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Tunable unidirectional propagation based on magnetoplasmonic structure

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Abstract. Unidirectional light propagation is achieved by use of magnetoplasmonic structure comprising magneto-optical material and photonic crystal. The physical mechanism of unidirectional propagation is analysed. Graphene layers are inserted into the dielectric layers of photonic crystal. The effect of graphene chemical potential on transmission is investigated. Active control of unidirectional propagation is realized due to the introduction of graphene layers. The dependence of transmission on incident angle is also investigated.

1. Introduction

Magneto-optic (MO) effect is an effective way to break Lorentz reciprocity in optical systems, in which the optical properties of materials are altered by external magnetic field. MO effects have been utilized to obtain nonreciprocal optical devices such as optical isolators. In recent years, there is a high demand for the miniaturization of nonreciprocal optical devices. A promising approach is combining MO materials with plasmonic nanostructures.

Surface plasmon polaritons (SPPs) are surface wave propagating along the metal-dielectric interface [1, 2]. SPPs result from the coupling between light and free electron oscillation on the metal surface. Applying a static magnetic field on SPPs can break the time-reversal symmetry and gives rise to nonreciprocal surface magnetoplasmons (SMPs) [3, 4]. Tamm plasmon polaritons (TPPs) are a new kind of optical state which are generated at the boundary between the metal and the periodic dielectric structure [5]. TPPs was used to enhance light absorption [6, 7] and one-way TPPs in MO photonic crystal-metal oxides structure was proposed [8].

In this paper, hybrid magnetoplasmonic structure is proposed to realize unidirectional light propagation. The structure consists of a magnetic semiconductor and photonic crystal (PC). Magnetic Tamm plasmon polaritons (MTPPs) are excited by applied magnetic field. Graphene has remarkable properties, especially its chemical potential can be dynamically tuned by varying gate voltage [9]. As a result, its optical response is gate-voltage dependent, which provides a possible platform for tunable plasmonic devices [10]. We insert graphene layers into the dielectric layers of PC to explore the dynamical property of device.

2. Structure and method

Figure 1 shows the schematic of hybrid magnetoplasmonic structure. Dielectric layers ε_1 and ε_2 are periodically arranged. Graphene layers are embedded between dielectric layers. The yellow part is magneto-optical semiconductor layer, which is coated on the surface of the 1D PC. The light propagates along z-axis. The +z and -z refer to forward and backward propagation, respectively. θ is the incident angle.
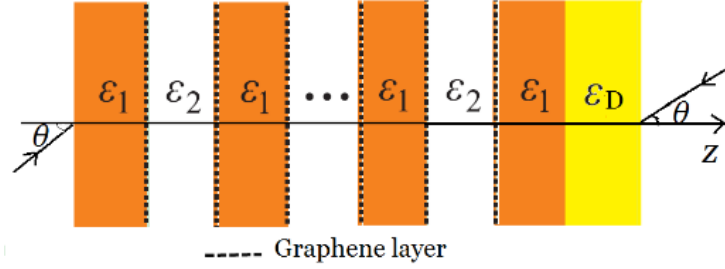
Figure 1. Schematic of the structure. Graphene layers are inserted into dielectric layers. θ is the incident angle.

The refractive index of dielectric layer is n_1=2.25 and n_2=1.46. The thickness d_1= d_2=1.45μm. The chemical potential of graphene is 0.2eV. The magneto-optical semiconductor is InSb and its thickness d_D=1.5μm. The dielectric tensor of InSb is expressed as [11]

$$\varepsilon_s \approx \varepsilon_\infty \begin{bmatrix} \varepsilon_D & i\Delta_D & 0 \\ -i\Delta_D & \varepsilon_D & 0 \\ 0 & 0 & \varepsilon_{zz} \end{bmatrix} \tag{1}$$

$$\varepsilon_D = 1 - \frac{\omega_p^2(1+\frac{i}{\omega\tau})}{(\omega+\frac{i}{\tau})^2 - \omega_c^2}, \quad \Delta_D = \frac{\omega_c\omega_p^2}{\omega((\omega+\frac{i}{\tau})^2 - \omega_c^2)}, \quad \varepsilon_{zz} = 1 - \frac{\omega_p^2}{\omega(\omega+\frac{i}{\tau})}. \tag{2}$$

where ω is the angular frequency, ω_p is the plasma frequency, ω_c is the electron cyclotron frequency. $\omega_c = eB_0/m^*$, where e and m^* are, respectively, the charge and effective mass of the electron. B is the external magnetic field. ε_∞=15.68. τ is related to the loss. It is seen that when B=0, Δ_D=0. Δ_D is determined by external magnetic field B.

