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Review

A method of implementation of all optical logic gates based on two photon absorption in silicon wire wave guide

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All optical logic gates NOT, NAND and AND gates using two photon absorption in silicon wire waveguide is proposed. Due to use of ultra short pulse there is negligible free carrier absorption effect and 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 silicon wire waveguide (Si wire WG) requires low energy pulse (few PJ) and is ultra fast one.

Key words: Silicon wire waveguide, two photon absorption, logic gate, photonic integration.

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) Connelley (2002), non linear optical fiber Islam (1990), and Periodically Poled Lithium Niobate (PPLN) Yeung et al. (2006) etc. In SOA there is some speed limitation and latency, the high power level for the non linear operation in the fiber and temperature and polarization sensitivity of PPLN make them less attractive. Recently NOR gate using Silicon wire Waveguide (Si wire WG) have been demonstrated (Liang et al., 2005; Naruse et al., 2005; Liang et al., 2005a). The high refractive index contrast (n = 3.5 for Si and 1.45 for SiO_2) makes it possible to realize sub micron size single mode planar wave guide (Tsuchizawa et al., 2005). Due to small effective area (< 0.1 μm^2) and high optical confinement, the Si wire WG can produce high intensity in low input optical powers used in telecommunications (Liang et al., 2006). Thus photonic integration is possible more efficiently in this Si wire WG based devices compared to other devices. The operating speed of the device depends on the pulse size and the shorter pulse will cause faster speed of operation. In this communication the author wish to propose ultra fast all optical logic gates NOT, NAND and AND exploiting Two Photon Absorption (TPA) in Si wire WG.

THEORY

A silicon crystal exhibits an inversion symmetry and thus the third order susceptibility $\chi^{(3)}$ generates the lowest order non linearity (Lin et al., 2007). An optical field E(r,t) propagating inside a silicon waveguide induces a non linear polarization which can be written in frequency domain (Bucher and Cotter, 1991; Boyd, 2003).

$$\tilde{P}_i^{(3)}(r,\omega_i) = \frac{3\varepsilon_0}{4[2\pi]^2}\iint \chi_{ijkl}^{(3)}(-\omega_i;\omega_j,-\omega_k,\omega_l)\tilde{E}_j(r,\omega_j)\tilde{E}_k^*(r,\omega_k)\tilde{E}_l(r,\omega_l)d\omega_j d\omega_k \quad (1)$$

Where $\omega_l = \omega_i + \omega_k - \omega_j$, and $\tilde{E}(r,\omega)$ represents the Fourier transform of ith component $E_i(r,t)$ of the electric field. The third order susceptibility of silicon has two dominant contributions can be expressed as:

$$\chi_{ijkl}^{3} = \chi_{ijkl}^{e} + \chi_{ijkl}^{R} \quad (2)$$

In the Equation (2), the first term represents electronic contribution and the second term represents Raman contribution. The electronic contribution stemming from oscillations of bound electrons and leading to the Two Photon Absorption (TPA) when the sum of the energies of the two photons is greater than the band gap of silicon.

