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Excitation of surface plasmons in multilayer structures containing alternate ε-negative and the μ-negative metamaterials

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ABSTRACT

The localized surface waves at the interface between a semi-infinite periodic multilayer structure containing alternate ε-negative (ENG) and the μ-negative (MNG) layers and a uniform right-handed material and also a uniform left-handed metamaterial have been investigated. We demonstrated that in the presence of uniform right-handed materials, this system can support TE and TM-polarized surface waves depending on the relative thicknesses of the ENG and the MNG layers. But, in the presence of uniform left-handed metamaterials, the supposed structure only support TM-polarized surface waves. These localized modes can have two different transverse structure related to the order of the ENG and the MNG layers; one with a hump at the interface between uniform material and the cap layer and the other one with a hump at the interface between the cap layer and the periodic multilayer structure.

KEYWORDS

Surface plasmons;
Left-handed metamaterials;
Single-negative metamaterials.

INTRODUCTION

Recently, metamaterials as specially engineered media with unconventional response functions has attracted a great deal of attention. Particularly, media in which both of the material parameters, permittivity (ε) and permeability (μ), can attain negative real parts in a certain frequency band, have been studied by numerous groups (see e.g., [1]). When both material parameters possess negative real parts, such double-negative (DNG) media can support wave propagation and exhibit the unusual phenomenon of negative refraction. Besides the DNG materials, we can also have materials in which only one of the two material parameters ε and μ is negative[2]. These so-called single negative (SNG) materials support evanescent wave in order to maintain positive definite energy density. Because ε and μ are frequency dependent, only within a certain frequency range we have $\varepsilon < 0$ and $\mu > 0$ (epsilon-negative) or $\varepsilon > 0$ and $\mu < 0$ (mu-negative), which is called the SNG frequency range. The DNG and SNG metamaterials, formed by embedding arrays of metallic split-ring resonators and wires in a host medium[2], have been successfully constructed in the microwave regime by several groups, and some of their unusual properties (e.g., negative refraction) have been experimentally demonstrated[1]. All these artificial composites (including DNG and SNG materials) have exhibited special features in photonic crystals (PCs)[3–5]. The essential property of PCs is the photonic band gap (PBG) structure originated from the consequence of Bragg scattering. Such a Bragg gap in conventional PCs is strongly

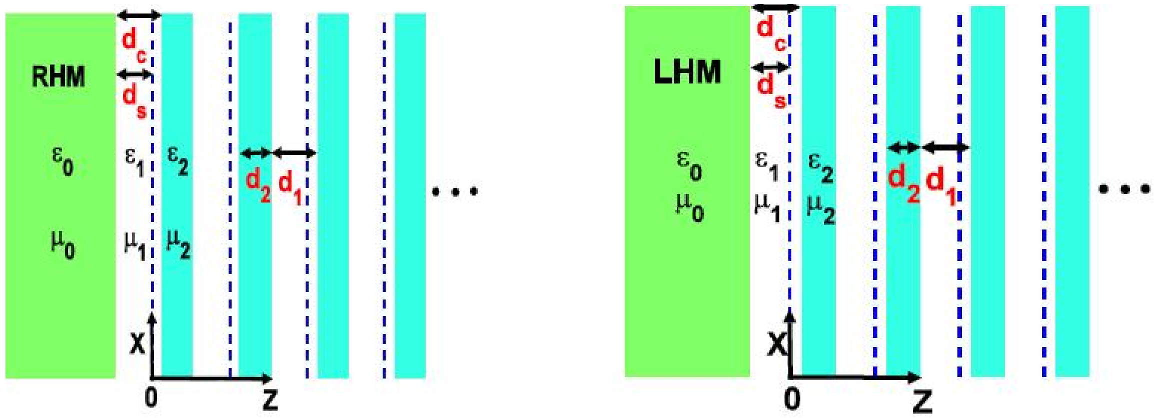

Figure 1 : Geometry of the problem. The left figure is the semi-infinite periodic multilayer structure containing alternate ε -negative (ENG) and the μ-negative (MNG) layers and a uniform right-handed material (RHM). The right figure is the semi-infinite periodic multilayer structure containing alternate ε-negative (ENG) and the μ-negative (MNG) layers and a uniform left-handed material (LHM)

dependent on the lattice constant, and the incident angle and polarization of light, and is affected by disorder of devices. Jiang et al.[5] found that the ENG-MNG multilayered periodic structures can possess a new type of photonic band gap (called the effective zero-phase gap), which is distinct from the Bragg gap but similar to the zero average index gap[6–8]. Such a zero-phase gap is an omnidirectional band gap and is insensitive to the incident angles and polarizations of the incident light[9–11].