Transmission spectrum is investigated by transfer matrix method [12]. Transmitted wave, reflected wave and incident waves are connected by the transfer matrix M'. The transmission T for TM polarization is expressed as:

$$T = \left| \frac{H_{out}^+}{H_{in}^+} \right|^2 = \left| \frac{1}{M'(1,1)} \right|^2 \tag{3}$$

where $M' = T_O^{-1}MT_O$. And $M=(M_1M_GM_2M_GM_1)^n M_D$, n is the period number of PC. M_i denotes the transfer matrix for ith layer. $M_i = T_i P_i^{-1} T_i^{-1}$.

For dielectric layers:

$$T_i = \begin{bmatrix} 1 & 1 \\ \dfrac{k_{zi}}{\omega\varepsilon_0\varepsilon_i} & -\dfrac{k_{zi}}{\omega\varepsilon_0\varepsilon_i} \end{bmatrix} (i=1, 2) \tag{4}$$

The matrix T_o for background dielectric can be obtained by Eq. (4).

For MO material:

$$T_D = \begin{bmatrix} 1 & 1 \\ -\dfrac{ik_x\Delta_D}{\omega\varepsilon_0\varepsilon_D\varepsilon_D'} + \dfrac{k_{zD}}{\omega\varepsilon_0\varepsilon_D'} & -\dfrac{ik_x\Delta_D}{\omega\varepsilon_0\varepsilon_D\varepsilon_D'} - \dfrac{k_{zD}}{\omega\varepsilon_0\varepsilon_D'} \end{bmatrix} \tag{5}$$

where $\varepsilon_D^{'} = (\varepsilon_D^2 - \Delta_D^2)/\varepsilon_D$, and k_x is the x component of the wave vector.

Matrix P_i discribes the phase change in ith layer. $\mathbf{P}_i = \begin{bmatrix} e^{ik_{zi}d_i} & 0 \\ 0 & e^{-ik_{zi}d_i} \end{bmatrix}$, k_{zi} is the z component of the

wave vector. The transfer matrix for graphene is given by $\mathbf{M}_G = \begin{bmatrix} 1 & \sigma_G \\ 0 & 1 \end{bmatrix}$. The conductivity σ_G is given

by Kubo formula [13]:

$$\sigma_G^{intra}(\omega) = \frac{e^2}{4\eta}\frac{i}{2\pi}\left\{ \frac{16k_BT}{\eta\omega}\ln(2\cosh(\frac{\mu_c}{2k_BT})) \right\}$$

$$\sigma_G^{inter}(\omega) = \frac{e^2}{4\eta}\left\{ \frac{1}{2} + \frac{1}{\pi}\arctan\frac{\eta\omega-2\mu_c}{2k_BT} - \frac{i}{2\pi}\ln\frac{(\eta\omega+2\mu_c)^2}{(\eta\omega-2\mu_c)^2+(2k_BT)^2} \right\}$$

(6)

The chemical potential μ_c of graphene can be controlled by the gate voltage.

The effective admittance-matching theory is used to explain the unidirectional phenomenon [14]. Based on this theory, the frequencies of excited surface MTPPs are determined. The effective optical admittance of PC is described as:

