第 46 卷第 8 期　　红外与激光工程　　2017 年 8 月
Vol.46 No.8　　Infrared and Laser Engineering　　Aug. 2017

Impact of groove depth of subwavelength metal grating on THz spoof SPPs

Du Mingdi[1,2], Jia Yaqiong[1,2], He Shuzhen[1]

(1. School of Electrical and Information Engineering, Hunan Institute of Technology, Hengyang 421002, China;
2. Key Laboratory of Signal and Information Processing, Hunan Institute of Technology, Hengyang 421002, China)

Abstract: The influence of groove depth in one dimensional (1D) subwavelength metal grating on THz spoof surface plasmon ploaritons (SPPs) was theoretically investigateal in detail. Two device geometries were proposed including uniform groove depth 1D metal grating and defect groove depth 1D metal grating. The electric field distribution of metal grating was stimulated by employing COMSOL software. For the uniform structure, the dispersion relation of SPPs propagating along grating can be tailored by groove depth. The metal grating with deeper groove has stronger THz electric field distribution and the spoof SPPs is better confined to grating surface. For the defect structure, electric field distribution characteristics of both sides are determined by the defect groove depth, which can be attributed to reflection and scattering of defect. Based on the proposed theoretical stimulation, the two different subwavelength metal grating structures can provide new functionality for THz wave devices such as wave guiding, attenuator and filter.

Key words: groove depth; spoof SPPs; electric field distribution

CLC number: TN214; TN252　　**Document code:** A　　**DOI**: 10.3788/IRLA201746.0825003

亚波长金属光栅的凹槽深度对太赫兹伪表面等离子体影响

杜鸣笛[1,2],贾雅琼[1,2],何淑珍[1]

(1. 湖南工学院 电气与信息工程学院,湖南 衡阳 421002;
2. 湖南工学院 信号与信息处理重点实验室,湖南 衡阳 421002)

摘　要: 从理论上详细研究了一维亚波长金属光栅的凹槽深度对太赫兹伪表面等离子的影响。分别对一维标准亚波长金属光栅和缺陷亚波长金属光栅进行了研究。电场分布情况采用了 COMSOL 软件进行模拟。得到的结论是:对于一维标准亚波长金属光栅,沿金属光栅传播的表面等离子体取决于槽深度,较深的槽具有更强的束缚能力;对于具有缺陷的光栅结构,电场强度的分布特点取决于缺陷槽的深度,这归功于缺陷槽对光的反射和散射。基于这一理论研究,这两种不同的亚波长金属光栅结构能为太赫兹器件如波导、衰减器及滤波器发展提供新的途征。

关键词: 凹槽深度; 伪表面等离子体; 电场分布

收稿日期:2016-12-05;　**修订日期:**2017-01-03

基金项目:湖南工学院博士科研启动基金(HQ15002);湖南省自然科学基金(14JJ6046)

作者简介:杜鸣笛(1978-),女,博士,主要从事高速光器件、太赫兹器件等方面的研究。Email:dumingdi168@163.com

0 Introduction

Recently the field of plasmonics has attracted great attention due to the fascinating character of confining electromagnetic (EM) radiation to sub-wavelength spatial domains via SPPs[1-4]. At the boundary between a conductor and a dielectric, surface modes are set up by the coupling of the EM field to conduction electrons [5-6]. By using nanoscale metal structure, plasmonics offers the potential to generate well-defined EM with nanometer dimensions. It is responsible for surface-enhanced optical nonlinear phenomena such as fluorescence, second harmonic generation, and so on.

However, there is a basic problem that SPPs offer sub-wavelength field localization only for frequencies close to the intrinsic plasma frequency of the conductor, which is the ultraviolet part of the spectrum for most metals. Most recently, in order to enable high field confinement at lower frequency, a new structure of engineering surface plasmon by cutting holes or grooves in flat metal surfaces was proposed[7-8], which is named corrugated metal grating. Because of its mimicking characteristics, the existence of geometry controlled surface waves are termed as spoof SPPs, which has been verified in the microwave regime [9-11]. In the structure, metals are regarded as perfect electric conductor(PEC, with an infinitely large imaginary part of the permittivity) due to the fact that the depth of the wave penetration into the metal is much shorter than the incident wavelength[12]. As a result, spoof SPPs is lossless at the process of propagation along the structured surface. More recently, it has been reported that spoof SPPs at terahertz frequencies can be sustained on different periodically corrugated metal structure[13-14].

