

## Low Energy Ultrafast Switching in Silicon Wire Waveguides

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**Abstract** 1.9ps optical switching at 40GHz repetition rate has been successfully demonstrated in submicron-size silicon wire waveguides. Ultrafast operation is achieved by induced optical absorption from two-photon absorption (TPA) process. The device requires very low energy, less than 3pJ, to accomplish 92% of modulation depth.

### Introduction

The high refractive index difference ( $\Delta > 41\%$ ) in Silicon-On-Insulator (SOI) platforms gives rise to the realization of sub-micron order singlemode optical wire waveguides [1]. In such structures, due to the high optical confinement, ultra-high optical intensities can be easily achieved with optical powers typically used in telecommunications. Therefore, the manifestation of nonlinear optical effects at low-energy is very attractive for the realization of optical devices, especially all-optical switching.

Up to now, most of the reported silicon-based switching devices rely on plasma dispersion effect for their operation principle. To produce the required absorption or phase shift in such devices, excess free carriers are introduced inside the waveguides either by external current injection [2] or optically excitation [3]. Thus the obtained speed, in the order of hundreds of picoseconds, is always limited by the effective carrier lifetime. The use of modulation based on TPA induced free-carrier absorption, which is intrinsically an ultrafast process [4], has also been demonstrated in silicon structures [5-6]. However, the speed was likewise limited in response time by carrier recombination.

In this paper, we demonstrate ultrafast switching based on non-degenerate TPA process [7] in sub-micron order singlemode optical wire waveguides. 1.9ps optical switching at 40GHz repetition rate has been successfully achieved by employing very low energy, less than 3pJ, to accomplish 92% of modulation depth.

### Working principle

The proposed approach relies on minimizing the free carriers generated inside the waveguide during the switching window, reducing in this way the number of carriers to be subsequently recombined and therefore mitigating the effect of slow recovery, which consequently allows high repetition rate cross-absorption modulation from TPA itself.

The amount of free carriers generated inside the waveguide, during the switching time frame, depends basically on three factors: 1) the peak power of the pulse, 2) the duration of the pulse, and 3) the parameters (physical properties and dimensions) of the waveguides. Since we used ultrashort pulses to achieve high peak power, the amount of free carriers generated during the switching time frame is small. Thus, the effect of slow response time due to free carrier recombination may be minimized by properly fit the pulsewidth and energy of the pump pulses with the parameters of used waveguide.

### Experiments

Figure 1 shows the simplified experimental setup. A semiconductor mode-locked laser generates pump pulses of 1.9ps FWHM pulsewidth at 10GHz in the wavelength of 1552nm. The pump pulses are multiplexed up to 40GHz, and then amplified before being combined with the CW probe signal, which is at the wavelength of 1535.3nm. The combined signals are coupled into the silicon waveguide. An optical bandpass filter (OBPF) suppresses the pump pulses after the waveguide, allowing only the 40GHz modulated CW signal at the output.

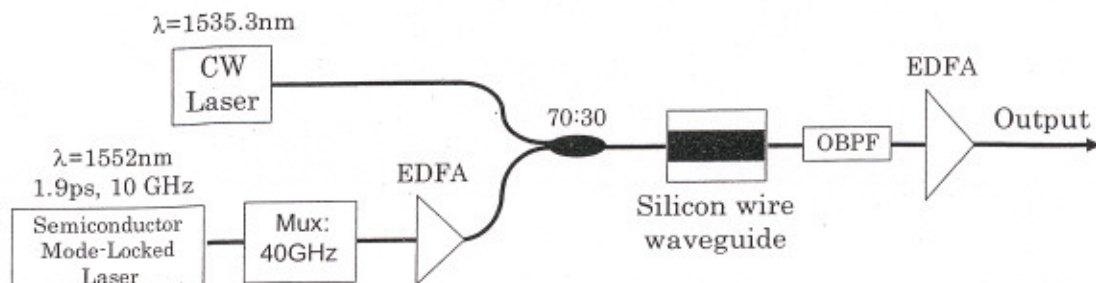


Fig. 1 Simplified Experimental Setup

The wire waveguides used in the experiments are 10mm in length, formed in spiral to fit in a very small foot print area. The waveguide core is formed by a silicon strip measuring 480 nm in width and 220 nm in height. The buried oxide layer is 1  $\mu$ m. The waveguide propagation loss is 0.5dB/mm and the light is coupled in the waveguides by gratings, which exhibit coupling losses of about 7dB per port. The waveguide fabrication process, details on coupling scheme, and characterization of the waveguides are described in [8].