$$\eta_{PC} = \frac{M_{PC}(1,1)\eta_0 + M_{PC}(1,2)}{M_{PC}(2,1)\eta_0 + M_{PC}(2,2)}$$
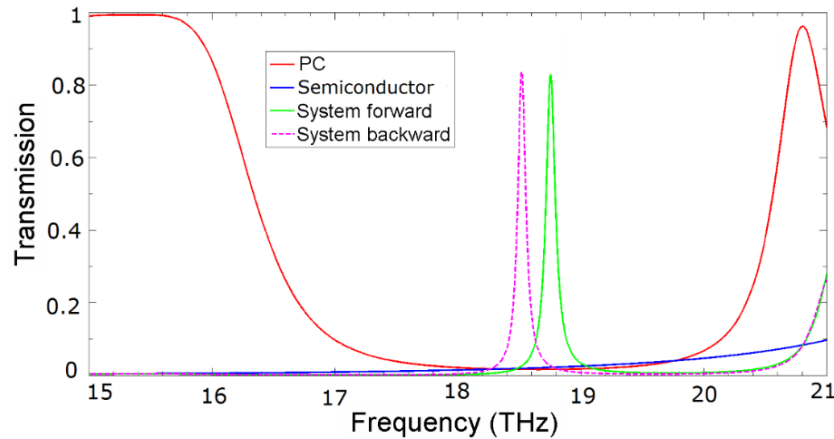
(7)

The optical admittance of semiconductor is given by

$$\eta_D^{\pm} = -\eta_0 \frac{\varepsilon_D^{'}\omega\varepsilon_D}{\pm i\Delta_D ck_x - \varepsilon_D\sqrt{\varepsilon_D^{'}\omega^2 - c^2k_x^2}}$$

(8)

The condition of supporting the surface mode at PC-semiconductor boundary is expressed as:

$$\Delta\eta = \left|\text{Re}(\eta_{PC}) - \text{Re}(\eta_D)\right| + \left|\text{Im}(\eta_{PC}) + \text{Im}(\eta_D)\right|$$

(9)

The ideal admittance-matching corresponds to $\Delta\eta=0$, in this case MTPPs will be excited and unidirectional propagation can be observed.

3. Results

Figure 2. Transmission spectra of individual PC, individual semiconductor and whole structure under applied external magnetic field.

Figure 2 shows the obtained transmission spectrum. External magnetic field B is 4T. For individual PC and semiconductor, the forward and backward transmission spectra are the same. However, for the whole structure there are two peaks in the bandgap, as shown by green and pink curves. The

frequencies of excited MTPPs for forward and backward are different. At 18.76THz, the forward light has high transmittance, which means forward light can pass through the structure. Because of the low transmittance, the backward light is prohibited. At 18.52THz, the forward propagation is prohibited while backward propagation is permitted. Unidirectional light propagation are achieved. It is known from Eq. (1) and (2) when external magnetic field is applied, the dielectric function of semiconductors becomes a nonreciprocal tensor. The unidirectional propagation phenomenon results from the symmetry broken.
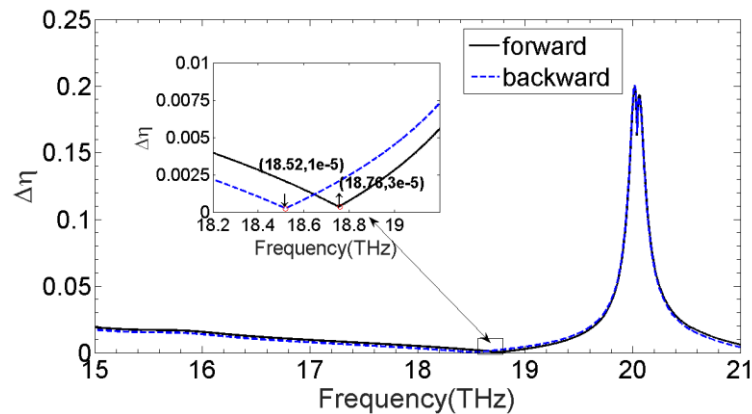

Figure 3. Dependence of $\Delta\eta$ on wavelength for forward and backward incident waves.

