Photonic Crystals: an unprecedented nanoscale enabler of light.

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Extended abstract

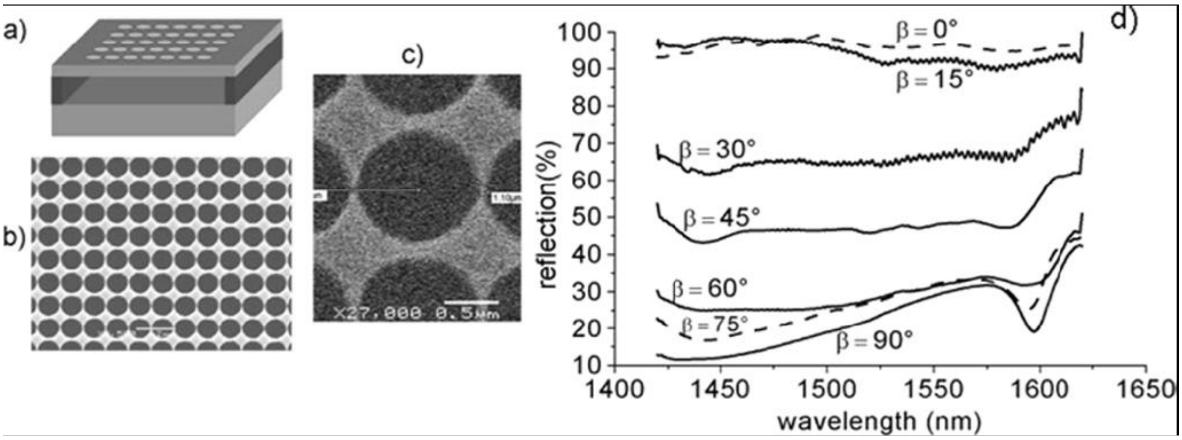
Inside the wide family of periodic photonic structures, dielectric photonic crystals have played a fast growing part during the last 25 years, their specificity inherently lying in the high index contrast of the periodic modulation (generally more than 200%) introduced in the optical medium. The concept of three dimensional photonic crystal (3D PhC) was simultaneously introduced by S. John [1] and E. Yablonovitch [2]: it is currently considered as a must for 3D spatial and temporal confinement of the light. In practice the fabrication of 3D PhCs is very difficult, and most of the developments have concerned the production of 1D and 2D PhCs formed in wave-guiding dielectric slabs. These high-index-contrast periodic structures can indeed be fabricated using planar technological approaches that are familiar to the world of integrated optics and microelectronics. They consist practically in 1D or 2D structuring of a planar dielectric/semiconductor membrane waveguide, where photons are “index guided”, that is to say vertically confined by the profile of the optical index. In most of the reported works, 1D-2D PhCs are meant to operate solely in the 2D wave-guiding configuration and, hence, are limited to a 2D control of photon trajectory: in this context, they have been the matter of an innumerable number of reports, publications, conferences and tutorials. In the present tutorial, we will not therefore contribute further to this abundant literature and will not talk about 2D PhCs operation, where control of light is restricted to the sole in plane wave-guiding configuration. We will instead concentrate on more recent developments where use is made of 1D-2D PhC membranes for efficient 3D harnessing of light, along a variety of configurations including both in plane wave-guided and free space radiated regimes.

The history of 1D-2D periodic photonic structures has started with the original discovery of diffraction gratings by James Gregory, a Scottish mathematician and astronomer, by passing sunlight through a bird feather and observing the diffraction pattern produced [3]. Since then, they have been the matter of considerable developments, namely for the manipulation of light in free space with angular and wavelength resolution. The seminal publication of Wood in 1902 [4], where the author reports on the observation of strong intensity variations (so called Wood anomalies) in the spectrum of an optical beam diffracted by a diffraction grating, has triggered the production of considerable amount of investigations throughout the 20th century, beginning with the theoretical treatment proposed by Rayleigh in 1907 [5], inspired by the genius intuition that propagating diffraction order can be converted into an evanescent diffraction order and vice versa. In the nineteen sixties, the emergence of rigorous theories of the diffraction and enough powerful computation tools allowed for the accurate description of Wood anomalies. In 1965, Hessel and Onliner introduce the concept of resonance anomalies, associated with the excitation of surface waves or guided waves, depending upon the structure considered [6]. Surface waves, which will be called, later on in the 20th century, surface plasmons, are observed in metallic gratings; the guided waves are observed in dielectric gratings and will be referred to as guided-mode resonances (GMRs). These authors share the common idea with Rayleigh that, when Wood anomalies are present, the photons experience successive modal conditions, where they propagate (or radiate) in free space and where they are wave-guided within the grating structures, that is to say evanescent in free space at least during the time spent within the gratings. The first experimental demonstration of guided

