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Recent trends in micro- and nanophotonics: A personal selection

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I give a brief overview of some recent results in micro- and nanophotonics. Due to the vast amount of research activity in these exploding areas I only concentrate on selected recent advances in (a) silicon photonics, (b) spatial and spatiotemporal optical solitons (alias light bullets) in microwaveguide arrays and in arrays of evanescently-coupled silicon-on-insulator nanowires, (c) spatial solitons in photorefractive materials, (d) nanoplasmonics, (e) photonic crystals, (f) metamaterials for micro- and nanophotonics including optical materials with negative refractive indices, (g) terahertz radiation and its applications, and (h) solid-state single photon sources and nanometric size optical cavities for quantum information processing.

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1. Introduction

The term "*photonics*" was coined in 1967 by Pierre Aigrain, a French scientist, who gave the following definition: "*Photonics is the science of the harnessing of light. Photonics encompasses the generation of light, the detection of light, the management of light through guidance, manipulation, and amplification, and most importantly, its utilization for the benefit of mankind*". In brief, photonics is the science of generating, controlling, and detecting photons and therefore *nanophotonics (nano-optics)* studies the unique behaviour of light at a nanometer scale (see, for example, two excellent introductory books [1]-[2] on this topic). Correspondingly, *microphotonics (micro-optics)*, deals with the behaviour of light at a micrometer scale.

Microphotonics and nanophotonics are now deemed new technologies whose time has come and that threaten to displace the existing technological solutions; emerging applications are envisaged in diverse areas such as information processing, high-speed data communication systems, imaging, lighting, displays, manufacturing, life sciences and health care, safety and security, etc.

This brief overview of recent trends in micro- and nanophotonics is organized as follows. In Sec. 2 I overview the recent advances in silicon photonics. Hot research topics such as silicon photonic nanowires, semiconductor quantum dots and silicon-organic slot waveguides for light emission, detection, guiding and control are discussed. Also, I briefly discuss recent progress in the study of both spatial and spatiotemporal optical solitons (alias light bullets) in microwaveguide arrays, and of spatial solitons in photorefractive materials.

The problem of light confinement in nanostructured noble metals is addressed in Sec. 3. Key issues of nanoplasmonics, such as ultrafast active plasmonics, plasmonic solar cells, surface plasmon resonance sensors for biosensing and chemical sensing applications, ability of metal nanoparticles to act as efficient pointlike sources of both light and heat, and subwavelength plasmonic lattice solitons in arrays of metallic nanowires embedded in nonlinear Kerr media will be briefly discussed.

Section 4 is devoted to recent advances in the study of photonic crystals and metamaterial structures (including engineered media with negative refractive indices). I briefly discuss the achievement of negative refractive index three-dimensional optical metamaterials with a very high figure of merit having a cascaded 'fishnet' structure and the demonstration of an engineered metamaterial made of alternating layers of negatively refracting (a silicon photonic crystal) and positively refracting (air) materials that strongly collimates a beam of near-infrared light at the telecommunication wavelength of 1550 nm. I also consider the issue of fabrication of low-loss plasmonic metamaterials made of semiconductors such as InAs-heterostructures for applications in mid-infrared frequency range.

In Sec. 5 I briefly overview a few recent studies of terahertz radiation and its various applications. The close link between nanophotonics and quantum information processing is discussed in Sec. 6. Finally, Sec. 7 concludes this paper.

2. Silicon photonics

In brief, *silicon photonics* is the photonic technology based on silicon chips. The highest impact of silicon photonics can be in optical interconnections between digital electronic chips [3]-[5]; for a collection of up-to-date articles on silicon photonic components and their integration, see the recent book [5]. In this Section I will only concentrate on all-optical high-speed signal processing with silicon-organic hybrid slot waveguides, periodically poled silicon, cladding-modulated Bragg gratings in silicon waveguides, light emission in silicon slot waveguides, enhancing nonlinearities in silicon photonic slot waveguides, and the possibility of light bullet formation in silicon-on-insulator (SOI) nanowires.

Silicon (Si) has an indirect bandgap meaning that the upper and the lower electronic states (conduction and valence bands) do not occur at the same value of the crystal momentum. It is worth mentioning that light can penetrate much farther before being absorbed in an indirect-band gap material than in a direct-bandgap one and this fact is crucial for photovoltaics (solar cells). However, silicon is still the most used solar-cell material, despite the fact that it is an indirect-bandgap semiconductor and therefore does not absorb light very well. It is well known that silicon is transparent in the fiber optic communication bands around 1300 nm and 1550 nm because the corresponding photon energies are less than the bandgap, which is about 1.1 eV for Si. Notice that persuading silicon to perform various photonic functions can bring optical communication to the world of chip interconnects, see Refs. [3]-[5]. Envisioned are silicon chips that communicate internally, or with other chips, using photons, in order to avoid the bandwidth limitation imposed by commonly used metallic interconnects. Other emerging applications include, e.g., low cost transceivers for 10 to 100 Gbit/s Ethernet (a transceiver is a device that has both a transmitter and a receiver which are combined and share common circuitry or a single housing), a new platform for mid-infrared photonics, and optically assisted analog-to-digital conversion, see Refs. [3] and [4]. Optical amplification and lasing, once considered forbidden in silicon, have been achieved in recent years. Silicon's nonlinear optical properties, enhanced by tight optical confinement in Si/SiO_2 structures, i.e., SOI nanostructures, are producing wavelength generation and conversion, which are central functions in multi-wavelength communications and signal processing [3]-[5]. The SOI technology, which refers to the use of a layered silicon-insulator-silicon substrate in place of conventional silicon substrates in semiconductor manufacturing is a key technology in both micro- and nanoelectronics and in micro- and nanophotonics.