To analyze the unidirectional propagation, the admittance of the MTPP is presented. Figure 3 shows the admittance mismatch $\Delta\eta$ as a function of wavelength. The inset shows the enlarged zone. $\Delta\eta=0$ means ideal admittance-matching. It is seen for the forward incident wave, $\Delta\eta$ reaches to a minimum at 18.76THz. The minimum of $\Delta\eta$ is as low as $1e^{-5}$, which means a good admittance matching. Therefore MTPPs are excited and forward incident wave can pass through the structure. However, $\Delta\eta$ is not the minimum for backward wave at this frequency. Low transmission occurs owing to the admittance mismatching. Nevertheless, $\Delta\eta$ reaches to a minimum at 18.52THz for backward incident wave. Good admittance matching leads to high transmission peak. The peak frequencies predicted by the effective admittance-matching theory agree well with those extracted from the transmission spectrum.
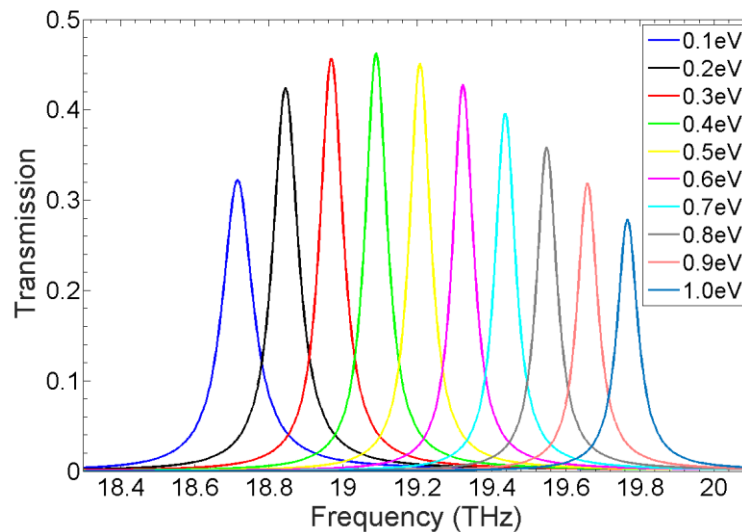
Figure 4. Transmission spectra at different chemical potential of graphene μ_c.

The influence of chemical potential μ_c is investigated. Figure 4 shows the transmission spectra at different chemical potential of graphene. With the increase of μ_c, the transmission peaks have a blue shift. The transmittance increases at first and then decreases. It is seen dynamical tuning is obtained by changing chemical potential of graphene. Because the chemical potential is dependent on the applied gate voltage, the tuning function is easily obtained by gate voltage instead of changing the geometric structure.
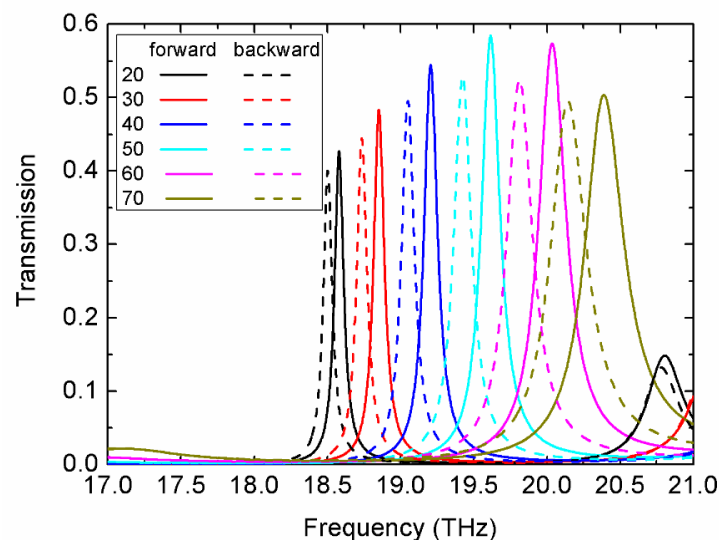
Figure 5. Transmission spectra at different incident angles for forward and backward incident waves.

The dependence of transmission on incident angle are also investigated. Figure 5 shows the transmission spectra at different incident angle. External magnetic field B is 2T. The transmission peaks shift to high frequency with the increase of θ. Likewise, the transmittance increase at first and then decrease. Thus one can tune the unidirectional frequency by flexibly modifying the incident angle.

4. Conclusions

Unidirectional light propagation is achieved by a hybrid magnetoplasmonic structure. The admittance-matching theory is presented to understand the physical mechanism of unidirectional propagation. The dynamical control on transmission is obtained by changing graphene chemical potential. The unidirectional propagation can be tuned by modifying incident angle. Our results provide a way to design the tunable nonreciprocal devices.

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