Low dimensional optics

F. Flory*[a,b], L. Escoubas[a], J. Le-Rouzo[a], G. Berginc[c], C. C. Lee[d]
[a] Aix Marseille Université, CNRS, IM2NP UMR 7334, , 13397 Marseille, France; [b] Ecole Centrale Marseille, 13451 Marseille, France; [c]Thalès Optronique S.A., 2 Avenue Gay-Lussac, 78995 Elancourt Cedex, France ; [d] Thin Film Technology Center, National Central University, Jhongli, Taiwan

ABSTRACT

Thanks to progresses in material science and nanotechnologies, surfaces and thin films can now be structured at different scales. Photonics components take benefit of this possibility to fulfill still more and more complex functions. They are composed as well of organic as inorganic materials, dielectric, semiconductor, and metallic materials, or a mixture of them. Multiscale and chiral structures can be used to control both spectral, spatial distribution of light together with its polarization state. The optical mode density in the near field and in the far field can then be designed in particular by combining more or less resonant structures for the optical waves, associating diffraction, interferences and anisotropic structures like Fabry-Perot, waveguide, plasmons, photonic crystals ... Artificially nanostructured materials often called metamaterials exhibit new properties. Different phenomena recently considered, including optical topological insulator and structures for vortex waves transporting angular momentum of photons, will be also discussed and illustrated. With the development of nanometer size structures another step is overtaken allowing the control of the intimate interaction of optical waves with materials to tune their basic electronic properties and permittivity. Both optical and electronic properties are also strongly dependent on coupling effects needing a global approach.

Keywords: Nanophotonics, optical coatings, nanostructured thin films, photonic crystals, plasmonics, quantum dots

1. INTRODUCTION

When we were asked to prepare this review we found ourselves quite embarrassed as the subject “low dimensional optics” is very wide and includes many concepts, structures, materials, technologies and applications. It concerns all nanophotonics which studies the interaction of light with nanostructure at a size scale for which electronic and optical properties are strongly interdependent and when surface effects become as important as bulk effects or more.

So, to have some chance to bring you some elements on this subject, we decided to limit ourselves and not to speak about single photons sources, entangled photons, short pulses, χ_2 or χ_3 or technologies. We will mainly consider the wavelength range from near UV to the near IR. Even though it is a very important topic, we will only talk briefly of recent concepts about photonics structures like photonic crystals or metamaterials which are widely described in the literature. Our paper will include very few equations, only when it is absolutely necessary, in such a way to try “*to understand complicated phenomena in a unified way, in term of a few simple principles*”, as Steven Weinberg said[1]. However this still leaves quite a lot of room.

At first we would like to give you our definition of low dimensional optics, and then we will briefly go back to some basics like coherence, interference, diffraction, optical coatings, and plasmon, considering phenomena more or less resonant. After, again briefly, we will discuss about micro/nano structured thin films and materials with structures not smaller than a few tens of nanometers. To go a step forward, or downward, to smaller structures we will come back another time to some basics, in particular on the notion of refractive index and quantum confinement. The main part of our presentation will be devoted to such very low dimensional optics and to coupling phenomena which seem to us fundamental in the understanding of light-matter interactions. We will end our presentation by giving the example of application of low dimensional optics to solar cells.

Most of our inspiration comes from nature[2]. In nature, structural colors come from the association of interference and diffraction in different nanostructured material. The structure is often multiscale with different sizes.

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Low dimension is a relative notion. In optics we generally consider that we are in this case when the critical dimension is smaller than the wavelength of light i.e. under the diffraction limit in free space propagation. Moreover, optical waves behave differently when the material typical size is close to the wavelength, when it is smaller than $\lambda/10$ for which the effective medium approximation applies, and when the dimension is of only a few nanometers for which classical physics is in default.

At first we will speak about the two first cases and then we will mostly focus our attention to structures of a few nanometers which can be referred as quantum structures. Going back again to basics, we will see that an interesting parallelism can be made between electronic and optical properties and that they are closely linked.

Such quantum structures may be embedded in host materials and light interacts with a volume of matter much larger. Then, material response generally comes from plenty of such quantum structures which can be coupled or not. So coupling phenomena appears to be very important in the real world and we will also discuss about coupling.

2. BACK TO BASICS 1: COHERENCE, DIFFRACTION, INTERFERENCE AND OPTICAL DENSITY OF STATES.

2.1 Coherence:

In physics, coherence is an ideal property of waves that enables stationary (i.e. temporally and spatially constant) interference[3]. When two waves are mixed, if their phase relation is defined, they will interfere. The coherence length defines the largest difference in path for the two waves above which they will not interfere. Temporal coherence describes the correlation or predictable relationship between the phases of waves observed at different moments in time. So the coherence time is the maximum time Δt above which the associated phase shift of the waves varies randomly. Such first order definition of coherence holds for any wave. So it concerns in particular both optical waves and electron wavefunction.

2.2 Diffraction:

Considering a 1D grating, when the period is larger than the incident light wavelength, different propagating diffracted orders are obtained and the light is spatially distributed depending of its wavelength. When the grating period decreases the diffracted orders disappear but evanescent modes may appear with an increase of the local field. When the periodic structure is made of gratings with different periods (different spatial frequencies) the light is dispersed in different diffraction orders. Each diffraction order corresponds to an eigenstate obtained from Maxwell equations. Such a discrete set of solution constitutes a vector space of finite dimension. A surface can be structured to control both the spectral and spatial distribution in amplitude and phase of the light field. This composes the important field of diffractive optics.

When the spatial frequencies make a continuum the vector space has an infinite dimension. If the depth of the surface profile is not too large the light is then scattered with a light distribution in the far field given by the Fourier transform of the autocorrelation function of the surface profile. In the case of very rough surfaces such a first order approach is not valid anymore and diffraction at higher orders must be taken into account[4]. Scattering methods as Small-Slope Approximation, for example, must then be used. The development of these approximations can provide new insight into electromagnetic scattering from rougher surfaces and films. With numerical solutions of these new theoretical solutions, we can now analyze extensively coherent phenomena due to multiple scattering for two-dimensional structures or three-dimensional films. In some cases of strongly inhomogeneous materials scattered light can be locally trapped in the volume, giving an Anderson localization phenomenon[5]. When a surface is rough the spatial frequency distribution is random, generally with a Gaussian distribution. It is possible to perform optical functions with such random rough surfaces by choosing the statistical distribution of the roughness and the correlation function of random rough surfaces [6].

2.3 Interference:

By stacking transparent layers of different refractive index one can change the spectral distribution in the specular directions. The properties are defined by multiple wave interferences in the stack. The layers thicknesses must be smaller than the coherence length of the incident light. A single layer is limited by two partially reflecting surfaces and gives interferences in normal incidence. A modulation with wavelength can then be seen in transmission and in reflection. The modulation depth depends on the change on refractive index at layer boundaries. A Fabry Perot interferometer is composed of two mirrors facing at an optical distance multiple of $\lambda_0/2$. Resonances of the optical field occur in the spacer medium at λ_0 and a discrete set of wavelengths corresponding to constructive interferences in transmission. The transmission function is given by the Airy function. Most of the lasers are made of a Fabry-Perot (FP) with a spacer medium exhibiting gain. It is also well known that mirrors can be made by stacking alternatively high and low refractive index layers, the optical thickness of which are quaterwave. Fabry-Perot structures can also be made with thin films and it is a way to make band pass filters. The mirrors are periodic structures made of alternated high and low refractive index quaterwave layers which can also be seen as gratings in thickness. More generally, a multilayer can be designed to make nearly any wavelength filter[7].

When considering waves propagating in the thickness of layers in total reflection on the boundaries only a discrete set of propagation constants can be found corresponding, of course, to guided modes. With such reflection coefficient of amplitude equals one the guided modes correspond to strong resonances for the optical waves. The guided modes are eigenmodes of the system.

2.4 Density of optical states:

The emission of light from a multilayer stack can take place both in free space and confined in the layer thickness when there are guided modes. The light distribution can then be given from a modal approach[8].

According to Fermi's Golden Rule, the rate of spontaneous emission from quantum emitters such as atoms, molecules, or quantum dots is proportional to the "local radiative density of states" (LDOS)[9,10], which counts the number of electromagnetic states at a given frequency, location and orientation of the dipolar emitters.

