All-Optical High Speed NOR Gate Based on Two Photon Absorption in Silicon Wire Waveguides

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Abstract: We demonstrate for the first time an all-optical logic NOR gate in submicron size silicon wire waveguides. High speed operation at equivalent 80Gbps data rate was achieved using pump induced non-degenerate two-photon absorption inside the waveguides. The device requires low pulse energy (few pJ) for logic gate operation.

OCIS codes: (230.7370) Waveguides; (190.4180) Multiphoton processes; (200.4560) Optical data processing; (200.3760) Logic-based optical processing;

1. Introduction:

Future high capacity optical networks will require all-optical digital signal processing to overcome the speed limitations of electronic signal processors. Optical logic gates are needed to perform such signal processing digitally. Various optical logic gates have been successfully demonstrated in different materials, such as nonlinear optical fibers [1], semiconductor optical amplifier (SOA) [2] and InGaAs/AlAsSb coupled double-quantum-well structures [3]. The long time latency and high optical power level for nonlinear operation make fiber-based devices unattractive for practical applications, while the long carrier lifetime in conventional SOAs may limit the speed unless some complicated differential switching scheme is employed. The reported logic gate on InGaAs/AlAsSb has a relatively low extinction ratio.

There have been much recent research on sub-micron size silicon wire waveguides. Silicon wire waveguides have extremely high index contrast (n=3.5 for silicon, and n=1.45 for SiO_2), which allows the realization of submicron size singlemode planar waveguides [4]. The strong optical confinement and small effective modal area ($<0.1\mu m^2$) of such waveguides can produce high optical intensities even at input optical powers typically used in telecommunications. The high optical intensities and long interaction lengths in the waveguides make nonlinear optical effects readily apparent. We demonstrated previously an ultrafast optical switch (<3ps) with pJ pump pulse energy in wire waveguides [5-6].

In this paper, we present for the first time a high speed (80Gbps) all-optical logic NOR gate based on two-photon absorption (TPA) in silicon wire waveguides. The results showed that the direct use of TPA in the silicon wire waveguides allows operation speeds which are not limited by the slow photo-generated carrier lifetime.

2. Working Principle:

Since the sum of energies of two photons at 1.55μm wavelength is greater than the bandgap of silicon, thus the high intensity pulses will experience TPA when propagating along the silicon waveguide. The amount of absorption is proportional to the square of the intensity [7] and the maximum transmitted power is limited. If there are two light beams with slightly different energies (or wavelengths), with one source at high peak power (pump) while the other one at low power (probe), the high power pump source will then induce absorption of the low power probe signal. This is the so called non-degenerate TPA process [8].

A preliminary time-resolved pump-probe experiment was performed to measure the nonlinear transmission of weak probe pulses in the presence of strong optical pulses in silicon wire waveguides. The fabrication and characterization of the waveguide was described in [9]. As shown in Fig. 1(a), the waveguide core was formed by a silicon strip measuring 480nm by 220nm. The length of the waveguide used in the experiment was 10mm. The measured transmission as a function of peak pump pulse levels is shown in Fig. 1(b). Both pump and probe pulses were generated by the spectral slicing of a broadband femtosecond passive mode-locked laser. By using ultrashort pulses (around 1.6ps FWHM pulsewidth) used, the additional absorption loss due to photo-generated free carriers was negligible. The coupled-peak power of probe pulse was less than 20mW. As shown in the curve, the probe pulse was extinguished by more than 90% at peak-coupled pump power of 5W. The nonlinear transmission characteristic was due to the pump depletion in the waveguide.

