1 Introduction

When thinking about traditional optical materials one invokes a notion of homogeneous media, where imperfections or variations in the material properties are minimal on the length scale of the wavelength of light λ (Fig. 1.1 (a)). Although built from discrete scatterers, such as atoms, material domains, etc., the optical response of discrete materials is typically "homogenized" or "averaged out" as long as scatterer sizes are significantly smaller than the wavelength of propagating light. Optical properties of such homogeneous isotropic materials can be simply characterized by the complex dielectric constant ε. Electromagnetic radiation of frequency ω in such a medium propagates in the form of plane waves $\mathbf{E}, \mathbf{H} \sim e^{i(\mathbf{k}\cdot\mathbf{r}-\omega t)}$ with the vectors of electric field $\mathbf{E}(\mathbf{r}, t)$, magnetic field $\mathbf{H}(\mathbf{r}, t)$, and a wave vector $\mathbf{k}$ forming an orthogonal triplet. In such materials, the dispersion relation connecting wave vector and frequency is given by $\varepsilon\omega^2 = c^2\mathbf{k}^2$, where c is the speed of light. In the case of a complex-valued dielectric constant ε, one typically considers frequency to be purely real, while allowing the wave vector to be complex. In this case, the complex dielectric constant defines an electromagnetic wave decaying in space, $|\mathbf{E}|, |\mathbf{H}| \sim e^{-\mathrm{Im}(\mathbf{k})\cdot\mathbf{r}}$, thus accounting for various radiation loss mechanisms, such as material absorption, radiation scattering, etc.

Another common scattering regime is a regime of geometrical optics. In this case, radiation is incoherently scattered by the structural features with sizes considerably larger than the wavelength of light λ (Fig. 1.1 (b)). Light scattering in the regime of geometrical optics can be quantified by the method of ray tracing. There, the rays are propagating through the piecewise homogeneous media, while experiencing partial reflections on the structure interfaces. At any spatial point, the net light intensity is computed by incoherent addition of the individual ray intensities.

The regime of operation of photonic crystals (PhC) falls in between the two limiting cases presented above. This is because a typical feature size in a photonic crystal structure is comparable to the wavelength of propagating light λ (Fig. 1.1(c)). Moreover, when scatterers are positioned in a periodic array (hence the name photonic crystals), coherent addition of scattered fields is possible, thus leading to an unprecedented flexibility in changing the dispersion relation and density distribution of electromagnetic states.

Originally, photonic crystals were introduced in the context of controlling spontaneous emission of atoms. [1,2] It was then immediately suggested that in many respects the behavior of light in periodic dielectrics is similar to the behavior of electrons in the periodic potential of a solid-state crystal, [3,4] and, therefore, one can manipulate the flow of light in photonic crystal circuits in a similar manner as one can manipulate

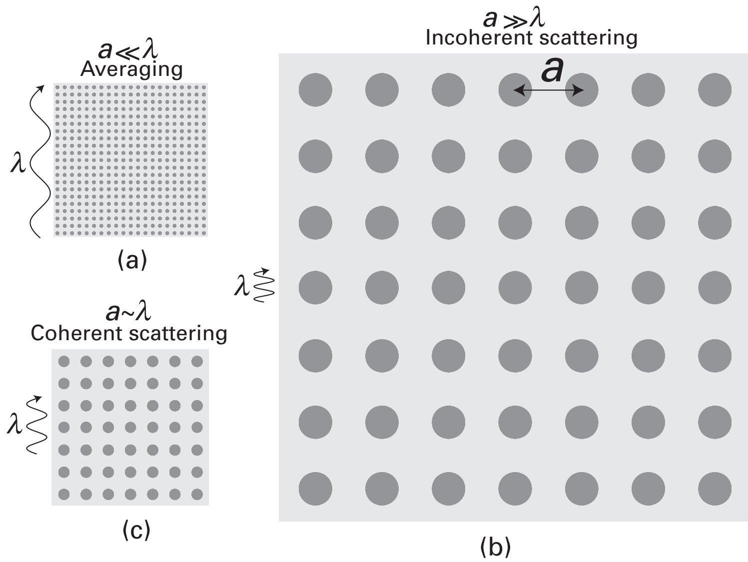

Figure 1.1 Scattering regimes. (a) Homogeneous media, averaging over individual scatterers. (b) Incoherent scattering in geometrical optics. (c) Coherent scattering from the structure with characteristic feature size comparable to the wavelength of light.

