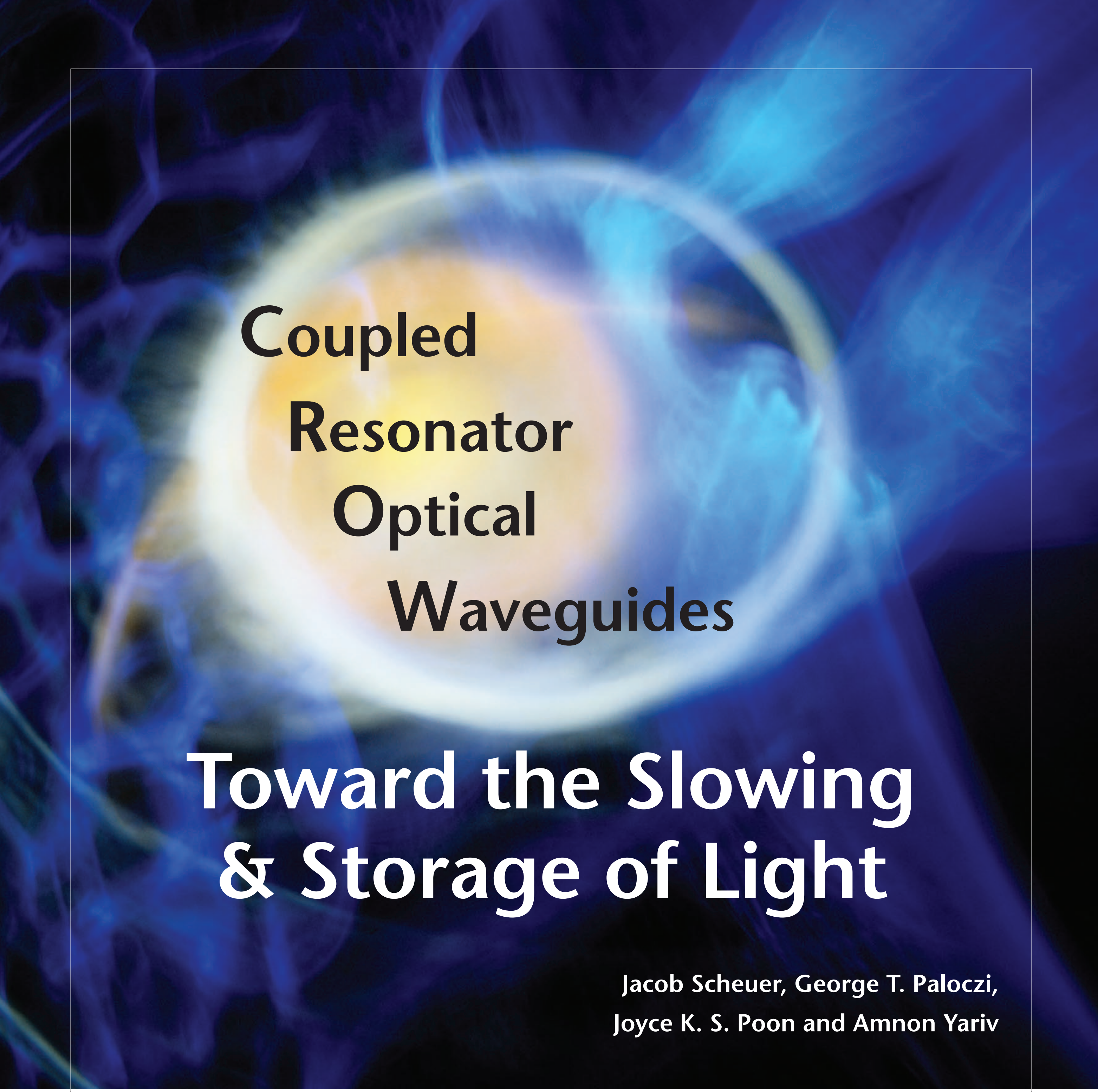

Coupled Resonator Optical Waveguides

Toward the Slowing & Storage of Light

Jacob Scheuer, George T. Paloczi, Joyce K. S. Poon and Amnon Yariv

The development of a simple solid-state-based technology to slow the propagation of light could prove an important step in the realization of the high-bit-rate communication systems of the future. Coherent atom-photon interactions have been used to demonstrate significant slowing and even freezing of light, but it is not easy to integrate this approach with conventional planar lightwave circuit technology. The authors explore the possibility of using coupled resonator optical waveguides (CROWs) as practical elements to slow and store light pulses.