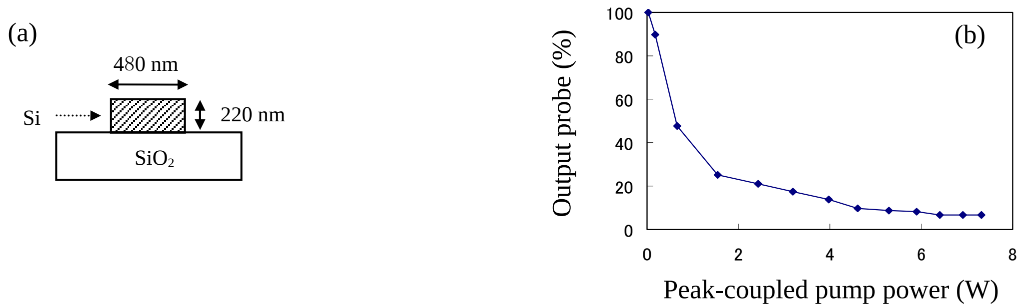
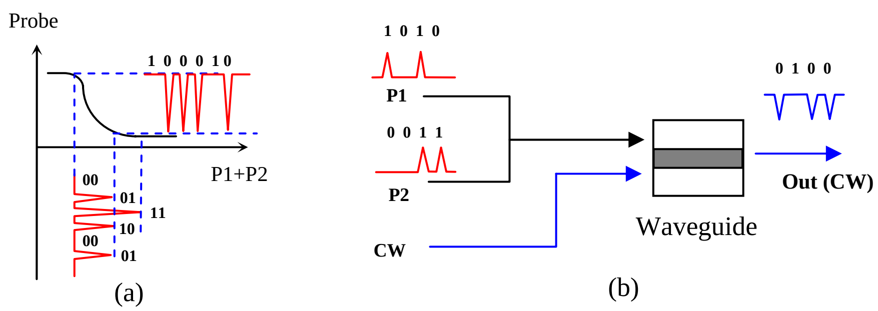


Fig. 1. (a). Waveguide structure. (b) Nonlinear transmission curve of probe signal under different pump peak powers.

The operation principle and experimental schematic of NOR gate based on the nonlinear transmission curve in silicon wire waveguides is shown in Fig. 2(a) and Fig. 2(b). Signal P1 and P2 with same peak power were combined together and coupled into the waveguide. The weak continuous-wave (CW) probe light at waveguide output was cross-modulated by the sum of P1 and P2 based on non-degenerate TPA process. The Boolean NOR operation was achieved in the form of dark pulses. The corresponding truth table is shown in Fig. 2(c).



NOR

P1	P2	Out
0	0	1
0	1	0
1	0	0
1	1	0

(c)

Fig. 2. (a) Operation principle. (b) Schematic diagram of NOR gate. (c) Truth table.

3. Experimental demonstration:

Shown in Fig.3 is the experimental setup for the demonstration of the optical NOR gate. A stretched pulse passively mode-locked fiber laser (MLFL) was used to generate femtosecond optical pulses at 20MHz repetition rate. The pulse source, with 50nm spectral width, was then split into two paths and passed through two optical tunable filters with center wavelengths at 1545nm and 1555nm respectively. Part of the passive mode-locked pulses was tapped out for the trigger in sampling oscilloscope. The pulses multiplexed by 25ps and 12.5ps delay lines, which correspond to 80Gbps data rate, were used as signal P1 and P2 respectively. Signal P1 carried the digital signal "1010", while signal P2 carried the signal "0011". A weak CW probe signal, generated by a tunable laser (TL) at 1560nm, was launched into the silicon wire waveguide together with P1 and P2. The tunable filter (5nm bandwidth) after the waveguide removed both signals. Finally, the CW probe formed output logic signal and was detected by a 50GHz bandwidth photodiode.

In the absence of both input logic signals, the CW probe will propagate through the waveguide without additional absorption loss. With only either P1 or P2, the CW probe will experience cross-absorption modulation induced by the strong pump pulses. According to the nonlinear transmission curve shown in Fig.1(b) and Fig.2(a), the absorption will saturate at certain level of pump powers. In the saturation regime, the absorption loss on the CW probe when both P1 and P2 are present simultaneously will be very similar to the case of a single pump signal. This behavior of the CW probe at the waveguide output corresponds to the logic NOR operation.

