Limiting nature of continuum generation in silicon

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Spectral broadening in silicon through self-phase modulation is studied numerically and experimentally in the normal dispersion regime. Temporal dynamics of the free carriers generated during the propagation of optical pulses, through the process of two-photon absorption, affect the amplitude and phase of the optical pulses, thereby determining the nature and extent of the generated spectral continuum. Experimental results are obtained by propagating picosecond optical pulses in a silicon waveguide for intensities that span two orders of magnitude ($1-150\ \mathrm{GW/cm^2}$). These results validate the conclusions drawn from numerical simulations that the continuum generation has a self-limiting nature in silicon.
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Broadband spectral continua find a diverse range of applications from chemical sensing to medical imaging to high throughput telecommunication. It has been also been used in fundamental research, such as a probe for chemical reactions in a photosynthesis process, and as a tool for accurate frequency and time measurements.[1,2] The generation of spectral continuum in silicon waveguides has been explored both experimentally as well as theoretically.[3–5] A numerical study emphasizing the impact of the two-photon absorption (TPA) on nonlinear phase shift at input intensity levels of $\sim 13\ \mathrm{GW/cm^2}$ was published recently.[6] These demonstrate that the TPA reduces the optical intensity and thereby affects the continuum generation. Recently, in a demonstration of continuum carving on a silicon chip, we noted that the free carriers that are generated during the TPA process significantly influence the continuum generation in a silicon waveguide.[7] In this letter, we explore the temporal dynamics of free-carrier effects numerically to evaluate their impact on spectral broadening, and validate these findings with experimental studies using optical intensities that span more than two orders of magnitude ($1-150\ \mathrm{GW/cm^2}$). It is seen that temporal evolution of the free carriers, along with TPA, limits the spectral broadening that may be achieved from a silicon waveguide.

In silicon, the intensity-dependent refractive index that leads to self-phase modulation (SPM) and the generation of spectral continuum has two contributions: (i) the Kerr nonlinearity and (ii) free-carrier refraction (FCR), the modulation of the refractive index of the medium through free carriers (electrons and holes) that are generated by TPA. It is instructive to examine these contributions in order to understand their impact on the continuum generation. The Kerr effect produces blueshifted spectral components on the trailing edge and redshifted spectral components on the leading edge of the optical pulse envelope. On the other hand, FCR causes blueshift on both edges of the pulse envelope, shown qualitatively in Fig. 1(a). Thus, at the leading edge of the pulse, Kerr and free-carrier effects tend to counteract each other, whereas they add at the trailing edge. The overall effect is to produce a net blueshift for the broadened spectrum. Free carriers also cause the absorption (FCA) of optical energy within the pulse, and the absorption coefficient is directly proportional to the density of the free carriers that are generated by TPA. Since free-carrier density follows the time integral of the pulse shape, more carriers are generated toward the trailing edge, as shown in Fig. 1(b). Thus, the blueshifted frequency components that reside in the trailing edge of the pulse suffer more attenuation than the redshifted components. These two effects, namely, the counteracting nature of Kerr effect and FCR at the leading edge of the pulse, and the significantly higher attenuation suffered by the blueshifted frequency components in the trailing edge of the pulse, limit the amount of spectral broadening that may be obtained from a silicon waveguide. Furthermore, TPA also reduces the peak power of the optical pulse, limiting the amount of spectral broadening. In the following, the propagation of pulses in silicon is investigated experimentally as well as numerically in order to explore the limiting nature of spectral broadening in silicon.

