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Nanoscale highly selective plasmonic quad wavelength demultiplexer based on a metal–insulator–metal

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ABSTRACT

A nanoscale plasmonic demultiplexer based on a plasmonic slot resonator is proposed. The device is optimized for high selectivity and minimum FWHM. The device is capable of achieving a demultiplexing FWHM of 9.8 nm for each channel with a high output transmission. The structure is optimized for double and quad channel demultiplexing near the 1550 nm. The proposed structure is simple, can be easily fabricated and can be cascaded for a large number of channel demultiplexing.

1. Introduction

Surface Plasmon Polaritons (SPPs) are electromagnetic waves that have the ability to confine and guide light in dimensions much smaller than the diffraction limit. This unique advantage opens the door for a wide range of applications [1,2]. However, the rapid decay of the field intensity of SPP with the propagation distance is considered a major challenge. This challenge motivates the research for innovating smaller scale devices to in a nanometric scale in order to reduce the effect of propagation loss on the total insertion loss of the plasmonic devices. This huge miniaturizing is also essential in integrating nanophotonics with electronics and circumventing the size mismatch dilemma between electronics and photonics.

Among various plasmonic waveguides, the metal–insulator–metal (MIM) waveguide, and its 3D counterpart plasmonic slot waveguide, are considered the most suitable configuration for high dense integration and tight confinement of optical fields [3]. However, coupling to a MIM waveguide with a few nanometer-wide cores is very challenging. Albeit the difficulties, coupling to an MIM waveguide can be achieved throughout the use of hybrid junctions [4,5]. This technique provides an efficient, wideband, and non-resonant coupling scheme to and from a silicon rib waveguide. On the other hand, the high propagation losses put stringent constraints on not making the device dimensions exceed a few microns to avoid the high associated propagation loss.

In the last few years, various novel devices have been proposed that satisfy these dimensions' constraints. These devices include band-pass and band-reject filters [6], resonators [7,8], interferometers [4,7,9], couplers [4,10], demultiplexers [6], logic gates [11], power splitters[12], and on chip sensors [13], which led the way for nanoscale optical system using plasmonic circuitry [1].

For such optical system with complex functionality, multiple channel operation is necessary. This requires high selectivity of the demultiplexer. However, wavelength division demultiplexing (WDM) is considered one of the challenging applications using SPP configuration. This is mainly due to the high associated losses that limit the ability of obtaining high resolution in channel selectivity. This resolution of the demultiplexer is essential to increase the number of channels that can be multiplexed over a given band. Plasmonic demultiplexers with high resolution can be achieved using dielectric loaded plasmonic (DLSPP) configuration [14–19]. In this configuration, the high index dielectric region can be utilized to reduce the propagation losses of the structure but requires a large area as it suffers from radiation losses. DLSPP is considered as another configuration that offers lower losses but at the cost of the size and high confinement. Even though the higher resolution of the MIM configuration is challenging, it is of prime importance in improving the functionalities of plasmonic circuits.

Various plasmonic demultiplexers have been proposed with large variations in terms of FWHM, peak transmission, and the

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ability to be tuned to a specific wavelength (tunability). In general, there is a tradeoff between FHWM and transmittance. For example, using nano-disk geometry, a demultiplexer was proposed in [20] that offers a high transmittance (on average, 85%) but with wide FWHM that is in the ranges of 80 nm. A nano-capillary based demultiplexer was recently proposed in [21], with transmittance in the ranges of 30% and a FWHM in the range of 100 nm. A wavelength filter based on plasmonic slot cavities shows a transmittance of around 65% and FWHM of around 50 nm [22].

Recently, the MIM configuration has been utilized to achieve a demultiplexing resolution of around 18 nm [23]. The device utilizes a Fano-like resonator based on an MIM waveguide and a baffle to stimulate the Fano resonance. The team managed to achieve these high resolutions with relatively high full width half-maximums.

In this paper, we propose a novel design of plasmonic demultiplexer based on a feedback resonator offering a competitive FWHM. An optimization procedure is applied in this work in order to achieve the required characteristics. The proposed optimal design succeeded to reach a FWHM of 9.8 nm with peak power of ~50%. The structure is also exploited for quad channel demultiplexing. The device is simple and allows easy cascading for a large number of channels.

2. Design methodology

Finite Difference Time Domain (FDTD) simulations are utilized to analyze and optimize the structure using a commercial tool [24]. An optimization methodology is exploited in order to obtain the design with minimum FWHM. For these simulations, a source of broadband frequency in the range of 1000–2000 nm is utilized. The simulations' time is set to a maximum of 1000 fs. A minimum mesh step size of 1 nm in the *x* and *y* directions to ensure accuracy and convergence. For the computational boundary, Perfectly Matched Layer (PML) boundary is utilized.