The LDOS is defined as

$$N(r,\omega,e_d) = \frac{1}{(2\pi)^3} \sum \int_{BZ} dk\delta(\omega - \omega_{n,k}) \left| e_d . E_{n,k}(r) \right|^2 \qquad (1)$$

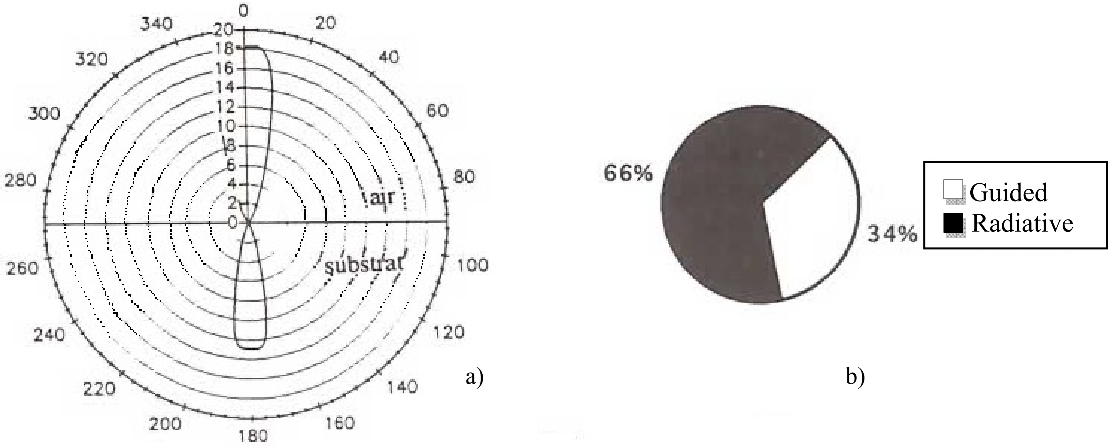
where integration over the **k** vector is performed in the first Brillouin Zone (BZ), n is the band index, and e is the orientation of the emitting dipole. The total DOS is the unit cell and dipole-orientation average of the LDOS defined as

$$N(\omega) = \sum_n \int_{BZ} dk\delta(\omega - \omega_{n,k}) \qquad (2)$$

The important quantities that determine the LDOS are the eigenfrequencies $\omega_{n,k}$ and electric field eigenmodes $E_{n,k}(r)$ for each ***k*** vector. LDOS takes high values for each resonance.

Figure 1a) shows an example of the emission diagram calculated for a Fabry-Perot filter of formula M6 2H M6. M6 is a mirror made of 6 alternated high and low refractive index quaterwave layers[11]. 2H is a half wave layer of high refractive index. Fig. 1b) gives the light intensity distribution into guided and radiative modes. Depending on the emitting dipole position the largest part of the emitted light can propagate in guided mode, in particular for TE0 mode. This mode corresponds to a stronger resonance than that of the radiative Fabry-Perot mode.

So, multilayer coatings can be designed to control the spatial and spectral emission of light.



a) b)

Figure 1: a) emission diagram calculated for a Fabry-Perot filter of formula M6 2H M6. M6 is a mirror made of 6 alternated high and low refractive index quaterwave layers and 2H is a half-wave layer of high refractive index; b) light intensity distribution into guided and radiative modes[11].

The internal quantum efficiency of OLED devices have been achieved near 100% but external quantum efficiency of conventional devices remains near 20% because of losses due to wave-guiding effect. The LDOS of the OLED can be tune to have a better light extraction by adding structures such as substrate modification, use of scattering medium, micro-lens arrays, micro-cavity effect, photonic crystals and nano-cavity, nano-particles, nano-structures and surface plasmon-enhanced techniques[12].

2.5 Plasmon:

Up to now we only consider dielectric materials. It is also of a great interest to consider surfaces, thin films and nanostructures made of a metal or of a mixture of metal and dielectric. Plasmon resonances can then be excited with optical waves. It is now well known that at a surface between a metal and a dielectric an optical wave of TM polarization can propagate with a propagation constant which depends on the permittivity of both media. Such wave called plasmon polariton extends only in a few hundreds of nanometer in the dielectric and in a few tens of nanometers in the metal. Only a TM evanescent wave can be used to excite such a mode. Plasmonic structures like metal strips can be used to make very small optical waveguide but, because of high propagation losses, they can be used only on a short distance.

When the metal is in the form of nanoparticles, plasmon resonances can be excited with propagating wave because each nanoparticle acts as a dipole. In this case the resonance is weaker and occurs at a different wavelength than for a single surface. The centering wavelength of the resonance depends on both the metal used and the nanoparticle size[13].

This field called nanoplasmonics finds already many applications such as sensing, biomedical diagnostics, labels for biomedical research, nano-antennas for light-emitting diodes, Surface Enhanced Raman Scattering, etc. Especially promising and important are applications to cancer treatment[14,15] and sensing. We will see after that it is of a great interest also for solar energy conversion. An excellent review on nanoplasmonics can be found in[16].

3. NANOSTRUCTURED THIN FILMS, PHOTONIC CRYSTALS AND METAMATERIALS

Thin films can be naturally structured depending on the deposition process, randomly because of surface roughness or because of inclusions or artificially controlled with well-defined patterns. New functions can be obtained by stacking such thin films to make 2D or 3D structures. When designing diffracting structures with multilayers it is possible to master the polarization, the spatial and the spectral distribution of light. Such photonic crystals and metamaterials which often combine metals, dielectrics, and semiconductors, are widely studied[17]. From the early fifties optical thin films which make 1D photonic crystals were prefiguring this strongly growing field. There are numerous applications such as optical filters, stealth surfaces, sharply bend waveguides, micro cavities, sensors, solar cells. This subject is widely described in the literature so we would like to emphasize only briefly some recent concepts full of promises.

During deposition, using conventional physical vapor deposition process like e-beam evaporation, most of the films exhibit a columnar structure[18,19]. Generally, to have a homogeneous coating, the substrates are rotating at high speed and the columns are growing perpendicular to the substrate surface. When the rotation is stopped during deposition the columns are inclined. For a low rotation speed, by changing the angle of incidence of the vapor, the columns change of orientation. By controlling this angle during deposition one can make so-called sculptured thin films (Fig. 2)[20].

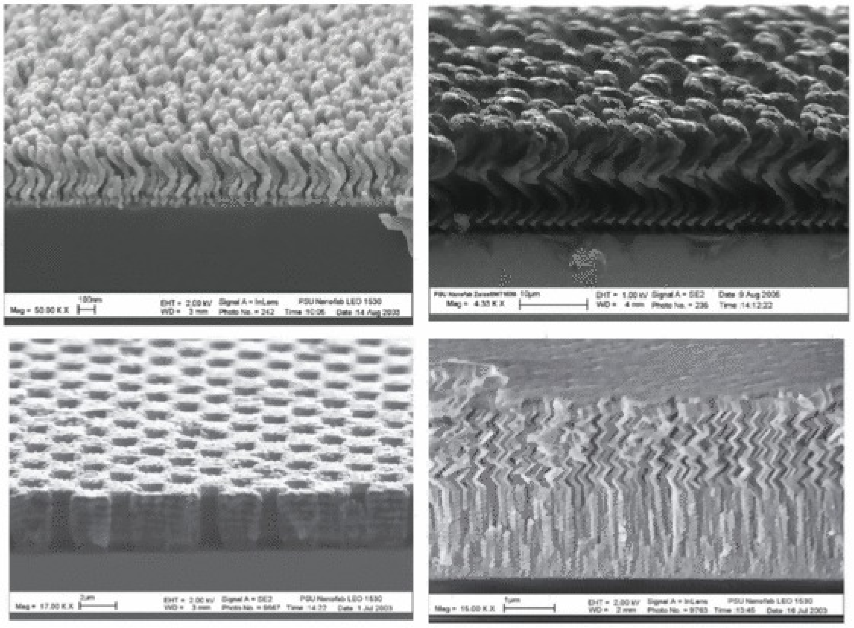


Figure 2: SEM pictures view of different sculptured thin films[20]

Columnar thin films exhibit strong anisotropy[21] which depends on the deposition angle[22]. The optical properties of films and multilayers made of anisotropic columnar films can be described with a 4x4 transfer matrix theory[21] but for thin film made of helicoidal bianistropic media, sculptured nematic thin films or more complex shapes made on topographic substrates, the model can be more complex[23]. Circular polarization filters can be made with such chiral films[24]. When a chiral film is deposited on a metal surface multiple surface plasmon modes may exists both for TM and TE polarization[25]. Combinations of different isotropic, chiral and anisotropic films offer a whole set of new properties on circular polarized light like circular Bragg reflector[26]. It is also interesting to note that waves propagating at the interface between two dielectric media may also exist. One dielectric must be anisotropic and periodically nonhomogeneous normal to the interface. Such waves are called Dyapanov-Tamm wave[27].

