasmonics [50]. The achievable material gain parameter of prospective materials for nanolasers including transition metal dichalcogenides (TMDCs), quantum dots, quantum wells and perovskites is shown in **Figure 5** while **Figure 6** depicts an overview of new materials for nanolasers.

4.3 Nonlinear optics in plasmonic nanostructures

Metallic plasmonic structure, such as nanoparticle, optical diffraction grating, and nano-aperture, is one well-known and commonly studied method to vastly enhance the efficiency of optical near-field as well as nonlinear optical interactions at the nanoscale, whereas their role is threefold in nonlinear optics; (i) to increase the effect of nonlinearity (ii) to reduce the size of nonlinear components (iii) to have an ultrafast response time, allowing optical signals to be manipulated on

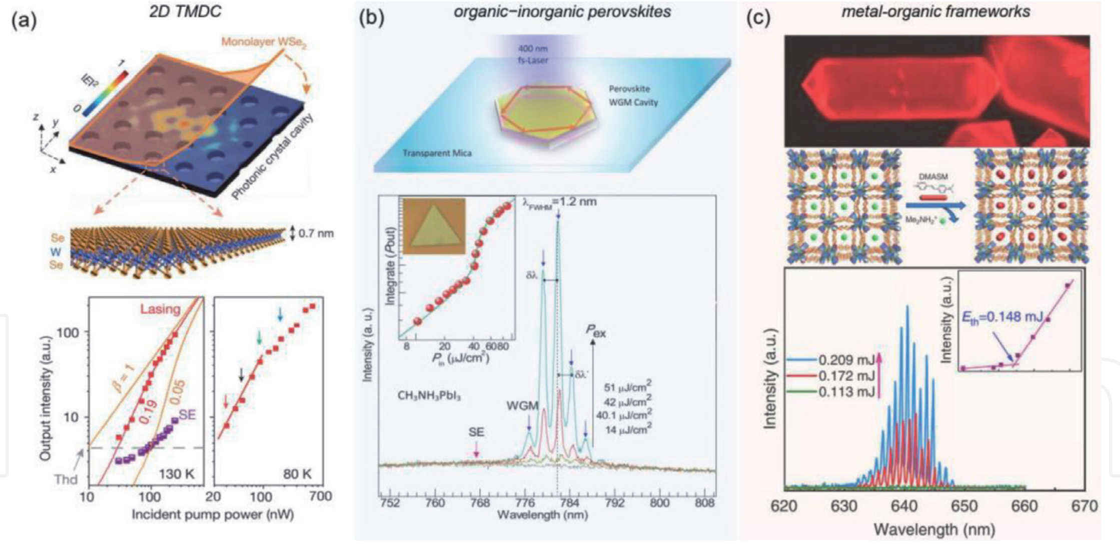

Figure 6.
An overview of new materials for nanolasers [50].

femtosecond timescales [53]. In plasmonics, metal dielectric interfaces support surface plasmon polaritons (SPP's) [54], which are p-polarized strongly scattered surface waves associated with oscillations of free electrons in metals, powerful spatial confinement and enhancement in the electric field occur at the interface between the two media following the production of these localized or propagating modes. Owing to the near confinement of the optical field of SPP's, surface effects at metal dielectric interfaces are especially sensitive to variations in the shape of plasmonic nanostructures and the dielectric properties of the embedding optical media. Surface plasmon-polariton modes have been suggested to limit the scale of lasers to sub-wavelength dimensions with the increase of plasmonics. Population inversion of emitters (QD's, fluorophore's) and feedback generated by plasmonic resonant structures are used to achieve lasing in such plasmonic-based structures. The development of new types of nano-resonators and active materials led to the development of a family of nanolasers that drew a lot of interest from the nanophotonics world [48, 50].

4.4 Nonlinear plasmonic metamaterials

Plasmonic metamaterials have potential prospects for all optical switching by tailoring the constituent's plasmonic resonances and the electromagnetic coupling between them. Both individual plasmonic resonances and their interactions can be altered as a function of variation in refractive index of the embedding dielectric or substrate, resulting in better nonlinear reactions. By controlling the binding power of molecular excitons, plasmonic excitations will result in effective all-optical modulation, and plasmonic metamaterials give a novel way to increase nonlinearity using epsilon-near-zero regime 'nonlocal' effects [53].

4.5 Quantum dot lasers and optical amplifiers

Quantum Dot (QD) based semiconductor optical amplifiers (SOA's) demonstrate ultrafast gain dynamics and pattern effect free amplification, both theoretically and experimentally [55]. Mode-locked (ML) lasers can be used as optical comb generators for high-frequency applications including time domain multiplexing because of its low alpha factor and wide spontaneous emission range of the quantum dot gain medium [56].

5. Nanophotonics: applications

5.1 Biomaterials and nanophotonics

Material engineers found biological structures to be a fertile ground, allowing for the creation of innovative nanotechnologies for a broad range of applications. Bioprocesses generate nearly flawless nanostructures that are biodegradable and can be used for efficient solar energy harvesting, filtering, high-density data storage, low-threshold lasing, and optical switching. For a wide range of photonic features, both active and passive nanophotonics systems can be employed in a wide range of biomaterials [6]. The four types of biomaterials are as follows;

i. Bio-derived materials have unrivaled molecular-level power for fine-tuning properties at both the single-molecule and bulk scales. Interdisciplinary approaches are needed for the design and engineering of bio-derived materials that use proteins, sugars and lipids as building blocks.

ii. Bio-inspired materials are synthetic nanostructures, produced by mimicking natural biological material synthesis processes using biological principles, whereas, biomimicry is a growing discipline that focuses on creating multifunctional hierarchical materials and morphologies that resemble nature and can be used as a light harvesting dendritic framework.

iii. Bio-templates are natural nanostructures with suitable morphologies and surface interactions that can be used as models to create multiscale and multicomponent photonics materials that provide reinforcing sites for photonic active structures to self-assemble.

iv. Bacteria bioreactors for metabolically engineering photonic polymers, where metabolically engineered materials are those generated by manipulating the naturally occurring bacterial biosynthetic mechanism to manufacture a family of helical polymers with a broad variety of optical properties.

