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New concepts for nanophotonics and nano-electronics

Photonic crystals and metamaterials

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Abstract

Recent results obtained on semiconductor-based photonic crystal devices are of great promise for future developments of photonic crystals and their applications to 'all-photonic' integrated circuits. Device performance mostly relies on the strong confinement of light thanks to photonic bandgap effects, but photonic crystals also exhibit remarkable dispersion properties in their transmission bands, thus opening the perspective of new optical functionalities. Slow light, supercollimation, superprism, and negative refraction effects are among the fascinating phenomena which strongly motivate the community. Studies in these directions parallel those on metamaterials, which are expected to provide a simultaneous control of the dielectric permittivity and of the magnetic permeability. In this article, we briefly review some important advances on photonic crystals and metamaterials, as these two topics received a particular attention during the "Nanosciences et Radioélectricité" workshop organized by CNFRS in Paris on the 20th and 21st of March 2007. ***To cite this article: J.-M. Lourtioz, C. R. Physique 9 (2008).***

Résumé

Cristaux photoniques et métamatériaux. Les résultats récents obtenus sur les composants semiconducteurs à cristal photonique sont très prometteurs pour les futurs développements des cristaux photoniques et de leurs applications aux circuits photoniques intégrés. Les performances des composants reposent surtout sur le fort confinement de la lumière dû aux effets de bande interdite photonique, mais les cristaux photoniques présentent aussi des propriétés remarquables de dispersion dans leurs bandes de transmission, ouvrant ainsi la perspective de nouvelles fonctions optiques. Les effets de lumière lente, de supercollimation, de superprisme et de réfraction négative sont parmi les phénomènes fascinants qui motivent aujourd'hui la communauté. Les études dans ces directions sont parallèles à celles sur les métamatériaux dont on attend un contrôle simultané de la permittivité diélectrique et de la perméabilité magnétique. Dans cet article, nous faisons une brève revue de quelques avancées importantes sur les cristaux photoniques et les métamatériaux, ces deux sujets ayant reçu une attention particulière à l'atelier « Nanosciences et Radioélectricité » organisé par le CNFRS à Paris les 20 et 21 Mars 2007. ***Pour citer cet article : J.-M. Lourtioz, C. R. Physique 9 (2008).***

Keywords: Photonic crystals; Integrated optics; Negative refraction; Metamaterials; Plasmonics

Mots-clés : Cristaux photoniques ; Optique intégrée ; Réfraction négative ; Métamatériaux ; Plasmonique

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1. Introduction

Since the pioneering demonstration by E. Yablonovitch et al. of a three-dimensional (3D) photonic bandgap in the microwave domain [1], photonic crystals have received a continually growing interest [2]. In the optical domain, most of the works on semiconductor-based photonic crystals have concentrated on two-dimensional structures with the perspective of applications to photonic integrated circuits (PICs) and, more generally, to optical telecommunications. Although technological difficulties made the progress slower than expected, outstanding results recently obtained on photonic crystal microcavities [3], microguides [4,5] and microlasers [6] as well as on the integration of these devices [7], have indeed marked a turning point in the development of 'all-photonic' integrated circuits. In most cases, the device performance still relies on the strong confinement of light that is achieved thanks to photonic bandgap effects. However, photonic crystals can also be used in their transmission bands where they exhibit remarkable dispersion properties, opening, in turn, the perspective of new optical functionalities and novel devices. Slow light [8], supercollimation [9], superprism [10], and negative refraction [11–13] are some of the fascinating phenomena which strongly motivate the community at this time. Studies in these directions parallel those undertaken on the so-called metamaterials, which are expected to provide another way towards negative refraction with a simultaneous control of the effective permittivity and the effective permeability [14–18]. Clearly, because metamaterial structures include not only dielectrics but also metals, their extension to the optical domain also participates to the strong revival of plasmonics with the hope of truly sub-wavelength photonics [19].

In this article, we briefly review some important advances in the fields of photonic crystals and metamaterials, as these two fields received a particular attention during the "Nanosciences et Radioélectricité" workshop organized by CNFRS in Paris on the 20th and 21st of March 2007. Following this introduction, the paper is organized in three sections. Recent breakthroughs accomplished in the field of basic semiconductor-based photonic crystal devices are presented in Section 2. Dispersive properties of photonic crystals are discussed in Section 3. Recent advances in the fabrication of metamaterials at optical frequencies are considered in Section 4 along with the new opportunities offered by these materials. This is followed by a conclusion and general prospects.

