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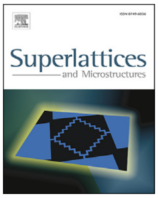

Localization of surface modes along a periodic/quasiperiodic structure containing a left-handed material

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ABSTRACT

We have investigated the optical properties of a one-dimensional (1-D) photonic periodic/quasiperiodic structure, designed as photonic crystal (PC)-Fibonacci (FN)-photonic crystal (PC) sections. The structure is composed of alternating layers of a right-handed material (RHM) and a left-handed material (LHM). The RHM dielectric function is frequency independent and the LHM (metamaterial) dielectric function and magnetic susceptibility are described according to the Drude model. Using attenuated total reflectivity geometry, we explore the coupling of light with the plasmons on the surface of the metamaterial layers of the hybrid structure. The excitation of surface modes in different frequency regions are investigated. We observed bands of surface modes with a significant selective spatial localization at which the intensity of the electric field is confined almost totally within one of the PC sections or within the FN one.

1. Introduction

Surface modes are a special type of wave localized at an interface between two different media, along which they are bounded while being evanescently confined in the direction normal to the interface. The optical properties of surface modes at the metal-dielectric interface are an important issue which has applications in many different fields, as in data storage applications [1,2], micro-/nano-optics for telecommunications [3], spectroscopy [4], biosensors [5,6]. However, since Veselago [7] suggested the theoretical left-handed metamaterial (LHM), characterized by simultaneously negative effective dielectric permittivity and negative effective magnetic permeability, which has recently been realized experimentally [8], metamaterials have attracted extensive attention because of their unusual electromagnetic properties [9–14]. Among these properties are precisely the TE and TM polarized guided modes, observed at interfaces between conventional dielectric and LHM, which is impossible for an interface between conventional dielectrics [11]. Surface modes have also been observed at interfaces separating a one-dimensional photonic crystal and a metamaterial, known as surface Tamm states [15].

A one-dimensional (1D) photonic crystal (PC) made up of alternating layers of a dielectric and a metamaterial may support modes at the interfaces [16,17]. Furthermore, these structures display novel properties such as zero energy gaps [18,19] and the possibility to obtain omnidirectional non-Bragg gaps [20], and have exhibited bulk plasmon polariton modes, whether the stacking arrangement is periodic, quasiperiodic, or even disordered [21–23]. It is because the disorder causes multiple light scattering that the extinction of coherent waves propagating through the photonic structure originates, and this leads to a

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dramatic change in the localization properties of the electromagnetic modes. Kohmoto et al. introduced the first system based on optical Fibonacci (FN) superlattices capable of localizing photons [24], and this was shown experimentally a few years later [25]. Moreover, light localization in FN superlattices containing a LHM has also been designed [26].

Recent studies show that surface modes can be amplified in PC with defects due to an increase in the density of states at the level of the defect [27]. Montalbán et al. found an illustrative way to directly visualize how waves propagate differently in quasiperiodic and periodic structures [28]. They combine both to create a hybrid structure and show how some of the waves become trapped in the quasiperiodic section of the structure. They also pointed out that the band gaps of FN superlattices are very robust against imperfections occurring in actual experiments. Based on these studies and suggestions of the use of hybrid-order devices, composed of both periodic and quasiperiodic subunits, each exhibiting a complementary optical response [29], the goal of this paper is to study the selective spatial localization of surface plasmons within a hybrid PC|FN|PC structure applying the attenuated total reflectivity (ATR) technique [30]. The presence of defects in the interior of the structure induces a coupling of the surface plasmons with modes associated to them on their interfaces. In order to study the surface modes in the PC|FN|PC structure, the band structure is calculated and plotted to show the frequency region where the surface modes exist and the field amplitudes are calculated within the superlattice to show the field enhancement.

2. Model and theory

2.1. Surface modes on a slab

It is well known that surface plasmons exist on a slab of left-handed material, and their properties depend on the slab thickness and the dielectric medium on both sides the slab. These surface waves always decay exponentially on both sides of the interfaces. For the slab of thickness b, where the medium at $z<0$ and $z>b$ is characterized by positive and frequency-independent parameters ε_1 and μ_1, and at $0<z<b$ with a Drude-like dispersion for the effective permitivity $\varepsilon_2(\omega)$ and permeability $\mu_2(\omega)$ [18] given by

$$\varepsilon_2(\omega)=\varepsilon_0-\frac{\omega_p^2}{\omega(\omega+\mathrm{i}\gamma)}, \tag{1a}$$

$$\mu_2(\omega)=\mu_0-\frac{\omega_p^2}{\omega(\omega+\mathrm{i}\gamma)}, \tag{1b}$$

where γ is the damping factor, the boundary conditions yield the surface polariton dispersion relations

$$\frac{\mu_2}{\mu_1}=-\frac{k_2}{k_1}\tanh(k_2b/2), \tag{2a}$$

$$\frac{\mu_2}{\mu_1}=-\frac{k_2}{k_1}\coth(k_2b/2), \tag{2b}$$

for the TE mode, and another two solutions

$$\frac{\varepsilon_2}{\varepsilon_1}=-\frac{k_2}{k_1}\tanh(k_2b/2), \tag{3a}$$

$$\frac{\varepsilon_2}{\varepsilon_1}=-\frac{k_2}{k_1}\coth(k_2b/2), \tag{3b}$$

for the TM mode. $k_{1,2}$ are the attenuation coefficients of the surface polariton field in normal direction z of the interface, which can be written as

$$k_{1,2}^2=\beta^2-\varepsilon_{1,2}\mu_{1,2}\omega^2\Big/c^2, \tag{4}$$

where β is the wave vector parallel to the slab along the direction x. In order to perform the numerical calculations, we focus on the structure for which the RHM is taken as vacuum with $\varepsilon_1=\mu_1=1$, and the LHM with $\varepsilon_0=1.21$, $\mu_0=1$ and $\omega_p=10c/\Lambda$ where $\Lambda=2b$. Since the electromagnetic waves must decrease exponentially on both sides of the interface,

$$\beta^2>\max\left[\varepsilon_{1,2}\mu_{1,2}\omega^2\Big/c^2\right]. \tag{5}$$

The existence regions and dispersion relation curves of surface plasmons in the plane (β,ω), obtained by solving Eqs. (2) and (3), are shown in Fig. 1. For convenience, here we have neglected the damping term γ. The thickness of the slab is given by Refs. $\beta_0b=\pi$, where $\beta_0=\omega_0/c=2\pi/\Lambda$.