The speed of light, one of the most fundamental quantities in nature, underlies many of the basic properties of the universe. The velocity of a pulse of light propagating in any medium (homogeneous or inhomogeneous) is determined by the group index n_g, a magnitude which should not be confused with the refractive index of the medium. The group velocity, given by $v_g = c/n_g$, where c is the speed of light in vacuum, is determined not only by the refractive

1047-6938/05/02/0036/5-$0015.00

index of the medium but also by the dispersive characteristics of the structure.

$$n_g = n + \omega \frac{\partial n}{\partial \omega}$$

The first term on the right-hand side of the equation is the index of refraction; the second term is the dispersion of the medium or, in other words, the dependence of the refractive index on the optical frequency. Depending on the properties of the medium and on the physical structure in which the light propagates, the group velocity can differ significantly from the phase velocity ($v_p = c/n$, with n being the index of refraction). The overall dispersion experienced by the wave packet can be divided into two contributions: material dispersion, which stems from the electronic configuration of the medium; and structural dispersion, which stems from the geometrical properties of the structure (e.g., the waveguide) in which the light propagates.

In a passive linear medium, the group velocity is generally slower than the phase velocity and than the speed of light in vacuum. Although the extremely high speed of light is often considered an advantage for communications systems, slow light propagation has been the object of growing interest. Low group velocity, for example, significantly reduces the input power thresholds for the observation of various nonlinear mechanisms. A reduction of the speed of light can also be useful for practical applications such as delay lines, optical memories and low-threshold lasers.

There are several ways to reduce the group velocity of light. The most straightforward is to let the light propagate in a medium which has a large index of refraction, n. Although such an approach is simple, its application is limited by the availability of optically transparent materials with a high—say $n > 4$—index of refraction. A more promising approach is to exploit the dependence of the group index, hence the group velocity, on the dispersion of the guiding medium ($\omega \partial n / \partial \omega$). Although materials can be highly dispersive close to an electronic resonant transition, such transitions are typically accompanied by large absorption, which induces large

