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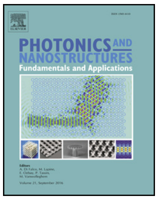

Plasmon modes supported by left-handed material slab waveguide with conducting interfaces

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ABSTRACT

Theoretical analysis of left-handed material core layer waveguide in the presence of interface free charge layers is presented. The thickness of the interface charge layer can be neglected compared with the incident wavelength. The tangential component of the magnetic field is no longer continuous due to the conducting interfaces. The non-homogeneous boundary conditions are solved and the corresponding dispersion relation is found. The dispersion properties are studied. The proposed structure is found to support even as well as odd plasmon modes. Moreover, the structure shows abnormal dispersion property of decreasing the effective index with the increase of the frequency which means negative group velocity.

1. Introduction

The concept of negative index media was first studied theoretically by Veselago in 1968 [1]. These materials have attracted physics community in recent years due to a set of unusual properties. These materials were called negative index materials (NIMs) or left-handed material (LHMs) due to the left-handed set formed by the electric field (**E**), magnetic field (**H**) and the wavevector (k). Pendry realized artificial structures with negative permittivity [2] and permeability [3]. Making use of these structures, Smith et al. verified experimentally the presence of LHMs of negative index of refraction [4]. Since then, a great deal of research has been conducted to inspect the private properties of these media and their applications in many fields in microwave and optical devices [5–9]. Among these applications, slab guiding structures with LHM layers have attracted much interest due to peculiar modal properties. The modal properties of grounded LHM slabs have been investigated [10,11]. Different LHM structures with symmetric and asymmetric configurations have been studied [12]. Excitation of surface polaritons in different LHM structures was also presented [13–16]. Multilayer structures of LHM have been studied and they showed a peculiar properties. Many interesting features have been found including the coexistence of eigen modes [5], sign-varying power flux [17], nonexistence of the fundamental mode [18], zero or negative group velocity [19], improvement of the evanescent field [20], and surface-waves suppressing in a LHM grounded slab [21]. Depending on these new features of LHMs, a set of applications have been proposed using LHM inclusions. The backward wave generator [22], band pass filter [5], and efficient waveguide sensor [23–26] were among these applications. Moreover, LHM structures can be used as compact resonator and phase shifters [27], microwave imager [15], energy-transfer enhancer [15], high capacity storage [28], and high-reflection coatings [5].

The increasing number of possible applications of surface waves was the motivation behind this work. Propagating surface plasmon polaritons were proposed for next-generation circuits that use light to overcome the speed limit of electronics [29]. Different waveguide structures supporting surface plasmon polaritons were studied, leading to a number of possible applications in many fields including spectroscopy [30], nanophotonics [31], imaging [32], biosensing [33,34], and circuitry [35].

Many interesting features can be found in studying surface waves generated at the interfaces. They are excited at an interface separating two media with opposite signs of either dielectric permittivity or magnetic permeability [36,37]. The propagation of surface waves along the interface of a LHM was investigated for both s- and p- polarized light [5]. Brillouin figures were plotted. It was shown that, after cutoff, there is a frequency range which corresponds to two possible propagation coefficients [5]. It was confirmed that the LHM heterostructures can support a richer variety of surface plasmon polaritons when compared to metallic ones [13]. Dispersion properties of the surface polaritons of a LHM slab were studies [14]. Four branches of TM-surface polaritons and two

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branches of TE-surface polaritons were discovered [14]. K. Park et al. studied in a recent work the effect of surface and bulk polaritons on a LHM embedded between two positive-index materials [15]. They focused on the reflectance from the proposed structure [15]. A variety of slab waveguide structures consisting of a metal and a LHM were investigated for surface polariton excitation [16]. P. Baccarelli et al. analyzed surface waves supported by a LHM on a ground plane [18]. They also investigated the possibility of these grounded slabs to behave as substrates for planar antennas [18]. The dispersion relations for s- and p-polarized light of surface polaritons excited by a grounded slab of LHM was investigated [21]. The conditions required to suppress guided-wave regime are also presented. The two types of surface polaritons (one evanescent only in air layer and the other evanescent both in air and core LHM layer) were taken into consideration [21]. It was confirmed that by placing a periodic structure consisting of many resistors near the LHM it is possible to suppress or to reduce the surface wave that is present at the interface between air and LHM layers [22]. Surface waves stimulated at the interface between LHM and a positive-index materials were investigated for refractometric applications [24].

Khorasani et al. investigated fast guided light modulation in planar waveguides with ultra-high switching speed [38]. The corresponding dielectric slab waveguide operation principle is totally dependent on the interaction of interface free charge layers and guided wave within the core layer. The density interface free charge layer is adjusted by applying a potential difference. The slab waveguide with interface free charge layers has significant applications such as optical storage and optical transistor. The transfer matrix method was employed for studying the propagation of waves in a stack of layers with conducting interfaces [39].

In this work, we present theoretical analysis of left-handed material core layer waveguide in the presence of interface free charge layers. In this device, we assume the thickness of the interface charge layer is ignorable compared with the incident wavelength. Maxwell equations subject to non-homogeneous boundary conditions are solved and the corresponding dispersion relation is found.

