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Effect of hybrid state of surface plasmon–polaritons, magnetic defect mode and optical Tamm state on nonreciprocal propagation

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ABSTRACT

A coupled system of semi-infinite one-dimensional photonic crystal coated with metal and magnetic films is proposed. The properties of hybrid states of surface plasmon–polaritons, magnetic defect mode and optical Tamm state from the system have been studied through the Bloch theorem of periodic structure and the transfer matrix method. In the hybrid states the magneto-optical effect is amplified due to the field resonance amplification at the interface between the metal and magneto-optical material. Tunable nonreciprocal propagation can be achieved from the hybrid states through changing the thickness of magneto-optical material layer. The nonreciprocity is found to be robust to the change of metal thickness.

1. Introduction

Surface electromagnetic waves which exist at the interfaces separating different media are proven to be important in many application fields, such as integrated optical circuits and biosensors. One of the most known types of such waves is surface plasmon–polaritons (SPPs), which exist at interfaces separating metals and dielectrics [1,2]. The other types of commonly known surface waves are optical Tamm states (OTCs), which exist on the surface of semi-infinite one-dimensional photonic crystals (PCs) [3–6]. A great advantage of OTSs in comparison with SPPs is their low attenuation. Thus, OTSs represent an excellent alternative for a variety of optical elements with a functionality relying on the surface waves. One common property of both the two types of surface waves is that they can achieve nonreciprocal behavior in the presence of an external magnetic field [7,8]. However, this nonreciprocity for SPPs is usually quite marginal, and/or it requires very large magnetic fields [7]. Nonreciprocity is also a subtle property of magnetic materials. In addition to violation of the time reversal symmetry it also requires removal of the mirror reflection symmetry [9–11]. There have been some efforts to achieve this, such as using OTSs in semi-infinite one-dimensional MPCs [7], using compound cell in MPCs [10,11], or exciting Tamm plasmon–polaritons (TPPs) on the interface between MPCs and conducting metal oxides [12]. More recently, the effect of magnetoptic phenomena on nonreciprocal resonant transmission/reflection based on a one-dimensional photonic crystal adjacent to the magneto-optical metal film has been studied [13]. The nonreciprocal resonant transmission/reflection in the above study is also based on the exciting of TPPs on the interface between PC and magneto-optical metal film similar to Ref. [12]. Also Optical Tamm states (OTSs) with nonreciprocal dispersion has been found at the boundary separating two different magnetophotonic crystals magnetized in the Voigt geometry [14]. The structure in Ref. [14] can be used for design of compact optical isolators.

On the other hand, nanosystems with combined magnetic and plasmonic functionalities have in recent years become an active topic of research [15–19] because SPPs can be controlled through external magnetic field. Simultaneously, the magneto-optical (MO) activity of these systems can be greatly increased due to the electromagnetic field enhancement associated with the plasmon resonance. Typically, a sandwiched structure metal/MO/metal is used for the nanosystems [20,21] in which an optimum combination of both MO and plasmonic characteristics can be obtained by mixing ferromagnets and noble metals. The ferromagnet endorses the MO activity to the system, whereas the noble metal allows SPPs excitation with low optical losses [15]. In these study, the transverse magneto-optic Kerr effect (TMOKE) is often considered.

However, a coupled system with combined MO defect state, SPPs and OTSs has not been studied which is just the study object of this paper. Such a system can be constructed just by replacing one metal layer in the sandwiched structure metal/MO/metal by a semi-infinite one-dimensional photonic crystal (1DPC). The MO layer can be looked as a surface defect of the 1DPC. Because MO defect state, SPPs and OTSs are all resonance units, their coupling will result in a unique hybrid state with merged and tunable

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optical functionalities. The dispersion of conventional SPPs can be modulated by the MO defect state and OTSs. On the other hand, the MO effect can be amplified due to the resonance effect of the hybrid state. The import of OTSs enlarges the dispersion range of coupled modes and results in more new features of surface electromagnetic waves. More important, tunable nonreciprocal propagations can be also achieved through the coupled system. Compared with previous works [13,14], our designed structure may excite more new physical phenomena. Our study is different from Ref. [13]. The work in Ref. [13] is based on the exciting of TPPs, while our work is based on the effect of hybrid states combining MO defect state, SPPs and OTSs. The hybrid states provide more tunable ways in designing optical isolators.

