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DESIGN AND EXCITATION OF A PLASMONIC METASURFACE V-NANOGROOVE BASED LOCALIZED SURFACE PLASMON FOR NANOPLASMONICS SENSING

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ABSTRACT: The extreme sensitivity of plasmonic-based sensors is well known in optics and photonics community. We design a metasurface V-nanogroove that is capable to excite a localized surface plasmon (LSP) for nanosplamonics sensing. Localised surface plasmon is the collective oscillation when light is coupled within conductive nanoparticles smaller than the incidence wavelength due to the interactions between the incident light and the surface electrons in a conduction band. The LSPs are excited when a coherent monochromatic light is sent through the nanogroove, and the excitation is monitored. Different metasurface plasmonic V-nanogrooves of various sizes (thickness) ranges from 50 to 150 nm were designed. The excited LSPs are used for sensing applications such as biosensing and detecting chemical contaminants in the environment.

Introduction

Plasmonic metasurfaces are artificially manufactured materials having unique optical properties that are not found in a naturally occurring materials. These artificial materials are engineered from metallic nanostructures with a size smaller than the incidence wavelength. The unit cells of the metasurfaces are arranged periodically to allow the manipulation of the geometrical properties in order to alter the bulk permittivity and permeability of the material leading to the unusual optical behaviour. This unusual optical behaviour is due to the collective oscillations of the nanostructures in resonance with the incoming (incident) light, known as localized surface plasmons (LSPs).

LSP is the collective oscillations when light is coupled within conductive nanoparticles smaller than the incidence wavelength due to the interactions between the incident light and the surface electrons in a conduction band. LSP has been used extensively in nanoplasmonic sensing to realize extraordinary optical transmission (Lawrie et al., 2013; Rodrigo et al., 2016; Liu & Lalanne, 2008). Extraordinary optical transmission (EOT) is the electromagnetic resonances generated in subwavelength apertures in either a flat or a corrugated metal film, providing a larger transmission of electromagnetic fields than would be expected from the small aperture size (Rodrigo et al., 2016**).** Plasmonic metasurfaces have been used for wide range applications including transformation optics (Chen et al., 2010), Imaging device (Zhang & Ziu, 2008), sensing platforms (Chen et al., 2012), quantum entanglement (Asano et al., 2015), quantum state engineering **(**Uriri et al., 2018) and many more. Recently, studies have started to probe optical metasurfaces for nanosplamonic sensing (Fan et al., 2015; Dowran et al., 2018**).** However, the use of LSPs in plasmonic metasurface for nanoplasmonic (or quantum) sensing is relatively new **(**Rodrigo et al., 2016). Nanosplamonic sensing using localized surface plasmon offers high sensitivity and precision (Caves, 1981; Goda et al., 2008). Of recent, Researchers demonstrated a sensitivity of 4 x 10^{-9} refractive index unit for a plasmonic biosensors based on extraordinary optical transmission (Ebbesen et al., 1998).

The excitation of LSPs in plasmonic metasurfaces does not depend on the incident photon wave-vector but depends on the size, shape, and dielectric function of the nanostructure material (Lawrie et al., 2013). This optical property makes LSPs a promising candidate for nanoplasmonic (quantum) sensing. The evanescent decay of LSPs through photon emission is independent of the incident wave-vector (Zayat & Simolyaninov, 2003). Because of the independent of the wave-vector on LSP excitation and decay, quantum LSPs can be used as a workbench for quantum nanoplasmonic sensing, quantum nanoimaging, and quantum information in plasmonic systems.

Surface plasmon resonance (SPR) sensors have been widely studied due to their high sensitivity that arises from nanoscale electric field confinement **(**Kawata et al., 2009; Ozbay, 2006; Lee et al., 2012; Tame et al., 2008; Homola et al., 1999). However, the sensitivity of SPR sensors is limited by the well know diffraction limit also known as the short noise limit (SNL) (Piliarik & Homola, 2009). Recently, (Lawrie et al., 2013; Huck et al., 2009) have shown that LSPs can coherently transduce squeezed states, resulting the possibility of quantum plasmonic nanosensors that can surpass the shot-noise limit (Fan, 2015).