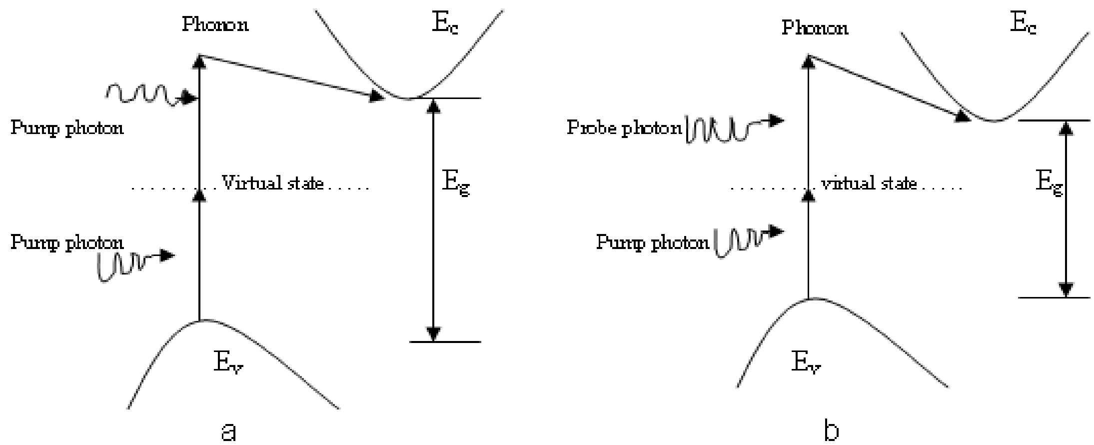

Figure 1. (a) Degenerate TPA: Two photons of same frequency are absorbed. The sum of energy of two hotons is greater than the band gap of silicon and (b) non degenerate TPA: Two photons of different frequencies are absorbed. The sum of energy of two photons is greater than the band gap of silicon.

The process is assisted by phonons to conserve momentum and the response time is very small, typically 10 fs (Bucher and Cotter, 1991; Sheik-Bahe and Van, 1999). So the switching is very fast and finds applications in ultra fast processing. The electronic contribution also causes Kerr effect through intensity dependent changes in refractive index. The complete description of electronic third order non linearity requires knowledge of the dispersive and tensorial properties of $\chi^{e}_{ijkl}\left(-\omega_l;\omega_j,-\omega_k,\omega_i\right)$. Using the property of m3m point group symmetry and intrinsic permutation symmetry $\chi^{e}_{ijkl}\left(-\omega_l;\omega_j,-\omega_k,\omega_i\right)$ can be written as:

$$\chi^{e}_{ijkl}\left(-\omega_l;\omega_j,-\omega_k,\omega_i\right) = \chi^{e}_{1111}\left[\frac{\rho}{3}\left(\delta_{ij}\delta_{kl}+\delta_{ik}\delta_{kl}+\delta_{il}\delta_{jl}\right)+(1-\rho)\delta_{ijkl}\right] \quad (3)$$

Where $\rho = 3\frac{\chi^{e}_{1122}}{\chi_{1111}e}$ characterizes the non linear anisotropy. Measuring the value of $\chi^{e}_{ijkl}\left(-\omega_l;\omega_j,-\omega_k,\omega_i\right)$ one can characterize the electronic non linearity, the real and imaginary part of which is related to the Kerr coefficient n_2 and TPA coefficient β by the relation

$$\frac{\omega}{c}n_2(\omega)+\frac{i}{2}\beta(\omega)=\frac{3\omega}{4\varepsilon_0 c^2 n_0^2(\omega)}\chi^{e}_{1111}(-\omega,\omega,-\omega,\omega) \quad (4)$$

Where $n_0(\omega)$ is the linear refractive index (Lin et al., 2007a). One can define a Non linear Figure of Merit (NFOM) Mizrahi et al. (1989) defined by $F_n = \frac{n_2}{\lambda\beta}$ and its value is very small at wavelengths 1.5 µm for silicon as reported in (Dinu et al., 2003; Lin et al., 2007).

WORKING PRINCIPLE

While propagating along a Si wire WG a highly intense pulse will experience TPA. This TPA is proportional to the square of the intensity and the maximum transmitted power is limited. The absorption of photon has two direct effects – the optical power depletion TPA and the generation of photo carriers. The former is an ultra fast process as explained in the previous section and the second one is slower. So TPA has no speed limitation due to photo generated carriers (Tsang et al., 1991). In the Figure 1, non degenerate 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 TPA as in the Figure 1a. When the sum of the pump photon and probe photon energies is larger than the band gap, phonon assisted non degenerate 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 ultra short pulses.