The excitation of surface waves (SWs) has recently been proposed[12–14] as a way to efficiently inject light into a PC waveguide, or to extract a focused beam from a channel. SWs on a 1DPC were observed almost 30 years ago[15,16]. The basic theory was developed at that time by Yariv and Yeh[17,18]. The effect of varying the thickness of the termination layer has been measured experimentally[19] and a sensor based on the properties of SWs has been proposed and demonstrated[20]. In parallel, numerical calculations for SWs in the band gaps have been performed[21-27].

In this paper, we study the properties of linear SWs at the interface between uniform right-handed (RHM) materials (and uniform left-handed metamaterial LHM) and a semi-infinite 1DPCs containing alternate ENG and MNG (or MNG and ENG) layers, and demonstrate a number of unique features of SWs in the SNG band gap. It is found out that in the considered periodic structure with ENG-MNG (or MNG-ENG) arrangement we can only excite the TE-polarized surface modes (SMs). These SMs can have two different transverse structures at the second SNG band gap of the photonic crystal depending on the type of arrangement of the layers of PC (ENG-MNG or MNG-ENG). In the ENG-MNG arrangement, the modes have a hump at the interface between the cap layer and the photonic crystal, while in the MNG-ENG arrangement the modes have a hump at the interface between uniform material and the cap layer. We show that in the ENG-MNG arrangement, the dispersion curves can be nearly omnidirectional for thick cap layers. Some other numerical results are given in the result section. In Sec. 2, we introduce the model of the system under consideration. In Sec. 3, the properties of SWs are studied. Finally, Sec. 4 concludes with brief comments.

THEORETICAL MODEL

In this section, we wish to describe SMs that form at the interface between a RH medium (and LHM medium) of refractive index, $n_0 = \sqrt{\varepsilon_0 \mu_0}$ and a semi-infinite 1DPCs containing SNG materials. We assume that each cell of PCs consists of the ENG-MNG or the MNG-ENG layers with the thickness d_i, relative permittivity ε_i and permeability μ_i (i = 1, 2) (see Figure 1). Now, we suppose that relative permittivity and permeability in the ENG materials are given by[3]

$$\varepsilon_i = 1 - \frac{\omega_{ep}^2}{\omega^2}, \qquad \mu_i = a, \tag{1}$$

and those in the MNG materials are given by

$$\varepsilon_i = b, \qquad \mu_i = 1 - \frac{\omega_{mp}^2}{\omega^2}, \qquad (2)$$

where ω is the angular frequency, ω_{ep} and ω_{mp} are the electronic plasma frequency and the magnetic plasma frequency, respectively. The frequency ω in the above equations is measured in 10^9 rad/s. Here both positive constants a and b are assumed to be a=b=3.0. Both ω_{ep} and ω_{mp} are set to be 10×10^9 rad/s[5].

In the frequency range of $\omega<\omega_{ep}$, ω_{mp}, either ε or μ is negative in each layer, that is, to say we have SNG materials. So, in the SNG frequency range of ω, we have $\varepsilon_1<0$, $\mu_1>0$, and $\varepsilon_2>0$ and $\mu_2<0$ for the periodic structure consists of the ENG-MNG layers. While, for a periodic structure consists of the MNG-ENG layers $\varepsilon_1>0$, $\mu_1<0$, and $\varepsilon_2<0$ and $\mu_2>0$. Hence, in each layer the refractive index is a pure imaginary number and the electromagnetic fields are evanescent. As shown in Figure 1, the crystal is capped by a layer of the same material but different width, d_c as an adjusting parameter. We consider the propagation of TE-polarized waves described by[24]

$$\begin{aligned} \mathbf{E} &= \mathbf{E}_y(z)\hat{\mathbf{e}}_y e^{i(k\beta x-\omega t)}, \\ \mathbf{H} &= (\mathbf{H}_x(z)\hat{\mathbf{e}}_x + \mathbf{H}_z(z)\hat{\mathbf{e}}_z)e^{i(k\beta x-\omega t)}, \end{aligned} \qquad (3)$$

with the electric field E in the y direction (the dielectric layers are in the x-y plane and the z direction is normal to the interface of each layer) (see Figure 1). Here k = ω/c is the vacuum wave number.

