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Photonic Band Gap Engineered Materials for Controlling the Group Velocity of Light

Andrea Blanco[1] and Joseba Zubía[2]
[1]Tecnalia Research & Innovation
[2]University of the Basque Country
Spain

1. Introduction

The power of creating engineered materials in which one can customize the propagation of light unleashes a huge range of fascinating applications. Commonly, these materials are based on the appearance of a forbidden frequency range, after which they are named photonic band gap materials or, more generally, photonic crystals. Photonic crystals are artificial, periodic arrangements of dielectric media with sub-wavelength periodicity lengths. As a consequence of the periodic dielectric function, in analogy with natural crystals where atoms or molecules are periodically spaced, a range of forbidden propagating energies may appear under the proper conditions, giving rise to a photonic band gap. Exploiting the effects associated to the photonic band gap, one can dramatically alter the flow of electro-magnetic waves (Joannopoulos et al., 2008).

One of the optical properties that can be radically modified in such materials is the group velocity of light pulses. Usually, the unmatched velocity of light (in vacuum c=299.792.458 m/s) is an advantage. Thanks to this fact, light confined within the core of an optical fiber could give a complete round to the equatorial circumference of Earth in 200 milliseconds (light in glass travels at c/1.5). In other cases, where processing the information carried by light pulses is needed, the huge speed of light entails a problem. In quantum optics, for instance, the quantum state of light can be stored for longer if light is slowed down. As another example, buffering and storing information on a photonic chip is crucial in all-optical communications routers and optical computing, the same as electronic RAMs are essential in conventional networks and computers. Furthermore, countless applications arise from the increase of energy density, and consequent stronger light-matter interaction, due to slower light propagation. Higher energy density implies enhanced nonlinearities, and therefore more efficient, compact, and low-power consuming nonlinear optical schemes, as Raman amplification or optical regenerators (Krauss, 2008). Stronger light-matter interaction is also beneficial for sensing applications, especially for biosening, and more efficient photovoltaic cells.

Unluckily, light is inherently difficult to control, not to mention how hard it is to store it. This is not only due to its speed, but also to the very nature of its basic unit, the photon, being massless and having no electric charge. A number of ingenious and diverse schemes to diminish the speed of light in a controllable fashion has been proposed, giving rise to the intriguing field of slow light. All slow light schemes are based in the same basic principle, in

spite of their interdisciplinary nature: the existence of a single sharp resonance or multiple resonances (Khurgin & Tucker, 2009). As it will be justified, photonic crystal devices are, to our understanding, the most promising approach for the development of practical photonic devices based on slow light.

This chapter begins by reviewing the motivation and principles of slow light, followed by a description and assessment of the different techniques to diminish the speed of light and the applications of this phenomenon. In a subsequent section the particularly promising approach of slow-light photonic crystal arrangements will be addressed. In that section, together with the fundamentals of photonic band gap materials, their simulation methods and fabrication techniques, simulations results and analysis on our designs of slow-light photonic crystal arrangements will be presented. The chapter will be concluded with an assessment of photonic band gap engineered materials as a technology for developing slow-light based devices for telecommunications and microwave photonics applications.

2. Slow light: From theory to practice

Being able of governing something as essentially free as light is captivating in itself. Along this section, the physical principles behind the drastic reduction of group velocity and the techniques to achieve it will be presented. However, what is more appealing about slow light is its significant number of applications. In practice, unfortunately, slow light entails severe difficulties and a noteworthy research effort is being done by many groups to cover the gap between theory and practical applications.

2.1 Principles of slow light

The term slow lights refers to the phenomenon of light propagation in media with reduced group velocity. It is thence convenient to throw some light on the concepts of group velocity, phase velocity, and front velocity. Fig. 1 serves as a reference for those concepts.

The group velocity is the speed at which the wave envelope, the overall shape of an amplitude varying wave, propagates. This is frequently considered to be the velocity of the information transported by light signals, which is correct for most cases. Nevertheless, as it will be discussed bellow, there are some exceptions to this statement. The group velocity of a wave in a certain medium corresponds to the velocity of light in vacuum, c, divided by the group index of the medium, n_g, and it is given by the equation

$$v_g = \frac{c}{n_g} = \frac{d\omega}{dk} \tag{1}$$

where ω is the angular frequency and k is the angular wave number. The variation ω with k is called the dispersion relation, and thence, the group velocity is given by the slope of the dispersion relation.

The phase velocity is the speed at which the phase of every particular frequency component of the wave travels and it is given by

$$v_p = \frac{\omega}{k} \tag{2}$$

It can be seen that for media in which ω varies linearly with k the phase and the group velocity coincide. However, in general, for dispersive media, phase and group velocities differ and both vary with frequency.

There is one last concept that it is worth to mention, the front velocity. The front velocity is the speed of the pulse leading edge, i.e. the velocity of the earliest part of a pulse. This is truly the velocity of the signal, i.e. of the information carried by the light wave. According to the principle of Einstein causality, information can never travel faster than light in vacuum and therefore the signal velocity it is always slower than c. This concept has led to discrepancies among the scientific community in the past, when some groups claimed measured superluminal *signal* velocity (Heitmann & Nimtz, 1994; Steinberg et al., 1993), menacing the validity of the special theory of relativity. In those experiments, the reported measured velocity corresponded to that of the peak of the photon's wave and that of the envelope of the signal, but not to the signal velocity itself. This is explained by the reshaping of the pulse along its propagation, so that its peak moves towards its leading edge. The velocity of the peak may be, in this case, faster than the velocity of light in vacuum, but the signal (front) velocity will remain bellow c. In other words, even if the group velocity appears to be higher than c, causality still holds.
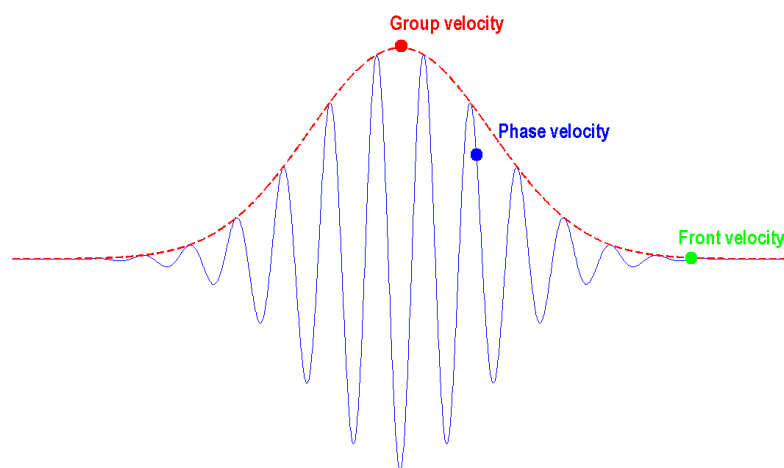

Fig. 1. Representation of the points of measurement for the group, phase and front velocities

Coming back to the point of slow light, it has been defined as the phenomenon of light propagation at reduced group velocity. Bearing in mind Eq. 1, it is straightforward to see that slow light relies on increasing the group index of the medium, which is given by

$$n_g = n + \omega \frac{dn}{d\omega} \tag{3}$$

The refractive index of the material n varies with frequency and can be slightly altered by making use of a plurality of phenomena, such as electro-optic or thermo-optic effects. Nonetheless, when aiming at a significant change in the group index, it is the second term in Eq. 3, $dn/d\omega$, the one that dominates, i.e. the dispersive behaviour of the media. This is the reason why sharp spectral resonances are always behind slow light techniques.

By making use of different approaches, that will be briefly reviewed in next section, extremely low group velocities have been achieved, as low as 17 m·s^{-1} (Hau et al., 1999).

Nonetheless, from the point of view of practical applications, a more useful figure of merit (FOM) than the absolute value of the group velocity itself is the number of pulse widths that can be delayed by the system. This FOM is given by the delay-bandwidth product, being the bandwidth inversely proportional to the duration of the pulse, and it gives an idea of the information storage capacity of the system (Boyd & Narum, 2007). The delay-bandwidth product is limited by two major impediments: the pulse distortion, mainly caused by group velocity dispersion, and the propagation loss. These two factors present different origin and significance for each slow-light approach but it is a common feature to all of them that higher delays come at the expense of bandwidth reductions and, usually, of higher loss.

2.2 Techniques to achieve slow light

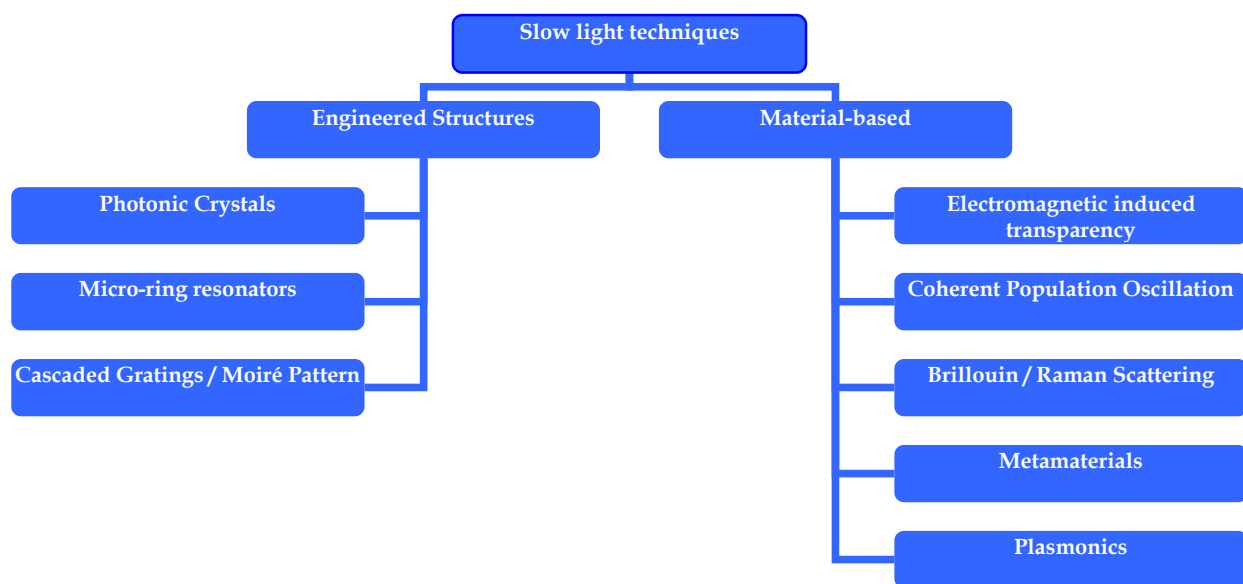In Fig. 2 we present a classification of the different approaches to slow light.