Silicon wire waveguide

A typical waveguide is shown in the Figure 2. The basic design of the waveguide as shown in the figure, the core

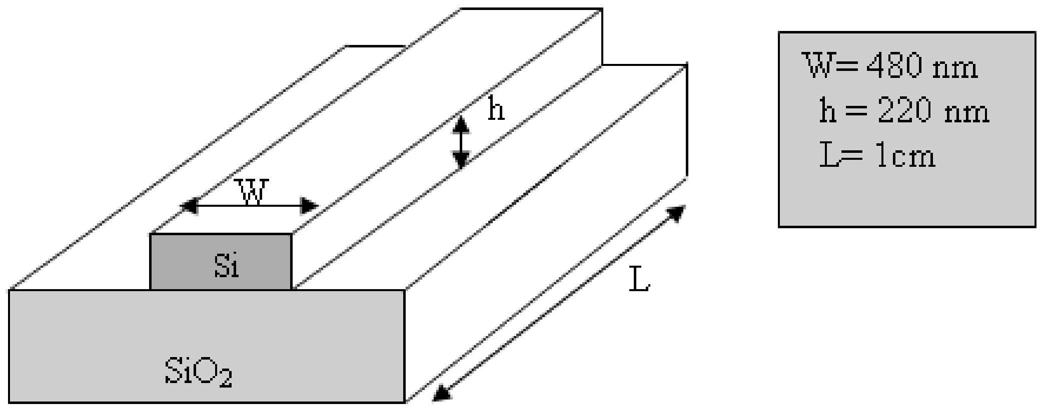

Figure 2. Silicon wire waveguide: The core is constructed by a silicon strip of dimension W by h and length L over a SiO_2 layer. Typical values of W, h and L are 480, 220 nm and 1 cm, respectively.

is constructed by a silicon strip of dimension W by h and length L over a SiO_2 layer. The details of the structure and characteristics are given elsewhere (Bogaerts et al., (2004). The wave guide core may be taken as a stripe of dimension 480 nm × 220 nm × 10 mm (Figure 2) for a typical experiment. 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. As reported in (Liang et al., 2006), the probe pulse was extinguished nearly 90% at pump power as low as 5 watt. This nonlinear characteristic is due to pump depletion in the waveguide. The pump depletion can be described by (Laughton et al., 1992).

$$\frac{dI}{dz} = -\alpha I + \beta I^2 - \alpha_f I \quad (5)$$

Where I is the intensity of the pulse, α and α_f are linear propagation loss and free carrier absorption loss, respectively. The free carrier absorption loss is related to the carrier density N (z) as (Bogaerts et al., 2004).

$$\alpha_f (z) = 1.45 \times 10^{-17} N(z) \quad (6)$$

Here N(z) is the carrier density created from a single pump pulse inside the waveguide along propagation direction z and is given by (Laughton et al., 1992) (taking Gaussian temporal profile of the pump).

$$N(z) = \frac{\beta \sqrt{\pi} T I_0^2(z)}{4h\nu} \quad (7)$$

Where β is the TPA coefficient, T is the pulse width, I_0 is the peak power and hυ is the photon energy. For Gaussian pump pulse with 1.6 ps pulse width and 2 W peak powers, 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 (Liang 2006).So for ultra short pulses both the Kerr contribution and free carrier absorption loss are negligible.

OPERATION OF DIFFERENT LOGIC GATES

The basic principle of operation lies on the transmission characteristics of the Si wire waveguide (Si wire WG). By adjusting the pump power we can control the pump depletion and hence two photon absorption can be created or photons can be transmitted according to our purpose. If there are two light beams with slightly different energies (or wavelengths), with one source at high peak power (pump) and the other one at low power (probe) are injected into the Si wire WG, the high power pump source will then induce absorption of the low power probe signal. So in the output of the Si wire WG there will be no signal. If the pump is not present then there will be no absorption and hence the probe will be transmitted.