Surface modes correspond to localized solutions with the field decaying from the interface in both directions. In the left-side homogeneous medium (semi-infinite LHM or RHM) z<ds the fields are decaying provided $\beta > \varepsilon_0\mu_0$. In the right-side periodic structure, the waves are the Bloch modes,

$$\mathbf{E}(z) = \psi(z)\exp(i\kappa_B z), \qquad (4)$$

where κ_B is the Bloch wave number, and $\psi(z)$ is the Bloch function which is periodic with the period of the photonic structure. In the periodic structure the waves will be decaying provided that κ_B is complex, and this condition defines the spectral gaps in a finite PC. For the calculation of the Bloch modes, we use the well-known transfer matrix method[18]. To find the SMs, we take solutions of Eq. (4) in a homogeneous medium and the Bloch modes in the periodic structure and satisfy the conditions of continuity of the tangential components of the electric and magnetic fields at the interface between the homogeneous medium and periodic structure[25]. In this way, we can obtain the exact dispersion relation $\omega=\omega(\beta)$ for TE-polarized SWs by numerically solving the following dispersion condition for the SMs:

$$\frac{q_0/\mu_0}{k_1/\mu_1} = -i\frac{\lambda - A - \tilde{B}}{\lambda - A + \tilde{B}}. \qquad (5)$$

Here

$$\begin{aligned} \lambda &= \frac{A+D}{2} \pm \sqrt{\left(\frac{A+D}{2}\right)^2 - 1}, \\ A &= e^{k_1 d_1}(\cosh(k_2 d_2) + 1/2(x+1/x)\sinh(k_2 d_2)), \\ \tilde{B} &= 1/2e^{k_1(d_1-2d_c)}(x-1/x)\sinh(k_2 d_2), \\ D &= e^{-k_1 d_1}(\cosh(k_2 d_2) - 1/2(x+1/x)\sinh(k_2 d_2)), \end{aligned} \qquad (6)$$

where $k_1 = k\sqrt{\beta^2 - \varepsilon_1\mu_1}$, $k_2 = k\sqrt{\beta^2 - \varepsilon_2\mu_2}$, $q0 = \sqrt{\beta^2 - n_0^2}$ and $x = \frac{k_2/\mu_2}{k_1/\mu_1}$.

These equations are valid only for the specific condition of $\varepsilon_1<1$, $\mu_1>1$, $\varepsilon_2>1$, $\mu_2<1$ or $\varepsilon_1>1$, $\mu_1<1$, $\varepsilon_2<1$, $\mu_2>1$.

RESULTS AND DISCUSSION

In the following, we summarize the dispersion properties of the SMs in the second SNG band gaps which are in the microwave range suitable for the SNG metamaterials. In Figure 2, we plotted the dispersion curves of TE-polarized SMs on the plane of ω versus the propagation constant β for different thickness of the cap layer (d_c). Here we used the structure with d_{ENG}=0.6 cm and d_{MNG} =0.8 cm. It is seen that the dispersion curve of TE-polarized SMs for a given dc depends on the type of arrangement of SNG layers: ENG-MNG arrangement (Figure 2(a)); MNG-ENG arrangement (Figure 2(b)). Specially, for thick cap layer the difference is obvious (see solid lines in Figure 2). As it is seen from Figure 2(a), we can have nearly omni-directional dispersion curve in the ENG-MNG arrangement, whilst in the MNG-ENG arrangement; disper-