For the development of plasmonic devices based on corrugated structures, a detailed knowledge of the characteristic of spoof SPPs is essential. In this paper, we discuss the groove depth of 1D metal grating impact on THz spoof SPPs electric field distribution using numerical calculation. The metal is also treated as PEC. We analyze two different structures: one is uniform groove depth metal grating while the other is defect groove depth metal grating. For two structures, the electric field distribution strongly depends on the uniform groove depth and defect groove depth, respectively. These results allow us to control and directly design SPPs by introducing a 1D metal grating, in THz frequency domain.

1 1D uniform metal grating

The 1D uniform metal grating consists of an array of grooves engraved in the metal surface, with depth h, air width a and lattice constant d, as shown in Fig.1.

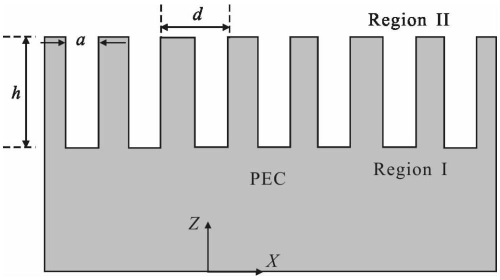

Fig.1 1D uniform groove depth metal grating model with air width a, lattice constant d and groove depth h

In this situation, the dispersion relation of 1D groove arrays for TM-polarized wave propagating along the x-axis can be obtained from the expression:

$$k_x=\frac{\omega}{c}\sqrt{\frac{a^2}{d^2}\tan^2\left(\frac{\omega h}{c}\right)+1} \tag{1}$$

Where c is the light velocity in vacuum, ω is the incident light angle frequency. The dispersion of the spoof SPPs can be easily tuned by changing the geometry of the indentations. When a=30 μm and d=50 μm, the dispersion curves of spoof SPPs for groove depth 50 μm and 80 μm are shown in Fig.2, respectively, in this figure, three black dash lines are corresponding to cutoff frequency of two different groove depth gratings and 0.7 THz incident wave frequency, respectively. It can be clearly seen that the dispersion curves significantly deviate from the light line, which indicates that adjusting the grating depth can modify the dispersion of the THz wave. Besides, the corresponding curve is gradually close to a specific cutoff frequency above which the SPPs can be no longer supported by the grating for each groove depth. Furthermore, our calculated results reveal that, for the fixed value *a* and *d*, a larger groove depth corresponds to a lower cutoff frequency. In other words, if we expect to get the lower frequency spoof SPPs, the grooves are required to be deeper.

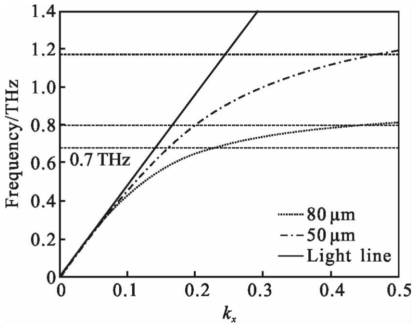

Fig.2 Dispersion curves of metal grating for a=30 μm, d=50 μm, h=50 μm and 80 μm, respectively

It is interesting to analyze the effect of the groove depth on THz spoof SPPs electric field distribution and confinement effect. We suppose that the incident EM frequency is 0.7 THz which is below the cutoff frequency of the structure with different groove depths. There isn't electric field distribution in PEC region (E_{I} =0). On the other hand, the x component of the electric field in region II (vacuum) can be expressed as:

$$E_x^{\mathrm{II}}(\rho,x)=\sum_{-\infty}^{\infty}C_nK_0(q_n\rho)\mathrm{e}^{ik_nx} \tag{2}$$

Where C_n are constants, $k_n=k_x+2\pi n/d$ and wave vector $q_n=\sqrt{k_n^2-k_0^2}$ ($k_0=\omega/c$). The radial is controlled by K_0. The zero-order modifies Neumann function $\rho\rightarrow\infty$. It can be seen from Fig.3 that electric field of 0.7 THz spoof SPPs effectively transmits and is strongly confined within a region near to the grating surface for two different groove depths. Additionally, comparing these two cases, 80 μm depths grating with better performance of electric field confinement is clearly observed in Fig.3(b). These results indicate that the EM energy can be confined more tightly to the grating surface if the incident wave frequency is nearer to cutoff′s. This is due to the fact that, for a given frequency being 0.7 THz, the 80 μm grating leads to a larger spoof SPPs propagation constant than that of the 50 μm grating (showing in Fig.2), resulting in larger wave vector and enhancing the field confinement.

