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A Study on Various Plasmonic Waveguide Structures

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***Abstract*—Surface Plasmon Polaritons (SPP) are surface electromagnetic waves that propagate at the interface between a dielectric and a metal. The wave propagates along the interface between two media and remains evanescently confused in both the media in the direction perpendicular to the interface. These surface electromagnetic waves arise due to the coupling of the electromagnetic fields to oscillations of the metal's electron plasma. The Single interface between a metal and dielectric (M-D) is the basic surface plasmon waveguide and the multilayer Dielectric-Metal-Dielectric (D-M-D) and its complementary structure Metal-Dielectric-Metal (M-D-M) are also considered to be the fundamental waveguides for SPP.**

***Index Terms*— Surface Plasmon Polaritons, dielectric, electromagnetic waves, Dielectric-Metal-Dielectric, Metal-Dielectric-Metal.**

I. INTRODUCTION

Surface plasmon (SP) waves are collective oscillation of electrons, moving back and forth near the surface of metal and dielectric layer. When light interacts with the collective oscillations of electrons, coupling between them occurs and surface plasmon polaritons (SPP) are formed. The decay lengths of SPP waves in the direction transverse to the interface are very small which make SPP a strong candidate to over sub-wavelength mode confinement and possibility to guide light in metallic nano-structures. Plasmonic circuits will bridge the gap between photonics and electronics. They potentially serve as building blocks for various optical components such as waveguides, couplers, switches etc.

II. DIFFERENT WAVEGUIDE STRUCTURES

The single interface between a metal and dielectric (M-D) forms the basic configuration for plasmonic waveguides. They have the ability to confine the subwavelength optical modes at metal–dielectric interfaces. The magnetic field is always concentrated at the interface, but it decays exponentially with distance away from the interface in both the metal and dielectric regions. We consider three different cases of the plasmonic waveguides and find the magnetic field associated with each case.

A. Single Metal-Dielectric interface

In this system it consists of two layers metal and the dielectric ,metal having negative permittivity and dielectric having positive permittivity .Assuming that the interface is positioned at x=0,the longitudinal electric field for TM modes:

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$E_Z(x) = E_0 e^{-\alpha c.x}$, , $x \geq 0$ (1)

$= E_0 e^{\gamma x}$, $x \leq 0$

With complete space-time dependence $E_Z(x)e^{j\omega t - j\omega z}$. The corresponding magnetic field is given as

$Hy(x) = -j\omega\epsilon 0E0(\epsilon c/\alpha c)e^{-\alpha cx}$,$x \geq 0$ (2)

$= -j\omega\epsilon 0E0(\epsilon f/\gamma)e^{-\gamma x}$,$x \leq 0$

The propagation factor β and the attenuation factors γ and α with wavenumber k0 can be written as

$\gamma = -(\epsilon f\alpha c)/\epsilon c \Rightarrow \beta^2 - k0^2\epsilon f$ (3)

or solving for β,γ and αc

$\beta = k0\sqrt{}\epsilon f\epsilon c/\epsilon f + \epsilon c$ (4a)

$\gamma = -k0\epsilon f/\sqrt{}-\epsilon f - \epsilon c$ and (4b)

$\alpha c = k0\epsilon c/\sqrt{}-\epsilon f - \epsilon c$ (4c)

where the square root signs have been selected to satisfy the requirements that β have negative imaginary part and β,γ and αc positive real parts.

We have taken an example for various metal-dielectric interfaces and plotted the graph for magnetic field intensity. Figure1 shows the magnetic field plot for the MD interface with silver as metal with permittivity $\epsilon f = -16 - 0.5j$ and dielectric as air with permittivity $\epsilon c = 1$ and operating wavelength is 632 nm .For the TM mode, the magnetic field has been plotted. . For the single-layer metal-dielectric interface, the magnetic-field is found at its peak t the interface and it decays from the interface on both sides, more towards the dielectric.

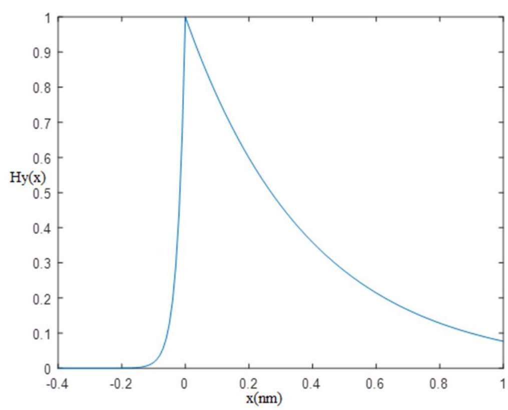
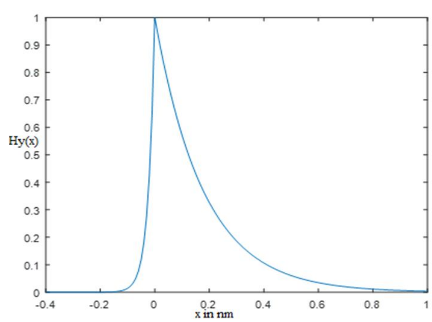