the flow of electrons in solid-state circuits. Since then, photonic crystals became a very dynamic research field, with many novel applications and fabrication methods discovered regularly. The existing body of work on photonic crystals is so vast that to do proper justice to all the great ideas is impossible in the context of a short review chapter. For a comprehensive introduction, we therefore refer the reader to several recent review articles and references thereof, which we summarize briefly in the remainder of this section.

1.1 Fabrication of photonic crystals

It is interesting to note that photonic crystals, despite their structural complexity, have many analogs in nature. Biologically occurring photonic crystals are discussed, for example, in [5] where the authors present an overview of natural photonic crystals and discuss their characteristic geometries, sizes, material composition, and bandgap structure. The authors conclude that a low-refractive-index contrast is a universal feature of biological photonic crystals, compared with artificial ones. Natural photonic crystals are also encountered in nonorganic compounds, such as opals.

Recently, artificial opals fabricated by self-assembly of colloidal particles became a popular research topic, mostly owing to the relatively simple and cost-effective methodology of producing large samples of periodic photonic structures. In [6,7], the authors survey some of the techniques used for promoting self-organization of the colloidal spheres into 2D and 3D ordered lattices, highlighting applications of these artificial crystals as photonic bandgap reflectors, as physical masks in lithographic patterning, and as diffractive elements for optical sensors. Furthermore, by infiltration of the artificial opals with high-refractive-index materials, and after removal of the original spheres, one can create "true" 3D photonic crystals with complete photonic bandgaps in all directions. Although the self-assembly approach is simple and cost effective, random lattice defects, such as dislocations and missing particles, limit the maximal size of a defect-free photonic crystal. Moreover, the lattice symmetries resulting from colloidal assembly are limited.

An alternative "mass production" technique developed for fabrication of the uniform 2D and 3D photonic crystals is a multi-beam interference lithography, also known as holographic lithography. In this technique, the periodic intensity pattern caused by several interfering beams is transferred to a photosensitive polymer substrate through a single exposure. In [8,9], the authors review the relationship between beam geometry and the symmetry of the interference patterns, the lithographic process, and various types of photoresist systems.

Just like the introduction of dopants into semiconductor crystals, to provide advanced functionalities to photonic crystals one has to introduce controlled defects into the photonic crystal's otherwise perfectly periodic lattice. While self-assembly of colloidal crystals and holography provides an efficient way of fabricating large-scale 2D and 3D photonic crystals, these methods have to be supplemented with other methods for defect incorporation. In [10] the authors cover recent advances in the fabrication of defects within photonic crystal lattices, including, among others, micromanipulation, direct writing, and multistep procedures involving the combination of 3D PhC fabrication methods and some types of 2D lithography. In particular, the micromanipulation approach uses nanopositioner robots and proceeds through serial assembly of nanoscale building blocks. Although this method has the potential of building nearly arbitrary 3D structures it suffers from the serial nature of the nanomanipulation process. Another methodology is the direct writing of photonic crystals in photosensitive materials. This method is interesting as it is relatively fast, easily parallelizable, and it treats on an equal footing the writing of periodic structures and the incorporation of nonperiodic defects. One of the implementations of a direct writing method is based on two-photon polymerization (TPP). This utilizes a nonlinear multiphoton excitation process to polymerize a photosensitive monomer in a very small volume (potentially subwavelength) around the focal point. This technique has been successfully tested in writing embedded features within holographic and self-assembled photonic crystals. Finally, several multistep methodologies have been developed for the incorporation of point, linear, and planar defects within self-assembled photonic crystals. These approaches generally involve three steps. The first step consists of growing a self-assembled colloidal crystal with flat surface termination. The second step involves deposition of an intermediate layer, followed by some kind of 2D lithographic patterning of the layer. Finally, self-assembly growth of the overlaying part of a photonic crystal concludes the process.

