Advances in Condensed Matter Physics 凝聚态物理学进展, 2018, 7(1), 1-6

https://doi.org/10.12677/cmp.2018.71001

Dispersion Characteristics in the Surface of Non-Collision Magnetized Plasmas and Dielectric Material

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Received: Nov. 22nd, 2017; accepted: Dec. 7th, 2017; published: Dec. 14th, 2017

Abstract

The dispersion relations on the surface of a non-collision magnetized plasma and dielectric material are derived based on Maxwell's Equations and boundary conditions. The dispersion characteristics affected by the applied magnetic field are discussed, and it is found that the tunable surface plasmon polaritons can appear in the surface.

Keywords

Plasma, Dispersion, Surface Plasmon Polariton

非碰撞磁化等离子体与介质表面色散特性研究

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收稿日期：2017年11月22日；录用日期：2017年12月7日；发布日期：2017年12月14日

摘要

基于麦克斯韦方程组和边界条件，推导磁化非碰撞等离子体和介质表面的色散关系，讨论了外加磁场对色散特性的影响，得到了基于磁场可调的表面等离子体激元。

文章引用: 陈成达, 亓丽梅, 姚远, 陈智娇, 俞俊生. 非碰撞磁化等离子体与介质表面色散特性研究[J]. 凝聚态物理学进展, 2018, 7(1): 1-6. DOI: 10.12677/cmp.2018.71001

关键词

等离子体，色散，表面等离子激元

1. 引言

表面等离子激元(Surface Plasmon Polaritons, SPP)是沿导体与介质的界面传播的电磁波，可用于波导、滤波器和传感器等设备的设计，光存储等领域。SPP 的研究多数基于金属(如金、银)结构，而当这些 SPP 器件被加工成型，其工作频率很难改变[1]-[15]。对于频率低于等离子体频率的电磁波，等离子体具有和金属相似的电子特性，并且等离子体的相对介电常数可以通过等离子体的参数，如外界磁场进行控制。

本文基于麦克斯韦方程组和边界条件，推导了等离子体和介质表面的色散关系，讨论了外加磁场对色散特性的影响，得到了基于磁场可调的表面等离子体激元。本论文的研究成果对可调器件的设计有重要的参考价值。

2. 等离子体与介质表面的色散曲线推导

在磁化等离子体的物理模型中，麦克斯韦方程满足：

$$\nabla \times H = \varepsilon_0 \hat{\varepsilon}_p \frac{\partial E}{\partial t} \tag{1}$$

其中，磁化非碰撞等离子体的有效介电常数为[16]：

$$\hat{\varepsilon}_p = \begin{pmatrix} \varepsilon_1 & 0 & j\varepsilon_2 \\ 0 & \varepsilon_3 & 0 \\ -j\varepsilon_2 & 0 & \varepsilon_1 \end{pmatrix} \tag{2}$$

$$\varepsilon_1 = 1 - \frac{\omega_p^2 \omega}{\omega\left(\omega^2 - \omega_c^2\right)}，\quad \varepsilon_2 = \frac{-\omega_p^2 \omega_c}{\omega\left(\omega^2 - \omega_c^2\right)}，\quad \varepsilon_3 = 1 - \frac{\omega_p^2}{\omega^2}$$

ω_p 为磁化等离子体震荡角频率，$\omega_c = \left(eB_0/m\right)e_y$ 是电子回旋频率。B_0 为外加磁场强度。

把方程(1)展开：

$$\frac{\partial H_y}{\partial z} = j\omega\varepsilon_0\left(\varepsilon_1 E_x + j\varepsilon_2 E_z\right) \tag{3}$$

$$\frac{\partial H_y}{\partial z} = j\omega\varepsilon_0\left(j\varepsilon_2 E_x - \varepsilon_1 E_z\right) \tag{4}$$

并与麦克斯韦方程

$$\nabla \times E = -\mu_0 \frac{\partial H}{\partial t} \tag{5}$$

联立结合可得：

$$\frac{\partial^2 H_y}{\partial z^2}+\frac{\partial^2 H_x}{\partial x^2}+k^2 H_y=0 \tag{6}$$

其中：

$$k^2=\frac{\omega^2}{c^2}\varepsilon_p \tag{7}$$

$$\varepsilon_p=\frac{\left(\omega^2-\omega_p^2\right)^2-\omega^2\omega_c^2}{\omega^2\left(\omega^2-\omega_c^2\right)-\omega^2\omega_p^2}=\frac{\left(\omega^2-\omega_p^2\right)^2-\omega^2\omega_c^2}{\omega^2\left(\omega^2-\omega_c^2-\omega_p^2\right)} \tag{8}$$