Figure 1. Magnetic field profile of Surface Plasmon

In the second and third examples the dielectric material was changed from air to denser medium keeping the metal constant. Figure 2 shows the magnetic field plot of metal-dielectric with silica as dielectric material and the permittivity being $\epsilon_{silica} = 2.1025$. In Figure 3 ,the dielectric used was silicon with permittivity $\epsilon_{si} = 3.9$.



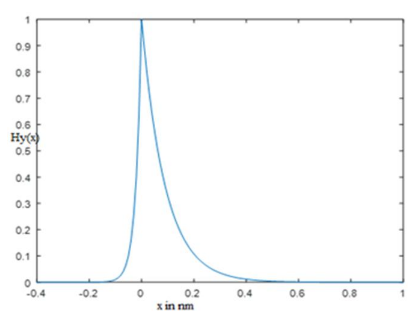


Figure 2. Magnetic field for silver-silica interface Figure 3. Magnetic field for silver-silicon interface

From the examples we can see that as permittivity of the dielectric layer is increased using different materials, the confinement becomes larger.

B. Metal-Dielectric-Metal interface

This system consist of three layers, a dielectric sandwiched between two metals. The metals are assumed to be lossy with permittivities that have both negative real and imaginary parts. The dielectric part is still assumed to be lossless, $\epsilon f > 0$.Moreever we have assumed that the real part satisfy the condition, $\epsilon f < \epsilon s < \epsilon c$, where the plasmons exist at both the interfaces Ref [2].

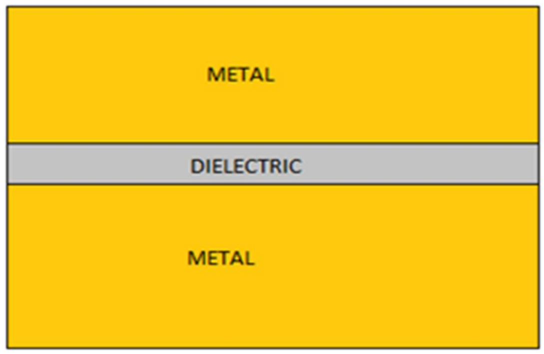


Figure 4 . Metal-Dielectric-Metal based structure

The propagation parameters $\beta,\gamma,\alpha c,\alpha s$, become complex valued . $\alpha c,\alpha s$ have positive real parts and β having negative imaginary part, so that the wave attenuates as it propagates along the positive z-direction, while it remains confined in the transverse direction Ref[2].

To illustrate this we have taken example of symmetric MDM waveguide. For symmetric waveguides the two metal layers will be same, Consider a silver-air-silver waveguide with given permittivity as $\epsilon s = \epsilon c = -19.6224-0.443j$, operating wavelength of $\lambda = 650$ nm and an airgap of width a=50nm Ref[2].The magnetic profile was plotted for different airgap width ranging from 50nm to 1000nm by keeping the other parameters constant. Hy(x) represents the magnetic field and x in nanometer represents the thickness of the dielectric

Figures 5&6 we can see how the light confinement varies with varying airgap width. For an airgap of 50nm, there confinement is low, but as the air gap increases to 100nm the light confinement becomes higher. Hence it can be found that the light confinement can be increased by increasing the gap-width of the dielectric layer embedded between the metal layers.

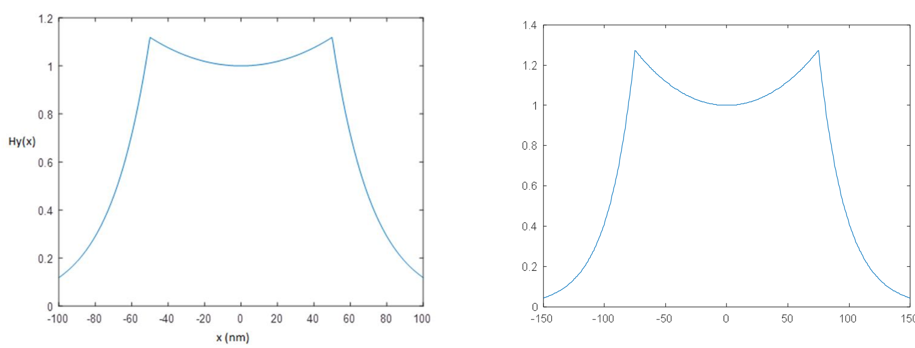


Figure 5. Magnetic field for silver-air-silver waveguide with airgap=50nm and 75 nm

Another example was taken for the asymmetric MDM waveguides,the metal layers were chosen to be different,the upper layer being gold (Au) and lower layer silver(Ag) and the dielectric being silica with relative permittivities chosen to be$-95.92-i10.97$, $-143.49-i9.52$, and 2.1025, respectively with operating wavelength of 1550 nm and the thickness being 50 nm Ref[3].

