Optical Logic Gates Using A Graphene Clad Two Surface Plasmonic Polariton Mode Coupler for Optical Processor

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Research Article

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Optical logic gates using A Graphene clad two surface plasmonic polariton mode coupler for optical processor

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Abstract

An optical pulse controlled 2x2 two mode interference (OTMI) coupler having silicon core surrounded by Graphene clad has been introduced as fundamental gates of optical processing. Considering strong light-matter interactions and nonlinear optical property of graphene, we have shown coupling characteristics depending on additional phase change between the excited surface plasmon polariton modes propagating through the silicon core. By applying optical pulse energy of 0.82 pJ and width of 4 ps on graphene clad, the NOT, AND, and OR logic gates are demonstrated. The coupling length of the proposed device is ~ 3.2 times less than that of already reported optical device based on SPP modes. Our results promise to obtain the development of integrated optical processor with high speed, compact and low power optical logic gates having high fabrication tolerance.

Key words: Graphene, surface plasmonics. Nonlinear refractive index, power imbalance. SPP waveguide.

Compact optical gates has become requisite in large scale integration of optical processor for high speed processing [1]-[3]. All optical logic gates have been reported using optical fibers [4], photonic crystal [5], dielectric mirroring resonators [6]-[7], multimode interference (MMI) coupler [2] and two mode interference (TMI) coupler [3]. Recently, TMI and MMI coupler have been preferred for the implementation of optical logic gates because of its polarization insensitivity and compactness. But the slight deviation from exact design values of device parameters (during fabrication) will affect much more on the performance of MMI coupler than that of TMI coupler due to having more number of waveguide parameters in case of MMI coupler [2] [8]. The integrated optics has disadvantage of restriction due to having fundamental property of diffraction of light energy to reduce device size further. The surface plasmonic polariton (SPP) wave technology removes this restriction with its light-electron excitation at metal-dielectric interface having confinement of electromagnetic energy at nano-scale [9] - [10]. The confinement of electromagnetic wave at nano scale with SPP wave assures large scale integration of complex optical processor. In this direction, optical processing has already been demonstrated by using SPP mode waveguide with Ag - Silicon interface [3], [11]. The SPP

waveguide with metallic interface has disadvantages of metallic losses, modal and chromatic dispersion causing distortion in modes propagated in SPP waveguide. Although the distortions of the modes are reduced by allowing fewer number of monochromatic SPP modes propagated in the waveguide [11]-[12], the reduction of metallic losses needs to consider new materials having small value of extinction constant of refractive index and also free electrons as in metal. In this direction, the graphene-dielectric interface is already studied for the generation of Dirac plasmons through interaction with infrared light due to having its positive value of imaginary part of refractive index [13]-[15].

The precise phase control is required to obtain different fundamental gates of optical processing. In this direction thermo-optic effect has already been used to obtain phase control [16]-[17] showing phase error due to having unwanted thermo-optic effect in unstable regions of waveguide. These errors degrade the device performance due to having difficulties to obtain precise phase control [17]. These errors are reduced by optical refractive index modulation in GaAsInP cladding [11]-[12]. But optical pulse energy applied to small area of GaAsInP causes the temperature rise producing local thermo-optic instability in SPP waveguide core. Hence very small optical pulse energy with short duration applied on cladding region causes negligible temperature increase in the core providing reduction of thermo-optic phase error. In this direction, the efficient modulation of refractive index has already been demonstrated in graphene by incidence of infrared light using nonlinear absorption [18]-[19].

Here, a two surface plasmonics polariton mode Graphene-silicon waveguide has been presented for fundamental optical gates of optical processing. Two SPP modes coupling as an optical pulse applied on Graphene cladding region are studied. The NOT, OR and AND gates are demonstrated theoretically with nonlinear refractive modulation of graphene clad with incidence of optical pulse.