Multilayer composed of isotropic and columnar anisotropic coatings have already many applications when the polarization state of the light is involved. An example of polarization rotator in reflection is given in [28] (Fig. 3).

A lot of progresses have been made this last decade in this field and a plenty exciting new applications should come in the near future[29].

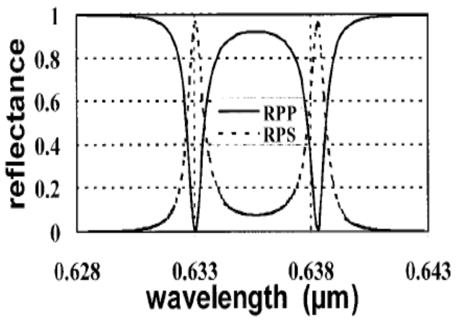


Figure 3: Calculated reflectance between crossed and parallel polarizers of an asymmetric Fabry–Perot filter having an anisotropic spacer layer. The design is substrate–M9BM9 4B* M9–air, where M9 denotes a mirror made of nine quarterwave layers of alternated high and low refractive index and 4B* is assumed to be made of silica with a small period Ti-implanted grating in a depth of 150nm. The s and p denote polarization states parallel and perpendicular to the gratings' stripes. [28]

The structuration at a small scale of different materials and their association compose the wide field of photonic crystals and metamaterials exhibiting extraordinary optical properties[30]. With periodic structures, or periodic structures with defects, forbidden photon band or strong microcavity resonances can be shaped.

By example the structure can be design in such a way (Fig. 4) that the light in normal incidence can be coupled to leaky guided modes. This is corresponding to flat part of the band diagram for which the life time of the photons is increased. This is particularly useful for organic thin films solar cells to increase light absorption and then their efficiency[31].

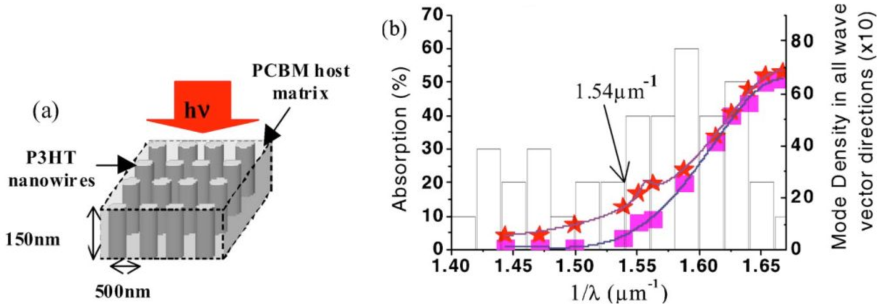


Figure 4: a) Structuration in the form of a Photonic Crystal of the organic solar cell active layer, made with the polymer couple P3HT/PCBM; b) Absorption and mode density in all wave vector directions[31].

Depending on the material used and especially when using a mixture of metal and dielectric, metamaterials exhibiting unusual optical properties as both negative permittivity and permeability can be designed[32]. Metamaterials find their applications in transformation optics[33,34].

There is a strong interest in making optical filters working over a very wide spectral range. These filters cannot easily be designed with multilayer thin films. Different patterns made in metallic layer associated with continuous dielectric layers have been studied to make such optical filters. An example for applications in stealth or thermophotovoltaics domains is given in [35] achieving low reflectivity from the visible up to 2.5 µm (Fig. 5b) and a mirror behavior up to 9 µm (Fig. 5b)) thanks to a fabricated metafilter. The structure is an inverted cone grating made of tungsten deposited on a polymer substrate (SEM pictures on Fig. 5a)) which makes the structure flexible as we can see on Fig. 5c).

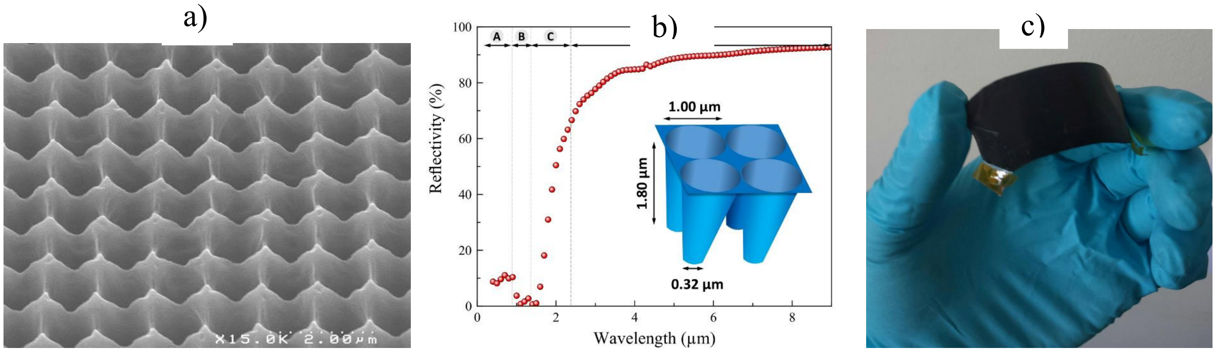


Figure 5: a) Tilted view from SEM images of the tungsten inverted cone gratings; b) Calculated reflectivity spectrum of the perforated tungsten plate. The inset shows the geometric parameters of the cones; c) Photograph of the fabricated metafilter[35].

Inspired by quantum physics, metamaterials with special optical properties are studied. In some case the metamaterial may be highly anisotropic with hyperbolic dispersion[36]. Such hyperbolic materials lead to broadband Purcell effect which can be used to engineer the radiative decay of photon sources[37]. Different material arrangements exhibit such a hyperbolic behavior. As examples, the material can be composed of a multilayer made of alternated metallic and dielectric thin films or made of an array of metallic nanowires. Associated with chiral properties the circular polarization Bragg effect is modified[38].

It is also interesting to consider the special case of Dirac cone dispersion[39]. The solution to Dirac equation for relativistic spin 1/2 particles gives an energy E linearly proportional to the wave vector $\boldsymbol{k}$. It is the case for graphene near Fermi level. Such a linear dispersion can also be obtained in 2D triangular photonic crystals for optical waves at the Brillouin zone boundary[40].

As n = $(\varepsilon_r\mu_r)^{1/2}$, a zero-refractive-index material can have either single zero ($\varepsilon_{eff} = 0$ or $\mu_{eff} = 0$) or double zero ($\varepsilon_{eff} = \mu_{eff} = 0$)[41]. There is no phase variance in the wave transport process inside a zero-index material. This can be achieved with photonic crystals having a *C4v* symmetry. Such zero index materials can be obtained by accidental degeneracy, which can be found by tuning system parameters. In this case the Dirac point is not at the Brillouin zone boundary but at the zone center. An example of a near zero refractive index is shown on Fig. 6. The structure is made of a periodic arrangement of SiO_2 and Si rectangular wires embedded in PMMA. Its band diagram is shown on Fig. 7.

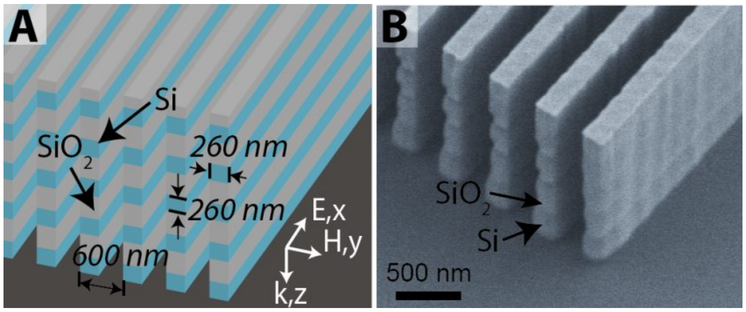


Figure 6: Example of a near zero refractive index metamaterial. The structure is made of a periodic arrangement of SiO2 and Si rectangular wires embedded in PMMA [41]

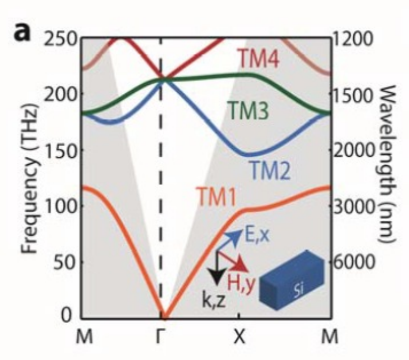


Figure 7: Band diagram of the structure shown on Fig. 6[41].

