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Design of microelectromechanically tunable metal–insulator–metal plasmonic band-pass/stop filter based on slit waveguides

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ABSTRACT

In this work, the ability of complex metal–insulator–metal (MIM) plasmonic structure to act as an optical band-pass/stop filter in telecommunication window, have been investigated. As a plasmonic device, surface plasmons (SP) and well-confined plasmonic modes are the main guiding tools to transport optical power to long range of MIM structure. In order to study the propagation of these surface waves (SPs) and formation of plasmonic modes in the gap distance between metals, we use both numerical and analytical methods. In which, we have considered finite difference time domain (FDTD) and finite element method (FEM) as numerical methods and microwave Transmission Line Method (TLM) for analytical one. The results of these calculations shows a significant transmission/reflection around $\lambda \sim 1.55\ \mu$ mmicrons where these spectral responses are acceptable for realizing band-pass/stop filtering in telecommunication window. Finally, tunability feature have been added by employing Microelectromechanically system (MEMS)—which is called comb-drive. Changing the gap distance between metallic sides in MIM slit, leads to a red or blue shift in the filtering spectra.

1. Introduction

Toward the integrating optical components with high speed electronic devices, to obtain high bandwidth and fast processing systems, the dimensions of these two structures must be consistent, but the photonic devices are much larger than electronic ones. So the special techniques must be employed to fabricate photonic devices at the intended dimensions [1]. But the main challenge is to overcome diffraction limit that occurs at sub-wavelength optical structures [2]. The astounding capability of plasmonic structures in confining and guiding the optical fields in certain frequencies (i.e. resonance frequency of SPs) can be a useful tool to dominate this limit. Indeed, free electrons that oscillate collectively at the surface of the metal – which known as surface plasmon – are the main factor of light confinement in an area smaller than the wavelength. Also, by coupling electromagnetic fields to surface plasmons, optical power can be carried by polaritons which known as surface plasmon polaritons (SPPs) [3]. Several types of plasmonic structures exist to support these surface waves, such as MIM [4], IMI [5], Channel [6,7] and nanoparticles chain waveguides [8]. But, this propagation is limited due to inherent damping of SPs at metal–dielectric interface. Therefore, one must find a way to dominate these loses in order to have a long range transmission. One way to overcome this, is to use gain-assisted plasmonic waveguides which continuously amplifies the light as it travels along the plasmonic waveguide [9]. Another way, not as well as first one, is to use sharp edged metallic structures which can enhance electric field locally [10–13]. But, if the design is optimized in a way to use this local field, the propagation length can dramatically increase in bend, T-shape, and rib structures [14,15]. Accordingly, the long propagation length and strong mode confinement can be provided in the case of proposed structure. Bio-sensors [16], filters [17], plasmonic tweezers [18] are some application which use these sharp-edged structures.

In a recent work done by Chyong-Hua Chen [19], nanoplasmonic band pass filter was proposed which theoretically present the analysis and design of a flat-top spectral characteristics by cascading a series of directly connected rectangular ring resonators based on MIM waveguides. Similarly, we use helical shaped coupled slit waveguides as a cascading system to realize the filtering property. A good example of using MIM system as like as our case, is a submicron plasmonic wavelength filtering/demultiplexing structure based on aperture-coupled slot cavities investigated by Feifei Hu and Zhiping Zhou [20]. Also several works done by [21–30], which uses plasmonic ring resonators and stubs of diverse shapes to control light in a subwavelength limit. Afterward, a mechanism for tuning and controlling the optical response of plasmonic filter have been considered. These mechanisms allow us to

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0030-4018/

Parameters	Value
x_0	1500 $[nm]$
y_0	1845 $[nm]$
a	125 $[nm]$
b	125 $[nm]$
d	125 $[nm]$
w	120 $[nm]$

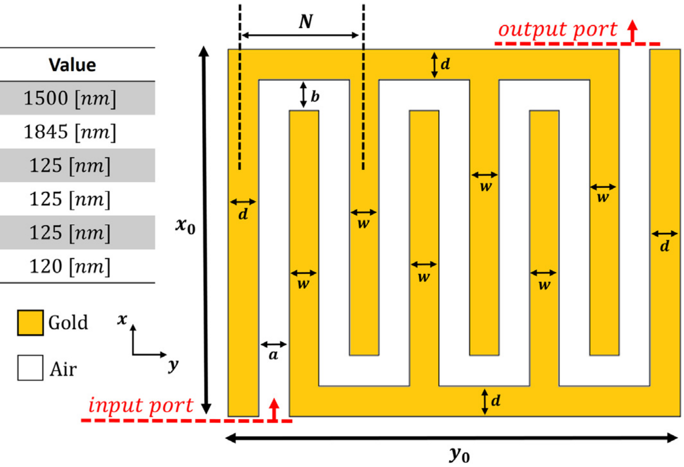

Fig. 1. Plasmonic band pass filter configuration with size parameter shown in table 1. "a" and "b" are the gap distance between metallic arms in vertical and horizontal directions, respectively. "w" and "d" are the width of inner and outer metallic parts and "N" is the period of structure.

have a full control on the transmission spectra. This control can either done by applying electrical potential directly to the structure or using electromechanical systems to move the structure instead [31–35]. In this work, our focus is on electromechanical approach. Wherein, comb-drive actuator is used to alter the gap distance between metals in MIM structure. This approaches for tunability open the door for wide range of applications such as tunable filters, tunable lasers, spectrum analyzer, and bio-sensors [36].

