Part II

Device Design

Chapter 5

Photonic Bandgap Devices: An Overview

Having developed the computational tools necessary for the design problem, we now return our focus to photonic bandgap (PBG) materials. Certainly, ever since Yablonovitch's publication [26] in 1987 the amount of research into PBG materials has been extraordinary. Even at its inception, it was anticipated that PBG materials would have a profound effect on semiconductor devices because of their ability to inhibit spontaneous emission rates. One goal of this chapter is to provide a general overview of some of the diverse applications that make use of these PBG materials as a functional device. It is well beyond the scope of this chapter to do a comprehensive review of the topic, so the devices described here will naturally be biased towards our own interests and experiences, but the idea is to provide a sense of where our work fits in within the field.

5.1 Introduction

The term photonic bandgap refers to the range of frequencies for which electromagnetic waves are not allowed to propagate within the material, so incident radiation on the surface will be perfectly reflected. We can locate these bandgaps by solving the Helmholtz equation (eqn. (2.15)) and looking at the allowed eigenvalues as demonstrated in chapter 2. A *complete* bandgap means the frequency is forbidden for all propagating directions. Much of the early work involved looking at these 'bulk' photonic crystal materials and verifying the existence of bandgaps [11, 27, 28, 29, 30] in various lattice geometries. A lot of work was done searching for the geometry that led to the largest bandgaps. Since waves cannot propagate through the material, they act like perfect mirrors at the forbidden frequencies.

The idea of introducing intentional defects to produce localized states [31, 32] came shortly thereafter, and the possibility of trapped states lead naturally to the idea of optical cavities and waveguides. Of course, if we think of bulk photonic crystals as perfect mirrors, then it seems reasonable to think you can 'trap' and 'guide' light within slabs of these photonic crystals. PBG materials promised to 'mold the flow of light' as suggested by the title of Joannopoulos' book [6]. To date, a huge part of the challenge has been in making these idealized devices. The 'holy grail' device requires the use of complete bandgap materials, but a complete 3D bandgap with controllable defects at optical frequencies is extremely difficult to fabricate, though there have been recent demonstrations [33, 34]. The reason for the difficulty is that the periodicity required for optical PBG materials is on the order of the optical wavelength, so the features on these devices are in the nanometer scale. By far the more common paradigm is to make quasi-2D PBG devices, where periodicity is introduced only in 2D (xy plane), and localization in the out-of-plane (z) direction is achieved not via the bandgap effect but by dielectric contrast (like conventional optical waveguides). Most of these are fabricated by the use of electron beam lithography and a combination of wet and dry etching techniques. Other fabrication techniques include self-assembly type approaches, but they are not reviewed here. The ease of fabrication of these planar photonic crystal devices is offset by the loss mechanism in the third dimension. There are two main types of defect that we consider here: the point defect and the line defect. We will see that these serve as building blocks for many important devices, particularly in the area of integrated photonics.

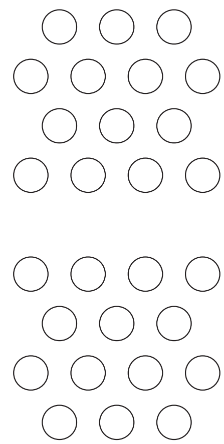

Figure 5.1: Nominal Geometry of a W1 photonic crystal waveguide.

5.2 Building Blocks

The basic building blocks for a photonic circuit are the waveguides and resonators. One of the problems with existing lightwave circuits is that conventional ridge waveguides require a large radius of curvature to minimize bend losses, which limits how compact these devices can be. Photonic crystal waveguides (PCWs) promise to overcome this limitation, making ultra-compact optical devices possible. The most basic conceptualization of the PCW is by removing a single line of holes, hence the name *line defect*. Light within the defect region is surrounded by a PBG material so it can only propagate along the defect region. We show such a waveguide structure for a hexagonal lattice known as the W1 waveguide in figure 5.1. However, achieving the benefits of this device in the planar configuration is still the subject of current research. Some guidelines on how their behavior translates from an infinite height approximation to a finite height slab structure are found here [35, 36]. Early work on these planar PCWs varied different parameters in an attempt to get some basic desirable properties, such as single mode operation [37, 38], or to control the frequencies of the waveguide modes [39]. Controlling losses in these PCWs [40] and PCW bends [41, 42] became an important consideration, as conventional planar lightwave circuits outperform PCWs considerably.