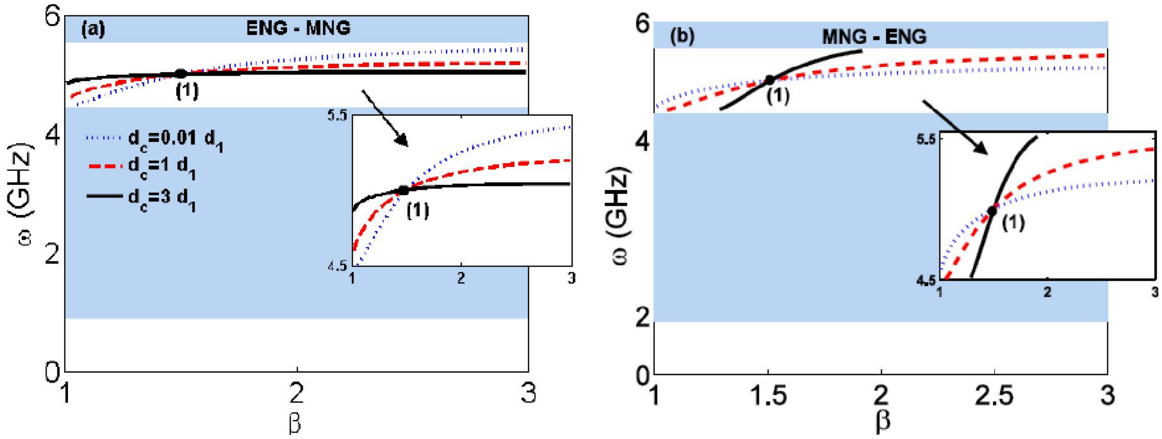

Figure 2 : Dispersion property of the TE-polarized SWs at the second SNG band gap for different thicknesses of the cap layer d_c= 0.01d_1 (dotted lines), d_c= 1d_1 (dashed lines) and d_c=3d_1 (solid lines) in (a) the ENG-MNG and (b) the MNG-ENG arrangements. The unshaded regions show the first and the second band gaps of the periodic multilayer structure with SNG constituents, while the shaded regions indicate the corresponding pass bands. In the used structure d_{ENG} = 0.6 cm, d_{MNG} = 0.8 cm and d_{ENG}/d_{MNG}< 1.

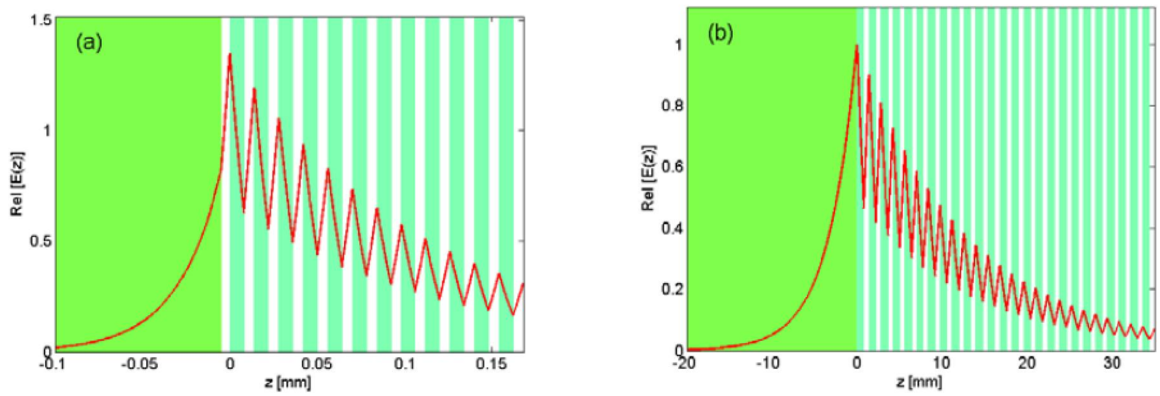

Figure 3 : The transverse profile of the SWs vs coordinate z for (a) d_c =1d_1 in the ENG-MNG arrangement, (b) d_c = 0.01d_1 in the MNG-ENG. Here β = 1.5, ω = 5 GHz and the other parameters are same as Figure 2

sion curve is limited to a narrow domain of incident angles for thick cap layer. More interestingly, one can see that the dispersion curves are intersected together at a single point on the (ω, β) plane for both the ENG-MNG and the MNG-ENG arrangements (point (1) in Figure 2).

