Cavity physical properties of SPP propagation in the MIM structure

Zhu Jun[1], Li Zhiquan[2], Qin Liuli[3]

(1. College of Electronic Engineering, Guangxi Normal University, Guilin 541004, China;
2. Institute of Electrical Engineering, Yanshan University, Qinhuangdao 066004, China;
3. College of Mathematics and Statistics, Guangxi Normal University, Guilin 541004, China)

Abstract: The effects of surface plasmon polariton (SPP) propagation on the physical properties of cavities in the MIM) structure was studies. Theory methods were drawed using waveguide mode, resonance, reflection coefficient, and phase. The effects of relevant parameters were discussed, including length and thickness, on cavities in SPP propagation. Moreover, the electromotive force (EMF) of Metal-Insulator-Metal (MIM) waveguide and the effect of structure by varying cavity length and reflection coefficient were simulated, etc. Results show that EMF, which is in the SPP propagation, becomes relatively larger than 1 V, and the energy field can be amplified. Moreover, the effective power increases with increased cavity length, and the cavity length has a similar effect on SPP propagation in different cavity thicknesses, with the propagation coefficient reaching a maximum value in the near field. In general, analysis and discussion of this text are significant in studies on nonlinear THz spectroscopy, nanophotoelectric detection, generation of SPP mode, and strong local field.

Key words: nonlinear optics; MIM waveguide; coupling mode; surface plasmon polarization

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MIM 结构中腔的物理性质对 SPP 传播的分析

朱 君[1],李志全[2],秦柳丽[3]

(1. 广西师范大学 电子工程学院,广西 桂林 541004;
2. 燕山大学 电气工程学院,河北 秦皇岛 066004;
3. 广西师范大学 数学与统计学院,广西 桂林 541004)

摘 要: 为了研究 MIM 结构中腔的物理性质对 SPP 传播的影响,采用了对波导模式、谐振和反射系数以及相位分析的理论方法,讨论了腔长和厚度对 SPP 传播的相关参数的影响,仿真了 MIM 波导中电动势、腔长和反射系数等参数在结构中作用。结果表明,SPP 传播产生的电动势能达到相对较大的 1V,激发产生的能场会有放大的作用;腔的有效功率变化与腔长变化一致,不同的腔厚度中腔长对 SPP 传播的结果趋势相同; 近场中传播系数存在一个最大值。这一问题的分析与讨论对非线性 THz 光谱研究、纳米级光电探测、SPP 模式的发生器、强局域场都具有一定的意义。

关键词: 非线性光学; MIM 波导; 耦合模式; 表面等离子激元

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作者简介: 朱君(1985-),讲师,博士,主要从事表面等离子体光学方面的研究。Email:zhujun1985@gxnu.edu.cn

0 Introduction

Research on surface plasmons (SPs) began in the 1980s. The main characteristics are investigated using Raman spectroscopy, which determines the form of molecular oscillation to analyze the molecular structure of the sample by observing the spectrum of the laser due to scattering by the sample[1-3]. In 1989, Tomas Ebbesen from the NEC Institute in Japan found that the energy of light waves that permeated gold film exceeded the value that is obtained by estimating the number and size of the holes according to light irradiation on the gold film with millions of tiny pores. After nine years, Ebbesen and his colleagues concluded that SP with gold film would enhance the transmission of light energy [4]. One of the most important directions in the research of SP is Metal – Insulator–Metal (MIM) waveguide structure, which has strong field of plasmon cavity with subwavelength nanostructures and can tune wavelength to excite resonance cavity. The capacity of plasmon cavity that could gather light on nanoscale levels has attracted the attention of researchers. Given that filed intensity of insulator is very strong and optical absorption can be amplified with MIM waveguide, MIM is useful for optoelectronic applications and non –linear optical processes [5-6]. However, in the slow change of SPP space field and under the influence of the strong gravity of plasmon, a clear quantitative analysis with MIM waveguide structure has not been achieved. Also, various bottlenecks have been encountered in studies on discontinuous and SPP reflection in multiple media . In the text, we study cavity physical properties of SPP propagation in the MIM structure This study analyzes the MIM SP physical properties of resonance and reflection of the SPP, and this feature presents the study on SP physical properties with MIM structure and reflection of the SPP, which promote and influence microwave nanoptical and biomedical research.

