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Compact all-optical interferometric logic gates based on one-dimensional metal–insulator–metal structures

Yusheng Bian, Qihuang Gong *

State Key Laboratory for Mesoscopic Physics, Department of Physics, Peking University, Beijing 100871, People's Republic of China

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ABSTRACT

The whole set of fundamental all-optical logic gates is realized theoretically using a multi-channel configuration based on one-dimensional (1D) metal–insulator–metal (MIM) structures by leveraging the linear interference between surface plasmon polariton modes. The working principle and conditions for different logic functions are analyzed and demonstrated numerically by means of the finite element method. In contrast to most of the previous studies that require more than one type of configuration to achieve different logic functions, a single geometry with fixed physical dimensions can realize all fundamental functions in our case studies. It is shown that by switching the optical signals to different input channels, the presented device can realize simple logic functions such as OR, AND and XOR. By adding signal in the control channel, more functions including NOT, XNOR, NAND and NOR can be implemented. For these considered logic functions, high intensity contrast ratios between Boolean logic states "1" and "0" can be achieved at the telecom wavelength. The presented all-optical logic device is simple, compact and efficient. Moreover, the proposed scheme can be applied to many other nanophotonic logic devices as well, thereby potentially offering useful guidelines for their designs and further applications in on-chip optical computing and optical interconnection networks.

1. Introduction

As one of the most important elements in optical computing networks, all-optical logic gates have recently attracted considerable attention [1–3]. The previously demonstrated all-optical logic gates can be divided into two major classes: one based on linear optical interferences [4–10], and the other enabled by nonlinear optical effects [11–16]. Since the logic operations of linear gates (also known as interferometric logic gates) depend on the relative optical phase of two input signals, the realizations of different Boolean logic states can thus be enabled by the constructive or destructive interference of the signals at the output region of the devices. Due to the fact that it is difficult to precisely control the optical phase difference, these linear type logic gates typically suffer from both inherent instabilities and relatively low intensity contrast ratios between the logic states "1" and "0" [17,18].

One of the most promising solutions to overcome the above challenges in linear all-optical logic gates is by device miniaturization and monolithic integration [3]. However, most of the interferometric logic gates based on conventional photonic structures such as photonic crystals and silicon components [4,8] are fundamentally subject to the diffraction limit, which restricts the further downscaling of their physical dimensions below the wavelength scale. In contrast to these dielectric-based counterparts, photonic components employing surface plasmons hold the promise to confine and transport light at the truly subwavelength scale [19]. Along with many other advantageous such as enabling simultaneous transmission of light and electric signals through the same configuration and allowing easy integrations with other configurations, plasmonic nanostructures have been widely employed to build ultra-compact high-performance opto-electronic components [20]. During recent years, all-optical logic devices based on surface plasmons have attracted increasing research attention and have already been regarded as intriguing alternatives to their photonic crystal based logic counterparts.

To date, several types of plasmonic interferometric logic devices have been intensively studied, which are based on metallic nanowire networks [8,9], metal slot waveguides [10,11] as well as hybrid plasmonic structures [9]. However, in most of these studies, two or even more types of different configurations are required in order to implement all fundamental logic functions, which introduce additional complexity for the designs and applications of these logic devices. To overcome this limitation, here we propose a novel all-optical logic device based on plasmonic waveguides. Through comprehensive numerical investigations on its properties at the telecom wavelength, we demonstrate the realization of the whole set of fundamental logic functions, i.e., OR, AND, NOT, XOR, XNOR, NAND and NOR, without any need of

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* Corresponding author.
E-mail address: qhgong@pku.edu.cn (Q. Gong).

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modifying or reconfiguring the device. In our design, one-dimensional (1D) metal–insulator–metal (MIM) waveguides are chosen to construct the entire logic device, due to their simple configuration as well as the capabilities of providing nanoscale light confinement, low crosstalk, reasonable propagation distance and nearly 100% transmission through sharp bends [21–26], which make them idea candidates for various ultra-compact devices [27–33] and other applications [34–37]. We show that the MIM-based logic device can effectively realize different logic functions through switching the signals in the input and the control channels. Furthermore, high intensity contrast ratios between logic states “1” and “0” can be achieved. The presented device is simple, compact, efficient and can be easily integrated with other nanophotonic devices as well, which renders it a promising building block for on-chip optical computing and optical interconnection networks.

2. Geometry of the all-optical logic device based on 1D MIM structure

The 2D geometry of the studied logic device is shown schematically in Fig. 1, which comprises four air channels cut into a silver background at the input port, while combining into a single channel at the output region. The input signals are assumed to be launched at port I_1, port I_2 and/or port I_3, whereas port C are the control port for the realizations of more complex functions. Port O is the output port for the Boolean logic states. The input channels, control channel and output channel are denoted by numbers 1–5. All the channels have the same thickness of t. As shown in Fig. 1, the vertical spacing between channels 1 and 2 is S_{12}. S_{14} denotes the separation between channels 1 and 4, while S_{23} represents the vertical distance between channels 2 and 3. In the simulations, all the corners are assumed to be 90° sharp corners. The optical characteristics of the MIM-based logic devices are investigated at $\lambda = 1550$ nm by means of the finite-element method (FEM) based software COMSOL 3.5a. The permittivities of Ag and air are $\varepsilon_m = -129 + 3.3i$ [38] and $\varepsilon_i = 1$, respectively. The modal properties of the MIM waveguides are analyzed by the eigenmode solver using the 2D *Perpendicular Wave* package in the *RF module*, whereas the operations of the logic gates are simulated by the *In-plane Harmonic Propagation* package. In order to perform a full-wave 2D numerical simulation of the mode propagation along the channels, the field distribution from the 2D eigenmode solver of a 1D MIM plasmonic waveguide is set as a source boundary condition for the 2D analysis.

