Nonlinear Silicon Photonics

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Outline

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• Self-Phase Modulation and Soliton Formation
• Higher-Order Solitons and Supercontinuum Generation
• Cross-Phase Modulation and Optical Switching
• Nonlinear Polarization Rotation and Ultrafast Switching
• Raman Amplification and Silicon Raman Lasers
• Four-Wave Mixing and Wavelength Conversion
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Silicon Photonics

- Silicon dominates microelectronics industry totally.
- Silicon photonics is a new research area trying to capitalize on the huge investment by the microelectronics industry.
- It has the potential for providing a monolithically integrated optoelectronic platform on a silicon chip.

Credit: Intel and IBM Websites
Silicon Photonics

- Intel introduced 50-Gb/s silicon-photonics links in 2010.
- Transmitter chip contains four hybrid silicon lasers and four optical modulators, each encoding data at 12.5 Gb/s.
- Four data streams are combined and fed into a single optical fiber.
- Receiver chip separates four WDM channels and directs them into separate photodetectors.
Silicon Nanowires

- Optical processing on a silicon chip requires photonic wires.
- They confine light just as electric wires confine electrons.
- Best solution: A silicon-on-insulator (SOI) waveguide in which a narrow silicon layer is surrounded by lower-index cladding layers.
- In a SOI waveguide, the thin silicon layer has a silica-glass layer at bottom and air or a polymer on top.
- Since a silicon substrate is used, it is not obvious how to create a silica layer just below the silicon surface.

- Silicon-on-Insulator Technology was developed to meet this need and its development has led to the new research area of silicon photonics.
Silicon-on-Insulator Technology

- Silica layer formed by implanting oxygen, followed with annealing.
- A rib or ridge structure used to confine light tightly within an effective mode area of $< 0.5 \, \mu m^2$.
- Nonlinear effects enhanced considerably at moderate power levels.
- Future circuits will need nonlinear effects for signal processing.
Nonlinear Effects and their Applications

- **Self-Phase Modulation (SPM)**
  Soliton-like pulse evolution, supercontinuum generation, all-optical regeneration of telecom channels

- **Cross-Phase Modulation (XPM)**
  Photonic switching, wavelength conversion, optical signal processing, polarization changes through TE–TM mode coupling

- **Four-Wave Mixing (FWM)**
  Parametric amplification, wavelength conversion, phase conjugation, tunable parametric delays

- **Stimulated Raman Scattering (SRS)**
  Raman amplification at any wavelength, optically pumped Raman lasers
Kerr Effect and Two-Photon Absorption

- Refractive index depends on local intensity (Kerr effect):
\[ n(\omega, I) = \bar{n}(\omega) + n_2(1 + ir)I(t). \]

- Material parameter \( n_2 = 3 \times 10^{-18} \text{ m}^2/\text{W} \) is larger for silicon by a factor of 100 compared with silica fibers.

- Dimensionless parameter \( r = \beta_{\text{TPA}}/(2k_0n_2) \) is related to two-photon absorption (TPA) occurring when \( h\nu \) exceeds \( E_g/2 \).

- TPA parameter: \( \beta_{\text{TPA}} = 5 \times 10^{-12} \text{ m/W} \) at wavelengths near 1550 nm.

- Dimensionless parameter \( r \approx 0.1 \) for silicon near 1550 nm.

- TPA is a major limiting factor for SOI waveguides because it creates free carriers (in addition to nonlinear losses).
Free-Carrier Generation

- TPA creates free carriers inside a silicon waveguide according to
  \[
  \frac{\partial N_c}{\partial t} = \beta_{\text{TPA}} \frac{I^2(z,t)}{2h\nu_0} - \frac{N_c}{\tau_c}.
  \]

- Carrier lifetime is relatively large for silicon (\(\tau_c > 10\) ns).

- It limits the device response time if carriers cannot be removed quickly enough.

- Free carriers also introduce loss and change the refractive index.

