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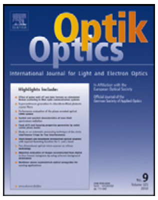

Simulation of two photon absorption in silicon wire waveguide for implementation of all optical logic gates

Kousik Mukherjee[a,*], Dharmadas Kumbhakar[a,b]

[a] Dept of Physics (UG & PG), B.B.College, Asansol, West Bengal, India
[b] Dept of Electronics and Communication Engineering, Asansol Engineering College, Asansol, West Bengal, India

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ABSTRACT

All optical switching action of silicon wire waveguide for the design of the proposed logic gates is simulated. This is one possible building block of the future all optical computer or photonic devices. All optical logic gates NOT, NAND and AND gates using two photon absorption in silicon wire waveguide are presented. Use of ultra short pulse has negligible free carrier absorption effect; hence the operating speed of the gates is very high and has potential application in photonic processing. NAND gate is universal one and thus one can perform any logical operation using this. The device (Si wire WG) requires low energy pulse and is ultrafast one.

1. Introduction

All optical logic gates are needed to perform future high speed optical signal processing digitally. Optical logic gates have been demonstrated using different techniques such as semiconductor optical amplifier (SOA) [1], nonlinear optical fiber [2], and periodically poled lithium niobate (PPLN) [3]. In SOA, there is some speed limitation and latency, the high power level for the nonlinear operation in the fiber and temperature and polarization sensitivity of PPLN make them less attractive. Recently NOR gate using Si wire waveguide (Si WG) have been demonstrated [4–6]. The high refractive index contrast ($n = 3.5$ for Si and 1.45 for SiO_2) makes it possible to realize submicron size single mode planar waveguide [7]. Due to small effective area ($<0.1\ \mu m^2$) and high optical confinement, the Si waveguide can produce high intensity in low input optical powers used in telecommunications [8]. Thus photonic integration is possible more efficiently in this Si wire waveguide based devices compared to other devices. The operating speed of the device depends on the pulse size and shorter the pulse faster will be the speed of operation. In this communication, the authors simulated the basic mechanism, TPA for ultrafast all optical logic gates NOT, NAND and AND using Si waveguide.

2. Working principle and theory

An optical pulse of high intensity propagating along Si waveguide experiences two photon absorption (TPA) which is proportional to the square of the intensity and the maximum transmitted power is therefore limited. The absorption of photon has two direct effects – the optical power depletion (TPA) and the generation of photo carriers. The former is an ultrafast process and the second one is slower. So TPA has no speed limitation due to photo generated carriers [9]. In Fig. 1, nondegenerate and degenerate TPA processes are shown.

When the sum of the energies of two pump photons is larger than the band gap of silicon, they will be absorbed by the process of phonon mediated degenerate two photon absorption (TPA) as in Fig. 1(a). When the sum of the pump photon and probe photon energies is larger than the band gap, phonon assisted nondegenerate TPA causes absorption of the two photons. This results in cross modulation of the probe light. Here excess free carrier absorption loss is neglected because both the pump and probe photons are ultrashort pulses.

By proper choice of the pump (ultra-short pulses) one can achieve high peak power and low average power [8], the amount of free carrier generated is small (since ultra-short pulses are used) and the corresponding loss is negligible.

The evolution of the pump and signal field intensities $I_p\,(z)$ and $I_s\,(z)$ of two different frequencies, along the propagation direction z, is governed by following expressions [10]

$$\frac{dI_p}{dz} = -(\alpha_p + \alpha_{FCA})I_p - \beta I_p^2 - 2\beta I_p I_s \tag{1}$$

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* Corresponding author.
E-mail address: lipton007@indiatimes.com (K. Mukherjee).

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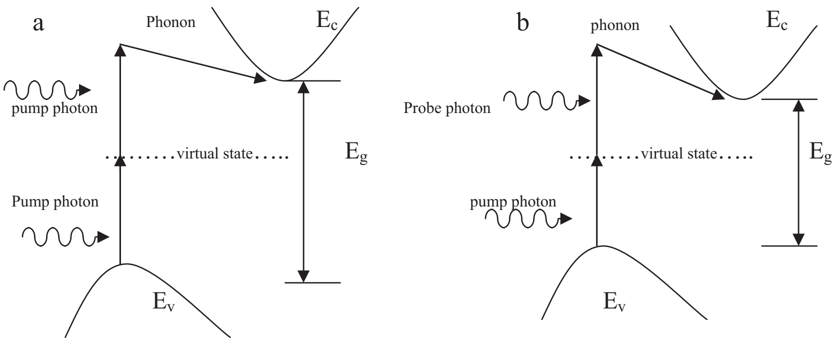

Fig. 1. (a): Degenerate TPA, (b): nondegenerate TPA.

$$\frac{dI_s}{dz} = -(\alpha_s + \alpha_{FCA})I_s - \beta I_s^2 - 2\beta I_P I_s \tag{2}$$

where $\alpha_{p,s}$ the linear propagation loss, β is the TPA coefficient, α_{FCA} is the free carrier absorption loss.

