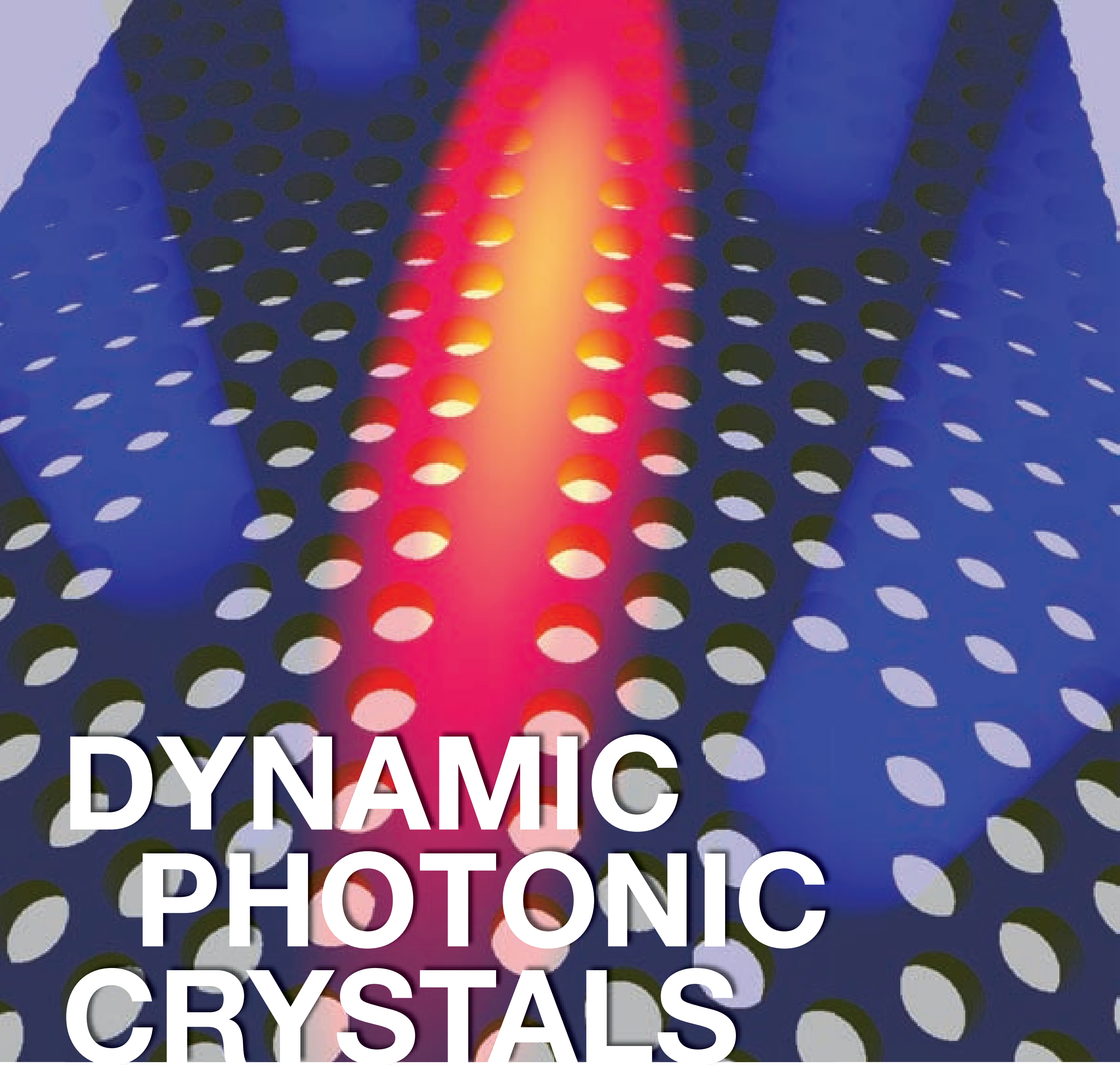

DYNAMIC PHOTONIC CRYSTALS

Shanhui Fan, Mehmet F. Yanik, Michelle L. Povinelli and Sunil Sandhu

When dynamic behaviors are introduced into photonic crystal systems, fascinating new possibilities emerge for controlling light. For example, the bandwidth of a pulse can be completely compressed to zero, resulting in on-chip all-optical stopping and storage of light pulses. The pulse spectrum can also be inverted around a center frequency to time-reverse an optical pulse.

