

Pulse compression and modelocking by using TPA in silicon waveguides

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Abstract: We demonstrate a novel broadband pulse compression and modelocking scheme by using two-photon absorption in silicon waveguides. Experimentally we obtain greater than 20 fold pulse compression and 200ps modelocked pulses. The free carrier lifetime and the width of the modulation signal are found to be two critical parameters affecting the output pulse width. Theoretical calculations indicate that optical pulses of less than 20ps width are achievable by using the same technique.

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OCIS codes: (130.5990) Semiconductors; (140.4050) Mode-locked lasers

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1. Introduction

Because of its promise to deliver low cost optoelectronic solutions to many applications and full optoelectronic integration, silicon photonics technology has attracted enormous research interest recently. In particular, the last three years have witnessed rapid development in light generation and amplification, fast electrooptic modulation and efficient wavelength conversion in silicon by using its nonlinear properties. The Raman effect was the enabling technology behind silicon based light sources and amplifiers. Soon after the first demonstration of stimulated Raman scattering [1], net gain amplification and lasing have been achieved in 2004 by using pulsed pumping techniques [2-4]. Two-Photon Absorption (TPA), another nonlinear property of silicon, has been utilized previously to demonstrate silicon-based autocorrelators [5]. However, accumulation of free carriers generated by the TPA process is a mitigating factor in semiconductor Raman amplifiers [6]. A p-i-n diode structure has been proposed [3,5] and implemented to sweep out these free carriers and hence achieve net gain amplification and lasing by using continuous wave (CW) pump lasers in a monolithic laser cavity [7,8]. Additionally, racetrack resonators have been utilized to achieve low threshold and high output power silicon Raman lasers [9]. Besides the Raman effect, Kerr nonlinearity and the free carrier plasma effect have been utilized for different applications such as electrooptic modulation [10, 11], wavelength conversion [12-14], and supercontinuum generation by using SPM and XPM effects [14-16].

Ultrafast sciences and modelocked pulse generators, on the other hand, are considered to be a separate research field. Conventional modelocked lasers utilize saturable absorbers based on III-V quantum well structures [17]. Recently, saturable absorbers based on pure Group IV materials made significant progress in generating ultra short optical pulses [18]. In this approach, laser modelocking by using thin germanium layers grown on silicon Bragg reflectors has been demonstrated. However, TPA is always present in all semiconductor structures. Because TPA introduces extra loss to the system it has been considered as a mechanism limiting the total output power. Nevertheless, it can also be used against Q-switching instability and achieve stable modelocking [17-20]. Excluding silicon-based Bragg reflectors, silicon and TPA have never played an active role in modelocking. Here, we propose a novel approach to utilize TPA and TPA-induced free-carrier absorption to facilitate pulse compression and laser modelocking by using bulk silicon.

In this paper, we demonstrate a novel scheme to facilitate pulse compression and modelocking by using two-photon absorption and free-carrier absorption in silicon waveguides [21]. Experimentally we demonstrate a greater than 20 fold pulse compression by TPA-induced free-carrier absorption at 1550nm. Additionally, we utilize the same scheme in a laser cavity to generate 200ps wide modelocked pulses. However, theoretical calculations indicate that pulse widths close to 1ps are achievable by using the same scheme. Furthermore, the proposed scheme is wavelength independent and will provide broadband modelocking anywhere between 1100nm and 2200nm in silicon waveguides.

2. Methodology and theoretical results

Two-photon absorption and free-carrier absorption are two ubiquitous nonlinear effects in silicon for any wavelength between 1.1 μm and 2.2 μm . Under CW injection condition, constant optical intensity creates steady free-carrier accumulation that is counterbalanced by the recombination process. At the steady state, the free-carrier concentration can be calculated as [15,22]:

$$N = \frac{\tau_o \cdot \beta \cdot I^2}{2h\nu} \quad (1)$$

Where τ_o is the free-carrier lifetime, β is the two-photon absorption coefficient and I is the intensity of the input beam, which remains constant over time. However, steady state assumption is invalid under the pulsed signal launching condition where the pulse width is shorter than the free-carrier lifetime and the pulse period is longer than free-carrier lifetime,. In this case, we can only consider the transient behavior of free-carrier concentration. At time t and position z , the free-carrier concentration can be calculated by using the signal profile as [15,22]:

$$N(z, t) = \frac{\tau_o \cdot \beta \int_0^{L_p} t^2(t, z) dz}{2h\nu \cdot A_{\text{eff}}^2 \cdot L_p} \quad (2)$$