1 Theory analysis of MIM waveguide in the SPP propagation

In newest research of nanoplasmon show SP with non–resonant produces significant amplification of EMF, and for thin enough insulator of MIM structures (Seen Fig.1) symmetric model can inhibit mode of mixed in the reflection cavity[7-10]. Then we only analyze SPP cavity field of forward propagation and reflection properties in order to know SPP lasing of MIM waveguide structure, finite MIM cavity resonance and constructing the symmetric resonator mode. Next, theoretical analyze properties of MIM resonance cavity in thin media and further discuss amplification EMF effect.

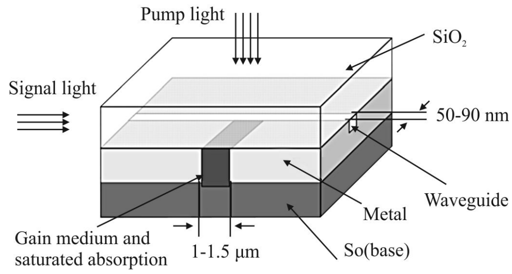

Fig. 1 Schematic of MIM structure chart

1.1 Analysis of waveguide mode and resonant

In the propagation of SPP momentum, variations would affect electronic motion, in which the relaxation time of momentum is a femtosecond. Then, we can consider SPP transmission to produce THz EMF. According to the energy conservation law, electronics follows local conservation. As we look at analysis of EMF and classical electromagnetic field theory of Maxwell equations, the following transverse mode in the SPP transmission is shown:

$$\begin{cases} E=M(t)(E_z z+E_{xy} xy)e^{i(kz-\omega t)} \\ H=M(t)H_\phi \phi e^{i(kz-\omega t)} \end{cases} \tag{1}$$

where $k=\frac{2\pi}{\omega}$. Using the above characteristics to analyze TM mode coupling with MIM waveguide, through reflection cavity of SPP and continuous filed E_z, we determine the amplitude using the following equation:

$$M(\rho)=\frac{t}{2\pi}\int_{-\infty}^{\infty}E_z^{plas}e^{-ik\rho z}dz-\delta(\rho) \quad (2)$$

where δ is the Dirac pulse. We explore the excitation characteristics of SPP in MIM waveguide structure. Considering the continuity of the x direction on the YZ-plane and the invariance of y direction, we arrive at the following equation:

$$t=\left(\frac{2A(0)\sqrt{\frac{\xi_0}{\mu_0}}}{\frac{1}{\lambda}\sqrt{\frac{\xi_0}{\mu_0}}\int_{-\infty}^{\infty}d\rho\frac{|A(\rho)^2|}{\sqrt{1-\rho^2}}-\int_{-\infty}^{\infty}dzE_z^{plas}H_y^{plas*}}\right)^* \quad (3)$$

where $A(\rho)=\int_{-\infty}^{\infty}E_z^{plas}e^{-ik_0\rho z}dz$, and power P at t moment is represented by the following equation: $P(t)=2\pi\int_0^{\infty}\overline{s_z}(L,t)|_{z=0}\rho d\rho$, where $\overline{S}(L,t)=(c/8\pi)\mathrm{Re}(E\times H^*)$. Afterward, we obtain E_z, E_{xy} and H_ϕ of Eq.1 are only associated with the cavity length L. Also, power can be rewritten in the following form:

$$p=\left|\frac{te^{i\partial l}}{1-L^2e^{2i\partial l}}\right|^2\int_{-\infty}^{\infty}dzE_z^{plas}H_y^{plas*}(1-|L|^2) \quad (4)$$

where l is the width of cavity. Using Eq.4, the transmission coefficient of cavity can be obtained using the following equation:

$$\mathrm{Tran}=\left|\frac{e^{i\beta l}}{1-L^2e^{2i\beta l}}\right|(1-|L|^2) \quad (5)$$