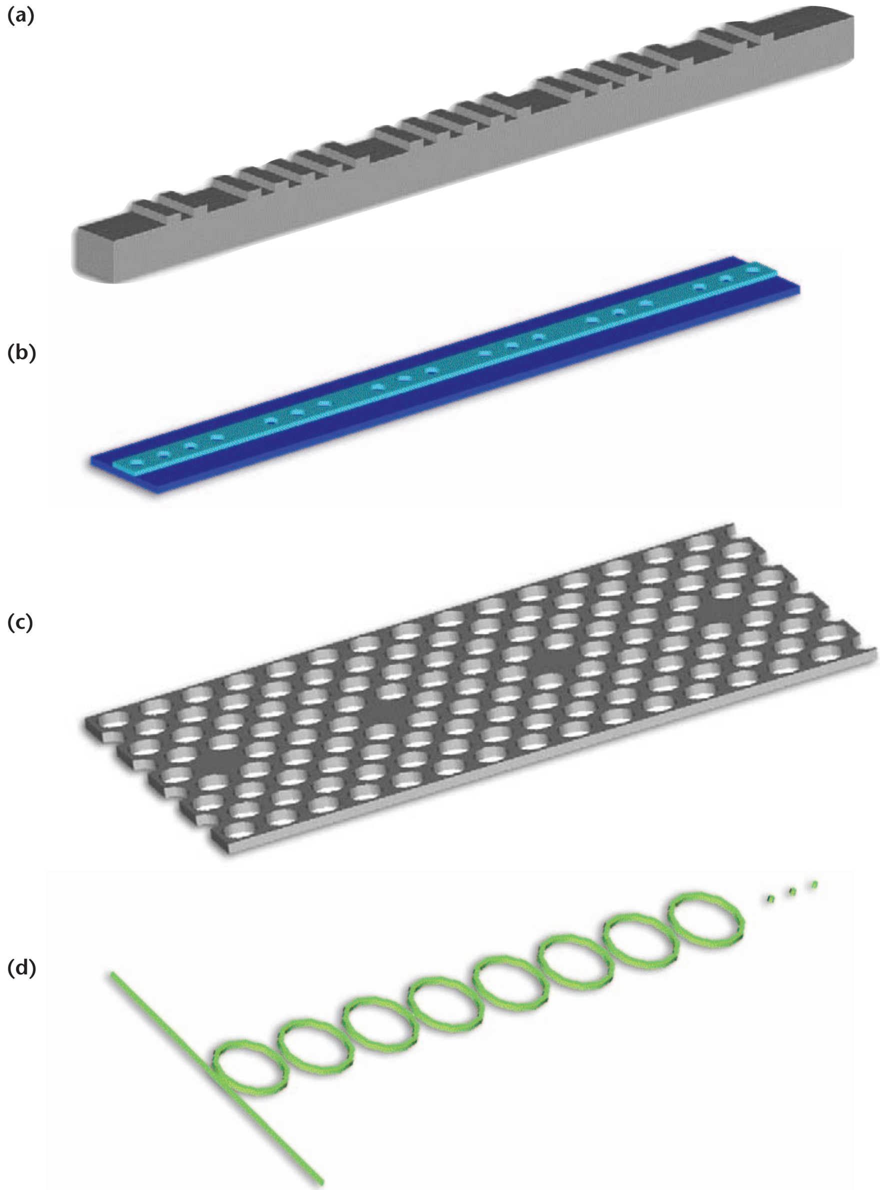

Figure 1. Various implementations of CROWs: (a) coupled Fabry-Pérot cavities; (b) one-dimensional (1D) coupled photonic crystal defects; (c) 2D coupled photonic crystal defects; (d) coupled microring resonators.

losses. The large absorption can, however, be significantly suppressed if a three-level medium is prepared in a specific quantum state and illuminated simultaneously with two laser sources at the transition frequencies of $|2\rangle \rightarrow |3\rangle$ and $|3\rangle \rightarrow |1\rangle$. The combined effect of the two sources on the initial quantum state (which is a specific superposition of $|1\rangle$ and $|2\rangle$) induces a destructive interference in the third level and suppresses the absorption. This effect, electromagnetically induced transparency (EIT), was recently used to demonstrate light velocity as slow as 17 m/s [Ref. 1].

Although EIT can produce significant slowing of light, it is not simple to implement in practical systems. A more technologically attractive approach to use of atomic/electronic resonances is the realization of large structural dispersion by appropriate engineering of the structure in which the light propagates. Slow-light structures based on engineered dispersion

