Tunable optical delay line in engineered slow light photonic crystal waveguides

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Abstract—**We propose a new design for compact tunable optical delay lines, based on adiabatic wavelength conversion and group velocity dispersion, in engineered silicon slow light photonic crystal waveguides. For a 3nm adiabatic wavelength shift, we obtain a simulated change in group index from n_g=25 to n_g=124.**

Keywords-tunable optical delay line; adiabatic tuning; photonic crystal waveguide; slow light; dispersion

I. Introduction

Tunable optical delay lines will provide an important functionality in future all-optical signal processing systems, to be employed in applications such as optical memories, optical packet switches and time division multiplexing. Different schemes have been proposed for generating tunable delays in miniaturised systems, mainly involving tuning chains of coupled cavities [1] or trapping and releasing optical pulses in a few resonators by dynamically varying their quality factors Q [2]. The former approach, however, requires the ability to precisely align and uniformly tune the resonant frequencies of many cavities; in the latter, the maximum achievable delay is limited by the photon lifetime. An alternative approach to realising tunable delay is based on wavelength conversion and dispersion: if an input signal is shifted in wavelength and coupled into a dispersive medium, it will propagate at a different speed with respect to an unshifted pulse, experiencing a different delay. Several demonstrations of tunable delay based on this technique have been reported using optical fibres as a dispersive medium, resulting in the highest optical delays to be observed [3]. Nevertheless, these solutions are extremely bulky and not suitable for integration with optoelectronic devices.

In this paper we investigate the possibility of realising a tunable optical delay line based on wavelength conversion and dispersion in compact silicon slow light photonic crystal (PhC) waveguides. Low-power adiabatic tuning is proposed as a means of achieving wavelength conversion.

II. Adiabatic Wavelength Conversion

Wavelength conversion in silicon is usually achieved through nonlinear optical effects such as four-wave mixing, which requires high pump powers and has very low efficiency (-20-30dB). Wavelength conversion may also be obtained through adiabatic tuning of an optical resonator, which is instead a linear effect: if the resonant frequency of a cavity is tuned whilst storing light, the wavelength of the light in the cavity follows the change in resonant wavelength [4]. This phenomenon is the optical equivalent of tuning a guitar string, and is relatively new in photonics, since it requires tuning of the system within the photon lifetime, which was not possible before the fabrication of high-Q cavities. Experimental observation of adiabatic wavelength conversion in a PhC cavity was reported in [5].

The same effect can also be obtained through use of slow light, since we may tune the properties of a waveguide while photons are present if light propagates slow enough, which is equivalent to a long photon lifetime in a cavity. This was recently demonstrated in the slow light regime of a short silicon W1 PhC waveguide, whose band diagram was blue-shifted by 0.39THz by illuminating the material with a pump pulse [6], with an estimated absorbed pump pulse energy of ~6pJ. Fig. 1 shows the output spectrum of the probe pulse as a function of the pump-probe delay τ. For τ<4ps the probe arrives before the pump, and therefore propagates in the unshifted band diagram. For τ>1ps the probe arrives after the pump and is reflected, since its frequency falls in the band gap of the blue-shifted band diagram. Around τ=-1ps pump and probe have maximum overlap, and the probe spectrum is adiabatically blue-shifted by 0.39THz, with an efficiency better than 80%.

III. Design

As adiabatic tuning is a linear effect, the relative frequency shift is proportional to the relative refractive index change, of the order of 10^{-3}-10^{-4}. Nevertheless, such a small frequency

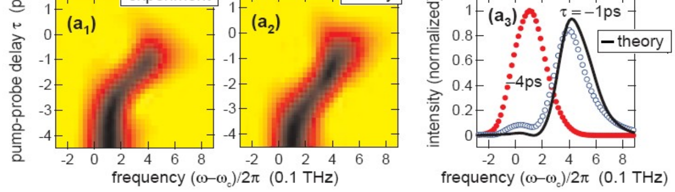

Figure 1. Adiabatic wavelength conversion in the slow light regime of a W1 PhC waveguide. (a1) Experimentally determined and (a2) calculated intensity spectra of the W1 waveguide response to a 1.3ps long input probe pulse at centre frequency $\omega_c/2\pi$=202THz, for different pump-probe delays τ. (a3) Measured and calculated output spectra at τ=-4ps and 1ps.

shift is sufficient for delay tuning if the dispersion of the subsequent medium is strong enough. This is in fact the case for the transition region from fast to slow light regime of dispersion-engineered slow light PhC waveguides obtained by shifting the position of the first two rows of holes adjacent to the line defect [7]. Such a waveguide will be therefore used as a dispersive section for a tunable delay line. The slow light modes of the very same waveguide, instead of the standard W1 used in [6], will be employed for adiabatic wavelength conversion.

