Design of All-optical Inverter using Nonlinear Plasmonic Two-mode Waveguide

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Abstract—*In this paper, we have proposed an all-optical boolean inverter gate based on surface plasmonic two-mode waveguide with nonlinear GaAsInP cladding, operating at wavelength of 1.33μm. Switching of boolean states is obtained by using index modulation of the nonlinear cladding by using varying optical pulse energy. The length of the coupling region in the device is ~53.6 and ~8.4 times compact than previously reported works. The optical pulse energy required to change boolean states is ~1.4 times lower than that in previous works.*

1. INTRODUCTION

High performance all-optical logic gates have become key components in optical computing and networking systems to perform a majority of optical signal processing functions [1]. All-optical control of these logic devices has become essential to achieve faster operation of present days' high speed communication system. In this direction, two-mode interference (TMI) coupler [2] is preferred as basic components of these devices because of its compactness, easy fabrication, larger fabrication tolerance and polarization insensitivity compared to other components. Various technologies have been reported to realize all-optical inverter logic, but most of them suffer from some fundamental limitations such as large size [3,4], complex architecture [5] and instability [6-9]. Recently, surface plasmon polariton (SPP) based waveguide devices [6-11] have attracted enormous attention due to their compactness over photonic devices. In this paper, we have proposed nonlinear plasmonic two-mode waveguide as a basic component for an optical boolean inverter gate operating at the wavelength of 1.33μm. The switching action of the inverter is controlled by optical pulse via index modulation of nonlinear cladding region.

2. DESIGN AND CONCEPT

The basic structure of the nonlinear plasmonic two-mode waveguide based all-optical inverter is made up of silicon core and GaAsInP side claddings sandwiched between two layers of silver. Fig.1 shows the three dimensional schematic view of the device consisting of two-mode coupling region of width *2w*, thickness *t* and coupling length *L* and access waveguides of width *2w* and thickness *t*. When input powers P_1 is launched into two-mode coupling region through input access waveguide-1 and optical pulse of energy *E* and width T_P is applied at the GaAsInP cladding, output power at access waveguide-3 and waveguide-4 are obtained as P_3 and P_4 respectively.

The refractive index of GaAsInP is a function of the applied optical pulse energy *E* and is written as [12]

$$n_2(E) = n_2(0) + \Delta n_2(E) \qquad (1)$$

where, $n_2(0)$ is the refractive index of GaAsInP when no optical pulse is applied and $\Delta n_2(E) = \dfrac{n_{nl}E}{1.605 A_C T_P}$ [12] is the refractive index change of GaAsInP due to application of optical pulse of energy *E* and pulse width T_P. The $n_{nl}=-2\times10^{-3}\mu m^2W^{-1}$ is the nonlinear coefficient of GaAsInP and $A_C=2W_Ct$ is the effective cladding area of GaAsInP cladding where W_C is the effective cladding width as shown in figure.

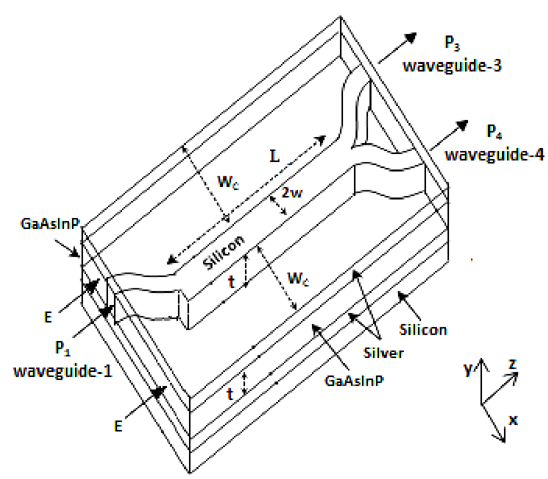

Fig.1: 3D schematic view of nonlinear plasmonic two-mode waveguide with core width *2w*, thickness *t* and coupling length *L*.

When the input field is incident at input access waveguide-1, SPP fundamental and first order modes are excited which propagate through the two-mode coupling region at different phase velocities. The phase difference between the two coupled SPP modes at *z=L* at the end of the coupling region depends on the length of coupling region and can be written as [10]

$$\Delta\phi(0) = [\beta_0(n_2(0)) - \beta_1(n_2(0))]L \quad (2)$$

where, $\beta_0(n_2(0))$ and $\beta_1(n_2(0))$ are the propagation constants of the fundamental and first order SPP modes respectively when no optical pulse is applied. When optical pulse of energy E and width T_P is applied at the the GaAsInP cladding, refractive index modulation of GaAsInP cladding occurs which introduces an additional phase change between the two coupled SPP modes. The phase difference between the two excited modes after application of optical pulse of energy E is written as [10]

$$\Delta\phi(E) = [\beta_0(n_2(E)) - \beta_1(n_2(E))]L = \Delta\phi(0) + \frac{2\pi L}{\lambda}\left[\Delta n_1^{eff}(E) - \Delta n_0^{eff}(E)\right] \quad (3)$$