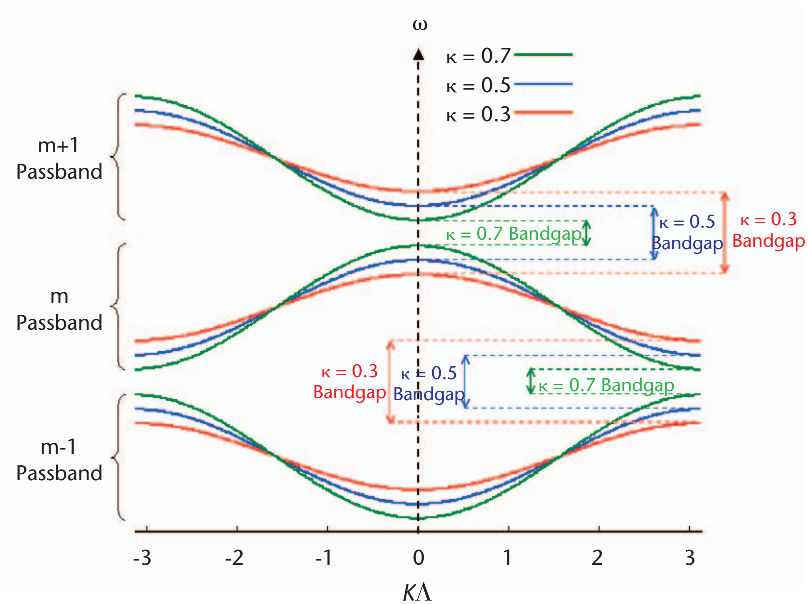

Figure 2. Dispersion curves for an infinite CROW for intracavity coupling ratios of 0.3 (*red*), 0.5 (*blue*) and 0.7 (*green*).

are not limited to wavelengths in the vicinity of a transition line; they can be designed for any desired wavelength. Moreover, the spectral properties of such structures can be dynamically tuned by changing the refractive index of the structure, for example, by use of the electro-optic effect or the thermo-optic effect.

Slow light propagation in periodic structures

Optical periodic structures have received significant attention in the past few decades, primarily because they contain a spectral gap in which optical frequencies cannot propagate. Periodic structures also offer the opportunity of engineering structural dispersion properties and hence, controlling the group velocity of light.[2,3]

A coupled resonator optical waveguide (CROW)[4] is a periodic structure that comprises a chain of resonators in which the light propagates by virtue of the coupling between adjacent resonators (see Fig. 1). Heuristically, the slowing of light is achieved by letting it bounce back and forth (in Fabry-Pérot cavities) or circulate (in circular cavities) in the resonators while it slowly tunnels from one resonator to another. Figure 1 depicts four possible implementations of CROWs: (a) Fabry-Pérot (FP) cavities; (b) one-dimensional (1D) photonic crystal (PC) cavities; (c) 2D PC cavities; and (d) ring resonators. Although the implementations differ in fine details such as the confinement and coupling mechanisms, the general characteristics (dispersion relation, band structure, etc.) are very similar and are determined primarily by the free spectral range (FSR), the quality-factor (Q) of each resonator and the coupling between adjacent resonators.

Figure 2 shows typical dispersion curves for an infinite, lossless CROW for various coupling coefficients. The propagating waves in the CROW are arranged in bands centered on the resonance frequencies of the individual resonators. For some frequency ranges, the corresponding wave numbers are complex. The frequency ranges described by these wave numbers belong to the bandgaps of the periodic structure and cannot propagate in the CROW. The group velocity in a CROW, which corresponds to the slope of the dispersion curve, depends on the coupling ratio k between the resonators and the FSR, and is given by $|v_g|=2\Lambda\cdot \mathrm{FSR}|\kappa \sin(\Lambda K)|$ where Λ is the periodicity of the CROW and K is the effective wave number. Close to the edges of the passbands, the group velocity is very low; at the edge itself, the group velocity is equal to zero. At the edge itself, however, the dependence of v_g of the frequency [or, in other words, the group velocity dispersion (GVD)], is very strong. The immediate consequence is that a pulse propagating in that particular spectral region is severely distorted. At the resonance of the individual resonators, on the other hand, the GVD (and, therefore, the distortion at the center of the passband) is minimal but the group velocity is maximal; it can be given by $|v_g|_{\mathrm{Cent}}=2\Lambda\cdot \mathrm{FSR}\cdot|\kappa|$. Although the group velocity is maximal within the passband, it can be decreased almost arbitrarily by a reduction in the FSR of each resonator in the CROW and by reducing the coupling coefficient between the resonators. Intuitively, the impact of these parameters on the group velocity is as follows: a reduction in the coupling coefficient between adjacent resonators increases the time it takes for the light to tunnel from one resonator to its neighbor; a decrease in the FSR, which is equivalent to an elongation of the optical path in the resonator, increases the round-trip time. Both actions effectively prolong the time the pulse "spends" in each resonator, giving rise to a slower propagation velocity.