Fig. 2. Classification of the proposed approaches to slow light

How to control something that has no mass and no electric charge? These fundamental properties make the task of stopping light very challenging. However, far from being intimidated, science community has dedicated a great number of research efforts to 'trap' light. More specifically, these efforts try, not to store the photons, but the information that they carry.

In Fig. 2 slow light techniques have been separated into two subclasses: those based in modifying the waveguide dispersion by using engineered structures, such as gratings, photonic crystals or micro-ring resonators; and those based upon the change of material dispersion to large and positive values involving the use and modification of properties inherent to the material, e.g. the transmission spectrum or the scattering effects.

2.2.1 Material-based slow light generation

Within material-based methods, the exploitation of atomic resonances was the first to be discovered. Dramatic modifications of the velocity of light are often based on this principle. Highly dispersive media present extreme values of the group velocity and thus they are well

suited for realizing this kind of systems, as in electromagnetically induced transparency (EIT), and coherent population oscillations (CPO). EIT and CPO have been used to create narrow transparency windows in absorbing materials. These techniques, not only allow making controllable the degree of slowing (or speeding), but they also alleviate other important issues related to strong atomic resonances: excessive absorption and dispersion.

The electromagnetically induced transparency is a quantum effect that permits the propagation of light through a medium otherwise opaque. In (Hau et al., 1999), the extremely low speed of light of 17 m s^{-1} was achieved by exploiting this technique. The biggest disadvantages of EIT arise because the method has a highly limited operation bandwidth owing to its narrow transparency window and to higher-order dispersion effects. Moreover EIT relies on delicate interference between two quantum amplitudes and thus the presence of collisions or any other dephasing effect can destroy the interference. On the face of it, EIT requires cryogenic temperatures and atomic media, preventing its practical use.

The quantum coherence technique of coherent population oscillations is studied as an alternative to EIT, due to its larger bandwidth and because it is highly insensitive to dephasing effects. The CPO method relies on creating a spectral hole due to population oscillations. Slow light propagation with a group velocity as low as 57.5m/s was observed employing CPO at room temperature in a ruby crystal (Bigelow et al., 2003). However, significant delays can only be achieved for signals of a few kb/s.

More recently, stimulated Brillouin and Raman scattering have also been proposed as material-based methods for slowing light. Brillouin scattering arises from the interaction of light with propagating density waves or acoustic phonons. Raman scattering arises from the interaction of light with the vibrational or rotational modes of the molecules in the scattering medium. The main advantage of these techniques is that they make use of optical fibers, which is an unmatched medium in terms of low attenuation levels. They are very adequate to provide practical moderate delays as in (Gonzalez-Herraez et al., 2005). Unluckily, Brillouin presents a limited bandwidth due to its narrow gain linewidth while Raman presents reduced slow-light efficiency.

The innovative realm of metamaterials has also been explored for developing photonic buffers. Metamaterials are artificial composites with dramatically different electromagnetic properties. The most noticeable approach to storing light in metamaterials is presented in (Tsakmakidis & Hess, 2007). So far, this theoretical approach is unfeasible due to the material losses, and, difficulty of fabrication in a light wavelength scale.

Recently, novel approaches to slow light based on plasmonics have been proposed, as in (Søndergaard & Bozhevolnyi, 2007). The main argument for using plasmonics is that it overcomes the diffraction limit affecting photonics, i.e. surface plasmon polaritons (SPPs) enable focusing light in nanoscale while photonics is size-limited to a wavelength scale. The main limitation to plasmonics today is that plasmons tend to dissipate after only a few millimetres. For sending data longer distances, the technology would need a great breakthrough. SPPs are also very sensitive to surface roughness and they are difficult to excite efficiently, although some "tricks" (e.g. Kretschmann geometry) have been already proposed for their excitation.

2.2.2 Engineered structures for slow-light generation

Differing from the previously explained material-based methods, the following slow-light mechanisms use strong spatial resonances between electromagnetic waves travelling along special structures. The structure-based slow-light approaches can be materialized in various types of arrangements, such as Fabry-Perot resonators, cascaded fiber Bragg gratings (FBGs), photonic crystals defects, or ring resonators. In general, these approaches outperform material-based ones for high-bandwidth signals, due to the fact that material resonances have generally a narrow linewidth and are more limited by dispersion effects (Melloni et al. 2010).

The election of a slow-light technique strongly depends on the targeted application. Photonic crystals constitute, to our understanding, the most promising approach in order to build devices for applications as the ones outlined bellow: small operating power (dozens of μW per cell), compact footprint (cell size around 10μm²), and fast access to information (tens to hundreds of picoseconds). Contributing to its practicality are also the facts that they can be operated at room temperature offering wide bandwidth. Finally, their fabrication processes can be made compatible with CMOS technology, enabling the use of silicon industry mass manufacturing facilities, and thus reducing mass fabrication costs and simplifying its integration with electronic circuitry.

2.3 Practical applications of slow light

The very first consequence of slow light is light pulse delaying. This fact unleashes in itself a series of valuable applications as optical buffers for optical packet switching (OPS) (Blanco et al. 2009a; Tucker, 2009), tuneable delay-lines for optical synchronization and correlation (Willner et al., 2009), or photonic true-time delay beamforming for phased array antennas, radio-over-fiber and analog-to-digital conversion (Capmany & Novak, 2007).
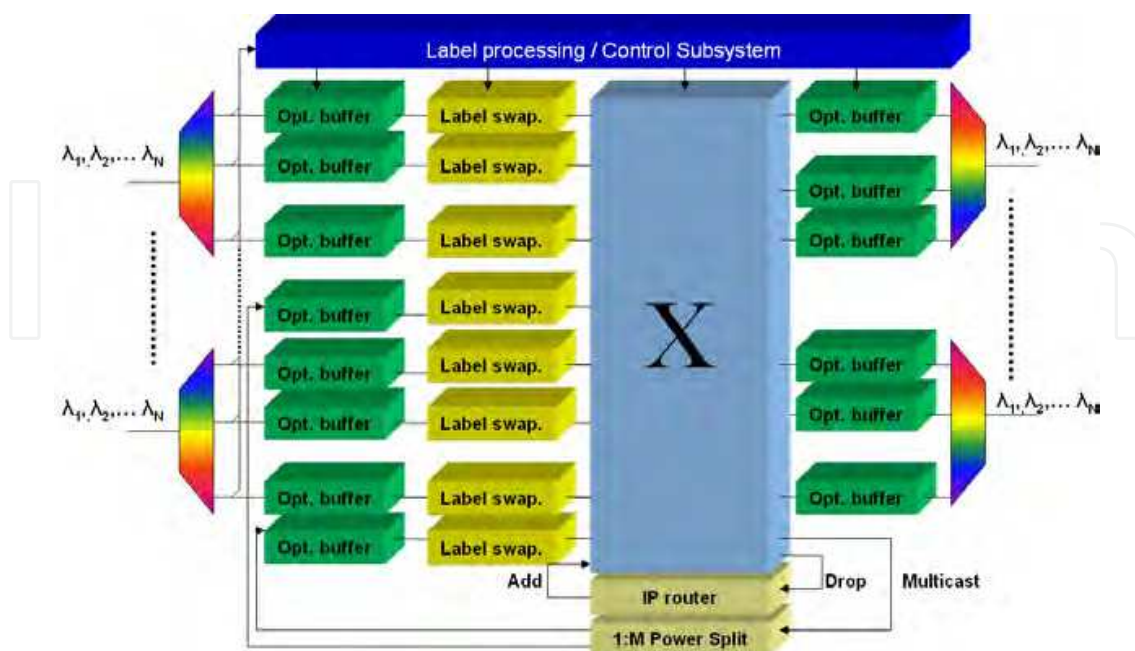

Fig. 3. Schematics of a proposed optical packet switching router design, including optical buffers and optical labels; a photonic switch fabric is represented by X (Blanco et al., 2009b)

To illustrate the use of optical buffers, Fig.3 shows the schematics of a proposed design for an OPS core router. Optical packets are wavelength-demultiplexed and immediately tapped: a copy of the packet is passed to the control subsystem while the other copy must remain "stored" in the optical domain. This latter copy must be released as soon as control decisions are made to ensure efficiency. Once the packets have been optically switched to the appropriate output, optical buffers are needed to resolve possibly arising collisions.

Not so obvious applications arise from the slow-light-based enhancement of light-matter interaction. Two facts explain this effect: on the one hand, slowly travelling photons are more likely to interact with the surrounding matter simply because it takes longer for them to go through it; on the other hand, at the very moment a light pulse enters a slow light device, its leading edge starts propagating at extraordinarily low speeds while the rest of the pulse is still propagating at normal velocities. This fact generates an accordion effect that implies spatial pulse compression and consequently an increase of local energy density and nonlinear effects. In Fig. 4 one of our simulations serves to illustrate the pulse compression and energy density increase suffered by a gaussian pulse entering in a photonic crystal slow light region from a conventional ridge waveguide.

Optical sensing, especially biosensing, is one of the application fields most benefitted from the strengthening of light-matter interaction, since its principle relies on identifying substance changes on the basis of light-matter relations. Higher standards of sensitivity and resolution are enabled by the use of slow light in sensing devices (Biallo et al., 2007; Pedersen et al., 2008). Fig. 5 illustrates the concept of optical biosensing using a slow-light photonic crystal waveguide to improve sensitivity to the biomarkers bounded to its surface.