II. Device concept

Figure-1a shows 3D view of a 2×2 Graphene clad based Two SPP mode interference coupler (GCTSPPMI) having coupling area of silicon core width $\sim 2w$ and thickness t . The coupler consists of two single mode input access waveguides (a_1

and a_2) and two output waveguides (b_1 and b_2) of core width w (Fig-1b). The silicon core of refractive index n_1 is surrounded by graphene clad having the complex refractive index of graphene n_2 (Fig-1b). There is a negligible change of complex part of refractive index with incidence of optical pulse energy on graphene [20], whereas the real part of refractive index has nonlinear change ($\Delta n(E)$) of graphene as function of optical pulse energy E and width T_p is represented as [20],

$$\Delta n(E) = n_2(E) - n_2(0) = \frac{n_{lg} E}{1.065 A_c T_p} \quad (1)$$

where, n_{lg} = nonlinear index coefficient of graphene $= 1.5 \times 10^{-9}$ (cm)² W⁻¹ [20] and A_{rl} = area of left or right graphene cladding on which optical pulse is incident for obtaining bar state $= 2w_r t$, w_r = width of left /right graphene cladding. To generate surface plasmonics, the light of wavelength $1.55 \mu\text{m}$ launched into the input access waveguide a_1 interacts with graphene-silicon (conducting medium-dielectric medium) interface. As a result, the local electric fields is induced at the interface and represented as surface plasmonic plasmon (SPP) modes in which number of modes depends on the width of silicon core. For the generation of two SPP modes (Fundamental and first order modes) in coupling region, the width of silicon core is fixed as $2w$, where w is width of single mode core. The real part of propagation constants of fundamental and first order modes (excited in coupling region) are determined by effective index method [18] with the boundary condition at the graphene-silicon interface) for $\lambda = 1.55 \mu\text{m}$, $n_1 = 3.49$, $n_2(0) = 3.2175 + j2.5233$ and $t = 7.5 \mu\text{m}$ as $\beta_o^r(n_1, n_2(0)) = 13.7871 (\mu\text{m})^{-1}$ $\beta_1^r(n_1, n_2(0)) = 13.07394 (\mu\text{m})^{-1}$ respectively where $2w = 0.55 \mu\text{m}$. The beat length (L_π) is

determined as [18], $L_\pi = \frac{\pi}{\beta_o^r(n_1, n_2(0)) - \beta_1^r(n_1, n_2(0))} = 4.3 \mu\text{m}$. The propagation lengths of fundamental and first order modes are estimated as [18], $L_{P,0} = \frac{1}{2\beta_o^{im}} = 4.63 \mu\text{m}$ and

$L_{P,1} = \frac{1}{2\beta_1^{im}} = 5 \mu\text{m}$ respectively which are greater than that of L_π where β_o^{im} = imaginary part of propagation constant of fundamental mode β_1^{im} = that of first order mode.

The input field $H_1(x, 0)$ entering into the coupling region through input access waveguide a_2 is expressed as a sum of the mode field of two excited SPP modes [18] and written in terms of,

$$H_1(x, 0) = \sum_{m=0}^1 b_m^T H_m(x) \quad (2)$$

where $b_m^T = m^{\text{th}}$ mode field excitation coefficient of the graphene clad plasmonic TMI coupler. The mode excitation coefficients are determined from Fourier series coefficients of odd periodic

functions. The $H_m(x)$ is the mode field of the m^{th} excited mode of TMI region at $z = 0$. The mode fields at output b_1 and b_2 are assumed to be single mode and contributed by excited modes. The power transferred to the output access waveguides is a function of optical pulse of energy E incident on left / right graphene cladding is written respectively as

$$\left. \begin{aligned} \frac{P_3}{P_2} &= \left| \frac{H_3(x, L, E)}{H_1(x)} \right|^2 \\ \frac{P_4}{P_2} &= \left| \frac{H_4(x + w, L, E)}{H_1(x)} \right|^2 \end{aligned} \right\} \quad (3)$$

