TuA2.2 Invited
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Dual-wavelength Mode-locked Laser in Silicon

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Abstract- We show that inline silicon waveguides inside a laser cavity facilitate laser modelocking due to TPA and TPA-induced FCA, and it can also provide Raman amplification and dual wavelength lasing in the same silicon waveguide.

I. INTRODUCTION

Nonlinear properties of silicon have been proven to be a practical route to realize active chip scale optical devices that can be integrated with CMOS based devices. Chip scale Raman lasers [1], Raman amplifiers [2] and fast electrooptic modulators operating beyond 10Gb/s have been demonstrated [3, 4]. Similarly, Kerr nonlinearity and two photon absorption (TPA) have been utilized in silicon for ultrafast applications such as parametric wavelength converters [5] and supercontinuum generation [6]. Recently, we demonstrated an approach for pulse compression and laser modelocking using free carrier transient effects [7]. Here, we present a theoretical study of free carrier absorption (FCA) transients and TPA with special emphasis on their effects on self pulse compression. Additionally, we experimentally show that created modelocked pulses can stimulate Raman effect in silicon and provide dual wavelength lasing. A dual-wavelength modelocked laser pulses operating at 1540nm and 1675nm have been demonstrated.

II. DUAL WAVLENEGHT LASING DEMONSTRATION

In the experiment we show that the generated modelocked pulses can stimulated other nonlinear effects in silicon such as Raman effect and increase its functionality without a extern pump laser. Figure 1 shows the laser modelocking setup to demonstrate pulse compression [7] and dual-wavelength operation. A laser cavity is formed by a gain medium, 250mW EDFA, followed by a 1.7cm long silicon waveguide with ~5µm^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 compression by transient effects, 500ps wide rectangular RF pulses with ~1MHz repetition rate are applied to an EO modulator. The WDM couplers separate the Stokes from the wavelength sensitive components in the cavity. A tunable time delay line is added between two WDM couplers and it aligns the pump and stokes in time domain when the Stokes loops back to the silicon waveguide. A 10GHz photodetector and a 20GHz sampling oscilloscope are used as diagnostics.Fig.2c illustrates the pulse measured at the laser output of pulse compression. The shortest pulse width is measured to be 100ps generated by using 500ps rectangular electrical signals.

Once the short pulses are created, we are able to utilize them as pump to achieve stimulated Raman scattering. Two WDM couplers and a tunable fiber time delay line are inserted into the cavity for Stokes signal circulation. The spectra of the lasers are shown in Fig.2a and Fig.2b. The spectrum width of the obtain pump pulses is 0.05nm and Stokes spectrum width is 0.5nm. The increase of spectrum width for Stokes is due to the instability of the fiber time delay line. The Raman laser output power is measured to be 3 µW. As the pump power changes from 0 to 6mW, the laser threshold is determined as ~3.75 mW in Fig.3.

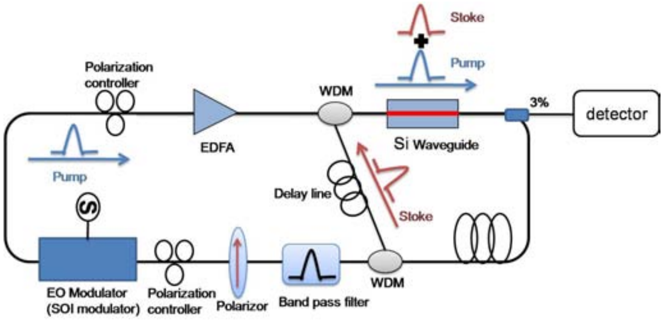

Figure 1. The experiment setup for dual wavelength lasing.

III. THEORETICAL RESULTS

To determine the interaction of the TPA and free carrier absorption ratio on the compressed pulse width, free carrier density and the nonlinear losses are the primary parameters to be considered. Based on the peak intensity and the pulse energy, the nonlinear response of silicon can be divided into two regimes: TPA dominated regime and FCA dominated regime [7]. By solving the nonlinear Schrödinger equations numerically for Gaussian pulses at the input, the outcomes of two different regimes are calculated (Fig. 4). Here, 20ps and 500ps optical pulses at 1550nm with 1kW peak power (corresponding to 20nJ and 500nJ pulse energies, respectively)

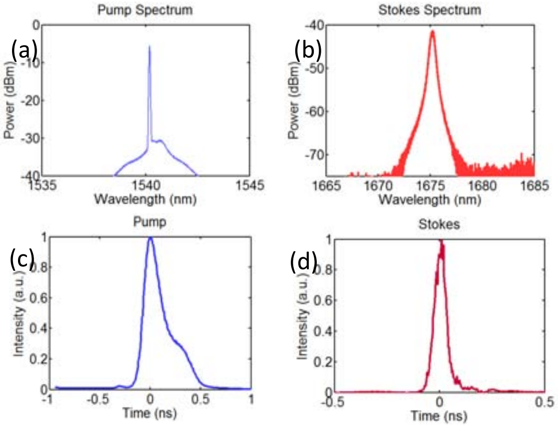

Figure 2. Spectra of (a) pump and (b) Stokes and temporal profiles for (c) pump and (d) Stokes.