In other words, there is a frequency and an angle of incidence for which, we can excite SWs independent of dc and the type of the arrangement (ENG-MNG or MNG-ENG). The results of our investigations show that the structure with the set of material parameters chosen in Figure 1 dose not supports TM-polarized SMs. So, in what follows, we discuss about the properties of TE-polarized SMs.

To show the difference between SMs in two ENG-MNG and MNG-ENG arrangements we plotted the transverse structure of SMs versus distance z in Figure

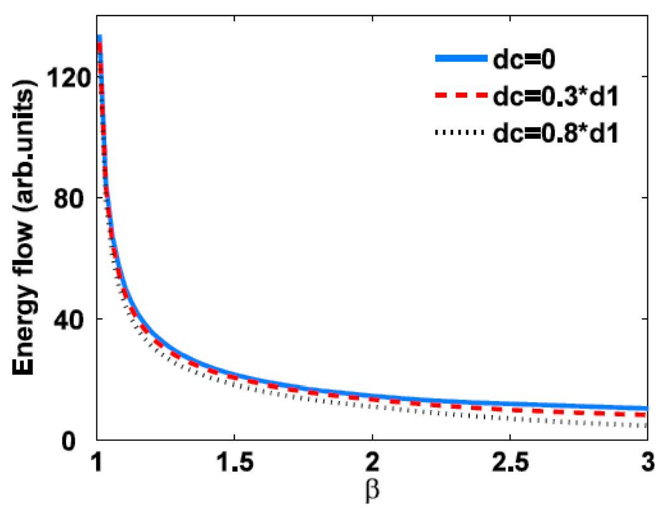

Figure 4 : Total energy flow of surface Tamm modes vs. β in the ENG-MNG. Dotted, dashed, and solid curves show the energy flow of the surface modes for d_c = 0 d_1, 0.3d_1, and 0.8d_1, respectively

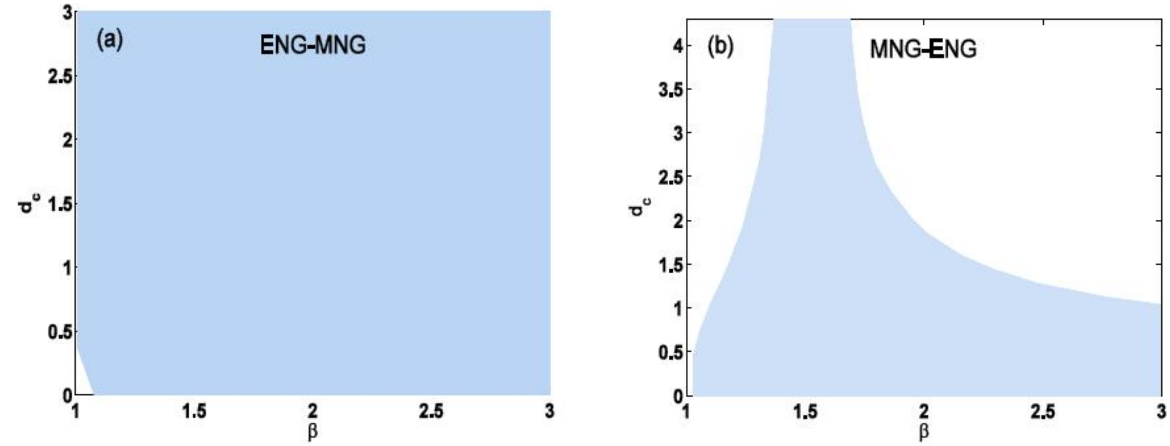

Figure 5 : Existence regions for the SMs; the modes exist in the shaded regions for (a) the ENG-MNG arrangement and (b) the MNG-ENG arrangement. The other parameters are the same as the Figure 2