A second key technology in nanophotonics is the scanning transmission electron microscopy (STEM) for nanoscale visualization. STEM is a special technique in which an electron transparent sample is bombarded with a finely focused electron beam (with a diameter of less than 10 nm) that can scan across the sample. This technique provides high resolution imaging of both inner structure and surface of a thin sample, as well as the possibility of chemical and structural characterization of both micrometer and nanometer sample domains through the evaluation of the X-ray spectra and the electron diffraction pattern. In a scanning transmission electron microscope, the size of the electron probe that is focused onto the specimen ultimately limits the spatial resolution. The resolution of a scanning transmission electron microscope is limited by the electron's de Broglie wavelength, e.g., for 300 kV electrons that limit is about 2 pm. Typically, the resolution is about 100 pm (about half the distance between atoms in some crystals) due to spherical aberration of electromagnetic lenses and finite size of electron source. Recently, by using a highly coherent focused electron probe in a fifth-order aberration-corrected transmission electron microscope, a crystal spacing of 50 pm was resolved [6].

It is believed that the highest impact of silicon photonics will be in high-speed data communications; consequently, most of the research has been aimed at producing sources of photons, electro-optic modulators, and photodetectors, see Refs. [3]-[5]. A fundamental problem with Si is its lack of a static dipole moment, a consequence of its centrosymmetric crystal structure. This means that the linear electro-optic (Pockels) effect, that unique phenomenon that makes lithium niobate ($LiNbO_3$) and III-V semiconductors good electro-optic materials, is absent in Si. However, Si is not able to detect signals at standard communication wavelengths of 1300 nm and 1550 nm because such photon energies are less than its bandgap. Yet these wavelengths represent standard telecommunication bands because optical fibers, to which devices must eventually interface, have low propagation losses in these frequency bands (about 0.2 dB/Km). The silicon's inability to absorb these wavelengths has been overcome by taking advantage of the small bandgap of germanium (Ge) grown on silicon. Raman scattering (a phenomenon that describes interaction of light with atomic vibrations of the crystal) and Kerr effect are two examples of nonlinear optical phenomena that only appear when silicon is pumped with high intensity laser light (intensities $I>10$ MW/cm^2). To avoid generating electrons and to prevent free carrier absorption, these devices use infrared light (at 1500 nm), so that the photon energy is less than the bandgap of silicon. However, because of high intensities involved, two-photon absorption occurs [7]. In the past years there has been important progress in the search for light amplification in silicon. Stimulated Raman scattering (SRS) was also reported in SOI waveguides [8]. In these seminal experiments, amplification of the Stokes signal, at 1542.3 nm, of up to 0.25 dB has been observed in such SOI waveguides, using a 1427 nm pump laser with a continuous-wave power of 1.6 W. It was also shown that the two-photon-absorption effects were found to be negligible at the pump power where SRS was observed [8].

A hot topic in nanophotonics is the study of semiconductor nanostructures in the form of both *quantum dots (QDs) and nanowires* for emission, detection, guiding and control of light [9]-[10]. It is to be mentioned that the large optical nonlinearities and the possibility of control of both linear and nonlinear optical properties by the size of the quantum dots are of special interest for emerging applications in integrated nanophotonic devices. In a recent work [11] saturated near-resonant refractive optical nonlinearities in CdTe quantum dots were reported. Thus, by using a continuous-wave laser excitation in a Z-scan experimental setup, it was observed the presence of saturated Kerr-type nonlinear optical properties of thiol-capped CdTe quantum dots, at low intensity levels [11];

see also Ref. [12] for a study of optical limiting and phase modulation in CdTe nanocrystal devices.

The quantum efficiency of the absorption on quantum confinement levels in spherical QDs was recently investigated [13]. It was shown that the size of QDs (with radius of about 1-3 nm) leads to negligible many body effects. For silicon QDs with radius of about 2.5 nm, which are embedded in amorphous silica, it was proved that the absorption threshold shifts toward the far infrared limit and that the spectral internal quantum efficiency reaches 4-5% at the threshold, see Ref. [13]. Semiconductor QDs, which are robust and bright light emitters, have also captured special interest in life-sciences, such as biology and medicine, namely their capability for microorganism labeling, see e.g., Ref. [14]. The synthesis and characterization of CdS semiconductor QDs for potential use in bio-imaging were recently reported [15]. Photoluminescence characteristics of the CdS nanocrystals were investigated by using two-photon excitation laser scanning microscopy [15].

Silicon photonic nanowires [7] can be used for on-chip communication and control and for chip-to-chip communications. These ultra-small silicon light guides can be used as miniature chip-scale waveguides for transmitting data signals at very high bit rates (greater than 1 Tb/s). Diverse applications of semiconductor nanowires in the areas of optical waveguides, reconfigurable optical add-drop multiplexers, lasers (both optically pumped and electrically pumped), all-silicon lasers, photodetectors, antireflection coatings, sensors (biosensors), photovoltaics, quantum optics (single photon sources), and for creating efficient tunable nanoantennas (optical antennas) are now emerging. Recently, all-optical high-speed signal processing with silicon-organic hybrid slot waveguides has been achieved [16]. It was fabricated a 4-mm-long silicon-organic hybrid nanowaveguide with a record Kerr nonlinearity parameter of 10^5 W^{-1} km^{-1}, which performed all-optical demultiplexing of 170.8 Gb/s to 42.7 Gb/s. This is, to the best of my knowledge, the fastest silicon photonic optical signal processing demonstrated up to date. The performance of both planar and wire-like silicon slot waveguides (Si/SiO_2/Si nanometric size slot waveguides) as key components of on-chip light sources was recently investigated [17]; it was obtained the spontaneous emission enhancement and waveguide coupling ratio for typical optical dopants such as Er in the low refractive index slot region containing SiO_2. It is worthy to mention that the enhanced luminescence efficiency and the strong coupling into a limited set of well-defined waveguide modes enables a new class of power-efficient waveguide-based light sources, which are compatible with complementary metal-oxide-semiconductor (CMOS) technology [17].