Delay, loss and bandwidth

The significant slowing of light that can be achieved by reducing the FSR and κ is not accomplished without drawbacks. Reducing the coupling (or the FSR) decreases the available bandwidth of the passband (see Fig. 1). A smaller coupling coefficient implies that the light remains longer in each resonator and thus that a stricter tolerance is imposed on the deviation of the optical frequency from the resonance frequencies of the resonators. In addition to reducing the usable bandwidth, reducing the coupling (or the FSR) may increase the overall loss in the CROW. In an ideal CROW which consists of loss-less resonators, light propagates without loss regardless of the number of resonators and the coupling between them. Passive resonators, on the other hand, have losses due to surface scattering, material absorption and waveguide-bending radiation. The more times the light circulates in each resonator, the larger the loss experienced by the pulse as it propagates along the CROW.[5]

One of the most attractive applications for a CROW is as an optical delay line. Optical delay lines have numerous applications in areas which include: optical processing (e.g., demultiplexing, buffering and synchronization); telecommunications; true time delay for broadband phased-array antennas; and interferometry. A good delay line should be compact and exhibit large delay, yet have low losses and wide bandwidth. As mentioned above, however, in a CROW delay line there are tradeoffs among achievable delay, usable bandwidth and overall loss. These quantities can be approximated by:

$$\tau=\frac{N}{2|\kappa|\mathrm{FSR}};\ \Delta\omega_{\mathrm{use}}=2|\kappa|\mathrm{FSR};\ \mathrm{Loss}=\frac{\alpha L_{RT}N}{|\kappa|}$$

where N is the number of resonators in the delay line, L_{RT} is the physical round-trip length of each resonator and α is the propagation loss. The direct tradeoff between the delay and the bandwidth is clearly seen because their product, $\Delta\omega_{\mathrm{use}}\tau=N$, depends only on the number of resonators. Figure 3 illustrates these tradeoffs for a CROW consisting of 10 coupled ring resonators having a FSR of 310 GHz and propagation loss of 4 dB/cm. The markers show the exact results computed numerically, while the lines are the analytic approximations. To achieve a long delay, a small coupling—which decreases the bandwidth of the CROW—is required, and the overall loss of the CROW becomes more sensitive to the intrinsic losses in the individual resonator. As a result, the limiting factor of the bandwidth-delay product is the acceptable loss of the delay line and the achievement of long delays requires resonators with high Qs.

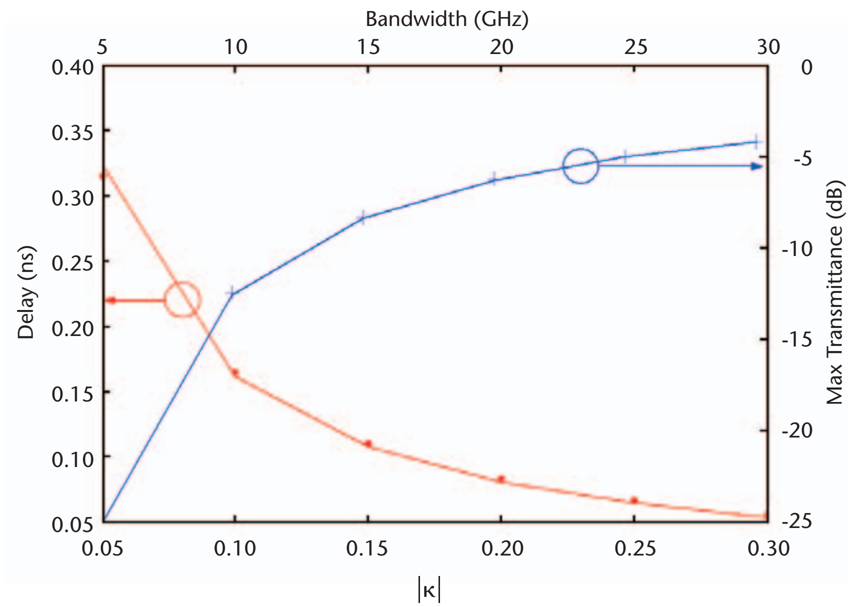

Figure 3. Tradeoffs among delay (*red*), losses (*blue*) and bandwidth for a CROW consisting of 10 coupled ring resonators having a FSR of 310 GHz and propagation loss of 4 dB/cm.