where, $P_2 = |H_1(x)|^2$

$$\begin{aligned} H_3(x, L, E) &= \exp \left[-j\beta_o^r(n_1, n_2(E))L \right] \sum_{i=0}^1 c_{3,m}^T H_m(x) \\ &\quad \exp \left[j \left\{ \beta_o^r(n_1, n_2(E)) - \beta_m^r(n_1, n_2(E)) \right\} L \right] \\ &\quad \exp \left[-\beta_m^{im}(n_1, n_2(E))L \right] \\ H_4(x + w, L, E) &= \exp \left[-j\beta_o^r(n_1, n_2(E))L \right] \sum_{i=0}^1 c_{4,m}^T H_m(x + w) \\ &\quad \exp \left[j \left\{ \beta_o^r(n_1, n_2(E)) - \beta_m^r(n_1, n_2(E)) \right\} L \right] \\ &\quad \exp \left[-\beta_m^{im}(n_1, n_2(E))L \right] \end{aligned}$$

The $c_{3,m}^T$ and $c_{4,m}^T$ are field contribution coefficient of m^{th} mode for output access waveguides b_1 and b_2 respectively derived by using a simple model based on SPP sinusoidal modes [10]. The propagation constants of fundamental and first order modes, $\beta_o(n_1, n_2(E))$ and $\beta_1(n_1, n_2(E))$ depending on optical pulse energy are written as

$$\begin{aligned} \beta_o(n_1, n_2(E)) &= \beta_o^r(n_1, n_2(E)) + j\beta_o^{im}(n_1, n_2(E)) \\ \beta_1(n_1, n_2(E)) &= \beta_1^r(n_1, n_2(E)) + j\beta_1^{im}(n_1, n_2(E)) \end{aligned} \quad (4)$$

The $\left[\beta_o^r(n_1, n_2(E)) - \beta_1^r(n_1, n_2(E)) \right] L$ is the phase difference between two excited modes with the application of optical pulse of energy E expressed as

$$\Delta \Phi_T(E) = \left[\beta_o^r(n_1, n_2(0)) - \beta_1^r(n_1, n_2(0)) \right] L + \Delta \phi(E) \quad (5)$$

where $\Delta \phi(E) = \left\{ \Delta \beta_1^r(n_1, n_2(E)) - \Delta \beta_o^r(n_1, n_2(E)) \right\} L$ = difference of phase change obtained between excited modes with incidence energy E on left and right graphene cladding and first part of the equation (5) provides phase difference between fundamental and first order modes found without launching optical pulse into left and right graphene cladding. The $\Delta \beta_1^r(n_1, n_2(E))$ are change of real part of propagation constants of first order mode obtained with

incidence of E whereas that of fundamental mode is expressed as $\Delta\beta_0^r(n_1, n_2(E))$. The $\Delta\beta_1^r(n_1, n_2(E))$ and $\Delta\beta_0^r(n_1, n_2(E))$ are written as

$$\Delta\beta_1^r(n_1, n_2(E)) = \beta_1^r(n_1, n_2(E)) - \beta_1^r(n_1, n_2(0)) \quad (6)$$

$$\Delta\beta_0^r(n_1, n_2(E)) = \beta_0^r(n_1, n_2(E)) - \beta_0^r(n_1, n_2(0)) \quad (7)$$

Figure -2a shows $\Delta\Phi(E)$ versus E obtained by using the equations(5)-(7) for $\lambda=1.55 \mu\text{m}$, $n_1=3.49$, $n_2(0)=3.2175 + j2.5233$, $w = 0.55 \mu\text{m}$ and $t = 7.5 \mu\text{m}$. The $\Delta\Phi(E)$ increases with increase of E. Although the rate of increase of $\Delta\Phi(E)$ with respect to E enhances with decrease of A_C , the fiber to device coupling efficiency (η) decreases drastically below $A_C = 3 \mu\text{m}^2$ (Figure -2b) where $\eta = \frac{A_C}{\pi^2} [n_1^2 - n_2^2(E)]$. The optimized value η are estimated at $A_C = 3 \mu\text{m}^2$ as $\sim 94 \%$ where diameter of fiber $= 2r = 2.4 \mu\text{m}$ and $n(E)$ = real refractive index $= 3.281$ to obtain π phase change with $E=0.82 \text{ pJ}$.