2. Light confinement in two-dimensional semiconductor-based photonic crystal devices

The typical arrangement of a two-dimensional photonic crystal in semiconductor technology is that of a periodic array of holes etched through one or several semiconductor layers that form a planar waveguide [2]. The hexagonal symmetry is generally preferred for the crystal since it allows obtaining an in-plane bandgap at least for one of the two polarizations of the light, namely the TE polarization with the electric field perpendicular to the hole axis. With this, the realization of optical devices and optical functionalities requires modifying the periodic array of holes either by locally changing the diameter of hole(s) or simply by omitting to drill one or several holes at suitably selected spots. While the existence of a two-dimensional bandgap ensures a strong in-plane confinement of light in the functional regions of the photonic crystal, the major obstacle to low loss devices stems from light leakage in out-of plane directions. As in classical optics, the light leakage in these directions is only limited by guiding mechanisms due to the index contrast between the core of the planar waveguide and the surrounding media. The standard configuration for optoelectronics, the so-called substrate approach, consists in using a multilayer waveguide with a low or moderate index contrast between the layers and the substrate. Because the guided modes largely extend to the cladding layers, deep holes and deep etching are required to minimize the diffraction losses at the photonic crystal holes [20]. A different configuration consists in deliberately using a high index contrast as the one provided by a semiconductor membrane suspended in the air. Because of the small $\lambda/2n_{\mathrm{eff}}$ thickness of the membrane, a standard reactive-ion-etching process can then be used, and clearly, this is with the membrane approach that the highest Q-factors, i.e. the lowest optical losses, are presently achieved (see Sections 2.1–2.4 hereafter). In turn, the membrane approach is penalized by an increased influence of heating effects as well as by a more difficult implementation of an electrical excitation. From this point of view, an alternative approach of great interest is that provided by the Silicon-on-Insulator (SoI) technology where the silicon layer constitutes a guiding layer of high refractive index between air and silica. Current effort is made to minimize parasitic coupling between TE and TM modes in this asymmetric waveguide system [21]. A variant of this approach is based on the report of a III–V photonic crystal membrane either on the silica layer [22] or on Bragg multilayers deposited on the SoI substrate [23]. This actually participates to the very active field of research for the integration of III–V optoelectronics on SoI [24].

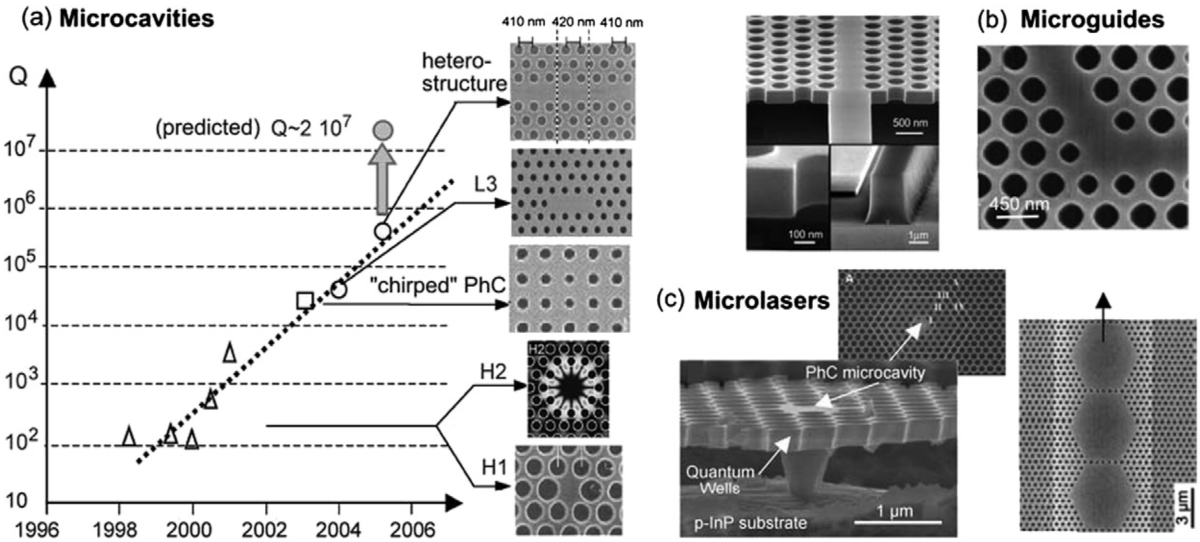

Fig. 1. Photonic crystal micro-devices. (a) Evolution of the Q-factor of photonic crystal microcavities during the last decade. (b) Left: W1 waveguide fabricated in the silicon membrane technology and formed by one row of missing holes in a hexagonal lattice of holes [33]. (b) Right: Light bent, realized in the same technology [5]. (c) Left: First electrically driven photonic crystal microcavity laser fabricated in the InP technology, the light being emitted vertically [6]. (c) Right: Edge-emitting coupled-cavity-waveguide laser fabricated on InP substrate [42].