Distributed Raman amplification is one of the nonlinear systems benefiting from slow light, with an expected efficiency improvement by a factor of 66.000 (McMillan et al., 2006). In quantum optics, as another example, slowing light down provides a mean to achieve sufficiently long storage time of quantum states to enable quantum operations (Dutton et al. 2004). Finally, it is worth to mention the role that slow light may play at improving the conversion efficiency of next generation solar cells. It is well known that recent thin film and organic photovoltaic (PV) technologies lack of a sufficient solar light-to-electrical energy conversion efficiency. By making photons travel slower within the active zone of the PV cell, up to a 50% increase in photon absorption (El Daif et al., 2010).
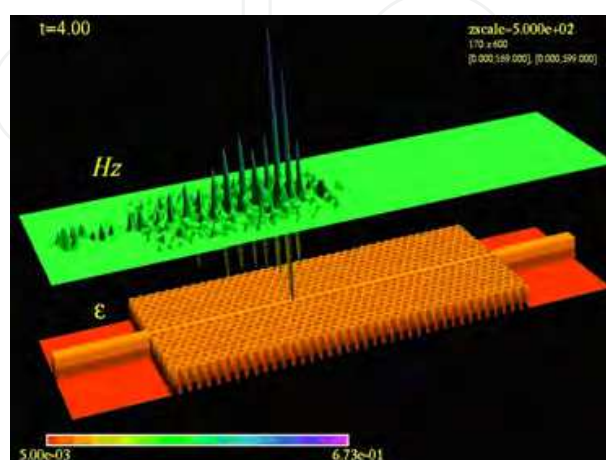

Fig. 4. Slow light photonic crystal waveguide (bottom inset), and transverse magnetic field component of the optical wave (top inset) to illustrate pulse compression
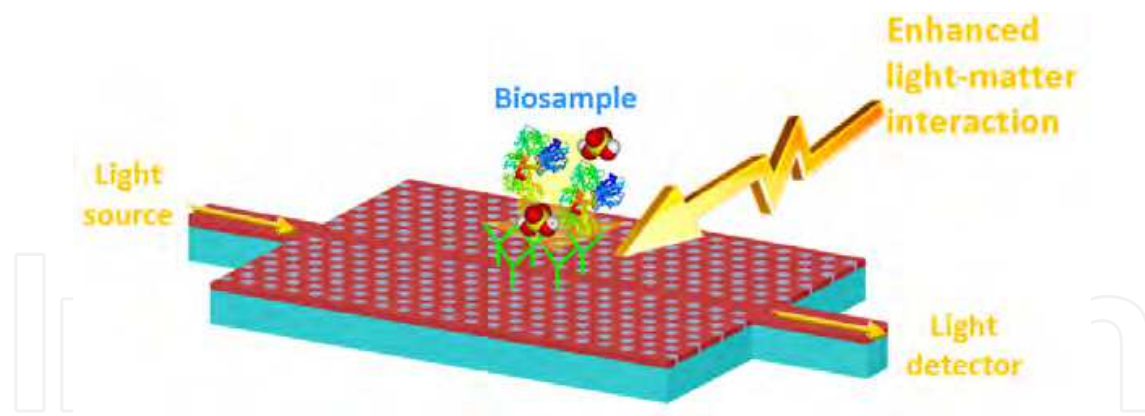
Fig. 5. Illustration of an optical biosensor based on a slow light photonic crystal waveguide.

3. Photonic band gap engineered materials for slow light applications

Dielectric materials having periodic dielectric constant present singular properties for electromagnetic waves propagation. The most remarkable of these properties is the appearance of the so called photonic band gap, a range of frequencies unable to propagate through the material. Many profitable effects stem from the existence of photonic band gaps: from the possibility of tight light confinement to the opportunity of achieving extremely low group velocities.

Photonic crystals are periodic, artificial, dielectric materials, which under certain conditions, present a photonic band gap. Biological photonic crystals are found in nature: in butterflies' wings, in peacocks' feathers, in comb-jellyfishes... The characteristics of photonics crystals confer these species their peculiar and outstanding colouration. Engineered or artificial photonic crystals can be designed with tailored electromagnetic and propagation properties, giving rise to a huge range of possibilities and practical applications. The next points give a flavour on the principles of design of photonic crystal devices with tailored group velocity.

3.1 Principles of photonic crystals

A photonic band gap engineered material, or a photonic crystal possessing a band gap, can be built from the periodic arrangement of different dielectric media in one, two or three dimensions. It has to be noticed that, even under the appropriate conditions of index contrast, lattice period and geometry, the photonic band gap will only appear in the plane of periodicity. Therefore, only a three-dimensional photonic crystal will be able to localize light in three dimensions by means of the photonic band gap, while light modes in one- or two-dimensional arrangements will only be localized in one or two dimensions respectively. Examples of one-, two-, and three-dimensional photonic crystals are shown in Fig. 6.

To understand how light propagates within a photonic crystal one has to resort to the macroscopic Maxwell equations and specialise to the particular case of mixed dielectric media in the absence of free currents or charges and in which the structure does not vary with time. This development has already been done in several excellent books and we refer the reader to (Joannopoulus et al., 2008) or (Sakoda, 2005), just to cite two of them, for a comprehensive understanding. In the following, the main results of this development,
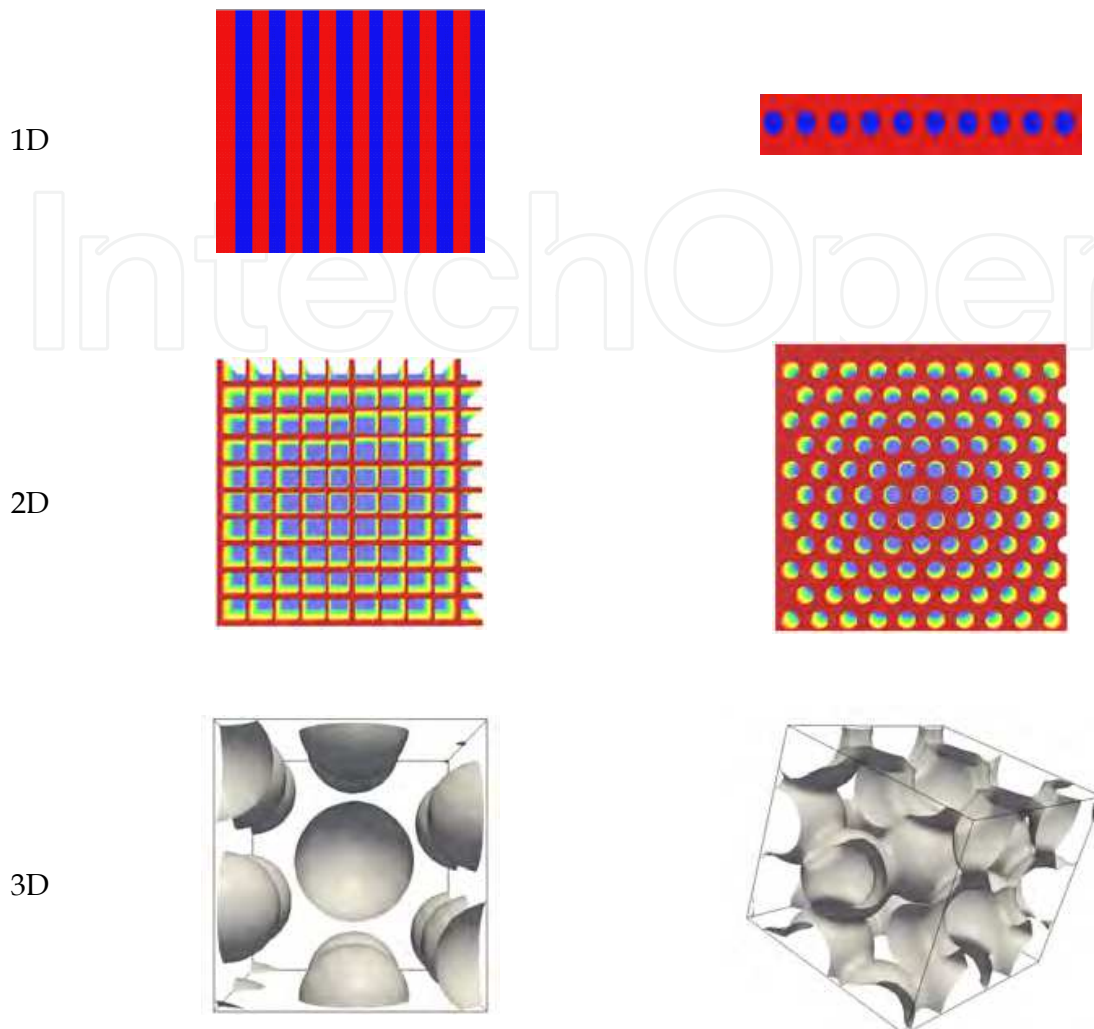
Fig. 6. Examples of one-, two- and three-dimensional photonic crystals.

indispensable to understand the basic principles of photonic crystals, are summarized. The resultant master equation is the following:

$$\nabla \times \left(\frac{1}{\varepsilon(r)} \nabla \times H(r) \right) = \left(\frac{\omega}{c} \right)^2 H(r) \tag{4}$$

Given a known spatial dielectric constant arrangement, $\varepsilon(r)$, one can find the magnetic field spatial profile of the modes allowed by the structure, $H(r)$, and their corresponding frequencies, ω, by solving Eq. 4 subject to the following transversality requirements:

$$\nabla \cdot H(r) = 0 \tag{5}$$

$$\nabla \cdot (\varepsilon(r)E(r)) = 0 \tag{6}$$

Subsequently one can obtain the electric field by using the following expression:

$$E(r) = \frac{i}{\omega \varepsilon_0 \varepsilon(r)} \nabla \times H(r) \tag{7}$$

The solutions to the master equation $H(r)$ can be written as Bloch states, i.e. as a product of a plane wave and a periodic function, with a period equal to the lattice period of the photonic crystal:

$$H_k(r) = e^{ikr} u_k(r) \tag{8}$$

All information about the spatial profile is given by the wave vector, k, and the periodic function, $u_k(r)$. For a given k, an infinite family of modes with discretely spaced frequencies $\omega_n(k)$ satisfy the master equation in Eq. 4 in particular these functions $\omega_n(k)$, represented in the *band structure* diagram, provide us with most of the valuable information about the optical properties of a given photonic crystal.

From this moment on, we will restrict our attention to two-dimensional structures, mainly because the state of the art fabrication techniques do not allow for reliable and cost-affordable realization of three-dimensional photonic crystals. Additionally, 2D structures are suitable for photonics on-chip integration. 3D light confinement can be obtained in 2D photonic crystals by using the photonic band gap effect to confine light laterally and total internal reflection for vertical confinement.

