Surface Plasmon Polaritons Scattering by Strong Magnetic field in Two-dimensional Material

Runzhang Xie[1,2] and Weida Hu[1] *

1. State Key Laboratory of Infrared Physics, Shanghai Institute of Technical Physics, Chinese Academy of Sciences, Shanghai 200083, China

2. Graduate University of the Chinese Academy of Sciences, Beijing 100049, People's Republic of China.

*wdhu@mail.sitp.ac.cn

***Abstract*—Scattering effect of surface plasmon polaritons in two-dimensional material based devices by magnetic fields are analytically studied within the framework of wave optics and plasma model. The theoretical explanation of magnetic scattering and related formulae are provided by considering plasmonic mechanics and solving the equation of motion of electron gas directly. Calculation results illustrating magnetic scattering phenomena are also given by applying an approximation to the first order.**

Keywords—surface plasmon polaritons, magnetic fields scattering, analytic methods, two-dimensional materials

I. INTRODUCTION

Surface plasmon polaritons (SPPs) are quasi-particles describing electron collective behavior in condensed matter system coupling photon and electron together which excited directly by suitably imposing electromagnetic field or other processes mediated by the induced electromagnetic field [1-5]. After the first experimental result collected by SNOM [6], SPPs derived in two-dimensional material based system has germinate into a fruitful branch of SPPs. Graphene encapsulated by hexagonal boron nitride (h-BN) has shown as one of the most efficient and promising structure [7-10].

Within the scope of plasma model of electron gas, the electrons are driven by time varying electric field and damped via collisions between electrons and nuclei characterized by the relaxation time τ of electron gas. Surface plasmon wave of bulk materials localized at the surface between a metal and a dielectric with a small penetration depth within tens of nanometers into the metal can be derived by using wave equation solely [11-14]. The case of two-dimensional material based plasmon polaritons are categorized and illustrated by the classical bulk counterparts differs only in the thickness of material. In other words, SPPs in two-dimensional material can be treated equally as in bulk systems. In this paper, we exert a third mechanism upon the two-dimensional plasma, and we can find a different nature induced by dimensional difference. A good demonstration of this distinction is given by the creation of a pseudo–magnetic field in graphene. This strain-induced gauge field can give rise to a pseudo–magnetic field greater than 300 tesla, which jumps out of the scope of ordinary consideration of magnetic field [15]. With this purpose, we analyzed the magnetic induced anisotropic behavior and nonlinear effect which must take into consideration [16-20]. We also derived electric field profiles by considering the anisotropic behavior under magnetic field in a small region that can be discussed analytically with the truncation of higher order terms.

II. CALCULATION

In this paper, we focus on the case of strong magnetic field only confined in a small circular area. To be concise and coherent, we follow the routine of plasma model to derive the plasma dielectric function in strong magnetic field.

The equation of motion for a constituent electron of plasma gas subjected to an harmonically varying external electric field and an static magnetic field can be directly written down:

$$m\, d^2x/dt^2 + m\,\gamma\, dx/dt = -q(\boldsymbol{E}+\boldsymbol{v}\times\boldsymbol{B}) \tag{1}$$

where m is the effective optical mass of electron, and we have defined $\gamma=1/\tau$ as the characteristic collision frequency. By solving this equation directly, the electron oscillation can be explicitly given. Eliminating irrelevant parts which should not appear in oscillating mode we are considering, we could ignore terms containing any unknown integration constants.

Note that when magnetic field is zero, we would move back to classical case of plasma model. Therefore, we expand the motion of the electron into Taylor series of B_z, and truncate high order terms:

$$\begin{aligned} v_x(t) &= \frac{E_x q e^{-itw}}{mw(w+ir)} + \frac{B_z^2 E_x q^3 e^{-itw}}{m^3 w(w+ir)^3} + O(B_z^4) \\ v_y(t) &= \frac{iB_z E_x q^2 e^{-itw}}{m^2 w(w+ir)^2} + \frac{iB_z^3 E_x q^4 e^{-itw}}{m^4 w(w+ir)^4} + O(B_z^5) \end{aligned} \tag{2}$$

we find that the first term in the x direction is just the case appeared in the theory of plasma model without magnetic field. The second term in the x direction and the first term in the y direction are lowest order correction term in their direction respectively. The z direction's equation is constant, as can be known from the configuration of magnetic field.