where, $\Delta n_0^{eff}(E)$ and $\Delta n_1^{eff}(E)$ are the effective refractive index changes for the fundamental and first order modes respectively and are given as

$$\Delta n_i^{eff}(E) = n_i^{eff}(0) - n_i^{eff}(E) \quad (4)$$

where i=0 and 1 denote the fundamental and first order mode respectively. The $n_i^{eff}(0)$ and $n_i^{eff}(E)$ are the effective refractive indices of the ith mode (i=0,1) before and after application of modulating optical pulse respectively. The length of coupling region required to get an additional π phase shift due to application of optical pulse of energy E (i.e., $\Delta\phi(E)=\pi$) can be written as [10]

$$L = \frac{\lambda}{2\{\Delta n_1^{eff}(E) - \Delta n_0^{eff}(E)\}} \quad (5)$$

The structure is numerically analyzed using effective index method [10,11] and the behaviour of the various eigen modes is studied. From effective index analysis of the basic device, it is seen that the first order mode appears at $2w$=0.45μm, whereas the second order mode appears at $2w$=0.88μm. Thus for two-mode propagation, the waveguide core width is chosen as $2w$=0.48μm. Moreover, previous analysis of the device using effective index methods [10] have shown that as the core thickness increases, propagation length also increases. Thus, to ensure better output intensity, core thickness is taken as t=5.0μm. For $2w$=0.48μm and t=5.0μm, the coupling length is calculated as L=92.35μm.

Fig.2 shows the variation of effective refractive index change $\Delta n_i^{eff}(E)$ (where i=0,1) with optical pulse energy E obtained by using equations (1) and (4) for n_1= 3.5, $n_2(0)$=3.17, n_m=0.394+8.2j, λ=1.33μm, $2w$=0.48μm, t=5.0μm, and T_P=1ps. It is evident from the figure that for both fundamental and first order modes, effective refractive index change $\Delta n_i^{eff}(E)$ increases with increase in optical pulse energy E, the rate of increase for first order mode being more than that for fundamental mode. The inset in Fig.2 shows the phase change $\Delta\varphi(E)$ versus optical pulse energy E for L=92.35μm. It is seen that $\Delta\varphi(E)$ increase almost linearly with E. The additional phase change due to optical pulse becomes π for optical pulse energy E=16.4pJ. At E=16.4pJ, the total phase difference between the coupled SPP modes is obtained as 31π.

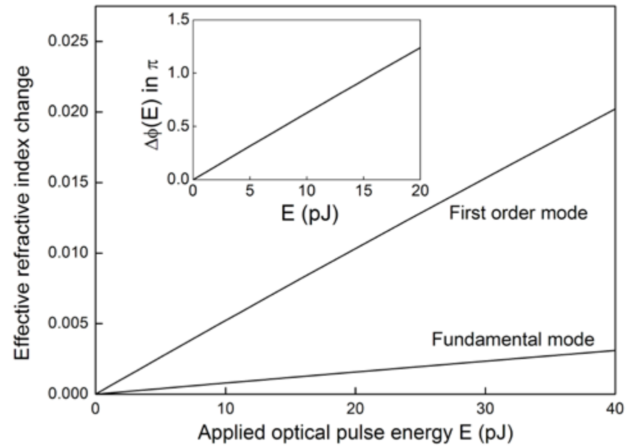

Fig. 2: Effective refractive index change for fundamental and first order modes versus optical pulse energy for nonlinear plasmonic two-mode waveguide based inverter with n_1= 3.5, $n_2(0)$=3.17, n_m=0.394+8.2j, λ=1.33μm, $2w$=0.48μm, t=5.0μm and L=92.35μm. In the inset, phase change in π versus optical pulse energy E is shown.

The normalized coupling power (where P_4/P_1=cross state power and P_3/P_1=bar state power) versus optical pulse energy E for the nonlinear plasmonic two-mode waveguide with n_1=3.5, $n_2(0)$=3.17, n_m=0.394+8.2j, λ=1.33μm, $2w$=0.48μm, t=5.0μm, L=92.35μm and T_P=1ps are shown in Fig.3.

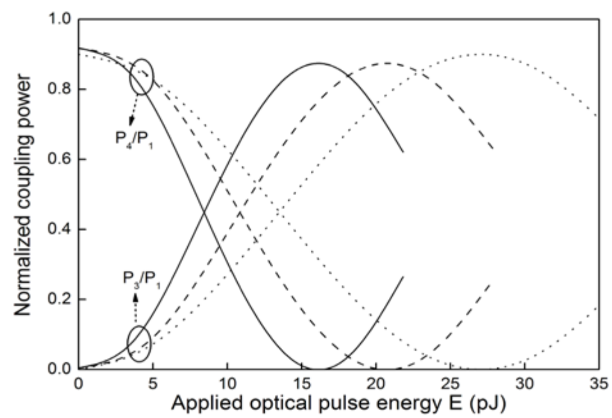

Fig. 3: Normalized cross state power (P_4/P_1) and bar state power (P_3/P_1) versus optical pulse of energy E for nonlinear plasmonic two-mode waveguide based inverter with n_1= 3.5, $n_2(0)$=3.17, n_m=0.394+8.2j, λ=1.33μm , $2w$=0.48μm, t=5.0μm and L=92.35μm and effective cladding area A_C=2.0 μm^2 (solid curves), A_C=2.5 μm^2 (dashed curves) and a previously reported device (dotted curves).

