Design of a Slow Light Propagating Waveguide Based on Electromagnetically-Induced Transparency for Subwavelength Filters

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Abstract: *A metal-insulator-metal (MIM) waveguide system that exhibits a slow-light effect, based on a plasmonic analogue of electromagnetically induced transparency (EIT), is proposed. We have found that MIM Plasmon waveguides with stub structure (a branch of the waveguide with a finite length), can function as wavelength selective filters of submicron size. The proposed compact configuration may also find potential applications in optical buffers.*

***Key Words*: Subwavelength Filter, Plasmon Waveguide, Electromagnetically-Induced Transparency, MIM waveguide, Slow light**

1. INTRODUCTION

The velocity of light in vacuum is 3×10^8 ms^{-1}. This high velocity is helpful for efficient data transmission, but it makes controlling of optical signals, in the time domain, a difficult task. This difficulty necessitates the reduction of velocity of light and here comes the idea of slow light [1,3]. The phenomenon of slow light introduces the possibility of various new applications including telecommunications.

Scientists are now developing photonic routers that can exploit all optical processing to avoid the opto-electronic conversion that introduces much inefficiency. Here, a key device is the plasmonic waveguide [2-4,7] that temporarily stores and adjusts the timing of optical packets. Plasmonic waveguide can also find potential applications in information storage, optical memory, sensor, nonlinear optics and optical buffers [6,25].

In general, there are three main approaches to generate slow light: quantum interference effects or EIT, photonic crystal waveguide, and stimulated Brillouin or Raman scattering [5,8]. So far, a variety of structures have been reported experimentally or theoretically to realize slow light [9,10].

In this paper, we introduce MIM plasmonic wavelength filtering and demultiplexing devices and present the EIT-like effects in MIM waveguide systems with simulations.

2. SURFACE PLASMON POLARITONS AND PLASMONIC WAVEGUIDE

Surface Plasmons (SPs) are coherent delocalized electron oscillations. Under certain conditions, the incident light couples with the surface plasmons to create surface Plasmon polaritons (SPPs) [14]. The surface Plasmon polaritons are electromagnetic waves coupled to the oscillations of conduction electrons propagating along the metal-dielectric or metal-insulator interface in the direction perpendicular to the interface [11,17,18]. The SPPs have the advantage that they can overcome the diffraction limit of light in a microchip-sized device [22] and that is why they are considered as one of the most promising candidates for integrated nano photonic components [21,23]. The MIM waveguides have the deep-subwavelength confinement of light along with an acceptable propagation length for SPP propagation.

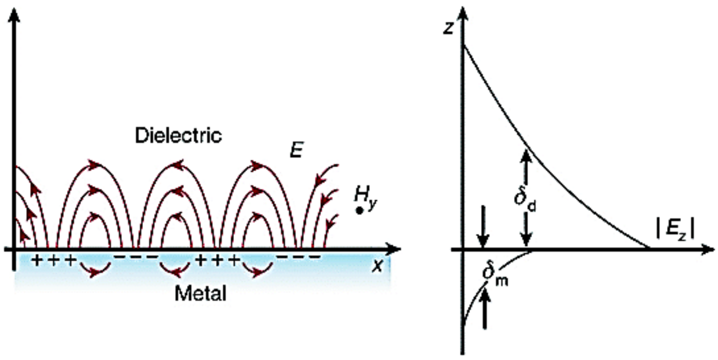

Fig-1. Propagation of Surface Plasmon Polaritons(SPPs).

3. ELECTROMAGNETICALLY INDUCED TRANSPARENCY

The electromagnetically induced transparency (EIT) effect is a nonlinear effect found in the interaction process between light and material. The EIT is observed in atomic systems that arises from quantum interference between the atomic resonances [12]. The transparency window of the EIT is caused by reduced absorption, because of the quantum level [15,16].

4. WAVELENGTH FILTERING & MULTIPLEXING

Wavelength Demultiplexers (WDMs) that can filter specific wavelengths [20] in different channels play very important role in the all-optical systems. Based on MIM-coupled resonators, some WDM structures were proposed [23,24]. However, the transmission efficiencies of those plasmonic

WDMs were too low. In our recent work, necessary emphasis has been put on the schemes to solve this problem [26–27].

5. STRUCTURE & PROPAGATION

To slow down the propagation of light and store optical pulses, waveguide is necessary. Stub structures are introduced into the MIM waveguides for the manipulation of light at the nanoscale. Recently, some analytical methods have been introduced to investigate the optical properties of stub waveguides. For instance, the microwave transmission line was proposed to characterize the transmission properties of MIM stub waveguides [19].