Where L_p is the pulse length in the semiconductor and A_{eff} is the modal area. As a result, the system will have time- and position-dependent free-carrier loss given by:

$$\alpha_{FC}(z, t) = 1.45 \times 10^{-17} \left(\frac{1.55}{\lambda} \right)^2 N(z, t) \quad (\text{cm}^{-1}) \quad (3)$$

Where λ is the operation wavelength in micrometers.

Figure 1 illustrates the schematic diagram of pulse propagation in a silicon waveguide where free-carrier losses are significant, and also the amount of free-carrier-induced losses. Upon entering the waveguide the front end of the pulse will be slightly attenuated by TPA and hence the free carriers will start to accumulate wherever the optical energy is present. As a result, the photons entering the waveguide will suffer from the free-carrier losses generated by the earlier photons. This process will lead to attenuation of the trailing edge of the pulse and hence the pulse compression in the time domain, [see Fig. 1(a)]. Because of the linear and nonlinear absorption, the free-carrier absorption will be spatially varying and will be much stronger at the input facet of the silicon waveguide. Figure 1(b) quantifies the loss and free-carrier accumulation along a 100ps rectangular pulse to give a better understanding of the concept. The results presented here are calculated for a silicon waveguide with 5 μm^2 effective area, similar to the one used in the experiment, for three different peak power values of 100W,

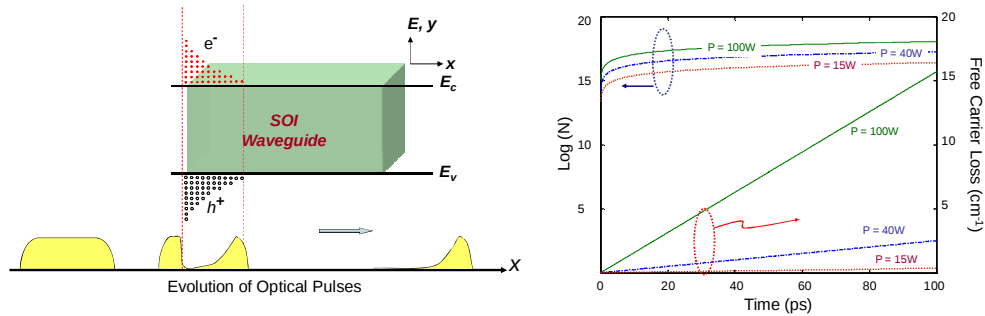


Fig. 1. (a). Schematic description of free-carrier accumulation for pulse compression. A high-intensity optical pulse will leave a trail of free carriers behind, which will contribute to pulse attenuation at the trailing edge and hence compression. (b) Temporal variation of free-carrier concentration and losses generated by 100ps optical pulses. The loss difference between the front and end of the pulse can be as high as 16 cm^{-1} for optical pulses with 100W peak power values.

40W and 15W. At the front facet of the waveguide an optical pulse with 100W peak power level is expected to create free carriers increasing from 0 to $>10^{19}\text{cm}^{-3}$ from beginning time ($t=0$) to end of the pulse ($t=100\text{ps}$). As a result, the trailing edge of the pulse is expected to experience 16 cm^{-1} free-carrier-induced loss at that position while the leading edge travels with only TPA loss. The same loss value reduces to $\sim 3\text{cm}^{-1}$ if the input peak power is reduced to 15W. These results show that dynamic control of free-carrier concentration at a given position can be used for optical signal processing and optical pulse compression.

