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Surface modes coupling in one-dimensional metamaterial photonic crystals with defects

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ABSTRACT

We have investigated optical properties of one-dimensional (1D) photonic crystals (PC) composed of alternating layers of a right hand material (RHM) and a left hand 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. P- or S polarized electromagnetic waves are considered to shine onto the 1D PC in the attenuated total reflectivity geometry to explore the coupling of light with the plasmons at the surfaces of the metamaterial layers. The metamaterial surface supports plasmons which in the single layer structure couple to form the symmetric and antisymmetric modes. These surface plasmons form a bulk mode in the multilayer system. The presence of a defect, which is obtained by varying the right hand layer thickness, at the middle of the layer structure, shows interesting features; the amplitude of the electric field at the defect site is enhanced and highly localized.

1. Introduction

Since the first evidence of light transmission with extraordinary characteristics [1] the surface modes study has been an important issue in the materials optical properties. On the other hand the

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surface modes existence at the metal–dielectric interface motivated investigations in plasmonics, which yielded the knowledge for applications in spectroscopy [2], nonlinear optics [3], telecommunications and information processing, molecular sensors, and biosensors [4–7]. The condition for plasmon propagation at the interface between two nonmagnetic media is that one medium should exhibit a positive while the other a negative dielectric constant. This condition may be met by the metals [8] in the Drude model. In addition materials with both negative dielectric permeability and magnetic permeability (metamaterials) [9] may also support surface or interface plasmon modes. Therefore the dielectric–metamaterial interface is suitable for plasmon propagation. Metamaterials or left hand materials [LHM] are not available in nature however they may be fabricated to yield artificial structures with both negative dielectric permeability and magnetic permeability values in some particular frequency regime, as suggested by Veselago [10] and recently realized experimentally by Pendry [11]. The dispersive characteristics together with the magnetic contributions by LHM may induce novel phenomena such as the presence of plasmon polaritons which could help to increase the microscopies resolutions, the LEDs efficiency, the chemical and biological device sensitivities [12–14].

A one-dimensional (1D) superlattice (photonic crystal) made up of alternating layers of a dielectric and a metamaterial may support modes at the interfaces. The condition of interface modes existence is that the dielectric material should exhibit a positive dielectric constant and the metamaterial should have both negative dielectric permeability and magnetic permittivity [15,16]. These structures display novel properties such as zero energy gaps [17,18] which are not manifested in metal–dielectric superlattices. Recent studies have demonstrated that in the frequency gap the light-plasmon coupling is weak reducing the plasmon polariton modes to plasmons of electric or magnetic characteristics [14].

In this work we study surface plasmon propagation at 1D metamaterial–dielectric photonic crystals applying the attenuated total reflectivity (ATR) technique [19,20]. In addition we consider the presence of defects in inner layers to explore the coupling of the surface plasmons with modes associated to the defect. The defect is created by allowing an inner layer to have a different thickness. It is known that the presence of defects in 1D photonic crystals induce a field amplitude amplification at the defect site. To study this effect 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. Theory

Let us consider the interface composed by a material with positive refraction index n and a multilayer system formed by alternating a layer of positive refraction index and a layer with negative refraction index (metamaterial), see Fig. 1. In the metamaterial both the dielectric permittivity ε_2 and magnetic permeability μ_2 are dispersive and absorptive with negative real parts. P (TM) or S (TE) polarized light interacts with the layer structure in the attenuated total reflectivity geometry. ε_2 and μ_2 are described by a Drude [17] type model as shown in the following Eqs. (1) and (2)

$$\varepsilon_2 = 1.21 - \frac{\omega_p^2}{\omega(\omega + i\gamma)} \quad (1)$$

$$\mu_2 = 1 - \frac{\omega_p^2}{\omega(\omega + i\gamma)} \quad (2)$$

where $\omega_p = 10c/\Lambda$ with $\Lambda = d_v + d_{\mathrm{LHM}}$, d_v and d_{LHM} are the thicknesses of the right hand and left hand layers, respectively, and $\gamma = 10^{-4}\omega_p$ is the damping factor. In this work the right hand material is taken as vacuum with $\varepsilon_1 = \mu_1 = 1$.

The electric and magnetic fields within a layer have the form:

$$\vec{E} = (\widehat{i}\, E_x - \widehat{k}\, E_z)e^{i(\beta x - qz - \omega t)} \quad (3)$$