ARTICLE IN PRESS

Optics Communications ∎ (∎∎∎∎) ∎∎∎–∎∎∎

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Nonlinear tuning techniques of plasmonic nano-filters

Rehab Kotb, Yehea Ismail, Mohamed A. Swillam *

University of Toronto, Physics/ECE, 60 St. Goerge Street, Toronto, Ontario, Canada L7L 6L4

ARTICLE INFO

Article history:
Received 30 June 2014
Received in revised form
16 September 2014
Accepted 24 September 2014

Keywords:
Plasmonics
Tunable filter
Nano-filter
Electrical tuning
Optical tuning

ABSTRACT

In this paper, a fitting model to the propagation constant and the losses of Metal–Insulator–Metal (MIM) plasmonic waveguide is proposed. Using this model, the modal characteristics of MIM plasmonic waveguide can be solved directly without solving Maxwell's equations from scratch. As a consequence, the simulation time and the computational cost that are needed to predict the response of different plasmonic structures can be reduced significantly. This fitting model is used to develop a closed form model that describes the behavior of a plasmonic nano-filter. Easy and accurate mechanisms to tune the filter are investigated and analyzed. The filter tunability is based on using a nonlinear dielectric material with Pockels or Kerr effect. The tunability is achieved by applying an external voltage or through controlling the input light intensity. The proposed nano-filter supports both red and blue shift in the resonance response depending on the type of the used non-linear material. A new approach to control the input light intensity by applying an external voltage to a previous stage is investigated. Therefore, the filter tunability to a stage that has Kerr material can be achieved by applying voltage to a previous stage that has Pockels material. Using this method, the Kerr effect can be achieved electrically instead of varying the intensity of the input source. This technique enhances the ability of the device integration for on-chip applications. Tuning the resonance wavelength with high accuracy, minimum insertion loss and high quality factor is obtained using these approaches.

1. Introduction

Plasmonic devices have received growing attention in the last decade due to their ability to confine light at sub-wavelength scale. The free electrons in metals interact with the electromagnetic field in the dielectric to form surface plasmon polaritons (SPPs) wave that propagates along the interface between the metal and the dielectric . [1] Recently, various optical devices have been realized based on SPPs such as modulators [2], Mach–Zehnder interferometers , [3] demultiplexers , [4, 5] optical switches , [6] power splitters , [7] filters , [8, 9] and sensors [10–12]. Furthermore, plasmonic structures have been used to design some semiconductor devices such as Terahertz lasers, [13] light emitter diodes, [14] and superluminescent diodes [15,16]. In these devices, SPPs manage to realize high power semiconductor devices. Using plasmonics, Terahertz lasers with high output power (>2 mW) is demonstrated , [13] which can be used in chemical detection and medical imaging. A novel method to enhance the efficiency of InGaN light-emitting diodes using SPPs has been reported. [14] Guiding light by SPP waveguides results in increasing spontaneous emission coupling in superluminescent diodes and hence high output power is achieved [15, 16].

Among various configurations, Metal–Insulator–Metal (MIM) is considered as a suitable structure for sensing and filtering applications. MIM consists of a sub-wavelength dielectric core surrounded by metal cladding. Extremely compact devices can be realized using MIM with their ability to provide a sub-diffraction confinement. The analytical model for MIM mesh waveguides has been demonstrated in [17]. MIM plasmonic waveguides are very attractive due to their ability to achieve lossless sharp bending which is impossible in the conventional dielectric waveguide. Despite the fact that MIM plasmonic waveguide suffers from coupling problem to and from its nano-core, this problem has been solved using ultra compact, ultra wide band coupler between plasmonic slot waveguide and silicon waveguide . [18, 19] The 3D version of this MIM plasmonic waveguide with more than 70% efficiency has been proposed [19]. MIM waveguides provide a solution to the mismatch problem between micro-scale optical devices and nano-scale electronics and allow for high dense integration. Therefore, they are used as a wide bandwidth optical interconnects that can be integrated with electronic devices at the transistor level of the integrated circuits . [20]

Optical tunable filters are needed in communication systems and sensing applications. In communication systems, tunable filters are used in monitoring and administrating communication

* Corresponding author.
E-mail address: m.swillam@utoronto.ca (M.A. Swillam).

http://dx.doi.org/10.1016/j.optcom.2014.09.062
0030-4018/© 2014 Published by Elsevier B.V.

channels. Their role in wavelength division multiplexing (WDM) has a great effect in increasing the capacity of optical networks [21]. Narrow bandwidth and wide tuning range filters are required in WDM to achieve high bit rate and to increase the number of communication channels. On the other hand, tunable filters are used in demultiplexers to have a single small device that can switch between different channels. In addition, tunable filters can be used in tunable laser and optical switching . [22] In biomedical diagnostics, fast and accurate tunable filter is required in application such as optical coherence tomography [23] and biomedical analysis of human fluids [24]. Easy, accurate, and fast tuning mechanisms are required for the aforementioned applications.