The electrical behavior of a multi-walled *carbon nanotube* network embedded in amorphous silicon nitride was recently studied by measuring the voltage and temperature dependences of the current [18]. The current-voltage curves present oscillations that are interpreted as due to percolation processes. The voltage percolation thresholds were related to the conductance minima, see Ref. [18]. Also, structural investigations of Ge nanoparticles embedded in an amorphous SiO_2 matrix were reported by using transmission electron microscopy and X-ray photoelectron spectroscopy [19]. Notice that the morphology of Si nanocrystallites embedded in a SiO_2 matrix was reported in a previous work performed by the same research group [20]. Studies of nanocomposite iron/porous silicon were performed [21], which revealed that the iron compounds are distributed both inside the pores' network and in the silicon skeleton [21]. Surface acoustic wave sensors with carbon nanotubes and SiO_2/Si nanoparticles based nanocomposites for volatile organic compunds detection were fabricated and experimentally studied [22]. Also, it was achieved the fabrication on thin aluminium nitride layers deposited by magnetron sputtering on high resistivity (100) oriented silicon substrates of surface acoustic wave resonators operating at 5 GHz [23]. It is well known that, as a centrosymmetric crystal, bulk silicon lacks second-order optical nonlinearity, which is the key element in nonlinear optics applications. Hence, its lowest-order optical nonlinearity originates from the third-order susceptibility, which gives rise to both Raman and Kerr effects. Conventional poling processes, such as those used for $LiNbO_3$ and nonlinear polymers do not apply to silicon because as it was said above it lacks second-order optical nonlinearity in its native form. However, a new class of photonic devices based on periodic stress fields in silicon that enable second-order nonlinearity as well as quasi-phase matching was recently proposed [24]. The periodically poled silicon waveguide is covered by a SiN cladding causing compressive stress and a SiN film is deposited astride the waveguide causing tensile stress. Numerical simulations reported in Ref. [24] show that mid-wave infrared radiation can be efficiently generated through difference frequency generation from near-infrared radiation with a conversion efficiency of up to 50%. This can be achieved with a 20-ps pump pulse with wavelength λ=1300 nm and peak intensity of 1 GW/cm^2 [24]. A cladding-modulated Bragg grating using a periodic placement of silicon cylinders along a waveguide was designed, fabricated and experimentally validated using a SOI material platform [25]. The coupling strength of the cladding-modulated distributed resonant structure was varied by changing the distance between the silicon cylinders and the waveguide. The period of the cladding modulation was chosen to satisfy the Bragg condition at a wavelength of about 1550 nm for the TE-polarized mode and the waveguide cross section was chosen to be single mode at this wavelength [25]. Recently, it has been proven by numerical simulations that by exploiting the advantages of the horizontal silicon slot waveguide structure the nonlinear interaction can be significantly increased compared to vertical slot waveguides [26]. Thus it has been shown that an optimized horizontal slot waveguide structure containing a 20 nm thin optically nonlinear layer with low refractive index sandwiched between two silicon photonic wires of 220 nm width and 205 nm height could enable a large Kerr nonlinearity coefficient of 2×10^7 W^{-1} km^{-1} [26]. Also, it is worthy to mention that studies of both linear and nonlinear (third-order) optical properties of nano-porous silicon were recently reported [27].

In the past decade there was a lot of activity in the area of both linear and nonlinear properties of engineered one- and two-dimensional *optical lattices* (e.g., both one- and two-dimensional microwaveguide arrays); see, for example Refs. [28]-[30]. Theoretical and experimental studies in the area of *optical discrete solitons* were recently overviewed [31]-[32]. These discrete solitons represent self-trapped wavepackets in nonlinear periodic structures, such as one- and two-dimensional nonlinear waveguide arrays, and they result from the interplay between lattice diffraction (or dispersion) and material optical nonlinearity. This class of self-localized structures has been experimentally observed in both one- and two-dimensional nonlinear photonic lattices (one- and two-dimensional nonlinear waveguide arrays). Theoretical and experimental studies of solitons' shapes and their mobility control in various kinds of optical lattices were also recently reviewed [33].

Another issue of much interest in the past two decades was that of *photorefractive spatial solitons* in various physical settings. The self-trapping of optical beams in photorefractive media was studied both theoretically [34] and experimentally [35]. However, from the point of view of practical applications lithium niobate is one of the key materials for the fabrication of both micro- and nanooptical waveguides, optical modulators and various other linear and nonlinear optical devices. Photorefractive screening-photovoltaic solitons were observed in lithium niobate [36]. Thus two-dimensional bright circular spatial optical solitons (self-confined optical beams) form due to a strong static bias field, externally applied, opposite to the photovoltaic internal field [36]. Moreover, the formation of self-confined beams in erbium-doped lithium niobate was observed [37]. Also, a very general dependence of the self-trapped beam waist on the refractive index change was experimentally derived, which is valid for every lithium niobate crystal, independent on its growing procedures or doping [37]. Arrays of soliton waveguides in lithium niobate for parallel coupling were also investigated [38].

A hot topic in micro- and nanophotonics is the study of *spatiotemporal optical solitons*, alias “light bullets” [39]-[50], which are spatially confined pulses of light, i.e., electromagnetic wave packets self-trapped in both space and time. These nondispersing and nondiffracting light structures could be used as natural information carriers. The term “light bullet” arises because the spatiotemporal optical soliton can be thought of as a tiny bead of light propagating long distances without changing its shape. It is believed that the “light bullets” are the ideal information units in both serial and parallel transmission and processing information systems. Recently, the first observation of three-dimensional light bullets in two-dimensional arrays of coupled waveguides was reported [51]. These genuine three-dimensional spatiotemporal solitons were excited by femtosecond pulses in a system featuring quasi-instantaneous cubic nonlinearity and a periodic, transversally modulated refractive index. It was shown earlier that arrays of evanescently coupled waveguides support stable light bullets in a limited domain of their existence range [52]. The recent experimental work [51] also confirmed the necessity of a finite energy threshold for the existence of stable three-dimensional discrete-continuous light bullets [52].