- Pulse propagation inside silicon waveguides is governed by
  \[
  \frac{\partial A}{\partial z} + \frac{i\beta_2}{2} \frac{\partial^2 A}{\partial t^2} = ik_0n_2(1 + ir)|A|^2A - \frac{\sigma}{2} (1 + i\mu)N_cA - \frac{\alpha_l}{2}A.
  \]
Free-Carrier Absorption (FCA)

- Loss induced by FCA: $\alpha_f = \sigma N_c$ with $\sigma = 1.45 \times 10^{-21}$ m$^2$.
- Free carriers also change the refractive index by $\Delta n = -\left(\frac{\mu}{2k_0}\right)\sigma N_c$ (free-carrier dispersion).
- This change is opposite to the index change $n_2I$ resulting from the Kerr effect.
- Parameter $\mu$ is known as the “linewidth enhancement factor” in the context of semiconductor lasers.
- Its value for silicon is close to 7.5 in the spectral region near 1550 nm.
- Absorption and index changes resulting from free carriers affect the performance of silicon waveguides.
- Quick removal of carriers helps (e.g., by applying a dc electric field).
Removal of Free Carriers

- A reversed-biased p-n junction is used for this purpose.
- Electric field across the waveguide removes electrons and holes.
- Drift time becomes shorter for larger applied voltages.
- Effective carrier lifetime can be shortened from >20 to <1 ns.
Self-Phase Modulation (SPM)

- Refractive index depends on intensity as \( n' = \tilde{n} + n_2 I(t) \).
- Propagation constant also becomes intensity-dependent:
  \[ \beta' = \beta + k_0 n_2 \left( \frac{P}{A_{\text{eff}}} \right) \equiv \beta + \gamma P. \]
- \( \gamma = k_0 n_2 / A_{\text{eff}} \) is larger for silicon nanowires by a factor of \( >10,000 \) compared with silica fibers.
- Nonlinear Phase shift:
  \[ \phi_{\text{NL}} = \int_0^L (\beta' - \beta) \, dz = \int_0^L \gamma P(z) \, dz = \gamma P_{\text{in}} L_{\text{eff}}. \]
  Here, \( P(z) = P_{\text{in}} e^{-\alpha z} \) and \( L_{\text{eff}} = (1 - e^{-\alpha L}) / \alpha \).
- Optical field modifies its own phase (SPM).
- Phase shift varies with time for pulses (chirping).
Chirping and Spectral Broadening

- In the case of optical pulses, \( \phi_{NL}(t) = \gamma P(t) L_{eff} \).
- Chirp is related to the phase derivative \( d\phi_{NL}/dt \).
- Phase and chirp profiles for super-Gaussian pulses are shown using \( P(t) = P_0 \exp[-(t/T)^{2m}] \) with \( m = 1 \) and \( m = 3 \).
- SPM creates new frequencies and leads to spectral broadening.
Self-Phase Modulation and TPA

- Preceding analysis neglected two-photon absorption.
- Its impact on SPM can be studied by solving:
  \[ \frac{\partial A}{\partial z} = i\gamma(1 + ir)|A|^2A - \frac{\alpha_l}{2}A. \]
- This equation ignores dispersive and free-carrier effects.
- Using \( A = \sqrt{P} \exp(i\phi_{NL}) \), we obtain the following analytic solution:
  \[ P(L,t) = \frac{P(0,t) \exp(-\alpha_lL)}{1 + 2r\gamma P(0,t)L_{\text{eff}}}, \]
  \[ \phi_{NL}(L,t) = \frac{1}{2r} \ln[1 + 2r\gamma P(0,t)L_{\text{eff}}]. \]
- TPA converts linear dependence of \( \phi_{NL} \) on power to a logarithmic one.
Impact of Two-Photon Absorption

- TPA reduces the maximum phase shift:
  \[ \phi_0 = \frac{\ln(1 + 2r\phi_{\text{max}})}{2r}. \]

- In the absence of TPA, \( \phi_0 = \phi_{\text{max}} = \gamma P_0 L_{\text{eff}}. \)

- Inset shows the reduction using \( r = 0.1. \)

- TPA-induced reduction becomes severe at high powers.

- When \( \phi_{\text{max}} = 100, \phi_0 \) is limited to a value of 15.

Impact of Free-Carrier Generation

Free carriers produce a nonlinear phase shift in the opposite direction.

\[ P(t) = P_0 e^{-t^2/T_0^2} \]
\[ T_0 = 10 \text{ ps} \]
\[ L = 2 \text{ cm} \]
\[ \tau_c = 1 \text{ ns} \]
\[ \alpha_l = 1 \text{ dB/cm} \]

Experimental Results


- First observation of SPM-induced spectral broadening in 2004.
- 4-ps pulses launched inside a 2-cm-long SOI waveguide.
- The 3-peak output spectrum broadened by a factor of 2 when peak intensity was 2.2 GW/cm² ($P_0 \approx 100$ W).
Experimental Results

- Larger broadening by 2006.
- 1.8-ps pulses launched inside a 4-mm-long waveguide.
- Width 470 nm height 226 nm.
- Spectral asymmetry is due to free-carrier effects.
- Inset shows the FROG trace.