The solid line and dashed line represents coupling curves for effective cladding area A_C=2.0μm^2 and 2.5μm^2 respectively. It is seen from the figure that at E=0pJ, the power is fully transferred to output access waveguide-4 (cross state). Due to application of optical pulse energy, the coupled power is gradually transferred to output access waveguide-3. The power is fully transferred to waveguide-3 (bar state) by launching of the optical pulse of energy E=16.4 and 22 pJ for A_C=2.0 and 2.5μm^2, respectively. As area A_C increases, optical pulse energy required to change cross state to bar state increases. So, we have chosen the effective cladding area as A_C=2.0μm^2 for which W_C=0.2μm. The figure also shows coupling curve for inverter based on optically controlled two-mode interference (OTMI) coupler reported previously. It is seen that the optical pulse energy required for switching of coupling states of the proposed inverter for A_C=2.0μm^2 is found to be ~1.65 times lower than that reported for OTMI coupler based inverter [4]. The coupling length is ~8.4 times compact than that of OTMI coupler based inverter [4] and ~53.6 times compact than that of the inverter using SiGe/Si based MMI coupler [3].

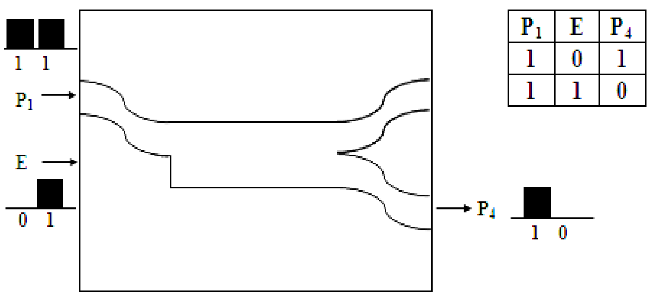

Fig. 4: Nonlinear plasmonic two-mode waveguide as a boolean inverter and the truth table.

Fig. 4 shows the inverter characteristics obtained by using the nonlinear plasmonic two-mode waveguide. For the inverter operation, the optical pulse of energy E applied in the cladding region is taken as input signal, whereas the power launched in waveguide-1 (P_1) is taken as the control signal. The output states of inverter gate are obtained at output waveguide-4. When no optical pulse (treated as the "0" state) is applied at the GaAsInP cladding region, the power P_1 incident at waveguide-1 is delivered to output access waveguide-4 due to cross state coupling (logic high) and almost zero signal power is obtained at access waveguide-3. When input optical pulse of energy E=16.4pJ (treated as the logic "1" state) is applied in the cladding region, the power P_1 incident at waveguide-1 is delivered to output access waveguide-3 due to bar state coupling of the device and almost zero signal power is obtained at access waveguide-4 (logic low). So the output power of waveguide-4 in the proposed device shows NOT gate characteristics as shown in Fig.4. The values of the designed parameters for the nonlinear plasmonic two-mode waveguide based inverter gate for operating wavelength of λ=1.33μm are shown in table-1.

Table 1: Device parameters for the proposed inverter for λ=1.33μm

Device parameters	Values
Silicon core refractive index (n_1)	3.5
Silver cladding refractive index (n_m)	0.394+8.2j
GaAsInP cladding refractive index ($n_2(0)$)	3.17
Nonlinear coefficient of GaAsInP (n_{nl})	-2×10^{-3}μm^{2}W^{-1}
Core width ($2w$)	0.48μm
Core thickness (t)	5.0μm
Length of coupling region (L)	92.35μm
Effective area of GaAsInP cladding (A_C)	2.0μm^2
Width of GaAsInP cladding (W_C)	0.2μm

3. CONCLUSION

In this paper, we have proposed an optical boolean inverter gate based on nonlinear plasmonic two-mode waveguide consisting of silicon core, silver upper and lower cladding and GaAsInP as the left and right claddings, to operate at the wavelength of 1.33μm. Switching of logic high and low states is achieved by applying optical pulse which causes refractive index modulation of GaAsInP cladding and thus introduces an additional phase change between the coupled SPP modes. The length of coupling region in the proposed inverter is found to be 92.35μm which is ~8.4 times compact than that of OTMI coupler based inverter [4] and ~53.6 times compact than that of the inverter using SiGe/Si based MMI coupler [3]. The optical pulse energy required for switching of logic states is E =16.4pJ which is ~1.65 times lower than that reported for OTMI coupler based inverter [4].

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