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In their pioneering work, Eli Yablonovitch and Sajeev John introduced the concept of photonic crystals—which provides a basic platform for controlling the flow of light. Since then, researchers have predicted and demonstrated many important properties of these crystals, including the existence of the complete photonic band gap, the control of spontaneous emission and the construction of ultra-compact light-wave circuits. The band structures of perfect crystals, as well as the properties of the defect states, have also been studied in great detail.

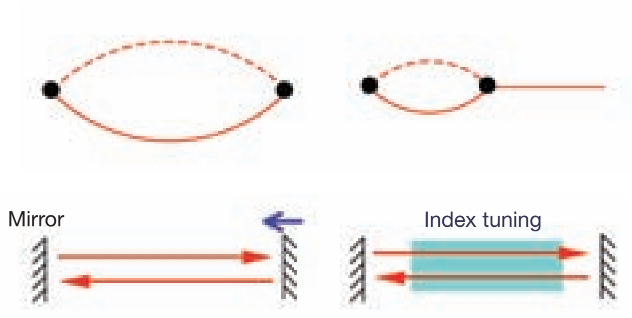
Recent research has therefore focused on functionalizing photonic crystal structures in order to exploit their remarkable properties to control even wider ranges of active, nonlinear and dynamic optical properties.

A dynamic photonic crystal is one in which the property of the crystal is modulated while a photon pulse is inside the crystal. The spectrum of the pulse can be molded at will with a small refractive index modulation, leading to highly useful information processing capabilities on a chip. For example, the bandwidth of a light pulse can be compressed to zero, resulting in all-optical stopping and storage of light. The spectrum of a light pulse can also be inverted to give a time-reversal operation.

A dynamic photonic crystal is one in which the property of the crystal is modulated while a photon pulse is inside the crystal.

One of the fundamental difficulties in integrated optics has been that different optical functionalities tend to require different material systems. For example, time-reversal is traditionally accomplished through phase-conjugation in nonlinear optical materials such as $LiNbO_3$, while light stopping has been demonstrated only in atomic gases under extreme conditions.

[Frequency conversion]



(Top) The frequency of a vibrating spring goes up as the length is shortened. (Bottom) The frequency of a photon can be changed by moving the cavity mirror or varying the refractive index of the material in the cavity while the photon is inside.

On the other hand, the small refractive index modulations that are required to create dynamic photonic crystals are readily achievable in standard optoelectronic systems. Thus, the use of dynamic photonic crystal structures, as we envision here, may provide a unifying platform for diverse optical information processing tasks in the future.

Molding the spectrum of light

By a dynamic photonic structure, we refer to the situation in which the structure is modulated while a photon is inside. Since such structure is not stationery, the frequency of the photon is not conserved. Consequently, a dynamic process immediately leads to the possibility of frequency conversion.

This concept of frequency conversion is familiar from everyday experience. If one shortens the length of a vibrating string (by, for example, sliding a finger down the string) the frequency of the vibration goes up—a process well known to anyone who has ever played a guitar. Similarly, in optics, the frequency of a photon inside a cavity increases if one simply shortens the length of the cavity or reduces the refractive index of the material inside the cavity.

In the case of refractive index modulation, the frequency shift is directly proportional to the fractional change of the index, while the modulation itself can be arbitrarily slow. (Similarly, in guitar playing, the characteristic frequency at which one slides the finger along the string is certainly much smaller compared with that of the acoustic vibration.) Thus, the dynamic process defined here differs fundamentally from typical nonlinear optical processes, where in order to convert the frequency of light from ω_1 to ω_2, modulations at a frequency $\omega_1 - \omega_2$ must be provided.

The main requirement for the dynamic frequency-conversion process is that the modulation occurs within the time-scale of the intrinsic cavity photon lifetime. In a macroscopic laser cavity, the implications of dynamic processes have been extensively discussed. For photonic crystals, the effects of frequency conversion have also been simulated in association with shock wave propagation. However, creating dynamic photonic crystals with standard optoelectronic technology becomes experimentally feasible only with the advent of high-Q cavities.