Formation of Optical Solitons

- Solitons balance SPM with dispersion and maintain their shape.
- Nonlinear length $L_{NL} = 1/(\gamma P_0) \sim 1$ mm at peak powers $<100$ W.
- Dispersion length, $L_D = T_0^2/|\beta_2|$, can be $\sim 1$ mm for fsec pulses.
- Pulses propagate as fundamental solitons when $\beta_2 < 0$ and
  \[
  N^2 = \frac{L_D}{L_{NL}} = \frac{\gamma P_0 T_0^2}{|\beta_2|} = 1.
  \]
- Perfect solitons do not exist because of TPA and other losses.
- Soliton-like propagation still possible with proper design.
130-fs pulses launched inside a 5-mm-long waveguide ($N = 1$).
Supercontinuum Generation

- Ultrashort pulses are affected by a multitude of nonlinear effects, such as SPM, XPM, FWM, and SRS, together with dispersion.
- All of these nonlinear processes are capable of generating new frequencies outside the input pulse spectrum.
- For sufficiently intense pulses, the pulse spectrum can become so broad that it extends over a frequency range exceeding 100 THz.
- Such extreme spectral broadening is referred to as supercontinuum generation.
- This phenomenon was first observed in solids and gases more than 35 years ago (late 1960s.)
- Since 2000, microstructure fibers have been used for supercontinuum generation.
SC Generation in a microstructured fiber


- Output spectrum generated in a 75-cm section of microstructured fiber using 100-fs pulses with 0.8 pJ energy.
- Even for such a short fiber, supercontinuum extends from 400 to 1600 nm.
- Supercontinuum is also relatively flat over the entire bandwidth.
SC Generation in Silicon Waveguides


- TPA reduces SC bandwidth but is not detrimental.
- Nearly 400-nm-wide supercontinuum created within a 3-mm-long waveguide.
- Required pulse energies are relatively modest (∼1 pJ).
SC Generation in Silicon Waveguides

- SOI waveguides also support higher-order solitons when $N = (\gamma P_0 T_0^2 / |\beta_2|)^{1/2}$ exceeds 1.

- Higher-order dispersion should lead to their fission into much shorter fundamental solitons: $T_k = T_0 / (2N + 1 - 2k)$.

- Intrapulse Raman scattering absent because of a narrow Raman bandwidth: no significant red-shifting of solitons.

- Similar to the case of optical fibers, each soliton emits dispersive waves on the blue side when $\beta_3 > 0$.

- Numerical simulations confirm the potential of SOI waveguides for SC generation.

- Spectral broadening over 350 nm is predicted for femtosecond pulses.
All-Optical Regeneration


- Signal regeneration requires a Kerr medium (for spectral broadening) followed with a bandpass filter.
- Both of these can be realized on a single silicon chip.
- A 2007 experiment employed 8-mm-long silicon nanowire followed with a ring resonator for spectral filtering.
All-Optical Regeneration (continued)

Considerable spectral broadening observed for 3.5 pulses. Ring resonator selects the blue-shifted peak.
Cross-Phase Modulation

- Consider two optical fields propagating simultaneously.
- Nonlinear refractive index seen by one wave depends on the intensity of the other wave as
  \[ \Delta n_{NL} = n_2(|A_1|^2 + b|A_2|^2). \]
- Total nonlinear phase shift in a fiber of length \( L \):
  \[ \phi_{NL} = \frac{2\pi L}{\lambda} n_2[I_1(t) + bI_2(t)]. \]
- An optical beam modifies not only its own phase but also of other copropagating beams (XPM).
- XPM induces nonlinear coupling among overlapping optical pulses.
XPM-Induced Spectral Changes


- 200-fs pump and probe pulses (at 1527 and 1590 nm) launched into a 4.7-mm-long SOI waveguide ($w = 445$ nm, $h = 220$ nm).

- Pump and probe pulses travel at different speeds (walk-off effect).

- XPM-induced phase shifts occurs as long as pulses overlap.