It was found that 50 nm slab does not support the gap plasmon mode, but increasing the silica thickness to 3μm allows the structure to support gap plasmon mode of both symmetries Ref [3].

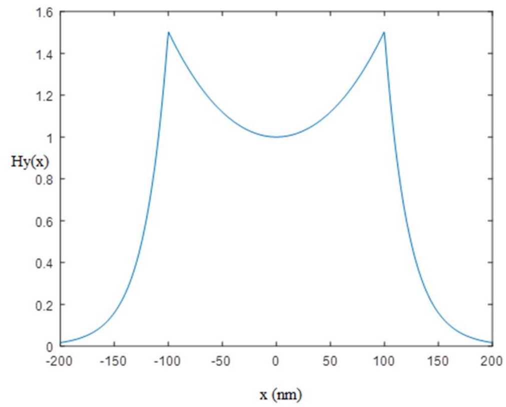


Figure 6. Magnetic field for silver-air-silver waveguide with airgap=100 nm

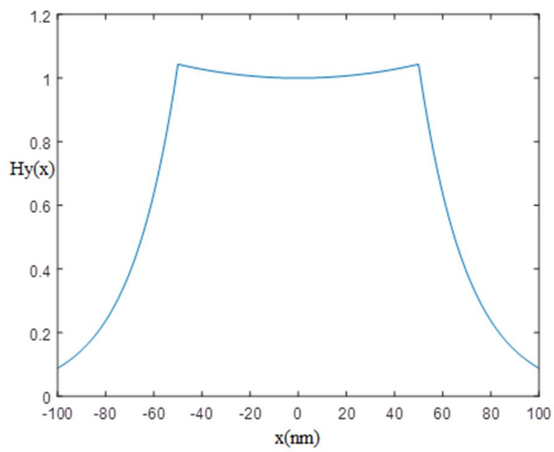


Figure 7. Magnetic field for gold-silica-silver MDM waveguide with airgap=50 nm

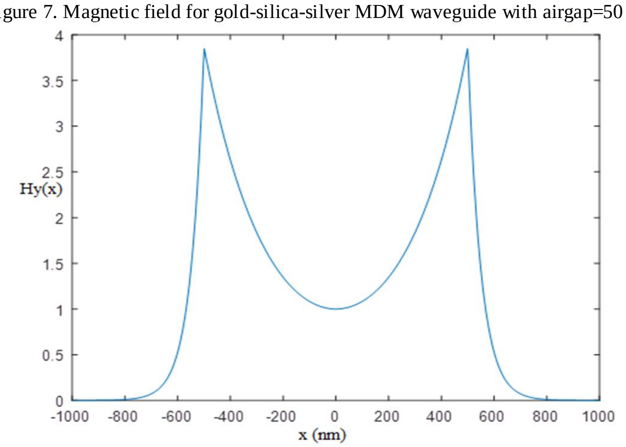


Figure 8. Magnetic field for gold-silica-silver MDM waveguide with airgap=3µm(3000) nm

C Dielectric-Metal-Dielectric interface

A DMD plasmonic waveguide consists of metal film ϵf, surrounded by two dielectrics layers which can have the same permittivity or different.it is operated at optical or infrared frequencies where metal has permittivity with negative real part and dielectric layer having positive real part Ref [2].

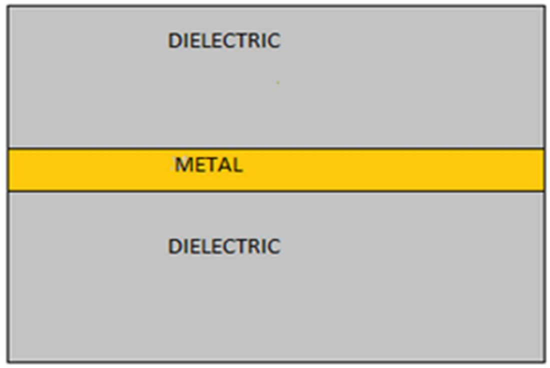


Figure 9. Dielectric-Metal-Dielectric based structure

For the symmetric DMD waveguides, we consider the operation of a 50-nm-thick silver film on a silica substrate at an operating wavelength of 1550 nm. The relative permittivities of silver and silica are −143.49−i9.52, and 2.1025 respectively Ref[3].The magnetic field for the following waveguide with various gap-width was plotted. It can be seen that the field confinement increases as the gap width is increased.

