Surface plasmon polaritons in subwavelength semiconductor-dielectric periodic structure in an external magnetic field

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Abstract

The problem of the surface wave's existence in a subwavelength periodic semiconductor-dielectric structure is studied theoretically. The interface of such structure and semi-infinite isotropic media is considered. The dispersion equation is derived for the surface waves under consideration. The influence of artificial anisotropy on excitation of surface waves is theoretically investigated.

1. Introduction

The recent advent of artificial electromagnetic materials (metamaterials) has opened new opportunities for engineering the media, which could provide additional control over the properties of propagating waves. Since spectral properties of periodic semiconductor materials depend on the external magnetic field, prospects of their practical application become wider. The periodic structures with magnetic and nonmagnetic layers may be promising for obtaining magnetic systems in semiconductor electronics and spintronics [1].

Surface plasmon polaritons are well known to play a key role in a wide spectrum of science, ranging from physics and materials science to biology. Surface waves can be tentatively divided into two classes. The first of them represents surface waves at the interface of medium with opposite signs of dielectric permittivities (or magnetic permeabilities) and strong frequency dispersion. This type of surface waves takes place near to resonant frequencies [2]. Second class of surface waves appears owing to anisotropy of contacting materials. They are called singular surface waves. Unlike surface waves of the first class, singular surface waves can be excited in bianisotropic materials with positive definite dielectric permittivity and magnetic permeability tensors and when dispersion is little [3]. Surface plasmon polaritons can serve as a basis for the design, fabrication and characterization of subwavelength waveguide components, modulators and switches, to name but a few [4].

In this paper, we consider a surface electromagnetic waves localized at an interface between two medium. The first medium is the subwavelength periodic structure and the second medium is vacuum with dielectric constant $\varepsilon_v = 1$.

2. Geometry of the problem. Dispersion equation

Let us consider the subwavelength periodic structure that consists of alternate semiconductor layers of thickness d_1 and dielectric layers of thickness d_2. We introduce a coordinates system such that the x-axis is parallel to the boundaries of the layers and z-axis is perpendicular to the layers. Let the structure be placed into an external magnetic field H_0 along y-axis. The incident, reflected and transmitted wave vectors lie in the xz plane. We assume that the structure is homogeneous in the x and y directions and put $\partial/\partial y = 0$. We consider such structure in the case when the period of the structure is much less than the wavelength. It has been shown that such structure represents the biaxial crystal with the effective components of permittivity, which depend as on physical parameters of the structure (plasma frequency, magnitude of the external magnetic field) and on geometrical (ratio of thickness of the layers, period of the structure)

$$\varepsilon_{xx} = \frac{\varepsilon_f d_1 + \varepsilon_d d_2}{d},\ \varepsilon_{yy} = \frac{\varepsilon_2 d_1 + \varepsilon_d d_2}{d},\ \varepsilon_{zz} = \frac{\varepsilon_{xx} d^2}{\varepsilon_{xx} d\left(\frac{d_2}{\varepsilon_d} + \frac{d_1}{\varepsilon_f}\right) + \frac{\left(\varepsilon_{xz}^p\right)^2 \varepsilon_d d_1 d_2}{\left(\varepsilon_{xx}^p\right)^2 \varepsilon_f}}, \tag{1}$$

here $d = d_1 + d_2$ is the period of the structure; ε_f and ε_d is the permittivity of the semiconductor and dielectric layers respectively; ε_{xx}^p and ε_{xz}^p is the components of semiconductor permittivity tensor. In the case under consideration the dispersion equation for surface waves takes next form

$$k_x^2 = \left(\frac{\omega}{c}\right)^2 \chi_x^2 = \left(\frac{\omega}{c}\right)^2 \frac{\varepsilon_{zz}\varepsilon_{\mathrm{v}}\left(\varepsilon_{xx} - \varepsilon_{\mathrm{v}}\right)}{\varepsilon_{zz}\varepsilon_{xx} - \varepsilon_{\mathrm{v}}^2}, \tag{2}$$

here χ_x is the surface waves refractive index.

Thus, a necessary condition of surface waves existence is negativity of ε_{xx}, whereas for ε_{zz} two variants are possible [2]. The first is a weak anisotropy ($\varepsilon_{zz} < 0$) when surface waves can propagate if $\varepsilon_{zz}\varepsilon_{xx} > \varepsilon_{\mathrm{v}}^2$; the second is a strong anisotropy ($\varepsilon_{zz} > 0$) when surface waves exist at $\varepsilon_{zz} > \varepsilon_{\mathrm{v}}$. According to the features of the fine-stratified structure and effective components of permittivity, efficient control of surface waves existence areas by the means of an external magnetic field, frequency and thickness of layers is possible. Fig. 1 presents the dispersion equation as a function of frequency (H_0 = 10 kOe) and magnetic field ($\omega = 6 \cdot 10^{12}$ s^{-1}) together with the light line $k_{\mathrm{sv}} = \omega/c$. The calculations was performed for the structure where: the first layer is semiconductor n-GaAs with $\varepsilon_0 = 13.2$ (here ε_0 is the part of the permittivity attributed to the lattice), d_1 = 500 nm, $\omega_{\mathrm{P}} = 5.3 \cdot 10^{12}$ s^{-1} (plasma frequency); the second layer is dielectric SiO$_2$ with $\varepsilon_{\mathrm{d}} = 4.0$, d_2 = 500 nm. The collision frequency $\nu = 0$, thereby we neglected the losses in the structure.

