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Numerical integral methods to study plasmonic modes in a photonic crystal waveguide with circular inclusions that involve a metamaterial☆

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Abstract

We present several numerical integral methods for the study of a photonic crystal waveguide, formed by two parallel conducting plates and an array of circular inclusions involving a conducting material and a metamaterial. Band structures and reflectance were calculated, for infinite and finite photonic crystal waveguides, respectively. The numerical results obtained show that the numerical methods applied provide good accuracy and efficiency. An interesting detail that resulted from this study was the appearance of a propagating mode in a band gap due to defects in the middle of the photonic crystal waveguide. This is equivalent to dope a semiconductor to introduce allowed energy states within a band gap. Our main interest in this work is to model photonic crystal waveguides that involve left-handed materials (LHMs). For the specific LHM considered, a surface plasmon mode on the vacuum–LHM interface was found.

Keywords: Integral methods; Plasmonic modes; Photonic crystal waveguides; Metamaterials

1. Introduction

Recent developments in the study of photonic crystal waveguides (PCWs) have created interest among scientists in different fields [1]. The photonic crystals that constitute periodic arrays of different materials with a unit cell of dimensions on the order of the wavelength, have the potential to develop a new technology of integrated optical circuits. Other kinds of structured materials that have recently attracted great interest are left-handed materials (LHMs), which owe their name to the fact that the light vectors **E**, **H** and **k** form a left-handed triad for a wave propagated through these media [2]. Although fundamental experiments with LHMs have been developed for the microwave region of the electromagnetic spectrum, some recent results indicating that LHMs are now available in visible and infrared regions [3–5]. Since these materials have a negative refractive index within a given range of the electromagnetic spectrum, some well-known optical phenomena present variations that make them potentially useful for new technological applications, such as sub-wavelength image reconstruction [6], wave guiding [7], optical

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sensing [8,9], cloaking [10], micro strip patch antenna [11], and wave absorbers [12]. As a result, the scientific community has begun to study a variety of optical systems that include LHM as regular components.

The case of the interaction of electromagnetic waves with corrugated surfaces and resonators with corrugated walls made of metals and perfect electric conductors (PECs) is not the exception. It has been shown both theoretically and experimentally that nanostructured metals consisting of PECs with the presence of any periodic indentation of the flat surface (for example, 1D arrays of grooves or 2D hole arrays) cause the appearance of surface-bound states that have strong similarities with the canonical surface plasmon polaritons (SPPs) of a flat metal surface [13,14]. More recently, this concept was extended by introducing of the idea of versatile plasmonic metamaterials [15] consisting of metal surfaces textured with sub-wavelength-scale corrugations, or dimples, that also have surface waves that mimic the properties of SPPs, even at the perfect-conductor limit [16]. Generally speaking, LHMs consist of ordered structures that form photonic crystals with a unit cell whose dimensions are of the order of the wavelength. These periodic structures have the potential to develop a new technology of integrated optical circuits [17].

Numerical simulations play an important role in the design of systems like those outlined above, particularly the modeling of photonic crystal fibers. To date, various modeling methods in which not only a full-vector model but also an approximate scalar model is used have been developed such as effective index approach [18], plane-wave expansion (PWE) method [19], localized-function method [20], multipole method (MM) [21], beam propagation method (BPM) [22], finite difference time-domain method (FDTD) [23], boundary element method (BEM) [24], and finite-element method (FEM) [25]. Although these methods permit the performance of many kinds of numerical calculations, yet in the case of highly-diffracted electromagnetic waves, the presence of complex geometries is an obstacle to obtaining accurate results. As a result, numerical integral methods are used extensively for studying scattering with very complex geometries, such as random or fractal surfaces [26]. Therefore, we believe that integral methods are necessary for the study of two-dimensional PCWs with arbitrary geometries. For this reason, this paper presents a set of numerical integral methods for modeling these kinds of interesting systems.

To this end, we analyze a physical system made up of a photonic crystal waveguide formed with two conductive parallel plates, that includes an array of circular or square inclusions. The material in these inclusions is either a conductor or a dispersive metamaterial. First, we considered a real material with finite conductivity, but the numerical calculations performed with the integral methods proposed required significant computational time because a highly-reflecting metal is characterized by a large (in absolute value) dielectric constant. In this context of diffraction and scattering calculations, the impedance boundary condition is known to represent a good approximation, and has even been shown to provide acceptable results [27–29]. For this reason, we use an impedance boundary condition to overcome this difficulty, because only the matrix elements associated with the electromagnetic field in vacuum are required to solve the scattering problem. Subsequently, we show the presence of a surface plasmon mode on the vacuum–LHM interface of the PCW that involves an LHM based on ideas presented in recently-published work [30].

The outline of this paper is as follows. Section 2 introduces a several numerical integral methods for studying a PCW formed by two parallel conducting plates and an array of circular inclusions, that involves a conducting material or metamaterial. It also presents the results of the band structures for a PCW of infinite length. In Section 3 we describe integral methods, that use the impedance boundary condition, to calculate band structures or reflectances for infinite or finite waveguides, respectively. Section 4 discusses the numerical results that show the presence of a surface plasmon mode in the PCW, formed by two flat conducting surfaces and an array of circular and square inclusions of LHM for TE polarization based on the ideas outlined elsewhere [31]. Finally, we present our main conclusions in Section 5.

2. Theoretical approach

In this section, we introduce integral methods to calculate the electromagnetic modes of a PCW formed by two parallel plates and an array of circular inclusions that include a conducting material.

2.1. Periodic Green's function

We consider a two-dimensional PCW, formed by two flat internal walls that enclose an array of circular bars. The surfaces involved are conducting materials and the medium between the walls and the bars is vacuum. The geometry of the system is sketched in Fig. 1.

In Fig. 1, P is the period of the waveguide in x-direction; b is the distance between the flat walls; r is the radius of each circular bar; the curves Γ_{1l}, Γ_{2l}