In our work, an improved model is employed to calculate the transmission for our MIM stub structures. Recently, a variety of structures have been reported experimentally and theoretically to realize the slow light effect. Nevertheless, these structures can only be operated at specific resonant wavelength. It is still a challenge to realize slow light over a broad bandwidth [13]. Here, we introduce the slow-light effect in a MIM plasmonic waveguide with quite broad wavelength as shown in Fig - 2.

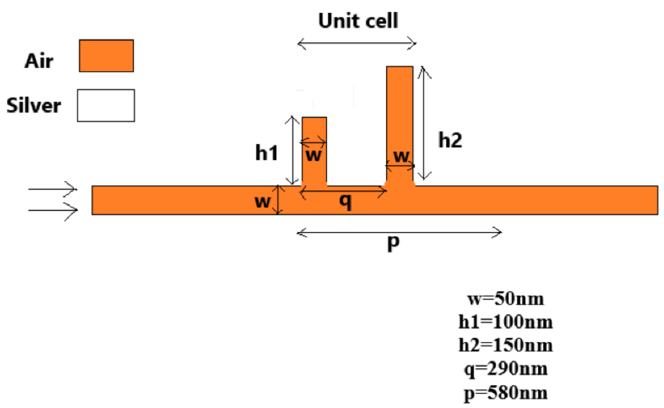

Fig – 2: Experimental Setup of slow light in MIM waveguide.

When a TM-polarized plane wave is coupled into the MIM waveguide, SPP wave can be excited at the metal-insulator interface and confined in the insulator layer. In our structure, silver is selected as metal and air as the insulator. The frequency-dependent relative permittivity of silver is given by the Drude model:

$$\varepsilon_m(\omega) = \varepsilon_\infty - \frac{\omega_p^2}{\omega(\omega + i\gamma)} \tag{1}$$

Here,

ε_∞ = Dielectric constant at infinite angular frequency
ω_p = Plasma frequency
ω = Angular frequency of the incident wave in vacuum
γ = Electron collision frequency

The values of these parameters can be set as ε_∞=3.7, ω_p = 9.5 eV and γ = 0.015 eV. According to the transmission line theory, the plasmonic waveguide system is equivalent to a parallel connection of an infinite transmission line with the characteristic impedance of

$$Z_s = \frac{\beta_s w}{\omega \varepsilon_o \varepsilon_{air}} \tag{2}$$

and serial finite transmission line with the characteristic impedance, Z_s terminated by a load Z_L (representing the stub). Here, MIM waveguide is represented by (2). An equivalent circuit of the system is illustrated in Fig - 3.

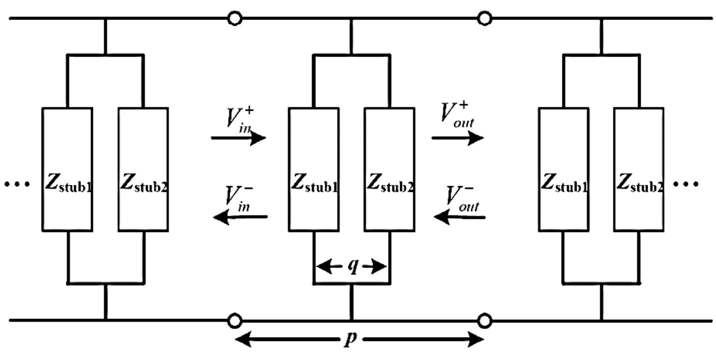

Fig – 3: Equivalent circuit of MIM plasmonic waveguide.

For simplicity, the stub section can be replaced by an effective impedance described by

$$Z_{stub} = \frac{Z_s[Z_L - iZ_s \tan(\beta_s h)]}{[Z_s - iZ_L \tan(\beta_s h)]} \tag{3}$$

Where

$$Z_L = Z_s \sqrt{\frac{\varepsilon_m}{\varepsilon_{air}}} \tag{4}$$

β_s is the propagation constant of the fundamental propagating TM mode in the MIM waveguide and h is the depth of the corresponding stubs where the short stub depth is h_1 and long stub depth is h_2. On the other hand, q is the distance between two stubs in a unit cell. Using transmission line theory, the transmission of plasmonic waveguide system can be expressed as

