Design and Characterization of MOEMS Optical Tweezers

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Recent years have seen the modern techniques of micro-machining, such as ion-beam sputtering, plasma sputtering and selective chemical etching, have been developed to the point that it is now possible to fabricate mechanical micro-structures monolithically on the same chip as electronic and optical devices. This has lead to a new class of integrated devices or circuits, which are called micro-opto-electro-mechanical devices or systems (MOEMS). Since this acronym is some what unwieldy, and since micro-electro-mechanical devices (MEMS) were developed before those including optical elements, the latter acronym is often used for both types of devices. Quite a few different types of MOEMS or MEMS have been fabricated to perform a wide variety of functions. In MEMS there are multiple applications since every device is going to be smaller and faster as compare to previous one. Some of them are for huge application and some are for small applications and some are for particle level studies. For particle level studies, we can use Surface Plasmon Resonance condition. Because in that Surface Plasmon Polariton are generated at the boundary of metal and dielectric, where thickness of metal is very small, in the order of few nano meters. Since guiding medium itself in the order of nano meters, we can study nano meter particle, for study of any particle it should be stay in a particular place, so we are using optical tweezer to hold the particle, so that study could be simple and we can get the time for study. General optical tweezer having laser as pump source is not properly suitable for the application because in these cases heating is larger for smaller particles and this is uncontrollable in the case of laser. so we are using SPR as pump source so in this we can control heating.

Keywords: Surface Plasmons, Integrated optical circuits, Optical Tweezers

I. INTRODUCTION

The concept of integrated optics emerged to describe circuits in which the signal that undergo processing and transmission were optical beams rather than electrical current [1, 2]. Integrated optics based on the fact that light beams can be contained by very thin layers (film) of transparent material. By combining such layers and shaping them into appropriate configuration, integrated optics technology has realized a large verity of component which can perform a wide range of operation on optical waves. Such that configuration is realized in physical world combining the different disciplines of optics.

Integrated optics gave rise to a new generation of opto electronics systems in which the wire and cable are replace by light guiding optical fiber and conventional integrated optics are replace by the optical integrated circuit (OIC). Other advantages of integrated optics systems includes reduced weight, increased bandwidth or multiplexing capacity, resistance to electromagnetic interference and low loss signal transmission. When the basic components such as light source, waveguiding channel, detector, etc. are all integrated on a single substrate, it is called as Optical Integrated Circuit (OIC). The implementation of this technology has provided continuing impetus to the development of new integrated optic devices and systems into the beginning years of the 21st century. Another technological advance that has encouraged the development of new integrated optical device in recent years is the availability of improved fabrication methods. Micro technology, which involves dimensions of the order of micrometers, has evolved into nanotechnology, in which nanometer-sized features are routinely produced [1].

That integrated optics approach to signal transmission and processing offers significant advantages in both performance and cost when compared to conventional electrical methods. An OIC is a thin-film-type optical circuit designed to perform a function by integrating a laser diode light source (Electro optics effect), functional components such as switches/modulators, interconnecting waveguides and photodiode detectors all on a single substrate [2]. Through integration, a more compact, stable and functional optical system can be produced. Therefore, the important point is how to design and fabricate good waveguides using the right materials and processes [2].

A. Optical Waveguide

An optical waveguide is a physical structure that guides electromagnetic waves in the optical spectrum.

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Optical waveguides are used as components in integrated optical circuits or as the transmission medium in local and long haul optical communication systems. The optical waveguide is the fundamental element that interconnects the various devices of an optical integrated circuit, just as a metallic strip does in an electrical integrated circuit. However, unlike electrical current that flows through a metal strip according to Ohm's law, optical waves travel in the waveguide in distinct optical modes through total internal reflection. Usually, a waveguide contains a region of increased refractive index (core), compared with the surrounding medium (cladding).

B. Micro-Electro-Mechanical-Systems-MEMS

MEMS is an acronym for micro electromechanical system. MEMS is a process technology used to create tiny integrated devices or systems that combine mechanical and electrical components. In the 21^{st} century MEMS most promising technology. They are fabricated using integrated circuit (IC) processing techniques and can range in size from a few micrometers to millimeters. The interdisciplinary nature of MEMS utilizes design, engineering and manufacturing expertise from a wide and diverse range of technical areas including integrated circuit fabrication technology, mechanical engineering, materials science, electrical engineering, chemistry and chemical engineering, as well as fluid engineering, optics, instrumentation and packaging. The complexity of MEMS is also shown in the extensive range of markets and applications that incorporate MEMS devices. MEMS can be found in systems ranging across automotive, medical, electronic, communication and defense applications.