An ideal 2D photonic crystal is homogeneous in z (real 2D photonic crystal devices will be patterned in slabs or membranes to ensure vertical confinement). Modes will oscillate in that direction with its wave vector k_z unrestricted. We can particularize Eq. 8 for this case, expressing the Bloch modes of a two-dimensional photonic crystal structure as a function of the mode index, n, the in-plane and off-plane wave vectors, $k_{||}$ and k_z, and the projection of r in the xy plane, ρ:

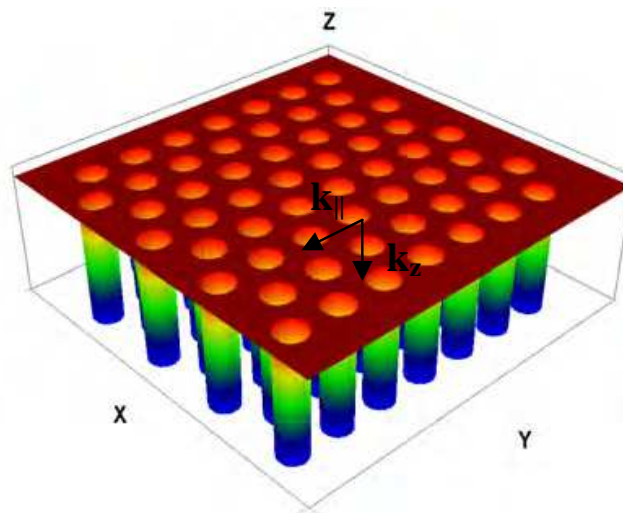$$H_{(n,k_z,k_{||})}(r) = e^{ik_{||}\rho} e^{ik_z r} u_{(n,k_z,k_{||})}(\rho) \tag{9}$$

Fig. 7. Modes propagating parallel to the plane of periodicity xy (k_z=0), can be classified in transverse electric (TE) and transverse magnetic (TM) in two dimensional photonic crystals

Modes propagating parallel to the periodicity plane have kz=0 and posess mirror symmetry through that plane. This allows us to classify modes in transverse electric (TE) and transverse magnetic (TM), having the electric field (E) in plane and the magnetic field (H) polarized in z and vice versa.

In Fig.8 the computed TE band structure for a two-dimensional photonic crystal made of air holes on silicon substrate is represented, accompanied by its transmission diagram. It is noticeable that transmission is zero at the photonic band gap frequencies. This type of arrangement, under certain conditions on index contrast and holes radii, presents a photonic band gap for TE and TM polarizations. Nonetheless, typically only TE polarized light is used since TE band gap is larger and therefore confinement will be stronger.

Several concepts must be clarified to be able to interpret this diagram correctly. First, notice that the wave vector in the plane of periodicity, $k_{||}$, is indexed in four points (Γ, M, K, Γ), representing the limits of the irreducible Brillouin zone for this particular structure. A complete description of Brillouin zone is given in the Appendix B of (Joannopoulus et al., 2008). Here we will just mention that the Brillouin zone is a primitive cell in the reciprocal lattice, the Fourier transform of the spatial function of the original lattice. The irreducible Brillouin zone is the first Brillouin zone reduced by all symmetries in the point group of the lattice, i.e. all periodicity- and symmetry-imposed redundancies in k are avoided. Secondly, the frequency is given in dimensionless units ωa/2πc, or equivalently a/λ. By normalizing all magnitudes, the frequency and the holes radii in this case, by the lattice period a it is possible to explode the inherent scalability of photonic crystals. If the given structure had a=1μm, the middle of the band gap ω_m=0.3 would be at a wavelength λ=1/0.3= 3.33 μm. If of one wanted to set the middle of the band gap at the third window of communications, λ=1550nm, it would suffice with setting a=0,3·1550=465nm.
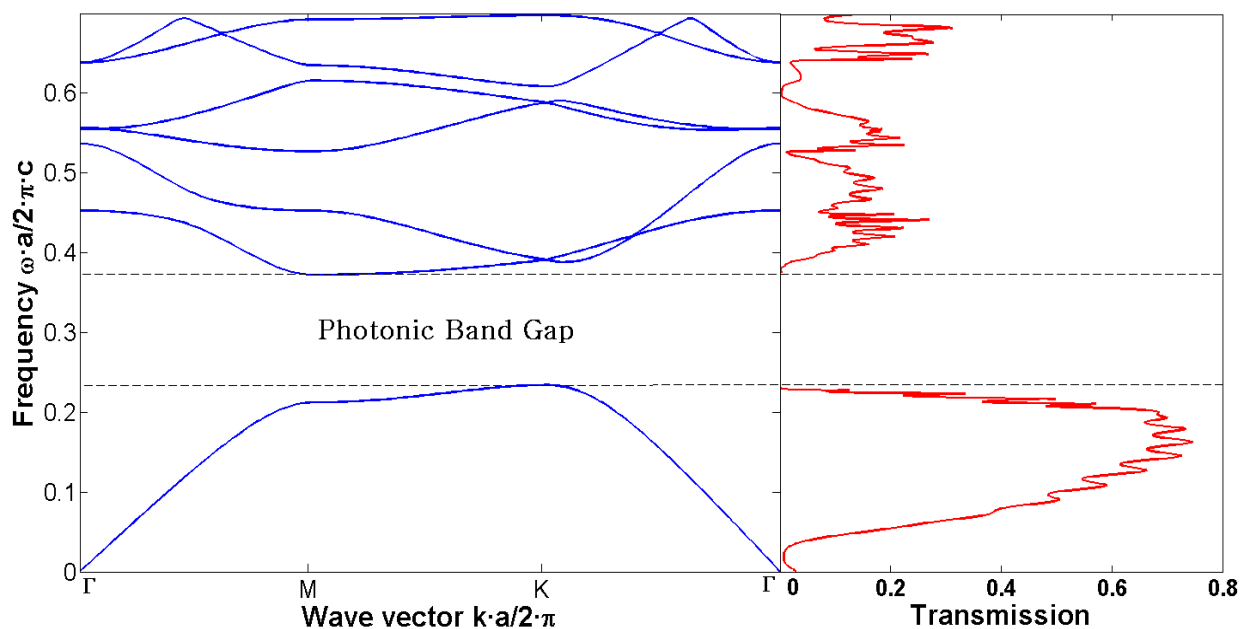

Fig. 8. Band structure and transmission diagram of a 2D photonic crystal made of air holes on silicon. The lattice period is a, the dielectric constant is ε=11,9716 and the hole radii r=0.36·a

3.2 Slow light photonic crystal waveguides and cavities

Unmodified photonic crystal structures, as the ones in the previous section, present a series of applications originating from the existence of a photonic band gap, as wavelength selective mirrors or stop-band filters. However, to fully exploit photonic crystal capacities for modelling electromagnetic propagation, one has to resort to the creation of defects within the otherwise perfectly periodic structure. Punctual and linear defects within the photonic crystal allow for tight confinement of light, at band gap frequencies, inside cavities and waveguides.

3.2.1 Photonic crystal slow-light waveguides

The band diagram of a photonic crystal waveguide on a two dimensional photonic crystal is shown in Fig.9. The periodicity has been broken in the y direction, due to the introduction of the linear defect, and thence only k_x is conserved. Therefore, the modes are not represented anymore over the irreducible Brillouin zone. Their projection on k_x is depicted instead. One can create a photonic crystal waveguide by simply removing a single row of holes. Such a waveguide, normally referred as W1, results in the appearance of a number of defect modes within the photonic band gap. As monomode behaviour is desirable, narrowing the waveguide is normally required. By reducing the width of W1 by a factor of 0.7, one gets a single defect mode within the band gap, the red-coloured band in Fig.9. Lateral confinement of the defect mode within the waveguide is ensured by the photonic bandgap, as the electric field density simulation in Fig.10 proves. Vertical confinement of light within the slab is achieved by total internal reflection at the interface between the high-dielectric constant slab and the surrounding air. The blue region in Fig. 9 represents the so called light cone, i.e. those extended modes propagating in air and not confined within the slab.
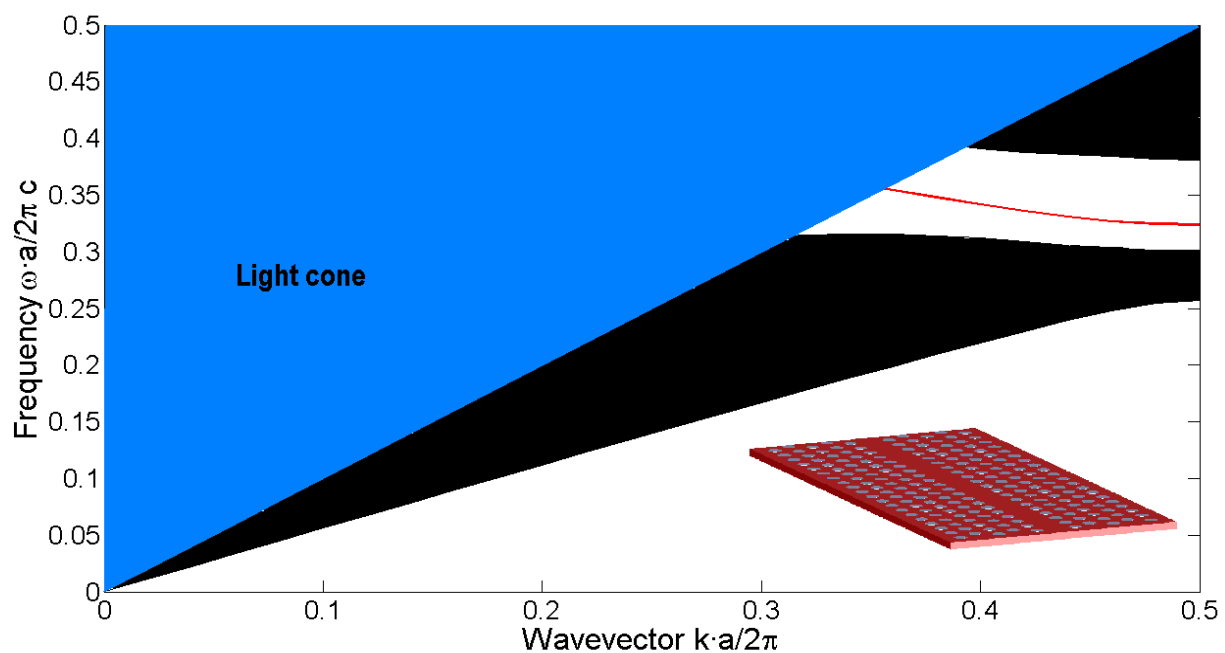