- Asymmetric XPM-induced spectral broadening depends on pump power (blue curve); Probe spectra without pump (red curve).
XPM-Induced Switching

- A Mach–Zehnder interferometer is often used for optical switching.
- Output switched to a different port using a control signal that shifts the phase through XPM.
- If control signal is in the form of a pulse train, a CW signal can be converted into a pulse train.
- Turn-on time quite fast but the generation of free carriers widens the switching window (depends on the carrier lifetime).
Experimental Demonstration


- A Mach–Zehnder interferometer used for optical switching.
- Short pump pulses (<1 ps) at 1560 nm pass through the arm containing a 2.5-cm-long SOI waveguide.
- CW probe experiences XPM-induced phase shift in that arm.
- Temporal slice of the probe overlapping with the pump is optically switched.
XPM-Induced Switching


• Instantaneous switching on the leading edge, as expected, with high on–off contrast.

• Long trailing edge results from the free-carrier effects.

• Free carriers provide an additional contribution to the probe phase by changing the refractive index.
Polarization-Based Kerr Switching

- Pump pulse propagates in the TE mode of a silicon waveguide.
- CW probe polarized at 45° excites TE and TM modes.
- Its TE component acquires an XPM-induced phase shift.
- Output probe elliptically polarized (nonlinear polarization rotation).
- Probe transmitted through the analyzer only when a pump pulse opens the Kerr gate.
Numerical Results


- Switching windows (red) for 4 different pump pulses (blue).
- Cross section: (left) $650 \times 450$ nm$^2$ and (right) $450 \times 450$ nm$^2$.
- Free-carrier and walk-off effects play important roles.
- Free-carrier effects reduced for short pump pulses.
- Birefringence effects minimized for square waveguides.
Experimental Setup

- Two EDFAs and PCs used for pump and probe (CW) signals.
- **CWDM** coupler combines the pump and probe.
- Optical bandpass filter (OBF) blocks the pump.
- Linear birefringence canceled by the PC at the output end.
- PBS helps us to display both probe components simultaneously.
Experimental Results


- Blue peaks show normal switching at 44-MHz repetition rate of 500-fs pump pulses.
- Red dips show the case in which each pump pulse blocks the probe transmission.
- Switching window $< 1$ ps wide at pump powers $< 2$ W.
Stimulated Raman Scattering

- Scattering of a pump beam from vibrating molecules creates a Stokes beam down-shifted in frequency by a specific amount.
- Frequency shift is set by a vibrational mode (phonons).
- Raman gain spectrum exhibits a dominant peak at 15.6 THz with a 105-GHz bandwidth ($\approx 1$ nm wide near 1550 nm).
- Peak gain for silicon $>1000$ larger compared with silica.

Theory behind Raman Amplifiers and Lasers

• Pump and signal powers satisfy a set of two coupled equations:

\[
\frac{\partial P_p}{\partial z} = -(\alpha_{lp} + \alpha_{fp}) P_p - \beta_{pp} P_p^2 - 2\beta_{ps} P_s P_p - g_R P_s P_p
\]

\[
\frac{\partial P_s}{\partial z} = -(\alpha_{ls} + \alpha_{fs}) P_s - \beta_{ss} P_s^2 - 2\beta_{sp} P_p P_s + g_R P_p P_s.
\]

• Signal loss by free carriers (\(\alpha_{fs} = \sigma_{fc} N\)) limits Raman amplification.

• For net amplification to occur, the carrier lifetime should satisfy

\[
\tau_0 < \tau_{th} \equiv \frac{\hbar \omega_p (g_R - 2\beta_{sp})^2}{2 \alpha_{ls} \sigma_{fc} \beta_{pp}}.
\]

• A Raman laser cannot function if this condition does not hold.

Raman Amplifiers

Jalali et al., IEEE JSTQE 12, 412 (2006)

- CW pumping leads to accumulation of free carriers through TPA.
- Free-carrier absorption introduces losses for pump and signal.
- No signal gain occurs for $\tau_{\text{eff}} > 10$ ns.
Pulsed Raman Amplifiers

Jalali et al., IEEE JSTQE 12, 412 (2006)

- Pulsed pumping can provide $>20$-dB gain if spacing among pulses is much larger than $\tau_{\text{eff}}$ ($R_p \tau_{\text{eff}} \ll 1$).
- Free carriers can then decay before the next pulse arrives.
- Pump pulses ($\sim 30$ ps) at 1540 used to amplify a 1673-nm signal.
- 20-dB net gain realized at 37-W peak power of pump pulses.
Raman Lasers


- Pumped with 30-ps pulses at 1540 nm at 25-MHz repetition rate.
- Produced 18 ps pulses at 1675 nm at the same repetition rate.
Control of Carrier Lifetime


- CW pumping can be used if free carriers are removed quickly.
- A reversed-biased p-n junction is used for this purpose.
- Electric field across the waveguide removes electrons and holes.
- Drift time of carriers is shorter for larger applied voltages.