Such material may lead to many peculiar properties[42] such as the tunneling of electromagnetic waves through subwavelength channels and bends, the tailoring of the radiation phase pattern of arbitrary sources, and the cloaking of objects inside a channel with specific boundary conditions.

Other notions inspired by quantum physics are studied in photonics. In photonics an external magnetic field can be used with magneto-optic materials to break time reversal symmetry and unidirectional backscattering immune electromagnetic wave propagation, analogous to quantum hall edge states, can be realized. Such ideas were indeed demonstrated using photonic crystals constructed with gyromagnetic materials[43].

Topological insulators are electronic materials that have a bulk band gap in the volume, like an ordinary insulator, but have a Dirac-cone surface state so a conduction of the electrons which follows the surface topology. A photonic topological insulator is composed of a truncated photonic crystal with a photonic lattice exhibiting topologically protected transport of visible light on the lattice edges[44]. As example, an array of evanescently coupled helical waveguides arranged in a graphene-like honeycomb lattice presents an optical topological insulator behavior (Fig. 8)[45]. Without the application of a magnetic field the helicity of the waveguides breaks z-reversal symmetry as proposed for Floquet topological insulators[46]. This structure results in the propagation of light in a one-way edge state following the topology of the material and protected from scattering.

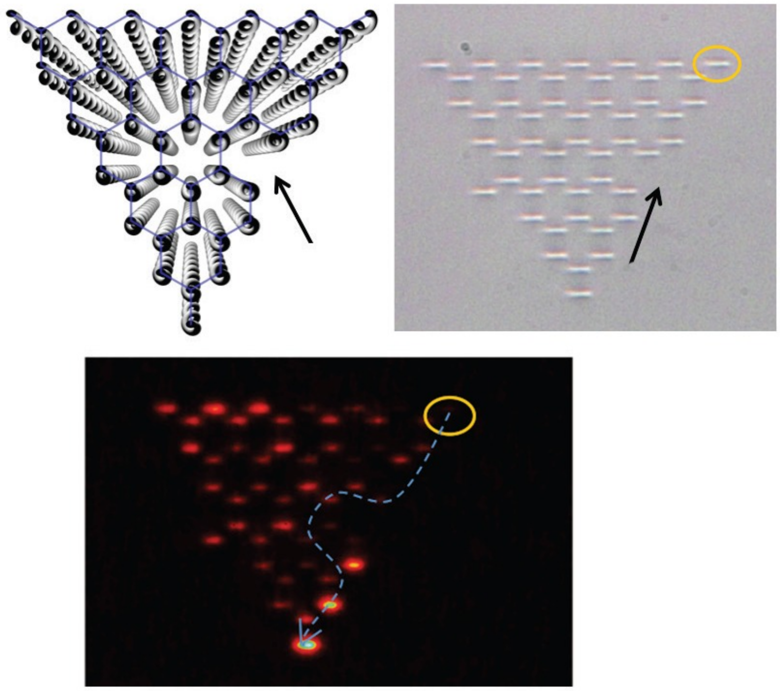


Figure 8: (a) Observation of photonic topological protection in a honeycomb array of waveguides with a 15 µm neighbor distance and 8 µm helix radius. (b) A missing waveguide at the edge acts as a defect; yellow circle indicates the waveguide with injected light. (c) Injected light moves clockwise and avoids the defect. Backscattering is suppressed due to topological protection. Such interesting robustness to perturbation has still to be studied[45].

Another fascinating phenomenon is called vortex beam which carries orbital angular momentum similar to spin-orbit coupling. This effect has been demonstrated in the near field[47] but also in the far field[48]. In this last case the structure is helical, 30 nm thick, made by ion milling on both side of a 300 nm thick metallic film. With such a structure the optical field has a rotating phase in the far field and the path-reversal symmetry is broken giving an optical diode effect without the use of a magneto-optic effect.

In analogy to stereoisomers in chemistry, the new concept of nanophotonics stereometamaterials has been proposed recently[49]. Stereometamaterials are made of metamaterials with the same constituents but different spatial arrangements. The twisting of stereometamaterials offers a way to engineer complex plasmonic nanostructures with a tailored electromagnetic response.

Thanks to the development of nanotechnologies a new range of applications is now open with materials structured at dimension smaller than a few tens of nanometers. However, to use electromagnetic theory, it is necessary to understand how light of wavelength in the range of 500 nm interacts with a nano object of a few nanometers. At such a scale a link must be made between quantum theory and electromagnetism. The notion of refractive index must be revisited.

4. BACK TO BASIC 2: REFRACTIVE INDEX AND QUANTUM STRUCTURES

The refractive index is the quantity which characterizes the interaction of light with matter. For non-metallic materials the absorption is large when the light frequency matches the resonant frequency of oscillators. As example, in the infrared range the absorption bands correspond to vibrational or rotational modes of molecules. In dielectric materials nucleus-electron couples compose oscillators with resonant frequencies corresponding to wavelengths in the violet, near UV or UV.

Considering the volume of the atom and the wavelength, a large number of such oscillators are excited together by the incident light and it is the incoherent sum of the response of each oscillator which governs the absorption. Even for a perfectly pure material the spectral absorption band is not infinitely thin. Many different phenomena induce a band widening: dispersion of the individual oscillator response, phonon coupling, collisions or Doppler effect in gas, natural widening, Förster coupling. It is then very difficult to develop a full model. When light frequency does not correspond to a resonant frequency the optical wave is weakly coupled to the local oscillators and is then only delayed without being attenuated. The real part of the refractive index which is used to take into account this delay is dispersive with wavelength. All of this is widely described in numerous books, as example in [50]. In practice, the real and imaginary parts of the refractive index are generally obtained from measurements.

So we see that electrons and photons have a linked destiny. Resonant frequency can correspond to the energy necessary for electrons to go from a fundamental state to an excited state. Because the atoms are periodically arranged, electron in semiconductors have their energy distributed in the valence band or, when excited, in the conduction band. To jump from the valence band to the conduction band the material must receive energy larger than the band gap. So, under the gap wavelength, light is absorbed. Electron behavior can be completely different when the semiconductor is a nano crystal of a few nanometers wide in 1D, 2D or 3D dimensions.

Indeed, when a semiconductor material is structured in dimensions below the thermal de Broglie wavelength, the electrons in the nanoparticle will give a coherent response to an optical wave[51]. The thermal de Broglie wavelength is given by:

$$\lambda_B = \frac{h}{\sqrt{2m_e^* k_B T}} \tag{3}$$

where m_e is the effective mass of the electron, k_B the Boltzmann constant and T the temperature. λ_B can be seen as the coherence length of the local oscillators.

When the material of nanometric dimension is surrounded by another semiconductor of larger bandgap we can have quantum confinement. Then the electrons and holes can only take discrete values of energy in the valence band and conduction band which depend on the size. So, the electrons in a quantum dot behave like in an atom with different discrete possible energies[52]. This has of course direct consequences on the optical properties[53]. Each possible energy level corresponds to an absorption maximum so that the absorption band is modulated contrary to that of the corresponding bulk semiconductor. Obviously, as the real and imaginary parts of the refractive index, n and k, are linked by Kramers-Krönig relations, n is also changed.

There are several accurate models to study electron steady states for single quantum structures. The energy values and their corresponding wave functions can easily be obtained with the approximation of the effective mass. By adding corrections for the non parabolicity of the band and Coulomb coupling between electron and hole excellent agreement with experimental results can be obtained[54]. Rigorous ab initio calculation can also be used but needs more computer power.

It is worth noting that the equations used to look for electron eigenstates in 2D structures (quantum wells - QWs), 1D structures (quantum wires) or 0D structures (spherical quantum dots -QDs) are similar to those used to find the propagation constant of the guided propagation eigenstates in planar waveguides, optical fibers, or resonant optical modes in spherical microcavities, respectively.

