Nonlinear Optics in Si Wires on an SOI Platform

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Abstract

We provide a discussion of the nonlinear-optical properties of Si wire waveguides and discuss their design and potential use for on-chip waveguide applications.

1. Introduction

Fiber optics is an enabling technology not only for light transport but also a means to manipulate the phase, timing, envelope, and wavelength of optical pulses. Using recent technology it is now possible to accomplish these fiber-optic functions entirely on-chip using SOI-based materials [1]. Rapid advances in the materials processing and integrated optical technology for submicrometer-scale Si waveguides are providing the basis for this capability. One important near-term application for this technology is to use these ultrasmall cross-section waveguides, called optical wires, as miniature optical buses for routing signals between processors in a multiprocessor computational system. In this paper, we will describe the use of silicon wires to accomplish many of these nonlinear optical functions.

Our experiments to demonstrate nonlinearities in Si wires make use of variety of laser waveforms from CW to femtosecond to pump low-propagation- and low-insertion-loss Si waveguides on wafer-bonded SOI wafers. The waveguides are typically of <0.1 \( \mu \)m2 cross-section channel guides with 3dB/cm propagation loss and 3dB input and output coupling loss at 1.55\( \mu \)m wavelength. With these waveguides, we have demonstrated a variety of important optical functionalities, from Raman amplification to optical parametric generation. A key feature of such integrated wire waveguides is that their dispersion can be engineered via waveguide geometry so that both normal and anomalous second-order dispersion can be designed in the waveguide.

2. Experimental

Our experiments employ single-mode SPWs with thicknesses ranging from 220 - 226 nm, widths ranging from 445 - 520 nm, and length of typically \( L \approx 4.7 \) mm, patterned on Unibond silicon-on-insulator (SOI) with a 1-\( \mu \)m-thick oxide layer and aligned along the [110] crystallographic direction. The devices, which are described in detail in Ref [2], were fabricated using the CMOS fabrication line at the IBM T.J. Watson Research Center. Each end of the waveguides has an inverse polymer mode-converter, which allows efficient in and out coupling. The measured intrinsic waveguide loss is \( \alpha_{in} \approx 3.6 \) dB/cm for the TE polarization near \( \lambda = 1550 \) nm; lower losses of 1.7 dB/cm have been measured [2]. The laser sources used here are a mode-locked fiber-laser and a Ti:sapphire-based optical parametric amplifier, which produce the pulses with pulse durations of \( T_0 \approx 200 \) fs and 2 ps, respectively, as measured by autocorrelation or frequency-resolved optical gating. An objective lens was used to couple light into the waveguide; the output was then collected by a tapered fiber connected to a power meter or an optical spectrum analyzer.
The coupling loss using the objective-lens waveguide coupler into the waveguide are typically between 25 to 35 dB.

Our experimental work has also been guided by the development of a full, rigorous theoretical treatment of nonlinear propagation in the crystal-silicon waveguide, which fully accounts for strong modal confinement and Si optical-nonlinearity anisotropy [3].

3. Dispersion Properties of Si Wires

Because of their sub-micrometer cross-sections and high index contrast and, hence, strong optical confinement, SPWs offer important new flexibility in tailoring the dispersive properties of integrated guided-wave devices as shown in Fig. 1 [3,4,5]. Demonstration of dispersion engineering has also been accomplished earlier in photonic crystal fibers and multimode fibers. The design of such silicon waveguide devices can be challenging because the usual computational approximations generally apply for standard integrated photonic structures fail when applied to high-refractive-index-contrast Si-wire devices. Instead the most commonly used approaches in this area use finite difference and/or finite element methods; these numerical techniques enable rigorous calculations to be done with great accuracy. In our calculations we employed the finite-element method (FEM); in addition, we have also shown that the full vectorial beam propagation method (BPM) can be used as well.

Table 1 below shows computation of optical dispersion related quantities carried out for a typical Si –wire waveguide at two different pulse widths, as well as a comparison of the comparable quantities for standard optical fiber. Note how the quantities are amenable to chip-scale experiments for the Si-wire waveguides.

<table>
<thead>
<tr>
<th>Dispersion and nonlinear parameters</th>
<th>SPW $T_p = 200$ fs</th>
<th>SPW $T_p = 10$ ps</th>
<th>Optical Fiber $T_p = 200$ fs</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_D$</td>
<td>$\sim 1$ cm</td>
<td>$\sim 25$ m</td>
<td>$\sim 2$ m</td>
</tr>
<tr>
<td>$L_D'$</td>
<td>$\sim 1$ cm</td>
<td>$\sim 2.5$ km</td>
<td>$\sim 80$ m</td>
</tr>
<tr>
<td>$L_{NL}$ at $P_p = 0.2$ W</td>
<td>$\sim 8$ mm</td>
<td>$\sim 8$ mm</td>
<td>$\sim 2$ km</td>
</tr>
<tr>
<td>$\gamma$ (m$^{-3}$W$^{-1}$)</td>
<td>$\sim 6\times10^2$</td>
<td>$\sim 6\times10^2$</td>
<td>$\sim 3\times10^3$</td>
</tr>
</tbody>
</table>

Table 1. Comparison of characteristic lengths for ultrashort (200 fs) and long (10 ps) pulses, and the nonlinear parameter ($\gamma$) in a Si photonic wire (dimensions: 220×450 nm$^2$) and a single-mode optical fiber for $\lambda = 1.55\mu$m.