NOT gate

Figure 3 shows the schematic diagram of a NOT gate. Signal (pulse) A is used as pump multiplexed by 12.5ps MUX; while another pulsed light is used as the probe which is multiplexed by a 25ps MUX. The detail of the generation of the pump and probe pulse is described in the work. When the pump signal is present (bit ‘1’), the pump pulse induces optical absorption on the probe pulse in Si wire WG by means of non degenerate TPA effect. So the output is LOW (‘0’bit). When the pump signal is absent (‘0’bit), the probe pulse is transmitted

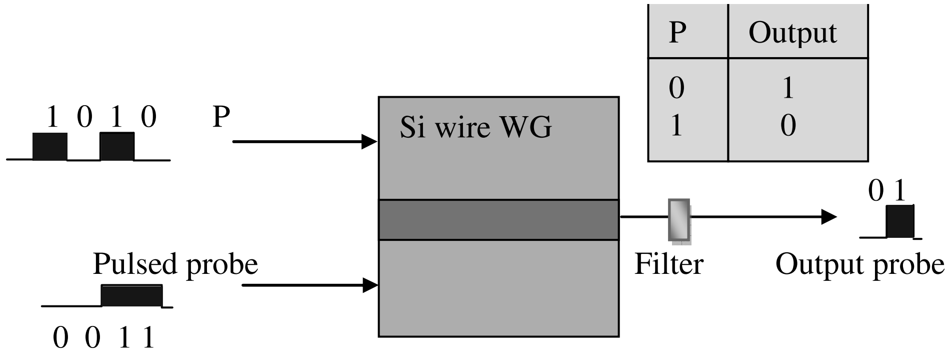

Figure 3. NOT gate based on Si wire WG: When A is present TPA causes cross absorption modulation of the CW probe resulting no output. When A is not present CW is transmitted and output is high. When A = 0, the output is 1 and when A = 1, the output is 0.

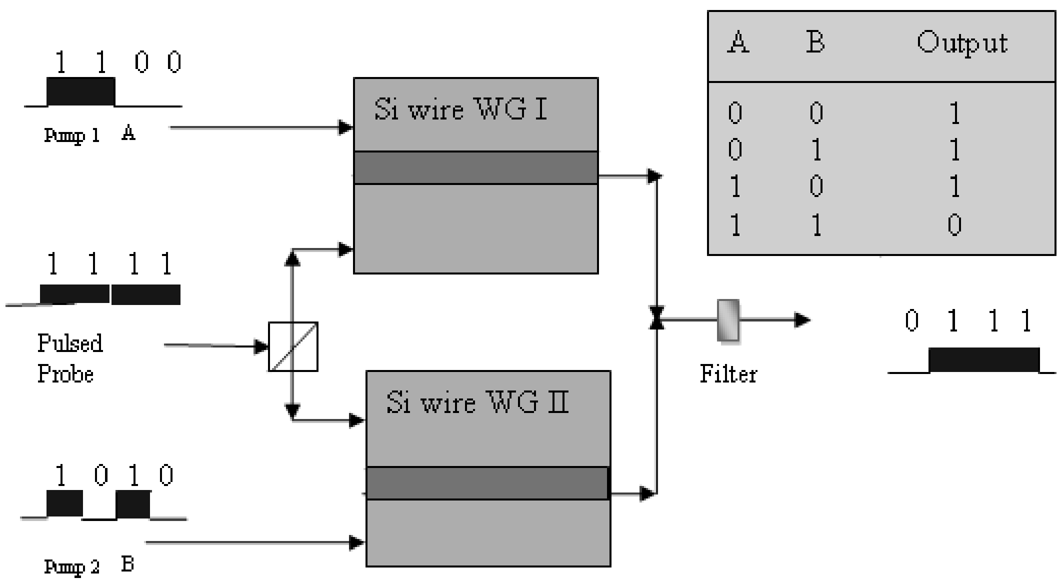

Figure 4. NAND gate realization by use of Si wire WG. When any one of A or Bis low then the output is high. When both A and B are high the output is low. A beam splitter is used to generate two probes. When any one of the input is 0, the out put is 1 and when both the inputs are 1, the output is 0.

through the waveguide without any non linear loss. Thus the output is HIGH ('1'bit).This is the NOT operation. A filter centered at probe wavelength removes the output of the Si wire WG.