In this paper we utilize the free-carrier absorption to demonstrate laser modelocking and short pulse generation by using silicon waveguides. This is a three-step process. In the first step, an optical modulation is needed to initiate pulsation in the cavity to increase peak power and start free-carrier transients. This modulation can be performed by using the silicon waveguide itself [4, 10-11] or bulk electrooptic modulators. In the second step, this pulse is amplified by a gain medium and then compressed by free carriers. The pulse compression will occur at the leading edge of the pulse by suppressing the trailing edge due to free-carrier absorption. In the third step, recirculation of this pulse helps to form short pulses at the steady state. Conventionally, passively modelocked lasers require saturable absorbers to suppress the low intensity background and initiate oscillation of intensity spikes. The active modelocked lasers, on the other hand, require optical modulators to initiate pulsation at harmonics of the fundamental cavity frequency. In order to create short pulses, the modulation signal has to be short. The free-carrier absorption can alleviate the short pulse modulation requirement if it is used as a pulse shaping mechanism inside the laser cavity. The modulation part of our scheme resembles the active modelocking. However, free-carrier absorption behaves like a saturable absorber on the trailing edge and provides unique pulse shaping method inside the cavity.

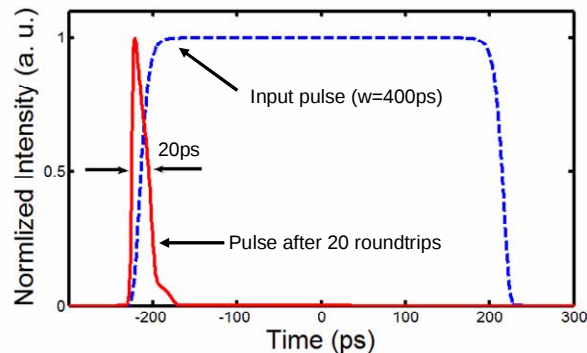


Fig. 2. Simulation results of modelocking by using 400ps modulation signals. A 400ps modulation signal compresses to 20ps after 20 roundtrips inside the cavity.

A case study has been conducted for 400ps electrooptic modulation followed by pulse propagation inside a laser cavity, (Fig. 2). The silicon waveguide is chosen to be 2cm long with $5\mu\text{m}^2$ effective area. We use pulse propagation equation developed earlier [15] to calculate final pulse width after 20 roundtrips. We observe that after 20 cavity roundtrips the pulse width inside the cavity reduces to 20ps. Here the 20 round trips case is chosen for illustration purposes and it is not the steady state value. However, the final pulse width will be a function of the modulation signal and the interplay between TPA and free-carrier loss. For larger roundtrips, the compression still continues at a slower rate and indicates that 1ps pulses might be achievable. The ultimate pulse width achievable by this technique is currently under investigation.

3. Experimental results

Proof of principle modelocking experiment has been demonstrated in a laser cavity formed by an erbium doped fiber amplifier (EDFA) gain medium, a silicon pulse compressor and a spool of standard fiber as illustrated in Fig. 3. The silicon waveguide used for pulse compression is a 1.7cm long silicon on insulator waveguide with $\sim 5\mu\text{m}^2$ effective area. Additionally, the waveguide has a p-i-n diode structure to inject carriers and hence a modulation capability. The output of the waveguide is connected to a 10/90 tap coupler where 10% used as an output and 90% is fed into the gain medium, a high power EDFA with 200mW saturated output power. The resonator is formed by launching the EDFA output back into the silicon waveguide input. Since the pulse shaping by free carriers requires a time-dependent optical signal circulating inside the cavity, an 8ns pulsed current source is connected to the waveguide to start initial pulsation at the fundamental cavity frequency of $\sim 1\text{MHz}$. The output pulse width is expected to be minimum when the frequency of the function generator matches the fundamental cavity frequency. Here, manual frequency locking is achieved by monitoring the pulse shape and the modulation frequency, simultaneously. The output of the resonator is connected to an optical spectrum analyzer and a photodetector followed by a 25GHz sampling oscilloscope or an RF spectrum analyzer to measure output characteristics.