We model spectral broadening in a silicon waveguide by solving the nonlinear Schrödinger equation, which governs the propagation of the optical pulses, simultaneously with the differential equation that governs the temporal evolution of the free carriers generated by TPA.[4,6,8] The FCA coefficient α_{FCA} and refractive index change due to free carriers n_{FCR} are given by[9]

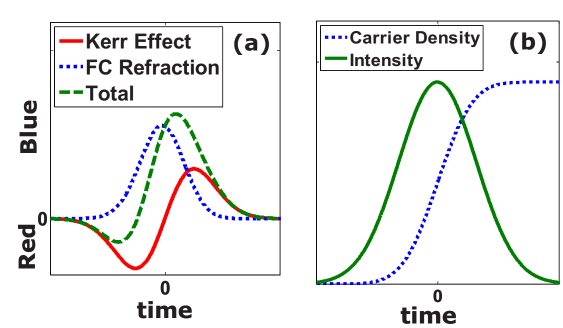

FIG. 1. (Color online) (a) Influence of Kerr effect and FCR on the spectral broadening. (b). Generation of free carriers in an optical pulse. Free carriers follow the integral of the optical pulse and accumulate toward the trailing edge of the pulse.

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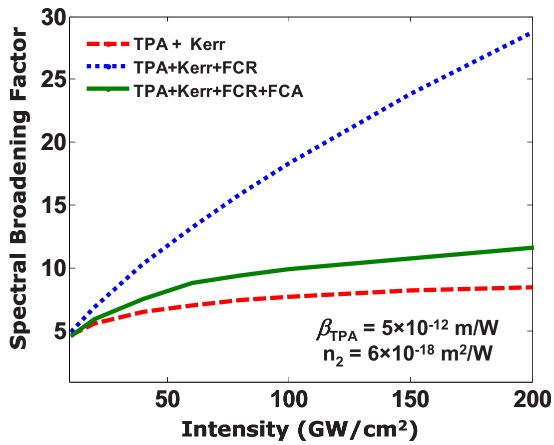

FIG. 2. (Color online) Influence of various physical phenomena on spectral broadening factor plotted as a function of the input intensity of the pulse.

$$n_{\mathrm{FCR}} = -(8.8 \times 10^{-22} N_e + 8.5 \times 10^{-18} N_h^{0.8}),$$

$$\alpha_{\mathrm{FCA}} = 8.5 \times 10^{-18} N_e + 6.0 \times 10^{-18} N_h,$$

where N_e and N_h are the densities of electrons and holes, respectively, in units of cm^{-3}. Numerical simulations are performed by propagating transform limited 3 ps wide Gaussian pulses through a 1 cm long silicon waveguide that has a modal area of 1 $\mu\mathrm{m}^2$, with a propagation loss of 0.5 dB/cm. The measured second order dispersion of these waveguides is around −9.5 fs/nm cm, mostly dominated by the material dispersion of silicon at 1550 nm. The measured carrier lifetime τ for such waveguides is in the range of 1–10 ns, which is much shorter than the repetition rates of 440 ns used in our measurements. Thus interpulse effects may safely be ignored. As waveguides with normal dispersion is considered in this study, modulation instability and solitonic effects do not play a role in the continuum generation. Four-wave mixing between generated spectral components is included naturally in the description of SPM through the nonlinear Schrodinger equation. In the following numerical analysis, we examine hypothetical scenarios by selectively introducing physical phenomena such as Kerr effect, FCR and FCA, to highlight their individual impact on spectral broadening.

Spectral broadening factor, defined as the ratio of the −20 dB spectral bandwidth at the output of the waveguide to that at the input, is plotted as a function of the peak intensity of the pulse at the input of the waveguide in Fig. 2. The values of TPA coeffecient β_{TPA} and Kerr nonlinearity n_2 used in the simulations are shown in the figure. The dashed curve shows the spectral broadening in the presence of only Kerr effect and TPA. It is seen that with 200 GW/cm^2 of peak intensity at the input, the spectrum may be broadened to around 26 nm at the output, corresponding to a broadening factor of ∼9. Combining the Kerr effect with free-carrier refractive index modulation (FCR) leads to broadening factors as high as 27 at 200 GW/cm^2, as depicted by the dotted curve. This is due to the fact that free carrier refraction causes a strong blueshift to the spectrum, with these spectral components residing in the trailing edge of the optical pulse. Thus, even though TPA reduces the peak power of the pulse as it propagates along the waveguide, it is still possible to obtain large broadening factors if the absorption due to free carriers (FCA) was absent.