4. Optical Nonlinearities in Si Wires

4.1 Self-Phase Modulation

Optical pulses propagating in a silicon photonic wire (SPW) show nonlinear behavior as the pump power is increased, including optical limiting behavior and increasing spectral modulation [6,7]. Here we discuss only spectral modulation. Specifically, our measurements show that as the input power is increased, the pulse spectrum broadens and then develops a multiple-peak structure. This behavior, which is a signature of the SPM, is the result of the phase interference between the pulse-frequency components with a time-dependent SPM-induced frequency chirp. Several important characteristics of SPW are important
for pulse propagation in these small cross section waveguides. These include their unusual dispersive effects, as discussed above and in the case of fs-pulse propagation, the importance of third-order dispersion in distorting the pulse envelope [9]. We find through our simulations that in Si wires, the SPM can be strongly influenced by the optical properties of the medium including two-photon absorption (TPA), TPA-induced free carriers, and TOD. Because of the small energy carried by an ultrashort pulse, the effect of FCA is generally less severe if not absent, as observed for the case of optical limiting above. Moreover, the laser pulse-repetition rate can play an important role if the lifetime of the carriers is longer or comparable with the interpulse temporal separation, since in this case, the carriers will accumulate over time and may become a source of loss as well as a source of phase shift. Accumulation is important if the carriers have a sufficiently long lifetime, as is typical for unbiased large cross-section waveguides, i.e., $A_0 > 1 \, \mu m^2$.

### 4.2 Cross-phase modulation

As we have shown above, SPM alters the phase of the optical pulse and as a result this effect can have important practical applications. Increased design flexibility can be achieved by controlling the phase of a pulse at one wavelength with a second, co-propagating pulse, at a different wavelength, i.e., cross phase modulation. Cross-phase modulation (XPM) is also described by our general coupled-mode theory such as described in Ref. [8]. We have measured XPM in SPWs using two pulses of different wavelengths that co-propagate in the same waveguide, as described in Ref. [8]. These two pulses are derived using an ultrafast mode-locked Er-doped fiber-laser having a pulse repetition rate of 37 MHz and a bandwidth of 80 nm. After passing through a beam splitter and bandpass filters, this laser beam is split into the pump and probe beams, with center wavelengths at $\lambda_p = 1527$ nm and $\lambda_s = 1590$ nm, respectively. The pulse width and bandwidth of the resulting pulses are approximately 200 fs and 15 nm, respectively. Both pulses are free-space coupled into the waveguide and are polarized along the direction of the field of the TE waveguide mode. The output was collected by a tapered fiber and sent to an OSA. Free-space coupling, rather than tapered fiber coupling, is employed to rule out SPM and XPM in the input fiber. The experiments have shown that XPM in SPWs exhibit much of the same behavior as it does in optical fibers. Thus overlap of the control pulse with the signal pulse causes a frequency shift of the signal pulse, which varies with the relative delay between the two pulses. Further full overlap of the two pulses causes a multiple-$\pi$ phase shift in the signal pulse, thus allowing change of the phase in the signal.

### 4.3 Supercontinuum Generation

Supercontinuum generation is a device functionality that has important applications in many areas of photonic integrated circuits. For example, in the case of wavelength-division multiplexing applications, it is often beneficial to use a single broadband laser source, select out filter-specific wavelength channels, and then modulate these channels, instead of using a separate laser for each wavelength channel. Figure 2 demonstrates the ultrahigh bit-rate capability of SPWs. Use of a single source with continuum generation reduces both the complexity of on- or off-chip multiple laser integration and its concomitant power dissipation. These are important considerations in telecommunication applications, such as optical transceivers, or in emerging on-chip optical networks for multi-processor chips. In addition, continuum generation is important in other non-communication applications. These include, for example, optical coherence tomography (OCT) where a low power Si supercontinuum source can enable measurement of axial features in a sample at optimum wavelengths, i.e., $\sim$1.3-1.5 $\mu m$, for imaging in nontransparent biological tissues.

![Fig 2: Eye diagrams of 300GHz data stream, using 24 C-band channels sent through SPW.](image-url)
We have recently observed continuum generation in SPWs at a variety of wavelengths from ~1.3 - 1.5 \( \mu \text{m} \) [10]. In particular using fs driving pulses we have observed spectral broadening of more than 350 nm, i.e., a 3/10 octave span, upon propagation of ultrashort 1.3-\( \mu \text{m} \)-wavelength optical pulses in a 4.7-mm-long silicon-photonic-wire waveguide. We have also measured the wavelength dependence of the spectral features and related it to the waveguide dispersion and input power. The spectral characteristics of the output pulses have been shown to be consistent, in part, with higher-order soliton-radiative effects [11].

5. Conclusion

In conclusion, optical nonlinearities have been observed and simulated in a high-performance Si photonic wire waveguides. Understanding these nonlinearities is important for two reasons: First, optical nonlinearities may present a new approach to optical control of on-chip signals, including elementary logic operations. Second, understanding optical nonlinearities is crucial to controlling the level of impairments in optical S/N for on chip interconnects. In fact recent measurements of this limitation has recently been examined in a preliminary way using 300GHz signal system, with 24 C-band channels; see Fig. 2.

6. Acknowledgments

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7. References