All-optical slow-light on a photonic chip

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Abstract: We demonstrate optically tunable delays in a silicon-on-insulator planar waveguide based on slow light induced by stimulated Raman scattering (SRS). Inside an 8-mm-long nanoscale waveguide, we produce a group-index change of 0.15 and generate controllable delays as large as 4 ps for signal pulses as short as 3 ps. The scheme can be implemented at bandwidths exceeding 100 GHz for wavelengths spanning the entire low-loss fiber-optics communications window and thus represents an important step in the development of chip-scale photonics devices that process light with light.

OCIS codes: (230.1150) All-optical devices; (190.5650) Raman effect; (999.9999) Slow light.

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1. Introduction

Over the past decade, there has been great interest in controlling the group velocity of pulses of light in optical materials [1]. Many of the techniques for achieving "slow light" rely on a laser-induced transmission window within a spectral absorption line of a material [2-6] to produce a reduction in the group velocity. If devices based on slow light are developed which accommodate telecommunication data rates exceeding 10 GHz, several critical applications such as data synchronization, tunable data buffers, and pattern correlation, can be implemented [7].

Development of silicon-based nanophotonic devices for photonics-on-chip technology has recently been the subject of substantial research activity. The silicon-on-insulator (SOI) platform has inherent advantages for all-optical devices due to the high index contrast between the silicon core and silica cladding, which allows for strong optical confinement, large effective optical nonlinearities, and highly compact photonic circuits [8]. Nonlinear effects in SOI waveguides have led to demonstrations of all-optical switching [9], Raman amplification [10-12], and Raman lasing [13-15] in silicon nanostructures. In particular, the large Raman gain coefficient in SOI waveguides allows for appreciable amplification over

Some degree of thermal tuning of these structures, similar to that in fiber Bragg gratings [23], has been demonstrated [21], but this restricts their use to those applications in which an ultrafast reconfiguration is not required. In addition, single-beam delay schemes have been realized in semiconductor waveguides [24], quantum dot amplifiers [25], and vertical-cavity surface-emitting laser amplifiers [26].

Here we demonstrate optically tunable delays in a robust and highly compact SOI architecture based on slow light induced by stimulated Raman scattering (SRS). Within a nanoscale waveguide, we produce group index changes as large as 0.15 and generate controllable delays greater than a full pulse width for signal pulses as short as 3 ps. Our scheme is noteworthy since it is compatible with silicon-on-insulator technology, the delay of each pulse within a pulse train can be separately controlled, tunable delays can be generated at telecommunication wavelengths and at bandwidths of up to 100 GHz, and the same waveguide can be used to produce delays at different wavelength channels across the entire telecommunication spectrum. These results thus represent a critical step in the development of chip-scale optical signal processing devices that control light with light.

2. Theory

In our work, we utilize the optically-induced change in the dispersion via SRS to generate tunable all-optical delay. For the case of a Raman-active material with a strong pump field applied, a weak signal field will experience gain (loss) when its frequency is detuned below (above) the pump frequency by the Raman frequency Ω_R of vibrational modes of a material. The magnitude of the gain depends on the intensity of the pump field, and the gain occurs over a certain bandwidth Γ_R of signal-pump detuning. Figure 1 shows the experimentally measured gain as a function of frequency for the silicon waveguide used in our experiment at a low level of amplification. The measured gain linewidth is $\Gamma_R/2\pi$ = 96.2 GHz (FWHM), which is slightly smaller than the phonon bandwidth (105 GHz) in silicon due to gain narrowing. Through the Kramers-Kronig relations, the Raman gain for the signal field will be accompanied by a frequency-dependent refractive index $n(\omega)$ that also depends on the intensity of the pump wave. The group index, which determines the speed of a signal pulse within the medium, is related to the refractive index through the relation

$$n_g(\omega) = n(\omega) + \omega \frac{dn}{d\omega} \quad . \tag{1}$$

By taking the Hilbert transform of a Lorentzian fit to the experimentally measured gain curve, we can infer the refractive index change due to this Raman contribution, and Fig. 2 shows the phase and group-index changes as functions of wavelength. At the peak of the Raman resonance the total delay ΔT_D of the signal pulse in passing through the material due to the presence of the pump field is given by [24]