The normalized bar state power (P_4/P_1) and cross state power (P_3/P_1) versus optical pulse energy E are obtained by using the equation (3) and (4) with Turbo C++ version 3.0 considering TE polarization [18] of SPP modes of coupling region for $n_1=3.49$, $2w=0.55 \mu\text{m}$, $\lambda=1.55 \mu\text{m}$, $t = 7.5 \mu\text{m}$ and coupling length $= 4.3 \mu\text{m}$ as shown in Fig-3. The figure shows that at $E = 0 \text{ pJ}$, the power is fully transmitted to output access waveguide b_1 as a cross state and the full power is transferred to waveguide b_2 (bar state) by incidence of optical pulse of energy $E = 0.6 \text{ pJ}$, 0.82 pJ and 1.12 pJ on graphene clad area of $A_C = 2, 3$ and $4 \mu\text{m}^2$ respectively due to having $\Delta\Phi(E) = \pi$ (Figure 2a). Although the pulse energy (E_π) required for full power transmitted to output is less for $A_C < 3 \mu\text{m}^2$, the power coupling efficiency η decreases drastically for $A_C < 3 \mu\text{m}^2$ (as shown in Fig-2b). As optical pulse energy required for obtaining bar state at $A_C = 3 \mu\text{m}^2$ is 20 times less than that for previous work [10], there is almost negligible refractive index change in silicon core with application of very little optical pulse energy of 0.82 pJ . The reduction of normalized peak output power (~ 0.95) for graphene clad is less than that (~ 0.85) of metal clad SPPTMI due to having more propagation loss of excited modes in metal clad waveguide than that of graphene clad waveguide. There is also S-bending loss in access waveguide of the device. Considering S-bending loss of $\sim 0.1 \text{ dB}$ [19] longitudinal length of access waveguide is determined as $L_T = \sqrt{H_T(4R - H_T)} \sim 11.6 \mu\text{m}$, where radius of curvature of bending (R) $= 8 \mu\text{m}$ and separation between access waveguides ($2H_T$) $= 10 \mu\text{m}$. The length of the device is determined as $2L_T + L_\pi = 27.5 \mu\text{m}$ which is ~ 30.3 times less than that of optical pulse controlled MMI device [2] and ~ 3.2 times less than that of metal clad SPP device [3] due to use of graphene clad.

The fabrication tolerance of device structure is an important performance parameter which reveals the effect on device performance if the deviation occurs from its designed values of its

parameters after fabrication (shown in Table I). Here its performance degradation of power imbalance ($10 \log_{10}(P_3/P_4)$)

has been studied with the deviation of its width ($\pm \delta w$) in comparison to that of MMI device of length $\sim 833.25 \mu\text{m}$ [2] and

SPPTMI device of coupling length $88 \mu\text{m}$ [3] as shown in Figure 4a ($2w=0.55 \mu\text{m}$). These curves are obtained by Turbo C++ version 3.0 using the equations (3)–(4) with $n_1 = 3.49$, $n_2(0)=3.2175$, $k = 2.5233$, $2w = 0.55 \mu\text{m}$, $t=7.5 \mu\text{m}$, $\lambda = 1.55 \mu\text{m}$. In the figures, the minimum value of power imbalance is estimated as $\sim -21.5 \text{ dB}$ which is almost close to that of previous works on SPPTMI switch [3]. Although the power imbalance of proposed GCTSPPMI switch is slightly higher than that of MMI device [2], the deviation of the power imbalance with small variation of width for GCTSPPMI switch is less than that of MMI device due to having more number of parameters in later case.

TABLE I

Design parameters of proposed GCTSPPMI device at wavelength $\lambda = 1.55 \mu\text{m}$.