As concerning another possible practical implementation of the light bullet concept we mention here a realistic physical setting based on *silicon photonic nanowires*. The conditions for low-power spatiotemporal soliton formation in arrays of evanescently-coupled SOI photonic nanowires have been thoroughly analyzed recently [53]. It was shown that pronounced soliton effects can be observed even in the presence of realistic loss, two-photon absorption, and higher-order group-velocity dispersion (GVD). The well established SOI technology offers an exciting opportunity in the area of spatiotemporal optical solitons because a strong anomalous GVD can be achieved with nanoscaled transverse dimensions and moreover, the enhanced nonlinear response resulting from this tight transverse spatial confinement of the electromagnetic field leads to soliton peak powers of only a few watts for 100-fs pulse widths (the corresponding soliton energy being only a few hundreds fJ). The arrays of SOI photonic nanowires seem to be suitable for the observation of both bulk and surface light bullets because an adequate design of nanowires can provide dispersion lengths in the range of 1 mm and coupling lengths of a few millimeters (for 100-fs pulse durations) [53]. Both numerical and experimental investigations of spatiotemporal nonlinear optical effects leading to spectral broadening in arrays of subwavelength silicon waveguides pumped with infrared femtosecond pulses were recently reported [54].

Silicon-based plasmonic waveguides as a means to confine and manipulate photonic signals were recently proposed and investigated [55]. Notice that the high refractive index of silicon at telecommunication wavelengths (about 1550 nm) assures strong confinement and a very high level of photonic integration with achievable waveguide separations of the order of 10 nm, see Ref. [55]. The aluminium and copper plasmonic material platforms, make silicon-based plasmonic waveguides fully compatible with the existing mature complementary metal-oxide-semiconductor fabrication technology. It is also possible to compensate the intrinsic surface plasmon propagation losses and to achieve up to 10 Tb/s signal transfer rates, see Ref. [55].

I conclude this Section with a few remarks on recent developments in integrated silicon photonics for “harnessing the digital data explosion”; see a recent brief overview of this hot research area published in March 2011 issue of ‘Optics and Photonics News” [56]. The Intel researchers demonstrated in laboratory conditions that the silicon photonics link reached 50 Gb/s. This 50 Gb/s silicon photonics link is comprised of four basic components: a silicon transmitter chip, a silicon receiver chip, CMOS integrated circuits chips and a passive fiber-optic connector [56]. This integrated silicon photonics link uses wavelength division multiplexing; thus each chip has four optical channels operating at 12.5 Gb/s (the total bandwidth is therefore 50 Gb/s on single fiber), see Ref. [56].

3. Nanoplasmonics

Nanoplasmonics aims to mould light flow at the nanoscale using metallic nanostructures (usually nanostructured noble metals such as Au and Ag) [57]-[64]; for a recent perspective on low-loss plasmonic metamaterials, see Ref. [65]. In this Section I will only concentrate on lasing in metal-insulator-metal subwavelength plasmonic waveguides, plasmonic slot waveguides, ultrafast active plasmonics, plasmonic solar cells, surface plasmon resonance sensors for biosensing and chemical sensing applications, and subwavelength plasmonic lattice solitons in arrays of metallic nanowires.

In a seminal work [57] published more than two decades ago, it was found that arrays of subwavelength holes in metallic films display unusual zero-order transmission spectra at wavelengths larger than the array period, beyond which no diffraction occurs (for an excellent overview of the current research activity in the area of extraordinary optical transmission through noble metal films like gold and silver with subwavelengths holes and slits see Ref. [60]). Notice that light transmission through subwavelength metallic channels was investigated in Ref. [62], and a resonant cavity-enhanced light transmission mechanism in metallic gratings with subwavelength apertures was put forward for operation with light in the visible spectral range. It was predicted that small variations of aperture shape or its spatial dimensions have a huge effect on the transmission properties of subwavelength metallic gratings [62].

Metals structured at a nanometer scale can lead to improved and sometimes surprising properties; e.g., metals can display colours which vary with their size. These colours result from the coupling of light with the free electrons of nanostructured metal particles embedded in a surrounding dielectric or semiconductor matrix or nanometer size metal films deposited on a dielectric substrate to form *surface plasmons* [61], [63]-[64] (for two excellent overviews of both the theory and the applications of surface plasmons, including long-range surface plasmon polaritons, see Refs. [66]-[67]). In short, surface plasmons are a specific kind of electromagnetic surface waves that occur at the interface between a noble metal (such as gold or silver) and a dielectric medium (such as glass or air). They can concentrate a huge electromagnetic field at the interface and, therefore, they strongly enhance both linear and nonlinear interaction between laser light and matter. Surface plasmons are considered a means to bridge nanoelectronics and nanophotonics. It is well known that photonic components are superior to electronic ones in terms of operational bandwidth, but the diffraction limit of light poses a significant challenge to the miniaturization and high-density integration of optical circuits. A possibility to avoid this problem is to exploit the hybrid nature of surface plasmons, which are light waves coupled to free electron oscillations in a metal that can be confined below the diffraction limit using subwavelength (nanometer size) noble metal structures. Notice that the simultaneous realization of strong light confinement and low propagation losses for practical applications proved to be a very difficult task. However metal/dielectric-based plasmonic waveguides [68] constitute the key elements in developing ultra-compact integrated planar lightwave circuits in addition to other novel waveguide structures proposed in recent years, such as silicon photonic crystal waveguides [69]-[72], and metallic or dielectric-based slot waveguides, such as silicon slot waveguides [73].