To date, probably the most studied process for photonic crystal device fabrication is based on 2D patterning of planar dielectric slabs using electron beam lithography. State-of-the-art lithography in combination with electrochemical or reactive-ion etching allows fabrication of low-imperfection 2D photonic crystals in various high-refractive-index material combinations, including silicon–air and III–V semiconductors. [10,11,12] The introduction of defects into these structures is carried out at the same time and on the same footing as periodic structure formation, resulting in excellent alignment between the defects and the surrounding lattice. By removing a single feature (a cylinder, for example) or a line of features from the perfectly periodic lattice, resonators (point defects) or waveguides (linear defects) can be introduced. Finally, the generalization of planar lithographical techniques to create 3D photonic crystals using multistep processes, such as wafer fusion and layer-by-layer photolithography, was recently reviewed in [10,13].

Despite their great potential, most photonic crystal-based devises are still in the research phase. Some of the few existing commercial applications of photonic crystals beyond 1D planar interference filters include glass and polymer based photonic crystal fibers (PCF). [14,15,16] Similar to conventional optical fibers, PCFs are slender cylinders with sizes ranging from below 100 μm to over 1 mm in diameter. In its cross-section, as the name suggests, the PCF features a 2D periodic pattern of holes or a 1D periodic pattern of concentric layers, as well as a localized defect serving as a fiber core. Lengthwise, PCFs can be of several meters to several kilometers. Photonic crystal fiber fabrication differs greatly from that of conventional photonic crystals as it typically proceeds through heating and elongation of a macroscale fiber preform. As a result, PCF fabrication is ideally suited for mass production, resulting in kilometers of high-quality, uniform fiber per single preform. Commercial applications of PCFs, among others, include supercontinuum generation for spectroscopic applications, [17,18] and photonic crystal fibers for radiation guidance in hollow, gas-filled, and subwavelength porous cores [19,20,21,22,23,24] thus enabling low-loss, low-nonlinearity, high-power delivery anywhere in the visible, IR, and even THZ spectral ranges.

1.2 Application of photonic crystals

In this section, we review some of the unique properties of photonic crystals that make them desirable for various light managing applications. As in the case of the overview of fabrication techniques presented earlier, we refer the reader to the recent review papers [5,6,7,8,9,10,11,12,13,14] for a more thorough introduction to possible PhC applications.

1.2.1 Photonic crystals as low-loss mirrors: photonic bandgap effects

The majority of applications of photonic crystals utilize the phenomenon of photonic bandgap (PBG). Photonic bandgap is defined as a frequency region characterized by zero density of the electromagnetic states. For the frequencies within PBG, the propagation of electromagnetic waves inside of a photonic crystal is, therefore, suppressed. The existence of PBGs opens the road to the design of efficient low-loss dielectric reflectors that can confine radiation in channels (waveguides) or localized defects (resonators) with sizes comparable to the wavelength of light.

In general, confining light presents a difficult task, as electromagnetic radiation propagates unimpeded in free space. Therefore, confining light is fundamentally different from confining direct electric currents for which free space acts as an isolator. Consider, for example, optical fiber, which is the optical analog of electric wire. Light in an optical fiber is confined inside the optically dense core, like the electric current, which is confined inside a wire core of low ohmic resistance. When optical fiber is bent, substantial radiation leakage from the fiber core into the fiber cladding is observed, as escaping radiation propagates freely through the cladding region. A similar effect is not observed in bent metallic wires, as free space surrounding the wire acts as an efficient current isolator.