2.1. Microcavities

Microcavities are key elements for a number of miniature optical devices including wavelength filters, microsources, optical switches, optical delay lines, etc. Interest in photonic crystal microcavities, compared to other semiconductor-based structures such as micropillars, microdisks and microtores [25], relies on the fact that they can exhibit the smallest mode volumes ($V \sim 0.3(\lambda/n)^3$). This characteristic can be now simultaneously achieved with very high Q-factors ($Q = \omega/\Delta\omega$) up to 10^6 thanks to recent progress in photonic crystal technology and microcavity engineering [3,26,27]. Fig. 1(a) shows the dramatic increase of the Q-factor of photonic crystal microcavities during the last decade. Last decisive progress was accomplished by the Noda's group first on small elongated cavities of the L3 type [26], then on the so-called 'photonic heterostructures' [3]. The photonic heterostructure is made of a small photonic crystal waveguide section sandwiched between two similar waveguides but with a slightly different lattice period. Because there is no hole to scatter the light at the cavity edges (i.e., at the edges of the middle waveguide section), the level of out-of-plane scattering losses is much lower than in other systems. Impressive results obtained on photonic heterostructures in the silicon membrane technology are now approached in III–V semiconductors [27]. A high Q-factor combined with a very small mode volume can lead to a dramatic enhancement of the spontaneous emission rate of an emitter in resonance with the cavity mode and even to the strong coupling regime between this emitter and the cavity [2]. The factor of merit for spontaneous emission enhancement, known as the Purcell factor [28], is proportional to Q/V while the factor to be maximized for the strong coupling regime is rather Q^2/V. All these effects open the route towards single-photon sources [29], single-quantum-dot lasers [30], quantum logical optical gates [31], photonic switches based on photon blockade [32] and, more generally, to quantum electrodynamics in a solid-state cavity.

2.2. Microguides

Microguides are other key elements of integrated optics. Their primary function is obviously to allow the propagation of light and the connection between the different devices of integrated circuits. From this point of view, interest in photonic crystal structures again stems from their small dimensions, leading, for instance, to sharp bends of light and compact optical circuitry. As for microcavities, considerable progress has been accomplished during last years. Propagation losses of the narrowest 'canonical' waveguide, formed by one row of missing holes in a two-dimensional array of holes (Fig. 1(b), left), are now found to be below $\sim$5 dB/cm [4,33]. The transmission of 120° light bends connecting one straight W1 waveguide to another (Fig. 1(b), right) reaches more than 90% [5]. All these performances, which are obtained in the 'membrane approach', are close to those reported for silicon photonic wires, i.e. for deeply etched ridge waveguides in the SoI technology [34]. The situation is quite different for photonic crystal waveguides in the 'substrate approach', since, in this case, the dispersion curves of guided modes cannot simultaneously lie in the gap and below the light line. In other words, guided modes in the 'substrate approach' are always leaky modes. Even with this, high-Q modes with low propagation losses are predicted for particular operating conditions [35]. Beyond compactness and low-loss performances, two-dimensional photonic crystal waveguides can also be strategic for single-mode edge-emitting lasers as well as for new optical devices exploiting slow light effects (see Sections 2.3, 2.4 and 3.1).

2.3. Microlasers

Progress in two-dimensional photonic crystal lasers and sources has essentially followed the development of photonic crystal microcavities and microguides in III–V semiconductors. One exception is that of the Bloch mode laser emitting near gap edge, since the photonic crystal is used as a whole without insertion of any defect [2,21,36]. Actually, photonic crystal lasers can be classified according as to whether the light is emitted vertically or in-plane. Photonic crystal VCSELs (Vertical Cavity Surface Emitting Lasers), Bloch mode lasers and microcavity lasers essentially belong to the first category, as they make use of out-of-plane losses. Photonic crystal VCSELs can be seen as slices of a microstructured semiconductor fiber, where the photonic crystal surrounding the vertical cavity provides the transverse mode control at high powers [37]. Bloch mode lasers, which present the simplest geometry, can exhibit low-threshold performances due to the fact that the lasing modes are basically slow modes strongly interacting with the gain medium [36,38]. Ultimate performances are expected to come from very-high-Q microcavity lasers. A decisive step in this direction was accomplished in 2004 by H.-G. Park et al. [6], who reported the first electrically photonic crystal microcavity laser fabricated in the InP technology (Fig. 1(c), left). Following this work, much effort is now engaged towards the development of quantum-dot photonic crystal microcavity lasers [30] with potential applications to quantum information and quantum cryptography. By contrast, the studies of in-plane or edge-emitting semiconductor photonic crystal waveguide lasers are more naturally oriented to integrated optics. The two-dimensional periodicity of the crystal and the strong index contrast associated to the corrugations of the waveguide edges offer a large variety of laser configurations and behaviors [39–42]. For example, Fig. 1(c) (right) shows an edge-emitting coupled-cavity-waveguide laser fabricated on InP substrate, which was capable of delivering 2.3 mW power in single-mode [42]. Recent works on edge-emitting photonic-heterostructure lasers also appear of great promise for future high-density photonic integrated circuits [43].

2.4. III–V photonic integrated circuits

Although III–V photonic integrated circuits based on photonic crystals are still in their infancy, decisive steps have been made during last years in parallel with the recent development of CMOS photonics [44]. For instance, GaAs-based W1 photonic crystal waveguides have been combined with InAs-based quantum dots to realize ultra-fast all-optical switches and logic devices [7]. As shown in Fig. 2(a), the all-optical switches include several directional couplers (DC) and a symmetrical Mach Zehnder whose optical phase shift arms are selectively embedded with quantum dots that exhibit strong refractive index non-linearity. The whole photonic structure, which is connected to external fibers, is $600 \times 300\ \mu m^2$ in size. The use of two control pulses allows operating the switch at the picosecond time scale with a switching energy of $\sim$100 fJ (Fig. 2(b)). Such a device marks a first step toward future ultra-fast optical digital processing. Photonic crystals and wavelength scale high index contrast structures can indeed bring the large-scale-level of integration into the world of photonics.