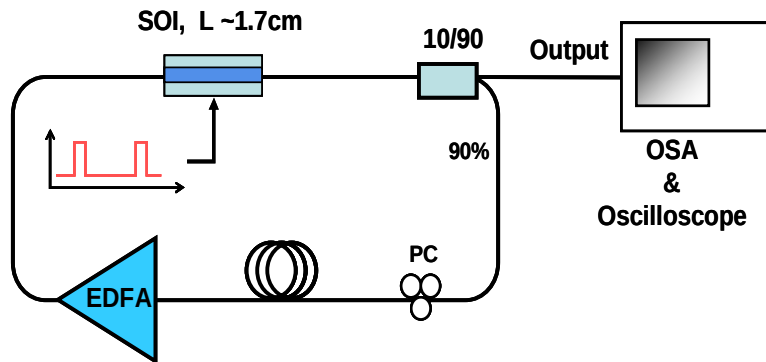


Fig. 3. Experimental setup used for TPA based modelocking scheme. SOI: Silicon on insulator waveguide, OSA: Optical spectrum analyzer, EDFA: erbium doped fiber amplifier.

In the first part of the experiment we confirm that the free carriers indeed help pulse

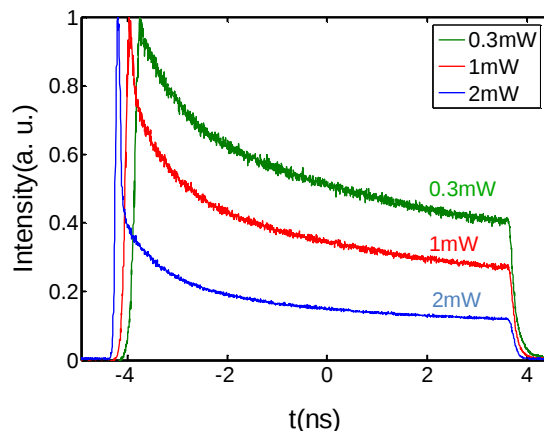


Fig. 4. Pulse compression results inside the laser cavity. Power values are measured at the output of the cavity.

compression by using 8ns electronic modulation with rectangular pulse shape. By adjusting the gain of EDFA we control the peak power circulating inside the cavity. We observe that at low powers ($<1\text{mW}$ at the output), the circulating signal is quite similar to the modulation signal, (Fig. 4). When we increase the gain of the EDFA to obtain 2mW at the output, we observe short pulse formation at the front edge of the pulse, as expected. Also, the experimental results show that most of the energy is contained under broad pedestal at these power levels and only a small portion of the energy is used for short pulse formation. However, as the power levels increase, the long pedestal is suppressed further down. These results indicate that this modelocking scheme will operate best at high intensities and will be limited by the broad pedestal at low intensity values.

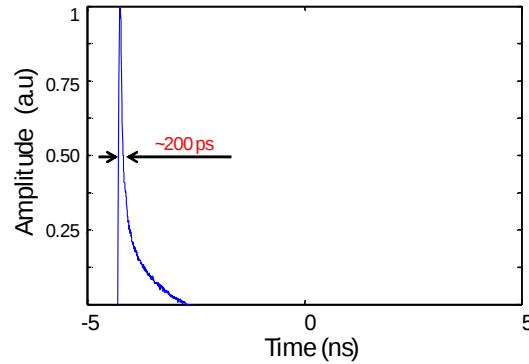


Fig. 5. 200 ps pulses measured at the laser output.

Figure 5 illustrates the laser output measured by a 25GHz sampling oscilloscope when EDFA is set to its maximum value and the modulation frequency of the 8ns signal is matched to the fundamental cavity frequency. The laser output power is measured to be 3mW . The corresponding pulse width at FWHM is measured to be 200ps. As experimental results illustrate, we still have small knee representing uncompressed optical energy, similar to Fig. 2. These results suggest that even at this power level, free carrier concentration is not strong enough to suppress the pedestal. We also believe that the waveguide length of 1.7cm is too long for the proposed application and it induces excessive loss that limits the circulating power and hence free-carrier accumulation. RF spectrum of the measured pulse indicates that steady modelocking is obtained around 1MHz repetition rates and there is no visible sign that Q switching or other phenomena are occurring, (Fig. 6). The noise spikes at intermediate frequencies are artifacts of the RF spectrum analyzer, which was confirmed independently without the laser output. The quality of the RF spectrum at the fundamental frequency (inset) is comparable to the modulation signal where noise floor is $\sim 60\text{dB}$ below. To confirm the modelocking we also monitored the pulse width as we tuned the modulation frequency. We