5.2 Nanophotonics for biotechnology and nanomedicine

Nanophotonics has a wide range of uses in biomedical science and technology, including nanomedicine applications for light-guided and light-activated treatment, and also studies of the fundamentals of interactions and processes at the single cell/molecule level. Nanomedicine is a developing discipline that focuses on the use of nanoparticles in the creation of novel noninvasive diagnostics for early disease detection, as well as for promoting selective drug distribution, treatment efficacy, and real-time drug tracking. A thorough understanding of drug–cell interactions, with an emphasis on molecular modifications at the single-cell level caused by the pre-onset state of a disease, can be used to develop "personalized" clinical treatments for disease control focused on molecular identification. Using optical methods, nanophotonics helps one to map drug consumption, clarify the cellular mechanism, and track subsequent cytosolic interactions. For this reason, biosensing, bioimaging, and single-cell biofunction trials utilizing optical probes are particularly beneficial. Light-guided and light-activated treatments have made significant progress in the field of nanomedicine-based molecular disease identification. Nanoparticles are now

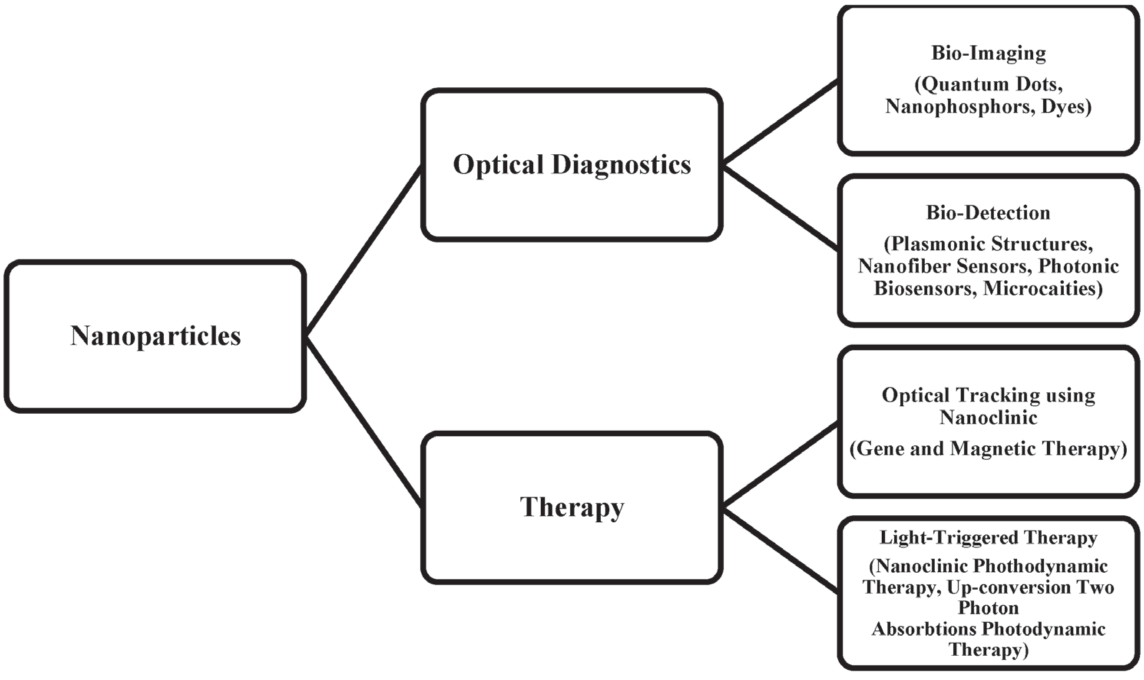

Table 5.
A glimpse of optical nanomaterials potential applications.

equipped with optical probes, advanced carrier groups, and light-activated therapeutic agents capable of guiding the nanoparticles to diseased cells or tissues to allow selective drug delivery and real-time drug efficacy monitoring [6].

5.3 Optical nanomaterials

At the moment, the most well-established applications for optical nanomaterials are in very low-tech applications such as sunscreen lotions and optical coatings, although many high-tech industrial solutions have recently emerged, including signal processing and photonic crystals for complex optical circuitry, as well as sensors for detecting and responding to chemical and biological challenges [6]. Several new companies have emerged to produce next-generation solar cells based on the nanoparticle principle, but they are still in the early stages of growth. Nanoparticles have also been shown to be useful in optical diagnostics, light-activated treatments, as well as in optical communication initiatives [6]. **Table 5** illustrates graphical applications of nanostructures in optics.

6. Conclusions

The nanoscale interaction dynamics and confinement of photons and electrons were depicted in this chapter, which served as fundamentals of nanophotonics. The foundation for modeling nanophotonic structures, as well as the methodologies used to tackle issues at the nanoscale regime, such as light propagation, scattering, localization, and multiscale problems, have been frequently discussed in terms of two forms of versatility. Nanophotonic structures are used in a wide range of applications, including nanomedicine, biomaterials, biotechnology as well as optical diagnostics, and they are the spark for the next forefront of economic development.

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