3. Control of the dispersion of light with photonic crystals

For most of the photonic crystal devices presented in previous sections, photonic crystals were essentially considered as photonic bandgap materials. A more intensive exploitation of photonic crystal chips obviously needs to consider photonic crystals in their transmission bands where they exhibit original dispersion and refraction properties.

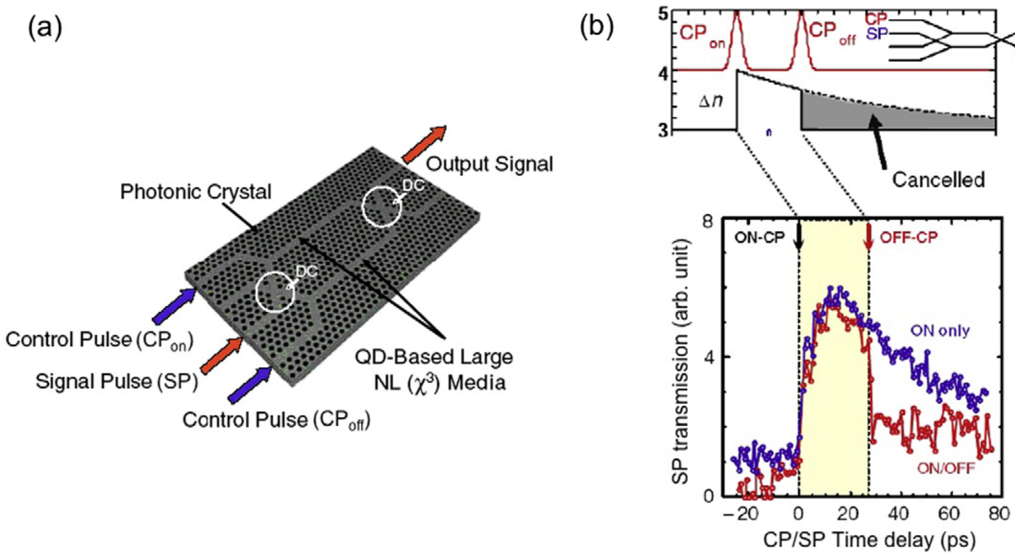

Fig. 2. Left: Schematic diagram of a photonic crystal all-optical switch using directional couplers (DC) and a symmetrical Mach Zehnder. Right: Measured output signal with only one control pulse (CP$_{on}$, blue curve) or with both control pulses (CP$_{on}$ and CP$_{off}$, red curve) [7]. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Photonic crystal waveguides, which are basically transmitting devices, also possess dispersion characteristics of great interest for applications.

3.1. Slow light effects

Because of the lattice periodicity and the existence of photonic gaps, allowed modes in a photonic crystal present dispersion lines $\omega(k)$ whose curvature strongly increases when approaching gap. Correspondingly, the derivative of $\omega(k)$ tends to zero. A similar situation occurs for the propagating modes in photonic crystal waveguides thanks to the periodic structure of waveguide edges. The group velocity of light ($v_g = \nabla_{k0}\omega(k)$) can thus be considerably reduced while the group velocity dispersion is increased in the same time [45]. These effects are all the more pronounced as the index contrast involved in the periodic lattice is strong. For example, a 100 μm long photonic crystal of air holes in a semiconductor matrix can compensate for the group velocity dispersion of 1 km long optical fiber! Recent experiments carried out by the Vlassov's group showed that the speed of light was reduced by a factor of more than 100 in a W1 waveguide [46]. A slowdown factor of 12 was obtained over a bandwidth of 2.5 THz by the Krauss' group in the case of a symmetrized W2 waveguide (with two rows of missing holes) [47]. Such slow light effects can actually be exploited with benefit in any active optical device, since they provide a strong enhancement of light–matter interactions [48,49]. This is especially true for non-linear devices as for instance the phase shift arms used in the Mach Zehnder shown in Fig. 2(a) [50]. In turn, a precise engineering of the coupling interface is essential to promote efficient coupling of light into the slow photonic crystal modes [46].

3.2. Refractive properties

In an isotropic homogeneous medium and for a given frequency, the wavevector amplitude is identical in all propagation directions. In other words, the isofrequency contour is circular or spherical in 2D or 3D, respectively. The situation is radically different for photonic crystals which are basically anisotropic materials. The isofrequency contour may present many different shapes, leading in turn to different behavior when an incident wave crosses the interface between a photonic crystal and a homogeneous medium. Several cases of interest are represented in Fig. 3, which also shows the 'construction' of the transmitted (refracted) waves from the isofrequency contours (k-space representations at the top). The construction must satisfy two conditions: (i) the wavevector component parallel to the interface is conserved, (ii) the group velocity is normal to the isofrequency contour. A square lattice is presently considered for the sake of simplicity.

