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Efficient excitation and amplification of the surface plasmons

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ABSTRACT

One dimensional (1D) grating has been fabricated (using focused ion beam) on 50 nm gold (Au) film deposited on higher refractive index Gallium phosphate (GaP) substrate. The sub-wavelength periodic metal nano structuring enable to couple photon to couple with the surface plasmons (SPs) excited by them. These grating devices provide the efficient control on the SPs which propagate on the interface of noble metal and dielectric whose frequency is dependent on the bulk electron plasma frequency of the metal. For a fixed periodicity ($\Lambda = 700$ nm) and slit width (w = 100 nm) in the grating device, the efficiency of SPP excitation is about 40% compared to the transmission in the near-field. Efficient coupling of SPs with photon in dielectric provide field localisation on sub-wavelength scale which is needed in Heat Assisted Magnetic recording (HAMR) systems. The GaP is also used to emulate Vertical Cavity Surface emitting laser (VCSEL) in order to provide cheaper alternative of light source being used in HAMR technology. In order to understand the underlying physics, far-and near-field results has been compared with the modelling results which are obtained using COMSOL RF module.

Apart from this, grating devices of smaller periodicity ($\Lambda = 280$ nm) and slit width (w = 22 nm) has been fabricated on GaP substrate which is photoluminescence material to observe amplified spontaneous emission of the SPs at wavelength of 805 nm when the grating device was excited with 532 nm laser light. This observation is unique and can have direct application in light emitting diodes (LEDs).

1. Introduction

A plasmon is a quantum of a plasma oscillation that is a quasi-particle, resulting from the quantization of plasma oscillations just like phonons and photons which are due to quantizations of heat and light, respectively [1]. The plasmons can be coupled with a photon to make another quasiparticle known as plasmon polariton. When the two waves are at resonance the photon-plasmon coupling entirely change the nature of the propagation and forbidden band is established due to the periodicity of the atoms (lattice) of the metal [1,2]. The surface plasmons (SPs) are the oscillations at the surface of the metal [3]. The surface plasmon's frequency ω_{SP} at metal surface can be determined from the frequency of a bulk plasmon of the metal as $\omega_{sp} = \frac{\omega_p}{\sqrt{2}}$, where ω_p is the plasma frequency. Different surface defects/nanostructures in the metals may modify the surface plasmon frequency [4,5]. The SPs take place at the interface of a vacuum or material with a positive dielectric constant, and a negative dielectric constant (usually a metal or doped dielectric). When light interact with the free electrons of the metal leads to collective oscillation as a resonance. This hybridized/coupled mode of the wave gives rise to its unique properties.

The SPs are of interest to a broad spectrum of scientists. The SPs were widely documented in the field of surface science [6]; however, present interest in SPs due to their properties to explore new features of their underlying science and to modify them for particular applications. For example, the plasmons have also been considered as a source of transmitting information on computer chips, since plasmons can sustain much higher frequencies (100 THz range, while traditional wires turn into very lossy in the tens of GHz). Similarly, plasmons have also been suggested as a source of high-resolution lithography and microscopy due to their tremendously small wavelengths. The SPs have the exceptional capability to confine light to very small dimensions which could make possible many other applications including heat assisted magnetic recording (HAMR). Due to the unique property of the SPs to concentrate the light at nanoscale due to subwavelength channel leads to find applications in miniaturization of the photonic circuits [7,8]. Such concentration of light stems from the different negative real part of the permittivity of the metal and positive real part of the adjacent media (known as dielectric) formatting interface where SPs are excited. This confinement of the light leads to an electric field enhancement initiate non-linear phenomena and finds applications in such surface-enhanced Raman spectroscopy (SERS) which is a technique that can detect a single molecule [9,10]. Hence, this enhanced field associated with SPs makes them appropriate for use as sensors [11], and commercial systems have already been industrial for sensing bio molecules

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[12,13].

Hence, the most efficient excitation of the SPs is of prime importance to realize their application in the real world. As the SPP wave vector is larger than that of the free-space photon in the adjacent medium, the incident light cannot directly excite SPs. The 1D diffraction grating is the most useful methods to excite the SPs as compared to an otherwise flat metal film on prism [14]. Many efforts have been put forward in the literature to develop integrated plasmon sources such as single defects/hole [15–19], slits [20–22], nanoantennas [23], and ridges [24,25]. Here we propose 1D gratings fabricated on ~50 nm of Au on GaP. Far- and near field characterization is performed to analyze the performance of the plasmonics device. This study also provides a correlation between far-field and near field features of SPPs. These results were well corroborated by finite element method (FEM) which also enabled a clear understanding to identify the SPP resonances. Furthermore more, grating with smaller periodicity has been employed to investigate spontaneous emission which is associated with the SPs.

1.1. Background theory

The interaction between the charge oscillation and incident electromagnetic (EM) field which make up the SP has two consequences. First, increase in the momentum of the SP mode, $\hbar k_{SP}$, as compared to a free-space photon of the same frequency, $\hbar k_o$, where $k_o = \omega/c$ is the free-space wavevector. This momentum mismatch must be fulfilled to couple light with SPs. Secondly, instead of the propagating nature of SPs along the surface, the field normal to the surface decays exponentially away from the surface. This field is evanescent or near field in nature and is a result of the bound, non-radiative nature of SPs, which stop power to be radiated from the surface.