The relative ratio of terms shown above is the same except for a sign. So it is convenient to define a exchange ratio as:

$$\theta = i\frac{B_z q}{mw + imr} \tag{3}$$

Even if the magnetic field is greater than 300 tesla, the exchange ratio is less than 1 in gold in near infrared region. By calculating the order of correction terms, we find the scattering problem can be seen as a perturbation of SPPs without magnetic field. By applying perturbative methods, we derived the following electric field profiles.

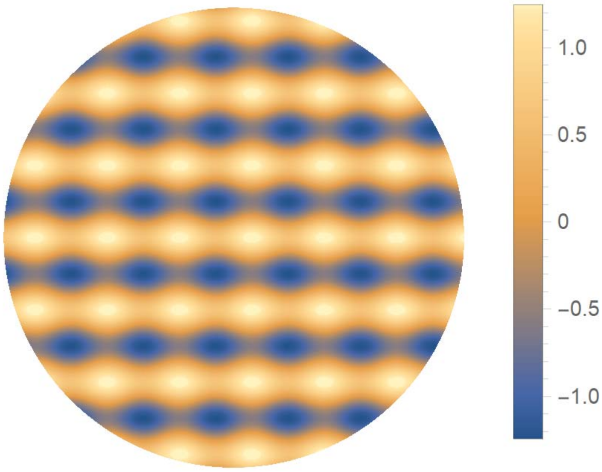

Fig. 1 Electric field in the static magnetic field area. There are just two propagation directions, the incident direction is the *y* direction. The exchange factor in this calculation is 0.3.

This orthogonality can be understood as a result of imaginary unit, in other words, this orthogonality is a side-effect of model approximation. This is schematically shown in figure below.

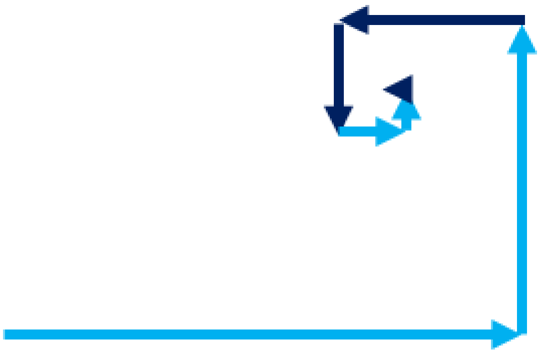

Fig. 2 Interference of different orders of scattering fields. Light blue arrows represent the plasmon wave, whose phase is constructive with respect to the lowest order of plasmon wave in this direction. Deep blue arrows represent the destructive wave. The direction of arrow represents the propagation direction. Remind that the phase shift of scattering is induced by the exchange factor, that is, the phase shift is the result of Lorentz force which is proportional to electron velocity. Lorentz force has a phase change compared with position.

III. Conclusion

In this paper, a analytic model of scattering of SPPs in strong magnetic field is proposed by modifying plasma model. By using a very strong approximation, we derived the electric field to the first order. The calculation shows the orthogonal scattering. We also provide a way of understanding the orthogonality in this scattering. Controllable beam splitters and phase shifters are possible application of this scattering.

References

[1] S. I. Pekar, "The Theory of Electromagnetic Waves in a Crystal in which Excitons Are Produced," *Soviet Journal of Experimental and Theoretical Physics,* vol. 6, no. 33, p. 785, 1958.

[2] S. A. Maier, "Electromagnetics of Metals," in *Plasmonics: Fundamentals and Applications*, S. A. Maier, Ed. New York, NY: Springer US, 2007, pp. 5-19.

