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Realization of single-mode plasmonic bandpass filters using improved nanodisk resonators

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ABSTRACT

In this paper, symmetric and asymmetric plasmonic bandpass filter (BPF) topologies based on the metal–insulator–metal (MIM) configuration are proposed. These filters are numerically investigated using finite difference time domain (FDTD) method. The metal and dielectric used for the realization of the filters are silver and air, respectively. The real and imaginary parts of silver's permittivity used in numerical simulation are based on the Drude–Lorentz and Palik models. Both structures are composed of two waveguides, a nanodisk, and parenthesis-shaped adjunctions. The inclusion of symmetrical and nonsymmetrical adjunctions results in single mode filters with higher transmission peaks compared to the original nanodisk-based filter. To provide better physical insight, various structural parameters of the filter are changed and their effects on filter's response are presented. It is observed that the resonance mode of proposed BPFs can be tuned by changing the nanodisk resonator radius. Such structures can be employed in various plasmonic devices such as multiplexers and demultiplexers for optical communication purposes.

1. Introduction

Surface plasmon polaritons (SPPs) are the electromagnetic excitations that propagate at the interface between metals and dielectric materials. Due to the remarkable capability to manipulate light in a nanoscale domain, SPPs are considered as an efficient basis for the realization of highly integrated optical circuits [1–3]. Growing demands for such elements motivates researchers to design numerous integrated nanoscale optical circuits and devices, such as optical filters, sensors [4,5], demultiplexers [6,7], switches [8,9], Mach–Zehnder modulators [10], splitters [11,12], couplers [13] and so on using the plasmonic technique. Also, at the plasmon resonance, the scattering and absorption cross sections of nanoparticles are enhanced. It can be used to increase the efficiency of solar cells [14]. Among the most important optical devices that have found wide application for wavelength selection are plasmonic filters. Such devices have been the center of attention in recent years. Among the plasmonic filters based on MIM structures, bandpass filters (BPFs) and bandstop filters (BSFs) are of high importance. In order to design an optical BPF the easiest method is to design an optical cavity which has a resonance frequency equal to the central frequency of the BPF. Such cavities are then laterally coupled to the input and output waveguides. If the resonance profile of the cavity matches the profile of the mode which propagates through the waveguides, a BPF can be conceived. To design BSFs, usually the cavity is side-coupled to a waveguide. The most common type of resonator used for realization of MIM plasmonic filters is a circular nanodisk. Such a disk is easy to implement and the resonance frequency can be tuned by variation of its radius.

Over the last few years, many plasmonic waveguide filters based on ring-shaped or circular resonator configurations have been proposed. For example using ring resonators, different BPFs have been designed in [15,16]. Nanodisk resonators were used to design BPFs in [17,18]. To investigate the effects of silver slabs in nanodisk resonator, a plasmonic BPF is proposed in [19] that leads to reduction of the filter dimensions. To achieve a higher Q factor, a filter composed of three cascaded disk-shaped cavities is presented in [20]. Drude model is used for simulation of metal behavior in [20]. Also, nanodisk resonators have been presented in a variety of different versions for filter applications which include hollow-core circular ring resonator [21], a nanodisk resonator coupled with stub resonator [22], L-shaped filter based on nanodisk resonator [23], and stub waveguide with nanodisk and fabry–perot resonator [24]. Other approaches such as plasmonic branch-shaped MIM waveguide with a triangular-annular channel [25], T-shaped plasmonic resonator [26], Archimedes' spiral nanostructure [27], and isosceles trapezoid cavities [28] have also been presented.

The metal–insulator–metal configuration is a relatively old technique for creation of microwave micro-strip filters [29–31]. In an

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integrated circuit the dielectric substrate and metal layers are already accessible. The same metal layers that convey the electric current between different transistors can be used to transport optical signals. MIM structures can be integrated with other electrical or optical components on a single chip. For example the photo-detectors, or laser sources needed for such structures can be implemented on-chip. An analog to digital convertor and a processor may also be integrated together to process the photodetector data. Although high quality optical filters and demultiplexers can be designed and implemented using photonic crystals [32,33], plasmonic devices can occupy far less area than similar photonic crystal devices [34–36], due to their ability to overcome the diffraction limit. Most importantly light amplification is possible in Schottky junction-based plasmonic waveguides. It creates unique capabilities [37,38]. It provides the ability to design a new genre of devices based on MIM topology. In case a Kerr-type nonlinear material is used as the dielectric, the resonance frequency of such filters can be tuned optically. Although Zheng et al. have proposed this technique for tuning the resonance filter the idea can also be employed for realization of all-optical switches [39]. Ring shaped structures can also be employed for design of power splitters [40].

Due to the relatively recent attention and interest to plasmonic filters, a huge amount of the results reported in the literature are still from the simulations only. Lots of such publications use plasma or Drude model for silver or gold in their finite difference time domain (FDTD) simulations. Such models provide nearly accurate results when simulating waveguides. However, we will show that they do not provide accurate outcome when the plasmonic structure contains a resonator. Here Drude, Drude–Lorentz and Palik models are used for numerical characterization of silver and the results are compared together. These methods will be briefly introduced in Section 2. It is observed that Palik and Drude–Lorentz model provide very similar results while the Drude model, which is very commonly used in many papers, is totally unacceptable for simulation of resonator based filters.