In this work, we design a special plasmonic metasurface based v-nanogroove that can be used to generate localized surface plasmons for nanoplasmonic sensing in plasmonic systems.

Theoretical background

Nanoplasmonic sensing that uses surface plasmonic resonance (SPR), in particular, localized surface plasmon is a commercial and practical label-free diagnostic technique that enables the investigation of Ligand-receptor interactions by making use of surface waves (Vasimalla et al., 2021). The technique made possible real time analysis of sensing different molecular species and their interaction at the quantum level. Surface plasmons consist of two surface waves: namely, surface plasmon polariton (SPPs) and localized surface plasmons (LSPs). SPPs are propagating, dispersive electromagnetic waves coupled to the electron plasma of a conductor at an interface of a dielectric (Maier, 2007). On the other hand, localized surface plasmons are non-propagating collective excitations of the conduction electrons of metallic nanostructures coupled to the electromagnetic field. This electromagnetic field induces a dipole moment, p, inside the v-nanogroove plasmonic nanostructure. SPPs are described by the dispersion relation (Maier, 2007):

$$K_{sp} = K_0 \frac{\epsilon_m \epsilon_d}{\epsilon_m + \epsilon_d}, \qquad 1.0$$

where K_{sp} is the propagation constant of surface plasmons. $K_0 = 2\pi / \lambda$ is the propagation constant of an incoming (incident) photon in free space, λ is the incident (excitation) wavelength. ε_m and ε_d are the permittivity of the metal and dielectric, respectively. However, it is difficult to excite SPPs due to the momentum mismatch ($K_{sp} > K_0$) usually experience, hence, the exploitation of a better alternative. The localized surface plasmons (LSPs) do not suffer from this difficulty, thus offer a better alternative for nanoplasmonic sensing. In this study, periodic v-nanogroove nanostructures are designed to generate localized surface plasmons. The designed v-nanogroove plasmonic nanoarrays are a class of 2D nanostructures photonics gratings that allow excitation of LSPs. When a p-polarised wave is incident on one of the axes of the v-groove plasmonic nanoholes of diameter $d << \lambda$, a higher transmission (Excited LSPs) is obtained that is much higher than what is expected by the Bethe's aperture theory (Bethe, 1944). This increase in transmitted light in the arrays of the v-groove plasmonic nanoholes which is due to extra-ordinary transmission (EOT) is well established in the literature **(**Ebbesen et al., 1998).

The Physics of EOT through periodic nanostructures have been studied extensively in the literature (Popov et al., 2000; Martin-Moreno et al., 2001). Zyablovskii et. al. (2017**)** presented a well described analytical model for physics of EOT. The wavelength of light that can be transmitted through the periodic plasmonic v-nanogroove is given by

$$\lambda_{sp} = \frac{\beta_0}{\sqrt{i^2 + j^2}} \sqrt{\frac{\epsilon_m \epsilon_d}{\epsilon_m + \epsilon_d}}, \qquad 1.1$$

Where β_0 is the distance between the v-nanogrooves, also known as the lattice constant. Ii + j are non-zero integral density surface wave scattering orders. $? = \sqrt{\epsilon_d}$ is the refractive index.

Design and Simulation

The plasmonic v-nanogroove nanostructure is designed using COMSOL Multiphysics, a powerful computational platform for engineering electromagnetic media. The design was done using the finite