So, the refractive index of semiconductor nano objects can be tuned not only by using different materials but also by controlling their size and this has a great interest for applications in optics. More than that, like atoms, these quantum objects are luminescent with an efficiency which can be very large. The luminescent band can be tuned with the size of the objects. The luminescent band is Stock shifted in front of the absorption band[55]. QWs are widely used for many years to make semiconductor lasers[56] or photodetectors[57]. QDs have already many applications in particular in biology, for single photon generation, to enhance solar cell efficiency [58]. The demonstration of quantum confinement has been shown for a lot of semiconductor materials. The interest in environment friendly materials leads to the study of QDs made of carbon and even of organics like peptides for which very promising results have been obtained[59]. Such peptides can also be arranged in nanotubes.

When quantum dots are put in a photonic structure with a controlled density of optical states like a grating, the spatial emission diagram can also be mastered[60].

5. COUPLING EFFECTS

In physical systems electronic or optical modes can simply add or can interfere in the case of coherent coupling. Many physical systems are composed of coupled sub systems. When the material is structured in low dimension, light generally interacts with a lot of individual structures together and the results are strongly different if the different parts are coupled or not.

It is well known that two coupled resonators of the same frequency may form a system with a frequency splitting. It is interesting to see that this similarly applies to both optical and electronic systems.

We will only consider here steady states.

5.1 Coupling in optics

In many optical systems coupling effects drive the response. As an example, a multilayer stack HLHL2HLHL2HLHLH, where H and L are quaterwave layers of high and low index respectively, exhibits two passing bands around the passing band of a single FP of formula HLHL2HLHLH (Fig. 9). So, multiple band pass filters can be made by coupling resonant cavities[61].

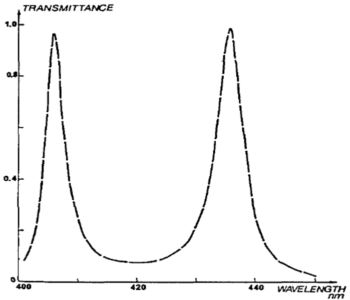


Figure 9: calculated spectral transmission of the design glass/(HLHLH)^3/glass. The centering wavelength is 420 nm[61].

A mode guided in the thickness of a layer corresponds also to a resonance of the optical wave. Beside we could consider such a propagation mode as a mode of a FP, the mirrors of which are composed of the totally reflecting layer surfaces. A prism can be used to excite such a mode. The guided mode is then leaky and the continuum of the free space propagation interferes with the resonant guided mode. Dark lines and interference fringes can then be seen in the reflected beam when using a monochromatic incident beam with an angular aperture of a few degrees (Fig. 10)[62].

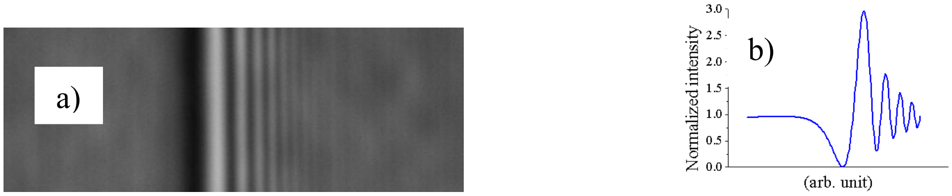


Figure 10: intensity reflected on a prism coupled to a planar waveguide. a) Measurement; b) Calculation[62].

The same kind of phenomenon can also be found in the Wood anomalies when a resonant surface wave is excited with a grating[63]. We are then concern with a Fano resonance[64] leading to a dissymmetry of the resonance peak. Fano resonance concerns numerous physical phenomena including nuclear, atomic, molecular, condensed mater physics and photonics. In this last field, more than the cases considered, Fano resonances are also obtained with plasmonic structures, photonic crystals and metamaterials. An excellent review of “Fano resonances in nanoscale structures” is given in [65].

When metallic nanoparticles (NPs) are close enough, plasmon resonances are coupled between the NPs. This induces a strong enhancement of the optical field between the NPs (Fig. 11)[66].

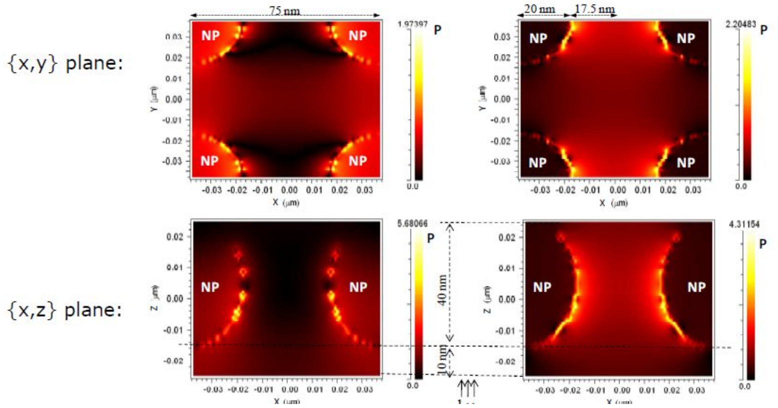


Figure 11: Ag NPs in P3HT :PCBM blend. Spatial distributions of the normalized P power densities[2] of the electromagnetic field for 2 different planes at 2 wavelengths (left: 450 nm; right: 600 nm)[66].

This is widely studied for Surface Enhanced Raman Scattering (SERS)[67]. It is interesting to note that such a field enhancement can also be obtained with semiconductor NPs (Fig. 12)[68].

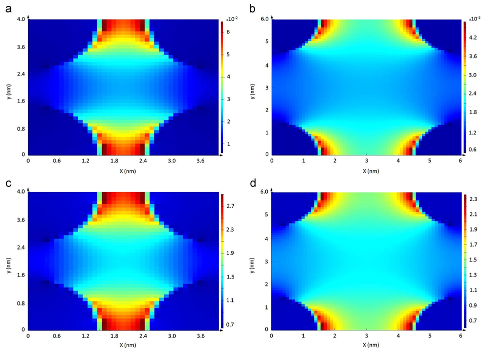


Figure 12: CdSe NPs surrounded by P3HT material. Electric field distribution in the NPs plane for two wavelengths and two different distances between the NPs. (a) The distance between the NPs is of 1nm and the simulation wavelength is 0.4 µm. (b) The distance between the NPs is 3 nm and the simulation wavelength is of 0.4 µm. (c) The distance between the NPs is 1 nm and the simulation wavelength is of 1 µm. (d) The distance between the NPs is 3 nm and the simulation wavelength is of 1 µm[68].

5.2 Electronic coupling

Atomic couplings in molecules induce vibrational modes (phonons) which split the electron level of the atoms. The same behavior is obtained with coupled quantum wells (QWs)[53]. Fig. 13 shows the energy splitting for 2, 3, 4, and 5 coupled QWs positioned at a distance of 1nm.

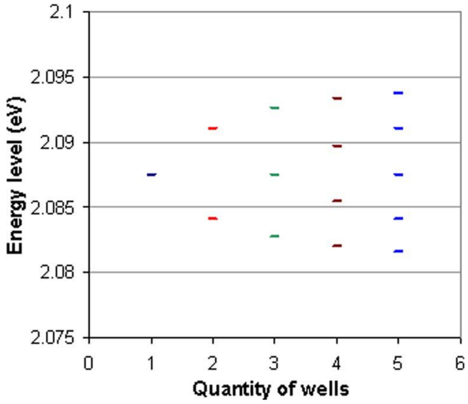


Figure 13: Splitting of the highest energy level of electrons in coupled quantum wells when considering 1, 2, 3, 4, and 5 identical coupled wells. Each well has a depth of 2.9 eV, a width of 1 nm, and the distance between the wells is also 1 nm[53].

When this coupling distance increases the energy difference between two degenerated levels is reduced. When the number of coupled QWs increases, the number of degenerated levels increases of the same amount. These sub levels are distributed in an energy band of a width which depends on the coupling distance. So, a system composed of a lot of coupled QWs has multiple energy bands possible for its electrons. A similar behavior is obtained for coupled QDs.

In a QDs cluster electrons can be localized around one QD or delocalized in the whole structure like electrons in different molecular orbital. So, QDs clusters can be considered as artificial molecules. Their electronic properties and then their optical properties can be tune if we can control the QDs size and their coupling distance by adequate ligands. This paves the way to a new class of materials made with such QDs clusters or artificial molecules.

The interesting new field of QDs doped with magnetic ions is part of solotronics which considers the properties of semiconductors with a single dopant or a single defect[69]. This research could help in the development of spintronics. Nonlinear optical properties of these materials would be worth studying.