There are some deficiencies associated with the waveguide-coupled disk resonator filter topologies reported in the literature. The first one is that for the wavelength range of 600 nm–2000 nm, which is the range reported in most of the papers, the central cavity is dual mode. Having a single-mode resonator is much more helpful when designing more complex structures such as optical demultiplexers. The second one is when such structures only provide high transmittance when the inaccurate Drude model (also known as plasma model) is used. We will show that when more accurate models are used the transmittance will be decreased to half of its original value. In this paper, parenthesis-shaped adjunctions are added to the original resonator structure. Two types of filters are proposed based on using symmetric or asymmetric parentheses. These filters eliminate the lower and higher wavelength resonance modes respectively and provide a single mode behavior for the 600 nm–2000 nm range. Furthermore, the inclusion of the parenthesis shaped structure improves the transmittance of the filter compared to the original nanodisk filters. The proposed structures can thus be used for design of much more complex structures such as sensors and demultiplexers.

Based on the direction of the light propagation, the plasmonic structures can be categorized into two main groups. The light can either propagate along the interface of metal or dielectric layers (in-plane propagation) or be perpendicular to a slab comprising an array of metal and dielectric shapes. In plasmonic crystals which use an array of metallic nanoparticles deposited on a dielectric layer or equally an array of holes etched in a metal surface, the incident light is usually perpendicular to the surface. For the first case, usually a plasmonic waveguide is created using a dielectric layer which is sandwiched between two metal layers. The MIM waveguides seem more appealing for those who seek to have all-optical integrated devices. They can be used for implementing much more complex structures such as demultiplexers [41], antennas [42,43], ring resonators [44,45], memristors [46], circulators [47], switches [48] etc. They can also be integrated with other electronic devices. The fact that such structures can be used to create Schottky plasmonic based amplifiers seems very promising [37,38].

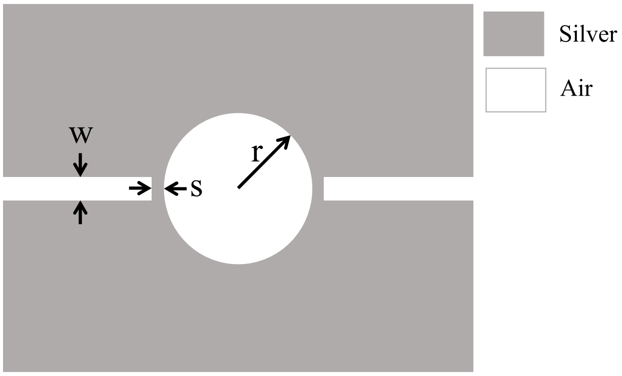

Fig. 1. Schematic configuration of the initial plasmonic filter.

Plasmonic crystals can act as an absorbers based on the localized surface plasmon resonance [49]. They are widely fabricated and used for bio-sensing applications [50,51]. Since the incident light is perpendicular to the surface, no coupling stage is needed for such structure. Only a light source and a photo detector are enough. There are lots of experimental papers published in this area. Some of them are reviewed in [52]. Although such structures are mostly used for sensors, they can also be used to improve solar cells [53,54], create nanolenses [55–57] etc. They are easy to fabricate. The fabrication methods and setups for such crystals are reviewed in [58].

To be able to use MIM waveguides, the optical fiber has to be coupled to it. Unlike the first method which involves metal layer deposition and lithography, it is much more expensive to fabricate and measure the results in these types of plasmonic devices. There has been numerous methods proposed to address the problem of coupling the light to the MIM waveguides. Experimentally tested solutions can be found in [59–62]. They usually involve an input grating coupler. In [63] experimental data and FDTD results for an MIM filter composed of SiO2 and Ag have been compared. Good agreement is observed between the simulation and measurement results in [63]. A same setup can be used for our proposed structure for experimental measurements. The rest of this paper is as follows: In Section 2, the original resonator-based filter is discussed; Drude, Drude Lorentz and Palik models are briefly reviewed and compared together. In Section 3 the proposed structure is presented. Section 4 discusses the results and the last section is devoted to conclusions.

2. Disk resonator-based filter

Fig. 1 shows the topology of the initial plasmonic BPF consisting of two slits (two semi-infinite separated waveguides) and a nanodisk between them. The parameters of the structure are as follows: the radius of the nanodisk ($r = 310$ nm), the widths of the waveguides ($w = 50$ nm), and the coupling distances between the waveguides and the nanodisk ($s = 16$ nm). The insulator material in the white areas is set to be air with relative permittivity of $\varepsilon_d = 1$. The material of the gray areas is assumed silver, which is characterized by Drude, Drude–Lorentz, and Palik models that will be discussed shortly after. Silver due to its low Ohmic resistance, compared to other metals, is one of the most widely used metals in plasmonic.

2.1. Drude model

The Drude model for the permittivity of a metal, which is the most simplified model, can be expressed as follows [16,23]:

$$\varepsilon_m(\omega) = \varepsilon_\infty - \frac{\omega_p^2}{\omega(\omega - j\gamma)} \qquad (1)$$