Current MEMS devices include accelerometers for airbag sensors, inkjet printer heads, computer disk drive read/write heads, projection display chips, blood pressure sensors, optical switches, micro-valves, bio-sensors and many other products that are all manufactured and shipped in high commercial volumes. devices (or systems) have the ability to sense, control and actuate on the micro scale.

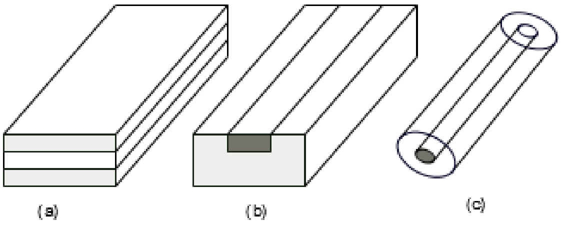

FIG. 1: Basic types of waveguide geometries: (a) Slab Waveguide (b) Channel Waveguide and (c) Cylindrical waveguide (Optical Fiber).

C. Optical Tweezers

Optical tweezers is a device used to trap the micro level particles by using Laser, since laser have very high intensity with a high coherence length to trap the particle. In this method, we impose optical beam on a particle and beam is scattered by the particle and the particle is trapped due to the forces applied in this. There are two types of particle can be trap by using this technique

- particle smaller than the 1 μm
- particle bigger than the 1 μm

For trapping micron level particle we need scattering force, gradient force and gravitational force. For trapping sub-micron level particle, we need scattering force, gradient force, thermal heating and gravitational force, which works on the particle and cancel out each other, so the total force on he particle is zero.

Since these all forces are vectors so by adding all vectors we can get resultant vector, which will be total force applied to this. If we are adding some negative vector then we can make resultant vector equal to zero. this can be done by applying some forces in negative direction, since vector is direction dependent. By making all forces equal to zero we can hold the particle at a particular place and so that it is trapped at that point. This is used in the biological field to hold the tissue and other bacterias, where we have to hold and tissue and burn it by using laser and for other laser operations. In this we can hold the particle any where in free space, so it can be used for the examining the properties of that particle.

II. METHODOLOGY

Surface plasmon polaritons are electromagnetic excitations propagating at the interface between a dielectric and a conductor, evanescently confined in the perpendicular direction. These electromagnetic surface waves arise via the coupling of the electromagnetic fields to oscillations of the conductors electron plasma. According to the simplest Drude model, the free electron oscillate 180° out of phase relative to the driving electric field. As a consequence, most metal posses a negative dielectric constant at optical frequencies which causes very high reflectivity. Furthermore, at optical frequencies the metal's free electron gas can sustain surface and volume charge density oscillations, called surface plasmon politron or surface plasmons with distinct resonance frequencies. The existence of plasmon is characteristic of interaction of metal nanostructure with light. The surface excitations are characterized in terms of their dispersion and spatial profile, together with a detailed discussion of the quantification of field confinement. The surface charge density oscillations associated with surface palsmons at the interference between a metal and a dielectric can give rise to strongly enhanced optical near-field, which are spatially confined near a metal surface. Similarly, if the electron is confined in three dimensions, as in the case of small subwavelength-scale particle, the overall displacement of the electron with respect to positive charge lattice leads to restoring force, which in turns give rise to specific particle-plasmon resonance depending on the geometry of the particle. In particles of suitable shape, extreme local charge accumulations can occur that are accompanied by strongly enhanced optical fields.

