Surface Modes of Polar Semiconductor in Unidirectional Magnetic Field

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Abstract— Surface plasmon polaritons on the surfaces of metal films possess interesting properties. Surface plasmon polariton has the dispersion relation and is a plane propagating surface mode. In contrast, localized surface plasmons (also called electromagnetic surface shape resonances) are confined to curved metal objects. They are characterized by discrete, complex frequencies, which depend on the size and shape of the object to which the surface plasmon is confined, and by its dielectric function. Localized surface plasmons can be resonantly excited with light of appropriate frequency (and polarization) irrespective of the wave vector of the exciting light The idea of two-dimensional surface polariton optics has been proposed and realized experimentally, resulting in the development of optical elements for surface polaritons that allow manipulating and directing SPP beams in the same way as optical beams are directed in three dimensions. Different types of SPP behaviour on rough surfaces, such as scattering, reflection, interference, backscattering, and localization is analyzed, and related theoretical models are presented. Here in this work there is theoretical study of surface excitation in presence of magnetic field on different compounds and results thus obtained is of great application to current world technologies.

Key words: Semiconductor, Unidirectional Magnetic Field

I. INTRODUCTION

In its simplest form a surface plasmon polariton (SPP) is an electromagnetic excitation that propagates in a wave like fashion along the planar interface between a metal and a dielectric medium, often vacuum, and whose amplitude decays exponentially with increasing distance into each medium from the interface [1–3].

Thus, a SPP is a surface electromagnetic wave, whose electromagnetic field is confined to the near vicinity of the dielectric–metal interface. This confinement leads to an enhancement of the electromagnetic field at the interface, resulting in an extraordinary sensitivity of SPPs to surface conditions. This sensitivity is extensively used for studying adsorbents on a surface, surface roughness, and related phenomena. Surface plasmon polariton-based devices exploiting this sensitivity are widely used in chemo- and bio-sensors [4]. The enhancement of the electromagnetic field at the interface is responsible for surface-enhanced optical phenomena such as Raman scattering, second harmonic generation (SHG), fluorescence, etc. [1,5].

The intrinsically two-dimensional nature of SPPs provides significant flexibility in engineering SPP based all-optical integrated circuits needed for optical communications and optical computing [6,7]. The relative ease of manipulating SPPs on a surface opens an opportunity for their application to photonics and optoelectronics for scaling down optical and electronic devices to nanometric dimensions. Most importantly, active photonic elements based on nonlinear surface plasmon polariton optics, which allow controlling optical properties with light, are much easier to realize with suitably patterned metal surfaces, due to the SPP-related electromagnetic field enhancement near a metal surface [7].

II. DERIVING EXPRESSION FOR COUPLING

If the bounding medium is ε_B then from the dispersion relation of three mode coupling we get

$$\left[\left(\bar{\varepsilon}(k\omega)-\left(\frac{\varepsilon_\infty(k\omega)\Omega^2-\varepsilon_0(k\omega)\frac{\omega_t^2}{\omega_p^2}}{\Omega^2-\frac{\omega_t^2}{\omega_p^2}}\right)\right)\right]\left(RZ_l(\delta kR)\right)' y_l(\alpha kR)$$
$$+\varepsilon_B(k\omega)\Omega^2(Ry_l(\alpha kR))'Z_l(\delta kR)-l^2X_l(\gamma kR)Z_l(\delta kR)\times$$
$$\left[\bar{\varepsilon}(k\omega)\varepsilon_B(k\omega)\right]=0 \tag{1}$$

$$RX_l'(\gamma kr)\left[\varepsilon_\infty(k\omega)\Omega^2-\varepsilon_0(k\omega)\frac{\omega_t^2}{\omega_p^2}\right]\times$$
$$\bar{\varepsilon}(k\omega)\left[\Omega^2-\frac{\omega_t^2}{\omega_p^2}-\left(\varepsilon_\infty(k\omega)\Omega^2\right)-\varepsilon_0(k\omega)\frac{\omega_t^2}{\omega_p^2}\Omega^2\right]\times$$
$$y_l(\alpha kR).(RZ_l(\delta kR))'+\left(\Omega^2-\frac{\omega_t^2}{\omega_p^2}\right)\Omega^2\varepsilon_B\left[(Ry_l(\alpha kR))'Z_l(\delta kR)\right]$$
$$-\left(\Omega^2-\frac{\omega_t^2}{\omega_p^2}\right)l^2\bar{\varepsilon}(k\omega)\varepsilon_B(k\omega)X_l(\gamma kR)y_l(\alpha kR).Z_l(\delta kR)=0 \tag{2}$$