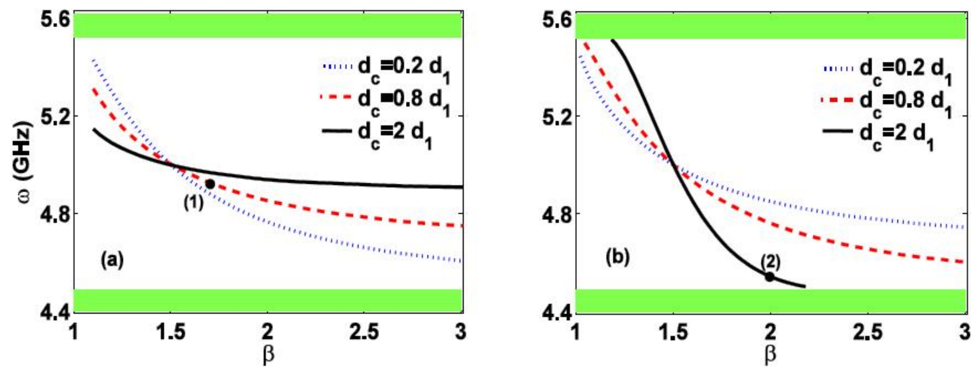

Figure 6 : Dispersion properties of the TM-polarized surface modes for (a) ENG-MNG and (b) MNG-ENG periodic structures. Unshaded regions show the zero-ϕ_{eff} spectral gap of the 1D PC containing SNG materials. Dotted, dashed, and solid curves show the dispersion of the surface modes for d_c= 0.2d_1, 0.8d_1 and 2d_1, respectively

3. From Figure 3, we see that the peak of the electric field is appeared at the interface of the cap layer and the 1DPC in the ENG-MNG arrangement, while in the case of MNG-ENG arrangement the peak of the electric field is located at the interface of the uniform medium and the cap layer. Here, the unusual structure of SMs comes from sharp jumps at the interface of layers resulting from opposite signs of permeability of adjacent layers and decaying evanescent waves in each layer.

By further inspection of dispersion curves we see that the dispersion curves have positive slopes. As the slope of the dispersion curve determines the corresponding group velocity of the mode and the direction of energy ûow at the surface, we see that in our structure all modes are forward modes (see Figure 4).

The type of arrangement of the structure not only affects the dispersion curves of SMs, but also it changes the existence regions of TE-polarized SMs. To demonstrate this, we plotted the existence regions of the SMs at the second SNG band gaps on the parameter plane (d_c, β) in Figure 5 in which the shaded areas show the existence regions of the TE-polarized SMs. From Figure 5 we can find that the considered structure can support SMs for almost every β and d_c in the ENG-MNG arrangement. But, the existence region of SMs is restricted to a narrow domain of incident angles for relatively large d_c in the MNG-ENG arrangement. The similar discussions can be offered for TM wave.

Up to now, we discussed the property of polarized SMs in the considered structure with RHM layer. Then, we theoretically study SWs that can be excited at the interfaces between a semi-infinite uniform LHM medium and a semi-infinite 1DPC containing two types of single-negative materials (ENG-MNG and MNG-ENG). As we know, the Tamm states exist in the gaps of the PBG spectrum (unshaded regions in Figure 5).

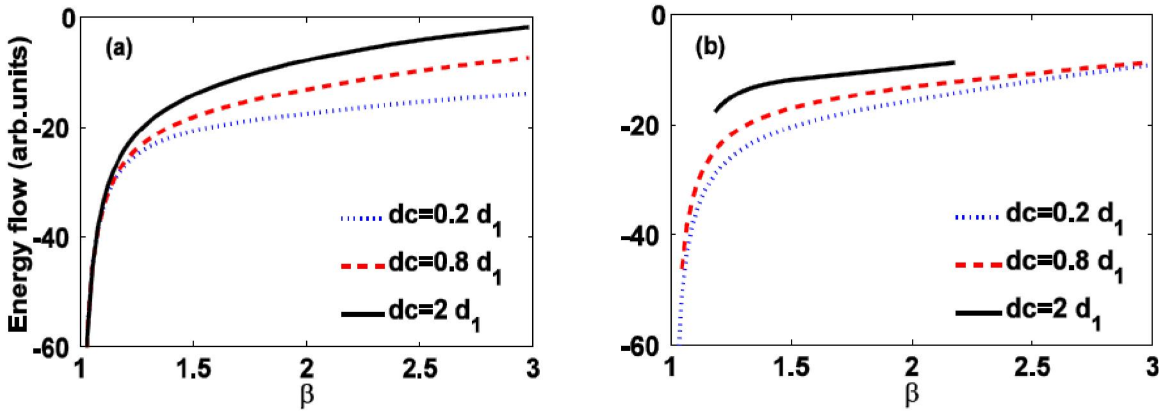

Figure 7 : Total energy flow of surface Tamm modes vs. β in the (a) ENG-MNG and (b) MNG-ENG periodic structures for different dc. Dotted, dashed, and solid curves show the energy flow of the surface modes for $d_c = 0.2d_1$, $0.8d_1$, and $2d_1$, respectively

