# Chapter 1　Introduction

## 1-1 Background

About 36 years ago Victor G. Veselago predicted theoretically that propagation of the electromagnetic waves in a hypothetical left-handed medium (LHM) [1], that can bend light in the opposite direction to normal reverse the way in which refraction usually works: this negative refraction index is due to simultaneously negative permeability and permittivity. The origin of these properties is the fact that the energy flux, $\boldsymbol{S}$ and the wave vector, $\boldsymbol{k}$ are antiparallel ( $\langle \boldsymbol{S} \rangle \cdot \boldsymbol{k} < 0$ );  the phase velocity, $\boldsymbol{v_p}$ and the group velocity, $\boldsymbol{v_g}$ are antiparallel ($\boldsymbol{v_p} \cdot \boldsymbol{v_g} < 0$) in the materials. In other words, if $\boldsymbol{k}$, **E**, **H** in materials obey a left-handed set of vectors, then these materials are called LHM or negative index of refraction materials (NIM). Although naturally occurring materials with simultaneously negative permittivity and permeability are not known; following Pendry's suggestions [2-4] for specific structures which can have both $\varepsilon_{eff}$ and $\mu_{eff}$ negative (over a range of frequencies), one LHM has been artificially realized as a periodic lattice of metallic rods and split-ring resonators. [5,6] Recently, the study of negative refraction has further received much attention both from the theoretical and experimental point of view.

To develop the negative refraction in the optical regime, one may turn to photonic crystals as interesting alternative. A photonic crystal is a structure whose refractive index is periodically modulated, and the resultant photonic dispersion exhibits a band nature analogous to the electronic band structure in a solid. It may not only possess a possibility of forbidding light propagation within a frequency band, i.e., a photonic band gap, but manipulate the flow of photons by distribution of periodic dielectric constant [7,8]. Over the last decade, the one-dimensional (1D) version of a photonic crystal has long been known as a multilayer reflector, but 2-dimention/3-dimention (2D/3D) photonic crystals have only recently started to attract attention after the appearance of a prediction that photonic insulators can be developed by photonic crystals.

In photonic crystals, light travels as Bloch waves, in a similar way to plane waves in continuous material. Bloch waves travel through crystals with a definite propagation direction despite the presence of scattering, but their propagation is complicated because it is influenced by the band structure. The essential explanation of these negative refractions should lay in the photonic band structure (PBS) and equal frequency surface (EFS). Furthermore, such a crystal behaves as a material having an effective refractive index, which can be negative, controllable by the PBS [9,10].

## 1-2 Motivation

We interest in that negative refraction phenomena can be achieved in photonic crystals, which physical principles allow negative refraction in the photonic crystals arising from the dispersion characteristics of wave propagation in a periodic medium, and the overall behavior of the wave propagation within a photonic crystal can be well described by a model based on the equal frequency surface (EFS) configuration and the conception of effective refraction index.

Recently an experimental observation that the electromagnetic waves undergo negative refraction in a two-dimensional photonic crystal prism in microwave frequency regime was performed by our group. Although the relative features of photonic crystals have been discussed, but there have been very few reports including all kinds of different refractions in the crystals so far. Further, in order to realize the refractive behaviors in the crystal we simulate and explain the prism structure similar to previous experimental frame by using an EFS analysis which is the important physics picture for qualitative explanation of negative refraction in photonic crystals. We would make efforts in systematic and consistent ways of understanding.

Besides an exhilarating proposal, the negative refraction leads to a superlensing effect [2] that can overcome the diffraction limit inherent in conventional lenses. In particular, the light propagation in photonic crystals with a negative effective index can theoretically generate several anomalous refraction behaviors, such as focusing and imaging rules by a flat surface of photonic crystal slab. As these problems interest us, hence we numerically calculate it and take a comparison with the conventional lens. More detailed discussions and performances of corresponding simulative results will be our weighty works consequently.

Recently an interesting opinion what negative refraction in photonic crystals could be accomplished at fundamental band, i.e., a frequency region without negatively effective refraction index; meanwhile, an imaging-like phenomenon seemed to be observed by Luo *et al.* [11] They presumed that is all-angle negative refraction in photonic crystals without negatively effective index. It makes confusion to us owing to the argument is not congruous with our discourse. Then it is an interesting and important task to inspect the dominant imaging causalities among all these possible factors. A routine to evaluate the same problem is to see whether it results from the all-angle negative refraction or existent other effects. This work will advance in a completeness of explanation for refraction behaviors in photonic crystals which is presented by us.

## 1-3 Organization of the thesis

The goal in my thesis is concentrated on the simulation and discussion of the negative refraction phenomena in two-dimensional (2D) photonic crystals. In order to realize and define the refractive behaviors, we introduce two kinds of calculation methods which are the finite-difference time-domain (FDTD) method for electromagnetic simulation and plane-wave expansion (PWE) method for band structure, equal frequency surface (EFS), and eigenmode patterns calculations, individually.

In chapter one, we introduce the concise reviews of negative refraction phenomena in photonic crystals and the topics which attract us. In chapter two, we brief the origin of the negative refraction and the refraction phenomena within photonic crystals. Then, we also drive and prove that PWE method and the FDTD method.

In chapter 3-1, the conceptions of EFS configuration and effective refraction index is presented. In chapter 3-2, we use the PWE method to calculate the photonic band structure (PBS) of a triangular-lattice photonic crystal and systematically analyze the EFS configurations; moreover, we also study the question: dependence of symmetry on excitation of eigenmodes. In addition we perform the positive refraction, negative refraction and total internal refraction in a photonic crystal prism by using the FDTD simulations; further we also confirm that uncoupling effect for antisymmetry of eigenmode patterns. In chapter 3-3, we would make efforts in this topic what anomalous imaging in virtue of focus effect by a flat surface of photonic crystal slab with negative refraction. Besides, we also take a comparison for the difference of imaging mechanisms between conventional lens and photonic crystal slab. In chapter 3-4, we commented on the paper “All-angle negative refraction without negative effective index” (*Phys. Rev. B 65, 201104 (2002)*), and define afresh and give the more complete and rigorous conclusions. Furthermore, we extend the new concept to other periodic structure cases. Finally we will conclude our results in the final chapter.