Lasing in metal-insulator-metal waveguides filled with electrically pumped semiconductor cores, with core width sizes below the diffraction limit has been also demonstrated [74]. These structures confine light (a TM mode) to waveguide core regions about half the diffraction limit in width, that is, about $\lambda/(2n)$, where n is the refractive index of the core material. The inherent losses in such sub-wavelength metal-insulator-metal waveguides can be overcome to create small plasmon mode lasers at wavelengths near 1500 nm. The room temperature lasing (a TE mode) in such waveguides, with approximately 310 nm wide semiconductor cores was reported [74]. The experimental demonstration of nanometre-scale plasmonic lasers was reported by two independent groups [75]-[76]. In Ref. [75] it was shown that 44-nm-diameter nanoparticles with a gold core and dye-doped silica shell allow us to completely overcome the loss of localized surface plasmons by gain and achieve a *surface plasmon amplification by stimulated emission of radiation (SPASER)* as theoretically predicted in the seminal work [77]. It is to be noticed that SPASER radiation consists of surface plasmons that obey Bose-Einstein statistics and undergo stimulated emission but in contrast to photons can be localized at the nanoscale, see Ref. [77]. Also notice that the SPASER operates on a dark mode; this means that enhanced local electromagnetic fields are generated but nothing is necessarily emitted in the far field. In Ref. [76] such nanolasers were achieved using a hybrid plasmonic waveguide consisting of a high-gain cadmium sulphide semiconductor nanowire, separated from a silver surface by a 5-nm-thick insulating gap; for an interesting theoretical discussion and interpretation of the results reported in these two experimental works, see Ref. [78]. A novel scheme of surface plasmon polariton amplification based on a minority carrier injection in a Schottky diode, which can be used to obtain surface plasmon lasing, was recently put forward [79]. Though the surface plasmons are intrinsically transverse magnetic (TM) polarized surface waves, the existence of transverse electric (TE) plasmons in bilayer graphene was predicted in a recent work [80]. It was shown that the plasmonic properties are much more pronounced in bilayer than in monolayer graphene [80]; for a previous seminal work on new electromagnetic modes in graphene, see Ref. [81].

A less explored research area in nonlinear plasmonics is the study of *nonlinear plasmonic slot waveguides* [82]. The properties of nonlinear modes in subwavelength slot waveguides created by a nonlinear (Kerr-like) dielectric slab sandwiched between two noble metals were studied [82]. Unique phenomena were uncovered, such as the existence of a symmetry-breaking bifurcation of the symmetric mode, which becomes primarily localized near one of the two dielectric-metal interfaces. This recent work on nonlinear plasmonic slot waveguides has generalized the earlier studies performed in the 1980s on nonlinear TM and TE plasmon polaritons that can be excited at metal-nonlinear dielectric interfaces [83]-[86].

Nanoplasmonics enables a convergence of semiconductor electronics and nonlinear optics at nanoscale lengths and at femtoseconds timescales. The ultimate goal of nanoplasmonics is to provide us with a new class of ultracompact (at nanometer scales) and ultrafast optical devices for all-optical information processing (for an overview, see, e.g., Ref. [87]). Femtosecond optical frequency surface plasmon pulses propagating along a metal–dielectric waveguide (an Al/silica interface) were modulated on the femtosecond timescale by direct ultrafast optical excitation of the metal, thereby offering unprecedented terahertz modulation bandwidth [88]. To the best of my knowledge, this is the first experimental evidence that femtosecond plasmon pulses can be generated, transmitted, modulated and decoupled for detection in a single optical device.

Recently, it was experimentally demonstrated the nanofocusing of surface plasmons in tapered metallic V-grooves down to the deep subwavelength scale at wavelength of 1500 nm with almost 50% power efficiency; the guided mode's beam width was scaled down to ~45 nm which corresponds to ~λ/40 [89]. The light scattering from metal nanoparticles near their localized plasmon resonance is a promising way of increasing the light absorption in thin-film solar cells; the field of plasmonic solar cells emerged from these recent studies [90]. These surface plasmon resonances in metallic nanoparticles are of much interest for a variety of applications due to the large optical field enhancement that occurs in the vicinity of the metal surfaces. It is worthy to mention that the resonance wavelength strongly depends on the metal nanoparticle size, shape, and on local dielectric environment. An engineered enhancement of optical absorption and photocurrent in semiconductors via the excitation of surface plasmon resonances in spherical gold nanoparticles deposited on the semiconductor surface was reported [91]. These results suggest new approaches for improving the performance of photodetectors, imaging arrays, and photovoltaic cells [92]. It is commonly believed that photovoltaics is one of the key technologies to slow down the present dramatic climate change. To this aim solar cells made of either amorphous or microcrystalline silicon are extremely attractive. However, the intrinsic low diffusion length of the holes in these media limits the thickness of the light absorbing layers to a few hundred nanometers for amorphous silicon and to a few microns for microcrystalline silicon, respectively. Therefore, not all incoming photons are absorbed in these commonly used solar cells. However, polymer-based solar cells exhibit some advantages as compared to those based on amorphous silicon, see, e.g., Refs. [93]-[94]. I also mention a recent study of dye-sensitized solar cell performances with regard to transparent conducting oxide substrates indium-doped tin oxide and fluorine-doped tin oxide, see Ref. [95].

A comprehensive study of absorption enhancement by metallic (silver) nanodiscs in thin-film amorphous silicon solar cells was performed in a recent work [96]. It was shown by rigorous numerical simulations of Maxwell's equations that 50% more photons can be absorbed using a physical setting where metallic nanoparticles were deposited on top of solar cells; this setting is accessible for current nanotechnology fabrication. The strong enhancement of photon absorption is intimately linked to the excitation of localized plasmons in the corresponding nanopatterned structure [96].