NAND gate

The next gate which will be realized is the NAND gate. The output of a NAND gate is HIGH ('1' state) if any one or both of the inputs are LOW ('0' state). When both the inputs are HIGH the output is LOW. The schematic diagram of a NAND gate using TPA in Si wire WG is shown in the Figure 4. When both the signals A and B are absent there is no non degenerate TPA in the both Si wire WG I and II hence the probe pulse is transmitted and the output is HIGH. When the signal A is absent but B is present there will be TPA in the Si wire WG II and the probe light will be transmitted through the Si wire WGI since there is no non degenerated TPA in this wave guide. So the output is HIGH due to the transmitted probe light through the WG I. Similarly when the signal A is present and B is absent, non degenerate TPA happens in the Upper WG I and transmission of probe light through Lower WG II results in HIGH output State again. Finally when both the signals A and B are present, non degenerate TPA is induced on both the waveguides and resulting absorption of the probe on both the waveguides

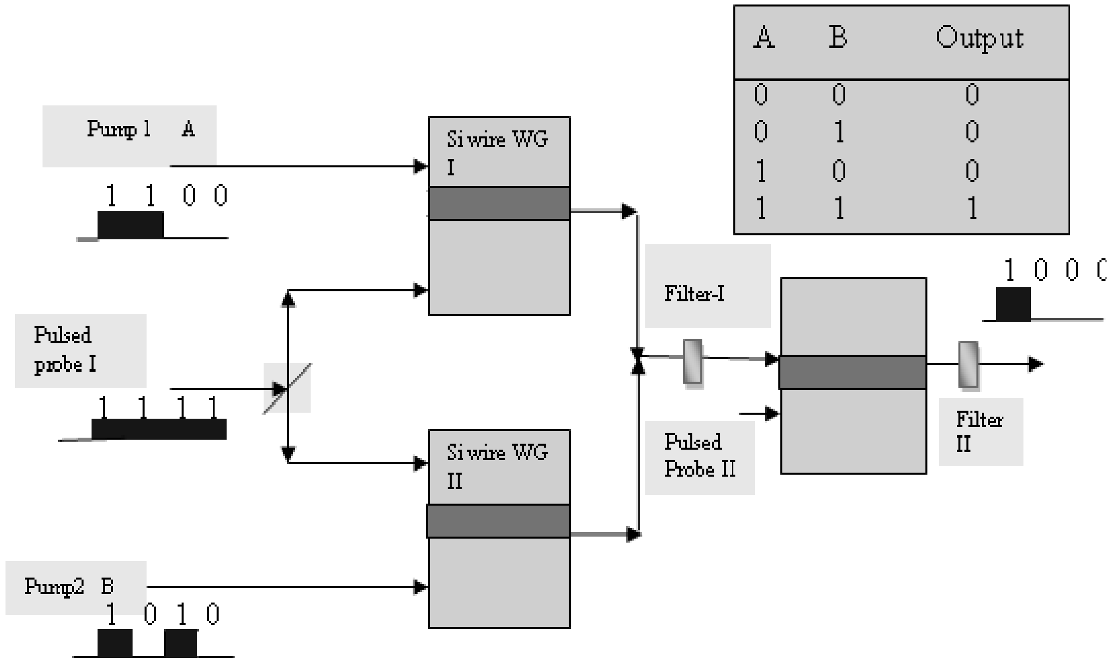

Figure 5. AND gate realization using Si wire wave guide. When both the inputs are high then the output is high and otherwise the output is high. A beam splitter is used to generate two probes. When any one of the input is 0, the out put is 0 and when both the inputs are 1, the output is 1.

and hence the output is LOW. This is the operation of a NAND gate.