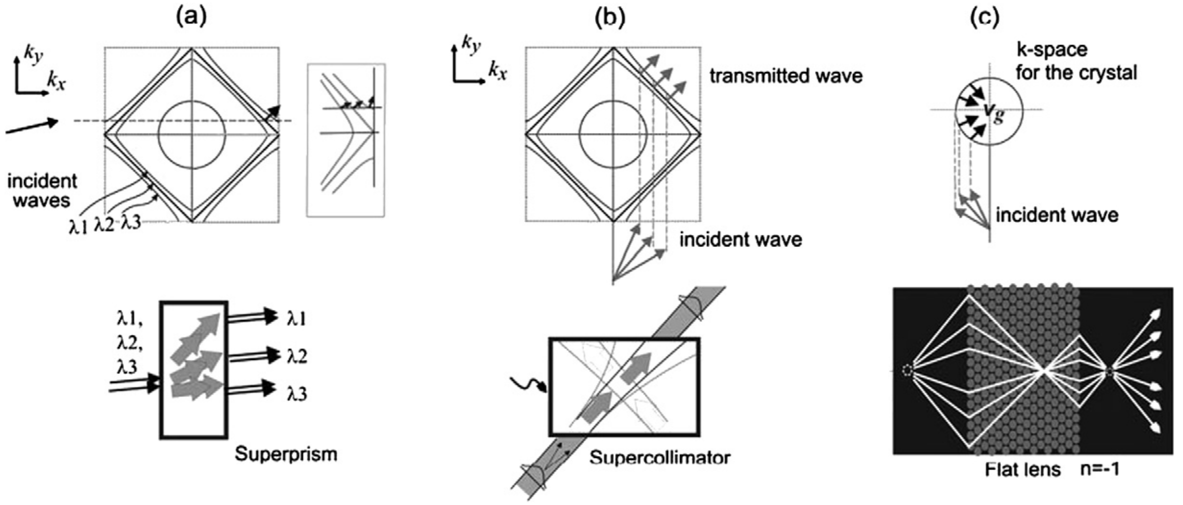

Fig. 3. Different cases of refraction occurring at the interface between a photonic crystal and a homogeneous medium. (a) Superprism effect, (b) supercollimation, (c) flat lens and negative refraction. In each case, the top figure gives a k-space representation, while the bottom figure corresponds to real space.

In the first case (Fig. 3(a), top), the construction of the refracted wave involves angular points of the isofrequency contour. Small frequency variations and thus small deformations of the isofrequency contour dramatically change the propagation direction of the refracted wave (Fig. 3(a), bottom). This is known as the superprism effect, which has been first demonstrated by Kosaka et al. in 1998 [10]. An angular selectivity of about $5°/\text{nm}$ was achieved in free space propagation, which was almost 100 times that of conventional glass prisms. A good angular selectivity was also obtained in several experiments in integrated optics [51–53], but further improvement of the transmission level is required to compete with other schemes [54] for applications to coarse wavelength (de)-multiplexers or spectrometers on-chip.

A different case of refraction occurs when the construction of refracted waves involves a flat region of the isofrequency contour (Fig. 3(b), top). All the k-components of a divergent incident beam are then re-directed in the same direction to form a collimated beam at the crystal output (Fig. 3(b), bottom). This self-collimation phenomenon, first reported in 1999 [9], has been discussed in detail in [55]. It opens the route toward channelless waveguiding in integrated optics with the possibility of using simplified architectures for the realization of optical functions. Fig. 4 illustrates the self-collimation phenomenon in the case of graded photonic crystals (see Section 3.3).

Finally, in the third example of Fig. 3, the isofrequency contour is circular with the normal oriented to the interior of the circle (Fig. 3(c), top). This situation occurs, for instance, for frequencies within the second transmission band of 2D photonic crystals and near the Γ point of the Brillouin zone [2]. All the k-components of the incident beam are then re-directed to the center of the circular contour. Thus, all happens as though the photonic crystal would possess a negative index of refraction [11]. Of particular interest is the case when $n = -1$ since, in principle, a small slice of photonic crystal is close to a perfect lens producing a stigmatic image of a point source (Fig. 3(c), bottom) [12,13]. The perfect flat lens was proposed by J. Pendry in 2000 in the general context of negative refraction materials [16] (see Section 4.2). Recent works showed that negative refraction photonic crystals could be used to focus light outside a photonic chip without using any additional lens [56].