Principles for stopping and time-reversing light

Both stopping and time-reversing light require reversible tuning of the spectrum of a light pulse. One will therefore need to provide a physical space to accommodate the pulse while the modulation occurs. We use a periodic array of coupled resonators, sometimes referred to as the coupled resonator optical waveguide (CROW), and modulate its properties while a pulse is propagating through.

The general properties of high-dimensional dynamic systems are very complicated. For our purposes, however, it turns out to be sufficient to use the modulations that have the following two properties:

▸ *Translational invariance*

When the system is modulated as periodicity is maintained, the wavevector is conserved and the concept of a band structure still holds. The properties of the system can then be described in terms of a time-varying band structure.

▸ *Adiabaticity*

Assuming that the modulation is sufficiently slow, the frequency of each wave vector component of the photon pulse then follows that of the band structure. The time evolution of the band structure thus directly controls the spectrum of the photon pulse inside. (Therefore, the process is in fact analogous to guitar playing, but in wave vector space.)

Both stopping and time-reversing light require reversible tuning of the spectrum of a light pulse.

To stop light, one starts with a large bandwidth crystal to allow a pulse to enter the crystal, with each frequency component corresponding to a unique wave vector. Once the pulse has entered, the photonic band is then flattened. As a result, the pulse bandwidth is compressed to zero, and the pulse is stopped inside the crystal. To release the pulse, one simply reverses the process to decompress the bandwidth of the pulse.

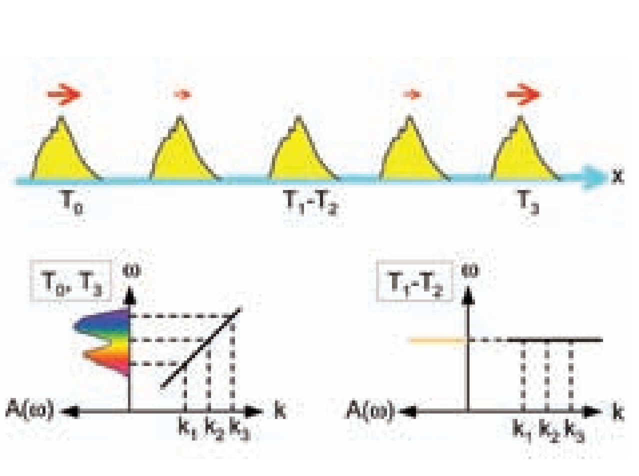
In this process, the delay of the pulse is no longer related to its bandwidth, and is instead entirely controlled by the user of the device. Thus, there is no longer a delay-bandwidth product constraint, which limits the performance of all delay line structures that are static. This process also preserves all information content of the incident pulse. Simulations have shown that the output pulse after this stop-and-release process has almost the same shape as the incident pulse, and in fact the dynamic process intrinsically suppresses the effect of dispersion that leads to pulse distortion.

For time-reversal purposes, one flips the slope of the photonic band to invert the pulse spectrum, which results in the reversal of a pulse in the time domain. Such a process is important for various signal-processing tasks, including dispersion compensation and image processing.

All-optical analogue to electromagnetically induced transparency

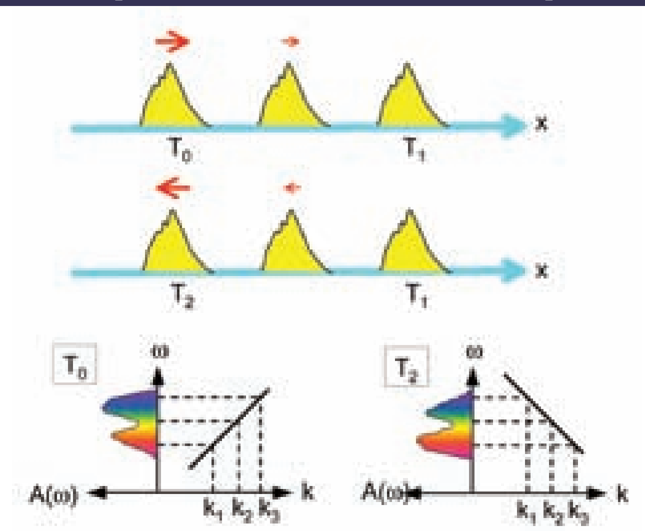
In order to create these dynamic processes, one needs to adjust the properties of a photonic crystal as a function of time. This can be accomplished by modulating the refractive

[The process for all-optical stopping of light]



(Top) a spatial waveform of a pulse at various times as it propagates through a dynamic photonic crystal. The length of the red arrows indicates the speed at which the pulse is propagating. (Bottom) Band structures of the medium when the pulse has just entered or exited the medium (left panel), and when the pulse is frozen inside the medium (right panel).