From Eq.5, we can obtain the maximum of transmission coefficient in the MIM waveguide, which can be used to determine the resonance length using the following equation:

$$L'=\frac{a\pi-\phi}{\pi}\frac{\lambda_{sp}}{2} \quad (6)$$

where $a=1, 2, 3\cdots$ represents the level resonance, and ϕ satisfies $L=|L|e^{i\phi}$.

1.2 Analysis of reflection parameters

Given that the SPP propag ation produces EMF and the electric field satisfies $U\sim PR^{-3}, E\sim PR^{-4}$, we observe that changes in EMF do not affect resonance characteristics. Then, we analyze characteristics with energy field of reflection in the SPP propagation. Using classical field theories, the energy of electric field W_e and magnetic field W_m can be determined using the following equations:

$$\begin{cases}W_e=\frac{1}{4}\int_\Omega E\cdot D^*d\Omega\\ W_m=\frac{1}{4}\int_\Omega E\cdot H^*d\Omega\\ \oint_v P\cdot ndA+2i\omega(W_e-W_m)=0\end{cases} \quad (7)$$

where P_o is the Ω Poynting flux, is the volume element, and V refers to the closed area of the direction with normal n. According to the characteristics of MIM waveguide structure, and when Ω is used instead of the cavity reflection space, we arrive at the following equation:

$$W_e-W_m=\frac{|1+L|^2\xi_0}{4\pi}\times\int_{\rho=1}^{\infty}\frac{|A(\rho)|^2}{\sqrt{\rho^2-1}}d\rho \quad (8)$$

Considering that most energy is lost in the near field, we only consider the near-field area. The energy in the cavity can be obtained using the following equation:

$$W=W_e+W_m=\frac{|1+L|^2\xi_0}{4\pi}\times\int_{\rho>1}^{\infty}\frac{|A(\rho)|}{\sqrt{\rho^2-1}}\times(1+\frac{1}{\rho^2-1})d\rho \quad (9)$$

Obviously, the total energy W decays rapidly as ρ increases. From above analysis, we find that the transverse mode of SPP propagation not only produces the THz EMF, but is also directly related to the metal characteristics and cavity thickness.

2 Simulation

2.1 Simulation of EMF

SPP propagation is a second-order nonlinear effect based on the theory of nonlinear optics, which will also lead to nonlinear THz and strong local electric field. Figure 2 shows the excitation energy as a function of EMF in the SPP propagation. As seen in Fig.2, EMF can reach the value of 1 V, which is relatively large. EMF exhibits an exponential upward trend as the excitation energy increases, which indicates that the energy field rapidly increases. This finding is very useful for EMF of femtosecond response and has a certain significant application for nanophotoelectric detection.

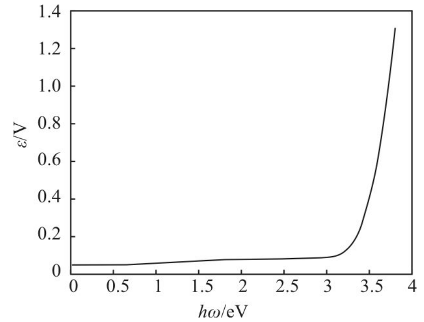

Fig.2 Curve of EMF and the excitation energy

2.2 Simulation of cavity length in the MIM waveguide

Symmetric SPP mode would be confined to a small model space as the thickness of insulator decreases in the MIM cavity, which already appears SPP lasing device, such as a quantum generator with MIM coupling cavity. Figure 3 shows the different media thicknesses represented by Th and percentage of effective power In as a function of waveguide cavity length *L*, which is the condition of SPP wavelength λ=750 nm in Ag–air–Ag waveguide structure. Evidently, the effective power increases as cavity length becomes larger. The same trend is observed as the thickness cavity increases. The obtained results are similar to theoretical analysis of effect, in which the cavity length is for power of SPP propagation. The results have effect in the generator with coupling SPP mode.