$$\Delta T_D = \frac{G}{\Gamma_R} \quad , \tag{2}$$

where $G = g_R I_p L$ is the Raman gain parameter, I_p is the pump intensity, and L is the length of the interaction region. The total Raman amplification experienced by the signal beam, that is, the ratio of the output signal power P_{out} to the input signal power P_{in}, is related to the gain parameter via $P_{out}/P_{in} = e^G$. Thus, the total delay experienced by the signal beam is linearly been made. While the Raman-based technique is compatible with existing telecommunication technology due to its ability to generate delays for pulses less than 1 ps in duration, the Raman bandwidth of silica glass is too large to produce significant delays at moderate pump powers and thus requires fiber lengths of ~1 km.

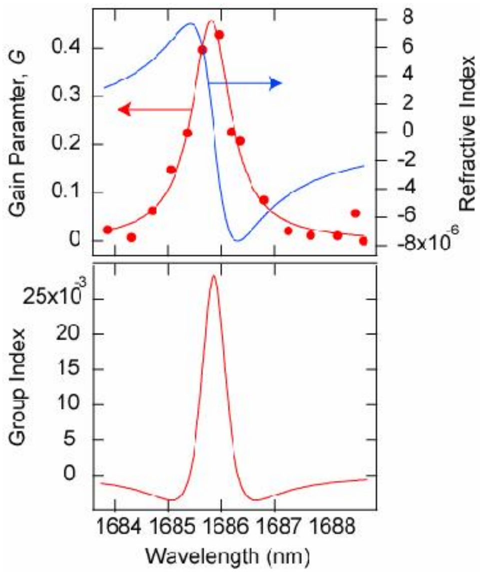

Fig. 1. Top: Measured Raman gain (solid circles) and inferred refractive index change as a function of wavelength, which is derived via the Kramers-Kronig relations from the Lorentzian best-fit curve of the experimental points. Bottom: Plot of the inferred group index as a function of wavelength derived from the index change in the top plot.

3. Experiment

By exploiting the larger Raman gain coefficient, narrower Raman linewidth, and highly confining geometries of silicon waveguides as compared to glass fibers, we generate large slow-light effects on chip. The source for our signal pulses is an optical parametric oscillator (OPO) with the central wavelength tuned to 1686.14 nm. The pulse bandwidth is 1.47 nm FWHM, which corresponds to a transform-limited pulsewidth of 2.67 ps. In order to generate the synchronous pump pulses, the OPO signal is detected using a fast photodiode and the photocurrent pulse is used to amplitude modulate a CW laser at 1549.97 nm to produce a pump pulse 50 ps in duration. This pump pulse is then amplified using an erbium-doped fiber amplifier (EDFA), and the signal and pump pulses are combined using a wavelength-division multiplexer (WDM) and coupled into the Si waveguide using an inverse nanotaper structure (see Fig. 2) [30]. The wavelengths of the pulses are adjusted such that the signal wavelength is at the peak of the Raman resonance. The waveguide sample consists of an 8-mm-long embedded waveguide with a silicon core cross section of 250 nm by 450 nm and a SiO_2 cladding. To measure the delay, we compare the signal pulse to a reference pulse (which does not interact with the pump) using Fourier transform spectral interferometry (FTSI) [29,31], which in our scheme allows for measurement of delays as small as 10 fs. A Michelson interferometer is used to generate signal and reference pulses. After both pulses go through relation between delay and gain (Eq. (1)) implies a Raman linewidth of 300 GHz. This value is larger than the Raman linewidth measured experimentally, and we conclude that this discrepancy results from the assumption of narrow pulse bandwidths compared to the Raman gain linewidth in the theory [32]. Since the bandwidth of the signal pulse is comparable to the linewidth of the Raman resonance, the spectral components near the edges of the pulse experience smaller induced delays than the central spectral components, which results in a reduced net pulse delay. Additionally, the gain in this case is limited by the bandwidth of the RF components used.