2. Dispersion relation for non-homogeneous boundary conditions

We consider asymmetric three layer waveguide having LHM core layer with parameters (ε_f, μ_f) and thickness d, a dielectric substrate with parameters (ε_s, μ_s) and a dielectric cladding with parameters (ε_c, μ_c). We assume lossy, isotropic and homogeneous LHM obeying the following dispersion

$$\varepsilon_f = 1 - \frac{\omega_p^2}{\omega^2 + i\Gamma_e\omega}, \tag{1}$$

$$\mu_f = 1 - \frac{F\omega^2}{\omega^2 - \omega_o^2 + i\Gamma_m\omega}, \tag{2}$$

where ω_p is the plasma frequency, ω_o is the resonance frequency, Γ_e and Γ_m are the electric and magnetic loss factors, ω is the angular frequency, and F is the fractional area of the unit cell occupied by the split ring.

The y-axis is assumed to be normal to the page and points outward. If two conducting interfaces with conductivities σ exist at $z=0$ and $z=d$, with an effective thickness much less than the guided light wavelength. Fig. 1 shows a schematic diagram of the waveguide structure under consideration.

For s-polarized light (TE), the wave equation in any of the three layers is given by

$$\left(\frac{\partial^2 E_y(x)}{\partial x^2}\right) + \left(\omega^2\varepsilon_i\mu_i - \beta^2\right) E_y(x) = 0, \tag{3}$$

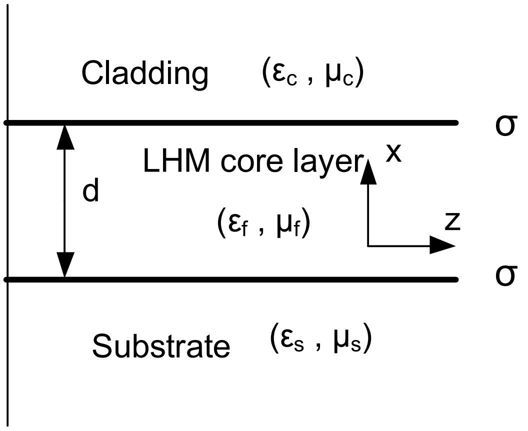

Fig. 1. Schematic diagram of left-handed material slab waveguide with conducting interfaces.

where ε_i and μ_i are the permittivity and permeability of medium i and β is the propagation constant in z-direction.

The solution of Eq. (3) in the media of the waveguide structure are given by

$$E_y(x) = Ae^{\alpha_s x},\ \alpha = \sqrt{\beta^2 - \omega^2\varepsilon_s\mu_s},\ x < 0 \tag{4}$$

$$E_y(x) = B_1 cos\alpha_f x + B_2 sin\alpha_f x,\ \alpha_f = \sqrt{\omega^2\varepsilon_f\mu_f - \beta^2},\ 0 < x < d \tag{5}$$

$$E_y(x) = Ce^{-\alpha_c(x-d)},\ \alpha_c = \sqrt{\beta^2 - \omega^2\varepsilon_c\mu_c},\ x > d \tag{6}$$

The nonzero components of the magnetic field are H_x and H_z. They can be calculated using the expanded form of Maxwell's relations where $H_x(x) = -\left(\frac{\beta}{\mu_i\omega}E_y(x)\right)$ and $H_z(x) = \left(\frac{i}{\mu_i\omega}\frac{\partial E_y(x)}{\partial x}.\right)$

$$H_z(x) = \frac{iA\alpha_s}{\mu_s\omega}e^{\alpha_s x},\ x < 0 \tag{7}$$

$$H_z(x) = \frac{i\alpha_f}{\mu_f\omega}\left(-B_1 sin\alpha_f x + B_2 cos\alpha_f x\right),\ 0 < x < d \tag{8}$$

$$H_z(x) = \frac{-iC\alpha_c}{\mu_c\omega}e^{-\alpha_c(x-d)},\ x > d \tag{9}$$

We now apply the boundary conditions. The continuity of E_y at $z=0$ and $z=d$ gives

$$A = B_1 \tag{10}$$

$$B_1 cos\alpha_f d + B_2 sin\alpha_f d = C \tag{11}$$

Due to the presence of the conducting interfaces, an interface current density is generated according to

$$J_s = \sigma E_{//}(x) \tag{12}$$

This current density generates a discontinuity in the tangential magnetic field (H_z) so that

$$H_{zs} - H_{zf} = \sigma\left(E_y\right)_{z=0} \tag{13}$$

This yields

$$A = \frac{i\alpha_f}{\mu_f\omega}\frac{B_2}{\left(\frac{i\alpha_s}{\mu_s\omega} - \sigma\right)} \tag{14}$$

Moreover,

$$H_{zf} - H_{zc} = \sigma\left(E_y\right)_{z=d} \tag{15}$$

$$C = \frac{i\alpha_f}{\mu_f\omega}\frac{-B_1 sin\alpha_f d + B_2 cos\alpha_f d}{\left(\sigma - \frac{i\alpha_c}{\mu_c\omega}\right)} \tag{16}$$