3.3. Graded photonic crystals

Graded photonics crystals are among the most remarkable examples of photonic crystal structures capable of molding the flow of light thanks to their dispersive properties [57,58]. They rely on gradual modifications of structure parameters such as the lattice period, the hole diameter, etc. For illustration, Fig. 4 shows how a photonic crystal with a one-dimensional lattice gradient can bend self-collimated light without requiring the incorporation of any defect. Here, the map of the Poynting vector is calculated from a finite difference time domain (FDTD) model (Fig. 4(a)). As light penetrates successive crystal layers, its propagation direction is deviated according to the local group velocity

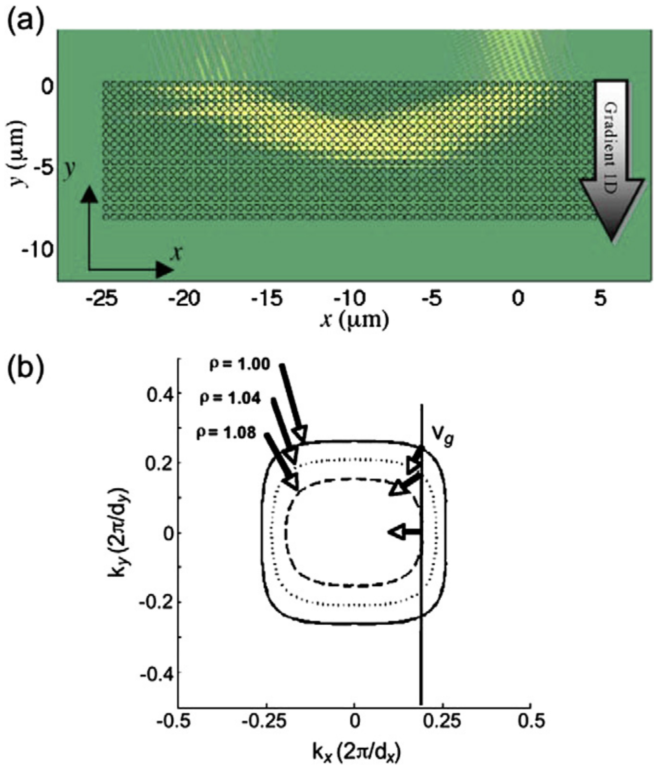

Fig. 4. (a) Light bend in a graded photonic crystal whose lattice period increases from top to bottom. (b) Isofrequency curves (IFC) calculated for different ratios $\rho = d_y/d_x$ where d_x and d_y are the lattice periods in the x and y directions, respectively. For each ρ, the group velocity of light v_g is normal to the isofrequency curve at the intersection point between the IFC and the construction line (results from E. Centeno at GES in Montpellier, France).

direction. The latter can be determined from the isofrequency curve (IFC) calculated for the local value of $\rho = d_y/d_x$, d_x and d_y being the lattice periods in the two crystal directions (Fig. 4(b)). The group velocity is actually normal to the isofrequency curve at the intersection point between the IFC and the construction line which expresses the conservation of k_x. As a major result of Fig. 4, it is seen that a 180° light bend can be achieved within a few crystal periods while preserving the width of the light beam. This behavior has been verified in recent experiments carried out in the microwave domain [59]. In the optical domain, the possibility of tuning the light path with the frequency opens another route toward very compact wavelength filters and on-chip spectrometers.

4. From photonic crystals to metamaterials

In parallel to photonic crystal studies, the perspective of achieving a simultaneous control of the effective permittivity (ε_{eff}) and the effective permeability (μ_{eff}) has been a major impetus to research on a new class of artificial materials, the so-called metamaterials, at the beginning of the 21st century. Using the approximation of homogeneous material, which means an elementary motif size much smaller than the wavelength, a very special situation occurs when both epsilon and mu are real and negative. As predicted by Veselago as early as in 1968 [14], such a metamaterial should be left-handed and possess a negative index of refraction with the consequences that the vectors **E**, **H** and **k** form a left-handed basis and that the phase velocity and the group velocity have opposite directions. In 1999, J. Pendry et al. proposed for the first time the practical realization of a negative mu by using a periodic array of metallic split ring resonators [15]. The next step was then to interleave such arrays with arrays of thin metallic wires [17,60], which were known to exhibit a negative epsilon at low frequencies [61]. The first experimental demonstration of negative refraction using these metamaterials was made in the GHz range by Smith et al. in 2000 [62]. Fig. 5 shows an example of a metamaterial of this type, which was optimized in transmission and bandwidth [63]. The negative index of refraction was estimated by measuring the displacement of a microwave beam when inserting a metamaterial plate in the beam path (Fig. 5(c)).

