Self-phase-modulation induced spectral broadening in silicon waveguides

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Abstract: The prospect for generating supercontinuum pulses on a silicon chip is studied. Using ~4ps optical pulses with 2.2GW/cm^2 peak power, a 2 fold spectral broadening is obtained. Theoretical calculations, that include the effect of two-photon-absorption, indicate up to 5 times spectral broadening is achievable at 10x higher peak powers. Representing a nonlinear loss mechanism at high intensities, TPA limits the maximum optical bandwidth that can be generated.

OCIS codes: (190.4390) Nonlinear optics, integrated optics, (230.4320) Nonlinear optical devices, (230.7370) Waveguides, (250.5300) Photonic integrated circuits.

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1. Introduction

Silicon on Insulator (SOI) has emerged as an attractive platform for passive planar lightwave circuits [1]. These devices make use of the excellent transmission properties of silicon in the near infrared, in particular, in the technologically important wavelength bands centered at 1320nm and 1550nm. At the same time, the large refractive index contrast between the Si waveguide core and SiO_2 cladding affects ultra tight confinement of light and localizes the optical power in the silicon core. The resulting high optical intensity combined with extended interaction along the waveguide length creates a situation that is conducive for nonlinear optical interactions.

Because of crystal symmetry, 2nd order nonlinear phenomenon in bulk silicon is too low to be of practical value. Auspiciously, the conclusion is different for 3rd order interactions, described by the 3rd order nonlinear susceptibility, $\chi^{(3)}$. For instance, Two Photon Absorption (TPA) is well documented and has been investigated as a means to create a Si autocorrelator device [2]. Optical amplification using Stimulated Raman Scattering (SRS), another 3rd order phenomenon, has recently been demonstrated in silicon waveguides [3]. Exploiting the Raman-induced four-wave mixing in silicon waveguides, wavelength conversion has also been reported [4-5].

With respect to the electronic non-resonant phenomenon in silicon, measurements of $\chi^{(3)}$ have been reported for bulk samples [6,7] and waveguides [8] with results suggesting a value that is two orders of magnitude higher than that in silica glass. The electronic 3rd order nonlinearity is an important phenomenon that gives rise to valuable capabilities such as extreme spectrum broadening, otherwise known as supercontinuum generation, in optical fibers. Supercontinuum generation followed by spectrum carving has been investigated for more than a decade and considered as a low cost source for Dense Wavelength Division Multiplexed (DWDM) optical networks [9].

In this paper, we report the observation of spectrum broadening in silicon waveguides. Experimentally we obtain 2-fold spectrum broadening in the 1550nm band with 2.2 GW/cm^2 of peak pulse power. To the best of our knowledge this is the first direct and explicit demonstration of spectrum broadening in silicon. Experimental results are in good agreement with a model based on Self Phase Modulation (SPM) and TPA. The model shows that more than 5 fold spectral broadening is possible with 20GW/cm^2 of peak power in the waveguide. These results can be considered as a first step towards chip-scale Supercontinuum (SC) generation, wherein multiple wavelengths are generated on the silicon chip from a single-wavelength external source.

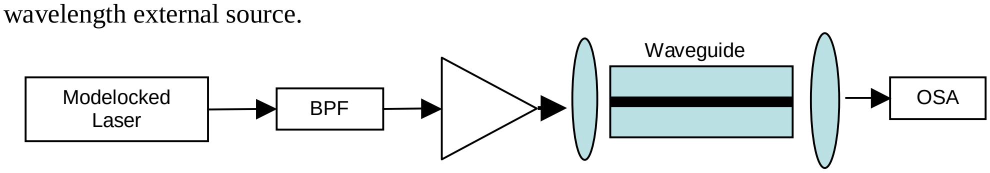

Fig. 1. Experimental setup used for measuring SPM in 2cm long silicon waveguides. 4ps short pulses with 2.2GW/cm^2 peak power level propagated through silicon waveguides and spectral broadening is measured at the output.

2. Experimental setup and results

Figure 1 illustrates the experimental setup used for SPM generation in silicon waveguides. A passively modelocked fiber laser generating 1ps short pulses at 20MHz is used as an external pulse generator for SPM generation in the silicon waveguide. Before amplifying the pulses to high peak power levels, an optical bandpass filter with around 1.2nm 3dB bandwidth is used to limit and shape the spectrum. After amplifying the pulses in an Erbium Doped Fiber Amplifier (EDFA) the output pulses are measured to be around 4ps by autocorrelation scan. The spectral shape of the output pulses indicates that some chirping and SPM effects occur within the EDFA. Later, this broadening is subtracted from the final output to obtain the broadening due to waveguide propagation. After amplification, pulses enter the silicon waveguide (described below). The peak power of the optical pulses in the waveguide is estimated to be ~110W corresponding to a power density of 2.2 GW/cm^2. Total loss, from

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EDFA to waveguide output, is measured to be 8 dB, which is attributed to Fresnel losses from the non-AR coated facets (~ 3dB), propagation loss of the waveguide, and TPA. After the waveguide, the pulses are coupled to a fiber patchcord and sent to an optical spectrum analyzer (OSA) to measure the spectrum broadening. Output coupling efficiency is intentionally kept low to eliminate further accumulation of SPM-induced nonlinear phase shift in the output patchcord.