6. LOW DIMENSIONAL OPTICS FOR THIN FILM SOLAR CELLS

There are five main challenges to develop competitive solar cell. At first the cell should capture the maximum of the solar photons, then these photons should become charge carriers with the best efficiency possible, third these carriers should not be lost before arriving to the electrodes, fourth the cell should last as long as possible and finally the materials and the processes used should be environment friendly. Here we will only focus on the use of low dimensional optics for light trapping or for improving sun light absorption on a wide spectrum.

In thin film solar cells, knowing the refractive indices, the thickness of each layer can be optimized to increase the absorption of optical field in the active layer, on the whole useful solar spectrum (Fig. 14)[70]. The dissipated energy of light within the thin-film solar cell Q(z,λ), which depends on the vertical position in the stack z and on the wavelength λ, is directly correlated to the squared modulus of the electromagnetic field by the formula:

$$Q(z,\lambda) = \alpha(\lambda) n_i / n_0 \, |E(z)/E_0|^2 \qquad (4)$$

Where $\alpha(\lambda)$ is the spectral extinction coefficient, n_i is the refractive index of the ith film, n_0 is the refractive index of the incident medium, E_0 is the amplitude of the incident electromagnetic field and E(z) the amplitude of the electromagnetic field at the vertical position z.

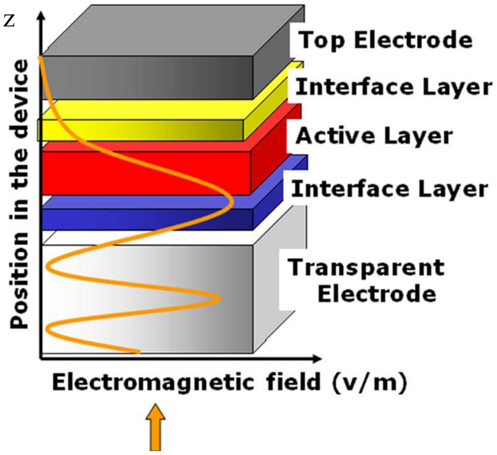


Figure 14: Scheme of the electromagnetic field in a thin-film solar cell[70].

Antireflection layer can be deposited on top of solar cell but solar cell surface or electrodes are also generally structured to make an antireflection effect and to increase the light path in the active material. As described before, photonic crystals can be particularly efficient for organic solar cells[31].

When silicon surface is nanostructured low reflection and strong absorption of visible light can be obtained. Such silicon is called black silicon and can be made by different techniques leading to different surface structures. By using the Electroless Metal Assisted Chemical Etching technique (EMACE)[71] very thin nanowire (~130 nm) of 25 µm length can be obtained (Fig.15).

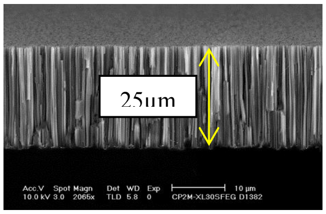


Figure 15: SEM picture of silicon nanowires obtained by Electroless Metal Assisted Chemical Etching technique (EMACE)[73].

This kind of structure is very interesting to make solar cells because electrons are conducted in the axis of the wires while photons are well absorbed for a large range of incident angles. The main challenge is to cover the wires with another material in such a way to make junctions[72]. Conformal PEDOT Electrodeposition under illumination has been performed successfully[73].

Thank to plasmon resonances, coupled metallic nanoparticles embedded in organic solar cells increase light absorption. By using Ag NPs and optimizing both NPs size and distribution the absorption can be increased in the active medium in the wavelength range of 500 nm to 650 nm for which the organic material is weakly absorbing[74].

Semiconductor quantum dots present different interests for thin film solar cells. By adequately choosing the material and the QDs size the band gap can be tuned. The luminescence can be used to make a down conversion layer changing UV into visible light[68]. This has two advantages which are to convert inefficient UV wavelength in more efficient wavelengths and to protect the solar cell from UV to increase its lifetime. QDs can also be used to create charge carriers. Depending on their size, CdSe nanoparticles produce electrons and holes by absorbing photons with different energies across the visible spectrum[75]. These nanoparticles can replace dye molecules in TiO_2 sensitized dye solar cells, the charges being transferred to the TiO_2 by resonant transfer. To increase the photovoltage, hot carriers created by high energy photons must be extracted from the photoconverter before they cool down by collisions with the atoms or phonons. The discretization of charge carrier energy in QDs increases the lifetime of the excited states and could leave enough time to collect hot electrons, leading to an increase of the open circuit voltage.

The photocurrent can be increased when energetic hot carriers generated in QDs by short wavelengths produce two or more electron-hole pairs through impact ionization (Multiple Exciton Generation: MEG)[76].

The association of different semiconductor QDs and photovoltaic materials should lead in the near future to very high efficiency thin film solar cells[77]. Up to 8.55% efficiency has recently been obtained[78]. Both the optical and electronic properties can take advantage of such NPs. Band diagram and charges transfer should be judiciously managed in particular by looking for resonant energy transfer (Fig.16). The solar cell lifetime is also a very important issue.

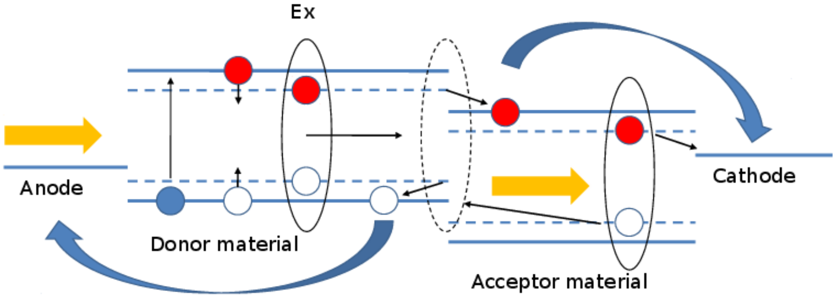


Figure 16: Scheme of charge transports in a simplified solar cell. The red circles represent electrons and the white circles represent holes[48].

New cheap and environment friendly QDs materials are under study to respond, at least partly, to the energy crisis and the future decay of polluting fossil coal, oil and gas.

7. CONCLUSION

This paper contains a number of original concepts for low-dimensional optics. Its purpose is to delineate and to make accessible a coherent outline of the principles of the physical phenomena based upon low-dimensional optics. Cross-fertilization between quantum physics, photonics and material sciences considering together electronic and optical properties of components structured at different scales paves the way toward new concepts and new applications.

Materials technology has traditionally been a key driver for progress in photonics. Examples are the optical fiber, quantum wells, wires and dots, erbium amplifiers. Nanostructured thin films, photonics crystals and metamaterials can generate step changes in knowledge for new applications at the crossroads between different technologies and disciplines. With progresses in surface chemistry, coupling of quantum structures with appropriate ligands, a very wide field is just opening with nano objects of engineered properties. Development of new devices based on metallic nanoparticles, nanostructured surfaces, controlled randomly rough films will have high potential for new photonic applications. The complete evaluation and definition of potential novel applications of such devices still require intensive research in the field, enabling to perform breakthroughs in optical components for industrial applications. All these technological fields will benefit both to new, high-tech industries and higher-value traditional industries. Facing the entire unknown we feel ourselves stupid but, as write Martin A. Schwartz, this is essential in scientific research[79].

REFERENCES

[1] Weinberg, S., 1979 Nobel Prize Lecture

[2] Palma, R.M. and Lakhtakia, A. co-edited, [Engineered Biomimicry], Elsevier publish. (2013)

[3] Mandel, L., Wolf, E., [Optical Coherence and Quantum Optics], Cambridge University Press, September 1995

[4] Berginc, G.,"Small-slope approximation method : a further study of vector wave scattering from two-dimensional surfaces and comparison with experimental data," Progress in Electromagnetic Research, PIER 37, Zhang, Y. and Grzegorczyk, T. M. (Ed.) EMW publishing Cambridge, Massachusetts, USA, Pages 251-287, (2002).

[5] Strudley, T., Zehender, T., Blejean, C., Bakkers, E. P. A. M. and Muskens, O. L., "Mesoscopic light transport by very strong collective multiple scattering in nanowire mats," Nature photonics online DOI: 10.1038/NPHOTON.2013.62

[6] Brissonneau, V., Escoubas, L., Flory, F., Berginc, G., Maire and G., Giovannini, H., "Laser assisted fabrication of random rough surfaces for optoelectronics," Appl. Surf. Science, Vol. 258, Issue 23, Pages 9171–9174 (2012).