On substituting the values of ε_B and ε_1 in eqn. (2) we get

$$\varepsilon_B=\varepsilon_1-\bar{\varepsilon}\frac{\omega_p^2}{\omega^2-\omega_c^2}$$
$$\varepsilon_1=\frac{\varepsilon_\infty\omega^2-\varepsilon_0\omega_t^2}{\omega^2-\omega_t^2} \tag{3}$$

$$\Omega^8\left[\left(\varepsilon_\infty-\varepsilon_\infty^2-\varepsilon_0\varepsilon_\infty\frac{\omega_t^2}{\omega_p^2}-\varepsilon_0\frac{\omega_t^2}{\omega_p^2}\right)-RX_l'(\gamma kR)y(\alpha kR)(RZ_l(\delta kR))'+\varepsilon_\infty\left(Ry_l(\alpha kR)\right)'Z_l(\delta kR)\right]$$
$$+\Omega^6\left[\begin{array}{l}\left\{\begin{array}{l}\left(\varepsilon_\infty\frac{\omega_c^2}{\omega_p^2}-2\varepsilon_\infty\frac{\omega_t^2}{\omega_p^2}+\varepsilon_\infty^2\frac{\omega_c^2}{\omega_p^2}+\varepsilon_\infty^2\frac{\omega_t^2}{\omega_p^2}+\varepsilon_0\frac{\omega_c^2}{\omega_p^2}.\frac{\omega_t^2}{\omega_p^2}(\varepsilon_\infty+1)+\right)\\+\varepsilon_0\left(\frac{\omega_t^2}{\omega_p^2}\right)^2\left(\varepsilon_\infty+1+\varepsilon_0\right)\end{array}\right\}RX_l'(\gamma kR)y(\alpha kR)(RZ_l(\delta kR))'\\+\left\{\left(\varepsilon_\infty\frac{\omega_c^2}{\omega_p^2}-\varepsilon_0\frac{\omega_t^2}{\omega_p^2}-\bar{\varepsilon}\right)\right\}\left(Ry_l(\alpha kR)\right)'RZ_l(\delta kR)\\+\left\{\varepsilon_\infty l^2\bar{\varepsilon}X_l'(\gamma kR)y_l(\alpha kR)Z_l(\delta kR)\right\}\end{array}\right]$$

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$$
\left[\begin{array}{l}
\left\{\begin{array}{l}\dfrac{\omega_c^2}{\omega_p^2}.\dfrac{\omega_t^2}{\omega_p^2}(\varepsilon_0+\varepsilon_\infty-2\varepsilon_0^2)+\left(\dfrac{\omega_t^2}{\omega_p^2}\right)^2\left(\varepsilon_\infty-\varepsilon_0\varepsilon_\infty\dfrac{\omega_c^2}{\omega_p^2}-\dfrac{\varepsilon_0\omega_c^2}{\omega_p^2}-\dfrac{\varepsilon_0\omega_t^2}{\omega_p^2}-\varepsilon_0^2\right)\\ +\dfrac{\omega_t^2}{\omega_p^2}(\varepsilon_0+\varepsilon_0\varepsilon_\infty)\end{array}\right\} y(\alpha kR)(RZ_l(\delta kR))' \\
+\left\{\left(\varepsilon_\infty\dfrac{\omega_c^2}{\omega_p^2}\dfrac{\omega_t^2}{\omega_p^2}-\bar{\varepsilon}\dfrac{\omega_c^2}{\omega_p^2}-\varepsilon_\infty\dfrac{\omega_t^2}{\omega_p^2}\right)\right\}\left(Ry_l(\alpha kR)\right)' Z_l(\delta kR) \\
+\left\{(-\varepsilon_\infty\dfrac{\omega_c^2}{\omega_p^2}-\varepsilon_0\dfrac{\omega_t^2}{\omega_p^2}-\bar{\varepsilon}-\varepsilon_\infty\dfrac{\omega_t^2}{\omega_p^2})\right\} l^2\bar{\varepsilon}X_l(\gamma kR)y_l(\alpha kR)Z_l(\delta kR)
\end{array}\right]
$$