[The process for time-reversal of light]



(Top) Spatial waveform of a pulse at various times as it propagates through a dynamic photonic crystal. The red arrows indicate the direction at which the pulse is propagating. (Bottom) The band structure of the medium before (left panel) and after (right panel) the pulse has been time-reversed.

index, either by using electro-optics or nonlinear optics. However, the amount of refractive index tuning that can be accomplished with standard optoelectronics technology is generally quite small, with a fractional change typically on the order of 10^{-3} to 10^{-4}.

Therefore, interference schemes need to be devised in which a small refractive index modulation leads to a very large fractional change of the bandwidth of the system.

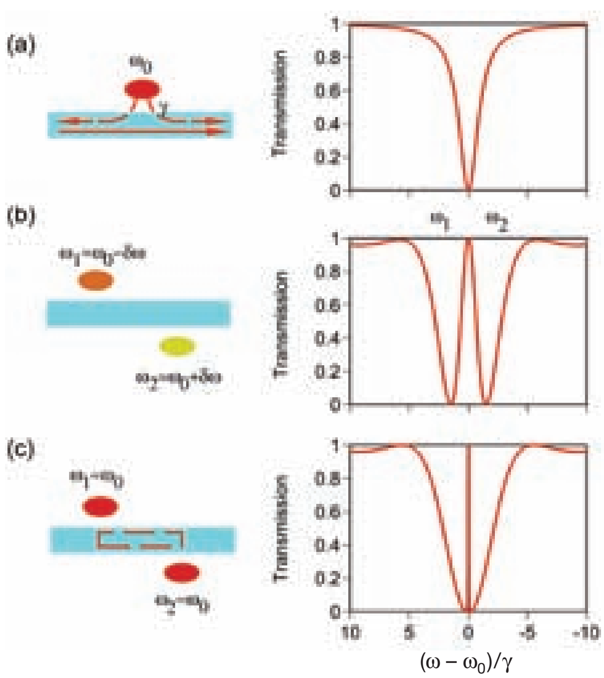
A particularly important system for resonant interference consists of a waveguide that is side-coupled to two standing-wave cavities (or, equivalently, two waveguides side-coupled to two ring resonators). This system represents an all-optical analogue of atomic systems exhibiting electromagnetically induced transparency (EIT). Each optical resonance here is analogous to the polarization between the energy levels in the EIT system.

To understand how this system works, first consider a mode in the waveguide passing through a single standing-wave cavity. At resonance, the incident wave excites the cavity. The power in the cavity decays along both the forward and backward directions. The decaying wave to the forward direction interferes destructively with the incoming wave, creating a narrow-band reflection in the vicinity of the resonant frequency. The width of the reflection band is controlled by the coupling strength of the waveguide and the cavity.

With a pair of cavities, and with the distance between the cavities appropriately chosen, a Fabry-Perot resonance is formed between the two standing wave cavities. The transmission spectrum features a sharp narrow transmission peak within the reflection band. This lineshape is identical to that of the EIT. For that reason, the sharp peak is sometimes referred to as the transparency resonance, even though the microscopic origins of the two effects are quite different.

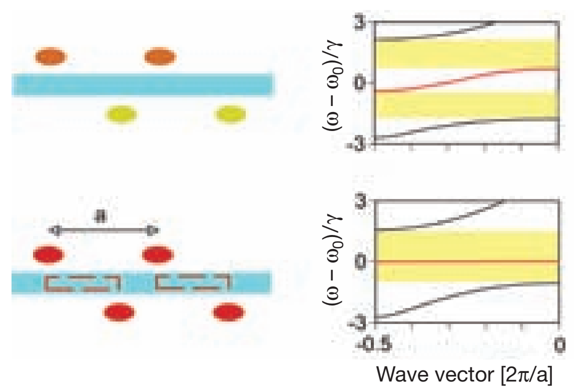
The width of the center peak becomes highly sensitive to the frequency detuning of the two cavities, and can in fact vanish,

[Creating an all-optical transparency resonance]