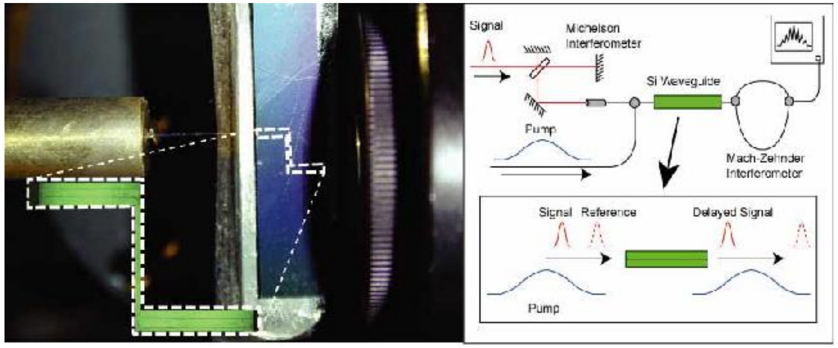

Fig. 2. Left: Experimental setup for coupling into the SOI planar waveguide. Right: Schematic configuration for generating and measuring delay. The signal and pump pulses are overlapped in time going into the waveguide.

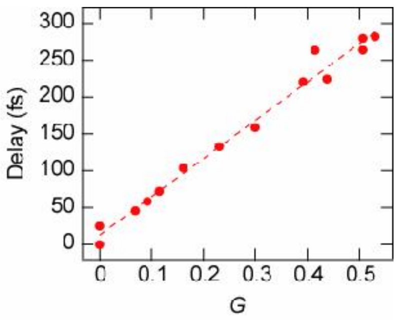

Fig. 3. Total measured delay as a function of the measured Raman gain parameter (dashed line represents the best fit to the data). Continuous tuning of the delay is generated between 0 and 282 fs. We observe the theoretically predicted linear relationship between the delay and the gain parameter.

To generate larger gain and, hence, larger delays, we take advantage of the dual wavelength output of the OPO in fs-mode. The OPO generates a short-wavelength pulse train having a broad spectrum ranging from 1540-1580 nm which can be spectrally filtered to obtain 7-ps pump pulses centered at 1549.97 nm. The long-wavelength pulse train has a spectrum ranging from 1660-1690 nm which is filtered to obtain signal pulses centered at 1686 nm. The pump pulses are amplified using an EDFA and are combined with the signal that can be achieved in a single-stage stimulated scattering system is limited to approximately 3, due to the occurrence of spontaneous scattering processes that deplete the pump wave [27] for very large values (>25) of G. However, this limitation can be overcome by using cascaded stages between which an absorber is placed to prevent the build-up of a spontaneously generated Stokes signal [28]. In such a cascaded configuration, additional care must be taken to ensure that the signal and pump pulses are synchronized when entering each amplification stage.

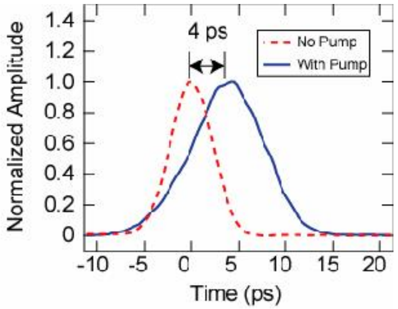

Fig. 4. Amplitude of the Fourier transformed interferograms with no pump pulse and with a pump pulse for which the total delay is 4 ps.

4. Conclusion

We have demonstrated tunable all-optical delays in a SOI waveguide with picosecond pulses, which represents the first step towards creating optically tunable dispersion on chip. The delay can be generated at any wavelength below the bandgap of silicon and is widely tunable since it is not constrained to a material or cavity resonance. Furthermore, the Raman linewidth in silicon makes it possible to support bandwidths associated with telecommunication pulses. Lastly, the short interaction length and pump-power dependent delay provide this scheme the advantage of having a fast reconfiguration time on the order of 70 GHz. This allows for tailored delay of individual pulses within a signal pulse train, provided that the pump pulse does not overlap with the subsequent pulse.

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