The sharp surface plasmon resonance can be used either in biosensing or in chemical sensing applications. These sensors use the absorbing light property of a nanometric thin noble metal layer (such as Au) deposited on a high refractive index glass substrate, which produces electron waves (surface plasmons) on the metal surface. This sharp resonance occurs only at a specific incidence angle (for a fixed value of the wavelength of the incident laser radiation) and is highly dependent on the metal surface, such that binding of a target analyte to a receptor on the metal surface produces a measurable optical signal, see, e.g., recent work on surface plasmon resonance biosensors using silica-core Bragg fibers [97] and on the optical sensor based on surface plasmon resonance operating in the mid-infrared range for the detection of CO_2 [98].

Surface plasmon resonance sensing was combined with surface enhanced Raman scattering detection on periodic arrays of subwavelength metallic nanoholes [99]. This synergistic approach on low-cost metallic films perforated with periodic arrays of subwavelength nanoholes opens a route for molecular detection to be integrated in lab-on-chip systems in order to increase the reliability of biosensing, see Ref. [99]. Also, a comprehensive study of the sensitivity of traveling wave photodetectors in superconducting box-shaped plasmon-polariton optical waveguides was performed in a recent work [100]; it was shown that the light confinement regimes and the power absorption efficiency in the superconducting layer can be maximized by optimizing only the plasmon-polariton waveguide geometry [100].

It was recently pointed out the remarkable ability of noble metal nanoparticles to act as efficient pointlike sources of both light and heat [101]-[102]. Thus nanoplasmonics provides novel nanotools for both biosciences and medicine and promises integrated functionalities for future point-of-care diagnostics and cancer therapies (e.g, by improving the efficiency of hyperthermia for cancer therapy, see Refs. [101]-[102]).

In recent years there has been a growing interest in the study of unique features of surface plasmons in the nonlinear regime [103]-[105]. Recently, in the surface enhanced Raman scattering (SERS) studies, an unusual anti-Stokes Raman spectrum distinguished by an abnormal intensity, which increases with the vibrational wavenumber, and some discrepancies with regard to the Stokes spectrum were analyzed [106]. It was demonstrated in Ref. [106] that the abnormal anti-Stokes Raman emission on single walled carbon nanotubes (SWCNTs) appears as a consequence of two corroborating effects: resonance, which occurs when the energy of the excitation light is near or coincident with the energy of an electronically allowed transition, and the SERS effect achieved by the excitation of surface plasmons. Thus it was reported on SWCNTs an abnormal intense Raman emission in the Stokes branch, which is reminiscent to a stimulated Raman effect, see Ref. [106]. Concluding this section, I also mention the recent theoretical prediction that stable subwavelength *plasmonic lattice solitons* (PLSs) can form in both one-dimensional and two-dimensional arrays of metallic nanowires embedded in nonlinear Kerr media [107]. The main physical mechanisms for balancing the beam diffraction and the formation of subwavelength PLSs is provided by the tight confinement of the guiding modes of the metallic nanowires, combined with the strong nonlinearity induced by the enhanced field at the noble metal (e.g., Ag) surface [107]. Moreover, *vortical PLSs*, which form in two-dimensional arrays of metallic nanowires embedded into nonlinear media with both focusing and defocusing Kerr nonlinearities were recently introduced and their existence, stability, and subwavelength spatial confinement were investigated in detail [108]. It is envisaged that these subwavelength PLSs can be used to optically manipulate with nanometer accuracy the power flow in ultracompact photonic devices and systems.

4. Photonic crystals and metamaterials for micro- and nanophotonics

The *photonic crystals* [109]-[110], specially engineered materials in which the atoms and molecules of a common crystal are replaced by macroscopic media with different dielectric permittivities so that the periodic potential is replaced by a periodic refractive index, allow us a complete control over light propagation in such an artificial material; see Ref. [69] for a comprehensive review of activity in this hot research area. The photonic crystals display photonic band gaps, i.e., light cannot propagate in certain directions with specific frequencies (“colours”). In the following I will briefly discuss recent advances in topics such as high quality factor photonic-crystal nanocavities and slow-light photonic crystal waveguides.

Silicon photonic crystals allow, e.g., the fabrication of nanometric size waveguides and sharp waveguide bends [70], an active control of slow light on a chip [71], as well as the achievement of high quality factor nanocavities [72]. Photonic crystal nanocavities with a photon lifetime of 2.1 ns, which corresponds to a quality factor of 2.5×10^6 were recently fabricated [111] by using photonic crystals with a triangular lattice of circular air holes with radii of 115 nm in a 250-nm-thick Si slab. The nanocavity itself consists of a line defect with the lattice constant increasing every two periods as it approaches the cavity center; for more details see Ref. [111] (for a review of earlier work in the area of optical microcavities which confine light to small volumes by resonant recirculation, see Ref. [112]). Green light emission through third-harmonic generation in a slow-light photonic-crystal waveguide was recently achieved [113]. Visible third-harmonic-generation at a wavelength of 520 nm with a peak pump power of a few watts only was observed, and it has been demonstrated a strong third-harmonic-generation enhancement due to the reduced group velocity of the near-infrared pump signal. The photonic device consists of an 80-mm-long photonic-crystal waveguide in a 220-nm-thick air-suspended silicon slab, coupled to two tapered ridge waveguides. It was observed visible green light emission for only 10 W peak pump power due to both the tight light confinement within the photonic-crystal waveguide (the effective mode area was about 0.4 μm^2) and the energy density enhancement provided by the slow-light mode (the group velocity was about $v_g = c/40$) [113].