$$
+\Omega^4\left[\begin{array}{l}
+\left\{\dfrac{\omega_c^2}{\omega_p^2}\dfrac{\omega_t^2}{\omega_p^2}\left(-\varepsilon_\infty\dfrac{\omega_t^2}{\omega_p^2}-\varepsilon_0\dfrac{\omega_t^2}{\omega_p^2}-\varepsilon_0\varepsilon_\infty\right)+\left(\dfrac{\omega_t^2}{\omega_p^2}\right)^2\left(\dfrac{\omega_c^2}{\omega_p^2}\varepsilon_0-\varepsilon_0\varepsilon_\infty\right)\right\} y_l(\alpha kR)RZ_l(\delta kR)' \\
+\left\{\varepsilon_\infty\dfrac{\omega_c^2}{\omega_p^2}\dfrac{\omega_t^2}{\omega_p^2}+\varepsilon_0\left(\dfrac{\omega_t^2}{\omega_p^2}\right)^2+\bar{\varepsilon}\dfrac{\omega_t^2}{\omega_p^2})\right\} Ry_l(\alpha kR)' Z_l(\delta kR) \\
+\left\{\varepsilon_0\dfrac{\omega_c^2}{\omega_p^2}\dfrac{\omega_t^2}{\omega_p^2}+\bar{\varepsilon}\dfrac{\omega_c^2}{\omega_p^2}+\varepsilon_\infty\dfrac{\omega_c^2}{\omega_p^2}\dfrac{\omega_t^2}{\omega_p^2}+\varepsilon_0\left(\dfrac{\omega_t^2}{\omega_p^2}\right)^2+\bar{\varepsilon}\dfrac{\omega_t^2}{\omega_p^2}\right\} l^2\bar{\varepsilon}X_l(\gamma kR)y_l(\alpha kR)' Z_l(\delta kR)
\end{array}\right]
$$

$$
+\Omega^2\left[\begin{array}{l}
\left\{\varepsilon_0\left(\dfrac{\omega_t^2}{\omega_p^2}\right)^3\dfrac{\omega_c^2}{\omega_p^2}+\varepsilon_0\varepsilon_\infty\dfrac{\omega_c^2}{\omega_p^2}\dfrac{\omega_t^2}{\omega_p^2}\right\} y_l(\alpha kR)RZ_l(\delta kR)' \\
+\left\{\varepsilon_0\left(\dfrac{\omega_c^2}{\omega_p^2}\right)^2\left(\dfrac{\omega_t^2}{\omega_p^2}\right)-\bar{\varepsilon}\left(\dfrac{\omega_c^2}{\omega_p^2}\right)\dfrac{\omega_t^2}{\omega_p^2}\right\} Ry_l(\alpha kR)' RZ_l(\delta kR)' \\
+\left\{-\varepsilon_0\dfrac{\omega_c^2}{\omega_p^2}\left(\dfrac{\omega_t^2}{\omega_p^2}\right)^2-\bar{\varepsilon}\dfrac{\omega_c^2}{\omega_p^2}\dfrac{\omega_t^2}{\omega_p^2}\right\} l^2\bar{\varepsilon}X_l(\gamma kR)y_l(\alpha kR)Z_l(\delta kR)
\end{array}\right]
$$

(4)

Or

$$A\Omega^8+B\Omega^6+C\Omega^4+D\Omega^2+E=0 \quad (5)$$

Now consider R is very small and X_l, Y_l and Z_l →0,
Simplifying above equation (5) becomes

$$\Omega^4+\frac{D}{C}\Omega^2+\frac{E}{C}=0 \quad (6)$$

And after putting the value of A,B,C D and E in Eqn. (5) we get.

$$\Omega^4-\left(\frac{\varepsilon_0\omega_t^2+\omega_P^2}{\varepsilon_\infty}+\omega_c^2\right)\Omega^2+\left(\frac{\varepsilon_0\omega_c^2+\omega_P^2}{\varepsilon_\infty}\right)\omega_t^2=0$$

(7)