由于在两个介质表面的 SPP 色散关系可以表示如下[17]：

$$\beta^2=k_0^2\frac{\varepsilon_d\varepsilon_p}{\varepsilon_d+\varepsilon_p} \tag{9}$$

将(8)式代入(9)式并整理得

$$\beta^2c^2=\frac{\omega^2\varepsilon_d\left(\omega^4+\omega_p^4-2\omega^2\omega_p^2-\omega^2\omega_c^2\right)}{\varepsilon_d\omega^2\left(\omega^2-\omega_c^2-\omega_p^2\right)+\omega^4+\omega_p^4-2\omega^2\omega_p^2-\omega^2\omega_c^2} \tag{10}$$

将方程(10)两边同时除以 ω_p^2，并让右侧分母同除以 ω_p^4 可得：

$$\left(\frac{\beta c}{\omega_p}\right)^2=\left(\frac{\omega}{\omega_p}\right)^2\varepsilon_1\frac{\left(\frac{\omega}{\omega_p}\right)^4+1-2\left(\frac{\omega}{\omega_p}\right)^2-\left(\frac{\omega}{\omega_p}\right)^2\left(\frac{\omega_c}{\omega_p}\right)^2}{\varepsilon_1\left[\left(\frac{\omega}{\omega_p}\right)^4-\left(\frac{\omega}{\omega_p}\right)^2\left(\frac{\omega_c}{\omega_p}\right)^2-\left(\frac{\omega}{\omega_p}\right)^2\right]+\left(\frac{\omega}{\omega_p}\right)^4+1-2\left(\frac{\omega}{\omega_p}\right)^2-\left(\frac{\omega}{\omega_p}\right)^2\left(\frac{\omega_c}{\omega_p}\right)^2} \tag{11}$$

令 $x=\dfrac{\beta c}{\omega_p}$， $y=\dfrac{\omega}{\omega_p}$ 得到

$$x^2=y^2\varepsilon_1\frac{y^4+1-2y^2-y^2\left(\frac{\omega_c}{\omega_p}\right)^2}{\varepsilon_1\left[y^4-y^2\left(\frac{\omega_c}{\omega_p}\right)^2-y^2\right]+y^4+1-2y^2-y^2\left(\frac{\omega_c}{\omega_p}\right)^2} \tag{12}$$

整理得到磁化等离子体与介质表面的色散关系表达式：

$$x^2=y^2\varepsilon_1\frac{y^4-2y^2-y^2\left(\frac{\omega_c}{\omega_p}\right)^2+1}{\left(\varepsilon_1+1\right)y^4-\left(\varepsilon_1+2\right)y^2-\left(\varepsilon_1+1\right)y^2\left(\frac{\omega_c}{\omega_p}\right)^2+1} \tag{13}$$

当 $\omega_c=0$ 时，即没有外加磁场情况下，等离子体与介质表面的色散关系表达式为：

$$x^2=y^2\varepsilon_1\frac{y^2-1}{\left(\varepsilon_1+1\right)y^2-1} \tag{14}$$

3. 等离子体与介质表面的色散分析

对应(13)、(14)两式可得到等离子体与介质表面的色散关系如图 1 和图 2 所示。

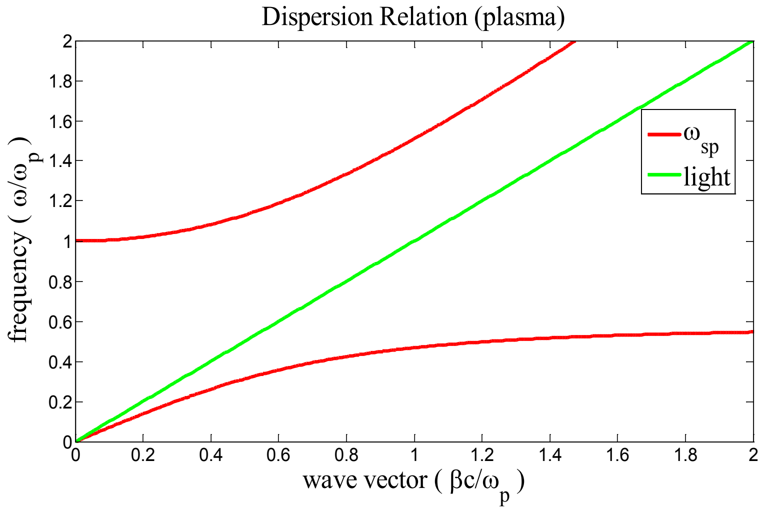

Figure 1. The dispersion relations on the surface of a non-magnetized plasma and dielectric material
图 1. 非磁化等离子体与介质表面色散关系