AND gate realization

The experimental realization of the AND gate using Si wire WG is shown in the Figure 5. In this experimental design three Si wire WG is used. When any both A and B are LOW, the probe I is transmitted through both the WG I and II and the input to the WG III is HIGH. This makes TPA to happen in the WG III and the final output of the WG III is LOW. Again when either one of A or B is LOW, the input to the WG III is HIGH resulting a HIGH out put in the WG III due to non degenerate TPA in WGIII. When both of the A and B are HIGH, the outputs of WG I and II are both LOW hence, the input of the WG III is LOW. This result in a transmission of the probe II that is, the final output is HIGH. This is the operation of an AND gate. The filters I and II are centered at wavelengths of probe I and II respectively.

PHYSICAL REQUIREMENT FOR EXPERIMENTAL DEMONSTRATION OF THE GATES

For the operation of different logic gates the pump and the probe pulse may be generated from a broad band femto-second passive Mode Locked Fiber Laser (MLFL) by spectral slicing in the following process (Figure 6). The output of the MLFL is divided into two parts, the upper and the lower part. The upper part is passed through a tunable filter with a center wavelength 1545 nm and multiplexed by a 12.5 ps MUX and then amplified. The lower part is passed through tunable filter with centre at 1550 nm, 25 ps MUX and then an attenuator to generate probe pulse. The relative pulse repetition rate of pump and probe for the different logic gates are shown in the figure of the corresponding gates. The probe II in the Si wire WG III should be different from probe I and it may be of wavelength 1560 nm.

CONCLUSION

In this paper three very useful gates for optical data processing are proposed with ultra fast operating speed. In the output for proper detection of the pulse one should use amplifier to enhance the power of the output signal. The device required for the implementation of the gates is very small in size and the operating powers requirement is very low and operation at any wavelengths between 1200 and beyond 1700 nm range is possible. For this the sum of the pump photon energy and probe photon energy should be greater than the band gap of the silicon. This implementation of the logic gates also shows that Si wires WG have potential applications in ultra fast optical photonic signal processing and very much

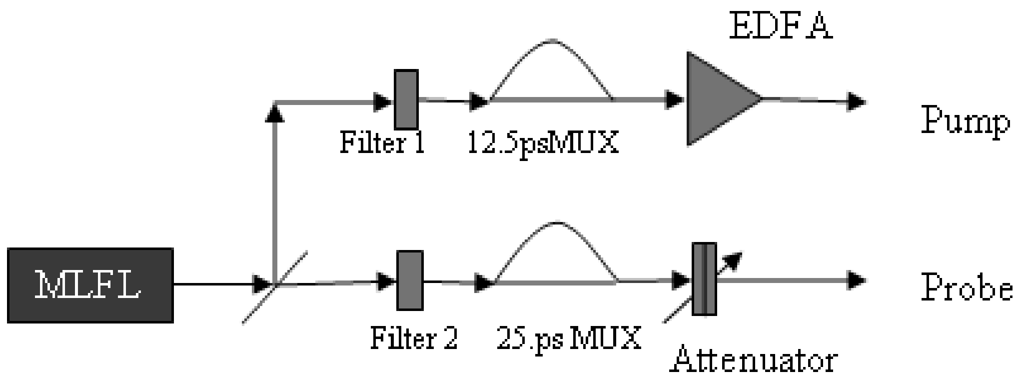

Figure 6. The scheme for generation probe and pumps signals necessary for the experimental set up. EDFA is an amplifier; attenuator is used when the probe intensity is comparatively large. Filter 1 and 2 are centered at pump and probe wavelengths, respectively.

applicable to telecommunications.

REFERENCES

Bogaerts W, Taillaert D, Luyssaert B, Dumon P, Van J, Campenhout P, Bienstman D, Van T, Baets R, Wiaux V, Beckx S (2004). “Basic structures for photonic integrated circuits in Silicon-on-insulator” Opt. Express, 12: 1583.