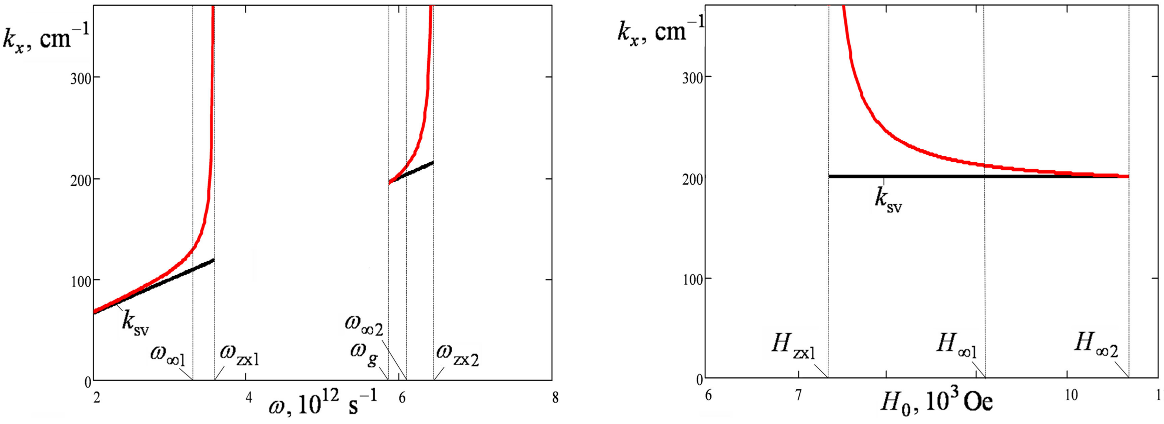

Fig. 1: Surface wave vector as a function of frequency (ω) and magnetic field (H_0).

At frequencies $\omega_{\infty 1}$, $\omega_{\infty 2}$, ω_g and at magnetic fields $H_{\infty 1,2}$, the components of permittivity ε_{xx} and ε_{zz} tend to infinity; for $\omega_{zx1,2}$ and H_{zx1}, the condition $\varepsilon_{zz}\,\varepsilon_{xx} = \varepsilon_v^2$ is satisfied. We also can notice, that the weak anisotropy take place in the value ranges $\omega_{\infty 1} < \omega < \omega_{zx1}$, $\omega_{\infty 2} < \omega < \omega_{zx2}$ and $H_{zx1} < H_0 < H_{\infty 1}$, whereas strong anisotropy occur in the areas $\omega < \omega_{\infty 1}$, $\omega_g < \omega < \omega_{\infty 2}$ and $H_{\infty 1} < H_0 < H_{\infty 2}$. When the losses in the structure is taken into account, the surface waves refractive index is a complex value, imaginary part of which determine an absorption coefficient α of surface waves. The inverse variable to the absorption coefficient is a free length of surface waves L:

$$L = 1/\alpha = c/2\omega\chi_x'' \,. \tag{3}$$

Fig. 2 shows the free length of surface waves as a function of frequency and external magnetic field. The curve 1 is for $\nu = 6\cdot 10^{10}$ s^{-1}; the curve 2 is for $\nu = 2\cdot 10^{11}$ s^{-1}; the curve 3 is for $\nu = 9\cdot 10^{11}$ s^{-1}.

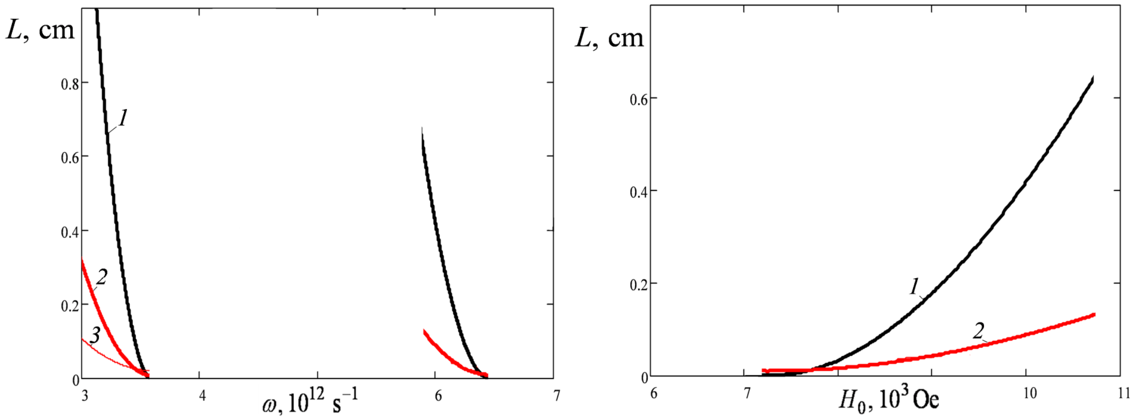

Fig. 2: Free length of surface waves versus frequency (ω) and magnetic field (H_0).

It can be clearly seen that, the free length of surface waves gets high values at the low frequencies and in the neighborhood of gyrotropic frequency ω_g and magnetic field $H_{\infty 2}$. On the contrary, the free length is minimum on the borders of areas of surface waves existence at $\omega \to \omega_{zx1,2}$ and $H_0 \to H_{zx1}$. Thus, the presence of losses in the structure results in restriction of free length of surface waves. Moreover, at high magnitudes of collision frequency one of the surface waves existence areas is degenerated due to peculiarity of the considered structure.

3. Conclusion

To sum up, we studied theoretically excitation of surface plasmons in the subwavelength periodic structure. We have shown that the peculiarities of the effective components of permittivity allow operating effectively parameters of the surface plasmons in such structure. The results of our investigations can be used in the implementation of the variety of microwave and optical devices, for the analysis of various kinds of photon crystals.

References

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