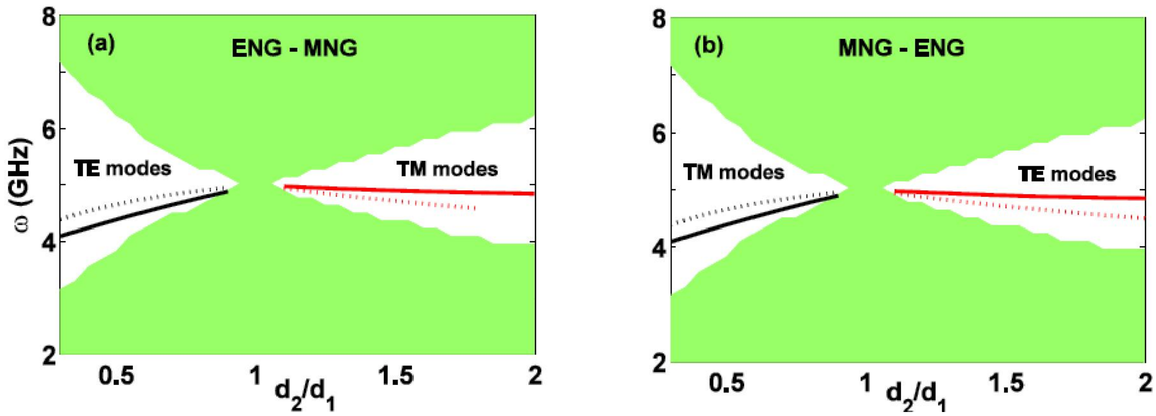

Figure 8 : The dependence of the zero-ϕ_{eff} PBG and surface modes on the ratio of d_2/d_1 for (a) ENG-MNG (b) MNG-ENG structures. The dotted and solid lines correspond to the surface modes with $d_c = 0.2d_1$ and $d_c = 1.5d_1$, respectively. Here, $\beta = 1.9$, and the other parameters are the same as the Figure 1

Since our studies show that we have only TM-polarized SWs for proposed structure we turn our attention to the TM-polarized SWs and present dispersion characteristic of SWs for different values of the cap layer thickness d_c For ENG-MNG and MNG-ENG multi-layered structures in Figures 6(a) and 6 (b), respectively. It is necessary to remember that in MNG-ENG structure the position of ENG and MNG layers in ENG-MNG structure is exchanged with the same geometry and physical parameters. As one can see from Figure 6, there are different dispersion curves for different values of d_c, which describe a possibility to control the dispersion properties of SWs by adjusting d_c. Corresponding values of d_c for dotted, dashed, and solid curves of dispersion are d_c= $0.2d_1$, $0.8d_1$ and $2d_1$, respectively. Moreover, Figure 6 shows that, in ENG-MNG structure, there are no limitation on the existence region of TM surface modes for large d_c, whilst in the case of MNG-ENG structure the existence region of TM surface modes decreases by increasing the thickness of cap layer d_c (see dashed and solid lines in Figure 6(b)).

Energy ûow of surface Tamm states for ENG-MNG and MNG-ENG structure has the same behavior as the negative values. To demonstrate this, in Figure 7, we plot total energy ûow as a function of the wave number β. We see from Figure 7 that all surface modes in ENG-MNG and MNG-ENG periodic structure have negative energy ûow, thus they are backward for different values of cap layer thicknesses d_c.