Metamaterials are artificially engineered structures that have unique properties, such as a negative refractive index, not attainable with naturally occurring materials [114]-[117]; also, for a recent perspective on metamaterials as artificial media structured on a size scale smaller than the wavelength of external stimuli, see Ref. [118].

In the past few years, new exciting developments in micro- and nano-structured metamaterials have given rise to negative refractive index media which have both negative dielectric permittivity and negative magnetic permeability in some frequency ranges. Negative refractive index metamaterials were first demonstrated at microwave frequencies. Metal-based negative refractive-index metamaterials have been extensively studied in that spectral region. Negative-refractive-index metamaterials are more difficult to obtain at near-infrared or visible wavelengths due to both difficulties of fabrication and poor optical properties of metals at these frequencies. However, the first fabrication and experimental verification of transversely structured metal-dielectric-metal multilayers exhibiting negative refractive indices in the near-infrared spectral region (around 2 μm) was reported in Ref. [119].

It was later experimentally demonstrated a three-dimensional optical metamaterial having negative refractive index with a very high figure of merit of 3.5 (that is, with a low loss) [120]. This metamaterial is made of cascaded ‘fishnet’ structures, with a negative refractive index existing over a broad spectral range. The fishnet structure consisted of alternating nanometer-thick layers of Ag and magnesium fluoride (MgF_2) with thicknesses of 30 nm and 50 nm, respectively. Furthermore, it was recently demonstrated that an engineered metamaterial made of alternating layers of negatively refracting (a silicon photonic crystal) and positively refracting (air) materials strongly collimates a beam of near-infrared light at 1550 nm [121]. This result can be regarded as a first explicit experimental verification of the concept of “optical antimatter" (a slab of metamaterial appears to "annihilate" a slab of air of equal thickness).

Zero-average-refractive-index band gaps in photonic crystal superlattices consisting of alternating stacks of negative-refractive-index photonic crystals and positive-refractive-index dielectric materials in the near-infrared range were recently reported [122]. The fabricated nanostructured superlattices demonstrated the presence of zeroth-order band gaps, in full agreement with theoretical predictions, for a wide range of superlattice periods and unit cell variations [122].

It is worth noticing that the use of photonic metamaterials as anisotropic media, in particular, nanostructured materials exhibiting tunable form-birefringence, is of particular interest in the area of the so-called Dyakonov-Tamm lossless surface waves [123]. These electromagnetic surface waves exist at interfaces between two homogeneous dielectric materials, one of them is isotropic and the other one is uniaxial with its optical axis aligned parallel to the interface [124]-[128]. Also, very recently, propagation of waves guided by a dielectric slab inserted in a sculptured nematic thin film was studied theoretically [129]. It was shown that propagation of both Dyakonov–Tamm waves and waveguide modes should occur in practice with negligible attenuation, in contrast to that of surface-plasmon-polariton waves that are guided when the dielectric slab is replaced by an ultrathin noble metal film [129]. Furthermore, the significance of Dyakonov-Tamm surface waves for optical sensing applications is quite obvious.

Recently, a method for building different photonic structures in As_2S_3 amorphous chalcogenide thin films has been developed by using femtosecond pulses [130]. Two-dimensional photonic configurations consisting of a regular assembly of rods (arranged in a triangular lattice) or micrometer period gratings have been fabricated. These chalcogenide photonic structures could be efficient for all-optical processing in the infrared spectral range (wavelength of several micrometers) [130]; for an overview on several techniques used to prepare two-dimensional photonic As-S glasses, see Ref. [131].

In Ref. [132] it was reported the creation of two-dimensional photonic structures imprinted on the surface of arsenic sulphide glasses by using femtosecond laser pulses. Laser induced modification of materials (via techniques such as laser ablation, two-photon photopolymerization, and near-field laser lithography) is currently used to get micro- and nanostructured materials, see, e.g., Ref. [133]. Thus, laser induced periodic surface structures were obtained on ZnO thin films deposited on sapphire substrate [134]. Ripples with a period of about 150 nm, spaced by grooves with about 50 nm width and about 100 nm depth have been obtained by scanning the sample surface with femtosecond laser beams, see Ref. [134]. An analysis of the behavior of a photonic crystal cavities coupled with optical waveguides, which is able to transfer electromagnetic energy only in the forward direction was recently performed [135]. This simple photonic device, which has potential applications in photonic crystal microcircuits, especially in the waveguide intersections, was investigated by using the coupled mode theory [135]. The possibility of achieving a single-mode vertically coupled microring resonator that can be obtained by wafer bonding was also investigated [136].

The biogenetic production of nanomaterials was overviewed in a recent work [137]. It was pointed out that nanoparticles of interest in both nanotechnology and in medicine (e.g, in the controlled release of drugs) can be produced by both anorganic and organic synthesis [137]. Complex conjugate materials, where the ratio of the complex electrical permittivity and the complex conjugate magnetic permeability is real were put forward in a recent seminal work [138]. They are characterized by a real refractive index and thus they allow non-attenuated propagation of electromagnetic waves. Such metamaterials could have important applications in miniaturized optical amplifiers and lasers, see Ref. [138].

Graphene is a "a rapidly rising star on the horizon of materials science and condensed-matter physics"; see the seminal paper [139] on electric field effect in atomically thin carbon films and the subsequent comprehensive review [140]. Graphene is a low-dimensional material (only one atom thick) with an unusual electronic spectrum. It adds electro-optical capability to metamaterials in the infrared and terahertz spectral domains. This unique capability of graphene exploits the spectral shift of electromagnetic response driven by the applied gate voltage [140].

A graphene-based ballistic diode, which is able to rectify an incident signal due to an oblique gate positioned between the two terminals of the device, was put forward in a recent work [141]. It was found that the rectifying properties of the graphene-based ultrafast diode are thus tunable, in deep contrast with usual semiconductor-based diodes [141]; also, for an early review on graphene-based quantum electronic devices, see Ref. [142].