Nonlinear mechanisms: frozen (stored) light

Dynamic storage of optical information (optical "RAM") is an enabling technology for future high-data-rate communications systems that employ all-optical packet switching. Many of the essential operations in such systems, including header processing and error correction, require direct access to the optical data. An interesting approach to storing light is to slow its group velocity to zero. In this case, the light pulse is frozen—and thus stored indefinitely—inside the "ultimate" delay line. As mentioned above, the dispersion curve of the CROW includes a zero group velocity point at the edge of the passband and therefore supports, in principle, light storage. Unfortunately, however, the GVD is maximal at this point, which means that the stored pulses will broaden and that data will eventually be lost. If, on the other hand, the CROW consists of a medium with a self-focusing Kerr nonlinearity, the GVD can be compensated completely. The local refractive index in a Kerr medium depends on the local intensity of the electric field. In a self-focusing Kerr medium, for larger intensities the index of refraction increases. As a result, a bell-shaped pulse of the proper profile (hyperbolic secant) induces an effective temporal lens, or waveguide, that can counteract the broadening effect of dispersion. Such wave forms, which are known as solitons, can be found in many nonlinear systems. For a bright soliton solution to be supported, the transmission channel must have anomalous GVD and self-focusing Kerr nonlinearity. It is also necessary for the higher order dispersion terms to be small because the Kerr effect cannot compensate for them and for the GVD simultaneously. The velocity of the soliton pulse is the channel's group velocity at the optical frequency. These requirements are fulfilled at the edge of the CROW's passband, where in addition to zero group velocity, the third order dispersion is zero and thus the frozen soliton does not disperse to a significant extent.[6]

Since the same device can be used to achieve both delay and storage, CROWs are a highly attractive option for delay lines. Moreover, the only difference between a CROW delay line and a CROW buffer is the band structure, which can be changed dynamically. Depending on the circumstances, the role of CROWs in communication systems can thus be toggled dynamically from delay line to buffer.