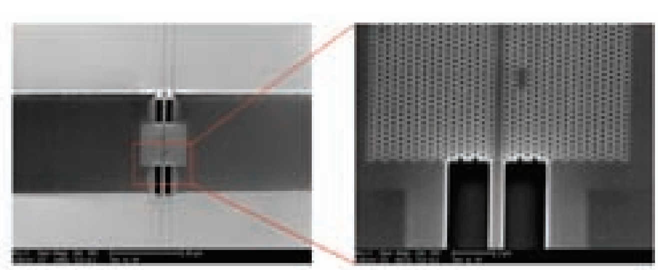
The long rectangles represent a single-mode waveguide, and the ellipses indicate standing-wave single mode cavities. The cavities have resonant frequency in the vicinity of ω_0, and couple to the waveguide at a rate $\gamma = 0.05\ \omega_0$. (a) Transmissions spectrum through a waveguide side-coupled to one cavity. The narrow band reflection in the vicinity of the resonant frequency arises from destructive interference between the incoming wave (solid arrow) and the decaying wave from the cavity (dashed arrow). (b) and (c) Transmission spectra through a waveguide side-coupled to two cavities. The distance along the waveguide between the cavities is $L_1 = 2\pi c/\omega_0$. The waveguide satisfies a dispersion relation $\beta(\omega) = \omega/c$, where c is the speed of light in the waveguide. In (b), $\omega_{1,2} = \omega_0 \pm 1.5\gamma$. In (c), $\omega_{1,2} = \omega_0 \pm 0.2\gamma$.

[From transparency resonance to a light-stopping system]



The left panel shows two unit cells of the coupled cavity structure considered, and the right panel is the corresponding band diagrams. Yellow regions represent the photonic band gap. The band that is used to stop light is in red. The bands are calculated using the same waveguide and cavity parameters as in (b) and (c) in the figure on the left, with the additional parameter $a = 1.7\ L_1$.

[Fabricated silicon photonic crystal]



A crystal fabricated for the purpose of demonstrating an all-optical analogue to electromagnetically induced transparency.

(Jun Pan, Yijie Huo, Prof. Martin Fejer and Prof. James Harris, Stanford University, unpublished results.)

resulting in a resonator with an infinite lifetime. In this instance, the two standing-wave cavities have the same resonant frequency, at which the roundtrip phase is exactly $2n\pi$.

By cascading such resonator pairs, one creates an array with a band structure that is highly sensitive to small shifts of the resonant frequencies. In fact, both light stopping and time reversal can be accomplished in this class of systems. While this is by no means the only kind of resonator arrangement for stopping light, this system actually allows maximal bandwidth compression for a given strength of refractive index modulation. Moreover, the presence of a band that has zero group velocity over the entire first Brillouin zone significantly suppresses dispersion effects that commonly occur in slow light systems.

In the past two years, critical progress has been made towards demonstrating many of the predicted dynamic and interference effects.

Experimental status and outlook

In the all-optical light-stopping scheme, the achievable bandwidths are on the order of 20 GHz for a small refractive index shift of $\delta n/n=10^{-4}$ (which is achievable in practical optoelectronic devices) and assuming a carrier frequency of approximately 200 THz, as used in optical communications. Such bandwidths are comparable to that of a single wavelength channel in high-speed optical systems. The storage times are limited only by the cavity lifetimes, which may eventually approach millisecond time scales, as restricted by residual loss in transparent materials.

The loss in optical resonator systems might be further counteracted with the use of gain media in the cavities, or with external amplification. With such performance, the capabilities for the on-chip stopping of light should have important implications for optical communication systems. Moreover, this occurs as a linear optics process at a single photon level, and should thus be important for quantum optics applications as well.

In the past two years, critical progress has been made towards demonstrating many of the predicted dynamic and interference effects. In particular, Michal Lipson's group at Cornell has observed the EIT-like two-cavity interference, as well as strongly tunable delay, using micro-ring cavities on a silicon chip. Experiments are currently ongoing at Stanford to observe EIT-like interference effects in photonic crystals.

Researchers have directly simulated frequency conversion due to refractive index tuning using three-dimensional finite-difference time-domain simulations. They are also developing alternative resonator configurations for dynamic stopping and storage of light. The use of dynamics in photonic crystals will open the door to on-chip information processing capabilities that are truly unprecedented.

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