To date, the most studied natural materials known to expel and reflect electromagnetic waves efficiently are metals. In the microwave regime, $\lambda \sim 1$ cm, most metals exhibit high reflectivity and low absorption loss per single reflection, which makes them ideal candidates for confining and managing electromagnetic radiation. For example, aluminium, which is one of the least expensive materials used to make mirrors, exhibits almost perfect reflectivity in the microwave region with $\sim$0.01% absorption-induced loss per single reflection. However, in the visible, $\lambda \sim 400$ nm–800 nm, and infrared (IR), $\lambda \sim 800$ nm–20 μm, the same material exhibits $\sim$10–20% loss per reflection, thus, considerably limiting its utility for managing light in these spectral regions.

Before the invention of all-dielectric photonic crystals, building compact light circuits in the IR spectral region was problematic because of the lack of low-loss, highly reflecting materials. As most dielectric materials in the IR have considerably lower losses than metals, all-dielectric photonic crystals have a potential to considerably outperform metal reflectors in terms of losses. Together with the ability of designing spectral position of the photonic bandgaps by means of varying the geometry, photonic crystals offer unprecedented flexibility in realizing low-loss, highly reflective medium for the applications of light guiding almost anywhere in the visible and IR regions.

Although interpretation of photonic crystals as efficient reflectors was known from their discovery, it was later established that this analogy can be advanced further, and the concept of omnidirectional reflectivity was suggested. By definition, omnidirectional reflectors exhibit almost perfect reflection in the vicinity of a designable wavelength for all angles of incidence and all polarizations (Fig. 1.2 (a)). Although much prior work has been done on dielectric multilayers, design criteria for the omnidirectional 1D periodic multilayer reflectors were first presented in [25]. This idea was later extended to waveguides, where the core can be of any material including lossless vacuum, while light is confined in the core by an omnidirectional reflector in the planar (Fig. 1.2 (c)) [26,27] or cylindrical geometry (Bragg fiber in Fig. 1.2 (d)). [19,20] Quasi-1D PhC reflectors in the form of a transverse concentric Bragg stack led to implementation of hollow waveguides, where most of the transmitted power is concentrated in the gas-filled hollow core, thus reducing propagation losses and nonlinearities. This enabled high-power laser guidance at various wavelengths in the mid-IR. [21]

It was later demonstrated theoretically [28] that, although helpful, omnidirectional reflectivity is not necessary for opening sizable bandgaps as well as for enabling efficient guidance of all polarizations in low refractive index cores. This was also verified