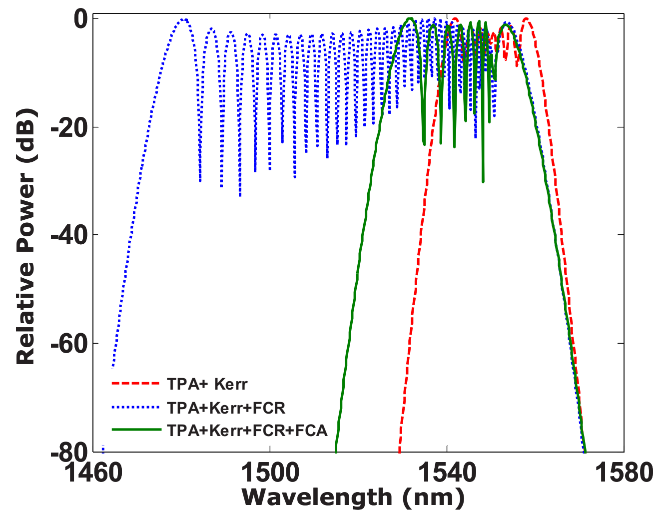

FIG. 3. (Color online) Simulated optical spectra at an input intensity of 200 GW/cm^2 showing free carrier induced effects.

The complete picture however is obtained when the effect of FCA is also is taken into account, as shown by the continuous curve in Fig. 2. Even though FCR produces a strong blueshift, these spectral components suffer higher optical losses due to the fact that FCA is higher toward the trailing edge of the optical pulse. This limits the spectral broadening factors to around 12 at the end of the 1 cm long waveguide. Figure 3 shows the optical spectra (200 GW/cm^2 input intensity) corresponding to the different scenarios illustrated in Fig. 2. It is also important to look at the influence of TPA in limiting the power available to generate continuum. The effect of optical limiting by TPA, for three different input intensities, spanning an order of magnitude, is depicted in Fig. 4(a). After 3 mm of propagation, the peak intensities of the pulses are within 1.3 dB of each other, and most of the spectral broadening occurs in these first few millimeters, as shown by Fig. 4(b).

We have also experimentally studied the nature of spectral broadening in silicon waveguides with normal dispersion. Optical pulses of ∼3.5 ps duration and −3 dB bandwidth of ∼2 nm were coupled to a silicon waveguide 2.3 cm in length, with a modal area of around 2.8 $\mu\mathrm{m}^2$. Measured output spectra at three different input peak intensity levels, along with the spectrum of the input signal, are shown in Fig.

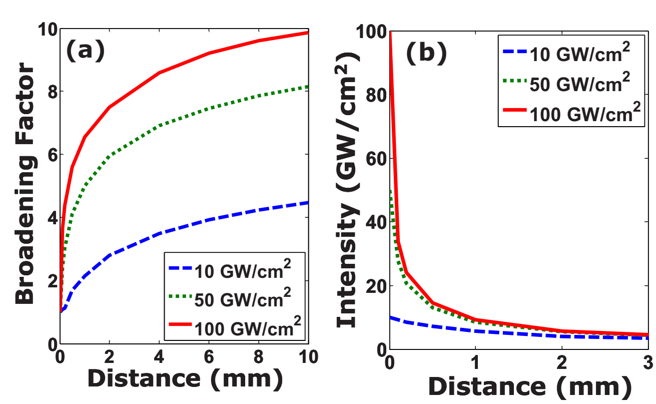

FIG. 4. (Color online) (a) Spectral broadening factor as a function of the length of the waveguide, for three different input intensities. (b) Influence of TPA in reducing the optical intensity of the pulse for three different input intensities.