Synthesis of optical transparent and electrical conductive polymer/nanocarbon composite films by infiltration method was recently reported [143]. Comprehensive studies of both linear and non-linear optical properties of carbon nanotubes were performed by using several spectroscopic tools [144]-[145]. I also mention recent studies on vibrational Tamm states and surface solitons at the edges of graphene nanoribbons [146]-[147].

A topic of much interest in recent years is the realization of low-loss plasmonic metamaterials, see, e.g., Ref. [148]. As is well known the conventional noble metals (Au, Ag) as plasmonic materials in the near-infrared and visible spectral ranges suffer from drawbacks such as large losses and incompatibility with the current semiconductor technology. These problems can be overcome by using an all-semiconductor-based approach to plasmonics, see Refs. [149]-[150]. In a recent work [150] it was shown that InAs-heterostructures are superior to other common semiconductors and metals for applications in plasmonic structures and metamaterials in mid-infrared frequency range.

5. Terahertz radiation and its applications

The *terahertz (THz) radiation*, i.e., the electromagnetic radiation with the wavelengths in the range 0.1-1 mm (3 THz-300 GHz) is a non-ionizing submillimeter microwave radiation. It cannot penetrate metal or water; however it can pass through paper, clothing, wood, masonry, plastic and ceramics. The envisaged applications comprise: (a) Medical imaging and clinical diagnostic, because the THz radiation is not expected to damage tissues and DNA, unlike X-rays, (b) Security checks (THz radiation can penetrate fabrics and plastic, so it can be used in security screening, to uncover, e.g., concealed weapons on a person, remotely), (c) Quality control of pharmaceutical and polymeric goods, (d) Detection of contamination in food products, and (e) "Indoor" wireless communication, etc. (for a comprehensive review of terahertz electromagnetic fields and their applications, see, e.g., Ref. [151]).

It is envisaged that within the next few years, various systems based on non-ionising THz electromagnetic waves will widen mankind's scientific and technical potential to a similar extend the X-rays scanners did over the past century. In the following I will briefly discuss the generation of terahertz radiation on metallic nanostructured surfaces and nanoparticle-enabled terahertz imaging of biological tissues.

Several configurations of *terahertz antennas* based on graphene were investigated in a recent work [152]. It was shown that the radiation pattern and the efficiency of such terahertz antennas are changed via the gate voltage applied on graphene [152]. The phenomenon of optical rectification was widely used to rectify ultrafast (picosecond or femtosecond) laser pulses from the visible to the terahertz frequency range. A resonant "incoherent" rectification process was reported [153], which rely on the excitation of surface plasmons on nanostructured noble metal surfaces. Thus it was recently achieved the excitation of nanostructured gold and silver films with 800 nm femtosecond laser pulses, which resulted in the emission of terahertz radiation with an angle-dependent efficiency [153].

The nanoparticle-contrast-agent-enabled terahertz imaging technique was recently introduced [154], which yields an enhanced sensitivity of the differential signal from cancer cells with nanoparticle contrast agents (e.g., gold nanorods). The THz reflection signal from the cancer cells increases by 20% upon their irradiation with infrared light compared to cancel cells without gold nanorods; see Ref. [154]. This enhanced sensitivity was due to the temperature rise of water in cancer cells by the excitation of surface plasmons. Therefore, THz cancer imaging can be realized with a micron resolution, which would facilitate the diagnosis of cancers at a very early stage, see Ref. [154].

6. Nanophotonics and quantum information processing

One of the main applications of nanophotonics to quantum physics and quantum information processing is to design *single-photon sources* based on the emission of cavities in photonic crystals or on the emission of quantum dots embedded in semiconductor nanowires which can be engineered to reduce the divergence of the far-field radiation.

The *semiconductor nanocrystals* (comprising a few hundred to a few thousand atoms) constitute the ideal single photon sources for quantum information applications. Several single-photon sources based on the emission of a quantum dot embedded in a semiconductor (GaAs) nanowire were designed [155]. The optical nanoantenna volume was of the order of $0.05\lambda^3$. In contrast to other optical nanoantennas based on surface plasmons, the approach developed in Ref. [155] does not rely on any resonance effect and the funneling was actually achieved over a very broad spectral range, $\Delta\lambda$=70 nm at λ=950 nm.

The slot-waveguide geometry recently introduced for nanophotonic applications in the near infrared range is also promising for quantum optical applications in the visible spectrum [156]. To this aim, diamond- and GaP-based slot-waveguide cavities compatible with *diamond color centers*, were recently introduced and single-photon Rabi frequency on the order of 10^{11} rad/s were predicted [156].

In a recent work [157] it was argued that color centers in diamond are prominent candidates to generate and manipulate quantum states of light, because they are photostable solid-state light sources of single photons at room temperature**.** In that comprehensive review on diamond-based single-photon emitters [157], a few experimental techniques used to characterize the quantum emitters and their photophysical properties were presented in detail.

7. Conclusions

In this paper I have attempted to give the interested reader a quite limited overview of the current state of activity into the exponentially growing research areas of micro- and nanophotonics. I conclude with the hope that this brief overview on some selected recent developments in these research fields will inspire further investigations.

Given the rapid growth of studies in micro- and nanophotonics in the past few years one can expect many new and exciting developments over the next decade.

No doubt, soon one can expect a maturity of these fast growing research fields, leading to new and interesting physical phenomena and to the utilization of their huge technological potential in various areas of human activity, e.g., in reducing energy consumption in lighting systems, developing novel biomedical and chemical sensors, fabrication of optical sensors able to detect even single molecules, designing of new solar cells with enhanced efficiency, and implementation of ultra high-speed telecommunication systems.

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