Ultrafast all-optical switching by cross-absorption modulation in silicon wire waveguides

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Abstract: We describe the use of two-photon absorption in submicron silicon wire waveguides for all-optical switching by cross-absorption modulation. Optical pulses of 3.2 ps were successfully converted from high power pump to low power continuous-wave signal with a fast recovery time. High speed operation was based on the induced optical absorption from non-degenerate two-photon absorption inside the waveguides.

OCIS codes: (130.5990) Semiconductors; (070.6020) Signal processing; (190.4180) Multiphoton processes; (190.4360) Nonlinear optics, devices; (230.1150) All-optical devices.

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1. Introduction

Silicon-on-insulator optical waveguides have extremely high index contrast, which allow the realization of submicron size singlemode planar waveguides [1-3]. Due to the strong optical confinement in such waveguides, ultra-high optical intensity can be easily achieved with input optical powers typically used in telecommunications. The high optical intensities and long interaction lengths in the waveguides can lead to the manifestation of nonlinear optical effects. Many kinds of silicon waveguide based optical switches have been reported so far [4-6]. Among them, the switching mechanisms in most of the devices are based on plasma dispersion effect. In such devices, excess free carriers are introduced inside the waveguides either by external current injection or optically excitation. The excess carriers lead to optical absorption and phase shift, which are the fundamental requirements for an optical switch. However, the switching speed is always limited by the effective carrier lifetime. The typical carrier lifetime may range from hundreds of picoseconds in submicron size silicon wire waveguides [7] to about one hundred nanoseconds in large size single mode silicon rib waveguides [8].

Two-photon absorption (TPA) is the dominant optical nonlinear absorption process in silicon waveguides at telecommunication wavelengths. The absorption of photons will lead to two direct consequences – the optical power depletion (photon absorption) and the generation of excess electron-hole pairs (free carriers). The former is intrinsically an ultrafast process [9], while the later is a slow process that will further attenuate the optical signal via free-carrier absorption and hot carrier assisted absorption [9]. Although optical modulation by TPA has been demonstrated in silicon rib waveguides [10], the high peak powers and the existence of slow carrier recombination process makes it difficult to become a practical ultrafast switching element.

In this paper, we demonstrate all-optical switching using non-degenerate TPA process inside silicon wire waveguides. The 3.2 ps pump pulses at 1 GHz repetition rate were successfully converted from 1552 nm to 1536 nm by using cross absorption modulation (XAM) on the continuous-wave (cw) probe signal. Our results showed that the direct use of TPA allows operation speeds which are not limited by the slow effective carrier lifetime in the silicon wire waveguides.

2. Working principle

When the high intensity pump pulses and weak cw light propagate along the waveguides, there are three major nonlinear absorption processes present. Figure 1 shows the schematic diagram of TPA process in silicon waveguides. When the sum of energy of two pump photons is greater than the bandgap of silicon, they will be absorbed by means of phonon-assisted degenerate TPA process (Fig. 1(a)). This results in pump power depletion (i.e., reduce in number of photons) along the waveguide.

The second effect contributes to the XAM process. As shown in Fig. 1(b), one photon from the pump and another photon from the cw signal are absorbed by means of photon-assisted non-degenerate TPA process [11]. Thus the cw signal is inversely cross modulated by the pump pulses. This process occurs as long as the sum of the energies of the cw photon and pump photon is greater than the silicon energy bandgap. Therefore, the wavelength range of cw signal can be very large.

Finally, the above two processes will create excess free carriers and lead to free carrier absorption on both the pump and cw signals. However, the use of ultrashort pulses having low pulse energies can effectively ensure that only a low density of free carriers is produced, thus minimizing the excess optical loss from free carriers [9]. The effect of the free carrier absorption was negligible in the following experiments, as evidenced by the absence of a slow carrier recovery process in the experimental observations.