Fig. 9. Band diagram of a photonic crystal waveguide on a high-dielectric constant slab.
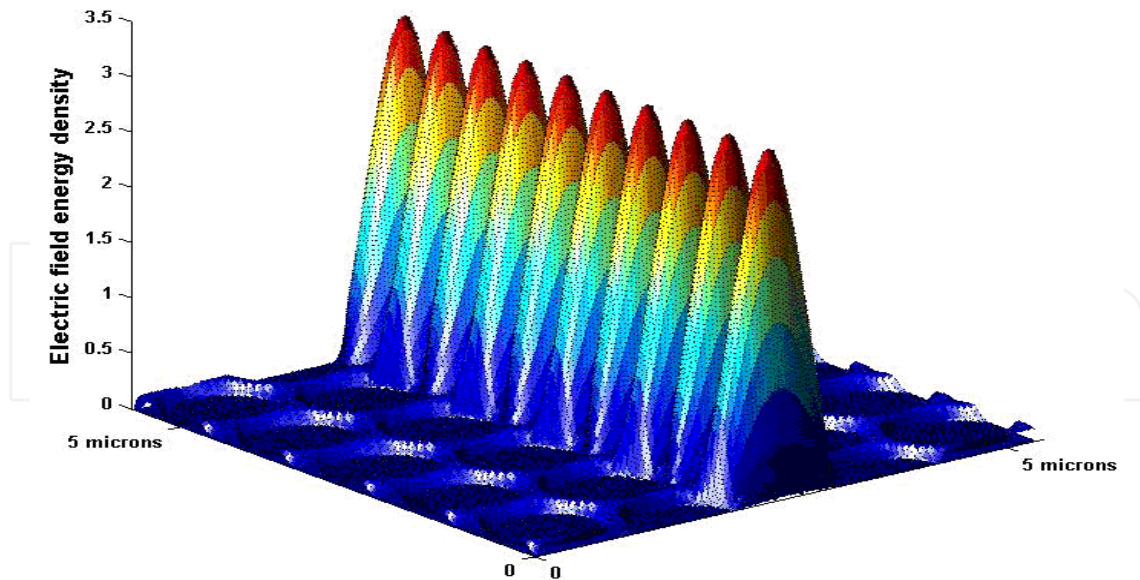
Fig. 10. Electric field energy density confined within the photonic crystal waveguide.

Group velocity is given by Eq. 1, i.e. by the slope of the modes appearing in the dispersion diagram. Computed group velocity for light pulses coupled to the defect mode is depicted in Fig. 11. The top graphic represents *vg* as a function of the longitudinal wave vector *kx* for the guided mode. It is noticeable that the group velocity is zero at the edges of the band and for certain wavelengths. Unfortunately, these working regions are not desirable in practice. At the band edges, any fluctuation in the structure, due to fabrication imperfections, causes oscillations between guided and not guided states. Moreover, the operational bandwidth for this ultra-low velocity is very small due to group velocity dispersion and higher-order dispersion. Special designs have been proposed to minimize dispersion and enable higher bandwidths (Baba, 2008; O'Faolain, 2009). The bottom graphic at Fig. 11 shows guided mode *vg* as a function of wavelength. By setting the lattice period *a* equal to 500nm the band gap is located around the third communications window. Since we are interested in guided modes and not in modes extended in air, we must only consider those frequencies out of the Light cone. These correspond to wavelengths superior to 1.4 µm.

Our group is working on optimized waveguide designs trying to achieve a balance between reduced group velocity and bandwidth. The waveguide depicted in Fig.12 has been created by diminishing the radii of a row of holes and filling it with a material of ε=7. Furthermore, to achieve monomode behaviour the waveguide width has been reduced by a factor of 0.64 (Andonegui et al., 2011). Group velocities of c/100 are achieved for a 33% of the k-vector space, achieving a good balance between low information velocity and bandwidth.

3.2.2 Photonic crystal cavities

The group velocity-bandwidth trade-off of photonic crystal waveguides can also be addressed by coupling a series of punctual defects (cavities) within the photonic band gap material. High quality factor (Q) photonic crystal cavities are capable to store photons for a relative long time in an extremely small volume. A high-Q photonic crystal cavity is the basic block of the so called coupled-resonator optical waveguides (CROWs). Remarkable achievements have been done in this field, as in (Notomi et al., 2008), where more than 100 high-Q cavities were coupled, achieving v_g of c/170 in pulse propagation experiments and notable storage capacity.
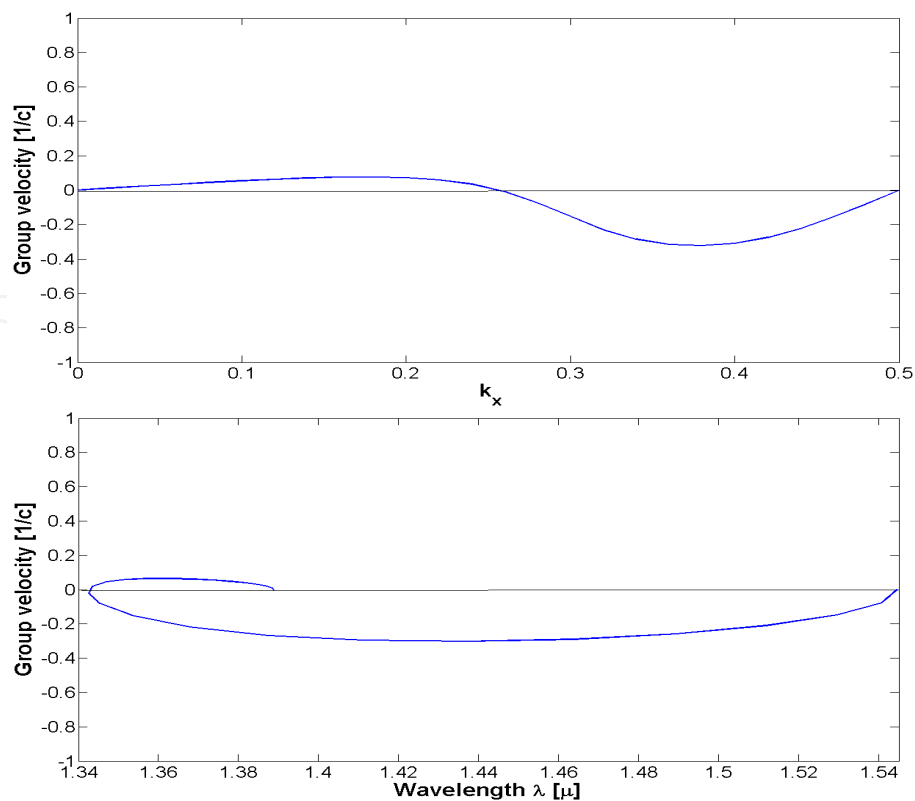
Fig. 11. Group velocity of light pulses coupled to the defect mode confined within the waveguide as a function of wave vector k_x (top) and as a function of wavelength (bottom)
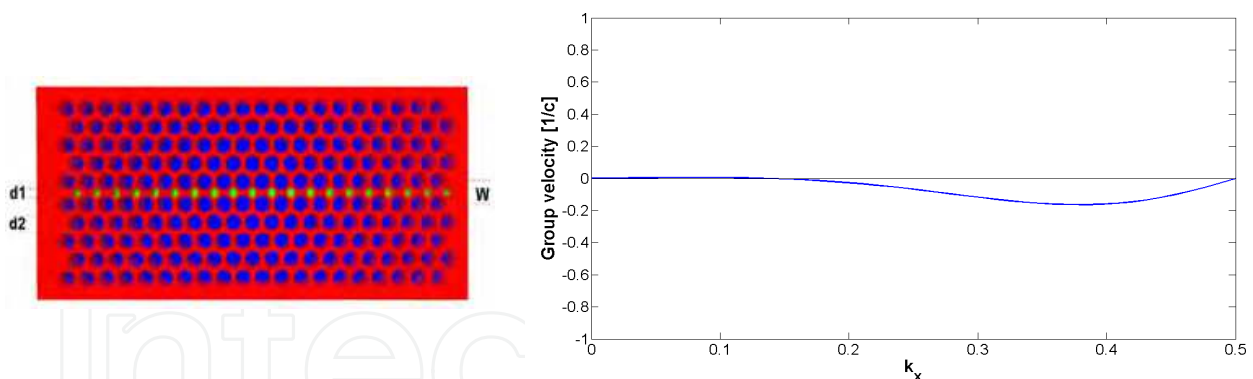

Fig. 12. Optimized photonic crystal waveguide on a triangular lattice of air holes on silicon with d1=0.51·a, d2=0.76·a, W=0.64·W (left) and group velocity of the defect mode (right)

By introducing a punctual defect the periodicity in both *x* and *y* direction is broken and therefore k vector is not conserved in any direction. Consequently, the band structure of a cavity is naïve and it is not usually represented. Nevertheless, it is very instructive to visualize the shape of the defect mode confined in the cavity, as in Fig. 13. Notice that the defect mode is parallel to the *k*-axis, giving useful information: a single resonant frequency remains confined into the cavity with zero group velocity, as illustrated in Fig.14.