[7] Macleod, A., [Thin film optical filters], IOP, Third edition (2001).

[8] Gérard, P., Benech, P., Ding, H. and Rimet, R., "A simple method for the determination of orthogonal radiation modes in planar multilayer structures," Opt. Com., Vol. 108, Issues 4–6, 1 June 1994, Pages 235–238

[9] Purcell, E. M., Phys. Rev. 69, 681 (1946)

[10] Jacob, Z., Kim, J.-Y., Naik, G.V., Boltasseva, A., Narimanov, E.E. and Shalaev ,V.M. "Engineering photonic density of states using metamaterials," Appl Phys B 100: 215–218 (2010)

[11] Rigneault, H., Amra, C., Robert, S., Monneret, S., and Flory, F., "Propriétés radiatives d'atomes luminescents placés dans une microcavité planaire," Ann. Phys. 20, 625-626 (1995)

[12] Saxena, K., Jain, V. K. and Metha, D.S., "A review on the light extraction techniques in organic electroluminescent devices," Opt. Mat., 32, 221-233 (2009).

[13] Maier, S. A., [Plasmonics: Fundamentals and Applications], Springer Verlag (New York), XXV, (2007)

[14] Lal, S., Clare, S. E., and Halas, N. J., "Nanoshell-enabled photothermal cancer therapy: Impending clinical impact," Accounts Chem. Res. 41, 1842–1851 (2008).

[15] Huang, X. H., Neretina, S., and El-Sayed, M. A., "Gold nanorods: From synthesis and properties to biological and biomedical applications," Adv. Mater. 21, 4880–4910 (2009).

[16] Stockman, M. I., "Nanoplasmonics: past, present, and glimpse into future," Opt. Exp. Vol. 19, No. 22 / 22029-22106, 24 October 201. http://dx.doi.org/10.1364/OE.19.022029

[17] Sakoda, K., [Optical Properties of Photonic Crystals], Springer Series in Optical Sciences, Edts.: Rhodes, W. T., Asakura, T., Brenner, K.-H., Vol. 50, Springer Verlag Berlin Heidelberg New York, 2nd Edition (2005)

[18] Flory, F., Escoubas, L., Berginc, G., "Optical properties of nanostructured materials: a review," J. Nanophoton. 5(1), 052502 (2011).

[19] Flory, F. and Escoubas, L., "Optical properties of nanostructured thin films," Progress in Quantum Electronics, 28, 89 – 112 (2004).

[20] Lakhtakia, A. and Messier, R., Chapter 9 in [Sculptured Thin Films: Nanoengineered Morphology and Optics], SPIE Press, Bellingham, WA (2005).

[21] Flory, F., Endelema, D., Pelletier, E., Hodgkinson, I., "Anisotropy in thin films: modelization and measurement of guided and non-guided optical properties. Application to TiO_2 films", Appl. Opt., 32, n°28, 5649-5659 (1993).

[22] Jänchen, H., Endelema, D., Kaiser, N., and Flory, F., "Determination of the refractive indices of highly biaxial anisotropic coatings using guided modes, Pure and Appl. Opt., JEOS, **5**, n°4, 405-415 (1996).

[23] Mackay, T. G. and Lakhtakia, A., “Modeling chiral sculptured thin films as platforms for surface plasmonic polaritonic optical sensing,” IEEE Sensors J., 12(2), 273–280 (2012), http://dx.doi.org/10.1109/JSEN.2010.2067448.

[24] Wu, Q., Hodgkinson, I. J., and Lakhtakia, A., “Circular polarization filters made of chiral sculptured thin films: experimental and simulation results,” Opt. Eng. 39(7), 1863–1868 (2000) http://dx.doi.org/10.1117/1.602570

[25] Faryad, M., Hall, A. S., Barber, G. D., Mallouk, T. E. and Lakhtakia, A., “Excitation of multiple surface-plasmon-polariton waves guided by the periodically corrugated interface of a metal and a periodic multilayered isotropic dielectric material,” J. Opt. Soc. Am. B, Vol. 29, No. 4 (2012).

[26] Faryad, M., Lakhtakia, A., “The circular Bragg phenomenon,” Advances in Optics and Photonics 6, 225–292 (2014)http://dx.doi.org/10.1364/AOP.6.000225

[27] Pulsifer, D. P., Faryad, M., Lakhtakia, A., Hall, A. S., and Liu, L., “Experimental excitation of the Dyakonov–Tamm wave in the grating-coupled configuration,” Opt. Lett., Vol. 39, No. 7, 2125-2128 (2014)

[28] Flory, F., Escoubas, L.and Lazaridés, B., "Artificial anisotropy and polarizing filters," Appl. Opt., 41 (16), 3332-3335, (2002).

[29] Lakhtakia, A., Demirel, M. C., Horn, M. W., Xu, J., “Six Emerging Directions in Sculptured-Thin-Film Research,” Advances in Solid State Physics Volume 46, 295-307 (2008).

[30] Wenshan, C., Vladimir, S. ,[Optical Metamaterials. Fundamentals and Applications], 2010, springer verlag (2010)

[31] Duché, D., Escoubas, L., Simon, J-J., Torchio, Ph., Vervisch, W., Flory, F., “Slow Bloch modes for enhancing the absorption of light in thin films for photovoltaic cells,” Appl. Phys. Lett., 92, 193310 (2008).

[32] Veselago, V. G., “The electrodynamics of substances with simultaneously negative values of ε and μ,” Soviet Physics Uspekhi, vol. 10, no. 4, p. 509, 1968.

[33] Kildishev, A. V., Shalaev, V. M., “Transformation optics and metamaterials,” Physics - Uspekhi 54 (1) 53-63 (2011) DOI: 10.3367/UFNe.0181.201101d.

[34] Pendry, J. B., Schurig, D. and Smith, D. R., “Controlling Electromagnetic Fields,” Science 312, 1780-1781 (2006).

[35] Brückner, J.B., Le Rouzo, J., Escoubas, L., Berginc, G., Calvo-Perez, O., Vukadinovic, N., and Flory, F., “Metamaterial filters at optical-infrared frequencies,” Optics Express, Vol. 21, No. 14, 16992 (2013) DOI:10.1364/OE.21.016992

[36] Poddubny, A., Iorsh, I., Belov P. and Kivshar, Y., “Hyperbolic metamaterials,” Nature Photonics, Vol 7 (2013)

[37] Jacob, Z., Smolyaninov, I. I. and Narimanov, E. E., “Broadband Purcell effect: Radiative decay engineering with metamaterials,” APL 100, 181105 (2012) doi :10.1063/1.4710548

[38] Lakhtakia, A., “Exhibition of circular Bragg phenomenon by hyperbolic, dielectric, structurally chiral materials,” Journal of Nanophotonics Vol. 8, 083998 1-9, 2014 (2000), http://dx.doi.org/10.1117/1.602570.

[39] Chan, C. T., Hang, Z.H. and Huang, X., “Dirac Dispersion in Two-Dimensional Photonic Crystals,” Advances in OptoElectronics, Volume 2012, Article ID 313984, 11 pages doi:10.1155/2012/313984

[40] Plihal, M. and Maradudin, A. A., “Photonic band structure of two-dimensional systems: the triangular lattice,” Phys. Rev. B, vol. 44, no. 16, 8565–8571, 1991.

