

# Effect of TPA and FCA Interplay on Pulse Compression in Silicon

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**Abstract-** FCA can be used as pulse compressor if it exceeds TPA at the pulse center by using sharper pulses or higher peak powers. Tripling rise time requires 7dB more power to achieve 80ps output pulses.

## I. INTRODUCTION

Nonlinear properties of silicon have been proven to be viable for chip scale and CMOS compatible optical devices. In particular, the Raman effect [1] and Two-Photon Absorption (TPA) [2-3] have been investigated extensively to merge silicon with optoelectronics to provide low cost solutions to photonic industry. Recently, chip scale Raman lasers which can be pumped by commercial DFB lasers [4], and fast electrooptic modulators operating beyond 10Gb/s are demonstrated [5]. Similarly, Kerr nonlinearity and TPA have been utilized in silicon for ultrafast applications such as parametric wavelength converters [6], supercontinuum generation [7-8]. In ultrafast applications, the transient behavior of TPA induced free carrier concentration has a prominent effect on the final outcome [8]. By using these transient effects, a novel approach for pulse compression and laser modelocking is proposed and demonstrated in our previous work [9]. However, these applications require careful control of interplay between free carrier absorption (FCA) and TPA, which has never been investigated thoroughly.

In this work, we study the transient behavior of TPA and TPA induced free carriers with special emphasis on their effects on self pulse compression. We calculated magnitude of TPA and free carrier losses for 10ps to 1000ps wide optical pulses with peak intensities up to 40GW/cm<sup>2</sup>. We show that TPA surpasses the free carrier losses for optical pulses shorter than 50ps and limits self compression. 60ps modelocked pulse generation experimentally in a laser modelocking setup confirms these predictions.

## II. THEORETICAL RESULTS

To assess the interplay between the TPA and free carrier absorption ratio, we compare the temporal widths of pulses at the input and output of the silicon waveguide with 5μm<sup>2</sup>. The calculation is done by solving nonlinear Schrödinger equations numerically for Gaussian pulses as the input [8]. We ignore dispersion and SPM effects inside the waveguide and only consider TPA and free carrier effects. The pulse width comparison is performed for single pass and effects of multiple passes due to oscillation in the laser cavities are ignored.

Figure 1a illustrates the compression behavior for optical pulses which have widths from 10ps to 1000ps in a 1cm long silicon waveguide. At low peak power levels, there are only

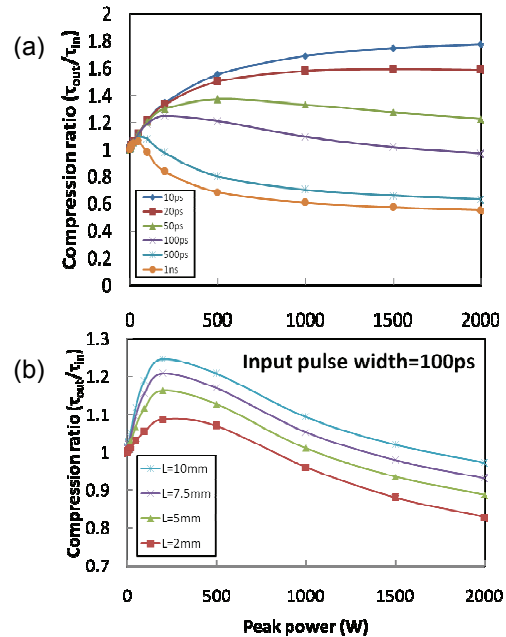


Fig. 3 Simulation results for (a) 1mm long waveguide. (b) 100ps input pulse with different waveguide lengths.

few free carriers generated to attenuate the trailing edge of the pulse and to provide self compression [9]. Contrarily, the strong attenuation at the center of the pulse due to TPA broadens the pulse width at 3dB point. 1ns pulses generate enough free carriers at 100W (2GW/cm<sup>2</sup>) level to overcome TPA losses at the center of the pulse and start self compression. As the pulse widths decreases to 500ps and 100ps, it requires 150W and 1600W to initiate compression, respectively. For input pulses shorter than 50ps, TPA induced pulse broadening surpasses the self compression and net pulse broadening is expected. Figure 1b demonstrates the effect of waveguide length on pulse compression. The results show that the increasing relative strength of TPA based pulse broadening at the later stages of the waveguide may limit the overall pulse compression. We estimate that the waveguides as short as 2mm can provide more effective pulse compression by using only 50% of peak power values that is required in 1cm long waveguides. These results indicate that effective utilization of TPA and TPA induced free carriers require optimization of waveguide dimensions for specific pulse parameters. Ultimately, the Auger recombination will determine the minimum thickness which can be used for pulse compression.