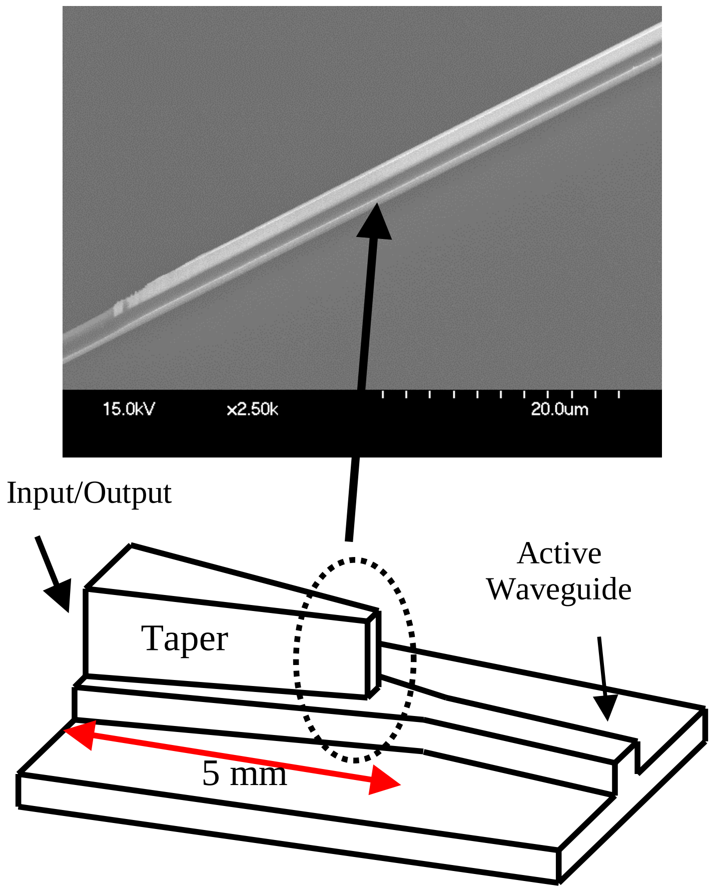

Fig. 2. SEM picture and schematic drawing of the tapered silicon waveguide.

The silicon rib waveguide was fabricated on a Silicon-On-Insulator (SOI) and had lateral tapers for maximizing input and output coupling [10]. The waveguides were made in 100 oriented silicon wafers. The width of the waveguide changes linearly from 9μm at the chip facet to 1μm over a distance of 5mm, as shown in Fig. 2. The taper width changes linearly from 8.5μm to 0.5μm to squeeze all optical power into the waveguide. The output rib waveguide has a width of 1μm, slab height of 2.88μm, total height of 4μm, and length of 2cm. The structure was designed and optimized using Beam Propagation Method (BPM) simulations. The calculated coupling efficiency from the taper into the active waveguide was ~62%. The waveguide modal area is calculated to be A_{eff} ~ 5μm^2 using BPM.

To maximize the spectral broadening, the pump polarization relative to waveguide direction must be chosen to correspond to the maximum value of $\chi^{(3)}$. In the present experiment, the pump-waveguide orientation corresponds to χ_{1221} in TE polarization and χ_{1331} in TM. Since $\chi_{1221} = \chi_{1331}$ this orientation results in minimum polarization sensitivity.

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However, the nonlinearity in χ_{1331} is half of the nonlinearity in χ_{1111} orientation. Therefore a 2x higher nonlinearity can be achieved, albeit at the expense of polarization sensitivity.

Spectral broadening in silicon waveguides is clearly visible in the measured spectrum, shown in Fig. 3. The spectrum at the filter output and the waveguide input is also shown for comparison. It is well known that SPM results in the generation of new spectral components with oscillatory power spectral density across the spectrum [11]. This is clearly evident in the measured output spectrum. As mentioned above, a modest amount of broadening occurs in the EDFA that precedes the waveguide (Fig. 1). The so produced weak oscillatory behavior can be observed in the input spectrum. As shown in Fig. 3, the spectral width of pulses entering the waveguide is measured to be approximately 1.5nm at the -5dB level. At the waveguide output, the spectral width is increased to ~3nm at the same level, yielding a 2 fold increase. The knee on the long wavelength side of the input spectrum is due to the soliton sideband effect, which is a typical characteristic of passively modelocked fiber laser such as the one used in the experiment.

