

Adiabatic frequency conversion for optical data transfer

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Slow light in a photonic crystal waveguide provides a fast, efficient and reversible process for tuning light on a silicon chip.

Light is already used to transfer information over the largest scales in the optical fibers that carry present-day Internet traffic. Scaling this down to also use light for data transfer on silicon chips is a way to overcome the clock-speed limitation in computers. One of the main advantages to using light, compared to existing electrical methods, is that many channels can be routed down the same information pipe by frequency multiplexing, that is, encoding each channel with a different frequency. Besides increasing the bandwidth, using light saves on-chip ‘real estate’ and helps counter problems with heating. To realize this, we need to integrate a few basic optical-network functions onto the silicon chips, including switching or rerouting signals between different places and different channels. Changing channels involves changing the frequency of the light.

Frequency conversion is usually done using non-linear materials with schemes such as cross-gain modulation, four-wave mixing, or difference frequency generation. However, silicon has little access to these processes, and they require high optical powers to be efficient. Also, the outcome of such non-linear conversion processes depends on the signal pulses, and this signal-dependent behavior poses serious complications for the design and operation of efficient networks. Linear optics in silicon is the preferred method for cost and practicability.

We have demonstrated the frequency conversion of a pulse using a linear and adiabatic process in silicon photonic crystal slow-light waveguides.¹ We tune the modes of a waveguide while a light pulse is inside, as illustrated in Figure 1. If we shift the modes while the pulse is trapped inside the waveguide, then the frequency of the pulse will be tuned concurrently. The tuning mechanism is a change Δn in the refractive index of the silicon, and it is usually achieved by the application of an ultrafast pump-pulse at frequencies above the (electronic) band-gap of silicon. The pump-pulse is absorbed, generating

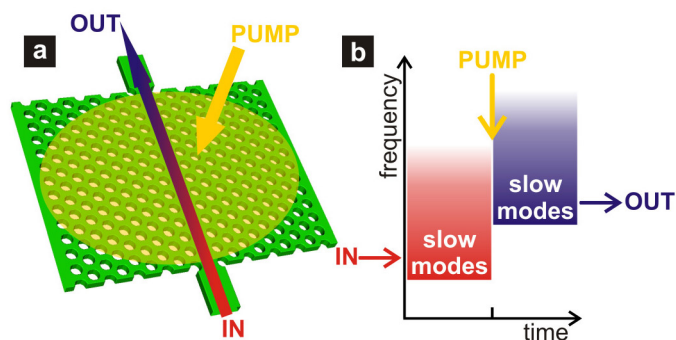


Figure 1. Illustration of the frequency conversion scheme. (a) The signal pulse is launched into our ‘W1’ photonic crystal waveguide, where it is acted upon by an ultrafast (100fs) pump pulse. The signal is blue-shifted before being output. (b) The mode spectrum of the waveguide as a function of time. The signal pulse is launched into the slow-light modes of the unperturbed waveguide, and the arrival of the pump-pulse blue-shifts the eigenfrequencies of these modes.

free electron-hole pairs, the presence of which reduces the refractive index due to the free-carrier dispersion effect.

Although 100% efficient in theory,² in practice two competing conditions must be fulfilled to observe efficient adiabatic conversions. First, for an adiabatic process, there must be no coupling out of the original mode to any other mode. This requires the external perturbation to act slowly. If the perturbation acts faster than the inverse frequency spacing between available modes of the system, then it will excite these modes, transferring power into them in a non-adiabatic manner. Second, only photons that are present when the perturbation acts will be converted, so for a high conversion efficiency, we need the maximum overlap between the pump and the signal. These conditions of slow perturbations and maximum overlap compete against one another in a kind of perfect storm. A slowly acting perturbation means that the signal pulse can travel large distances while it acts, which (in turn) increases the volume of silicon we need to pump to get maximum overlap.

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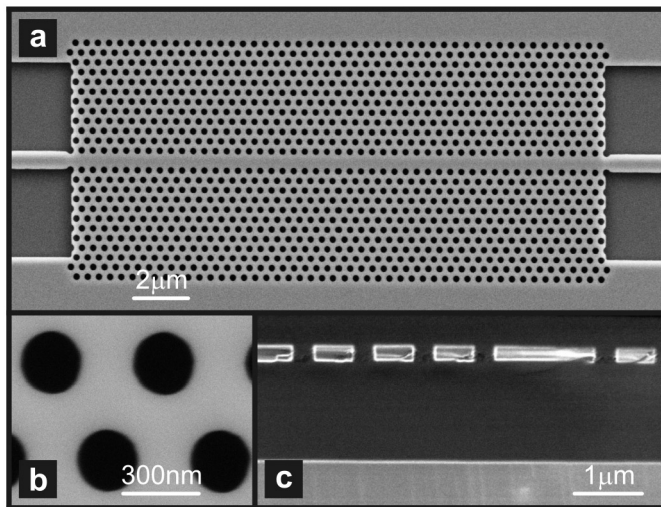


Figure 2. Scanning electron microscope images of the W1 photonic crystal waveguides. (a) Overall view of the waveguide from the top. (b) Close-up of the holes (of diameter 280nm and separation 390nm) perforating the silicon membrane. (c) Cross-section of the final device. The layer structure is (from the top) – silica top-cladding (550nm), silicon layer (220nm) perforated with holes, silica bottom-cladding (2 μ m), and finally the silicon substrate.

