Ultrafast nonlinear optical processes and free-carrier lifetime in silicon nanowaveguides

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Abstract: We report self-consistent femtosecond studies of two-photon absorption, optical Kerr-effect and free-carrier index and loss in silicon nanowaveguides using heterodyne pump-probe. Free-carrier lifetime was reduced to 33ps with only 8dB/cm added loss using proton bombardment.

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The nonlinear optical properties of silicon are of increasing importance to the development of integrated photonics and have been subject to considerable previous investigation [1-3]. Here we present the results of self-consistent femtosecond studies of these properties at 1.5μm in silicon nanowaveguides using a heterodyne pump-probe technique for the first time. This measurement technique is sensitive to both instantaneous and longer-lived optically induced loss and index of refraction changes. Therefore, both loss and refractive index changes are measured simultaneously using the same technique. The longer lasting changes due to optically excited free carriers are investigated as a function of proton bombardment level, and recovery times as short as 33ps are observed for additional induced losses of only 8dB/cm.

The complex index of refraction of the waveguide material can be described by [3]:

$$n = n_R + in_I = n_0 + n_2 I + \xi f_\phi(N) - i\frac{\lambda}{4\pi}\left(\alpha_{lin} + \beta I + \sigma f_\alpha(N)\right), \tag{1}$$

where n_0 is the refractive index of the device, n_2 is the optical Kerr coefficient, λ is the wavelength, α_{lin} is the linear optical loss coefficient, β is the two photon absorption (TPA) coefficient, $\xi f_\phi(N)$ and $\sigma f_\alpha(N)$ are the loss and phase changes respectively due to the TPA-generated free-carriers of density N, and I is the optical intensity. The optical Kerr effect and TPA are instantaneous and depend upon the optical intensity in the waveguide. TPA generates free electron-hole pairs that introduce longer-lived loss and index of refraction changes. Their recovery is monitored in a conventional femtosecond pump-probe manner.

Silicon waveguides with a cross section of 497nm x 106nm and length of 1.49cm were fabricated on SiO_2 with a 1μm-thick HSQ overcladding layer[4]. Optical power was coupled into and out of the waveguides using a pair of lens-tipped fibers. The optical source for the pump-probe study was an optical parametric oscillator, generating 180fs pulses at a repetition rate of 80MHz. Phase sensitive heterodyne detection [5] of the probe beam was enabled by a time-synchronous reference beam that was shifted in frequency by 1.7MHz with respect to it. Detection separation was accomplished by frequency shifting the probe and reference beams from the pump beam by 35MHz and 36.7MHz, respectively, with acousto-optic modulators. From the observed amplitude modulation (AM) detection of the probe beam, the instantaneous nonlinear losses due to TPA and long-lifetime free-carrier absorption (FCA) can be determined. Figure 1 illustrates examples of the AM heterodyne pump-probe traces along with plots of both TPA and FCA-induced losses as a function of pump power. Phase modulation (PM) traces are shown in Figure 2 along with an inset of the phase changes due to the optical Kerr effect and the induced free carriers as a function of pump power. Extraction of the nonlinear optical coefficients from these data is achieved by careful analysis of the mode profiles and intensities as a function of distance in the waveguides [6]. The results are summarized in the table below.

In addition, the effects of proton bombardment on the carrier lifetime in the waveguides was studied for 10^{12}, 10^{13}, 10^{14}, and $10^{15}/cm^2$ doses. To ensure penetration of the proton beam to the waveguide layers, the samples were proton bombarded with a mix of 80KeV, 90KeV, and 100KeV beam energies. The result of this study is shown in Figure 3. The carrier lifetime of the device was shortened from 320ps to 33ps with an induced increase in linear loss of 8dB/cm with proton bombardment of $10^{15}/cm^2$ dose.

