Dynamic characterization of silicon nanowires using a terahertz optical asymmetric demultiplexer-based pump-probe scheme

H. Ji(1), C. S. Cleary(2), J. M. Dailey(2), R. P. Webb(2), R. J. Manning. (2), M. Galili(1), P. Jeppesen(1), M. Pu(1), K. Yvind(1) and L. K. Oxenløwe(1)

(1) DTU Fotonik, Technical University of Denmark, Kgs. Lyngby, 2800, Denmark, huji@fotonik.dtu.dk
(2) Tyndall National Institute & Department of Physics, University College Cork, Lee Maltings, Cork, Ireland, james.dailey@tyndall.ie

***Abstract* — Dynamic phase and amplitude all-optical responses of silicon nanowires are characterized using a terahertz optical asymmetric demultiplexer (TOAD) based pump-probe scheme. Ultra-fast recovery is observed for moderate pump powers.**

Keywords- silicon nanowire, pump-probe, TPA, FCA.

I. INTRODUCTION

Pure silicon nanowires have been developed for optical data signal processing due to their high nonlinearity, wide bandwidth and potential of compactness. Ultra-fast nonlinear Kerr effects in silicon nanowires, including four-wave mixing (FWM), cross-phase modulation (XPM) and self-phase modulation (SPM), have been used to realize several optical data signal processing schemes, such as 10 Gbit/s all-optical data signal regeneration [1],160 Gbit/s [2] and 1.28 Tbit/s [3] signal demultiplexing, 640 Gbit/s signal wavelength conversion [4], and 1.28 Tbit/s waveform sampling [3]. However, the nonlinear performance of silicon nanowires can be impaired due to two-photon absorption (TPA) at telecommunication wavelengths. As the recovery time of the free carriers generated through TPA is relatively long (~ns scale), the free-carrier absorption (FCA) will be harmful to the ultrafast Kerr nonlinearity , especially at high speed.

In this paper, a terahertz optical asymmetric demultiplexer (TOAD)-based pump-probe scheme is used to characterize the dynamics of the silicon nanowires so that we can evaluate the impairment from TPA and TPA-induced FCA.

II. PUMP-PROBE SCHEME

The pump-probe scheme is based on a terahertz optical asymmetric demultiplexer (TOAD) as described in reference [5], shown in Fig. 1. Two tunable mode-locked lasers (TMLLs) are driven by a 10.645 GHz synthesizer and generate 10.645 GHz pulse trains which are used as pump and probe signals. Using optical modulators, the repetition rate of these pulse trains is reduced to 665 MHz and used as pump and probe signals. The central wavelength of the pump is selected to be 1555 nm and the probe to be 1540 nm. The pump and probe pulses are both 5 ps wide. The pump and probe beams are sent into the TOAD, which consists of a loop of fiber with a silicon nanowire offset from the loop's center by several nanoseconds. The polarizations of the incoming pump and probe signals are adjusted with two polarization controllers so that they are aligned with the TE mode of the silicon nanowire. The polarization of the TOAD loop is set for full reflection of the probe in the absence of a pump pulse. The amplitude and phase responses in the silicon nanowire are derived from the measured intensities at the transmission and reflection ports [5]. The silicon nanowire measured here has 450 nm width, 250 nm height and 3.6 mm length.

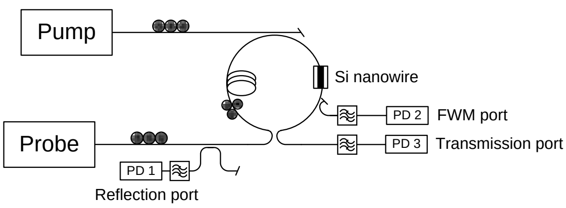
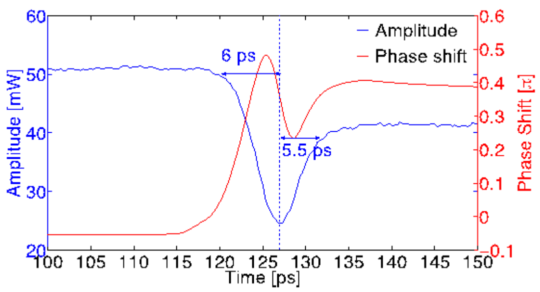