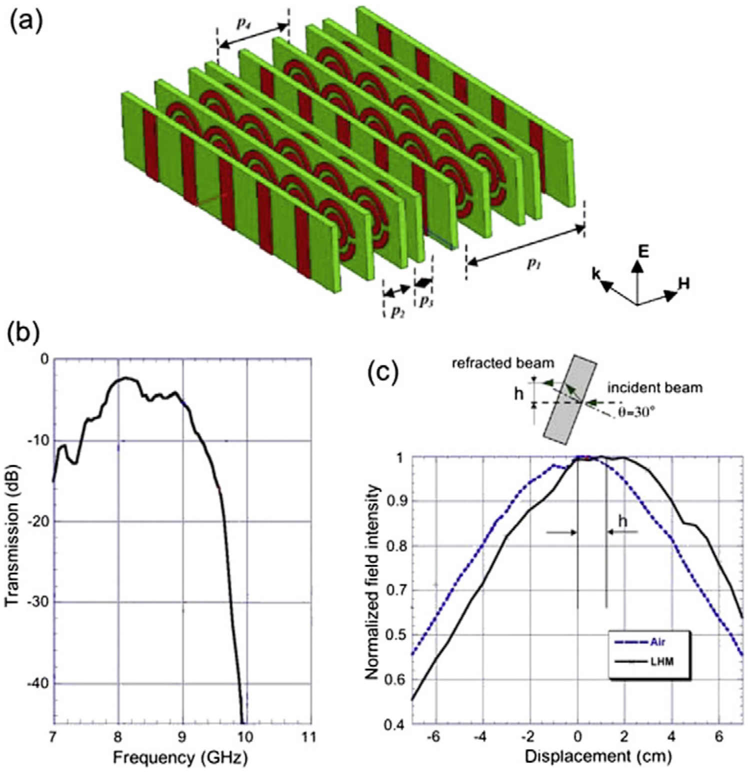

Fig. 5. (a) Left-handed material (LHM) fabricated in the printed circuit technology. The use of several split ring resonator layers unequally spaced within each period allows simultaneously optimizing the LHM transmission and bandwidth [63]. (b) Measured transmission around the LHM resonance. (c) Displacement of the microwave beam transmitted by the LHM.

4.1. Metamaterials in the optical domain

Going from microwaves to optics represents a real challenge in terms of physics and technology. Indeed, it is admitted that the magnetic susceptibility χ of all natural materials tails off at microwave frequencies [64]. The question is then to know whether or not it is possible to exploit the inductive response from structured non-magnetic materials to obtain high-frequency magnetism. Another difficulty may come from the fabrication of very small structures so as to satisfy the condition of homogeneous material at the optical wavelengths. Finally, the use of metals may also lead to prohibitive losses at short wavelengths. Several works have thus been recently carried out to investigate the possibility of extending microwave results to the optical domain. Fig. 6(a) shows a miniaturized version of a periodic array of metallic split ring resonators fabricated on glass [65]. Transmission measurements at normal incidence revealed indeed an LC type resonance (electric field parallel to the air gap) at 1.5 μm. Magnetic resonances and thus mu values different from one were claimed at both the 0.8 and 1.5 μm wavelengths for an oblique incidence and a non-zero magnetic field component perpendicular to the ring resonator plane. The metamaterial structure of Fig. 6(b) combines metallic wires and split ring resonators as in negative refraction metamaterials at microwave frequencies (Fig. 5(a)). Actually, both motifs were fabricated on top of a silicon substrate. The presence of continuous wires was found to significantly modify the structure behavior as compared to that previously described for the structure of Fig. 6(a) [66]. Not only a strong attenuation was observed at long wavelengths for the light polarized parallel to the wires, but also a left-handed behavior was revealed at normal incidence from a detailed comparison between experimental results and the results of numerical modeling (see the work by B. Kante et al. [67], in this issue). Fig. 6(c) shows a quite different metamaterial structure formed by a periodic array of dual metallic pillars on glass, which mimics a collection of magnetic atoms or molecules [68]. Its magnetic (or quadrupole) response in the visible was indeed attributed to antisymmetric plasmon resonances of each individual pair of gold pillars. This work also emphasized the important role of localized plasmons in metamaterials at optical wavelengths (see also Section 4.3 hereafter).

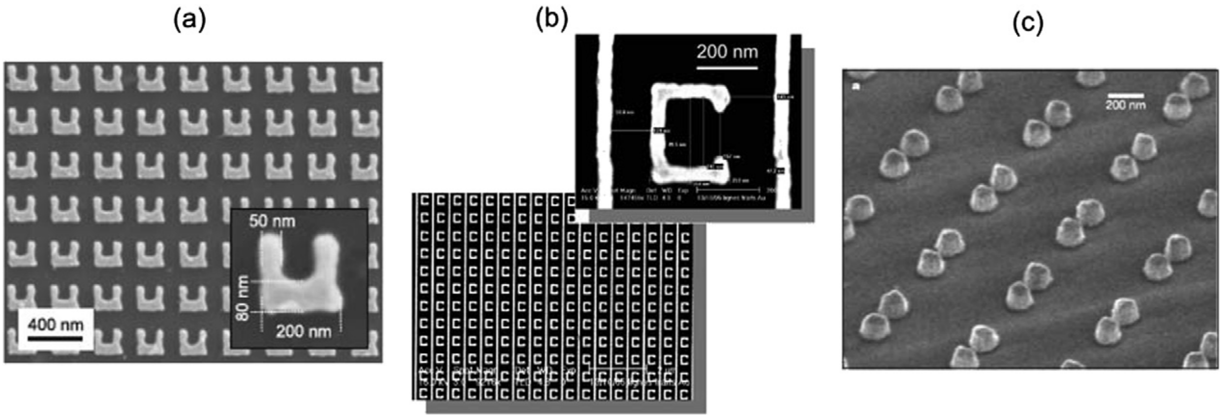

Fig. 6. Metamaterials with magnetic properties at short wavelengths: (a) periodic array of gold split ring resonators on glass showing a magnetic response at the visible and telecommunication wavelengths [65], (b) periodic array of gold wires and split ring resonators on silicon with left-handed properties in the near infrared [66] (see also the work by B. Kante et al. [67] in this issue), (c) periodic array of dual gold pillars with negative permeability in the visible [68].