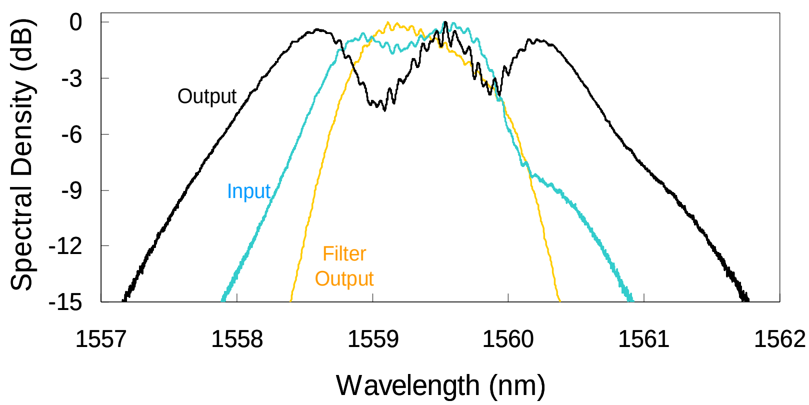

Fig. 3. Measured spectrum at the filter output, at the waveguide input and broadened spectrum at the waveguide output.

SPM results in a phase shift of the pulse carrier, the magnitude of which depends on the nonlinear refractive index, peak power, and propagation length. The amount of nonlinear phase shift can be estimated by the number of spectral oscillations [11]. By doing so, we can deduce a total nonlinear phase shift of approximately 2.5π radians. The phase shift is given by $\varphi_{NL} = \gamma PL$ where P is the peak power and L is the length. The nonlinear constant γ depends on the third order nonlinearity, $\chi^{(3)}$, through the relation, $\gamma = \chi^{(3)}\omega / c^2 n^2 \varepsilon_0 A_{eff}\ \ (1/W.km)$. Here, ω is the angular frequency of the optical carrier and c is the speed of light. Using the known modal area (5 μm^2) and the measured nonlinear phase shift, the nonlinear constant is calculated to be γ ~3 $W^{-1}.m^{-1}$. This is ~1000 times higher than that in the standard optical fibers. Based on this and the peak power value of 110W (2.2 GW/cm^2) at the waveguide, we can estimate that more than 2π radians phase shift occurs in the silicon waveguide. The remaining π/2 phase shift occurs in the EDFA before the waveguide.

Next, theoretical calculations are carried out to study the spectrum broadening effect in the waveguide. We invoke the well known approach of solving the Non-Linear Schrödinger Equation (NLSE). The NLSE governing the pulse propagation is given by,

$$\frac{\partial A}{\partial z} + \frac{i}{2}\beta_2 \frac{\partial^2 A}{\partial t^2} + \frac{\alpha}{2} A = i\gamma |A|^2 A$$

where A is the complex amplitude of the electric field, β_2 (ps^2/m) is the second order dispersion, α (1/m) is the loss coefficient, [11]. The Raman term in the NLSE is ignored since the input pulses (~4 ps) are shorter than the Raman response time in silicon (~10 ps [3]). In

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addition, the walk-off between the pulse and its Stokes component (~3 ps) will further reduce the Raman efficiency.

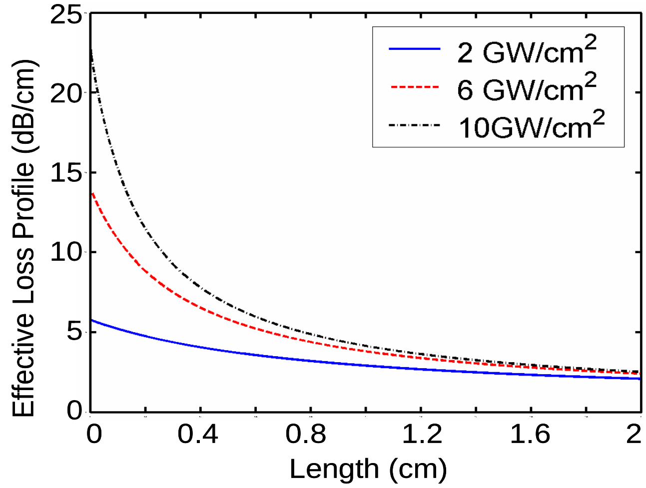

Fig. 4. Effective loss profile inside the waveguide. Due to two photon absorption light is attenuated rapidly in the front end of the waveguide.