Besides the guiding functionality of the device, one of the most interesting properties of the PCW is their dispersion characteristics. In particular, the group velocity in these waveguides were found to be orders of magnitude less than ordinary waveguides and even show anomalous behavior. Johnson et al. [43] proposed making ultra compact and efficient modulators using PCWs within Mach-Zehnder based devices by taking advantage of this property. Kuipers' group have devised a beautiful experimental setup [44] to measure and verify this PCW dispersion. There was tremendous excitement about these PCWs, leading some to claim that they "can design light paths with *made-to-order* dispersion"(emphasis added)[45], although all that has been demonstrated is that dispersion is a function of the geometry. The purpose of design is of course to advance from dependence to control. The distinction is important because in a PCW, pulse distortion due to its dispersion can occur over much shorter length scales as compared with conventional waveguides, so the unique feature of the PCW becomes another component that needs to be managed unless one can control the dispersion. Dispersion management in general is a very important issue in the field of telecommunications, where pulse broadening limits the bit rate of a communication channel (since adjacent 1's and 0's broaden and blend together making them indistinguishable). Some efforts at controlling the dispersion properties can be found in these references [46, 47, 48], but to our knowledge, there have been no demonstrations of *arbitrary* dispersion design. For integrated optics applications, the effectiveness of add/drop filters and other such components would be severely compromised without managing pulse distortion on the chip. The problem we address using our technique is to design a PCW that achieves an arbitrary target dispersion relation.

The other building block we will examine is the optical resonator, or the PBG cavity. This is conceptualized in a manner similar to the PCW, where we have some region surrounded by PBG materials acting as perfect reflectors. Light within that region becomes trapped. PBG cavities can be point defects (a break in the lattice symmetry at a single lattice point), or enclose a larger region, such as with ring resonators by arranging PCWs in a suitable configuration. Optical resonators in general are useful for use as filters, and the figure of merit is the quality factor Q, which is a measure of the linewidth of the transmission spectrum of the cavity. Point defect PBG cavities can have high Qs ($\sim O(10^6)$ or higher) with mode volume of the order of the wavelength of light. Such cavities are desirable for many applications, such as low-threshold lasers [49], or as add/drop filters [50, 51] when integrated with PCWs for de/multiplexing applications, or for chemical detection in lab-on-a-chip type applications [52, 53]. High-Q small-mode volume cavities are also crucial for achieving strong coupling between an atom and the optical field in cavity quantum electrodynamics (cQED) experiments. Our group's initial venture into the world of PBG came as a collaboration with Axel Scherer's group, studying the feasibility of using PBG cavities in the strong coupling regime [54].

5.3 PBG and Atomic Physics

Cavity quantum electrodynamics (cQED) provides a setting in which atoms interact with the electromagnetic field within an optical resonator. It is one of the first experimentally realizable systems whereby one can quantitatively study the dynamics of an open quantum system under continuous observation, and as such provides a means for testing the laws of quantum measurement, such as quantum trajectory theory [55]. In particular, experimental advances in recent years have crossed the threshold where the intrinsic quantum mechanical atom-field interaction dominates the dissipative and decoherence mechanisms into what is known as the strong coupling regime [56]. Under strong coupling, the presence of a single atom or photon is sufficient to affect the properties of the system, enabling the possibility of single atom switching and single photon nonlinear optics. Other exotic applications within strong coupling include quantum state mapping between atomic and optical states [57], which is critical for the realization of quantum information processing [58].