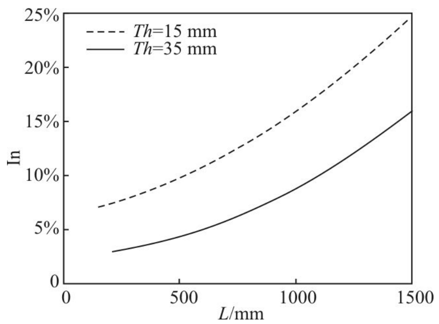

Fig.3 Curves of percentage of effective power In and cavity length *L* in the condition of λ=750 nm and Ag–air–Ag waveguide

2.3 Simulation of transmission coefficient and phase

Given that the mode does not match and exist coupling evanescent mode in the cavity (Seen theoretical analysis), transmission coefficient Tran has a maximum value in the near field. In this case, Fig.4 shows SPP wavelength λ above waveguide structure is, in the condition of cavity thickness *Th*=35 nm, length *L*=450 nm, a function of transmission co efficient Tran. The results show that the simulation is the same as theoretical verification, in which a maximum of transmission coefficient exists. The validation is good for tuning more effective cavity by selecting the appropriate wavelength and can lead to the production of a strong local field.

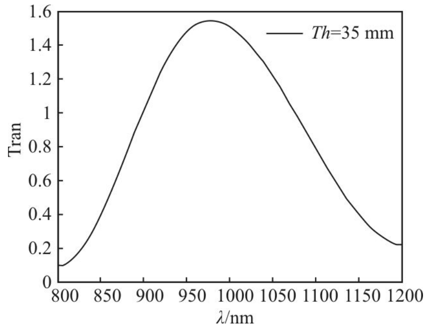

Fig.4 Curve of cavity propagation coefficient thickness Tran and SPP wavelength λ in the condition of thickness *Th* =35 nm, length *L*=450 nm

When the cavity thickness is reduced, near–field energy and reflection phase will simultaneously become smaller as in the metal exists aperture effect and evanescent mode. Figure 5 shows that the reflection phase ϕ is the function of SPP wavelength, λ . The reflection phase can be observed to monotonically decrease as the wavelength increases. Combined with the results in Fig.4, the results show that SPP wavelength and phase are at the opposite addition direction, which can lead to resonance length invariance based on theoretical analysis of resonance length. The SPP resonance is determined and tuned by the reflection phase and wavelength in MIM waveguide structure. The consequence of validation is useful for studying resonant frequency and designing SP resonant device that is given wavelength.

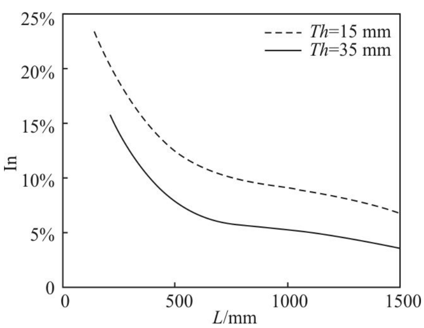

Fig.5 Curves of reflection phase and SPP wavelength in the MIM waveguide

3 Conclusion

The THz femtosecond EMF which is in the SPP propagation reaching a relatively large to 1 V and analysis of transmission coefficient indicate MIM waveguide is one of applications of amplification with SPP. Then, combined with the effect of physical properties of cavities on the SPP propagation, we know this structure can control according to design through structure parameters. The research in this text have potential value for nanoscale detection of femtosecond optical and SPP application of THz spectroscopy.

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