A more sophisticated cavity consisting on a missing hole and a gradual change of surrounding holes radii is shown in the design of Fig.15. The cavity is adjacent to a waveguide so that the

light at certain resonant frequency can be coupled from the waveguide to the cavity. This light will be coupled back from the waveguide to the cavity after a time, $t_{storage}$, proportional to Q.
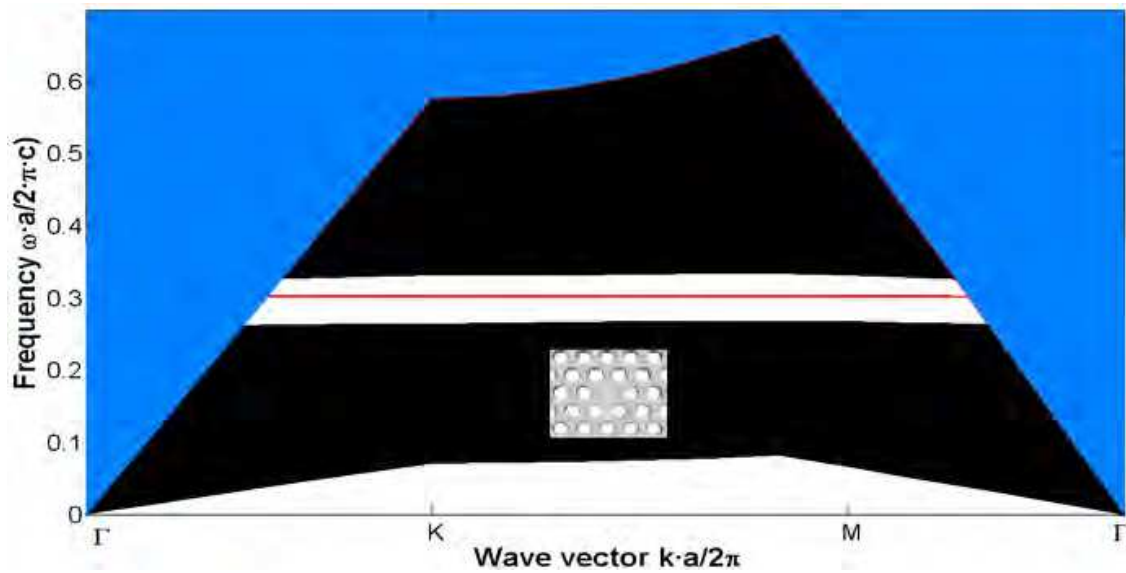

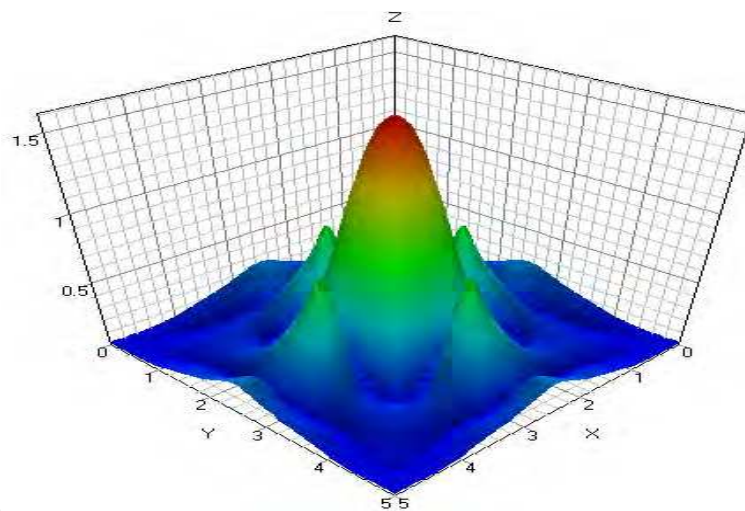Fig. 13. Band diagram of a photonic crystal cavity on a high-dielectric constant slab.

Fig. 14. Amplitude of the H_y component of the optical field confined within the cavity.

3.2.3 Tunability of photonic crystal slow light structures

Fast and fine device tunability is a requirement for many applications of slow light, e.g. for optical buffer memories. Fast reconfiguration of the photonic crystal device can be achieved by a variety of effects: by using thermo-optical effect, electro-optic effect, or carrier injection among others. Along this section, we show how photonic crystal waveguides and cavities can be fast and efficiently tuned by exploiting Pockels effect.

Lithium niobate (LiNbO$_3$) is an anisotropic crystalline material, i.e. its refractive index depends on the crystal axis direction. Consequently its response to the electro-optic effect is given by a matrix of coefficients giving the electro-optic response for each direction. LiNbO$_3$ index response to an applied field along the z axis, depicted in Fig.16, is given by the expression
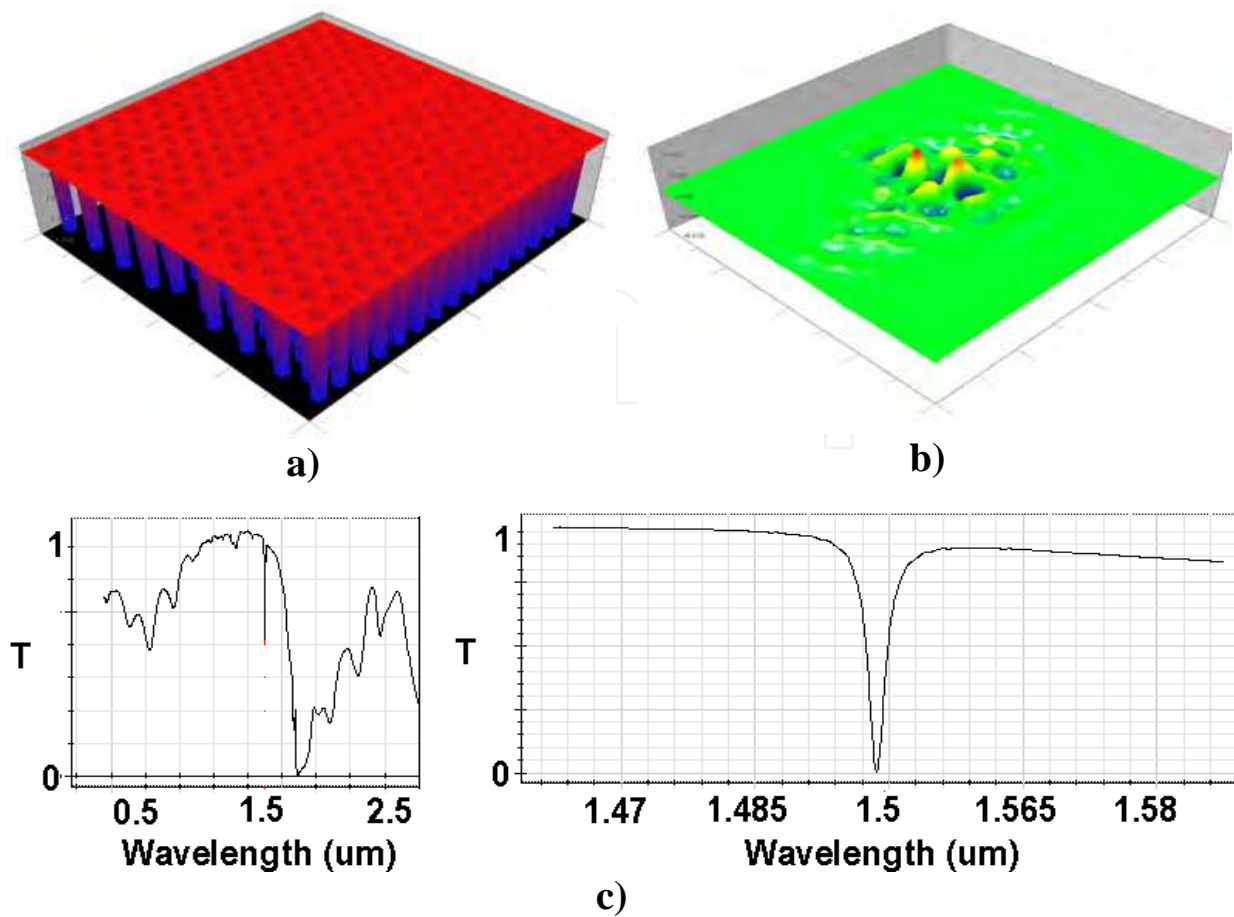
Fig. 15. a) Dielectric constant structure of a cavity coupled to a waveguide on a 2D triangular lattice of holes in lithium niobate; b) DFT of H⊥; c) Transmission diagram over wavelength and detail of the resonance and surrounding wavelengths.

$$\Delta n = \left(\frac{n^3}{2} \right) \cdot r_{33} \left(\frac{V}{d} \right) \tag{10}$$

where r_{33} is one of the matrix component and d is the electrode width. A refractive index change of $\Delta n = 1 \times 10^{-3}$ is given by an electric field of $\Delta E_0 = -6.45$ V/µm. Taking into account that electrode width will be of the order of half a micron, small electric fields will be needed to achieve tunability.

We subsequently consider the appliance of an incremental electric field, by steps of $|\Delta E_0| = 64.5$ mV/µm, to a LiNbO$_3$ slab patterned with a 2D photonic crystal. This generates refractive index changes from 10^{-5} to 10^{-1}, later we will see how only a range of these index changes is achievable in practice. This is achieved by a means of a voltage supplied to electrodes placed on the surface of the photonic crystal device, as in the inset of Fig.15.

First, we pay attention to waveguides reconfigurability. The red line in the band diagram of Fig.9 represented the frequencies of the defect mode guided within the waveguide as a function of the longitudinal wave vector. The group velocity of the guided mode was also computed and represented in Fig.11. Now, we explore how the group velocity of the signals coupled to this mode can be dynamically switched. The graphic in Fig.17 is evidence for the

defect mode frequency shift as a response to a refractive index change originating from the supplied voltage. When light at a proper wavelength proceeding from a narrow-width optical source (laser) is launched into the slow light device, it couples to the guided mode.
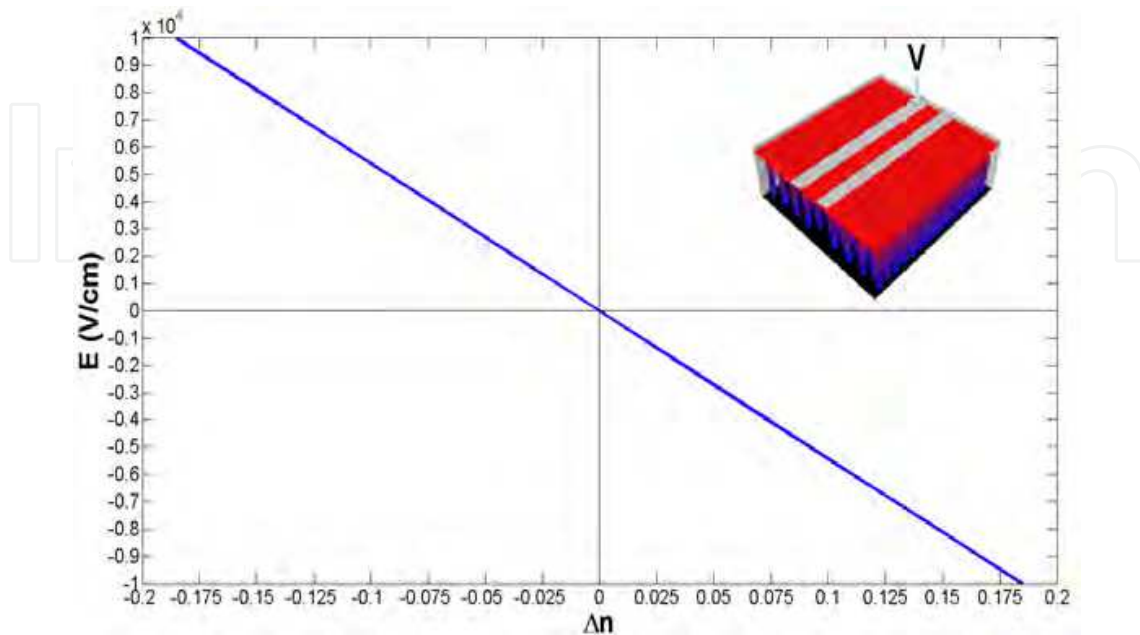

Fig. 16. Lithium niobate refractive index response to an electric field applied due to Pockels effect. The inset shows how to exploit this effect by applying a voltage to the electrodes placed on the lateral sides of the waveguide.