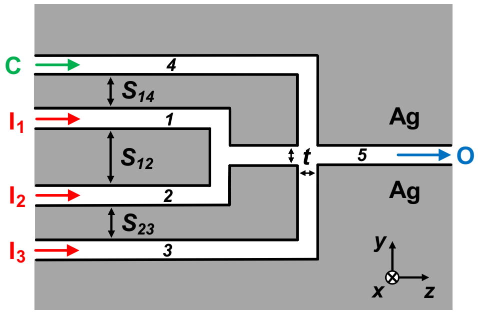

Fig. 1. Schematic of the studied logic device, which consists of four air channels embedded inside a silver background. Port I_1, port I_2 and port I_3 are the input ports where signals are excited. Port C is the control port where control signal is enabled. Port O is the output region for the Boolean logic states. The input channels, control channel and output channel are denoted by numbers 1–5, which share the same thickness of t. S_{12}, S_{14} and S_{23} are the vertical separations between the corresponding channels.

3. Guided mode's properties of 1D MIM structure

Before conducting detailed investigations on the operations of the logic gates, we firstly take a look at the surface plasmon mode traveling along a single air channel cut into a silver background, which is also the fundamental plasmonic mode supported by a one-dimensional (1D) MIM structure. The calculated results for the real part of the modal effective index ($n_{eff} = Re(N_{eff})$) and the propagation length (L) of the considered plasmonic mode are shown in Fig. 2(a) and (b) as the thickness of the air channel varies from 0 nm to 200 nm. Here, the propagation length (L) is obtained by $L = \lambda/[4\pi \mathrm{Im}(N_{eff})]$. It is seen from Fig. 2 that, both the modal effective index and the propagation loss decrease monotonically with the increased size of the air channel. By contrast, the corresponding mode size, although not shown here, gradually increases as t gets larger. To compromise between the physical dimension, modal loss and spatial size of the mode as well as ensuring a single-mode condition, here we chose a 50-nm-thick insulator layer (air channel) to construct the logic device.

Since the proposed logic device contains several parallel air channels, the coupling properties between different channels are also investigated for the MIM structures. The normalized coupling length defined as the ratio of the calculated coupling length (L_c) of the system to the propagation length (L) of the plasmonic mode supported by a single waveguide [39], is shown in Fig. 3 as the separation (S) varies from 10 nm to 100 nm. According to the coupled mode theory [40], the coupling length can be obtained by $L_c = \pi/|k_s - k_a|$, where k_s and k_a are the wavenumbers of the symmetric and anti-symmetric modes of two coupled waveguides, respectively. As seen from Fig. 3, the normalized coupling length can exceed 1 when S is larger than ~70 nm, indicating that low-crosstalk can be enabled under these circumstances. Based on the discussions of coupling characteristics, the separations between adjacent channels should be larger than the critical value to ensure successful operation of the logic device without significant cross-talk between different channels.

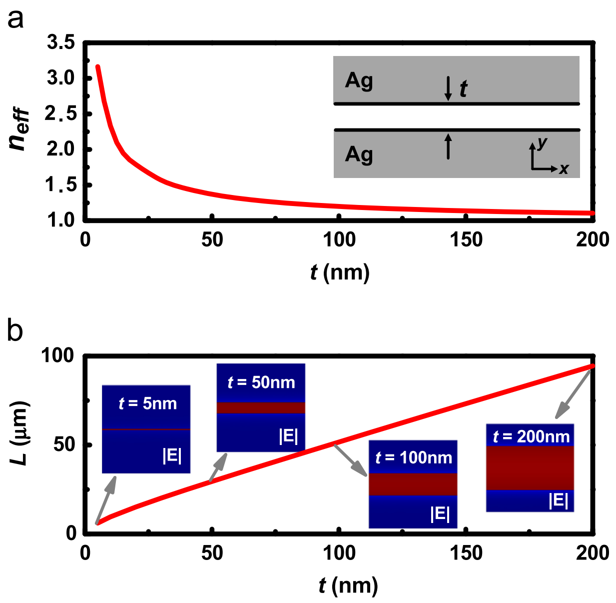

Fig. 2. (a)–(b) Dependence of the real part of the modal effective index (n_{eff}) and the propagation length (L) of the fundamental plasmonic mode on the thickness of the insulator layer (air channel). The insets in (a) shows the cross-sectional view of the MIM waveguide, whereas the insets in (b) depict the electric field for typical configurations (from left to right: $t = 5$ nm, $t = 50$ nm, $t = 100$ nm and $t = 200$ nm).