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Optical response of a photonic crystal waveguide that includes a dispersive left-handed material☆

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Abstract

This work considers a photonic crystal waveguide composed of two periodic, perfectly conducting, rippled surfaces that involves a dispersive left-handed material. An integral numerical method was applied to determine the intensity field of its electromagnetic modes under TM polarization. We found that the variation of the ripple amplitudes makes it possible to obtain an electromagnetic surface mode. Moreover, the manifestation of classical chaotic dynamics in the corresponding proposed electromagnetic system gives rise to an electromagnetic chaotic behaviour.

Keywords: Photonic crystal waveguide; Metamaterial; Surface wave; Electromagnetic chaos

1. Introduction

Metamaterials, or left-handed materials (LHMs), are artificial materials with a subwavelength structure [1] that enables the translation of magnetic and electric responses into spectral regions not accessible through naturally-occurring materials [2]. Although fundamental experiments with LHMs have been developed for the microwave region of the electromagnetic spectrum, there exist recent results indicating that LHMs are now available at visible and infrared regions [3–5]. Since these materials have a negative refractive index within a given range of the electromagnetic spectrum, some of the well-known optical phenomena present variations that make them potentially useful for new technological applications, such as subwavelength image reconstruction [6], wave guiding [7], optical sensing [8–11], cloaking [12], micro strip patch antenna [13], and wave absorbers [14]. 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 theoretically and experimentally that nanostructured metals consisting on PEC with the presence of any periodic indentation of the flat surface (for example, 1D arrays of grooves or 2D hole arrays) provokes the appearance of surface bound states that have strong similarities with the canonical surface plasmon polaritons (SPPs) of a flat metal surface [15,16]. More recently, the concept was extended with the introduction of the idea of versatile plasmonic metamaterials [17] consisting of metal sur-

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faces textured with sub-wavelength-scale corrugations, or dimples, that also have surface waves which mimic the properties of SPPs even in the perfect-conductor limit [18]. Generally speaking, LHMs consist of ordered structures which 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 [19].

This paper considers a photonic crystal waveguide composed of two periodic, perfectly conducting, rippled surfaces that involves a dispersive left-handed material. This system has two particularly interesting optical properties, one of which is that it shows an electromagnetic surface mode for certain parameters. The second is related to the chaos phenomenon, which is understandable because the geometry of waveguides with smooth rippled surfaces has been considered in the constitution of some billiard systems in order to study their quantum and classical transport properties [20,21]. Hence, it is important to mention that under certain conditions using the geometry of the proposed system to model a photonic crystal waveguide generates chaotic electromagnetic behaviour [22]. In the paper by Perez-Aguilar (see Ref. [22]), the vacuum is the medium between the PEC surfaces. The novelty of the present paper consists in considering a dispersive LHM between the PEC surfaces of the periodic waveguide. Considered together with the geometry of the system, this feature leads to two interesting phenomena: surface modes and electromagnetic chaos. The issue of chaotic behaviour in LHMs is addressed in Ref. [23].

This paper is organized as follows. The section on the theoretical approach introduce an integral method to calculate the field intensity of the electromagnetic modes of our system based on ideas for dispersive LHMs outlined elsewhere [22,24]. Section 3 analyses an electromagnetic surface mode for the proposed system with TM polarization, while Section 4 uses the same geometry to show classical chaotic behaviour and its electromagnetic counterpart in a photonic crystal waveguide. Finally, the principal conclusions are presented in Section 5.

2. Theoretical approach

Assuming a time harmonic dependence $e^{-i\omega t}$ for the electromagnetic fields, the wave equation can be transformed to the Helmholtz equation

$$\nabla^2\Psi(\mathbf{r}) + k^2\Psi(\mathbf{r}) = 0. \tag{1}$$

In this equation $\Psi(\mathbf{r})$ represents the magnetic field in the case of TM-polarization in the LHM and $\mathrm{r} = x\hat{\mathbf{i}} + y\hat{\mathbf{j}}$ is the position vector on the x–y plane. The magnitude of the wave vector is given by $k = n(\omega)\omega/c$, being $n(\omega) = -\sqrt{\mu(\omega)\varepsilon(\omega)}$ the refractive index that involves the properties of the material, given in terms of the magnetic permeability $\mu(\omega)$ and the electric permittivity $\varepsilon(\omega)$; both of these functions depend on frequency ω. The speed of light is indicated by c.

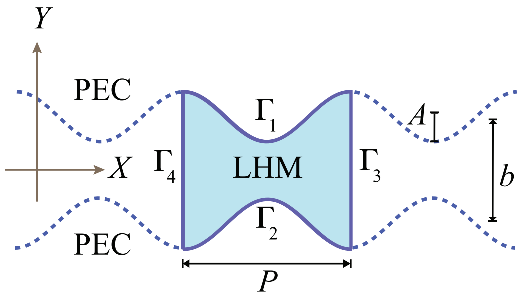

Fig. 1. Graphic description of the waveguide formed by two rippled PEC surfaces that involve dispersive LHM. The Γ_i ($i = 1, 2, 3, 4$) contours define the unit cell of the system with periodicity in the x-direction.

The optical properties of LHM given by $\varepsilon(\omega)$ and $\mu(\omega)$ are expressed in the form [25]

$$\varepsilon(\omega) = 1 - \frac{\omega_p^2}{\omega^2} \quad \text{and} \quad \mu(\omega) = 1 - \frac{F\omega^2}{\omega^2 - \omega_0^2}, \tag{2}$$

with the plasma frequency ω_p and the resonance frequencies ω_0. Taking into account the parameters $\omega_p = 10/2\pi$, $\omega_0 = 4/2\pi = 0.6366$ and $F = 0.56$, the region where the LHM is found has a negative refractive index within the frequency range $\omega_0 < \omega < \omega_{LM}$ with $\omega_{LM} = \omega_0/\sqrt{1-F} = 0.9597$.

We consider a waveguide composed of two periodic, perfectly conducting, rippled surfaces. The medium between the surfaces is a dispersive LHM. The system is sketched in Fig. 1.

In order to describe the infinite waveguide formed by two rippled surfaces on the xy-plane (shown in Fig. 1), we consider that the periodic profiles of the surfaces have period P, that the average width of the waveguide is given by b, and that the surface profiles can be represented by the harmonic functions $y_1(x) = b/2 + A\cos(2\pi x/P)$ (upper profile) and $y_2(x) = -b/2 + A\cos(2\pi x/P - \Delta\phi)$ (lower profile), where A represents the amplitude and $\Delta\phi$ stands for a phase difference between the two profiles. The region enclosed by the curves Γ_1, Γ_2, Γ_3 and Γ_4 can be considered as a unit cell of the system. The set of an infinite number of unit cells is a waveguide of infinite length represented by a perfect crystal.

Periodicity in the x-direction is a symmetry condition that requires special consideration. Due to this property and the form of the differential Eq. (1) the Bloch theorem can be applied for the x-direction, so as to derive the