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Long-range spoof surface plasmons on the doubly corrugated metal surfaces

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ABSTRACT

In this paper, symmetric spoof surface plasmon (SSP) mode on the doubly corrugated metal surfaces is indentified as long-range spoof surface plasmon (LRSSP) because of its extreme low propagation loss and symmetric dominant field profile so as short-range SSP (SRSSP) for anti-symmetric mode. Based on theoretical calculation and numerical simulation of finite integration method, symmetric and anti-symmetric SSP modes with various gap sizes between these two identical corrugated metal surfaces are investigated in terahertz (THz) regime and good agreement is realized. Besides, the low loss superiority of LRSSP diminishes along with the increased gap size. This work opens up new avenues to utilize this long-range surface mode in far-infrared, THz or lower frequency band and can find many potential applications such as low-loss waveguide, filters and novel electronic sources.

1. Introduction

The topic about the hybrid coupling excitation associated with photons and collective oscillation of free conduction electron on the metal surface, i.e. surface plasmon polariton (SPP) has attracted considerable attentions because of its excellent properties and can bring out many novel phenomena from optics to microwave [1–5]. However, the strong confinement of SPP on the single metal-dielectric interface usually induces tremendous propagation losses stem from the ohmic dissipation on the metal surface. One effective way to reduce losses subsequently lead to long propagation distance is to bound metal film or strip with symmetric dielectrics. As metal film thickness decreases, SPP on these two single metal-dielectric interfaces becomes couple with each other and a symmetric SPP mode is formed, i.e. long-range surface plasmon polariton (LRSPP, also known as s_b mode) [6] which has also been verified experimentally soon later [7]. The other anti-symmetric SPP mode with relatively large attenuation is termed as short-range SPP (SRSPP). Besides, the decay constant of LRSPP is very low with extremely thin metal film which is the long range merit in the symmetric dielectric environment. Unfortunately, LRSPP suffers from the symmetric dielectric claddings and is strongly dependent on the difference of dielectrics which bound the metal film, the issue about LRSPP cutoff and radiation with asymmetric dielectric claddings is studied specifically in Ref. [8] and the propagation loss of metal strip with different dielectrics on the substrate is handled at optical band in Ref. [9]. The detailed theoretical analysis of LRSPP bound mode with different film thickness and limited width on the symmetric structure is implemented in Ref. [10] and a comprehensive overview about LRSPP exists in Ref. [11]. Because of its relatively long propagation distance compared with single interface SPP mode and moderate confinement property, LRSPP has revealed many promising applications in the integrated optics [9,12,13] and many variants from above insulator-metal-insulator structures have been proposed. Various structures such as asymmetric double electrode structure [14], Bragg gratings [15], metal strip on the membranes [16], etc can also be used to sustain LRSPP. Among these derivants for LRSPP, metal-dielectric-metal [17,18] or metal-air-metal structure [19] with or without corrugations are widely studied in the telecommunication wavelength. Recently, much attention and efforts has been focused on the SPP on the doubly corrugated metal surfaces at lower frequency band like Terahertz (THz) or microwave in the context of spoof surface plasmon (SSP) [20]. By structuring metal surfaces with patterned schemes such as periodical holes [21,22] or groove arrays [23], helical groove arrays [24], wedge structure [25], etc, SSP can be confined well on the metal surface compared with that on flat surface. SSP on the structured metal surfaces has also been verified experimentally in THz frequencies [22]. Some functional SSP devices based on the doubly corrugated metal surfaces in this band have been studied and implemented experimentally, like filter [26], waveguide [27], mode convertor [28] etc. SSP on the doubly corrugated metal surfaces is very promising to develop into a new class of devices from THz to microwave band. However, the propagation losses of these two different modes for real metallic structure are not

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treated and compared carefully. Besides, long range SSP (LRSSP) mode on the doubly corrugated metal surfaces has not yet been revealed.

2. Model and theory

In order to give a deep insight into the symmetric and anti-symmetric mode evolution with various gap sizes on the doubly corrugated metal surfaces, the propagation characteristics and losses of these two modes are both treated by theoretical calculation and numerical simulation based on finite integration method (FIM), the two-dimensional structure to be studied is shown in Fig. 1 schematically. The doubly corrugated metal surfaces in the x–z plane are formed by mirror symmetry of single rectangular corrugation shape along gap center and SSP propagates along axial z direction. In what follows SSP modes are assumed to be excited on the structure by using some specified approaches like direct incident light or some electronic means. The representative structure parameters are groove width a, lattice period d, corrugation depth h and gap size G. The dispersion on the doubly-corrugated metal surfaces has been studied in [27] with full-field analysis and/or in [28] by transfer matrix method. Because it's reasonable to treat metal as perfect electrical conductor in THz band, here we develop a simplified modal field expansion method based on the continuity of tangential fields on the two-dimensional interfaces based on above assumption. By solving Maxwell' equations and using boundary conditions on the groove bottoms in region II and III, axial electric field and transverse magnetic fields can be obtained. Also, in the gap region I, the fields can be obtained on the assumption that SSP mode is assumed transverse magnetic mode (TM) along z direction. The Bloch harmonic modes are also considered. Then dispersion relations arise by matching boundary conditions at $z=\pm G/2$. For symmetric SSP mode the analytical dispersion relation is:

$$\frac{d}{a}\frac{\cot(kh)}{k} = \sum_{n=-\infty}^{\infty} \frac{1}{k_{xn}} \sin c^2\left(\frac{\beta_n}{2}a\right)\coth\left(\frac{k_{xn}}{2}G\right) \tag{1}$$

For anti-symmetric SSP mode, the dispersion relation is:

$$\frac{d}{a}\frac{\cot(kh)}{k} = \sum_{n=-\infty}^{\infty} \frac{1}{k_{xn}} \sin c^2\left(\frac{\beta_n}{2}a\right)\tanh\left(\frac{k_{xn}}{2}G\right) \tag{2}$$

where $\beta_n=\beta_0+2\pi n/d$ $(n=0, \pm 1, \pm 2, \pm 3\ldots)$ is propagation constant of SSP mode along z direction, $k_{xn}^2=\beta_n^2-k^2$ and $k=\omega/c$ is wave vector in free space.