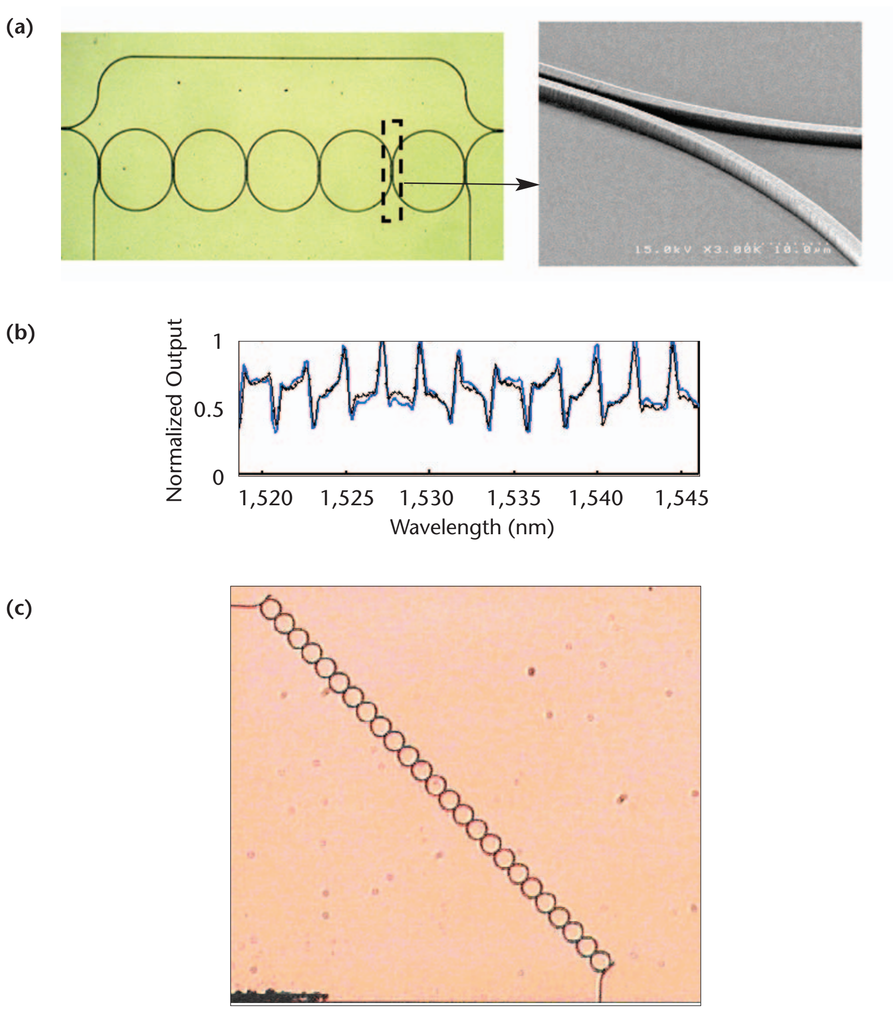

Figure 4. (a) Optical image of the CROW-MZI and SEM zoom of the coupling region; (b) Theoretical fit (*blue*) and a measurement (*black*) of the CROW-MZI transmission. The fit parameters are κ = 0.46 and loss is 30 dB/cm; (c) CROW consisting of 25 resonators.

Experimental progress

Studies of the optical characteristics of CROWs began shortly after they were first proposed. To date, modest delays at optical frequencies (~ 1 ps) have been achieved by means of a CROW consisting of one-dimensional (1D) photonic crystal defect cavities [see Fig. 1(b)]. Although CROWs consisting of 2D PC cavities and Bragg stacks have also been studied, to date no substantial delays have been demonstrated.

Among the various possibilities shown in Fig. 1, the most promising building block for implementation of a CROW delay line is likely to be the microring resonator. Single-mode, high Q ($> 10^6$), planar-technology-based microrings are being fabricated by many research groups as well as by several companies. The realization of microrings is simple: a single fabrication step is all that is required, and there is no need for ultrahigh-resolution lithography.

Figure 4(a) depicts a Mach-Zehnder interferometer (MZI) in which one of the arms consists of a microring-based CROW.[7] With this device, it is possible to study the wavelength dependent phase characteristics (i.e., the dispersion) of the CROW which determine the delay. The waveguides, consisting of SU-8 core material, are written directly on thermally grown silicon-oxide lower-clad by use of electron-beam lithography. The dimensions of the core are 1.6 μm x 2.0 μm and the circumference of the resonators is ~730 μm, which yields an FSR of ~ 2.2 nm.

Figure 4(b) shows the theoretical fit (blue) of the CROW-MZI transmission superimposed on the experimental data (black) of the power transmission of the actual device. According to the fit, the average delay of the device is ~ 4 ps and the average loss is ~3 dB per resonator. Although the loss characteristics may seem less than ideal, with improvements in the waveguides (loss of ~ 1 dB/cm), one can obtain a significantly reduced loss of ~ 0.1 dB/resonator. It should be emphasized that the unique characteristics of a CROW (dispersion curve, group delay, usable bandwidth, etc.) are only achievable in a device that consists of a large number of resonators. Figure 4(c) depicts an optical image of such a device, comprised of 25 coupled resonators.

Summary

The coupled resonator waveguide concept offers a path to the realization of slow propagating light in practical systems. With state-of-the-art waveguide technology, it is possible to realize substantial delays at reasonable loss and bandwidth. Microring resonators exhibit high potential for the realization of practical, low-loss, conventional waveguide-compatible CROWs. Tunable microresonator based CROWs with Kerr nonlinearity can enable a variety of all-optical processing operations and pave the way to future high-data-rate communications systems.

Acknowledgment

This research was supported by the Defense Advanced Research Projects Agency and by the Air Force Office for Scientific Research.

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