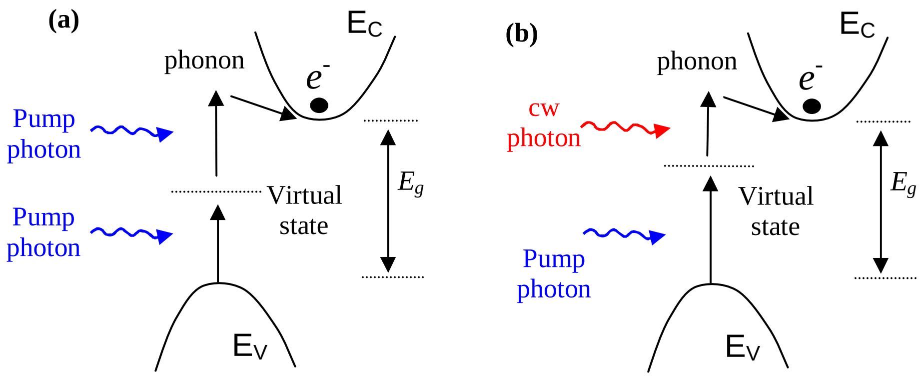

Fig. 1. Schematic diagram of TPA in silicon. (a) degenerate TPA. (b) nondegenerate TPA.

3. Experiments

The fabrication and characterization of the waveguide was described in [12]. The waveguide core was formed by the silicon strip measuring 480 nm x 220 nm. The length of the waveguide used in the experiment was 10 mm. To prevent leakage of the guided mode into the silicon substrate, the buried oxide layer was 1 μm.

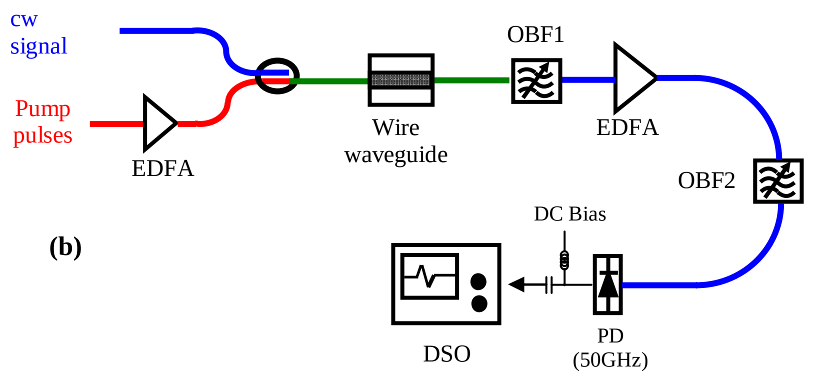

Fig. 2. Experimental setup. EDFA: Erbium-doped fiber amplifier, OBF: optical bandpass filter, PD: photodiode, DSO: digital sampling oscilloscope.

Shown in Fig. 2 is the experimental setup for the switching experiment. A mode-locked fiber ring laser was used to generate pump pulses with 1 GHz repetition rate and 3.2 ps full-width at half-maximum (FWHM) pulsewidth at 1552 nm. The pump pulses were then boosted up to high power by an erbium-doped fiber amplifier (EDFA). The cw signal was generated from a tunable laser operated at 1536 nm. An optical coupler combined the pump and signal light, then coupled into the wire waveguide by a grating based coupler with coupling

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efficiency of about 20% [13]. The average pump power coupled into the waveguide was estimated to be 6 mW (correspond to 1.9 W peak power), while the average power of cw signal was 1 mW. Another EDFA was placed after the waveguide to compensate the insertion loss. We used an optical bandpass filter (OBF) to filter out the pump pulses at the waveguide output. Finally, the cross-modulated cw signal was measured by a 50 GHz bandwidth photodiode and a digital sampling oscilloscope (DSO).

4. Results and Discussion

The optical spectra of the combined signals before the waveguide and the modulated cw signal after the filter are shown in Fig. 3(a) and 3(b) respectively. To remove the residual pump pulses at the receiver side, the high extinction ratio optical bandpass filter is required. As shown in Fig. 3(b), the pump pulses were almost completely removed by the first optical filter after the waveguide.