$$T = A(\frac{p-q}{2})B(Z_{stub_1})A(p)B(Z_{stub_2})A(\frac{p-q}{2}) \tag{5}$$

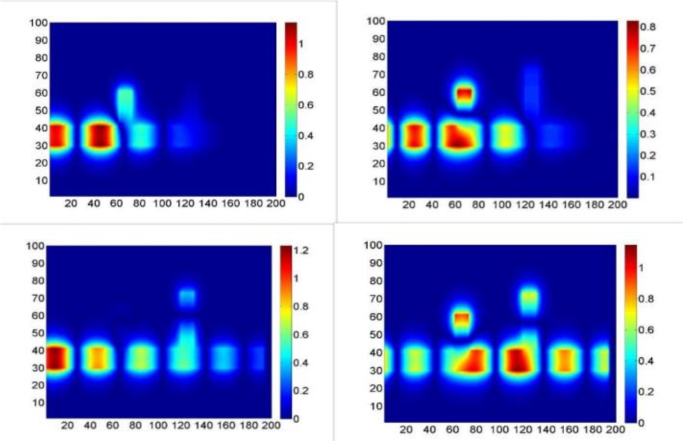

Fig – 4: Propagation of slow light in MIM waveguide

6. TRANSMITTANCE SPECTRUM

We investigate the transmission properties of the MIM waveguide coupled to one-unit cell. The propagation of slow light in this waveguide is shown in Fig - 4. The EIT-like transmission spectrum which can be tuned by changing the distance between the two stubs is depicted in Fig - 5.

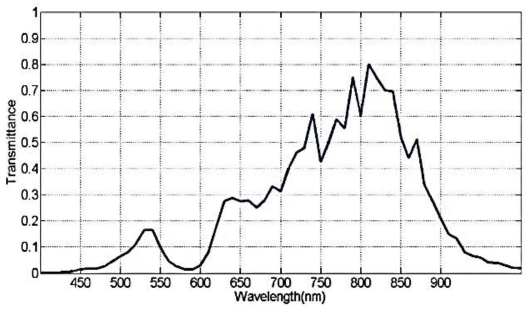

Fig – 5: Transmittance vs. wavelength graph of slow light in MIM waveguide

From CHART- 1 and CHART - 2, we can see that the central wavelength of the narrow-band linearly increases with the simultaneous increasing of h_1 and h_2.

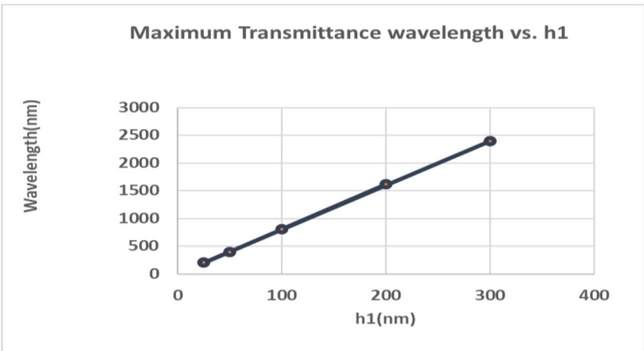

CHART 1: Variation of Maximum transmittance wavelength with respect to h_1

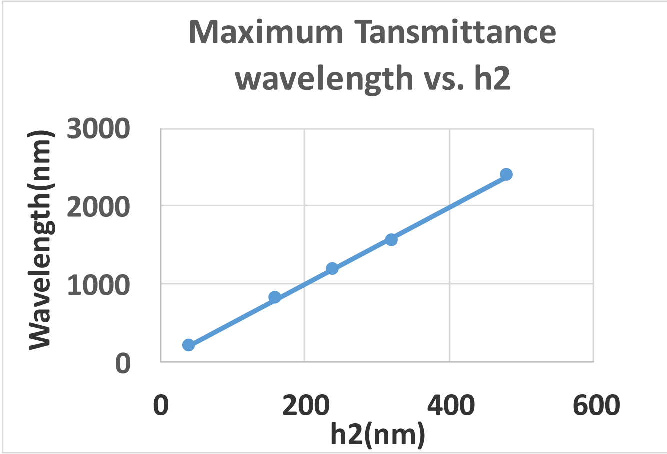

CHART 2: Variation of Maximum transmittance wavelength with respect to h_2

7. CONCLUSION

In this paper, we mainly focus on our work about the manipulation of light in the MIM plasmonic waveguides. Especially, plasmonic wavelength filtering and demultiplexing have been introduced. Additionally, the EIT effect in the MIM plasmonic systems have been described. We propose and investigate a subwavelength slow-light waveguide system. The transmission properties are investigated. Highest amount of power (80%) is transmitted at wavelength of around 815 nm and considerable amount of power is transmitted in the range of around 590 to 1050 nm. The EIT-based slow light waveguide shows noticeable transmittance and thus can be used as a band pass filter. We have also found that the wavelength at which maximum transmittance occurs, varies linearly with the stub depth h_1 and h_2. This plasmonic waveguide system can find other potential applications on slow-light systems as well.

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