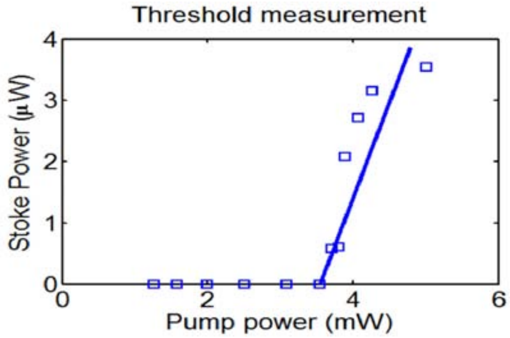

Figure 3. Threshold measurement

are launched into a 1cm long silicon waveguide with 5μm^2 effective area and 16ns free carrier lifetime. Since the peak powers are fixed at 1kW, the amount of TPA are equal for both pulses, 90% attenuation at the center, as shown in Fig. 4a. However, since absoprtion of two photons generate a pair of free carriers, wave packet with larger number of photons will induce larger free carriers densities than the lower one. As a result, FCA generated by 500nJ is 40 times stronger than that by 20ps pulses at 1kW peak power values (20GW/cm^2). We estimate that while 20nJ pulses are being broadened due to dominant TPA loss, 500nJ pulses are being compressed to 350ps wide pulses by dominant FCA, Fig 4b.

Figure 4c illustrates the compression behavior for optical pulses which have widths from 10ps to 1000ps. At low peak power levels, there are few free carriers generated to attenuate the trailing edge of the pulse and to provide self compression [7]. 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^2) level to overcome TPA losses at the center of the pulse and start self compression. As the pulse widths decrease 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 pulse broadening is expected. In a further study we investigated the effect of waveguide length on pulse compression and modelocking. 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 even though it starts as compressive pulse propagation.

IV. SUMMARY

Pulse compression and modelocking can be achieved in the silicon waveguide by TPA and TPA-induced FCA. Other optical nonlinear effects can be stimulated in the same silicon chip. Experimentally, the compressed pulses are used as pump for stimulated Raman scattering. In the experiment, a dual-wavelength modelocked laser operating at 1540nm and 1675nm have been realized.

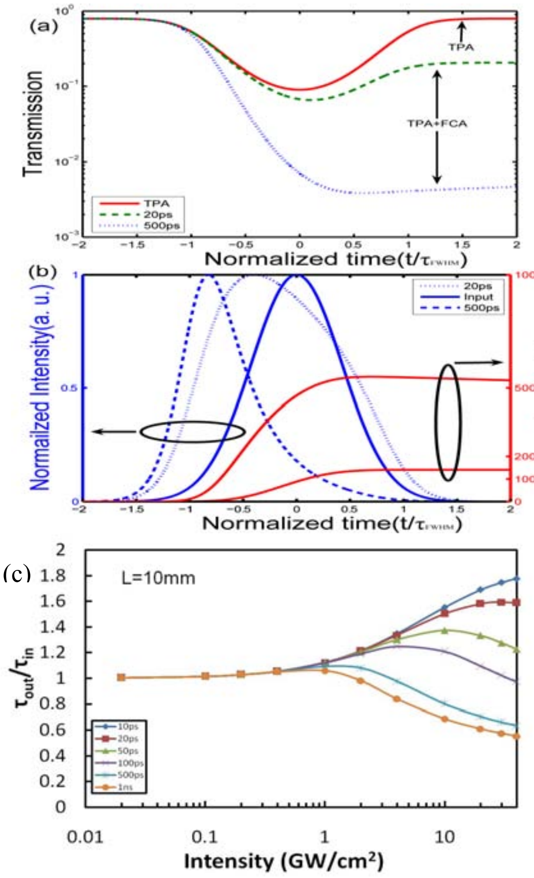

Figure 4. (a) TPA and free carrier loss profiles of 20ps and 500ps wide input pulses. (b) Estimated output pulses and chirp induced by free carrier plasma effect. Front end of both pulses are under TPA dominant nonlinear regime. (c) Predicted pulse compression ratio in 10mm long silicon waveguide for different initial pulse widths

References

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