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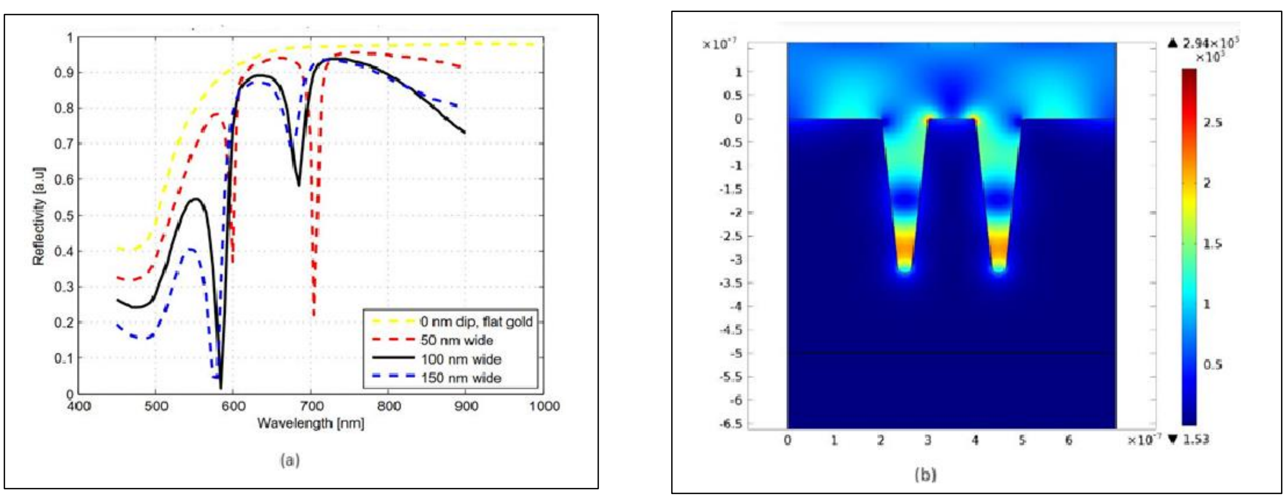
elements package of COMSOL Multiphysics. The arrays of the plasmonic v-groove were patterned on a gold thin film. The geometry of the nanostructure (model) was then discretized into finite elements formed by 2D meshing. Set of linear partial differential Maxwell equations are solved at a point where the modes intersect. Convergence of the individual elements is obtained to achieve the whole model solution. Floquent periodic boundary conditions are then applied to address the periodic v-groove nanoarrays. Only a quarter of the unit cells were simulated due to large computational time involved. To generates LSPs in the designed v-groove plasmonic nanostructure, the two boundaries that are perpendicular to the y-axis and x-axis, were set as perfect magnetic conductors and perfect electric conductors, respectively. The two boundaries or layers act as the incident s-polarized or p-polarized photons propagating into unbounded (open) space or region. The top area of the designed sensor structure is called the analyte while the bottom area is called the substrate. Here, the refractive index, n_d, of the analyte used in the simulation is $n_d = 1.33$ to $n_d = 1.41$ and the substrate, silica n_s. A modified Drude model is used to include the frequency dependent of gold (Rakie et al., 1998). To excite the LSPs, a transverse mode (TM)-polarized plane wave incident from the side of the substrate is used. A strong absorbing perfect-material layer (PMC) is used to terminate the top and bottom boundaries to avoid unwanted numerical reflection back into the interior part of the v-groove plasmonic nanostructure.

Results and discussion

The v-nanogroove plasmonic based nanostructure used in our design have a thickness of 100 nm, internal spacing between the groove is 200 nm and the width is 100 nm. Due to the dependence of surface plasmon on size, we calculated the reflectivity for different depths of the v-nanogroove. To realize localized surface plasmon in the designed plasmonic v-nanogroove, we modeled the expected transmission response by exciting the structure with incident light and integrated a white light spectrum into the simulated spectrum.

Fig 1 (a) shows the transmission spectra when the incident light hits the plasmonic v-nanogroove nanostructure consisting of gold and the analyte. Figs 1 (b to d) show the excitation of the localized surface plasmons at the output of the v-nanogroove for 150 nm, 100 nm, and 50 nm, respectively. The localized surface plasmon realized in the v-nanogroove is due to extraordinary optical transmission (EOT).