An emerging reality in the laboratory is the use of nanofabricated optical resonators such as PBG cavities [59], microdisks [60], and microtoroids [61] for cQED experiments with cold atoms. By incorporating a network of photonic crystal devices with single trapped atoms [58] operated under the strong coupling regime [62], scalable quantum information processing can be performed in a quantum network. To motivate the shift to these nanofabricated resonators, consider the pioneering works in strong coupling that make use of high finesse Fabry-Perot cavities. These cavities are much more sensitive to vibrational noise that is not common-mode relative to the two mirrors. To maintain the proper coupling with the atom of interest, the distance between the two mirrors of the Fabry-Perot must be stabilized to $\sim 10^{-15}$ m via active servo control because of the narrow linewidth. The desire to operate at the single photon sensitivity makes it impossible to derive an error signal directly from the 'physics' signal for the servo lock. Therefore, an additional auxiliary frequency stabilized laser is required, and its wavelength must be far enough detuned so that it does not interact with the atom in the cavity. The operating complexity continues to increase as frequency stabilizing this auxiliary laser involves another optical cavity, which also requires another servo control. This extensive amount of labor overhead that precedes each experiment renders this paradigm unscalable for networking purposes.

5.3.1 Waveguide dispersion design

In a quantum networking scenario, individual quantum nodes (physically realized using coupled atom-cavity systems) are connected via photonic crystal waveguides. Quantum information stored in an atom can be mapped onto a photon using cQED, and the information transmitted to the next node as the photon performs another cQED interaction with the trapped atom there [57]. The successful implementation of the system will require attention to both the losses as well as the dispersion characteristics in the waveguide. The desire to limit losses in a PCW as it goes through bends and other optical elements is certainly not unique to this application, as we reviewed earlier. Perhaps more unique to the application here is a demanding constraint on the dispersion characteristics of the waveguide, because the photon emission from one quantum node needs to be temporally (and spatially) mode matched for proper excitation of the next node. Losses and pulse distortion will compromise the coupling efficiency to the atom and cause a decrease in transmission fidelity. What is desired is the ability to *arbitrarily* control the dispersion of a waveguide right on the atom chip to compensate for the pulse shape distortion. In contrast to the usual notion of dispersion compensation, where it is only the slope within some small **k**-vector window that gets adjusted, we seek to specify the full dispersion curve. We have not seen in the literature any method that enables arbitrary dispersion engineering of a PCW.

5.3.2 Large defect region cavity design

The second element to the scheme involves the optical cavity. In coupling a single atom to a point defect nanocavity, much of the emphasis has been on finding high-Q and small-mode volume cavities in order to achieve strong coupling [63, 64]. However, what is also desired is a large air (vacuum) opening in which the atom can be trapped, since we wish to minimize the interaction between the atom and the PBG material. Other applications where a large air hole defect is desirable include lab-on-a-chip devices, where we wish to maximize the amount of analyte that can be introduced into the optical excitation region for analyte detection [52] and on-chip optical spectroscopy [53]. In these applications, the important property to consider is that the atom (or chemical) interacts with the electric field that is localized in the air (or vacuum) region. Consider again the h_1 structure where the electric field is localized near the defect region. Given a particular bulk hole radius (r_{bulk}), if we attempt to increase the defect region by increasing the radius of the defect hole (r_{defect}), then as we transition from $r_{defect} < r_{bulk}$ to $r_{defect} > r_{bulk}$, we change from an *acceptor* type mode (figure 5.2a,b) to a *donor* type mode (figure 5.2c,d) [31].