2. Model and equations

As shown in Fig. 1, the whole coupled system is denoted as MDABAB…AB. Layers M and D are noble metal silver and MO media, respectively, which are coated on the surface of the 1DPC composed of layers A, B. The permittivity for layer M can be expressed as the Drude Model:

$$\varepsilon_A = 1-\omega_{ep}^2/(\omega^2+i\omega\tau) \tag{1}$$

here $\omega_{ep}=1.2\times10^{16}\ \mathrm{s}^{-1}$ is the electronic plasma frequency and $\tau=1.45\times10^{13}\ \mathrm{s}^{-1}$ is the damping constant referring to the loss [22]. Layer D with a thickness of d_D can be regarded as a surface defect of the PC. The permittivities and thicknesses for layers A and B are ε_A, d_A and ε_B, d_B, respectively. We use a gyrotropic material, Bismuth iron garnet (BIG) for layer D. In the Cotton–Mouton (Voigt) geometry, the optical property of BIG is characterized by a dielectric tensor

$$\overline{\varepsilon_d} = \begin{bmatrix} \varepsilon_d & 0 & -i\Delta_d \\ 0 & \varepsilon_d & 0 \\ i\Delta_d & 0 & \varepsilon_d \end{bmatrix} \tag{2}$$

TM modes and TE modes are completely decoupled in the Voigt geometry [12]. The whole structure is placed along the z axis and in the background of air. z_N is the position of the front interface of the N-th structure period of 1DPC. The front interface of layer M is at z_0 ($z=0$). For TM modes, H field direction is along the y axis and the electric field direction is in the xz plane. The electromagnetic waves propagate in the xz plane. k_x is the x component of wave vector which keeps constant in layered structure. In any layer of the PC, the magnetic field is the sum of transmitted wave and reflected wave which can be written as

$$H(x,z) = H_0^+\exp[i(k_x x+k_{zj}z)]+H_0^-\exp[i(k_x x-k_{zj}z)] = H^+ + H^- \tag{3}$$

where "+" and "−" denote transmitted wave and reflected wave, respectively. Imposing the continuity of electromagnetic (EM) field at the interface between two layers j and i leads to

$$T_j\begin{bmatrix} H_j^+ \\ H_j^- \end{bmatrix} = T_i\begin{bmatrix} H_i^+ \\ H_i^- \end{bmatrix} \tag{4}$$

$$T_{j(i)} = \begin{bmatrix} 1 & 1 \\ -\frac{ik_x\Delta_{j(i)}}{\omega\varepsilon_0\varepsilon_{j(i)}\varepsilon'_{j(i)}}+\frac{k_{zj(i)}}{\omega\varepsilon_0\varepsilon'_{j(i)}} & -\frac{ik_x\Delta_{j(i)}}{\omega\varepsilon_0\varepsilon_{j(i)}\varepsilon'_{j(i)}}-\frac{k_{zj(i)}}{\omega\varepsilon_0\varepsilon'_{j(i)}} \end{bmatrix} \tag{5}$$

where $\varepsilon'_{j(i)}=(\varepsilon_{j(i)}^2-\Delta_{j(i)}^2)/\varepsilon_{j(i)}$ and $T_{j(i)}$ is called the dynamical matrix which guides the wave transmission through the interface. $k_{zj(i)}=\sqrt{(\omega^2/c^2)\varepsilon'_{j(i)}-k_x^2}$ is the z component of wave vector in layer j or i. For layers A, B and air, we just let $\Delta=0$ in all equations. Eq. (4) can be also written as

$$\begin{bmatrix} H_j^+ \\ H_j^- \end{bmatrix} = T_{ij}\begin{bmatrix} H_i^+ \\ H_i^- \end{bmatrix} \tag{6}$$