4.2. *Negative refraction: metamaterials versus photonic crystals*

First results on short wavelength metamaterials are very encouraging, but regarding negative refraction and its application to near-field imaging and focusing systems, one should not forget the potentialities of photonic crystals as previously discussed in Section 3.2. Unlike metamaterials, negative refraction in photonic crystals can be obtained using purely dielectric constituents, which is a decisive advantage for making low-loss devices in the infrared and visible regions. In turn, photonic crystals are operated near or above their optical gap, where the working wavelength is comparable to the size of the elementary motifs. Thus, they can never be approximated as homogeneous materials. Because of that, a slab of negative refraction photonic crystal can generate an image of a point source, but this image is never stigmatic since it cannot contain all the energy radiated by the point source [69]. In other words, negative refraction photonic crystals remain of strong interest for micrometer scale focusing systems, whereas they can only approach the optical properties of a superlens. The ‘amplification’ of evanescent waves and the achievement of a transmission equal to one are restricted to the case of structures having not only an effective index equal to -1, but also an effective permittivity and an effective permeability close to -1 as in the case of a perfect left-handed material [70]. At this step, it is worthwhile mentioning sub-diffraction-limited imaging experiments where a thin silver layer with $\varepsilon < 0$, but $\mu > 0$ was used as a superlens [71]. An enhanced transmission of evanescent waves was achieved in this simple system thanks to surface plasmon excitation [72]. These experiments as the ones described in Section 4.1 also show that optical losses in metallic structures can remain at an acceptable level as far as small dimensions and/or small metal filling factors are concerned.

4.3. *From metamaterials to plasmonics*

As seen previously, metamaterial studies originally performed in the microwave domain can generate new ideas and new schemes in the optical domain. Perfect near field imaging is, indeed, the best illustration of the efforts aimed at translating the concept of metamaterials to optics. Metamaterial-based sub-λ cavities demonstrated at microwave frequencies [73] (see B. Kante et al. [67] in this issue) can also open a new way of confining infrared or visible light in ultra-small volumes. In a close context, recent works on metamaterial cloaks at microwave frequencies [74,75] have motivated the scientific community to design cloaking materials for producing the ultimate illusion of invisibility at optical wavelengths [76]. However, despite these very fruitful interactions between microwaves and optics, the direct transposition of microwave structures to optics must be taken with some care. Not only the technology and scale are different, but also the physical mechanisms and the distribution of electromagnetic fields and currents within the structures may be radically different. Resonant effects used to tailor mu and epsilon in optical metamaterials are essentially plasmon resonances. For instance, there is no need for employing electrical engineering terms to define the so-called LC resonance which is but the fundamental plasmonic (odd) mode of the split ring resonator [77]. Unlike the microwave regime, electromagnetic fields are well localised in the metallic regions since plasmon resonances involve resonant oscillations of charges in metals. For all these reasons, future developments of optical metamaterials will be linked to the progress in plasmonics [78].

5. Conclusions

We have shown that decisive progress has been accomplished during last years in the physics and technology of photonic crystals and metamaterials. Clearly, integrated optoelectronics have not followed the Moore's law, but wavelength-scale photonic crystals and plasmonic structures are a real opportunity to bring the large scale level of integration into the world of photonics. Owing to the recent advances in photonic crystal-microcavities, microguides and microlasers, there are now many entrance points for functional photonic crystal devices, for which the market place becomes a reality more than a dream. Integration of these devices in first 'all-photonic' circuits is also in progress. Further developments are expected to come from a more intense use of slow wave and dispersion effects in photonic crystals along with the exploration of ultimate devices such as quantum optical gates or solid-state sources operated either in the strong or weak coupling regime. This in turn requires the development of appropriate techniques for characterizing and/or adjusting the properties of photonic crystals at sub-wavelength scales [79,80] (see the work by B. Cluzel et al. [81] in this issue). At this stage, one should not forget the remarkable development of microstructured fibers and photonic crystal fibers during the recent years. From a practical standpoint, these fibers open up unprecedented prospects with respect to the control of propagation mode in fiber-optics and to the control of chromatic dispersion. Although the present article has been exclusively focused on photonic crystals in planar guided optics, the reader is referred, for instance, to review papers [82,83] for some technology and modeling aspects of microstructured fibers and photonic crystal fibers.

From an exploratory point of view, photonic crystals and metamaterials offer a wealth of new phenomena in optics and electromagnetism including negative refraction, near-field focusing, artificial magnetism, optical invisibility and the amplification of evanescent waves. The past few years have illustrated the power of the metamaterial approach, because new material responses, some with no analog in usual materials, are now available for exploration. Pioneering experiments have been carried out in the RF and microwave domains with millimeter or micrometer scale structures, but there is now a strong motivation for extending them to the optical domain using nanometer scale structures available with nanotechnology. This extension was in the spirit of the "Nanosciences et Radioélectricité" workshop organized by CNFRS in March 2007. Developing plasmonic metamaterials was indeed felt to be strategic for future photonic circuits and systems.

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