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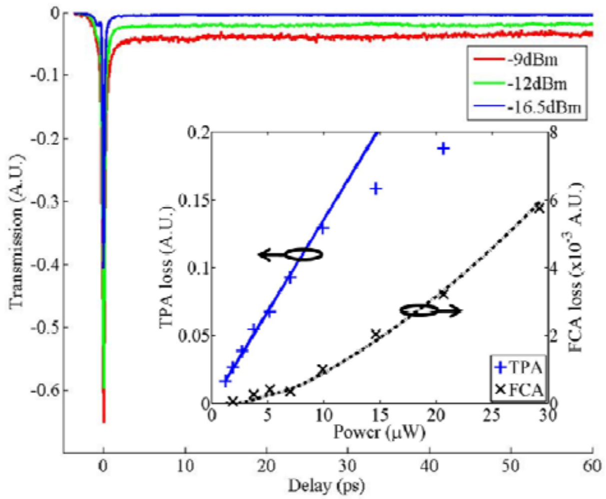

Figure1. Magnitude of the transmitted probe as a function of the probe delay with respect to the pump. TPA and FCA loss as a function of the pump power obtained from the pump probe traces (Inset).

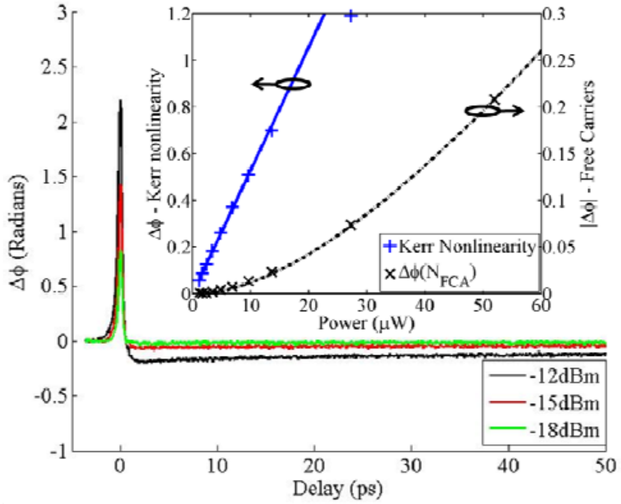

Figure2. Phase of the transmitted probe as a function of its delay with respect to the pump. Kerr nonlinearity and free-carrier induced refractive index change as a function of the pump power obtained from the pump probe traces (Inset).

TPA coefficient (β)	0.68 cm/GW
FCA effective cross section (σ)	$1.9\text{x}10^{-17}$ cm^2
Kerr nonlinearity (n_2)	$0.32\text{x}10^{-13}$ cm^2/W
Free-carrier index change (ξ)	-5.5 x 10^{-21} cm^3
Linear loss (α_{lin})	1.5 cm^{-1}
Wavelength (λ)	1500 nm

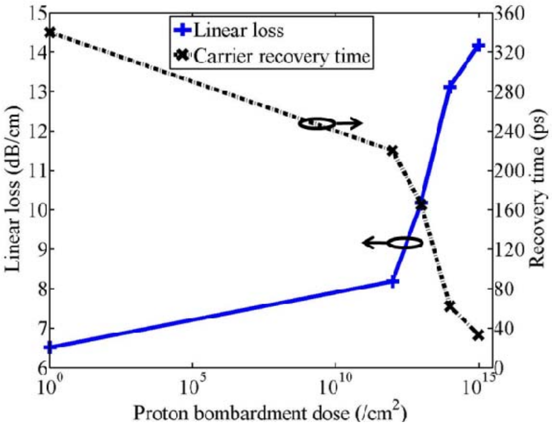

Figure 3. Linear loss and carrier recovery times as a function of proton bombardment level

In conclusion, we have determined the nonlinear optical parameters of silicon using a time-resolved phase-sensitive method that permits direct observation of both instantaneous and longer lived loss and index of refraction changes. The effect of proton bombardment on the recovery of the longer-lived, free-carrier, effects was also investigated.

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