Device parameters	Values
Core width ($2w$)	$0.55 \mu\text{m}$
Core thickness (t)	$7.5 \mu\text{m}$
Coupling length (L_C)	$4.3 \mu\text{m}$
Longitudinal length of access waveguides	$11.6 \mu\text{m}$
Width of Left / right graphene Clad (W_{cl})	$0.4 \mu\text{m}$
Silicon Core refractive index (n_1)	3.49
Refractive index of graphene (n_2)	$3.2175 + j2.5233$
Nonlinear coefficient of Graphene (n_{nl}) [19]-[20]	$1.5 \times 10^{-9} (\text{cm})^2 \text{W}^{-1}$

Optical Logic Gates

By using the coupling characteristics of the proposed Graphene clad SPP based compact TMI coupler, we have demonstrated basic optical logic gate operation. Table 1 shows the values of the designed parameters of the proposed device (mentioned earlier in the paper) for logic gate operation. The power launched in a_1 input of the devices is considered as a control signal, and the optical pulse of energy E applied in left and right graphene clad and optical power launched into input waveguide-2 are taken input signals whereas output states of logic gates are obtained at one of outputs of the device (b_1 and b_2).

Figure- 5 shows theoretical demonstration of the proposed device for the operation of fundamental logic gates (NOT, AND and OR). The NOT gate operation is derived by incidence of the control signal P_1 into a_1 and an optical pulse of energy E at Graphene clad whereas the power (P_4) delivered to the output b_2 is treated as output of NOT gate. When no optical pulse (treated as the “0” state) is applied at the graphene clad, the signal incident on input a_1 is delivered to the output b_2 as a “1” state due to cross state coupling (Figure-3) as shown in Figure-5a. When an optical pulse

of energy E of 0.82 pJ (treated as the “1” state) is incident on the clad, no signal is delivered to b_2 due to bar state coupling as obtained in Figure-3 and treated as a “0” state (Figure-5a). Hence the output power P_4 of the device is verified as a NOT gate characteristics in the proposed device.

Figure-5b shows the operation of AND gate obtained by incidence of power on a_2 input and an optical pulse of energy E of 0.82 pJ as input signals, and the power (P_4) delivered to output b_2 is taken as an output. For an AND gate operation no control signal power is required at the input a_1 . When no optical pulse is incident at the cladding region and no power is incident on a_2 input, no output is obtained at b_2 and treated as a “0” state. When no optical pulse is incident and an input signal is applied at a_2 , no power delivered to output b_2 is treated as a “0” state due to cross state coupling (Figure-3). When an optical pulse of energy $E=0.82$ pJ is applied on graphene clad and no input signal is applied at a_2 , no power delivered to output b_2 is treated as a “0” state (Figure-3). When an optical pulse of energy $E=0.82$ pJ is incident on graphene clad and an input signal P_2 is applied at a_2 , the power delivered to output b_2 is treated as a “1” state due to having bar state coupling (as per Figure-3).

Figure-5c shows an OR gate obtained by applying an optical power on a_2 input and an optical pulse of energy E of 0.82 pJ as input signals, and the power (P_3) delivered to output b_1 is taken as an output. For an OR gate operation, the signal power is applied at the input a_1 as a control signal (which is always “1”). When no optical pulse is incident on graphene cladding region and no power is applied at a_2 input, no power is obtained at output b_1 and treated as a “0” state (as shown Figure-3). When no optical pulse is incident and an input signal is applied at a_2 , the power is delivered to output b_1 due to having cross state coupling (as per Figure-3) and treated as a “1” state. When an optical pulse of energy $E=0.82$ pJ is applied on graphene clad and no input signal is applied at a_2 , the power delivered to output b_1 is treated as a “1” state due to having cross state coupling (as per Figure-3). When an optical pulse of energy $E=0.82$ pJ is incident on graphene clad and an input signal P_2 is applied at a_2 , the power delivered to output b_1 is treated as a “1” state due to having bar state coupling (as per Figure-3).

The operating time of the gate is almost the same as the recovery time of nonlinearity in the refractive index of graphene which is of the order of ~ 4 ps. The power consumption is 0.82 pJ which is close to the optical pulse energy. The graphene cladding silicon waveguide structure assure integration of these fundamental logic gates to obtain integrated optical processor due to its ultra fast operation and low power consumption. Moreover, same structure is used for getting all three fundamental logic gates by changing inputs of the GCTSPPMI structure.