**Results and discussions**

Due to the response of the 50GHz used photodetector, the real modulation depth could not be measured by direct detection and observation on the oscilloscope. Thus, we performed time resolved two color pump-probe measurements. The experiments were performed with both wavelengths with pulsewidth of 1.5ps at 50MHz, and pump pulse with energy less than 3pJ. The results of the experiments, shown in Fig. 2, indicate that 92% of modulation depth can be achieved at such low switching energy. The switching time is about the value of the pump pulsewidth. From the same figure, we also confirmed the absence of the slow response due to carrier recombination.

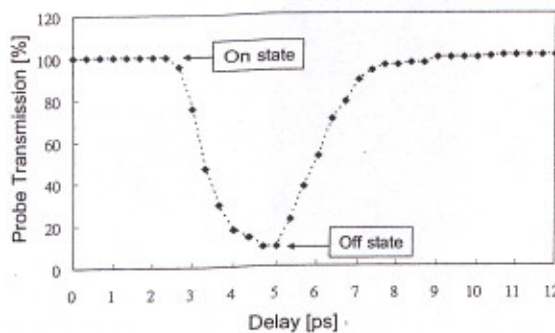


Fig.2. Pump-probe measurements: response time.

We also confirmed the absence of free carrier accumulation at high repetition rates by performing experiments at 10, 20, and 40 GHz.

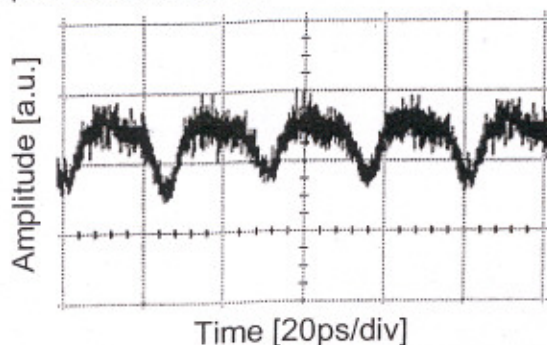


Fig.3 Time domain trace of the 40GHz Modulated CW after suppression of pump signal.

After passing through the wire waveguide, the CW signal was inversely cross modulated by the pump pulses. The CW signal coupled into the waveguide was -5dBm. Figure 3 shows the time domain trace of the 40GHz modulated CW light in the form of dark pulses. The shown pulses were broadened to about 13ps due to the limited bandwidth of the photodetector.

The spectrum of the 40GHz modulated CW signal is shown in Fig. 4. The clear spectral lines with 40GHz spaced from the CW, the center peak, emphasize the efficiency of the modulation.

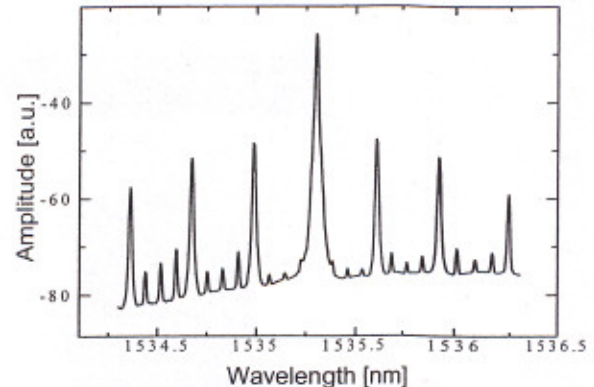


Fig.4 Optical spectrum of 40GHz modulated CW signal

Our results show that the effect of slow response time due to free carrier recombination in semiconductors may be reduced by appropriately choosing the pump and probe pulse energies that best fit the parameters of used waveguide. Thus, the proposed scheme can potentially operate at femtosecond switching regime.

As the conversion mechanism was based on TPA process, the signal wavelength can be anywhere between 1200nm to beyond 1700nm – range at which the sum of pump photon energy and signal photon energy is always higher than the bandgap of silicon.

**Conclusion**

We demonstrated ultrafast optical switching in silicon wire waveguides by TPA cross absorption modulation. We confirmed the absence of free carrier accumulation at high bit rates. 92% of modulation depth was achieved with switching energy less than 3pJ. Our results show that silicon waveguides have potential applications in ultrafast photonic signal processing.

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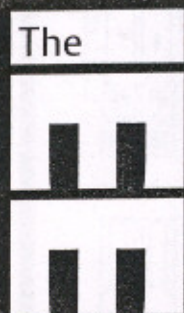
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