The proposed photonic structure for achieving tunable delay through wavelength conversion and dispersion is an engineered slow light waveguide which acts both as a dispersive medium and, in its initial section, as frequency conversion component (Fig. 2). A signal pulse enters the structure in the slow light regime (Fig. 3a). Here, low group velocity and compression in space are both fundamental to accomplishing adiabatic blue-shift of light due to refractive index tuning. The blue-shifted pulse propagates through the waveguide and enters the untuned region (Fig. 3b), where its new frequency is associated with a faster mode.

IV. Results

A concrete example is given by the TE band diagram of Fig. 3 (red line), obtained through a 3D MPB (MIT Photonic Band) simulation of an engineered slow light waveguide realised in a 220nm thick silicon membrane (refractive index of 3.5), with lattice constant a=448nm, radius r=0.29a and displacements of the first and second rows of holes s_1=-0.11a and s_2=0.08a respectively, where shifts towards the waveguide centre are defined to be positive. The input wavelength of 1685.5nm corresponds to a group index n_g of ~124. According to [6], we may assume to be able to adiabatically blue-shift the signal wavelength up to ~3nm, where n_g is decreased to ~25. Given these quantities, the maximum achievable delay range Δt depends on the waveguide length L as $\Delta t = L\Delta n_g/c$. On the other hand, L is related to the minimum pulse duration T_0 allowed by group velocity dispersion, through the dispersion length expression $L = T_0^2/|\beta_{2,max}|$, where $\beta_2 = d^2k/d\omega^2$. If we aim at a delay-bandwidth product $\Delta t/T_0$ of 8 pulsewidths (i.e. one byte), the pulse duration T_0 may be taken as short as 7.8ps, corresponding to a dispersion length L of 189μm.

For the same band structure we can instead choose to maximise $\Delta t/T_0$ by increasing L. The maximum allowed length will depend on propagation loss α. Assuming that α increases linearly with n_g in the transition region between fast and slow light regime [8], we may estimate the maximum propagation loss α_{max} to be comparable with the maximum n_g. By setting the maximum overall loss to a reasonable value of 10dB, we find that a ~808μm long waveguide delays a 16ps pulse (allowed by dispersion) by 334ps for n_g~124 (untuned) and by 67ps for

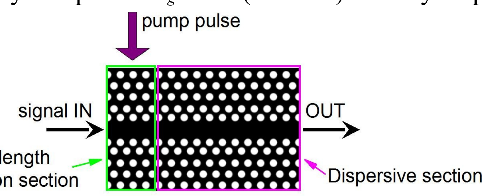

Figure 2. Schematic of the proposed tunable delay line based on wavelength conversion and dispersion in an engineered slow light PhC waveguide.

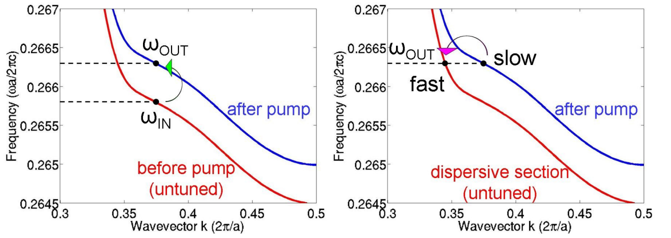

Figure 3. (a) Adiabatic wavelength conversion in an engineered PhC waveguide: an input pulse is blue-shifted, following the frequency shift of the fundamental TE mode. (b) Coupling of the blue-shifted pulse to the untuned dispersive section, where it propagates with a higher group velocity.

n_g~25 (tuned). This corresponds to a delay range of 267ps (~16 pulsewidths).

The length of the initial section for wavelength conversion is equal to the physical size of the input pulse which, propagating in a slow mode, is compressed in space. This is the only part of the waveguide needing tuning through carrier injection. The size of a pulse of time duration T_0 propagating at a group index n_g may be evaluated as $l = cT_0/n_g$. If n_g~124, we have l~19μm for T_0=7.8ps.

V. Conclusion

We have proposed a new design for realising a miniaturised tunable optical delay line, based on adiabatic wavelength conversion and group velocity dispersion in a silicon engineered slow light PhC waveguide.

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