Depending on the source frequency (or wavelength) the signal will propagate with a given group velocity as given by the graphics in Fig.11. At this point, if a voltage is applied to the device electrodes, the mode shifts in frequency but the injected frequency remains the same. In consequence, the signal is switched to another velocity regime or even from a guided- to a non-guided regime. This simple mechanism enables a plurality of device applications from tunable delay lines to transistors, modulators or tunable filters.
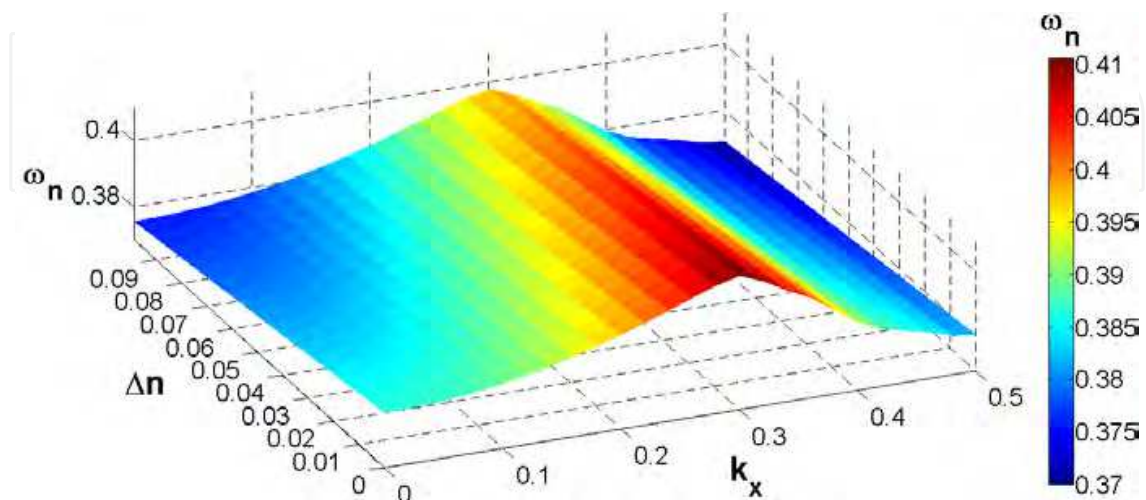

Fig. 17. Frequency shift of a photonic crystal waveguide guided mode as a function of refractive index change stimulated by Pockels effect.

The reconfiguration possibilities of waveguides are somehow limited when compared with that of the cavities. The reconfiguration capabilities of the photonic crystal cavity proposed in Fig. 15 via electro-optic effects are presented next. Recall that the cavity had a resonant frequency at around 1500nm, precisely at 1499.1nm. We alter the refractive index of the photonic crystal material from 0 to 0.1 in steps of 10^{-5} by exploiting Pockels. The overlap of transmission spectra for different refractive index values proves the resonant wavelength red-shift. This diagram resulting from our FDTD simulations is presented in Fig. 18. Subsequently we have focused in index changes achievable for reasonable values of applied electric field in normal applications, i.e. from 0.1 to 10MV/ μm. This reduces the range of achievable index changes to values up to $1.55 \cdot 10^{-3}$. In Fig.19 we represent the computed cavity resonant wavelengths as a function of the index change generated by Pockels effect using realistic electric field values. This simulation results are the proof of the concept of fast (switching time bellow 1 ns) and efficient (every $|\Delta E_0| = 64.5$ mV/μm implies $\Delta\lambda = 6$pm) reconfigurability.
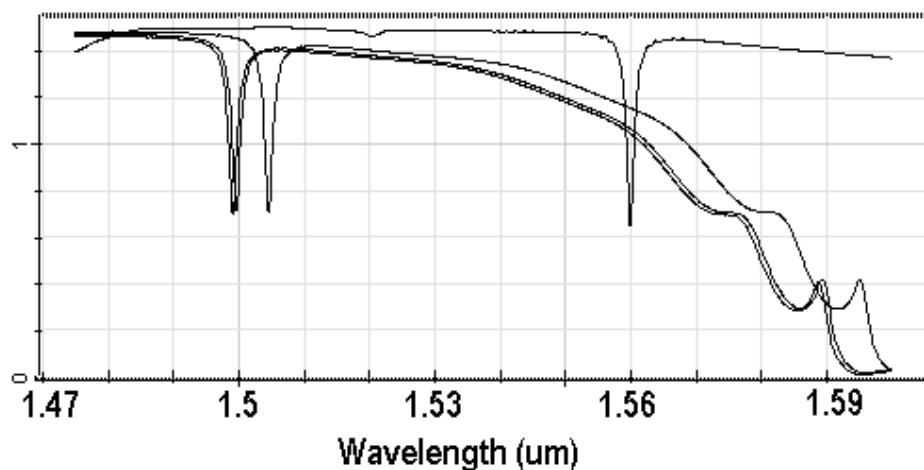

Fig. 18. Overlapped transmission spectrum for refractive index increments of Δn=(0, 0.001, 0.01, 0.1)
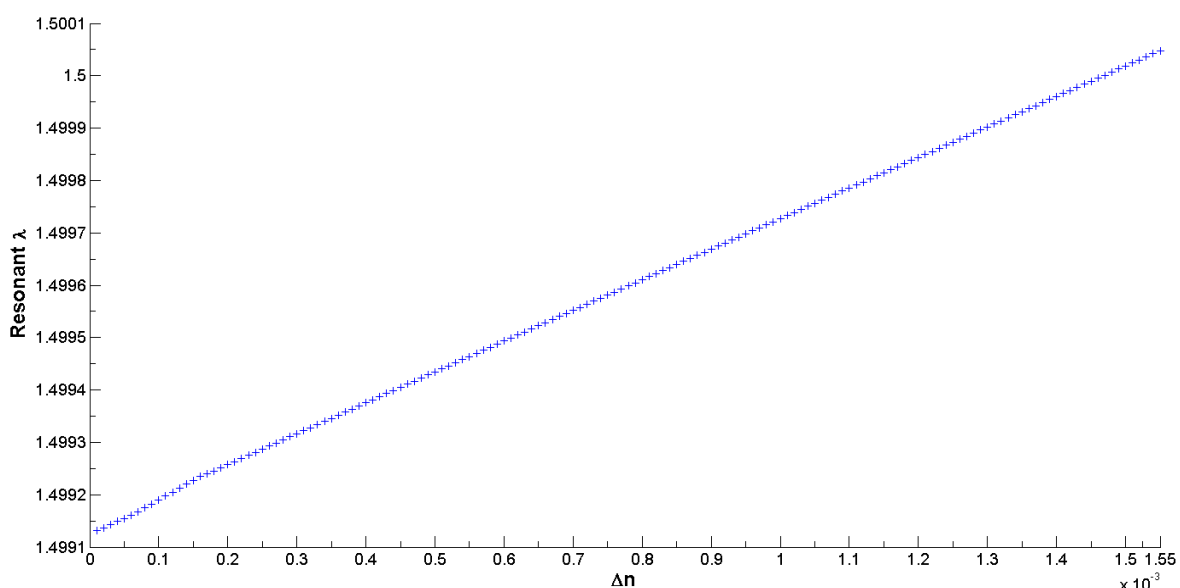

Fig. 19. Resonant wavelength versus refractive index change for the photonic crystal cavity shown in Fig.15.

3.3 Computational methods and fabrication techniques

Substantial work has been done to provide numerical solution of Maxwell equations. In this subsection a rough idea on the different computational methods to solve photonic crystal problems is given, for a broader notion we refer the reader to (Joannopoulus et al., 2008).

As a first approach, one can divide computational methods in frequency domain methods and time-domain methods, each of them useful for solving different problems typologies. Frequency domain methods are used to solve problems such as the computation of band diagrams and stationary mode profiles. On the other side, time-domain methods are better suited to perform computations involving time evolution of fields, such as transmission and reflection spectra or resonant cavities decay in time. Numerical methods can be alternatively classified on the basis of the used discretization schemes in: finite differences, finite elements, boundary-element and spectral methods.

Several commercial and open-source software packages implementing different numerical methods are available for computational photonics. Just to cite a few of these free-software products we will mention MPB (using plane wave expansion frequency-domain method) and Meep (implementing finite differences in time domain) MIT's packages and CAMFR (based in eigenmode expansion and advanced boundary conditions like perfectly matched layers).

Next, a coarse notion on the fabrication techniques to synthesize photonic crystals is given. A good set of references about 3D and 2D photonic crystal fabrication techniques is given in (Skorobogatiy & Yang, 2009). It has to be noticed that, in spite of its outstanding potential, photonic crystals mostly remain at research stage and this is mostly due to current technological limitations of fabrication techniques. Focused Ion Beam (FIB) and electron beam (e-beam) lithography combined with reactive ion-etching (RIE) are two the methods used in laboratories for high accuracy and high-resolution fabrication of planar 2D photonic crystals. However, it is necessary to start moving photonic crystal technology out of the laboratory and onto the production floor for building photonic devices for practical applications. Recent advances in nano-imprint lithography are fulfilling this goal (Kreindl et al., 2010).