Fig. 1 (Inset) shows the schematic of the SPPs on the interface consisting of metal film and dielectric, with a metal film of dielectric constant ε_m and adjacent medium of ε_d which is considered to be Re ε_d $(\omega) > 1$ and lossless (Im $\varepsilon_d = 0$) materials. Two independent surface polariton modes may exist on the film interfaces may exist if the film thickness is sufficiently thick. The electric field of the SPPs propagating on the metal interface ($y = 0$) along the x-can be written as [3].

$$E_{SP(x,y)} = E_o e^{ik_{SP}x - k_y|y|} \tag{1}$$

This electric field corresponds to a surface mode propagating along the surface with wavevector $k_{||} = k_{SP}$ and exponentially decaying from the surface.

Solution of Maxwell's equations leads to frequency-dependent SP dispersion relation [26].

$$k_{SP} = k_o\sqrt{\frac{\varepsilon_m\varepsilon_d}{\varepsilon_m + \varepsilon_d}} \tag{2}$$

The corresponding dispersion curve is shown in Fig. 1b along with the light line in air. The k_y determines the SPP field decay from the surface is given by Ref. [3].

$$k_y^2 = k_{SP}^2 - \left(\frac{\omega}{c}\right)^2 \tag{3}$$

The dielectric constant of a metal is larger than the adjacent dielectric which leads smaller penetration depth of the SPP in a metal as compared to an adjacent dielectric.

As the SPP have transverse and longitudinal components of the electromagnetic field and the ratio of the transverse (y-) to longitudinal (x-) components can be written as;

$$E_y = i\frac{k_{SP}}{k_y}E_x \tag{4}$$

Where, the E_y is the transverse component of the SPPs. When the k_{sp} have smaller values i.e. the dispersion curve is close to a light line refers to photon-like excitations whereas for larger value of the wavevectors of the SPP the transverse and longitudinal components are comparable and this excitation is recognized as plasmon-like excitations. In the latter case, the SPP phase velocity is much smaller than former case, as the SPP dispersion comes near the surface plasmon.

In order to plot a dispersion curve for k_{SPP} for Au/air and Au/GaP interface, the complex valued function $\varepsilon_m(\omega)$ is obtained from handbook [27]. This dispersion plot (Fig. 1) have some interesting region to understand the physical nature of SPPs. Just below the asymptotic SPs frequency ($\omega_{SP} = \frac{\omega_p}{\sqrt{1+\varepsilon_d}}$) [28], the SPP mode have much higher momentum as compared to free space photon. At this higher energies the field extent and wavelength of the SPP mode is reduced. Near the SPs frequency, the SPP's nature is purely charge oscillatory. In this region, the SPP are referred as surface plasmonic in nature which was anticipated by Ritchie. At the bottom, the SPP mode lies closer to the light line where the SPP are surface polaritonic in character and analogous to the surface waves which was explored by Sommerfeld and Zenneck. This is the region which will be discussed here.

It is clear from Fig. 1a, the SPP wavevector is larger than the photon wavevector in the adjacent dielectric medium; thus, light incident on a flat surface cannot be directly coupled to surface polaritons. So far three techniques has been used to provide momentum. First technique utilizes prism coupling [29,30], the second engage scattering from the defects on the surface, such as a subwavelength protrusion or hole, used to generate SPs locally [7,31] whereas third involves a periodic corrugation in the metal's surface [32].

If a diffraction grating is formed at a part of an otherwise flat metal film (Fig. 1b), components of the diffracted light whose wavevector coincides with the SPP wavevector will be coupled to surface polaritons as follows [33].

$$k_{SP} = k_o\sqrt{\frac{\varepsilon_m\varepsilon_d}{\varepsilon_m + \varepsilon_d}} = \frac{\omega}{c}n\sin\theta\delta_p \pm p\frac{2\pi}{\Lambda}u_x \tag{5}$$

where $\delta p = 1$ for p-polarized incident light and 0 for s-polarized light, n

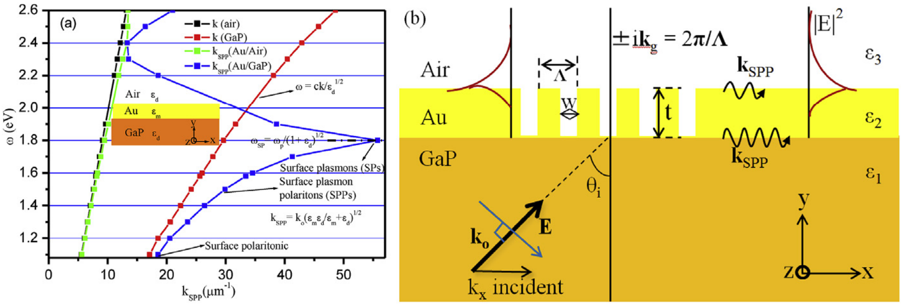

Fig. 1. (a) Dispersion plots for p-polarized light incident upon Air/Au and GaP/Au interface representing $k_{SP} = k_o\sqrt{\frac{\varepsilon_m\varepsilon_d}{\varepsilon_m + \varepsilon_d}}$ in blue and green respectively where as black and red lines represents, $\omega = {}^{ck}/_{\sqrt{\varepsilon}_d}$ light in air and light in GaP respectively. (Inset) Schematic of SPPs on the interfaces of metal film. (b) Schematic of the 1D diffraction grating. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)