[3] D. K. Gramotnev and S. I. Bozhevolnyi, "Plasmonics beyond the diffraction limit," *Nature Photonics,* vol. 4, no. 2, pp. 83-91, Feb 2010.

[4] E. Verhagen, A. Polman, and L. Kuipers, "Nanofocusing in laterally tapered plasmonic waveguides," *Optics Express,* vol. 16, no. 1, pp. 45-57, 2008/01/07 2008.

[5] E. N. Economou, "Surface Plasmons in Thin Films," *Physical Review,* vol. 182, no. 2, pp. 539-554, 06/10/ 1969.

[6] Z. Fei *et al.*, "Gate-tuning of graphene plasmons revealed by infrared nano-imaging," *Nature,* vol. 487, p. 82, 06/20/online 2012.

[7] A. Woessner *et al.*, "Highly confined low-loss plasmons in graphene–boron nitride heterostructures," *Nature Materials,* Article vol. 14, p. 421, 12/22/online 2014.

[8] S. Dai *et al.*, "Subdiffractional focusing and guiding of polaritonic rays in a natural hyperbolic material," *Nature Communications,* Article vol. 6, p. 6963, 04/22/online 2015.

[9] S. Dai *et al.*, "Graphene on hexagonal boron nitride as a tunable hyperbolic metamaterial," *Nature Nanotechnology,* vol. 10, p. 682, 06/22/online 2015.

[10] G. X. Ni *et al.*, "Fundamental limits to graphene plasmonics," *Nature,* vol. 557, no. 7706, pp. 530-533, 2018/05/01 2018.

[11] T. C. Berkelbach, M. S. Hybertsen, and D. R. Reichman, "Theory of neutral and charged excitons in monolayer transition metal dichalcogenides," *Physical Review B,* vol. 88, no. 4, p. 045318, 07/25/ 2013.

[12] X. Cui *et al.*, "Multi-terminal transport measurements of MoS2 using a van der Waals heterostructure device platform," *Nature Nanotechnology,* Article vol. 10, p. 534, 04/27/online 2015.

[13] T. Low *et al.*, "Polaritons in layered two-dimensional materials," *Nature Materials,* Review Article vol. 16, p. 182, 11/28/online 2016.

[14] Z. Fei *et al.*, "Nano-optical imaging of WS_2 waveguide modes revealing light-exciton interactions," *Physical Review B,* vol. 94, no. 8, p. 081402, 08/01/ 2016.

[15] N. Levy *et al.*, "Strain-Induced Pseudo–Magnetic Fields Greater Than 300 Tesla in Graphene Nanobubbles," *Science,* vol. 329, no. 5991, pp. 544-547, 2010.

[16] D. F. P. Pile and D. K. Gramotnev, "Nanoscale Fabry–Pérot Interferometer using channel plasmon-polaritons in triangular metallic grooves," *Applied Physics Letters,* vol. 86, no. 16, p. 161101, 2005.

[17] D. F. P. Pile and D. K. Gramotnev, "Plasmonic subwavelength waveguides: next to zero losses at sharp bends," *Optics Letters,* vol. 30, no. 10, pp. 1186-1188, 2005/05/15 2005.

[18] K. C. Vernon, D. K. Gramotnev, and D. F. P. Pile, "Adiabatic nanofocusing of plasmons by a sharp metal wedge on a dielectric substrate," *Journal of Applied Physics,* vol. 101, no. 10, p. 104312, 2007/05/15 2007.

[19] R. F. Oulton, V. J. Sorger, D. A. Genov, D. F. P. Pile, and X. Zhang, "A hybrid plasmonic waveguide for subwavelength confinement and long-range propagation," *Nature Photonics,* vol. 2, p. 496, 07/11/online 2008.

[20] E. Ferreiro-Vila *et al.*, "Intertwined magneto-optical and plasmonic effects in Ag/Co/Ag layered structures," *Physical Review B,* vol. 80, no. 12, Sep 2009, Art. no. 125132.