The free carrier absorption loss is related to the carrier density $N(z)$ as [11]

$$\alpha_{FCA}(z) = 1.45 \times 10^{-17} N(z) \tag{3}$$

Here $N(z)$ is the carrier density created from a single pump pulse inside the waveguide along propagation direction z and is given by [12] (taking Gaussian temporal profile of the pump).

$$N(z) = \frac{\beta\sqrt{\pi}TI_0^2(z)}{4h\nu} \tag{4}$$

where β is the TPA coefficient, T is the pulse width; I_0 is the peak power and $h\nu$ is the photon energy. For Gaussian pump pulse with 1.6 ps pulse-width and 2 W peak power, the calculated free-carrier absorption loss after 1 cm long waveguide will be less than 0.18 dB. Thus the additional loss from photo-generated carriers is almost negligible [8].

3. Simulation and result

The simulation of Eqs. (1)–(4) has done using MATLAB and the results are shown in Figs. 3–6. In Fig. 3, the variation of α_{FCA} with input pump power for different pulse width (T = 0.1 ps, 0.5 ps and 1 ps) is shown. The linear loss α and free carrier absorption loss α_{FCA} of both the pump and probe beam can be neglected as discussed. From Fig. 3, it is clear that the value of α_{FCA} is negligibly small in the power range 0–1 GW/cm^2 and thus we have taken $\alpha_{FCA} = 0$. It is also interesting to note that less is the pulse width less is the value of α_{FCA} and a pulse width of the order of 1 ps is very much effective for proper operation of the devices proposed. The linear absorption loss α is also neglected since the waveguide has very small dimension and the non linear effects are more dominant. We have also excluded the dispersive terms and the real part of the nonlinear index which is also in effect leads to some kind of dispersion only.

In Fig. 4, the transmitted intensity shows a little variation about 4% for T = 1 ps and the variation decreases for low values of T. For T = 0.5 or less the intensity transmitted is almost negligible. But a large pulse width (2 ps) may cause sufficient decrease in the intensity. So the selection of the pulse width of the input probe is a crucial factor. Any pulse width of the order of 1 ps is best for the operation of the devices. It is also interesting to note in Fig. 4 that the decrease in the fraction of intensity is less for pump with less initial peak power I_0 (1 GW and 0.5 GW is shown in the figure here). So suitably we can choose the pump intensity keeping in mind the factor of pulse width T for more proper operation of the device.

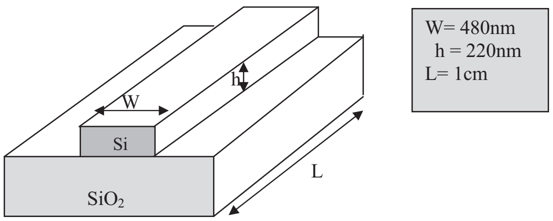

Fig. 2. Silicon wire waveguide.

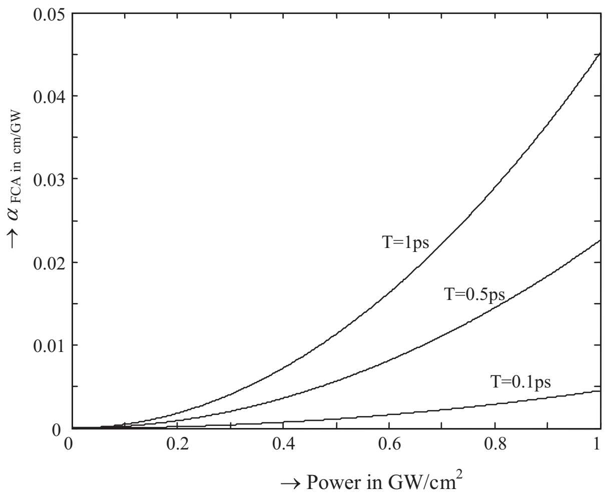

Fig. 3. Variation of α_{FCA} with input power for different pulse widths.

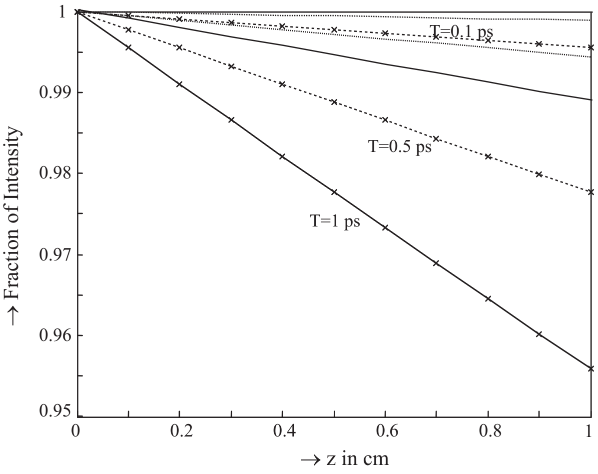

Fig. 4. Variation of fraction of transmitted intensity with length z of the waveguide for different pulse width and for two different initial intensity I_0.