In order to investigate the physical properties of surface plasmon polaritons (SPPs), we have to apply Maxwells equations to the flat interface between a conductor and a dielectric. To present this discussion most clearly, it is advantageous to cast the equations first in a general form applicable to the guiding of electromagnetic waves, the wave equation.

$$\begin{aligned} P(\omega) &= \epsilon_0 \chi_e(\omega) E(\omega) \\ D(\omega) &= \epsilon_0 \epsilon(\omega) E(\omega) = \epsilon_0 E(\omega) + P(\omega) \\ \epsilon(\omega) &= 1 + \chi_e(\omega) \end{aligned} \tag{1}$$

These equations clearly suggests the dependence of electric permittivity on the frequency of electromagnetic wave imposed on the metal. Therefore we get χ_e, which is frequency dependent. The nature of dielectric permittivity on frequency is shown in figure 2. It is noted that the real part is negative while the imaginary part is positive in metals.

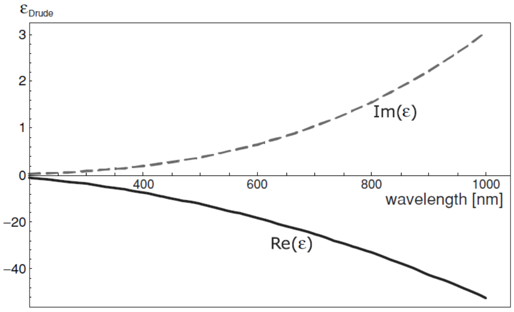

FIG. 2: Real and imaginary part of the dielectric constant for the gold according to Drude-Sommerfeld free electron model. The solid lines are for real part and the dashes lines are for imaginary parts.

A. Metals in absence of photon

Here we consider only the effects of the free electrons and apply the Drude-Sommerfeld model for the free-electron gas

$$m_e \frac{\partial^2 r}{\partial t^2} + m_e \Gamma \frac{\partial r}{\partial t} = e E_0 e^{-i\omega t} \tag{2}$$

where e and m_e are the charge and the effective mass of the free electrons, and E_0 and ω are the amplitude and the frequency of the applied electric field. The damping term is proportional to $\Gamma = \nu_F / l$ where ν_F is the Fermi velocity and l is the electron mean free path between scattering events.

$$\epsilon_{Drude}(\omega) = 1 - \frac{\omega_p^2}{\omega^2 + i\Gamma\omega} \tag{3}$$

Here $\omega_p = \sqrt{ne^2/(m_e \epsilon_0)}$ is the volume plasma frequency. Expression can be divided into real and imaginary parts as follows

$$\epsilon_{drude}(\omega) = 1 - \frac{\omega_p^2}{\omega^2 + \gamma^2} + i \frac{\Gamma \omega_p^2}{\omega(\omega^2 + \Gamma^2)} \tag{4}$$

B. Metals in presence of photon

When light falls on the metal it exits the electron of the metal from valance band to conduction band and make them free. This makes a cloud of free electrons. This is because higher-energy photons can promote electrons of lower-lying bands into the conduction band. In a classical picture such transitions may be described by exciting the oscillation of bound electrons. The equation of motion for a bound electron reads as

$$m \frac{\partial^2 r}{\partial t^2} + m\gamma \frac{\partial r}{\partial t} + \alpha r = e E_0 e^{-i\omega t} \tag{5}$$

Here, m is the effective mass of the bound electrons, which is in general different from the effective mass of a free electron in a periodic potential, γ is the damping constant describing mainly radiative damping in the case of bound electrons, and α is the spring constant of the potential that keeps the electron in place. Using the same equations as before we find the contribution of bound electrons to the dielectric function

$$\epsilon_{interband}(\omega) = 1 + \frac{\varpi_p^{-2}}{(\omega_0^2 - \omega^2 - i\gamma\omega)} \tag{6}$$

Here $\varpi = \sqrt{\eta e^2 / m \epsilon_0}$ with η being the density of the bound electrons. ϖ is introduced in analogy to the plasma frequency in the DrudeSommerfeld model, however, obviously here with a different physical meaning and $\omega_0 = \sqrt{\alpha/m}$ Again we can rewrite to separate the real and imaginary parts

$$\epsilon_{interband}(\omega) = 1 + \frac{\varpi_p^2 (\omega_0^2 - \omega^2)}{(\omega_0^2 - \omega^2)^2 + \gamma^2\omega^2} + i \frac{\gamma \varpi_p^2 \omega}{(\omega_0^2 - \omega^2)^2 + \gamma^2\omega^2} \tag{7}$$