Gaussain pulses are assumed and the peak power in the simulations is varied from 20W to 1kW (corresponding 0.4GW/cm^2-20GW/cm^2 in the waveguide). The model presented is here tries to match roughly the pulse width and the bandwidth at the amplifier output to estimate the approximate spectral broadening in the waveguide. For a better accuracy, a model considering the pulse shape at the laser output and nonlinearity in the EDFA should be developed. The extracted γ value of 3 $W^{-1}.m^{-1}$ was used in the simulations. Dispersion in the waveguide was measured by interferometric chromatic dispersion measurement technique [8] and the measured value of β_2 = 1118x10^{-27} s^2/m was used in the simulations. This value is excellent agreement with those reported in Reference [8]. This agreement is expected because the dispersion in silicon rib waveguides is dominated by the material dispersion of silicon. The loss profile in the waveguide is more complicated than a linear propagation loss because of the TPA. The linear propagation loss was measured to be 1 dB/cm. Being an intensity dependent loss, TPA is modeled as a z-dependent loss in addition to the linear loss. The total loss due to TPA and linear loss is given by $e^{\alpha L}(1+BL_{eff}\,/\,A_{eff}P_{in})$, where parameter B is the TPA constant with measured value of B = 4.4x10^{-10} cm/W is the [3]. Shown in Figure 4 is the total loss in the waveguide for different power levels. At high power levels, TPA results in a nonlinear loss behavior in the front section of the waveguide.

The NLSE is solved by using the split step Fourier method [11]. A chirped Gaussian pulse is used at the input to the waveguide to account for propagation in fiber patch cord and the EDFA. The chirp parameter was chosen to match the input spectrum approximately shown in Fig. 3. After solving the NSLE the amount of spectral broadening for various power levels is obtained and summarized in Fig. 5. The spectral broadening factor is obtained by measuring the spectral width at -5dB level to be consistent with experimental results. The results suggest a 2x spectral broadening for input peak power levels of ~2GW/ cm^2, in good agreement with experimental results. As the peak power reaches 20GW/cm^2, a factor of 5 spectral broadening is expected. Since the simulations take the loss due to TPA into account, such amount of broadening should be experimentally realizable, as long as the required high peak intensity can be achieved. Nonetheless, TPA does limit the maximum broadening and is responsible for the saturation behavior observed in Fig. 5.

Simulations also reveal that an order of magnitude broadening can be achieved by using transform-limited pulses with peak intensities of 20 GW/cm^2. However, generating transform limited pulses with very high peak power levels can be subject to pulse breakup in dispersive elements before the waveguide, including the EDFA or fiber patch cords.

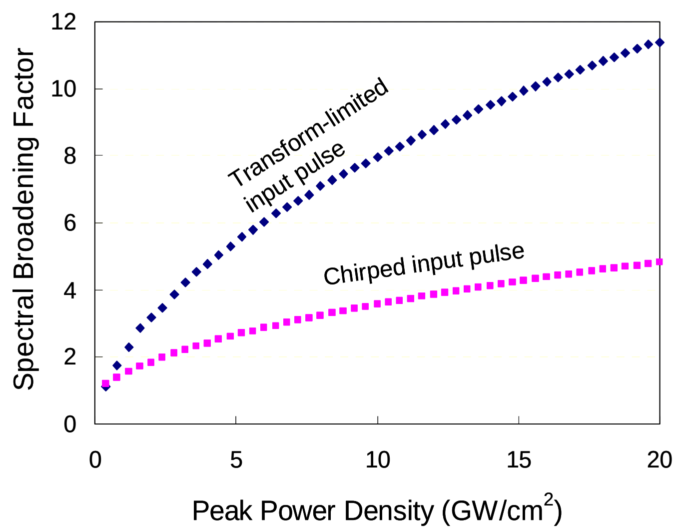

Fig. 5. Simulated spectrum broadening versus power density, for a chirped Gaussian input pulse. Results show a 5 times broadening for 20 GW/cm^2 peak intensity values. A 10x broadening can be achieved with a transform-limited input pulse. The maximum spectrum broadening is limited by two photon absorption.

3. Summary

In summary, we have demonstrated spectral broadening due to the SPM affect in silicon waveguides. By using ~4ps optical pulses with 2.2GW/ cm^2 peak power, a 2 fold spectral broadening is obtained. Theoretical calculations, that include the effect of TPA, indicate up to 5 times spectral broadening is achievable at 10x higher peak powers. Representing a nonlinear loss mechanism at high intensities, TPA establishes a limit on the maximum spectral broadening that can be achieved.

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