[41] Moitra, P., Yang, Y., Anderson, Z., Kravchenko, I. I., Briggs, D. P. and Valentine, J., “Realization of an all-dielectric zero-index optical metamaterial,” Nature Photonics 7, 791–795 (2013) doi:10.1038/nphoton.2013.214

[42] Shekhar, P., Atkinson J. and Jacob, Z., [Hyperbolic metamaterials: fundamentals and applications], Cornell University Library, Mesoscale and Nanoscale Physics (cond-mat.mes-hall), eprint arXiv:1401.2453, (2014)

[43] Wang, Z., Chong, Y. D., Joannopoulos, J. D. and Soljačić, M., “Reflection-Free One-Way Edge Modes in a Gyromagnetic Photonic Crystal,” Phys. Rev. Lett. 100, 013905 (2008). DOI: 10.1103/PhysRevLett.100.013905

[44] Rechtsman, M. C., Zeuner, J. M., Plotnik, Y., Lumer, Y., Podolsky, D., Dreisow, F., Nolte, S., Segev, M. and Szameit, A., “Photonic Floquet topological insulators,” Nature 496, 196–200 (11 April 2013) doi:10.1038/nature12066

[45] Haldane, F. D. M. and Raghu, S., “Possible Realization of Directional Optical Waveguides in Photonic Crystals with Broken Time-Reversal Symmetry,” Phys. Rev. Lett. 100, 013904 (10 January 2008). http://dx.doi.org/10.1103/PhysRevLett.100.013904

[46] Lindner, N. H., Refael, G. and Galitski, V., “Floquet topological insulator in semiconductor quantum wells,” Nature Physics7, 490–495 (2011) doi:10.1038/nphys1926

[47] Pendry, J.B., “A chiral route to negative refraction,” Science 306, 1353-1355 (2004)

[48] Gorodetski, Y., Drezet, A., Genet, C. and Ebbesen, T. W., “Generating Far-Field Orbital Angular Momenta from Near-Field Optical Chirality,” Phys. Rev. Lett. 110, 203906 (2013)

[49] Liu, N., Liu, H., Zhu, S. and Giessen, H., “Stereometamaterials,” Nature Photonics 3, 157 - 162 (2009) Published online: 22 February 2009 | doi:10.1038/nphoton.2009.4

[50] Born M. and Wolf, E., [Principles of optics], 7th edition, Cambridge University Press (2007)

[51] de Broglie, L.V. "On the Theory of Quanta" Thesis (1925)

[52] Ekimov, A.I., Efros, A.L., Onushchenko, A.A., “Quantum size effect in semiconductor microcrystals,” Solid State Com., vol 56, 921–924 (1985)

[53] Flory, F., Chen, Y.-J., Lee, C.-C., Escoubas, L., Simon, J.-J., Torchio, P., Le-Rouzo, J., Vedraine, S., Derbal-Habak, H., Shupyk, I., Didane, Y. and Ackermann, J., “Optical properties of dielectric thin films including quantum dots”, Appl. Opt. 50 (9), 129-134 (2011)

[54] Thierry, F., Le-Rouzo, J., Escoubas, L., Berginc, G., “A new and fast numerical method for the determination of the optical properties of quantum structures,” oral presentation at Nanophotonic Materials XI, SPIE Optics + Photonics symposium, San Diego (August 2014)

[55] Demchenko, D.O., Wang, L.W., “Optical transitions and nature of Stokes shift in spherical CdS quantum dots,” Phys. Rev. B 73, 155326 – (2006).

[56] Faist, J., Capasso, F., Sivco, D. L., Sirtori, C., Hutchinson, A. L. and Cho, A. Y., “Quantum Cascade Laser,” Science 22 April 1994: Vol. 264, no. 5158, 553-556 DOI: 10.1126/science.264.5158.553

[57] Levine, B. F., “Quantum well infrared photodetectors,” J. Appl. Phys. 74, R1 (1993); http://dx.doi.org/10.1063/1.354252

[58] Prabhakaran, P., Kim, W. J., Lee, K.S. and Prasad, P. N., “Quantum dots (QDs) for photonic applications,” Opt. Mat. Exp. Vol. 2, No. 5, 578-593 (2012).

[59] Amdursky, N., Molotskii, M., Gazit, E. and Rosenman, G., “Elementary Building Blocks of Self-Assembled Peptide Nanotubes,” J. Am. Chem. Soc. 132, 15632–15636 (2010).

[60] Lin, H. J., Flory, F., Le-Rouzo, J. and Lee, C.C., “investigation of nanostructured hybrid organic/ semiconductor quantum dots in thin film and spatial distributed of the emission,” Appl. Opt., Vol. 53, Issue 4, A169-A174 (2014) http://dx.doi.org/10.1364/AO.53.00A169

[61] Pelletier, E., Macleod, H. A., “Interference filters with multiple peaks,” J. Opt. Soc. Am., Vol. 72, No. 6, 683-687 (1982).

[62] Monneret, S., Huguet-Chantôme, P., Flory, F., "m -lines technique: prism coupling measurement and discussion of accuracy for homogeneous waveguides, " Journal of Optics A: Pure and Applied Optics, Vol. 2, Number 3, 188-195 (2000)

[63] Wood, R.W. “On a remarkable case of uneven distribution of light in a diffraction grating spectrum,” Philos. Mag. 4, 396–402 (1902)

[64] Fano U., “Effects of Configuration Interaction on Intensities and Phase Shifts,” Phys. Rev. 124, 1866–1878 (1961) doi:10.1103/PhysRev.124.1866

[65] Miroshnichenko, A. E., Flach, S. and Kivshar, Y. S., “Fano resonances in nanoscale structures,” Rev. Mod. Phys. 82, 2257-2298 (2010) doi: 10.1103/RevModPhys.82.2257

[66] Duche, D., Torchio, Ph., Escoubas, L., Monestier, F., Simon, J.J., Flory, F., Mathian, G., “Improving Light Absorption in Organic Solar Cells by Plasmonic Contribution,” Solar Energy Materials and Solar Cells, Vol. 93, 1377-1382 (2009)

[67] Stiles, P. L., Dieringer, J. A., Shah, N. C. and Van Duyne, R. P., “Surface-Enhanced Raman Spectroscopy,” An. Rev. of Anal. Chem., Vol. 1, 601-626 (2008)

[68] Lin, H.J., Vedraine, S., Le-Rouzo, J., Chen, S.H., Flory, F. and Lee, C.C., “Optical Properties of Quantum Dots Layers: Application to Photovoltaic Solar Cells,” Solmat, Vol. 117, 652–656 (October 2013).

[69] Kobak, J., Smolenski, T., Goryca, M., Papaj, M., Gietka, K., Bogucki, A., Koperski, M., Rousset, J.-G., Suffczynski, J., Janik, E., Nawrocki, M., Golnik, A., Kossacki P. and Pacuski, W., “Designing quantum dots for solotronics, “Nat. Com., 5:3191 DOI: 10.1038/ncomms4191.

[70] Monestier, F., Simon, J.J., Torchio, P. Escoubas, L., Flory,F., Bailly,S., de Bettignies, R., Guillerez, S. and Defranoux, C., “Optical modeling of organic solar cells based on CuPc and C-60,” Appl. Opt. Vol 47, 13, C251-C256 (2008).

[71] Huang, Z., Geyer, N., Werner, P., de Boor, J., Gösele, U., “Metal-assisted chemical etching of silicon: a review.,” Adv. Mater., 23, 285–308 (2011).

[72] Yu, P, Tsai, CY, Chang, JK, Lai, CC, Chen, PH, Lai, YC, Tsai, PT, Li, MC, Pan, HT, Huang, YY, Wu, CI, Chueh, YL, Chen, SW, Du, CH, Horng, SF, Meng, HF, “13% Efficiency Hybrid Organic/Silicon-Nanowire Heterojunction Solar Cell via Interface Engineering,” ACS Nano, 7 (12), 10780–10787 (2013), DOI: 10.1021/nn403982b.

[73] Zhu, M., “Silicon nanowires for hybrid solar cells,” PhD Thesis, Ecole Centrale Marseille, December 2013.

[74] Vedraine, S., Torchio, P., Duché, D., Flory, F., Simon, J.-J., Le-Rouzo, J., Escoubas, L., “Intrinsic absorption of plasmonic structures for organic solar cells,” Solmat, , 95 : S57-S64 (2011)

[75] Kongkanand, A., Tvrdy, K., Takechi, K., Kuno, M. and Kamat, P. V., “Quantum Dot Solar Cells. Tuning Photoresponse through Size and Shape Control of CdSe-TiO2 Architecture,” J. Am. Chem. Soc., 130, 4007-4015 (2008).

[76] Nozik, A. J., “Multiple exciton generation in semiconductor quantum dots,” Chemical Physics Letters, vol 457 (1-3), 3-11(2008).

[77] Kamat, P.V., “Quantum Dot Solar Cells. The Next Big Thing in Photovoltaics,” J. Phys. Chem. Lett., 2013, 4 (6), 908–918 DOI: 10.1021/jz400052e

[78] Chuang, C.-H. M., Brown, P. R., Bulovic, V. Bawendi, M. G., “Improved Performance and Stability in Quantum Dot Solar Cells through Band Alignment,” Nat. Mater. (2014). DOI: 10.1038/nmat3984.

[79] Schwartz, M. A., “The importance of stupidity in scientific research,” J Cell Sci 121,1771 (2008) doi: 10.1242/jcs.033340