III. RESULTS

Solving the model under frequency domain using the equation of motion of an electromagnetic wave,

$$\triangledown \times \mu_r^{-1} (\triangledown \times E) - k_0^2 (\epsilon_r - \frac{j\sigma}{\omega \epsilon_0}) E = 0 \tag{8}$$

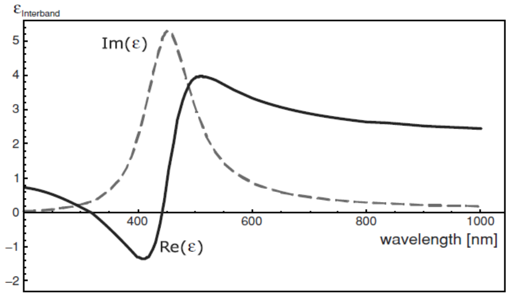

FIG. 3: Contribution of bound electrons to the dielectric function of gold. for wavelength of 450nm. The solid line is real part and the dashed line is for imaginary part of the dielectric function associated with the bound electrons.

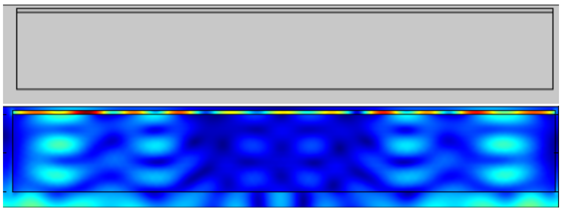

FIG. 4: SPR generation model in COMSOL ,with high intense area as red color and low intense area a blue color. This is plane geometry.

Frequency domain analysis is firstly used for solving the wave equation

$$\nabla \times (\nabla \times E) - k_0^2(\epsilon_r - \frac{j\sigma}{\omega\epsilon_0}). \tag{9}$$

Then for frequency domain, perfect electric boundary is assumed from

$$n \times E = 0. \tag{10}$$

In the geometry, light launched at ports by defining the electrics field

$$S = \frac{\int (E - E_1) \cdot E_1}{\int E_1 \cdot E_1}. \tag{11}$$

SPR is used for the sub-wavelength focusing of light and trapping the light inside a metal dielectric boundary. By using which it is possible to trap a sub-wavelength particle. The simulated results are shown in Figures 4. The upper part of the results shows the design geometry used, while the lower part shows the electric field amplitudes.

It is clear from the figures that SPR are excited at the boundary between the metal and dielectric interface. In order to understand the excited SPR waves, we make few more simulations at the interface.

In COMSOL multiphysics we assumed a silicom wafer as asubstrate. A nano layer of (50 nm) Gold is assumed to be deposited on the substrate. For simulation purposes and for better understanding, light is initially launched without gold layer. In second step same situation is reproduced in the presence of Gold layer. The difference is understood. In the presence of gold a high impulse is coming at the position of gold at 1050 nm, where it is absent in the absence of gold layer as shown in figure 4.

For the trapping of the particle gradient force should be greater than scattering force. When gradient force overcomes the scattering force we can trap the particle. The scattering force on the metal layer boundary with respect to x-direction that is width is shown by the figure 4. In this graph we have seen that gradient force is in positive in negative direction and negative in positive direction so that we can hold a particle in a single point.

The forces applied on the particle are the electric and magnetic field applied. The forces are calculated and the values are represented by arrows. The length arrow is proportional to the magnitude of the force. The length of the arrow is proportional to logarithmic value of magnitude of the force. In this figure 5we are showing the particular area where direction of gradient force is opposite to each other so that we can trap the particle and can be used as a optical tweezers.