2. Structure and methodology

Fig. 1 schematically shows the structure of plasmonic filter. As it seen, light travels in a long range of multiple bends. This ability of guiding is done through the lightning—rod effects that occurs at each corner of bends [37]. Due to the highest density of charges at sharpest edges of structure, electric field are stronger at this points [38]. When a traveling optical waves reached to this point, localized, concentrate and enhanced at this point. Sharp edges at each bend effectively focus the incoming light from the waveguide before bending and transport to the next waveguide that faced the wave after each bend it [39]. In fact, the focused electric field acts like a secondary source.

Previous studies on light bending by plasmonic slit structures shows the efficient light transmission and stop-band behavior of slit waveguide with the gap distance of (d_{gap} < 100 nm) for wavelengths λ > 600 nm [39–41]. According to these works, structural parameters have been optimized to have an efficient transmission and stop-band behavior in telecommunication window with an acceptable amplitude (see table 1) which optimizes the performance of previous structures. In this paper, the transportation of optical fields by SPPs and plasmonic waveguide modes have been studied, separately [42]. Presented structure in Fig. 1 is suitable for transporting SPPs, where to verify this, numerical methods such as FDTD and FEM have been considered. But, for plasmonic modes, some considerations should take into account. First, the outer metallic parts should be semi-infinite planes. This can ensure the formation of waveguide modes instead of SPPs [42–46]. Another consideration is that, the gap distance between metallic parts should be small enough to ensure that the optical waves are travel only as fundamental plasmonic modes ($d_{gap} < \lambda$) [40]. In our proposed structure, "a" and "b" parameters are much smaller than the operational wavelength, So only the "d" parameter should take to be large ($d \to \infty$). Fig. 2 presents the appropriate structure which can support waveguide modes. In this case, besides the numerical solutions, microwave transmission line theory [47,48] can be a useful tool to handle the problem analytically. It should be noted that, in the case of SPPs, the proposed structure acts as band-pass filter while for plasmonic modes we have band-stop filter in telecommunication window (see Fig. 2).

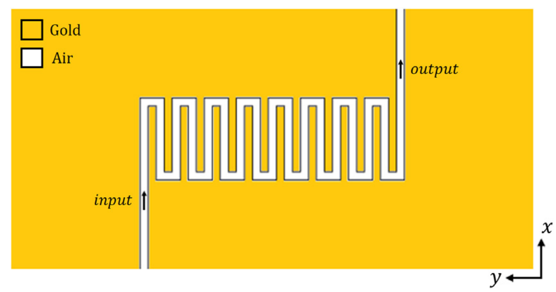

Fig. 2. Plasmonic band-stop filter configuration for $N = 8$. Size parameters are the same with band-pass filter but only the "d" parameter have been considered as infinite ($d \to \infty$).

3. Analytical model

Transmission line method for microwave network analysis, which uses the lumped-element circuit to model the conductors in transmission line, is the best choice to give an analytical solution to the problem of traveling light in slit waveguides. This is due to the analogous between two-conductor transmission lines in microwave and plasmonic MIM structures. Recently, several authors [25–27,49–51] have proposed an equivalent circuit model for their own plasmonic structures. Among them, the equivalent model for plasmonic MIM waveguide with single or multiple stub [25] has the most interest in this work. Where we have considered bend plasmonic waveguide as a plasmonic waveguide with a single stub, which ends in an equivalent impedance with metallic wall ones [48] and has the stub with an arbitrary load. Fig. 3 illustrates the equivalent transmission-line representation for bend plasmonic waveguide that perceived form single stub plasmonic waveguide.

In our proposed structure, where these bend waveguides are combined together, Z_L^s can be defined as the input impedance of the latter bend structure that seen looking toward the previous one. Z_{MDM}, Z_{stub} and Z_{wall} impedances can be obtained according to the following equations [25].

$$Z_{MDM} \approx \frac{\beta_w d_{gap}}{\omega \varepsilon_0 \varepsilon_d} \tag{1}$$

$$Z_{wall} = \sqrt{\frac{\varepsilon_d}{\varepsilon_m}} Z_i, \quad \left(Z_i = Z_{MDM}, Z_s\right) \tag{2}$$

$$Z_{stub} = Z_s \frac{Z_L^s - jZ_s \tan\left(\beta_s d_{stub}\right)}{Z_s - jZ_L^s \tan\left(\beta_s d_{stub}\right)} \tag{3}$$

where in these equations, d_{gap} and d_{stub} are the width of waveguide and stub, ε_d and ε_m are permittivity of dielectric and metallic regions, β_w and