In Figure 8, we study the dependence of surface modes on the ratio of the thicknesses of two SNG layers (d_2/d_1) for (a) ENG-MNG (b) MNG-ENG structures. The dotted and solid lines correspond to the surface modes with d_c= $0.2d_1$ and dc = $1.5d_1$, respec-

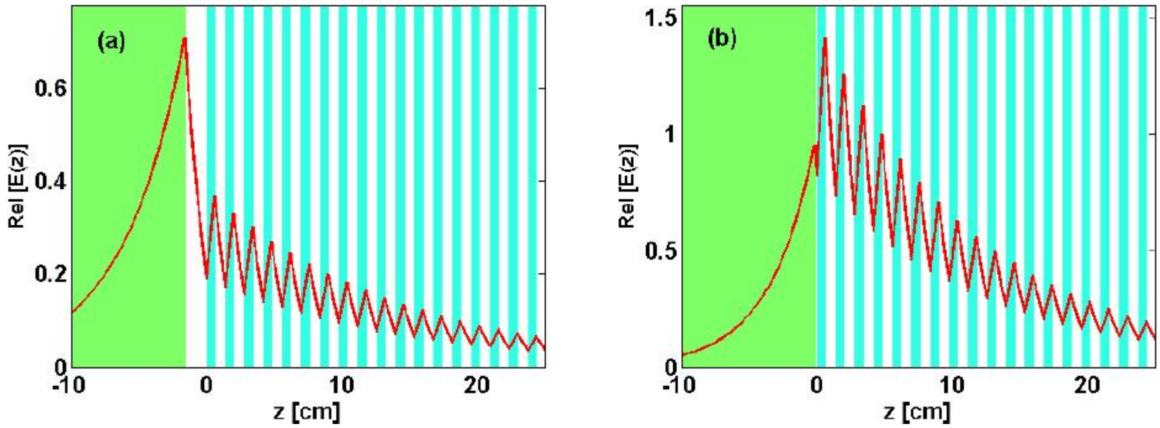

Figure 9 : Examples of the backward TM surface modes. (a) ENG-MNG structure: ω= 4.6 GHz, β=1.85, and $d_c = 2d_1$. (b) MNG-ENG structure: ω=4.562 GHz, β=1.94, and $d_c = 0.2d_1$. Modes (a), and (b) correspond to the points (1) and (2) in Figure 2, respectively. The other parameters are the same as the Figure 1

tively. Here, β=1.9, and the other parameters are the same as those in Figure 1. The unshaded regions are omnidirectional zero-ϕ_{eff}PBG in which the existence of TM or TE surface modes are indicated. As one can see from Figure 8, in ENG-MNG structure, TE polarized SWs exist only for the relative thickness (d_2/d_1) less than one, and TM polarized SWs exist only for the relative thickness more than one, while in the case of MNG-ENG structure TE-polarized SWs exist only for the relative thickness (d_2/d_1) more than one, and TM-polarized SWs exist only for the relative thickness less than one.

Profiles of points (1) and (2), situated in Figure 2, are shown in Figure 9, where we plotted the proûles of the mode (1) in the ENG-MNG structure and the mode (2) in MNG-ENG structure. Figure 9 shows that in MNG-ENG arrangement (Figure 9a), the peak of SWs is located at the interface between DNG material and cap layer. But, in ENG-MNG arrangement (Figure 9b) the peak of SWs is located at the interface between the cap layer and photonic crystal.

CONCLUSION

In summery, we studied the linear SWs at the interface between a uniform RHM medium (and LHM medium) and a semi-inûnite 1DPC made of SNG materials. We showed that in the presence of uniform right-handed materials, the considered structure can support TE and TM-polarized surface waves depending on the relative thicknesses of the ENG and the MNG layers. But, in the presence of uniform left-handed metamaterials, the supposed structure only support TM-polarized surface waves. These SMs depending on the arrangement of the layers of PC (MNG-ENG or ENG-MNG) can have two diûerent transverse structures of ûeld at the second SNG band gap of the PC. In the ENG-MNG arrangement the peak of SMs are located at the interface between the cap layer and the photonic crystal. But, in the MNG-ENG arrangement, the peak of SMs is located at the interface between uniform material and the cap layer. We have demonstrated that in the presence of a LHM layer there are only backward TM-polarized waves, while in the presence of a RHM layer there are forward waves. More interestingly, we demonstrated that the occurrence of the TE- polarized and the TM-polarized surface waves depends on the ratio of the thicknesses of the ENG layer to the MNG layer.

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