Chapter 1

Introduction

1.1 Overview

The field of photonic bandgap (PBG) materials, or photonic crystals, has expanded tremendously over a relatively short period of time. These 'semiconductors of light' are artificially engineered materials that possess a periodicity in the index of refraction, leading to bands of frequencies for which electromagnetic waves cannot propagate in the material. Much effort has been poured into the field because of the enormous potential for ground-breaking applications using these novel materials. However, there have been many barriers towards taking full advantage of their properties. The idealized PBG materials have a full three-dimensional periodicity, but this has been difficult to fabricate, especially if intentional defects need to be inserted at precise locations to add functionality to the material. Hence, most device performances to date have yet to reach the promised potential, because they only use the bandgap effect in two-dimensions.

The two-dimensional (2D) system is less ideal, because losses can occur in the third dimension, so the coupling mechanism for the losses needs to be understood for different in-plane configurations. This greatly increases the importance and complexity of the design process. Since the field is relatively new (only 20 years), much of the research has been performed by scientists using trial and error. Parameters of the system are meticulously varied with the environment controlled, and the results of those changes analyzed and studied. In true double-edged sword fashion, one is fortunate in that one has enormous freedom on how to arrange the index of refraction, so many designs are possible. Unfortunately it also means that it can be an endless design challenge in the quest for better and better devices because of the vast number of degrees of freedom.

We seek a better alternative to an exhaustive search technique for photonic crystal device design, i.e., an algorithmic approach that removes the guesswork part of the process. The basic idea behind an inverse problem approach is to formulate the problem backwards. We start with the design goal we want accomplished, and then work backwards to find the geometry that would have produced the intended effect.

Finally, our inverse problem design method is derived *ab initio* using Maxwell's equations. We do not make use of approximate models to the system we wish to design. As such, for self-consistency we take great care in interpreting our results accordingly, and the drawback is that the designs may not readily apply to real structures one can fabricate currently. However, we can make far more general statements about the limitations and challenges of the design problem because our work is done *ab initio*.

1.2 Organization of the Thesis

The work in this thesis is an amalgamation of several fields that traditionally have minimal overlap. There has definitely been an increased interest in adapting inverse problem techniques to the PBG problem in recent years, but given the amount of research in each separate area, the degree of overlap is comparatively small. Convex optimization methods is another established field of research that is being successfully applied to many problems [1], but has yet to be relevant to the PBG community. As such, this thesis is aimed at the practitioner in any one of these fields interested in seeing how these come together to solve an engineering problem. Therefore, it is written in a way that is accessible for an incoming graduate student in any of the disciplines, although admittedly it does have more of a physics bias and assumes more background in physics.

The thesis is divided into two parts. The first part develops the necessary mathematical formalism in the three areas. In chapter 2 we review the basic physics of PBG materials and derive and work out the solution of the Helmholtz equation using the plane wave basis. Chapter 3 discusses the idea of an inverse problem, and works out a numerical example to illustrate what an inverse problem is and how to solve these notoriously difficult problems. We conclude part I with a chapter on convex optimization methods, which we will use as a specialized tool for solving photonic inverse problems. Again, a numerical example is provided to help provide some basic intuition into how the algorithm works.

Having provided the necessary mathematical background, we are then prepared to shift our focus to the problem of device design. We begin part II with an overview of PBG materials and devices in chapter 5. Readers familiar with PBG devices can safely skip most of the chapter, although in section 5.3 we motivate the design problems that we will tackle using our method. Chapter 3 reviews other inverse problem based design methods in the literature, and highlights some advantages and disadvantages to our approach. We derive *ab initio* the inverse Helmholtz equation, and perform a proof of principle demonstration to conclude the chapter. We proceed to adapt the inverse problem into a design methodology in chapter 7, revealing fundamental limitations towards achieving optimal designs. Despite these difficulties, we demonstrate the feasibility of a modified method that gives excellent results for our design goals that cannot be obtained with other methods.