4. Conclusion

Photonic band gap materials are a powerful tool for tailoring light propagation properties. This Chapter has put the emphasis on the control over the signal group velocity given the wide range of applications enabled by slow light. All slow light techniques reviewed rely on slowing down the information or the energy transported by light signals, more than on slowing the photons themselves.

Among the plurality of foreseen slow-light applications we have mainly highlighted two due to its high technological and societal expected impact. The development of optical buffer memories is of utmost importance for the deployment of all-optical networks. Slow light is a promising approach for fast, scalable and low-power consuming on-chip optical buffers. Given the state of the art of the technology, nowadays, such devices cannot replace electronic RAMs in their current functions; however major breakthroughs are still expected in this field. Concerning slow light application to biosensing, not so bandwidth demanding and less affected by losses, near future commercial prospects are encouraging.

Slow light engineered structures perform better than material-based methods for high bandwidths. On the other hand, their feasibility into devices for practical applications is higher, due to the materials employed and their operation conditions. In particular, photonic crystals are proving to be a suitable technology to take slow light into practice. Small operating power, compact footprint, and the possibility of monolithic integration with electronics and CMOS fabrication are some of their strong points. Along this Chapter the capabilities of fast and efficient switching using electro-optic effects have been justified on the basis of computing and simulations.

So far our work in this field has been focused on high-index contrast photonic crystal structures, exploiting the use of materials as silicon and lithium niobate. Our future research lines will explore the use of *intelligent* materials such as hydrogel polymers and chalcogenide glass (Eggleton et al.,2011), in order to achieve added functionalities to the photonic crystal devices.

In spite of all these promising and almost magic properties of photonic band gap materials, they still remain at research stage. Some difficulties such as high propagation losses in the slow light regime, dispersive effects, coupling inefficiencies and fabrication roughness or inaccuracies are somehow hampering their evolution to commercial devices. Recent advances in dispersion engineering and loss reduction-oriented design approaches, together with the continuous improvement of fabrication processes, are taking slow light in photonic crystal closer to practical applications. In addition to this, the refinement of nanoimprint lithography, as an alternative for accurate mass production, herald a brighter future for real slow-light photonic crystal devices.

5. Acknowledgements

6. References

Andonegi, I., Blanco, A., Garcia-Adeva, A. (2011). Characterization of Slow Light Regime in 2D Photonic Crystal Waveguides, *Proceedings of PPM 2011 Photonics, Plasmonics and Magnetooptics - ImagineNano 2011*, Bilbao, Spain, April 12 - 17, 2011

Baba, T. (2008). Slow Light in Photonic Crystals. *Nature Photonics,* Vol.2, (August 2008), pp. 465-473, ISSN 1749-4885

Biallo, D. et al. (2007). High Sensitivity Photonic Crystal Pressure Sensor. *Journal of the European Optical Society*, Vol. 2, (May 2007), pp. 1-5, ISSN 1990-2573

Bigelow, M. S., Lepeshkin, N. N. & Boyd, R. W. (2003). Observation of Ultraslow Light Propagation in a Ruby Crystal at Room Temperature. *Physical Review Letters*, Vol. 90, No. 11, (March 2003), pp. 1139031-4, ISSN 1079-7114.

Blanco, A., Beltrán, P., & Zubía, J. (2009). Slow Light Buffers for Future All-Optical Packet Switched Networks, *Proceedings of ICUMT 2009 International Conference on Ultra Modern Telecommunications & Workshops*, pp. 1-6, ISBN 978-1-4244-3942-3, Saint Petersburg, Russia, October 12-14, 2009

Blanco, A., Areizaga, E., Zubia, J. (2009). Slow Light for Microwave Photonics Applications, *Proceedings of MMS 2009 9th Mediterranean Microwave Symposium,* pp. 1-5, ISBN: 978-1-4244-4664-3, Tangiers, Morocco, November 15-17, 2009

Boyd, R. W., Narum, P., Slow- and Fast-light: Fundamental Limitations. *Journal of Modern Optics*, Vol.54, Nos. 16-17, (November 2007), pp. 2403-2411, ISSN 0950-0340.

Capmany, J., Novak, D. (2007) Microwave Photonics Combines Two Worlds. *Nature Photonics*, Vol. 1, (June 2007), pp.319-330, ISSN 1749-4885

Eggleton, B. J., Luther-Davies, B. & Richardson, K. (2011). Chalcogenide Photonics. *Nature Photonics,* Vol. 5, (February 2011), pp. 141–148, ISSN 1749-4885

El Daif, O. et al. (2010). Absorbing one-dimensional planar photonic crystal for amorphous silicon solar cell. *Optics Express*, Vol. 18, No. 103, (September 2010), pp. 293-299, ISSN 1094-4087

Dutton, Z., Ginsberg, N. S., Slowe, C. & Hau, L. V. (2004) The Art of Taming Light: Ultra-slow and Stopped Light. *Europhysic News*, Vol. 35 (March/April 2004), pp. 33 – 39, ISSN 1432-1092

Gonzalez-Herraez, M, Song, K. Y. & Thevenaz, T. (2005) Optically-controlled slow and fast light in optical fibers by means of stimulated Brillouin scattering. *Applied Physics Letters*, Vol. 87, Issue 8., (August 2005) p. 081113, ISSN 0003-6951

Hau, L.V., Harris, S. E., Dutton, Z. Light (1999) Speed Reduction to 17 Metres per Second in an Ultracold Atomic Gas. *Nature*, Vol. 397, (February 1999), p. 594, 1999, ISSN 0028-0836

Heitmann, W. & Nimtz, G. (1994). On Causality Proofs of Superluminal Barrier Transversal of Frequency band Limited Wave Packets. *Physics Letters A*, Vol. 196, (December 1994), pp. 154-158, ISSN 0375-9301

Joannopoulos, J., Johnson, S., Winn, J. & Meade R. (2008). *Photonic Crystals: Molding the Flow of Light,* Princeton University Press, ISBN 978-0-691-12456-8, Princeton, New Jersey, USA

Khurgin, J. & R. Tucker (2009). *Slow Light: Science and Applications*, CRC Press - Taylor and Francis Group, ISBN 978-1-4200-6151-2, Boca Raton, USA

Krauss, T. F. (2008). Why Do We Need Slow Light. *Nature Photonics*, Vol.2, No. 8, (August 2008), pp- 448-450, ISSN 1749-4885

Kreindl, G., Glinsner, T & Miller, R. (2010), Next-generation Lithography: Making a Good Impression. *Nature Photonics Technology Focus, Vol. 4*, (January 2010), pp.27-28, ISSN 1749-4885

McMillan, J. F., Yang, X., Panoiu, N. C., Osgood, R. M. & Wong, C. W. (2006). Enhanced Stimulated Raman Scattering in Slow-Light Photonic Crystal Waveguides. *Optics Letters*, Vol 31, (January 2006), pp. 1235–1237, ISSN 1539-4794

Melloni, A., Canciamilla, A., Ferrari, C., Morichetti, F, O'Faolain, L., Krauss, F., De La Rue, R., Samarelli, A. & Sorel, M. (2010) Tunable Delay Lines in Silicon Photonics: Coupled resonators and Photonic Crystals, a Comparison. *IEEE Photonics Journal*, Vol. 2, No. 2, (April 2010), ISSN 1943-0655

Notomi, M, Kuramochi, E. & Tanabe, T. (2008) Large-Scale Arrays of Ultrahigh-Q Coupled Nanocavities. *Nature Photonics*, Vol. 2, (December 2008), pp. 741-747, ISSN 1749-4885

O'Faolain, L, Li, J., Gomez-Iglesias, A., & Krauss, T. (2009). Low Loss Dispersion Engineered Photonic Crystal Waveguides for Optical Delay Lines, *Proceedings of 6th IEEE*

International Conference on Group IV Photonics, pp. 40 – 42, ISBN: 978-1-4244-4402-1, San Francisco, CA, USA, September 9-11, 2009

Pedersen, J., Xiao, S. & Mortensen, N.A. (2008). Slow-Light Enhanced Absorption for Biochemical Sensing Applications: Potential of Low-Contrast Lossy Materials. *Journal of the European Optical Society*, 08007 Vol. 3, Issue 3, (February 2008), pp. 1-4, ISSN 0963-9659

Sakoda, K. (2005). *Optical Properties of Photonic Crystals*, Springer, ISBN 3-540-20682-5, Berlin, Germany

Søndergaard, T. & Bozhevolnyi, S. I. (2007) Slow-plasmon resonant nanostructures: scattering and field enhancements, Physical Review B, Vol. 75, (February 2007), pp. 0734021-4, ISSN 1098-0121.

Skorobogatiy, M. & Yang, J. (2009) *Fundamentals of Photonic Crystal Guiding*, Cambridge University Press, ISBN 978-0-521-51328-9, New York, USA

Steinberg, A.M., Kwiat, P.G., Chiao, R.Y. (1993). Measurement of Single-Photon, Tunneling Time. *Physics Review Letters*, Vol.71, No. 5, (August 1993), pp. 708-711, ISSN 0031-9007

Tsakmakidis, K.L., Boardman, A. & Hess, O. (2007). 'Trapped Rainbow' Storage of Light in Metamaterials. *Nature*, Vol. 450, (November 2007), pp. 397-401, ISSN 0028-0836.

Tucker, R. S. (2009) Slow Light Buffers for Packet Switching, In: *Slow Light: Science and Applications*, Khurgin, J., pp. 347-365, CRC Press, ISBN 978-1-4200-6151-2, Boca Raton, USA

Willner, A.E., Zhang, B., & Zhang, L. (2009) Reconfigurable Signal Processing Using Slow-Light-Based Tunable Optical Delay Lines, In: *Slow Light: Science and Applications*, Khurgin, J., pp. 321-346, CRC Press, ISBN 978-1-4200-6151-2, Boca Raton, USA
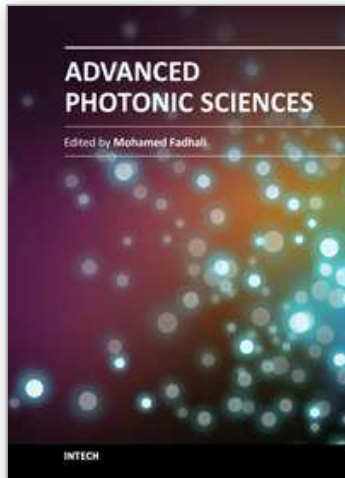
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Edited by Dr. Mohamed Fadhali

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