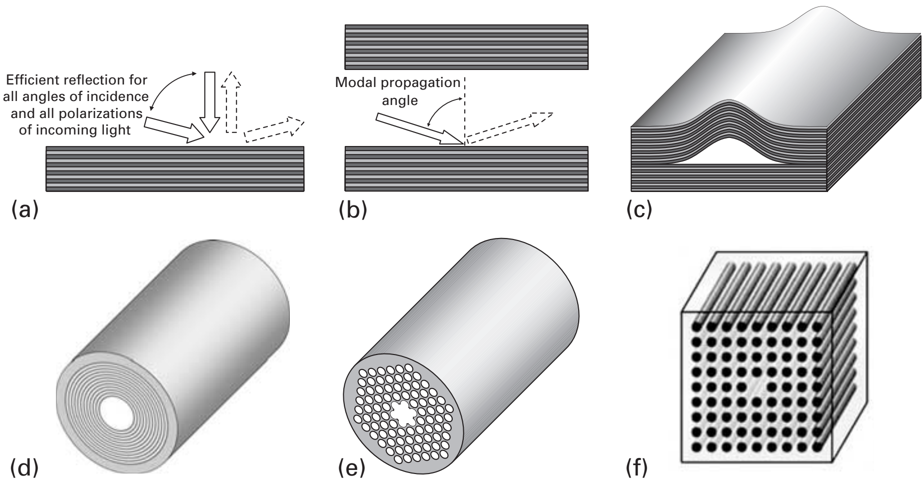

Figure 1.2 Photonic crystal waveguides and fibers guiding in the lower refractive index cores. (a) Omnidirectional reflectors. For any polarization and angle of incidence of the incoming light, radiation is completely reflected in a certain frequency window, also known as a bandgap. (b) Light can be trapped inside a hollow core when completely surrounded by a photonic crystal reflector. (c, d, e) Practical implementations of the hollow core waveguides in the form of an integrated 1D-periodic waveguide (c), Bragg fiber featuring concentric quasi-1D periodic reflector (d), and photonic bandgap fiber featuring 2D photonic crystal reflector (e). (f) Optically induced reconfigurable photonic lattice with a single site defect inside of a photorefractive crystal.

experimentally in various low index contrast photonic crystal and Bragg fibers. [29,30,31] This is related to the fact that modal propagation inside a photonic crystal waveguide, especially one having a large core diameter, can be described as a sequence of consecutive bounces of the trapped radiation at the core–reflector interface (Fig. 1.2 (b)). The angle of incidence of such radiation onto a reflector can be typically characterized by the effective modal propagation angle. Therefore, to enable guidance in the low refractive index core, it is only necessary to design a photonic crystal reflector that is efficient for a particular modal propagation angle. Finally, we note that an alternative way of confining radiation in the low refractive index core is by using 2D photonic crystal reflectors made of a periodic array of air holes embedded into the fiber cladding material (Fig. 1.2 (e)). [22,23] Such fibers are typically referred to as photonic bandgap fibers and are made of silica glass. Although periodic cladding in such fibers exhibits relatively high index contrast, the corresponding photonic crystal reflectors are, however, not omnidirectional.

Another PCF-like system with even weaker refractive-index contrasts is a photorefractive crystal imprinted with an optically induced photonic lattice (Fig. 1.2 (f)). The photonic lattice in such a system can be created by interference of several plane waves, [32] while localized defects in a photonic lattice can be created using amplitude masks. [33] Owing to the crystal's photosensitivity, the externally induced photonic lattice creates a periodic refractive-index variation on the order of 10^{-3} inside the crystal. Even for such a small index contrast, linear bandgap guidance in the low-refractive-index core is possible. [33] The significant advantage of optically induced photonic lattices is that the experimental configuration of the photonic lattice is dynamically adjustable, thus allowing real-time control of the lattice spacing and amount of index variation. Therefore, it provides a convenient test bed for the study of bandgap guidance in the weak index-contrast systems. Another useful property of these photonic lattices is that nonlinear effects of light appear at very low intensities (on the order of 1 mW/cm^2). In addition, the nonlinearity can change from focusing to defocusing by simply reversing the DC electric field applied to a crystal. The nonlinearity gives rise to stationary solitons propagating along the direction of lattice uniformity. These solitons, when launched along a nonnormal direction, can also navigate through the lattice with little energy loss, and can, in principle, enable light-routing applications in lattice networks. [34,35]

Up till now we have described the use of photonic crystal reflectors to confine light inside low-refractive-index core waveguides and fibers (Figs. 1.2 (c),(d),(e)), where radiation guidance is along the waveguide axis. A related application of photonic crystal waveguides is their use as interconnect elements in integrated optical circuitry. In principle, by bending the waveguide, one can steer radiation away from its original propagation direction. However, when decreasing the bending radius, radiation leakage from such waveguides increases dramatically. Enhanced radiation leakage occurs because by bending a waveguide, one also perturbs the geometry and, hence, the reflection properties of a photonic crystal reflector, rendering it ineffective when the perturbation is strong. If the photonic crystal waveguides are to be used in integrated optical circuits it is, therefore, necessary to implement compact light steering elements such as bends, T and Y junctions, etc., with as low radiation loss as possible (Fig. 1.3 (a)). In [36] the authors proposed that such light-steering elements can be introduced as defects in otherwise perfectly periodic 2D photonic crystals featuring omnidirectional bandgaps (for at least one of the light polarizations). As there is no physical bending present in such systems, the omnidirectional reflector structure remains unperturbed and, thus, suppresses any radiation that is not propagating along the direction of a defect (Fig. 1.3 (b)). As a result, all the radiation coming into the steering element can be either propagated along or reflected back with no radiation loss into the cladding.