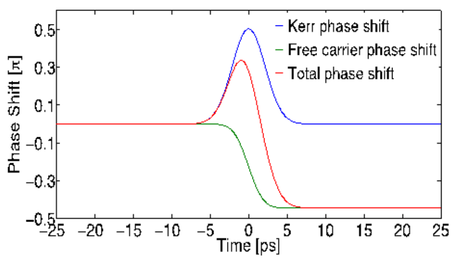
Figure 1. TOAD-based pump-probe scheme

III. EXPERIMENTAL RESULTS AND DISCUSSION

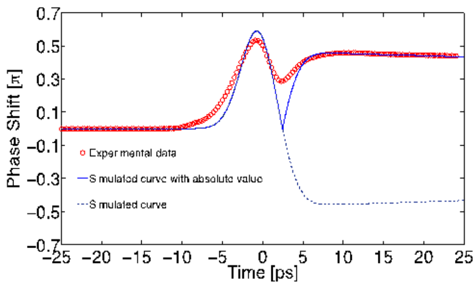
Fig. 2(a) shows the measured amplitude and phase response, for an input pump pulse with 40 dBm peak power. The amplitude response has two components. The first part of the response is an ultra-fast absorption feature. The duration is 6 ps, which is pulse-width limited. We associate this mainly with the nonlinear process of TPA between pump and probe pulses. The second part is the recovery process, which includes an ultra-fast recovery followed by a slow recovery tail. The fast recovery time is about 5.5 ps, which is also related to the TPA. The long slow recovery tail is due to the long lifetime of free carriers in silicon, which in this case are generated by TPA. By linear fitting to the slow recovery tail, the free carrier recovery time is estimated to be 10 ns. Note that for the silicon waveguide characterized here, there is no active extraction of the carriers, so the recovery time relies on the surface recombination. The measured phase response appears positive at all times because the TOAD setup measures the absolute value of the phase. To analyze the phase response, we use the model described in reference [6], taking into account the Kerr effect, TPA, and free carrier effects to simulate the phase curve. Fig. 2(b) shows the simulated phase response. The blue solid and green solid curves show the phase change induced by the nonlinear Kerr effect and the free carrier effect, respectively. The nonlinear Kerr effect results in a positive phase shift and the free carrier effect results in a negative phase shift. The total phase change is the sum of the Kerr and the free carrier induced phase shifts and is shown as the red solid curve. To compare it with the experimental result, we flip the negative part to positive (blue dotted curve to blue solid curve) in Fig. 2(c). The experimental data from the TOAD setup contains a further convolution with the probe pulse (source of the finite temporal resolution of the TOAD), and as a result, several features in the experimental data are broadened with respect to the simulated data. This is why the initial phase response appears slightly smaller and broader in the experimental data. The experimental results agree with the model very well.



(a)



(b)



(c)

Figure 2. (a) Amplitude and phase response measured using the TOAD-based pump-probe scheme. (b) Simulation curves of phase shift induced by Kerr effects and free-carrier effects (c) Comparison between theoretical and experimental curves.

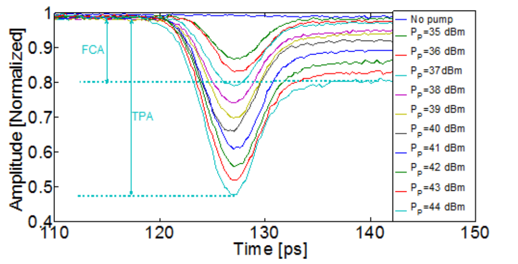


Figure 3. The amplitude responses at different input pump powers.

From the simulated curve, we can see that when the pump pulse peak power is 40 dBm, the nonlinear Kerr effect induced phase shift is about 0.6π radians and the free carrier induced phase shift is about -0.5π radians. Interestingly, the associated chirp (negative time derivative of the phase response) will consist of an ultra-fast red-shift followed by an equally ultra-fast blue-shift, as the slow recovery component does not generate any significant chirp.

Fig. 3 shows the amplitude responses at different average input pump powers. We can see that with higher pump powers, the FCA provides an increasingly large portion of the device's response. With increasing pump power, the TPA-induced FCA tends to decrease the efficiency of other Kerr nonlinear processes such as FWM and decrease the parametric bandwidth as well. However, for our device geometry, when the input peak power of the pump pulse is kept below ~ 38 dBm, the FCA impact can be minimized. This may help to explain why the silicon nanowire can be used for high speed optical signal processing, such as in reference [4].

IV. Conclusion

We have measured the dynamic responses of a silicon nanowire with cross-section of 450 nm × 250 nm using a TOAD-based pump-probe scheme. The silicon nanowire exhibits an ultra-fast response process. The recovery time of TPA-induced free carriers is estimated to be 10 ns. The relative impact of TPA-induced free carriers on the recovery increases with the pump power. However, it can be negligible when the peak power of the pump pulse is lower than 38 dBm.

Acknowledgement

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