In spite of the ability of the plasmonic devices to confine light at sub-wavelength scale and provide high density integration, designing tunable plasmonic nano-filter for the aforementioned applications is challenging. There are different methods of tuning mechanisms, either mechanically using Micro/Nano Electro Mechanical Systems (MEMS/NEMS) or by using the electro optic (EO) effect of some dielectric materials. The mechanical actuation suffers from many problems such as: it leads to increasing the device area, fragile and has small range of tunability . [25–27] As a consequence, the electro-optic actuation is considered as an effective solution to the aforementioned problems. Many optical devices based on electrical actuation have been proposed. In [28, 29] a plasmonic ring resonator is used to design an optical switch by the electro-optic effect. The applied voltage controls the coupling between the ring and an adjacent waveguide to control the output response of the device. However, their range of tunability is small and suffers from critical fabrication process to be able to adjust the gab size between the ring and the waveguide. Electro optical effect is used also to design optical modulators based on Mach–Zehnder interferometer (MZI). [30, 31] These designs managed to realize high bandwidth modulator with low voltage that can transmit high data rate. However, the fabrication of MZI is very challenging and the two arms of the interferometer have never been fabricated exactly the same as designed. This results in undesired path difference affects the overall device performance. In addition to control the device behavior by applying voltage, the output response can be controlled by adjusting the input intensity. Various optical devices such as optical switches , [6, 32] and couplers [33] are using the nonlinear effect of Kerr materials to control the device behavior optically.

Generally, plasmonic structures are highly sensitive to the design parameters. As a result, accurate and efficient numerical method is needed to reliably predict the performance of a new device. Currently, finite difference time domain (FDTD) is the most common method used to analyze and optimize plasmonic devices. However, by increasing the complexity of optical devices and using fine mesh to achieve accurate results, FDTD method results in considerable computational costs and long simulation time. In addition, this method does not provide a detailed physical insight into the device to allow understanding of its behavior. Thus, accurate, fast, and memory-efficient numerical modeling is needed to design plasmonic-based devices. An analytical model that enables the designer to understand the behavior of plasmonic waves inside different plasmonic structures is of prime importance.

In this paper, a highly compact and efficient plasmonic nano-filter is proposed. An analytical model that describes the behavior of the filter is introduced. The model is based on the physical parameters of MIM plasmonic waveguide. A fitting model to the modal characteristics of MIM plasmonic waveguide is proposed for the first time, to the best of our knowledge. A direct fitting to the propagation constant and losses obtained from FDTD simulations is demonstrated. This model paves the way to find closed formulas to different plasmonic structures instead of solving Maxwell's equations to find the propagation mode. As a result, the needed simulation time and computational resources to find the response of different plasmonic structures is reduced significantly. The accuracy of the model is verified by comparing its result with FDTD simulations. This analytical model to the propagation constant and losses results in having a full theoretical model that can be used to optimize the design of the proposed filter. For the first time, the sensitivity of a plasmonic structure to the different design parameters is investigated analytically. Therefore, the design of the filter can be optimized in fast, easy, accurate, and efficient way. The demonstrated inline nano-filter can be tuned easily using different tuning mechanisms. A wide range of tunability is achieved depending on the non-linearity of the material used as the waveguide core. By changing the applied voltage or the intensity of the input light, the output response can be controlled. The behavior of the filter using both Pockels and Kerr effect are introduced and analyzed. By applying an external voltage, a range of tunability up to 47 nm is achieved. On the other hand, tuning the filter by adjusting the input light intensity leads to tunability range up to 80 nm. One of the main advantages of this filter is that it supports both red and blue shift in the resonance wavelength. By having an electro-optic material with positive or negative non-linearity, a red or blue shift in the resonance wavelength can be demonstrated. Therefore, the behavior of the filter and the direction of resonance shift can be controlled by properly choosing the material of the dielectric core. A new approach of multi-stage electro-optic tuning is proposed for the first time. By filling the filter with Pockels material, the output intensity of this stage can be controlled electrically. This controlled output intensity can be used as input light to a second stage filled with Kerr material. Therefore, the output of this second stage can be tuned. Using this approach a wide range of tunability using a very low power can be achieved. Using this new cascading method, 60 nm shift in the resonance wavelength per 10 V is demonstrated. The proposed plasmonic filer has compact size, sharp response, low loss and hence a good quality factor.

2. MIM plasmonic resonator

The design of the proposed filter is shown in Fig. 1. It consists of dielectric core surrounded by metal slabs and two transverse metal sides (M_1 and M_2). The metal used in this design is silver . [34] In Metal–Insulator–Metal (MIM) waveguides, the quasistatic approximation can be applied as long as the dielectric core width is much smaller than the wavelength . [17] Generally, the excited plasmonic wave propagates along the interface between the metal and the dielectric. By reducing the core diameter of MIM to a few tens of nanometers, the waves on both upper and lower interfaces couple to each other and create a propagation mode. The wave

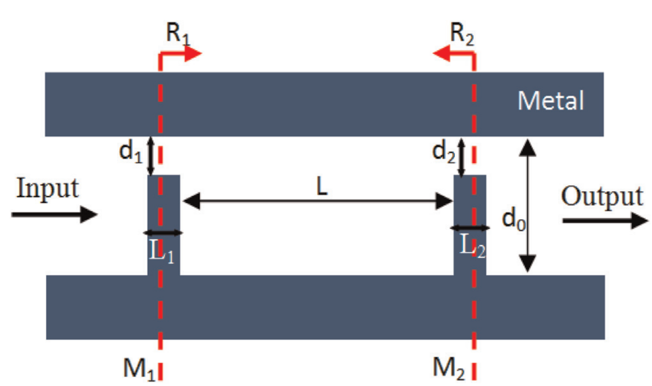

Fig. 1. Schematic diagram to the inline nano-filter.

Please cite this article as: R. Kotb, et al., Optics Communications (2014), http://dx.doi.org/10.1016/j.optcom.2014.09.062