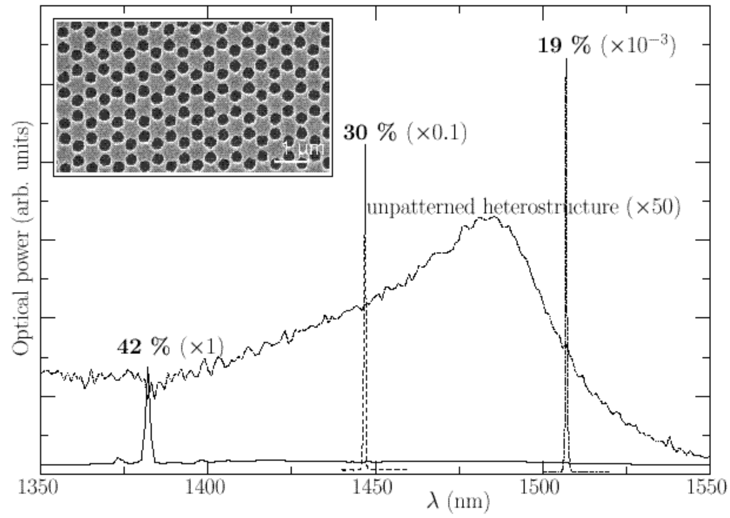
mode resonances in dielectric gratings was reported by Mashev and Popov [7]. The first practical applications based on these resonant periodic structures, proposed by Magnusson *et al.* [8], [9] (tunable filters, polarization resolved reflectors…), have stimulated number of works, made possible by the relentless progress of lithographic and etching techniques.
The observation and analysis of Wood anomalies (or GMRs) have also been reported in 1D and 2D dimension PhC membrane structures [10], the general applied concepts being essentially the same as those used in a conventional dielectric grating. As analysed in detail for the first time by X. Letartre *et al.* in [11], one specific added value of the high index contrast typical of PhC structures, within the general context of resonant gratings, lies in the capability of PhC membrane waveguides to provide an efficient lateral confinement of photons during their wave-guided stage. In particular, if the wave-guided resonances operate around a high symmetry point (e.g., the so-called Γ-point of the first Brillouin zone), where the dispersion characteristics are very flat, the light is efficiently slowed down. This specificity offers the possibility to design and produce very compact surface-addressable devices, endowed with comfortable angular aperture, while retaining excellent characteristics such as, for instance, a high reflectivity yield.

The physical principles of surface-addressable resonant PhC membrane structures will be presented in detail: they build on the numerous works published since the seminal publication of Wood and are based on the resonant coupling of incoming optical beam (radiated mode) with wave-guided Bloch modes in the PC membrane, which may occur whenever wavelength and *k*-vector matching conditions are met. The essential driving forces and controlling parameters will be described and routes for simple design rules, resulting in the production of structures endowed with the desired characteristics in the space-time domain will be given.

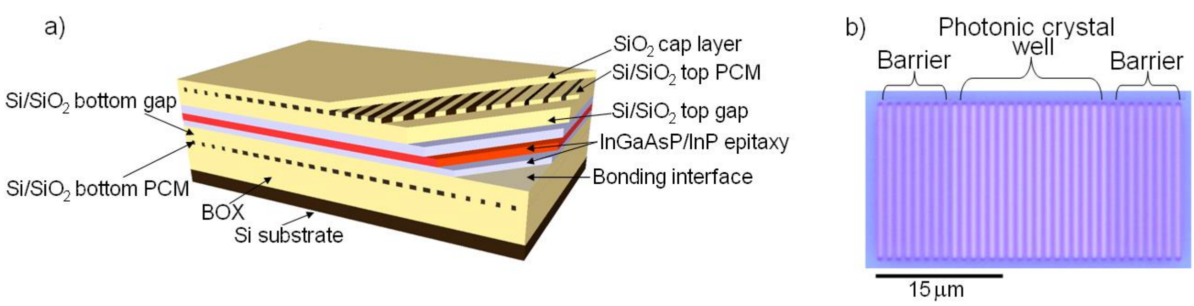
Exemplifying use of surface-addressable resonant PhC membrane structures in a variety of devices will be presented [12]: this will include large bandwidth compact reflectors [13, 14], narrow bandwidth single PhC membrane active resonators for laser emission [15], optical amplification and bi-stability [16], new family of VCSEL devices [17-19], including CMOS-compatible ultra-compact 1.55-µm emitting VCSELs using double photonic crystal mirrors [20, 21]. A few illustrations of these devices are shown below.



(a) Schematic representation of broadband and compact 2-D Photonic Crystal reflector. (b) SEM general view. (c) SEM close-up view of one cell of the lattice. (d) Experimental reflectivity spectra of the square lattice with elliptical holes, for various angles of polarization of the incident wave (see [14]).



Low threshold, room temperature vertical emitting laser based on an InP two-dimensional photonic crystal membrane (graphite lattice): laser emission spectra for various air hole filling factors. A SEM top view of the structures is shown in the inset (see [15]).



CMOS-compatible VCSELs using double photonic crystal mirrors: schematic view (a) and top SEM view (b) (see [21])

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