Moreover, by introduction of a topology-optimized resonator into the structure of a steering element one can design narrow [37] and wide bandwidth [38] steering elements exhibiting almost perfect transmission (Fig. 1.3 (c)), no crosstalk and no back reflection. As sizes of the individual features in photonic crystals are comparable to the wavelength of guided light, the above-mentioned approach allows design of compact steering elements with sizes on the order of the light wavelength.

Another prominent application of photonic crystals is their use as confining media for the photonic microcavities. Microcavities are essential components for various integrated optical devices, such as wavelength filters, add–drop multiplexers, and lasers. When a uniform dielectric region is surrounded by a photonic crystal reflector featuring omnidirectional reflectivity (complete bandgap), such a structure can serve as a high-quality resonator able to trap and store light. When looking at the density of electromagnetic states of a photonic crystal featuring a point defect (resonator), a localized resonator state

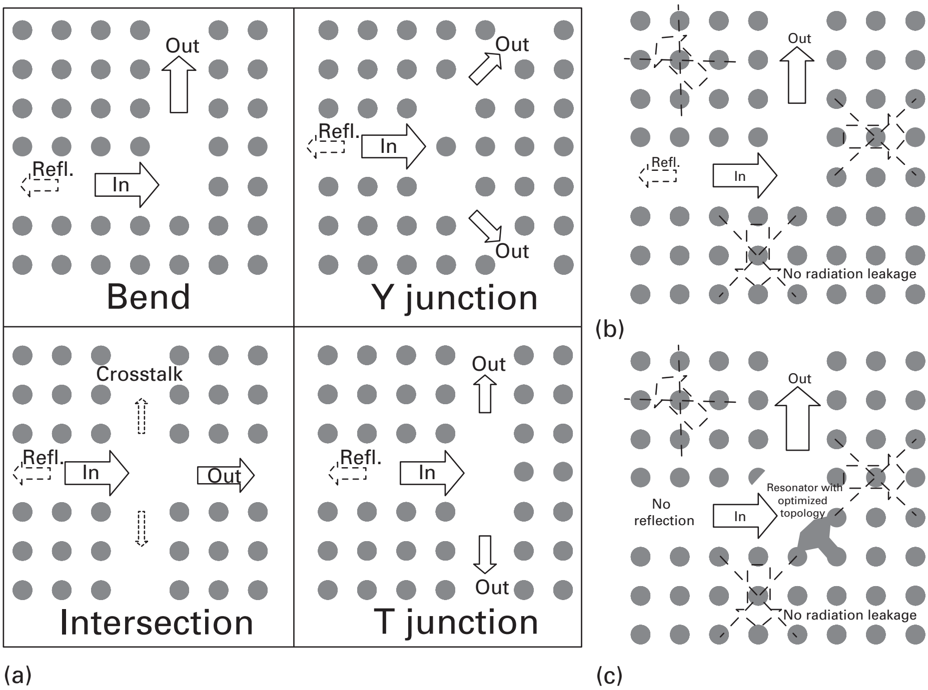

Figure 1.3 Compact light-steering elements based on photonic crystals for integrated optical circuits. (a) Various types of light steering elements such as bends, waveguide intersections, Y and T junctions. (b) Light launched into a steering element (a waveguide bend in this figure) surrounded by an omnidirectional photonic crystal reflector can only propagate along the direction of a defect. Radiation propagation outward from the defect is suppressed by the reflector bandgap. In the unoptimized defect structure, back reflection can be substantial. (c) By introduction of a topology-optimized resonator into the defect structure one can obtain narrow and wide bandwidth steering elements exhibiting almost perfect transmission and no crosstalk (for waveguide intersections).

manifests itself as a delta function positioned inside the photonic bandgap of a surrounding photonic crystal [4]. Various geometries of the microcavities have been explored over the years with the goal of increasing the quality factor of a cavity, while reducing the microcavity volume. Two main cavity geometries can be distinguished as those based on concentric Bragg reflectors [39] (Fig. 1.4 (a)), and those based on localized defects in slab photonic crystals [40,41] (Fig. 1.4 (b)) (here we omit discussion of ring resonators, which do not operate using bandgap effects).