Others have tried to address this issue by trapping the light in a resonator. A high- Q cavity must be used, as the photon lifetime must be longer than the duration of the perturbation (for maximum overlap), which itself should be longer than the inverse frequency spacing (for adiabaticity), necessitating a small volume. However, it is difficult to contain an entire pulse in just one resonator in the time it takes to perturb the system, resulting in reduced conversion efficiencies such as 12% (for a shift of 0.1THz)³ or non-adiabatic transitions.⁴ Waveguide approaches are more scalable, as longer pulses can be accommodated by adjusting the length of the waveguide without affecting the mode spectrum. Therefore, waveguide approaches look more promising, especially if we could slow down the light to hold the entire pulse for longer.

We did this by using the slow-light modes of a specially designed photonic crystal waveguide known as a ‘W1’. Our W1 is a hexagonal array of air holes that perforate a 220nm thin silicon membrane, as shown schematically in Figure 1. The waveguide is only 19 μ m long and is formed by one row of missing holes from the hexagonal pattern (see Figure 2). Light is confined to the silicon membrane by total internal reflection and guided along the W1 by the photonic band-gap effect. Within certain frequency ranges, the guided light travels as slowly as a hundredth of the speed of light in air. This ‘slow light’ is a resonant

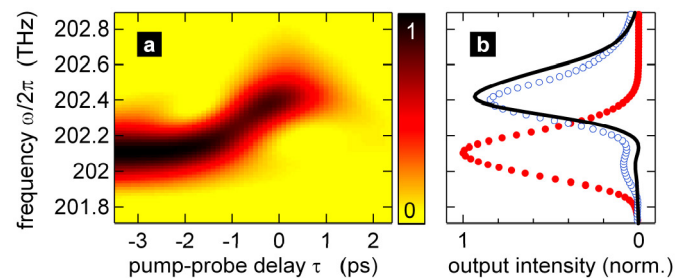


Figure 3. (a) Measured output intensity spectra from the W1 photonic crystal waveguide as a function of pump-probe delay. (b) Measured output spectra for an unperturbed waveguide ($\tau = -5ps$, red dots) and one displaying maximum overlap between pump and signal pulses ($\tau=0$, blue dots). The black line is the output predicted from an analytical theory based on an adiabatic process.

effect that occurs in periodic optical structures such as photonic crystals: the interference of forwards and backwards traveling components near the Bragg condition gives a slowly forward moving envelope.

To demonstrate the frequency conversion, we performed a pump-probe experiment using the slow-light photonic crystal waveguide. We launch the probe signal pulse into the slow-light modes relative to a delay time, τ , after the pump beam has perturbed the system. By measuring the spectral output as a function of the pump-probe delay τ , we can monitor the pump-induced changes to the system. Figure 3 shows the results.

Large negative delays ($\tau \ll 0$) mean that the signal pulse arrives before the pump, and so encounters the unperturbed photonic crystal waveguide and is transmitted in the slow modes present. For delays $\tau \gg 0$, the signal pulse arrives after the pump has perturbed the waveguide. There are no longer any modes present at the frequencies of the signal pulse, and so it is reflected; no output is seen.

For delays $\tau \approx 0$, the pump pulse arrives while the signal pulse is inside the waveguide. As long as we ensure that the length of the signal pulse is shorter than the transit time through the waveguide, the entire light pulse undergoes adiabatic conversion from its original frequency (around 200THz) to the frequency of the shifted eigenmodes. The conversion amounts to a blue-shift of 0.3THz with a demonstrated efficiency of 80%. Such a shift is large enough to switch a signal across several channels in a frequency multiplexing system. The adiabatic behavior may come as a surprise, since the modes in a waveguide have arbitrarily small frequency spacing. Here, the coupling of these modes (having different wavevectors) is prevented by homogeneous pumping of the waveguide.

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To enable efficient adiabatic frequency conversion of a light signal on a silicon chip, slow-light waveguide approaches such as ours seem the most promising, allowing us to trap and operate on entire pulses. The next major step is to demonstrate an integrated version, injecting the carriers that drive the frequency conversion on-chip, rather than generating them with an external laser pump pulse.

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