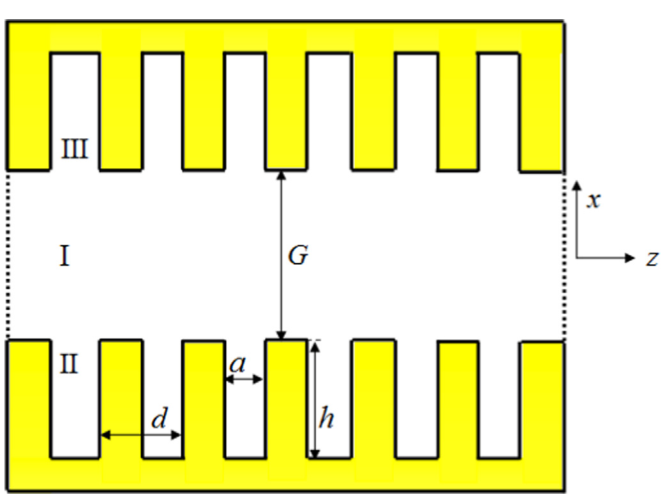

Fig. 1. The un-staggered doubly-corrugated metal surfaces on x–z plane. The upper and lower corrugated metal surface with the same groove width a, period d, depth h are separated by vacuum with a distance of G. The whole structure is divided into three regions of I, II and III for the study of dispersion theory.

3. Results and discussions

By solving above transcendental dispersion expressions about $\omega\sim\beta_n$ $(0\le\beta_n\le\pi/d)$ relation and set dimensional parameters as: $a/d=0.5$, $a=15$ μm, $h=66$ μm, $G=90$ μm which are kept constant if not mentioned additionally, we get the normalized fundamental symmetric and anti-symmetric SSP dispersion mode as shown in Fig. 2 of blue and red circular line respectively. We can notice that for the given gap size symmetric and anti-symmetric SSP modes overlap with each other when it comes to asymptotical frequency (where $\beta=\pi/d$). The light line is also indicated by black solid line and we can easily figure out that the symmetric SSP mode lies below light line thoroughly, which means there is no cutoff frequency (where $\beta=0$). But for anti-symmetric mode it intersects with light line and there is a cutoff frequency. From the following studies we can see that by changing the gap size this cutoff frequency can be tuned. The high panel and low panel of inset is the dominant transverse field contours of symmetric and anti-symmetric SSP mode as indicated by the vertical black dotted line in the dispersion curves respectively. We can inspect that mirror symmetric and anti-symmetric field profiles along gap center are revealed for symmetric and anti-symmetric SSP mode accordingly. Besides, for symmetric mode the field on the separate corrugation surface couples with each other but not for anti-symmetric SSP mode.

From the dominant field distribution of SSP modes on the doubly corrugated metal surfaces, field profiles mainly reside in the space of the gap between these two separate corrugation surfaces. It's interesting and meaningful to study the dispersion modes and field evolution with different gap size. This topic has been partly studied in Ref. [29] and it is shown that the symmetric and anti-symmetric SSP mode departs from each other near asymptotical frequency when the gap size is extremely small. The

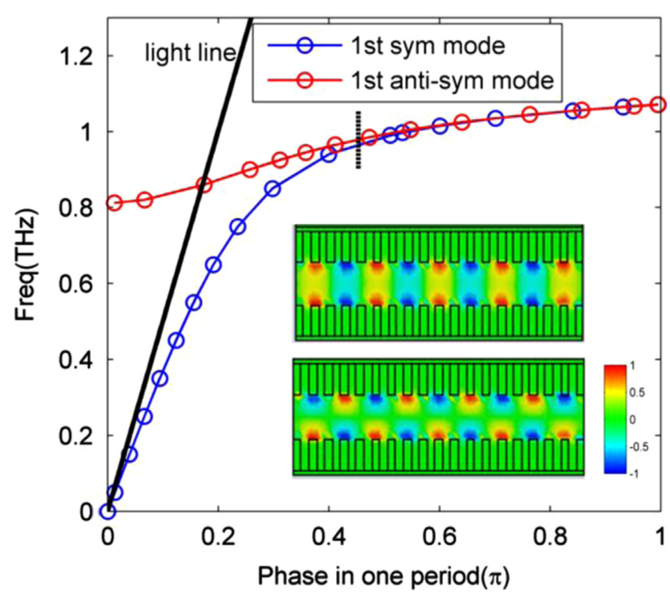

Fig. 2. The fundamental symmetric (blue circle) and anti-symmetric (red circle) SSP mode on the doubly corrugated metal surface structure. The plotted dispersion modes are based on expression (1) and (2). The dominant transverse field profiles of symmetric and anti-symmetric modes by FIM which intersect with vertical dotted black line in curves are plotted in the high panel and low panel of inset respectively. Light line is plotted as black solid line. Useful structure parameters are: $a/d=0.5$, $a=15$ μm, $h=66$ μm, $G=90$ μm. (For interpretation of the references to color in this figure legend,the reader is referred to the web version of this article)