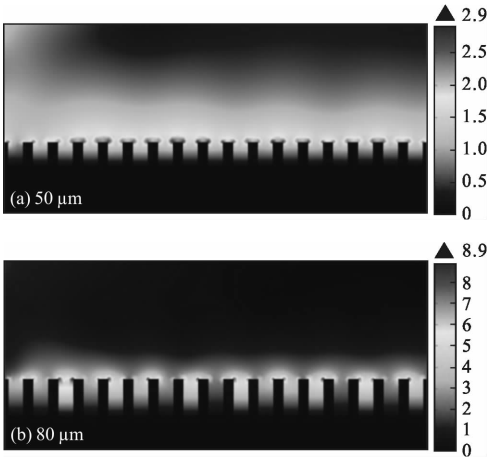

Fig.3 Electric field distribution of THz spoof SPPs for groove depth h

In order to vividly describe grating spatial confinement on THz spoof SPPs, Fig.4 displays the electric field dependence on the distance from metal grating surface. For 50 μm and 80 μm groove depth grating, the electric field amplitude reduces to 20% at the position 32 μm and 96 μm away from grating surface, respectively. In addition, for the 80 μm depth grating, the electric field reduces rapidly and nearly

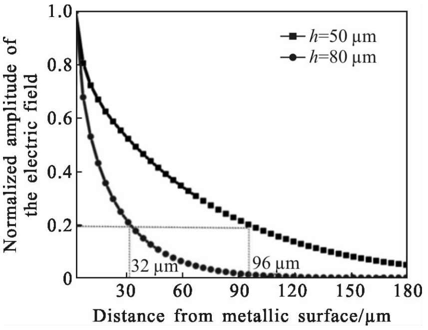

Fig.4 Amplitude of the electric field as a function of distance from the grating surface for h=50 μm and h=80 μm, respectively

disappears at the position of about 90 μm (much less than the incident wavelength). The dispersion relation and sub-wavelength confinement effect of spoof SPPs on the structured metal rely on geometrical parameter of groove depth. Therefore, the electric field characteristics of THz SPPs can be controlled by groove depth, and the deeper groove grating could lead to higher performance of confinement.

2 1D Defect metal grating

In the following section, we discuss THz spoof SPPs on defect structure whose defect groove depth is larger or smaller than the others. In the model, air width a=30 μm, lattice constant d=50 μm, groove depth h=80 μm(the same as the previous uniform grating structure) and defect groove depth is h_1, as all shown in Fig.5. For this set of geometrical parameters, incident EM frequency is also supposed to be 0.7 THz.

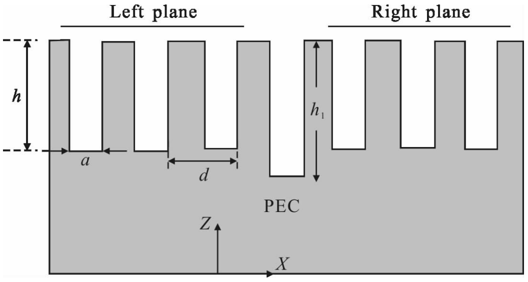

Fig.5 1D defect depth groove metal grating model with air width a, lattice constant d and groove depth h and defect depth h_1. The left plane and the right plane all are 10 μm away from the grating surface

In order to investigate the effects of a 1D surface defect on THz SPPs, we firstly introduce defect depth h_1=100 μm. In the model, the electric field of SPPs is considered respectively two parts, the regions to the left and right of the defect, and the field distribution of THz spoof SPPs is shown in Fig.6. Obviously, field distribution is different from the uniform structure and most of the electric field is in the left region of defect. In addition, the left field amplitude is much stronger than the uniform structure (compared with Fig.3(b)).

Fig.6 Corresponding electric field distribution of spoof SPPs for h_1=100 μm, based on the Fig.5 model

Then we take the defect depth h_1 ranging from 60 μm to 100 μm and consider electric field distribution of both side planes 10 μm away from the grating surface. The normalized electric field amplitude as a function of defect groove depth is shown in Fig.7. It can be seen that, for the defect groove depth below 80 μm, the electric field of both side planes is approximately equal. It means that spoof SPPs can effectively pass through defect and influence of reflection and scattering by defect groove is so weak that it can be neglected. According to the Eq.(1), 0.7 THz cutoff frequency is corresponding to 97 μm groove depth. When the defect depth ranges from 80 μm to 97 μm, the field of the left increases and that of the right decreases with the increase of defect groove depth. These results indicate that the defect is sensitive to response of the incident EM wave. It is reasonable to deduce that spoof SPPs reflection increases while the transmission decreases with increasing the defect groove depth. When the depth is more than 97 μm, it