where $T_{ij}=T_j^{-1}T_i=\frac{1}{2N_j}\begin{bmatrix} N_j-M_j+(N_i+M_i) & N_j-M_j-(N_i-M_i) \\ N_j+M_j-(N_i+M_i) & N_j+M_j+(N_i-M_i) \end{bmatrix}$ and $M_{j(i)}=-(ik_x\Delta_{j(i)}/\varepsilon_{j(i)}\varepsilon'_{j(i)})$, $N_{j(i)}=k_{zj(i)}/\varepsilon'_{j(i)}$. Therefore, the magnetic field at two interfaces of a period z_N and z_{N+1} satisfies

$$\begin{bmatrix} H_{N+1}^+ \\ H_{N+1}^- \end{bmatrix} = T_{BA}P_BT_{AB}P_A\begin{bmatrix} H_N^+ \\ H_N^- \end{bmatrix} = T\begin{bmatrix} H_N^+ \\ H_N^- \end{bmatrix}\quad (T=T_{BA}P_BT_{AB}P_A), \tag{7}$$

where $P_{A(B)}=\begin{bmatrix} \exp(ik_{zA(B)}d_{A(B)}) & 0 \\ 0 & \exp(-ik_{zA(B)}d_{A(B)}) \end{bmatrix}$ accounts for the phase change within one layer. According to the Bloch theorem of periodic structure [12], the eigen vectors of T satisfy the relation

$$T\begin{pmatrix} H_N^+ \\ H_N^- \end{pmatrix} = e^{iKd}\begin{pmatrix} H_N^+ \\ H_N^- \end{pmatrix} \tag{8}$$

where K is Bloch wave vector and $d=d_A+d_B$ is the structure period. From Eq. (8), we obtain the eigen vector

$$X = \begin{bmatrix} 1 \\ \frac{e^{iKd}-T(1,1)}{T(1,2)} \end{bmatrix} \tag{9}$$

The magnetic field at any interface z_N should satisfy Eq. (9). According to Eqs. (4) and (6), at the interface between layers D and A we have

$$T_D\begin{bmatrix} H_D^+ \\ H_D^- \end{bmatrix} = T_A\begin{bmatrix} H_A^+ \\ H_A^- \end{bmatrix} = T_AX \tag{10}$$

The magnetic field at the front interface of layer D from the air side $\begin{bmatrix} H_0^+ \\ H_0^- \end{bmatrix}$ can be written as

$$\begin{bmatrix} H_0^+ \\ H_0^- \end{bmatrix} = T_{M0}P_MT_{DM}P_D\begin{bmatrix} H_D^+ \\ H_D^- \end{bmatrix} = T_{M0}P_MT_{DM}P_DT_{AD}X$$
$$\left(P_l=\begin{bmatrix} \exp(-i\delta_l) & 0 \\ 0 & \exp(i\delta_l) \end{bmatrix},\quad \delta_l=k_{zl}d_l,\quad l=\mathrm{M\ or\ D}\right) \tag{11}$$

To excite coupled resonance within layers M and D the EM waves must be evanescent within the air and the 1DPC. Thus the z component k_{z0} of wave vector $\mathbf{k_0}$ in the air must be an imaginary number written as $k_{z0}=i\sqrt{k_x^2-k_0^2}(k_0<k_x)$ and the wave in the air

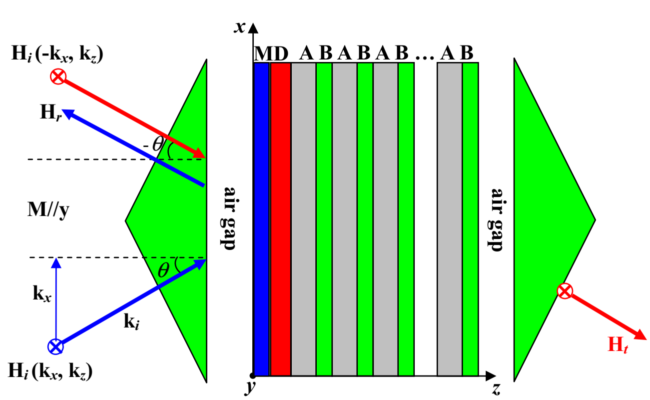

Fig. 1. Schematic of the coupled system denoted as MDABAB…AB. Layers M and D are noble metal and MO media, respectively. ABAB…AB is semi-finite one-dimensional PC composed of ordinary materials. Two green triangles are coupling prisms. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)