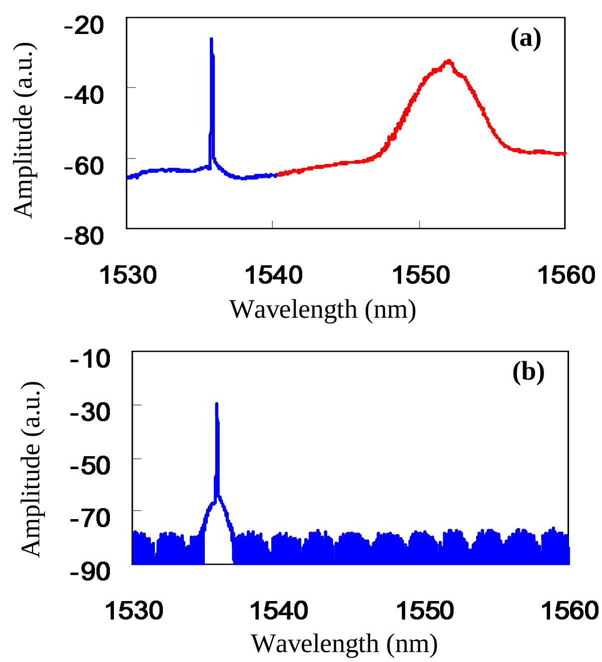

Fig. 3. (a) Optical spectrum of combined signal before waveguide. (b) cw signal after optical filter.

A pump pulse measured by the oscilloscope is shown in Fig. 4(a). The pulse was broadened to about 13 ps due to the limited bandwidth of the photodetector (50GHz) we used. The FWHM of the pump pulse was measured to be 3.2 ps by using an autocorrelator. After passing through the wire waveguide, the pump pulses induced optical absorption on the cw signal. Figure 4(b) shows the modulated cw light in the form of dark pulse. The FWHM pulsewidth of the dark pulses were measured to be 13 ps, which denoted the converted pulsewidth was also limited by the photodetector response. The transients observed in both figures were the typical response of photodetector on ultrashort pulses.

The measured value is limited by the temporal resolution of the measurement equipment. In principle, the switching time should be close to the pump pulse width and it is possible to achieve much sub-picosecond switching time if much shorter pump pulses were used [9]. As a matter of fact, much faster switching time (<3 ps) in current device has been experimentally observed, which will be published elsewhere.

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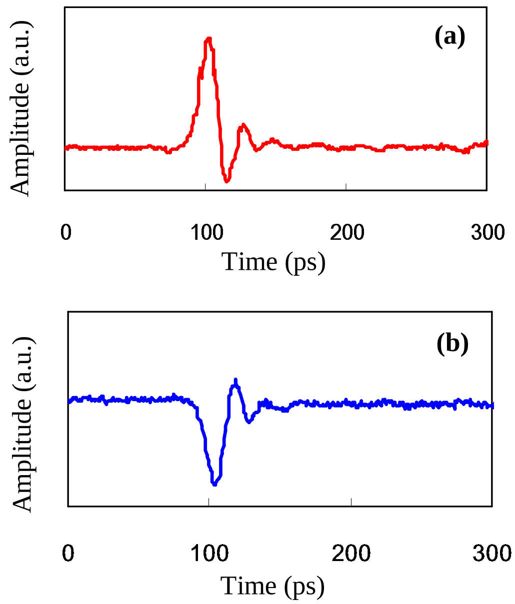

Fig. 4. (a) Pump pulses at 1552nm. (b) Cross-absorption modulated cw signal at 1536 nm

The built-in capacitive coupling of the bias circuit of the 50 GHz bandwidth photodetector prevented the measurement of the modulation depth on digital sampling oscilloscope. Therefore, we tried to measure the converted dark pulse by a streak camera. However the timing jitter in the measuring system limited the temporal resolution and we observed a modulation depth of 70% at a broadened pulse width of around 13 ps with the pump power level employed in the experiment, as shown in Fig. 5.