We find that above equation is quadratic in Ω^2 we have already said that ω_t^2 are the roots of equation (7) $\varepsilon_{z2}=0$. This gives the condition for the existence of surface mode i.e. the above eqn. gives:-

$$\omega_\pm^2=1/2\left[\frac{\varepsilon_0\omega_t^2+\omega_P^2}{\varepsilon_\infty}+\omega_c^2\right]\pm\left[\left\{\left(\frac{\varepsilon_\infty\omega_t^2+\omega_P^2}{\varepsilon_\infty}\right)+\omega_c^2\right\}-4\left(\frac{\varepsilon_0\omega_c^2+\omega_P^2}{\varepsilon_\infty}\omega_t^2\right)\right]^{1/2}$$

(8)

Dividing above equation by ω_t^2, we get

$$X_\pm^2=1/2\left[\frac{\varepsilon_0+\left(\omega_P/\omega_t\right)^2)}{\varepsilon_\infty}+\frac{\omega_c^2}{\omega_t^2}\right]\pm\frac{1}{2}\left\{\left(\frac{\varepsilon_0+(\omega_P/\omega_t)^2}{\varepsilon_\infty}\right)+\left(\frac{\omega_c}{\omega_t}\right)^2\right\}^2+4\left(\frac{\varepsilon_0(\omega_c/\omega_t)^2+(\omega_P/\omega_t)^2}{\varepsilon_\infty}\right)^{1/2}$$

(9)

Now let us assume that

$$X=\omega/\omega_t,\quad \omega_+/\omega_t=X_+ \quad\text{and}\quad \omega_-/\omega_t=X_- \quad (10)$$

Now when d.c. magnetic field is applied in x direction on the polar semiconductor of cylindrical surface, under condition R→∞, then the Voigt constant be given by-

$$\varepsilon_V=\frac{\varepsilon_{zz}^2+\varepsilon_{zy}^2}{\varepsilon_{zz}} \quad (10)$$

Now

$$\varepsilon_{zz}=\frac{\varepsilon_\infty\left(X^2-X_+^2\right)\left(X^2-X_-^2\right)}{\left(X^2-1\right)\left(X^2-\omega_c^2/\omega_t^2\right)} \quad (11)$$

$$\varepsilon_{yz}=\frac{\left(\omega_c/\omega_t\right)^2}{X^2}\left[\frac{\left(\omega_p/\omega_t\right)^4}{\left[X^2-\left(\omega_c/\omega_t\right)^2\right]^2}\right] \quad (12)$$

With the help of (11) and (12) and eqn. (10) we get-

$$\left(\varepsilon_V X^2\right)=\frac{1}{\left[X^2-\left(\dfrac{\omega_c}{\omega_t}\right)^2\right]}\left[\frac{\varepsilon_\infty\left(X^2-X_+^2\right)\left(X^2-X_-^2\right)X^2}{\left(X^2-1\right)}-\frac{\left(X^2-1\right)\left(\omega_c/\omega_t\right)^2\left(\omega_P/\omega_t\right)^2}{\varepsilon_\infty\left(X^2-X_+^2\right)\left(X^2-X_-^2\right)}\right]$$

(13)

Now consider following compounds to study the properties with help of eqn (13)

$$X_\pm^2=\frac{1}{2}\left[\frac{\varepsilon_0+\left(\omega_P/\omega_t)^2\right)}{\varepsilon_\infty}+\frac{\omega_c^2}{\omega_t^2}\right]\pm\frac{1}{2}\left\{\left(\frac{\varepsilon_0+(\omega_P/\omega_t)^2}{\varepsilon_\infty}\right)+\left(\frac{\omega_c}{\omega_t}\right)^2\right\}^2-4\left(\frac{\varepsilon_0(\omega_c/\omega_t)^2+(\omega_P/\omega_t)^2}{\varepsilon_\infty}\right)^{1/2}$$

(14)

Element	X+	X-
GaP	1.39033	0.588259
GaAs	1.203685299	0.900634
InSb	1.258305	0.909353
InAs	1.390054	0.911011
InP	1.538900051	0.916581

Table 1: elements

With the help of the above equations and datas, graphs between $\varepsilon_V X^2$ and X (that is, between $\varepsilon_V(\omega/\omega_T)^2$ and ω/ω_T) for all the five semiconductors Vs InAs, GaP, InP, GaAs and InSb $\varepsilon_V(\omega/\omega_T)^2$ is plotted Verses ω/ω_T using the Equation

$$\varepsilon_V X^2=\frac{1}{X^2-\left(\omega_c/\omega_T\right)^2}\left[\frac{\varepsilon_\infty\left(X^2-X_+^2\right)\left(X^2-X_-^2\right)X^2}{X^2-1}-\frac{\left(X^2-1\right)\left(\omega_c/\omega_T\right)^2\left(\omega_p/\omega_T\right)^2}{\varepsilon_\infty\left(X^2-X_+^2\right)\left(X^2-X_-^2\right)}\right]$$