Conclusion

Here a compact graphene clad SPPTMI structure is proposed for all optical logic circuits. By modulating the refractive

index of graphene clad with incidence of optical pulse, an additional phase change $\Delta\Phi(E)$ between the excited SPP modes propagating through the silicon coupling region is required for obtaining different states of switching. The optical pulse energy required as an input signal to obtain fundamental gate (AND and OR) operations, the cross state to bar state coupling is ~ 0.82 pJ which is ~ 20 times less than that reported in the previous works [3] due to use of graphene cladding whereas the operation time is obtained as 4ps. The coupling length of the proposed GCTSPPMI device is 3.2 times less than that of our previous works [3] and 30.3 times less than that of MMI device [2]. The degradation of power imbalance due to small change of waveguide width and thickness for graphene clad SPPTMI switch is less than that of MMI device due to having more number of parameters. Our results promises large scale integration of these fundamental logic gates to obtain integrated optical processor due to its ultra fast operation and low power consumption.

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Author Contribution: Sahu conceived the idea developed the theory, performed the simulation, analyzed the data and wrote the manuscript.

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Availability of Data and materials: All data that support the findings of this study are available from the corresponding author upon reasonable request.

Declarations

Ethics Approval: The author have followed the ethical principles and accurate references to scientific sources in my original article.

Code availability: All the codes that require for obtaining theoretical and simulation results are available from the corresponding authors on reasonable request.

Consent for Publication: I consent to the publication of my original research article.

Consent to participate: I consent to participate in the revision and publication of my original article.

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Fig-1 (a) 3D view of 2x2 Graphene clad two SPP mode interference (TMI) coupler of core width $2w$ and thickness t having incidence of optical pulse energy E in left and right graphene region of width w_{cl} for control of propagation of signal power (P_1) inside silicon core. The powers at the output ports of the device are cross state P_3 and bar state P_4 (b) 2D view of coupler having input access waveguides I_1 , and I_2 and output access waveguides O_1 and O_2 (c) cross section view of TMI region of the device with silicon core of refractive index n_1 surrounded by Graphene clad of complex refractive index $n_2 = n + jk$

Fig-2: (a) $\Delta \phi(E)$ versus E estimated by using the equation (5)-(7) with $\lambda=1.55 \mu\text{m}$, $n_1=3.49$, $n_2(0)=3.2175 + j2.5233$ and $t = 7.5 \mu\text{m}$. (b) fiber to device coupling efficiency (η) versus A_c with $\lambda=1.55 \mu\text{m}$, $t = 7.5 \mu\text{m}$, $w = 0.55 \mu\text{m}$ and pulse width $T_p=3.8 \text{ ps}$

Fig-3 Normalized cross state (P_3/P_1) and bar state power (P_4/P_1) versus E (pJ) for $A_c = 2, 2$ and $4 (\mu\text{m}^2)$ with $\lambda=1.55 \mu\text{m}$, $n_1=3.49$, $n_2(0)=3.2175 + j2.5233$, $t = 7.5 \mu\text{m}$ and $2w = 0.55 \mu\text{m}$, $T_p=3.8 \text{ ps}$

Fig-4: Power Imbalance (P_4/P_3 in dB) vs δw (fabrication tolerance) for the proposed Graphene clad TSPPMI (GCTSPPMI) switch with $L_C = 4.3 \mu m$ (solid line), SPPTMI switch with $L_C = 88 \mu m$ and all optical MMI switch using MMI device with $L_C = 833.25 \mu m$ with $n_1 = 3.49$, $n_2(0) = 3.2175 + j2.5233$, $2w = 0.55 \mu m$, $t = 7.5 \mu m$, $\lambda = 1.55 \mu m$.

Fig-5: GCTSPPMI coupler as a logic gate (a) NOT gate (b) AND gate (c) OR gate