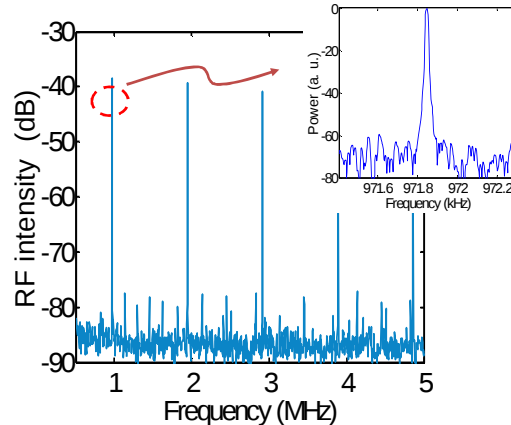


Fig. 6. RF spectrum measured of the laser output.

observed that the output pulse width will increase significantly (up to 50x) as we move the modulation frequency by as low as 15Hz away from the fundamental cavity frequency. Theoretically, operation at the harmonics of the fundamental cavity frequency is achievable at the expense of more power. Highest repetition rate ultimately will be limited by the free carrier lifetime of the waveguide, which is 16ns in this experiment.

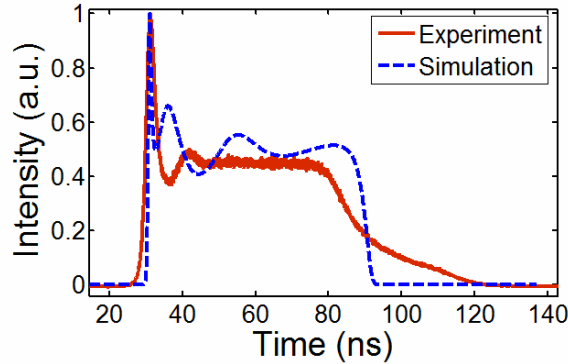


Fig. 7. Effect of long modulation signals on laser output and formation of pedestal. Pulses longer than free carrier lifetime will form a long pedestal at the output.

We also studied the output pulse characteristics with respect to modulation parameters to determine how to achieve pico-second output pulses. Theoretical results indicate that the rise/fall time and the width of the modulation are critical parameters in pulse compression and modelocking. To confirm that we experimentally changed rise/fall times and the width of modulation signals to 100ns to determine output pulse characteristics, (Fig. 7). At the steady state, the output pulses have two components. The first component is 5ns compressed optical pulses. The second component is a less compressed >50ns pedestal. The pedestal confirms our expectation that due to the large difference between free-carrier lifetime, ~16ns, and the 100ns modulation pulse width, the front end of the pulse will utilize the free carrier transients for compression and the trailing edge will see a constant attenuation similar to CW injection. Theoretical calculations closely match the measured results, Fig. 7. Here we use a 100ns super-Gaussian pulse, similar to the modulation signal, with 30W peak power as the initial condition for our simulation. However, modulated optical signal is not as well behaved as a super-Gaussian signal and exhibits a non-uniform decay profile. The difference at the tail mainly originates from this slow fall time. The final pulse shape is calculated by pulse propagation equation developed before [15]. We also observe that as pulses are compressed they tend to move towards the front edge of the modulation signal where they suffer from high losses due to the modulation signal if the rise time is too long. This may add an additional constraint on the final pulse width.

4. Summary

We demonstrate a novel pulse compression and modelocking scheme by utilizing two-photon absorption and free-carrier absorption in silicon waveguides. Experimentally we show 200ps modelocked pulses at 1560nm by using a 1.7cm silicon waveguide. Shorter pulse widths can be achieved by using modulation signals much shorter than the free-carrier lifetime of the silicon waveguide (~16ns). The proposed method is wavelength independent between 1.1 μ m and 2.2 μ m and it will provide modelocking at any wavelength where TPA is present. The same scheme potentially can be extended to germanium waveguides to facilitate modelocking up to 3.4 μ m. Finally, the proposed scheme utilizes waveguide structures. Hence, interaction length and waveguide dimensions can be used as tuning parameters to facilitate modelocked lasers with extremely high energies.