Boyd RW (2003). non linear optics, 2nd Ed(Academic press,Boston,2003).

Bucher PN, Cotter D (1991). The elements of non linear optics (Cambridge University press, Newyork, 1991).

Connelley MJ (2002). Semiconductor Optical Amplifiers, Kluwer Academic.

Dinu M, Quochi F, Garcia H (2003). “Third order nonlinearities in silicon at telecom wavelengths,” Appl. Phys. Lett., 82: 2954-2956.

Islam MN (1990). ”All optical cascadable NOR gate” Opt. Lett. 415-417.

Laughton FR, Marsh JH, John SR (1992). “Intutive model to include the effect of free carrier absorption in calculating the two- photon coefficient” Appl. Phys. Lett., 60: 166.

Liang a TK, Nunes LR, Tsuchiya M, Abedin KS, Miyazaki T, Van Thourhout D, Bogaerts W, Dumon P, Baets R, Tsang HK (2006). “High speed logic gate using two-photon absorption in silicon waveguides Opt. Comm., 265: 171.

Liang TK, Nunes LR, Tsuchiya M, Abedin KS, Miyazaki T, Van Thourhout D, Dumon P, Baets R, Tsang HK (2005). “All- optical high speed NOR gate based on Two Photon Absorption in silicon wire waveguides” OFP1 Opt. Soc. Am., p. 3.

Liang TK, Nunes TLR, Sakamoto T, Sasagawa K, Kawanishi T, Tsuchiya M, Priem GRA, Van Thourhout D, Dumon P, Baets R, Tsang HK (2005a). “Ultrafast all-optical switching by cross-absorption modulation in silicon wire waveguides”, Opt. Express, 13: 72-98.

Lin Q, Painter OJ, Agarwal GP (2007). ”Non linear optical phenomena in silicon waveguides: Modeling and applications”, Opt. Exp., 15: 25-16604.

Lin Q, Zhang J, Piredda G, Boyd RW, Fauchet PM, Agarwal GP (2007a). “Dispersion of silicon nonlinearities in the near-infrared region.” Appl. Lett., 90: 021111.

Mizrahi V, DeLong KW, Stegeman GI, Saifi MA, Andrejco MJ (1989). “Two photon absorption as a limitation to all optical computing.” Opt. Lett., 14: 1140-1142.

Naruse M, Yoshida H, Miyazaki T, Kubota F, Ishikawa H (2005). “Ultrafast all-optical NOR gate based on inter subband and interband transitions”, IEEE Phot. Techl. Lett., 17: 1701.

Sheik-Bahe M, Van Stryland EW (1999). “Optical nonlinearities in the transparency region of bulk semiconductors” in Non linear optics in semiconductors I.E. Garmire and A Kost, Eds. Semiconductor and semimetals, Vol 58 (Academic, Boston, 1999).

Tsang HK, Penty RV, White IH, Grant RS, Sibbett W, Soole JBD, Leblanc HP, Andreadakis NC, Bhat R, Koza MA (1991). “Two-photon absorption and self-phase modulation in InGaAsP/InP multi-quantum-well waveguides” J. Appl. Phys., 70: 3992.

Tsuchizawa T, Yamada K, Fukuda H, Watanabe T, Jun-ichi T, Takahashi M, Shoji T, Tamechika E, Itabashi S, Morita H (2005). “Microphotonics devices based on silicon microfabrication technology,” IEEE J Sel Top in Quant. Elect., 11: 232.

Yeung L, Bong-Ahn Y, Tae JE, Woojin S, Changsoo J, Young-Chul N, Jongmin L, Do-Kyeong K, Kyunghwan O (2006). “All-optical AND and NAND gates based on cascaded second-order nonlinear processes in a Ti-diffused periodically poled $LiNbO_3$ waveguide”. Opt. Exp., 14: 772-776.