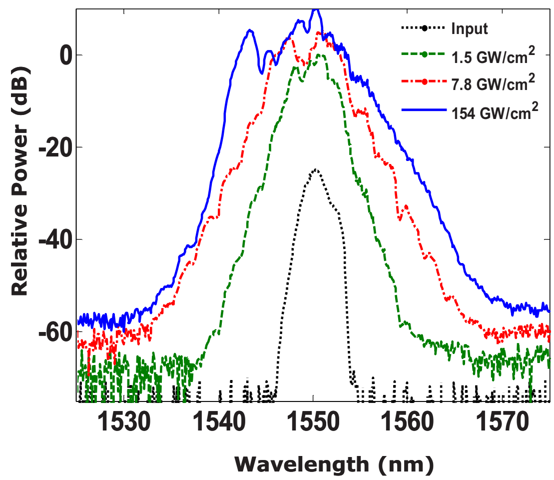

FIG. 5. (Color online) Experimentally observed continua for various input intensities.

5. The self-limiting nature of continuum generation becomes apparent by comparing the spectral spread in these plots. The measured spectral broadening factor as a function of the optical intensity inside the waveguide is plotted in Fig. 6. A clear saturation of the broadening factor is observed experimentally, as predicted by numerical simulations. It is seen that experimental curve saturates faster than that predicted by numerical simulations. However, even at optical intensities as high as 150 GW/cm^2, the agreement between simulations and experimental results is within a factor of 1.3.

In the simulations, the magnitude of the free carrier induced index change is obtained through an empirical model proposed by Soref and Bennet.[9] This model is based on experimental data on refractive index change for impurity doped silicon. Physically, this is different from the present situation where the carriers are generated in the medium by high power optical pulses. It is also known that optical nonlinearities saturate at very high optical intensities.[10] Thus, at high optical intensities, it may be necessary to modify the Soref model to include the saturation of nonlinearity. In addition, the mobility of free carriers is influenced by the presence of strong electric fields.[11] Specifically, at high dc fields, carriers acquire energy from the field, leading to an increase in their scattering with lattice vibrations (phonons). This increased scattering reduces their mobility. To first order, the FCA coefficient is inversely proportional to their mobility. Thus a reduction in mobility can further increase FCA, thereby influencing the spectral broadening. Although electric field due to an optical wave oscillates rapidly, qualitative predictions of the dc mobility model may be relevant. Fields strengths as high as 10^6 V/cm exist inside the optical waveguide for an optical intensity of 200 GW/cm^2, and it is possible that this field influences the mobility of the free carriers. In general, the Soref model might not be adequate to describe physical phenomena that manifest at very high optical intensities. However, given the simplicity of this model, it gives remarkably good agreement with experimental results, and provides valuable insights.

In summary, the temporal dynamics of free-carrier generation and its impact on the phase and amplitude of the optical pulses limit the spectral broadening of intense optical pulses in silicon waveguides. This has been studied numerically and validated experimentally over optical intensities that span two orders of magnitude from 1 to 150 GW/cm^2. Even though the broadening factor may not be much larger than the present case, for applications that require ultrabroadband continuum radiation, continua produced using ultrashort (10–100 fs pulses) optical pulses with high intensities may be used.[12]

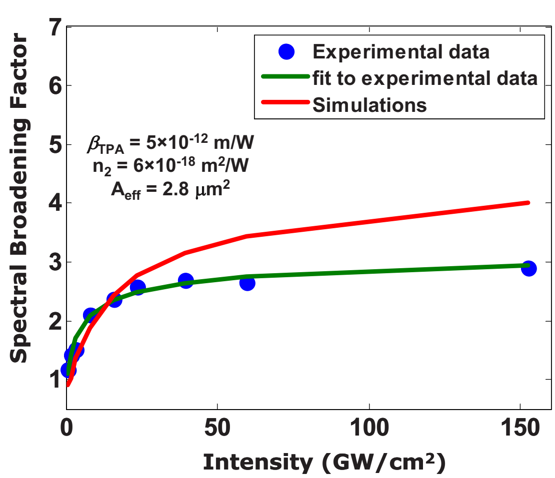

FIG. 6. (Color online) Comparison of experimentally observed spectral broadening factor with simulated values, plotted as a function of the input optical intensity.

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