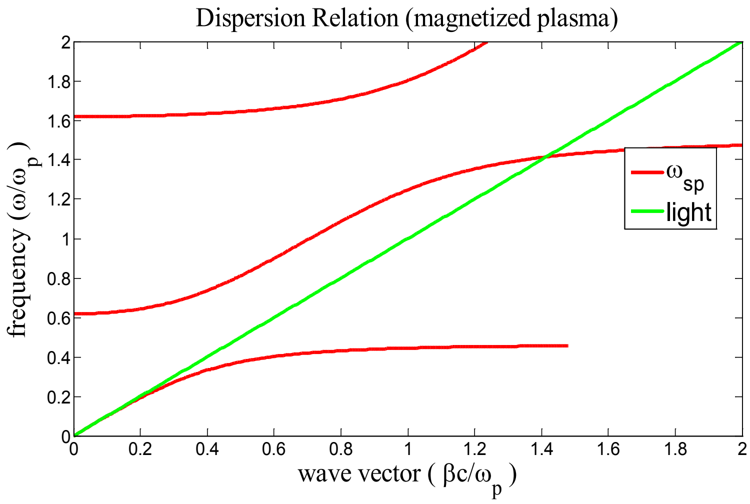

Figure 2. The dispersion relations on the surface of a magnetized plasma and dielectric material
图 2. 磁化等离子体与介质表面色散关系

在图 1 与图 2 中，横坐标代表归一化波矢量，纵坐标代表与等离子频率相比的相对入射波频率。绿线代表电磁波在真空中的色散曲线，红色曲线是等离子体与介质表面的色散曲线。由图 1 可知，同频率下 SPP 的波矢大于空气中光子的波矢，因此非磁化等离子体无法激发 SPP，但是在磁化等离子体中，SPP 色散曲线与真空中电磁波的色散曲线产生了交点，说明在该点波矢匹配条件成立，可以激发 SPP。

在方程(13)中，令

$$B=\frac{\omega_c}{\omega_p} \tag{15}$$

图 3 给出了外加磁场对色散特性的影响，可见，随着 B 增大，即随着外加磁场B_0的增大，激发表面等离子激元的匹配频率变得更低，从而在等离子和介质表面更易激发表面等离子激元。

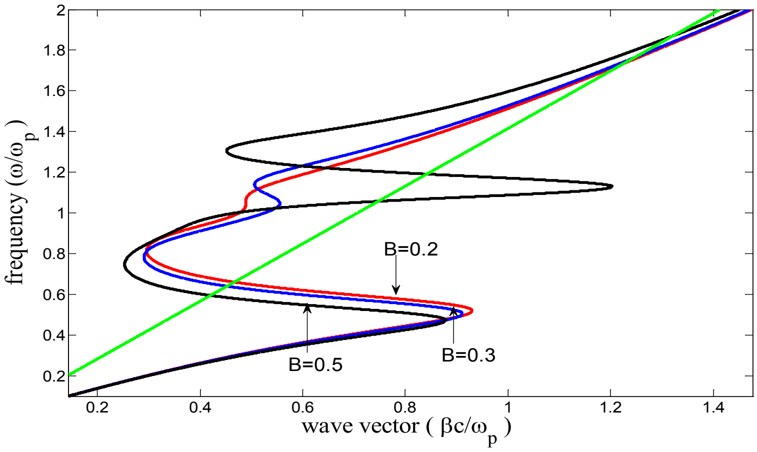

Figure 3. Influence of applied magnetic field on the dispersion relations
图 3. 外加磁场对色散关系的影响

4. 结论

通过研究磁化等离体与介质表面的色散特性，发现在磁化等离子和介质表面可以直接产生表面等离子激元。调节外加磁场可以得到可调表面等离子激元，增大外加磁场可以更易激发表面等离子激元。这些研究结果对设计可调表面等离子激元器件有一定的指导作用。

基金项目

本项目得到了国家自然科学基金(No. 61107030)，毫米波国家重点实验室开放课题(No. K201703)和中央高校基本科研业务费专项资金项目的支持。

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