TRENDS IN NANOPHOTONICS: A PERSONAL SELECTION

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Abstract. *I give a brief overview of recent results in the area of nanophotonics. I concentrate on recent advances in silicon photonics, nanoplasmonics, plasmonic solar cells, surface plasmon resonance sensors for biosensing and chemical sensing applications, high quality factor photonic-crystal nanocavities, optical materials with negative refractive indices, generation of terahertz radiation on metalic nanostructured surfaces, nanoparticle-enabled terahertz imaging, solid-state single photon sources, and nanometric size optical cavities for quantum information processing.*

Keywords: nanophotonics, silicon photonics, plasmonics, photonic crystals, metamaterials

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 utilisation for the benefit of mankind".

In brief, photonics is the science of generating, controlling, and detecting photons and therefore *nanophotonics* study the unique behavior of light on the nanometer scale. Nanophotonics is deemed a new technology whose time has come and that threatens to displace the existing technology solutions; applications are envisaged in diverse areas such as information processing, communication systems, imaging, lighting, displays, manufacturing, life sciences and health care, safety and security, etc. This work is organized as follows. In Sec. 2 we briefly 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. The problem of light confinement in nanostructured noble metal structures is discussed in Sec. 3. Section 4 is devoted to recent advances in the study of photonic crystals and metamaterials with negative refractive indices. In Sec. 5 we 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. 5 concludes this paper.

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2. Silicon photonics

Silicon photonics is the photonic technology based on silicon chips. The highest impact of silicon photonics may be in optical interconnections between digital electronic chips [1]-[2]. Silicon (Si) has an indirect bandgap that means 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 worthy to mention 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. 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 (about 1.1 eV for Si). Persuading Si to perform photonic functions can bring optical communication to the world of chip interconnects. 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 opportunities abound, including low cost transceivers for 10 to 100 Gbit/s Ethernet, a new platform for mid-infrared photonics, and optically assisted analog-to-digital conversion (a transceiver is a device that has both a transmitter and a receiver which are combined and share common circuitry or a single housing). Optical amplification and lasing, once considered forbidden in silicon, have been achieved. Silicon’s nonlinear optical properties, enhanced by tight optical confinement in Si/SiO_2 structures, *i.e.*, silicon-on-insulator (SOI) nanostructures, are producing wavelength generation and conversion, which are central functions in multi-wavelength communications and signal processing. 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 nanophotonics. The 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) which can be scanned 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 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,

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the resolution is about 100 pm (about twice the distance between atoms in 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 less than 50 pm was resolved [3].

The highest impact of silicon photonics is believed to be in data communications; consequently, most of the research has been aimed at producing sources of photons, electro-optic modulators, and photodetectors. 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. Silicon is not able to detect signals at standard communication wavelengths of 1300 nm and 1550 nm because such photon energies are less than the bandgap. Yet these wavelengths represent standard communication bands because optical fibers, to which devices must eventually interface, have low propagation losses in these frequency bands. 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 examples of nonlinear optical phenomena which only appear when silicon is pumped with high intensity laser light ($I>10$ 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. However, because of high intensities involved, two-photon absorption occurs [4].

A hot topic in nanophotonic is the study of semiconductor nanostructures in the form of nanowires and quantum dots for emission, detection, guiding and control of light. Silicon photonic nanowires [4] 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 emerging.

Recently, all-optical high-speed signal processing with silicon-organic hybrid slot waveguides has been achieved [5]. 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,

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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 [6]; it was obtained the spontaneous emission enhancement and waveguide coupling ratio for popular 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 [6].

Another topic of much interest in the past years is the study of *spatiotemporal optical solitons*, alias "light bullets" [7]-[12], 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 in future all-optical information processing systems. 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. As concerning the 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 [13]. 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 energy being only a few hundreds fJ). The arrays of SOI photonic nanowires seem to be suitable for the observation of discrete surface light bullets because a suitable 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) [13].

3. Nanoplasmonics

Nanoplasmonics aims to mould light flow at the nanoscale using metallic nanostructures (usually nanostructured noble metals such as Au and Ag). Metals structured on the nanometer scale can lead to improved and sometimes

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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* [14]. 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. The simultaneous realization of strong light confinement and a low propagation loss for practical applications proved to be a very difficult task. However metal/dielectric-based plasmonic waveguides [15] 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 [16], and metalic or dielectric-based slot waveguides, such as silicon slot waveguides [17].

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. Recently [18] 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. 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 [19]. 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 *plasmon solar cells* emerged from these recent studies [20].

The sharp surface plasmon resonance can be used in biosensing or 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

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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 [21] and on the optical sensor based on surface plasmon resonance operating in the mid-infrared range for the detection of CO_2 [22].

4. Photonic crystals and metamaterials with negative refractive indices

The *photonic crystals*, metamaterials in which the atoms and molecules of a common crystal are replaced by macroscopic media with different dielectric permittivities and 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. [16] for a recent up-to-date 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"). Silicon photonic crystals allow, *e.g*., the fabrication of nanometric size waveguides, sharp waveguide bends as well as the realization of high quality factor nanocavities. Photonic crystal nanocavities with a photon lifetime of 2.1 ns, which corresponds to a quality factor of 2.5×10^6 were fabricated [23] 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. [23]. Green light emission through third-harmonic generation in a slow-light photonic-crystal waveguide was recently achieved [24]. Visible third-harmonic-generation at a wavelength of 520 nm with only a few watts of peak pump power was observed, and it has been demonstrated strong third-harmonic-generation enhancement due to the reduced group velocity of the near-infrared pump signal. The photonic device consisted 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 slowlight mode (the group velocity was about v_g=c/40) [24].

Metamaterials are artificially engineered structures that have unique properties, such as a negative refractive index, not attainable with naturally occurring materials. 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

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in some frequency ranges. Negative refractive index metamaterials were first demonstrated at microwave frequencies. However, recently it was 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) [25]. 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. Also, it was 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 [26]. 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).

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 (it 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, (e) "Indoor" wireless communication, etc. It is envisaged that by the year 2015, 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 100 years. The phenomenon of optical rectification was widely used to rectify ultrafast (picosecond or femtosecond) laser pulses from the visible (typically 800 nm) to the terahertz frequency range. A resonant "incoherent" rectification process was reported [27], 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 [27]. The nanoparticle-contrast-agent-enabled terahertz imaging technique was recently introduced [28], 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 increased by 20% upon their irradiation with infrared light compared to cancel cells without gold nanorods. This enhanced sensitivity was

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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.

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 in Ref. [29]. The optical nanoantenna volume was of the order of 0.05 λ^3. In contrast to other optical nanoantennas based on surface plasmons, the approach developed in Ref. [29] does not rely on any resonance effect and the funnelling 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 [30]. To this aim, diamond- and GaP-based slot-waveguide cavities compatible with diamond colour centres, were recently introduced and single-photon Rabi frequency on the order of 10^{11} rad/s were predicted [30].

Conclusions

We conclude with the hope that this brief introductory review on recent developments in the area of nanophotonics will inspire further investigations. Given the rapid growth of this research area 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 this field, leading to new and interesting physics and to the utilization of its huge technological potential.

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