However, for the applications we have contemplated, a donor mode would not be appropriate since an electric field node is located at the center of the evacuated region. One strategy would be to increase r_{bulk} along with r_{defect}, but that would compromise the physical integrity of the device (see figure 5.3), as well as increase the scattering losses [54]. What we seek then is a re-distribution of the layers surrounding the defect hole in a way that increases the overall amount of dielectric (to an acceptable level of

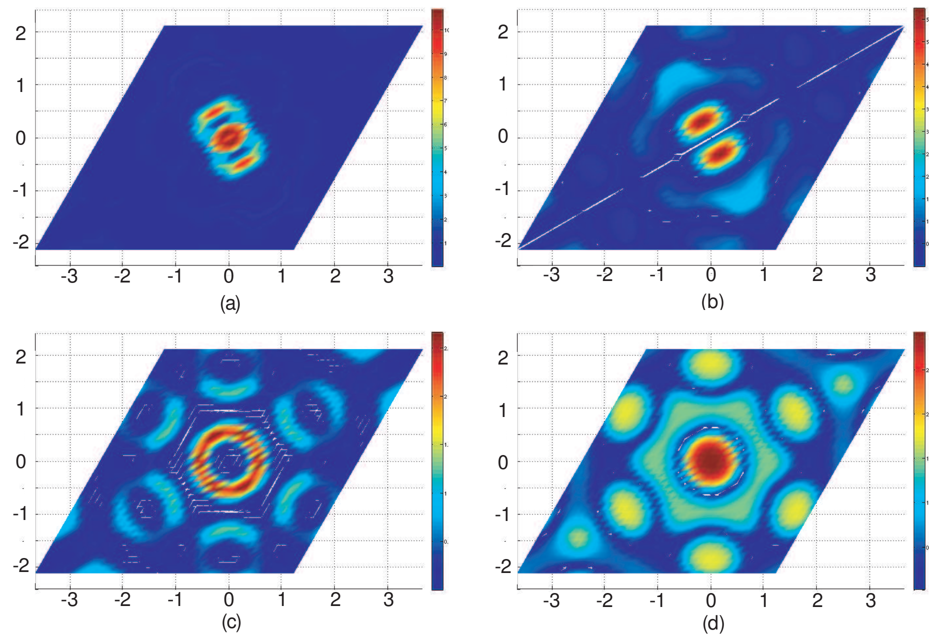

Figure 5.2: (a) Electric Field intensity of an acceptor mode. Note the field maximum at the center of the air defect region. (b) Magnetic Field intensity. (c) Electric Field intensity of a donor mode. Note the field minimum at the center of the air defect region. (d) Magnetic Field intensity.

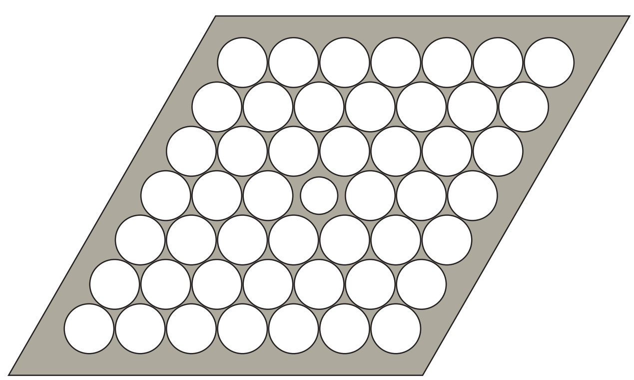

Figure 5.3: h_1 geometry with large bulk hole radius. Fabrication uncertainty could lead to entire sections of photonic crystal collapsing.

mechanical strength), while still retaining the desirable qualities of an acceptor mode. Quantitatively, we can require

$$\overline{\eta}_{\mathcal{D}} \equiv \frac{\int_{\mathcal{D}} \eta(r)dr}{\mathcal{A}_{\mathcal{D}}} > \frac{\int_{\mathcal{B}} \eta(r)dr}{\mathcal{A}_{\mathcal{B}}} \equiv \overline{\eta}_{\mathcal{B}} \tag{5.1}$$

where $\mathcal{A}$ is the area, and $\mathcal{D}$ and $\mathcal{B}$ designate the defect and bulk region respectively. Other groups have demonstrated that we do not require a localized defect within a perfectly periodic lattice in order to localize a mode [65, 66], although it is not clear whether it is possible to violate the simple donor/acceptor mode intuition by rearranging the bulk region. Even if it were possible, intuition fails to provide guidance as to how the redistribution should happen. We examine this problem using our approach.