The time step used is 0.00495157 fs, with a stability factor of 0.7, with a maximum simulation time of 1000 fs. For the silver metal, the refractive index data is taken from Johnson and Christy with a multi-coefficient fitting approach [24] utilized by in the FDTD tool. This tool has been verified using experimental results of palsmonics waveguides made using silver and show good matching [4].

The initial design utilized is the modified configuration of the feedback resonator studied in [9] and shown in Fig.1. The

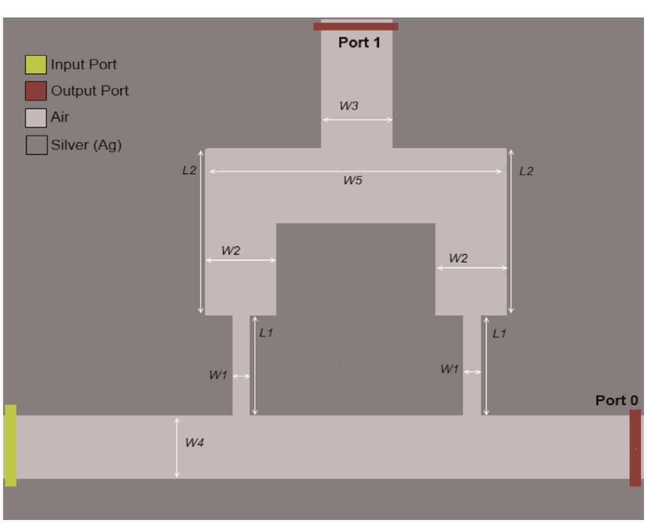

Fig. 1. Schematics of the initial demultiplexer.

transmission output of port 0, and port 1 are shown in Fig.2. It is clear from this figure that the response has a wide FWHM and requires further optimization.

Thus, the design problem is set as an optimization problem. This optimization problem can be rewritten as

$$\min_{\boldsymbol{p}} f$$
$$\text{Subject to } \mathrm{Lb} \le \boldsymbol{p} \le \mathrm{Ub} \tag{1}$$

where $f = \sum_n |\Delta\lambda_n|$, and $\Delta\lambda_n$ is the FWHM of the nth channel in the multiplexer. The vector of design parameters, $\boldsymbol{p}$ includes all the geometrical design parameters and the allowed power limits in each channel. Lb and Ub in (1) are the vectors containing the lower and upper bounds for all the design parameters. These limits assure that the obtained optimal design parameters satisfy the physical constraints of the proposed structure. The objective function can be also modified depending on the application, for example, for FWHM application, the function can be modified to be $f = \max_n |\Delta\lambda_n|$ to insure uniform FWHM for all the channels.

The initial demultiplexer, shown in Fig. 1, offers FWHM of 114 nm, and peak transmission of around 21%. The feedback loop present by having both nozzles (see Fig. 1) connected to the input waveguide creates a highly resonant cavity, but hinders its output transmission. These nozzles are the reason behind the relatively low output transmission in port 1, see Fig. 2(b) and the band-reject filter like effect shown in Fig. 2(a). To achieve these results, we set the parameters in Fig. 1 to; W_1=20 nm, W_2=86 nm, W_3=90 nm, W_4=90 nm, W_5=375 nm, L_1=200 nm, and L_2=235 nm.

3. The proposed optimal designs

3.1. Single channel filter

The optimization problem in (1) is solved in two steps. The first step, is defining the lower and upper limit of each design variable to create a grid space for each variable and then calculate the response of few design points using the full wave FDTD. These design points are chosen randomly to cover the design space and guide the optimizer. The second step utilizes pattern search [25] optimization approach to solve the problem in (1) using FDTD simulations and get the optimized design parameters. 2D-FDTD has been utilized in order reduce the computational cost of the optimization process.

Following this approach, the optimized single channel demultiplexer is obtained and shown in Fig. 3. The design can be also utilized as a highly selective bandpass filter. The optimization process has the FWHM $\Delta\lambda$ as the objective function that has to be minimized. The Lb constraints are taken to be 20 nm. This minimum dimension value is chosen in order to avoid unrealistic dimensions that cannot be fabricated using the current technology. This minimum value can be achieved using focused ion beam milling (FIB). It can be also achieved using electron beam lithography (EBL) and lift off approach. The metal thickness should not exceed 100 nm to achieve this dimension. This thickness does not affect the functionality of the structure if it has a larger value than the minimum width of the structure. The proposed design is tunable, and has full width half-maximum (FWHM) of 10.5 nm, and peak transmission ratio of 48% with resonance at 1494 nm as shown in Fig.4. The proposed structure is composed of three cavity sections. This resonance wavelength can be estimated using the simple Fabry Perrot resonance wavelength. However, in our case the effective index is varying in each section of the cavity and hence the expression should be generalized to be in the form