Nonlinear Self-Distortion of Picosecond Optical Pulses in Silicon Wire Waveguides

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Abstract: We experimentally observed the self-distortion of picosecond pulses propagating in silicon wire waveguides. The asymmetry of output pulse shape was due to two-photon absorption generated free carriers within the pulse duration.

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Introduction: There has 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 [1]. The strong optical confinement and small effective modal area (~$0.1\mu m^2$) of such waveguides can easily produce extremely high optical intensities at moderate input optical power levels. The advancement of the nanofabrication technology in microelectronics industry allows the realization of low loss (<2 dB/cm) silicon wire waveguides. Therefore, the high optical intensities and long interaction lengths in the waveguides make nonlinear optical effects readily apparent. Two photon absorption (TPA), which involves the simultaneous absorption of two photons below the bandgap, is a promising effect in silicon waveguides for making attractive nonlinear optical devices. We have reported an ultrafast optical switch using TPA previously [2]. The absorption of photons creates electron-hole pairs in silicon and produces a secondary effect: free-carrier absorption. This secondary effect has been widely used in silicon-based switching devices [3] because the excess free carriers change the optical absorption coefficient and phase in the waveguides.

In this paper, we study the temporal nonlinear transmission characteristic of high intensity picosecond pulse in silicon wire waveguides. The generation of free carriers along the pulse duration leads to the asymmetric profile of the output pulse. We also show that the maximum transmitted pulse peak power is limited at certain power levels. The experimental results agreed well with a theoretical model of pulse distortion due to excess loss arising from TPA generated free carriers.

Experiment: The waveguide core was formed by the silicon strip measuring 480nm x 220nm, as shown in Fig. 1(a). The length of the waveguide used in the experiment was 2 mm. The fabrication and characterization of the waveguide was described elsewhere [4].

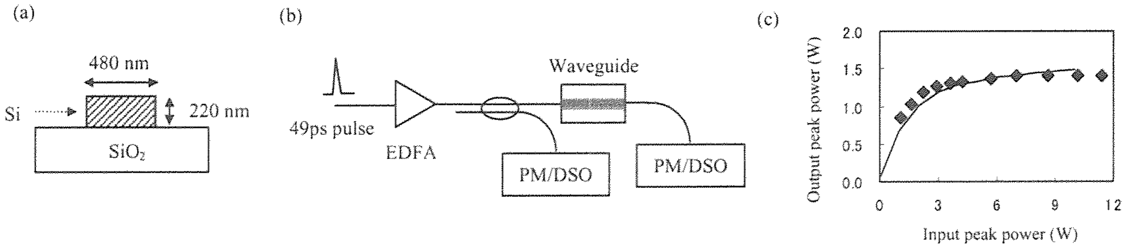

Fig. 1. (a). Waveguide structure. (b) Experimental setup. PM: power meter, DSO: digital sampling oscilloscope. (c) Transmission of pulses at various peak powers. Diamond: measurement data, Solid curve: theoretical calculation.

The pump pulses, generated from spectral slicing (0.6nm) of a 50MHz stretched-pulse passively mode-locked fiber laser, were broadened to 49ps FWHM pulsewidth by chromatic dispersion in 5km single mode fiber. The use of the long pulsewidth allowed sufficient free-carrier generation within pulse duration and also enabled the pulse profile to be readily measured on a sampling oscilloscope. A 3-dB optical coupler was placed in front of the waveguide to monitor the input pulse. Optical power meter (PM) and digital sampling oscilloscope (DSO) with 50GHz bandwidth photodetector were used to measure the input/output powers and pulse profiles respectively. The output pulse peak powers as a function of input peak powers is shown in Fig. 1(c). The maximum transmitted peak power is limited at around 1.5W.

Figure 2 shows the output pulse profiles measured by photodetector at various peak-coupled powers. The asymmetry of pulse profile is clearly observed at peak powers higher than 4W, as shown in Fig. 2(b) to 2(d). When the pulse was propagating along the waveguide, the leading part of the pulse generated free carriers and attenuated the trailing part of the pulse. Thus the output pulse experienced different attenuation coefficients within the pulse duration. Further increasing the input power will not increase the peak power at output, but produce increased asymmetry in the pulse. Similar behavior of pulse distortion has been observed in semiconductor laser amplifiers [5].

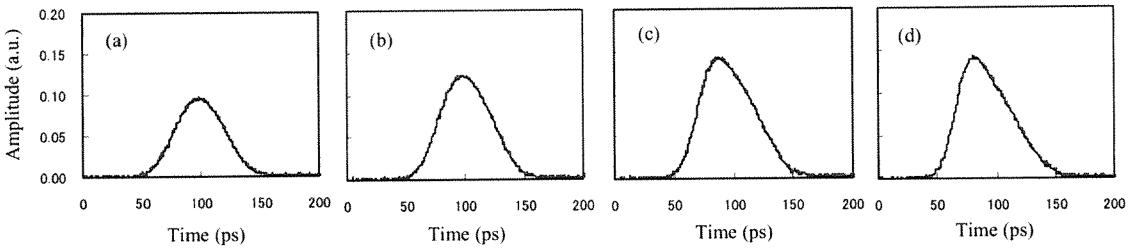

Fig. 2. Measured output pulse profiles at various peak-coupled powers. (a) 1W, (b) 1.6W, (c) 4.2W, and (d) 10W.

The propagation of high power pulse in silicon waveguides can be described by

$$\frac{dI(t)}{dz} = -\alpha I(t) - \beta I^2(t) - \sigma N I(t) \qquad (1)$$

where $I(t)$ is the temporal intensity profile, α and β are the linear loss and TPA coefficients respectively, σ is the free-carrier absorption coefficient and N is the carrier density. By solving above equation with a suitable pulse profile function, e.g. Gaussian shape, we can calculate free carrier density in temporal domain at output waveguide facet. Using appropriate parameters, the theoretical calculation of the output pulse profiles with same peak powers used in the experiment are shown in Fig. 3. The results are almost identical with the experimental data.

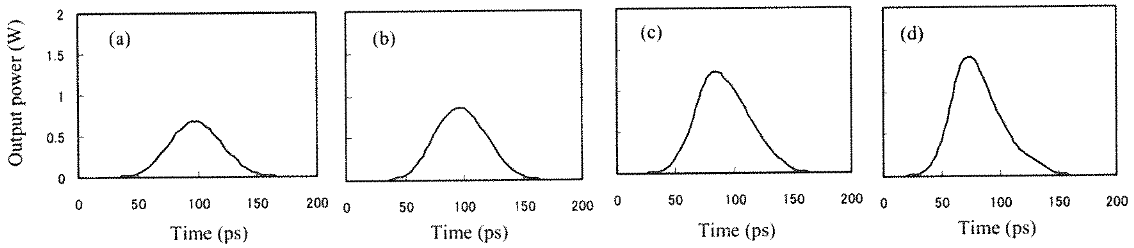

Fig.3. Theoretical calculation of output pulse profiles at same peak-coupled powers (1W, 1.6W, 4.2W and 10W).

Conclusion: Optical pulse asymmetry at high intensity is observed in silicon wire waveguides. Our results show that silicon wire waveguides may find applications in nonlinear pulse shaping devices such as pulse compressor or signal regenerators in optical communications.

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