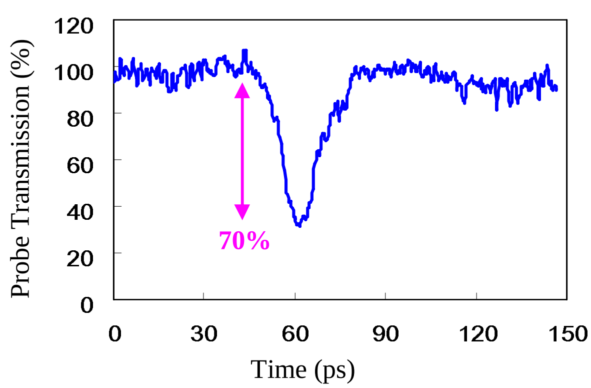

Fig. 5. Cross-absorption modulated cw signal measured by streak camera.

The expected modulation depth can be calculated theoretically in the following way. Along the wire, both pump and probe power will decrease as a result of linear loss. The pump will also suffer from the degenerate TPA process, while the probe is further depleted by the non-degenerate TPA process induced by the pump. Both effects are assumed to be instantaneous. Free carrier effects are neglected as mentioned in the Section 2.

$$\frac{dP_{pump}}{dz}(z,t) = -\alpha P_{pump}(z,t) - \beta_{\deg} P_{pump}(z,t) P_{pump}(z,t) \quad (1)$$

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$$\frac{dP_{probe}}{dz}(z,t) = -\alpha P_{probe}(z,t) - \beta_{non-\deg} P_{pump}(z,t) P_{probe}(z,t) \qquad (2)$$

where z is the propagation direction and α is the linear loss coefficient. β_{deg} and β_{nondeg} are degenerate and non-degenerate TPA coefficients respectively. The relationship of β_{deg} and β_{nondeg} in semiconductors have been described in [14, 15]. To calculate the modulation depth explicitly, the following parameters are used: α=5 dB/cm [12] and β_{deg} = 0.8 cm/GW [16]. Figure 6 shows the modulation depth of cw probe as a function of pump powers. For a peak input power of P_{pump} =1875 mW – which corresponds to an average input power of 6 mW, a modulation depth of 81% is predicted for a wire length of 10 mm. Taking into account the timing jitter limitations of the streak camera, this result corresponds very well with the 70% modulation depth observed experimentally. Calculations including free-carrier absorption also confirmed that free carrier effects are indeed negligible. By using longer wires and higher pump powers, the modulation depth can be further improved, although the additional improvement for wires longer than 10 mm is limited.

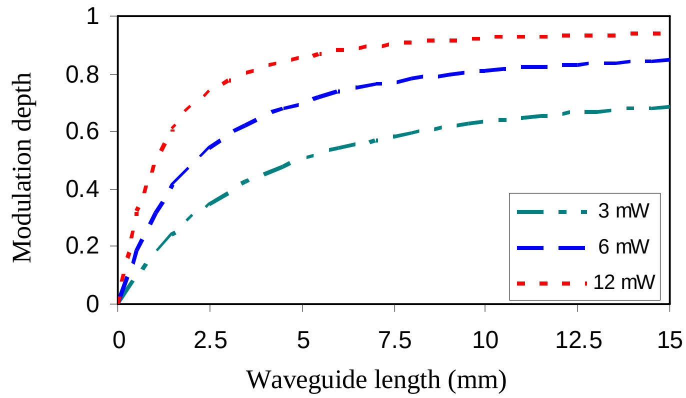

Fig. 6. Calculation of modulation depth as function of wire lengths

Since the pump pulses were wavelength converted from 1552 nm to 1536 nm in the form of dark pulses, this scheme may have potential application for broadband all optical wavelength conversion in future optical communication systems. The primary advantage of this wavelength conversion scheme lies in the fact that the signal wavelength can be anywhere between 1200 nm to beyond 1700 nm (i.e. the range at which the sum of pump photon energy and signal photon energy is greater than the bandgap of silicon). It is also worthy to mention that only a single straight waveguide was used in the experiment. The low pump power used in the experiment revealed that it is possible to have practical nonlinear optical devices on silicon wire waveguides.

5. Conclusion

We demonstrated ultrafast optical switching in silicon wire waveguides by TPA cross absorption modulation scheme. Our results show that silicon wire waveguides have potential applications in ultrafast photonic signal processing regime (e.g. future 160 Gb/s optical communication systems).

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