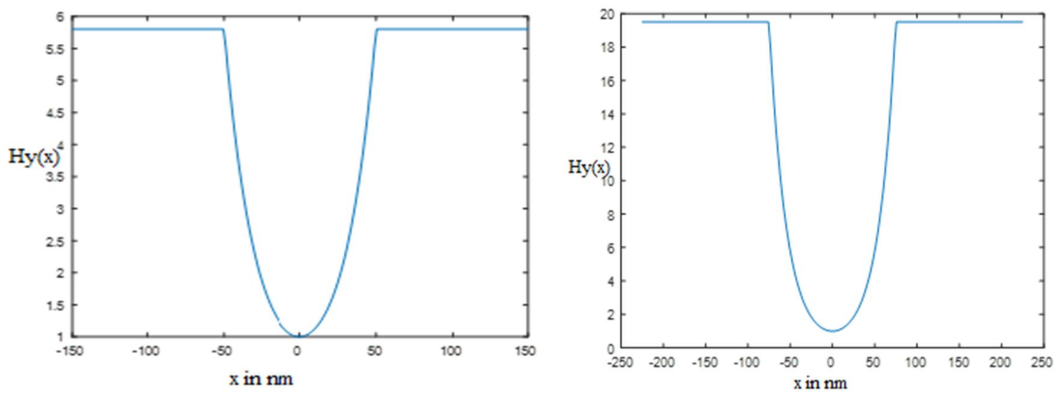


Figure10. Magnetic field for air-silver-silica DMD waveguide with gap width of 50 nm and 75nm

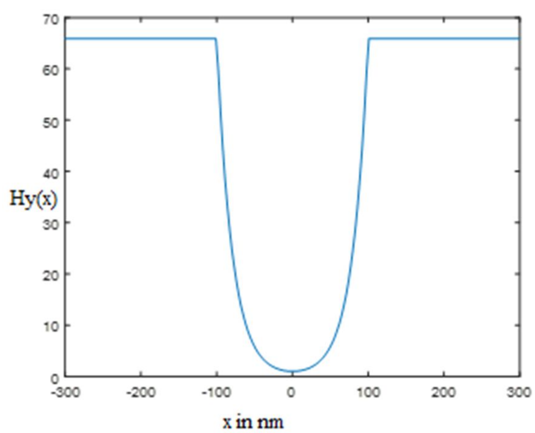


Figure11. Magnetic field for air-silver-silica DMD waveguide with gap width of 100nm

For the asymmetric DMD waveguides, the dielectric layer above was air with permittivity $\epsilon c=1$ and below the dielectric layer was chosen to be silica with a permittivity of 2.1025 with a gap width of 50nm.The magnetic plot for the structure is given below. The field was plotted for even mode.

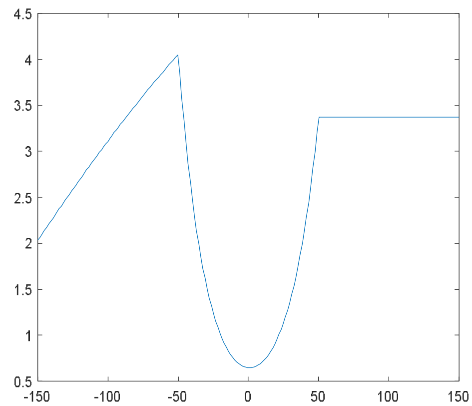


Figure12. Magnetic field for air-silver-silica DMD waveguide with gap width of 50 nm

III. CONCLUSIONS

The various structures for plasmonic waveguides namely single metal-dielectric interface and the three layer structure metal-dielectric-metal and dielectric-metal-dielectric has been studied. The field plots for various structures gives an idea about the confinement of light in the interface between the two types of materials having positive and negative dielectric constants.

In a three-layer system i.e. MDM or DMD structures the gap-width is one of the factors that decides the light confinement, the larger the width, the larger the confinement. The light confinement also depends on the operating wavelength.it exist in the visible regions for wavelength ranging approximately between 630 to 800 nm and in the ultraviolet regions of wavelength between 1300 to 1550 nm.

It has the advantage over dielectric waveguides where light can be confined to subwavelength range. Thus, such a waveguide could be potentially important in providing an interface between conventional optics and subwavelength electronic and optoelectronic devices. There have been several theoretical studies of MIM waveguides showing clear evidence of a subwavelength guided mode with substantial propagation distances Ref [7].

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