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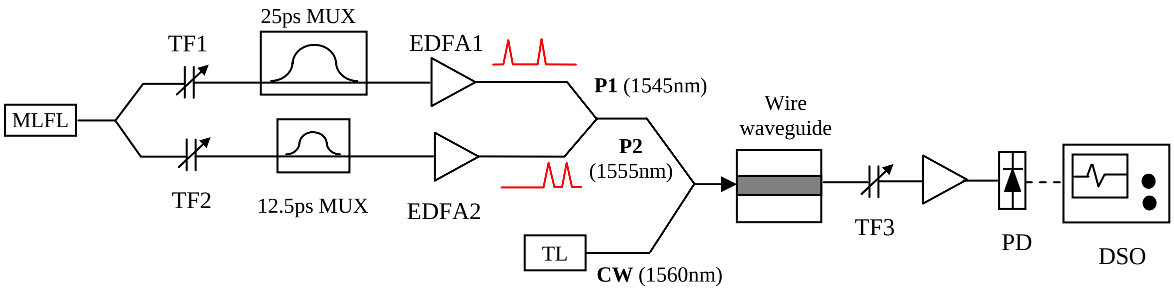

Fig. 3. Experimental setup of all-optical logic NOR gate. MLFL: mode-locked fiber laser. TF: Tunable filter. MUX: multiplexer. EDFA: Erbium-doped fiber amplifier. TL: Tunable laser. PD: Photodetector. DSO: Digital sampling oscilloscope.

The signal P1 and P2 are shown in Fig. 4(a) and (b) respectively. The pulsewidth of the signals after TF1 and TF2 were both measured to be 1.6ps FWHM by an autocorrelator. The measured pulses on the sampling oscilloscope were broadened to around 13ps due to the limited bandwidth of the photodetector. Two signals at different wavelengths were selected to avoid interference and thereby ensure a stable output waveform. The peak powers of P1 and P2 was less than 5W and corresponding pulse energy was less than 8pJ. Thus the modulation depth of the output dark pulse is expected to be more than 90%. However, the real modulation depth cannot be measured directly by the limited bandwidth photodetector. It is apparent from Fig. 4(c) that the output logic NOR operation was "0100". It should be noted that the dark pulse output can easily be avoided if the CW probe light is replaced by pulse train. Since the time separation between two digits was 12.5ps, the equivalent data rate of the optical NOR gate was 80Gbps. In addition, the logic output can be obtained at any arbitrary wavelength range below the bandgap of silicon.

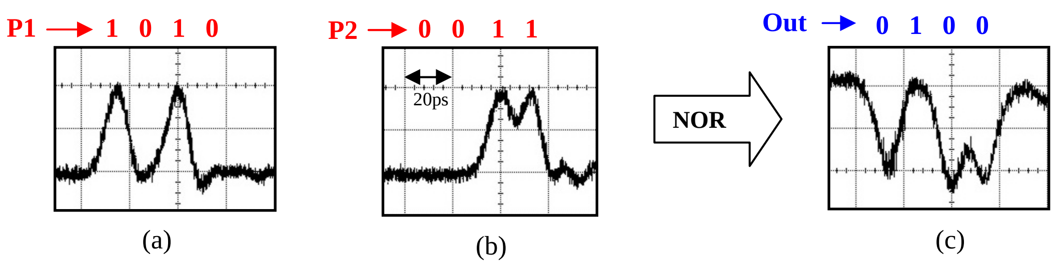

Fig.4. (a) Signal P1. (b) Signal P2. (c). Output cross-modulated CW probe with logic NOR operation.

4. Conclusion:

An 80Gbps optical logic NOR gate using silicon wire waveguide was demonstrated. The device consisted of only a single 1-cm long waveguide. Only low pump pulse energy is required and operation at any wavelength between 1200nm to beyond 1700nm range is possible provided the sum of pump photon energy and signal photon energy is higher than the bandgap of silicon.

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