## III. EXPERIMENTAL RESULTS

Laser modelocking setup is used to assess the effect of free carrier transients and TPA on final pulse width [6]. A laser cavity is formed by a gain medium, 250mW EDFA, followed by a 1.7cm long silicon waveguide with  $\sim 5\mu\text{m}^2$  effective area, and an electrooptic modulator. The output of the waveguide is connected to a 3/97 tap coupler where 3% is used as an output and 97% is fed into the electrooptic (EO) modulator and the following gain medium. To initiate pulse formation and pulse compression by transient effects, 1.5ns wide rectangular RF pulses with 1MHz repetition rate are applied to an EO modulator. A 10GHz photodetector and a 20GHz sampling oscilloscope are used as diagnostics.

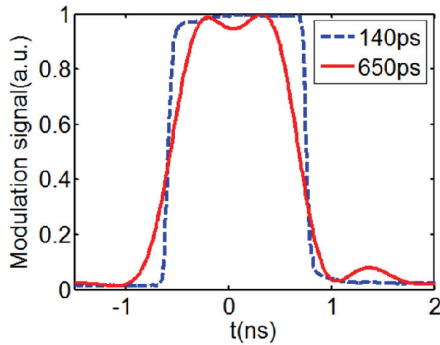


Fig.2 Modulation signals used for mode locking experiment

The absorption of a photon pair by TPA generates an electron-hole pair. The process is intensity square dependent. At constant pulse width, the variation of rise and fall time can be used as tuning parameter for number of free carriers generated by an optical pulse at fixed peak power and fixed energy. Experimentally we use low pass RF filters with cutoff frequencies of 800MHz and 500MHz to tune rise and fall time of 1.5ns electrical signals from 140ps to 450ps and 650ps, respectively. Figure 2 shows modulated signals measured at the output of the modulator with a CW laser input.

Figure 3a illustrates the pulse widths measured at the laser output with different peak power values and different rise/fall times. The shortest pulse width is measured to be 60ps generated by using electrical signals with 140ps rise/fall times (Fig. 3a). Figure 3b shows the tendency of the pulse compression with respect to different peak powers and different rise and fall times. At fixed pulse energy, slower rise time results in fewer free carrier generation. As a result, the pulse width increases to 85ps if the rise time is tuned to 650ps with the same pulse energy. These measurements indicate that free carrier concentration increases more rapidly for modulation signals with sharper rise times. This difference eventually results in stronger attenuation at the center of the pulse than at the trailing edge and hence pulse is broadened instead of compressed for longer rise times. As illustrated in Fig. 3b, to compensate the slope effect we need to increase pulse energy to achieve the same compression. To achieve 80ps output pulses, the average power in the cavity has to be maintained at 9dBm, 13dBm and 16dBm for 140ps, 450ps and

650ps rise and fall times, respectively. This tendency also matches the theoretical expectations.

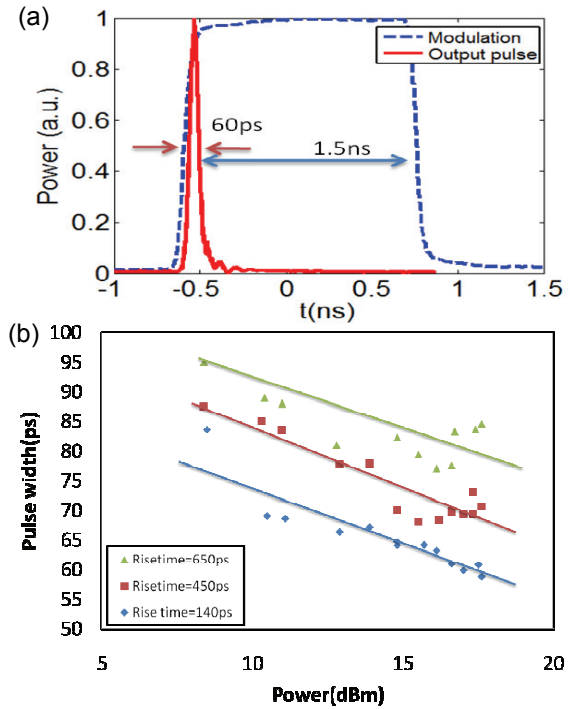


Fig. 3 (a) Laser output for 140ps rise time. (b) Variation of output pulse width with respect pulse energy and pulse slope

#### IV. SUMMARY

In summary, we show that FCA should be stronger than TPA at the center of the pulse to have pulse compression. This condition can be satisfied with high energy pulses sharp rise/fall times.

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