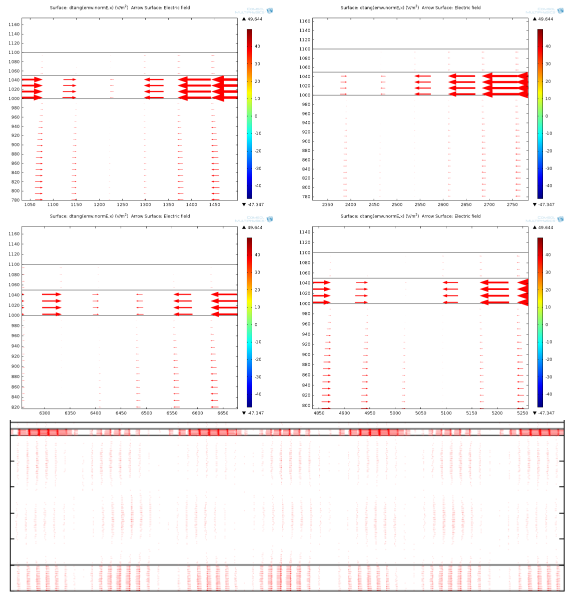

FIG. 5: Demonstration of resultant forces on a submicron size particles. The arrows represent E_x and E_y vectors. The sample is XY plane. The first row shows the E_x components, while second row shows E_y component at two different locations. The bottom image is the resultant of E_x and E_y vectors. Please, look at the boundaries.

By calculating the data from above figures, we have decided to make holes at points, where gradient force are opposite to each others. The reasoning for this may be attributed to the previous theoretical calculations. It may be recalled that, in order to trap a transparent dielectric particle, we need to exert forces from all possible direction to trap the particle within a region. Accordingly, we redisgned the gold layer with voids at appropriate locations. The locations of voids are selected such that, at these locations gradient forces of plasmonic waves propagate in opposite direction as demonstrated in the figure.

The holes are shown in figure 6. The upper part of the figure shows the Comsol geometry and lower part is showing its simulation and light intensity on it.

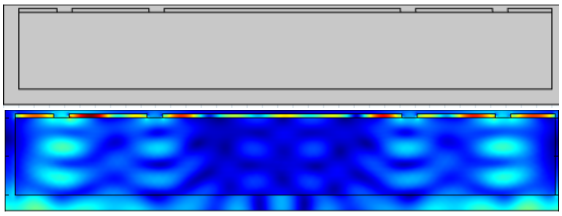

FIG. 6: SPR generation model in comsol,with high intense area as red color and low intense area a blue color. This geometry is with holes.

In the figures 7, Electric field is plotted in x direction and y direction respectively and seeing that this force is high at the positions of holes.

In the figure 8 we are seeing the gradient force applied in the metal air boundary. So that we can overcome scattering force and can trap the particle.

IV. CONCLUSIONS

To conclude, we excited surface plasmons on the interface between metal-dielectric. The generated plasmons propagate in all possible directions. Selection of metal, metal thickness, proper dielectric medium will decide on the properties of plasmon. From the theoretically estimated values of optimized parameters surface plasmons will be generated. Properly guiding them and diverting them will create radiation pressure. The radiation pressure may exert force on the particle being passed on this system. Suitable modifying the surface of the interface may lead to the reflection of plasmons, such that they may be allowed to oscillate in the interface. The classical equation for the understanding of radiation pressure will be adopted. With required modifications the gradient, scattering and thermal forces on the particle will be understood. The Helmholtz equations will be verified again for light propagation. The theoretical force requirement will be defined and given in the units of pN.

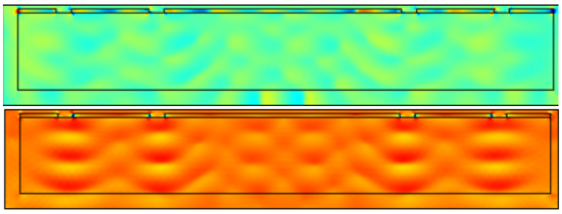

FIG. 7: Electric field gradients in x and y directions.

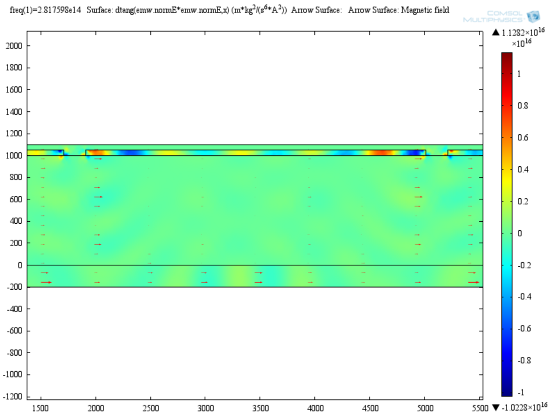

FIG. 8: Gradient force on the metal plate

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