- A 4.8-cm-long waveguide CW pumped at 1458 nm (signal at 1684 nm).
- Output pump and signal powers increase with applied voltage.
- Effective carrier lifetime decreases from 16 to 1 ns.
CW Silicon Raman Lasers

Rong et al., Nature Photonics 1, 232 (2007)
Four-Wave Mixing (FWM)

- FWM is a nonlinear process that transfers energy from pumps to signal and idler waves.
- FWM requires conservation of
  - Energy: \( \omega_1 + \omega_2 = \omega_3 + \omega_4 \)
  - Momentum: \( \beta_1 + \beta_2 = \beta_3 + \beta_4 \)
- Degenerate FWM: Single pump (\( \omega_1 = \omega_2 \)).
Parametric Amplifiers

• FWM can be used to amplify a weak signal.
• Pump power is transferred to signal through FWM.
• The idler (generated as a byproduct) acts as a copy of the signal at a new wavelength (useful for wavelength conversion).
• Parametric amplifiers can provide gain at any wavelength using suitable pumps.
• They are also useful for all-optical signal processing.
• Optical fibers are often used, but the use of SOI waveguides would result in a much more compact device.
• Impact of two-photon and free-carrier absorption requires further study.
FWM Theory for Silicon Waveguides

- Theory should include TPA and free-carrier effects fully.
- Polarization and Raman effects should also be included.
- Free-carrier absorption limits the gain for a CW pump.
- $\beta_2 < 0$ (red); $\beta_2 = 0$ (blue); $\beta_2 > 0$ (green).
FWM with Short Pump Pulses


- FCA is reduced significantly for pump pulses much shorter than carrier lifetime $\tau_c$.
- Figure shows the case of 10-ps pump pulses with $\tau_c = 1$ ns.
- Phase-matching condition is satisfied even for signal that is shifted by 70 nm from the pump wavelength.
Single and Dual-Pump Configurations


- Parametric amplifiers with a large bandwidth can be realized by pumping an SOI waveguide with two pumps.
- This is possible because of a relatively short device length.
- Recent experiments with SOI waveguides are encouraging.
Wavelength Conversion of Telecom Channels


- Dispersion control essential (300 nm $\times$ 750 nm device).
- FWM efficiency $-15$ dBm (CW pump);
  Conversion bandwidth $>150$ nm.
- Eye diagrams show no degradation when the wavelength of a 10-Gbs/s signal is converted using a 300 nm $\times$ 500 nm device.
Tunable Parametric Delays


- Wavelength conversion performed in the first FWM device.
- Transmission through a fiber provides delay with pulse broadening.
- Second Wavelength conversion using a silicon chip.
- A second fiber used to compensate dispersion and compress the pulse back to original width.
- Delays > 1 $\mu$s demonstrated in this 2009 experiment.
Demultiplexing at 160 Gb/s

Demultiplexing at 1280 Gb/s

Oxenlowe et al., IEEE JSTQE 18, 996 (2012)
Photon-Pair Generation


- Spontaneous FWM in fibers creates entangled photon pairs but suffers from the noise induced by Raman scattering.
- The use of SOI waveguides avoids this problem because Raman scattering does not occur when TM mode is excited.
- Several experiments have confirmed our theoretical predictions.
Experimental Results


- Sharping et al. (Opt. Exp. 14, 12388, 2006) used 5-ps pump pulses to generate good-quality photon pairs.

- Takesue et al. (Opt. Exp. 16, 5721, 2008) used 90-ps pump pulses to create polarization-entangled photon pairs.

- Clemen et al. used a CW pump with <6 mW power and generated photon pairs over a 40-nm bandwidth.
Concluding Remarks

- Nonlinear effects in silicon waveguides can be used to make many active and passive components.
- SPM is useful for supercontinuum generation among other things.
- Cross-phase modulation can be used for optical switching, wavelength conversion, and optical signal processing.
- Nonlinear polarization rotation useful for making ultrafast photonic switches.
- Stimulated Raman scattering converts silicon waveguides into Raman amplifiers and lasers.
- Four-wave mixing is useful for wavelength conversion, tunable parametric delays, phase conjugation, and photon-pair generation.
Further Reading

- S. Fathpour and B. Jalali, *Silicon Photonics for Telecommunications and Biomedicine* (CRC, 2011)