14: Photonic Crystal Fundamentals

14.1 Introduction to Photonic Crystals

Photons are very hard to manipulate and control, because most materials either absorb\(^a\) the photon or interact with it only weakly. In earlier chapters of this book we have seen how transparent, weakly-interacting materials can be used to build lenses and waveguides, and we have learned how to use absorptive, strongly-interacting materials (metals) as mirrors and gratings. A third method for controlling optical fields is to use many weak interactions that combine coherently to a strong interaction. This approach to control of electromagnetic radiation is the basis for Photonic Crystals (PCs).

We have already looked at one simple type of Photonic Crystal. The Bragg reflectors covered in Chapters 3.4.2 and 6.6, and briefly in Chapter 13.2.2, are one-dimensional PCs. These Bragg gratings consist of periodic layers of alternating high and low refractive index. The periodicity is on the order of the wavelength of the light (half the wavelength to be exact). This concept can be generalized to two and three dimensions, so we may loosely define Photonic Crystals as periodic structures in one, two, or three dimensions with periodicities on the order of the wavelength of electromagnetic radiation. Photonic Crystals can therefore take any size depending on the wavelength.

In current practice, Photonic-Crystal technology has been developed for Radio Frequencies with wavelengths up to tens of centimeter, and for visible and near-infrared light with wavelengths from 0.4 μm to 2 μm. It is a fortuitous fact that the size range of PCs for visible and near-IR radiation is compatible with standard MEMS fabrication and packaging. This creates opportunities for integration of MEMS and Photonic Crystals, enabling new and improved photonic devices, some of which are described in Chapter 15.

In this chapter we introduce the fundamentals of Photonic-Crystal theory and practice. The field is very large and well documented \([1,2,3,4,5]\), so our goal is

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\(^a\) Electronic buffs will maintain that the best way to control a photon is to absorb it and convert it to an electronic excitation!
not a comprehensive overview, but rather a focused introduction with emphasis on concepts and technologies that are most important and exciting to designers of microoptical systems and optical MEMS.

We start by describing at the band structure of PCs and how their band-gaps can be used to create very compact waveguides and resonators for integrated photonics. Then we switch our attention to the use of one and two-dimensional PCs that are of special interest because of their relatively simple fabrication. We cover the concept of Guided Resonance, and describe a simple, analytical theory for how it changes the flow of light through 2-D PCs. With the help of the theory, we show how PCs can be used to create a variety of optical components for miniaturized, free-space optics. We finish the Chapter with a brief section that compares and contrast Photonic Crystals and their role in optics, to natural crystals and their role in electronics.

### 14.2 Photonic Crystal Basics

The examples in Fig. 14.1 illustrate the variety of Photonic Crystals. Structures of one, two, or three dimensions have very different characteristics, and also present very different design and fabrication challenges. All the crystal structures of Fig. 14.1 are important in microphotonics, some directly and some in supporting roles.

One-dimensional Bragg reflectors are used as high-quality mirrors in sophisticated Optical MEMS, but represent a fabrication challenge due to the thermal stresses caused by different thermal expansion coefficients of the layers of the stack. These fabrication challenges can be overcome, but it complicates and increases the cost of manufacture, so Bragg Mirrors are used sparingly in microphotonics. The exceptions are VCSELs (Chapter 13.6.1) and other III-V devices. Bragg mirrors are important components in the supporting structures that interface the microphotonics to the external world, however. The same is true for another technologically important 1-D Photonic Crystal, the Fiber Bragg Filter or Fiber Bragg Sensor (not shown in Fig. 14.1 – see Chapter 6.6).

One-dimensional, planar gratings and two-dimensional PC slabs are straightforward to integrate with ICs and MEMS, because of their planar geometry and size compatibility. These structures therefore form the basis of most experimental demonstrations and product developments of PC microphotonics. One of their compelling properties is that they can be designed to have many of the desirable characteristics of Bragg reflectors, and may therefore be used as replacements for multilayer-stacks in integrated optics and microphotonics.

The Holey Fiber [6,7] is a low-dispersion medium that allows practical delivery of femto-second laser pulses to microphotonics components and subsystems. It is fabricated by stacking quartz tubes in a hexagonal, or other configuration, and draw-