Microcavities of both types can be used as laser cavities if a gain media is placed inside, leading to a possibility of compact lasers with designable direction of emission that can be easily integrated with other planar PhC components. [39,42,43] When the cavity is filled with a nonlinear material all-optical devices become possible where light routing and information transmission is enabled by the same beam. [44]

To excite a microcavity one typically uses the mode of a bus waveguide weakly coupled to a cavity state. When the microcavity is used for filtering, a mix of several wavelengths

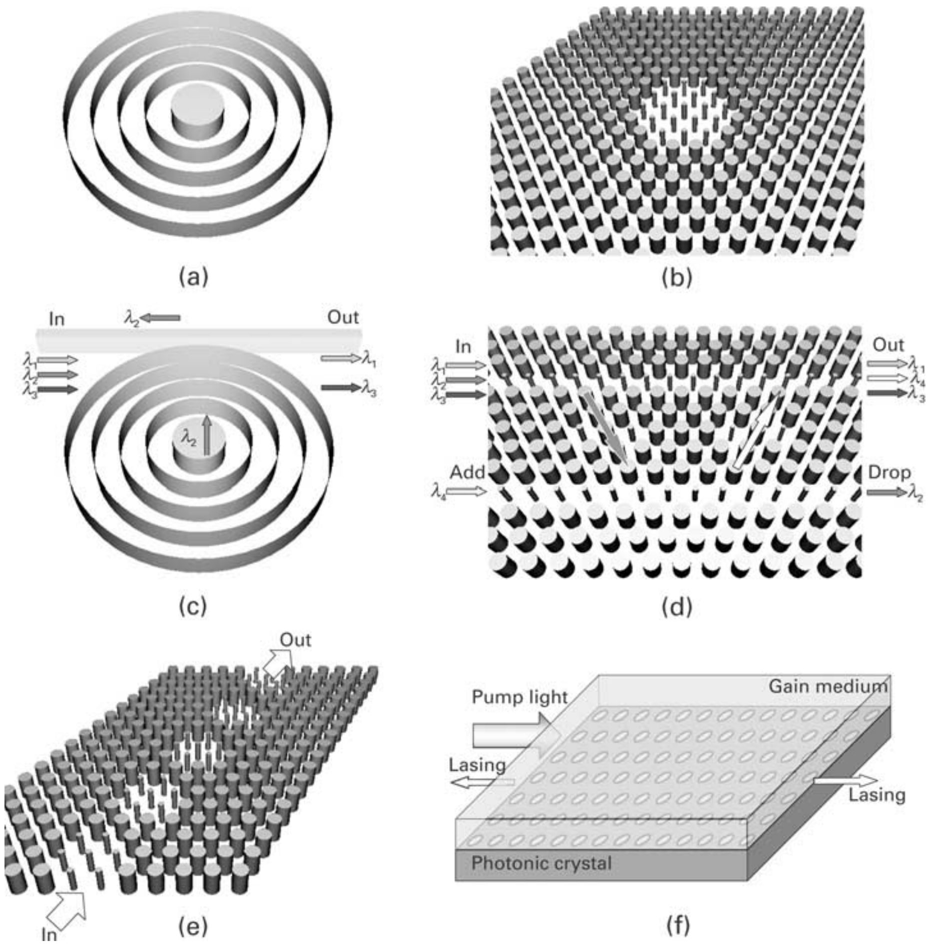

Figure 1.4 Schematics of various PhC components and devices. (a) Microcavity in a circular Bragg reflector geometry. (b) Microcavity as a point defect in a photonic crystal lattice. (c) Optical narrow band rejection filter comprising a bus waveguide and a microcavity. (d) All optical add–drop multiplexer comprising two bus waveguides, one drop resonator and one add resonator. (e) Coupled resonator optical waveguide for slow light applications. (f) Bloch-mode laser comprising a planar waveguide made of a gain media and covering a 2D PhC. The periodic structure of the PhC provides feedback for lasing.