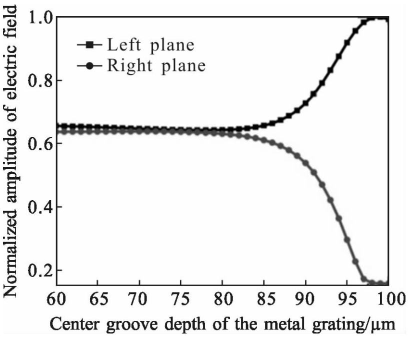

Fig.7 Normalized electric field amplitude of both side planes, in 10 μm away from the grating surface, is as a function of defect groove depth

can be found that the field of both sides remains unchanged with defect groove depth increasing and the maximum amplitude is about 10 times as large as the minimum′s. Based on the phenomenon, it is necessary to have a further explanation that, when the incident EM wave frequency is higher than the corresponding cutoff frequency, spoof SPPs is almost reflected to the left and there are no SPPs propagation over the defect groove. But there is weak field in the right, which comes from defect scattering. And scattering is not sensitive to depth changing. In a word, the reflecting and scattering of defect groove can have influence on spoof SPPs distribution. Therefore, it is a good way to get THz attenuator and filter by changing the defect groove depth.

3 Conclusions

In summary, we have theoretically discussed the groove depth of subwavelength metal grating influence on THz spoof SPPs in detail. The uniform groove depth metal grating as well as the defect groove depth metal grating has been taken into account. For the first structure, it is found that, if incident wave frequency is under the cutoff frequency, the metal grating can transmit and confine spoof SPPs. In addition, the grating with larger groove depth has stronger confinement effect. For the defect structure, the electric field distribution depends on the defect groove depth. If the defect groove depth is less than the other grooves′, the electric field of the two sides is equal. However, once the defect groove depth exceeds the other grooves′, the electric field of the left is obviously stronger than that of the right due to the defect groove reflection and scattering. Based on these analyses, we can conclude that the two structures have the advantage of these features and promising potentials in the future to realize novel application such as wave guiding, sensing, attenuator and filter in THz frequency domain.

References:

[1] Kim S, Jang M S, Brar V W, et al. Electronically tunable extraordinary optical transmission in graphene plasmonic ribbons coupled to subwavelength metallic slit arrays [J]. ***Nature Communications***, 2016, 7: 1-8.

[2] Cao P, Cheng L, Zhang X, et al. Near-infrared plasmonic far-field nanofocusing effects with elongated depth of focus based on hybrid Au-dielectric-Ag subwavelength structures [J]. ***Plasmonic***s, 2016, 11(5): 1-13.

[3] Ren F, Li M, Gao Q, et al. Surface-normal plasmonic modulator using sub-wavelength metal grating on electro-optic polymer thin film [J]. ***Optics Communications***, 2015, 352: 116-120.

[4] Wu A′ni, Li Chenyu, Zhou Qingli, et al. Influence of temperature on resonant properties in terahertz subwavelength metal structures [J]. ***Infrared and Laser Engineering***, 2015, 44(6): 1833-1835. (in Chinese)

[5] Barnes W L, Dereux A, Ebbesen T W. Surface plasmon subwavelength optics [J]. ***Nature***, 2003, 424: 824-830.

[6] Zheng Hongquan, Ning Haichun. Research on waveguide transmission characteristics of spine type medium load surface Plasmon [J]. ***Infrared and Laser Engineering***, 2016, 45(10): 0102005.

[7] Pendry J B, Martin-Moreno L, Garcia-Vidal F J. Mimicking surface plasmons with structured surfaces [J]. ***Science***, 2004, 305: 847-848.

[8] Garcia-Vidal F J, Martin-Moreno L, Pendry J B. Surfaces with holes in them: new plasmonic metal materials [J]. ***J Opt A: Pure App Opt***, 2005, 7: S97-S100.

[9] Liu J, Liang H, Zhang M, et al. THz wave transmission within the metal film coated double-dielectric-slab waveguides and the tunable filter application [J]. ***Optics Communications***, 2015, 351: 103-108.

[10] Liu J, Liang H, Zhang M, et al. Terahertz wave transmission within metal-clad antiresonant reflecting hollow waveguides [J]. ***Applied Optics***, 2015, 54(14): 4549-4555.

[11] Liu L, Li Z, Ning P, et al. Deep-subwavelength guiding and superfocusing of spoof surface plasmon polaritons on helically grooved metal wire[J]. ***Plasmonics***, 2016, 11(2): 359-364.

[12] Ruan Z, Qiu M. Slow electromagnetic wave guided in subwavelength region along one-dimensional periodically structured metal surface [J]. ***Applied Physics Letters***, 2007, 90: 201906.

[13] Monnai H, Shinoda H, Hillmer Y. Focused terahertz radiation formed by coherently scattered surface plasmon polaritons from partially uncorrugated metal surfaces [J]. ***Applied Physics B***, 2011, 104: 913-917.

[14] Song K J, Mazumder P. Active terahertz spoof surface plasmon polariton switch comprising the perfect conductor metal material [J]. ***IEEE Transactions on Electron Devices***, 2009, 56(11): 2792-2799.