Where X= ω/ω_T

$$X_\pm^2=\frac{1}{2}\left[\frac{\varepsilon_0+\left(\omega_p/\omega_m\right)^2}{\varepsilon_\infty}+\frac{\omega_c^2}{\omega_T^2}\right]+\left[\left\{\frac{\varepsilon_0+\left(\omega_p/\omega_m\right)^2}{\varepsilon_\infty}+\frac{\omega_c^2}{\omega_T^2}\right\}^2-\frac{\varepsilon_0\left(\omega_c/\omega_T\right)^2+\left(\omega_p/\omega_T\right)^2}{\varepsilon_\infty}\right]^{1/2}$$

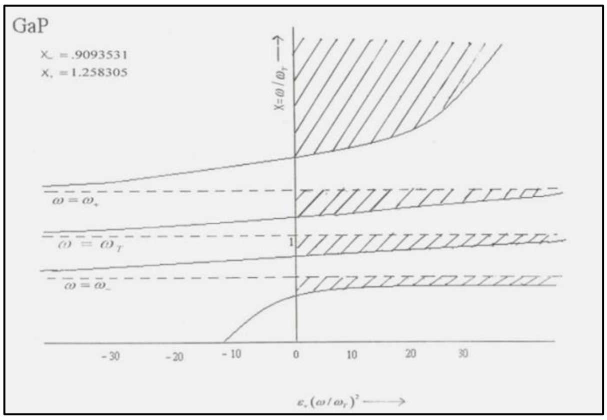

Fig. 1:

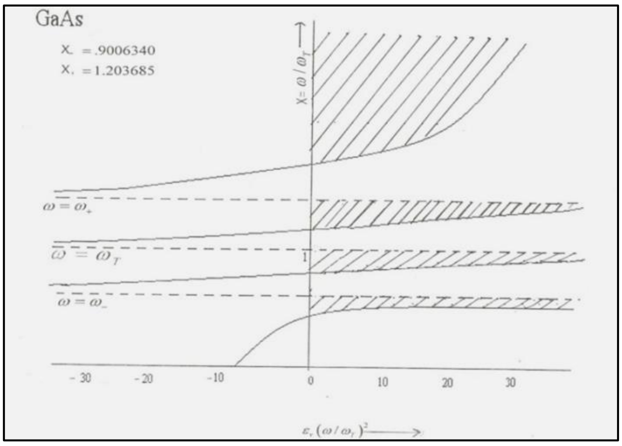

Fig. 2:

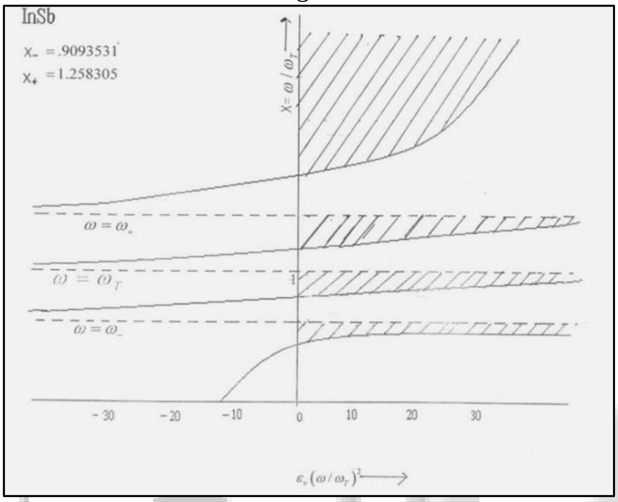

Fig. 3:

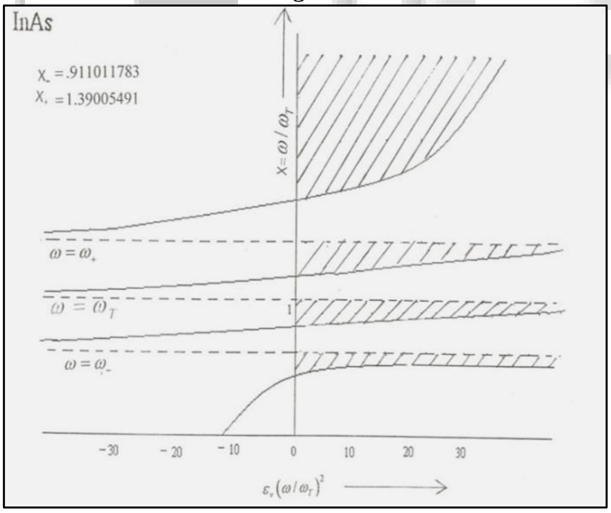

Fig. 4:

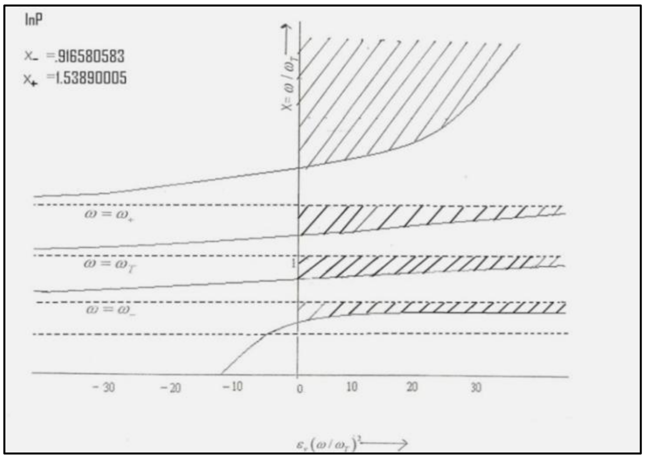

Fig. 5:

The shaded region corresponds to negative values of α_1^2 that is, where surface modes do not exist but the wave propagates through the surface.

III. Conclusions

In the entire five graphs we observe that for frequencies well below $\omega = \omega_-$ $\varepsilon_V\left(\omega/\omega_T\right)^2$ is large and negative. Now, as $\left(\omega/\omega_T\right)^2$ is always positive, it means that ε_V is negative. Observing equation (13) it is seen that in this case α_1^2 will be positive. Hence surface waves would exist. Also, if α_1^2 is positive q_{Z1}^2 will be negative and, therefore there will be no propagation of waves through the surface for region just below $\omega = \omega_+ . \varepsilon_V$ is large and positive, so that , α_1^2 (eqn. 6.28) is negative. Consequently, there are no surface modes and the wave propagates through the surface. This region has been shown by the shaded area on the graphs (1-5).

Between $\omega = \omega_-$ and $\omega = \omega_T$ and $\omega = \omega_+$ also between $\omega = \omega_T$ and $\omega = \omega_+$ also, there are regions of no propagation where surface modes exist and also regions of propagation where surface modes exist and also regions of propagations where surface modes do not exists . One thing that is conspicuous in the graph (1-5) is that the no. of region of propagation of waves has increased with the application of a D.C. magnetic field .Hence the surface still acts as a band pass filter, but with an increased number of bands.

From figures (1) and (5) we observe that although the values of $\left(\omega_p/\omega_t\right)$ and $\left(\omega_c/\omega_t\right)$ are same for both GaAs and GaP the bands of forbidden surfaces modes are closer for GaAs for which $\varepsilon_0 - \varepsilon_\infty$ is less. The same thing is observed for InSb and InAs. We also observe from the graph that for a frequency $\omega > \omega_+$ the surface acts as a high pass filter. All the frequencies above this value are allowed to propagate. Hence, there are no surface modes for these frequencies of $\varepsilon_0 - \varepsilon_\infty$. As $\varepsilon_0 - \varepsilon_\infty$ is a measure of polarizability, we can conclude that for more that for more polarizability compounds the bands of allowed frequencies are farther apart and the surface becomes a high pass filter at a higher frequency.

D.C. magnetic field exerted an extra force on plasmons of surface polar semiconductor and these surface plasmons are known as magneto plasmons. Thus in three modes coupling if we apply external D.C. magnetic field the three mode coupling becomes four modes coupling on the cylindrical polar semiconductor. The region in the graph where the propagation of waves exists is shown as shaded region in figures.

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