is launched into a bus waveguide; a wavelength resonant with that of a cavity state (drop wavelength) is then reflected back into the input arm of a filter (wavelength λ_2 in Fig. 1.4 (c)), while the rest of the wavelengths are passed through. Optical coupling of the cavity to free space (vertical radiation loss) can also be used to partially extract the drop wavelength into the out-of-plane direction. [45] A complete add–drop multiplexer can be designed using two bus waveguides and a sequence of resonators of certain symmetry. [46] In such a multiplexer (Fig. 1.4 (d)), a mix of wavelengths is launched into the input arm of a device; a specific wavelength (λ_2 in Fig. 1.4 (d)) can then be dropped into the lower right arm of the device with the aid of a first resonator without any back reflection into the input or add arms of the device. A second resonator can then be used to add a different wavelength (λ_4 in Fig. 1.4 (d)) into the output arm of the device, again without any back reflection into the input or add arms of the device.

Finally, when placing several microcavities in a row (Fig. 1.4 (e)), and assuming weak interaction between individual cavities, one can realize a so-called coupled resonator optical waveguide (CROW). [47,48] The CROW guides light from one end of the chain to the other by photon tunneling between adjacent resonators; therefore, in the limit of weak coupling one expects considerable slowing down of the modes propagating in such waveguides. Coupling of the individual resonator modes creates flat bands within the photonic gap of a surrounding photonic crystal, each of them centered on a mode of the isolated microcavity. Varying the number of rows between resonators, one can adjust the coupling strength, and, as a consequence, the group velocity of guided modes. Potential applications of slow light in CROW structures include compact optical delay lines, optical memory, and devices based on enhanced nonlinear interactions.

1.2.2 Photonic crystals for out-of-bandgap operation

Another way of using PhCs is in the frequency regime outside of the photonic bandgap. In this case transmission through the bulk of a crystal is allowed, however, owing to coherent reflection from the periodic structure of a crystal, propagation of radiation will be considerably modified from the propagation in a uniform dielectric material. For example, for the frequencies right below or above the bandgap edge the group velocity of propagating light is typically greatly reduced. This, in turn, leads to a substantial increase in the propagation time through the PhC device enhancing material–radiation interaction, which is of prime interest for lasing, nonlinear, and sensor applications.

Lasers that use PhC lattices as a whole and do not require microcavities are known as Bloch mode lasers or band-edge lasers (Fig. 1.4 (f)). Such structures use the radiative losses of modes to extract light from the active region. Lasing typically occurs for slow Bloch modes characterized by wavevectors in the vicinity of the high symmetry points of a first Brillouin zone, where light strongly interacts with the active medium. [49,50] In their spirit, Bloch mode lasers can be considered as 2D analog of the widespread distributed feedback lasers.

Finally, PhCs, being geometrically anisotropic, can also possess highly anisotropic dispersion. This property enables such PhC applications as superprisms and supercollimators. Particularly, PhCs can be designed so that the direction of radiation propagation through such a device is highly sensitive to the frequency and initial launch direction. It is then possible to design superprisms [51,52] – devices that exhibit very large refraction, such that a mix of wavelengths traveling in a single direction is split into several monochromatic waves propagating at considerably different angles. Using highly anisotropic energy flow of Bloch waves, one can also design such devices as supercollimators, [53,54] in which a beam of light self-collimates and does not spread when propagating through a photonic crystal.