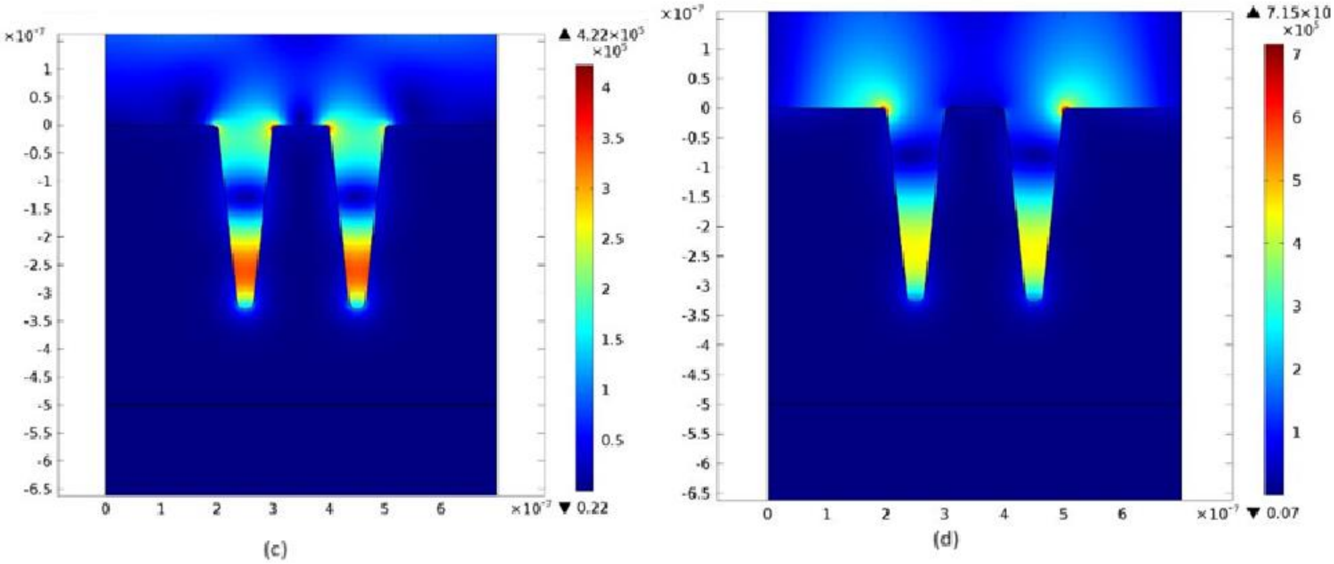


Fig 1: (a) Simulated transmission spectra (calculated reflectivity) of the plasmonic v-groove nanohole array in liquid analyte with a refractive index ranging from n = 1.31 to n = 1.42. (b) Shows the excitation of localized surface plasmon in a 150 nm wide gold v-groove nanohole array. (c) Shows the excitation of localized surface plasmon in a 100 nm wide gold v-groove nanohole array. (d) Shows the excitation of localized surface plasmon in a 50 nm wide gold v-groove nanohole array. The optical depth for all the v nanogroove nanohole array is 150 nm and internal spacing between the array is 200 nm.

The peaks (reflectivity dip) around 590 nm and 700 nm in figure 1(a) are due to the excitation of localized surface plasmon in the gold v-groove nanohole array. The peak around 490 nm is usually ignored in sensing analysis because it is due to the gold thin film associated with the Interband transition. Figure 1 (b) to (d) shows the excitation of the localized surface plasmon in the gold v-groove nanohole array for 150 nm, 100 nm, and 50 nm wide, respectively. The excitation of the localized surface plasmon in the groove is stronger for design with smaller width as shown in Figure 1 (b) to (d). This is also a clear indication that we have successfully excited localized surface plasmon in our design because LSPs depends on the size of the nanostructure or nanohole array.

Conclusion

A plasmonic v-nanogrooves nanostructures for generating localized surface plasmon for nanoplasmonic sensing is designed and investigated. The generated localized surface plasmon in the v-nanogrooves is due to extraordinary optical transmission. The v-nanogrooves are designed in COMSOL Multiphysics on a substrate with refractive index of 1.33 to 141. Our results indicated the excited LSPs depend strongly on the size of the v-nanogroove and was more pronounced for those nanogrooves with smaller sizes. The peaks (reflectivity dip) were found to be around 590 nm and 700 nm. The designed v-nanogroove can be used in a nanoplasmonic sensing platform for biological, chemical, and environmental sensing. These designed plasmonic v-nanogroove can also be used in an onchip photonic sensing platform where the use of a sensor is needed on the go.

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